Plate motions: fundamentals

- Assume a pie-shaped wedge plate B, rotating around E (=rotation pole) with respect to a fixed plate A.
  - Angular velocity of B with respect to A = ${}_{A}\omega_{B}$ (rad/yr)
  - Linear velocity of point b on plate B with respect to A: $V_b = r \times {}_{A}\omega_{B}$
  - Ex: ${}_{A}\omega_{B}$ = 10-8 rad/yr and r = 1000 km $\Rightarrow V_b = 1$ cm/yr.
- **Velocity field** = ensemble of vectors that show linear velocities on a plate
- Velocities (linear) on plate B increase with distance from the rotation pole E
- What about strain?

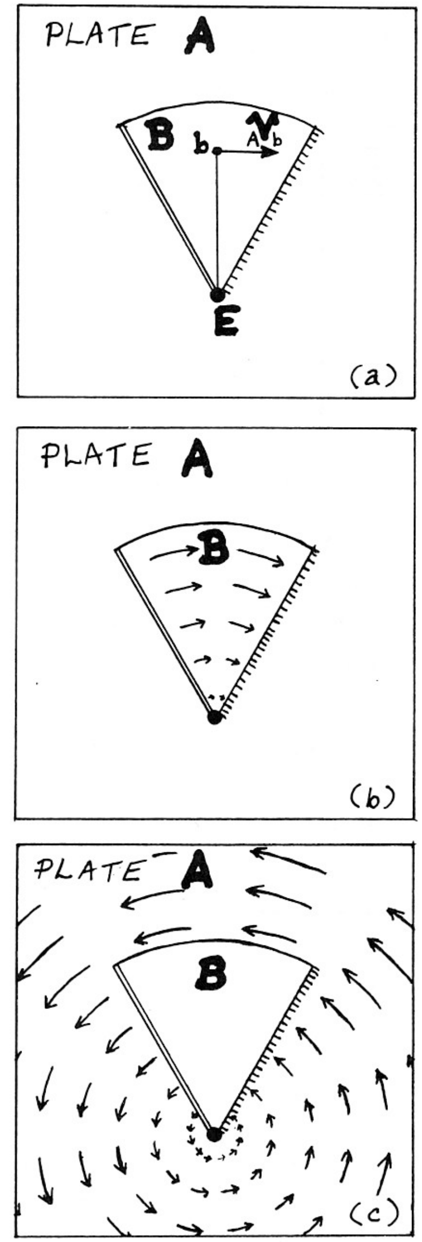


Plate motions: fundamentals

- A more realistic plate B, moving with respect to plate A assumed fixed
- Transforms:
  - Arcs centered on E = small circles
  - Parallel to the linear velocity of points along (near) them
- Ridges:
  - Usually linear
  - Usually perpendicular to transform faults
  - Usually perpendicular to the linear velocity of points along (near) them
- Trenches:
  - Usually not linear
  - Not necessarily perpendicular to the linear velocity of points along (near) them

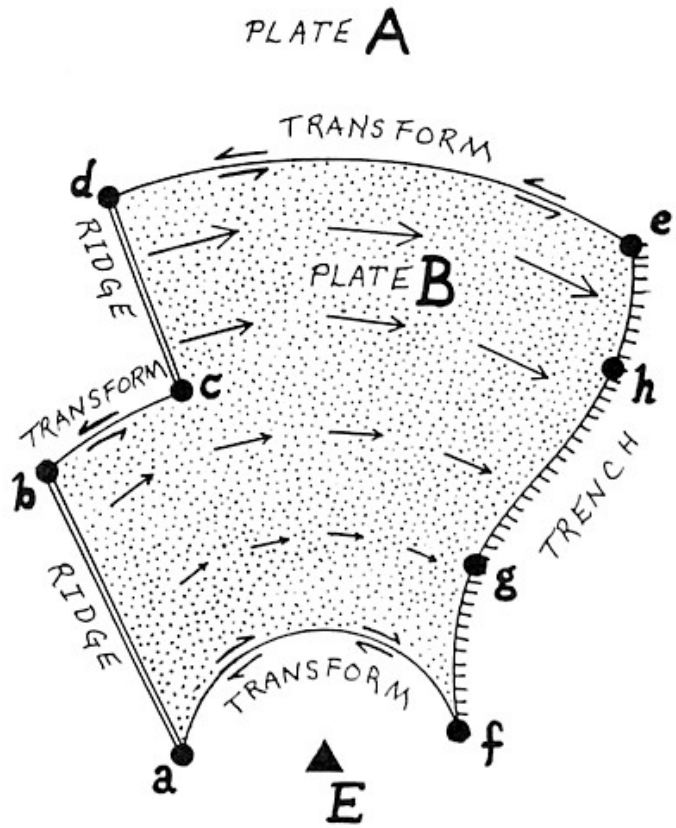
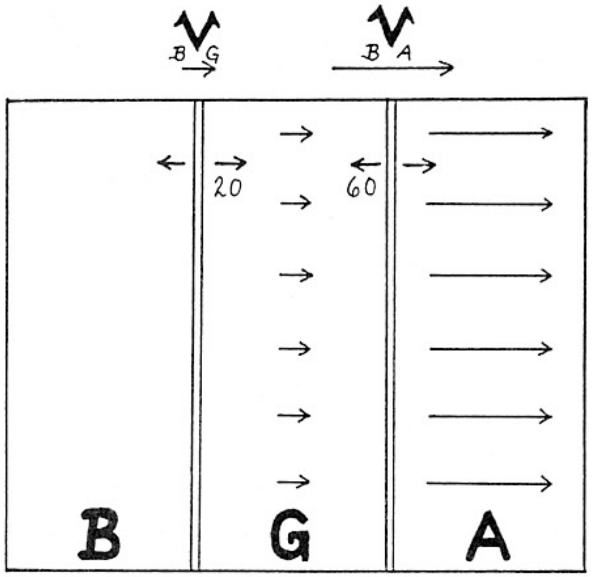
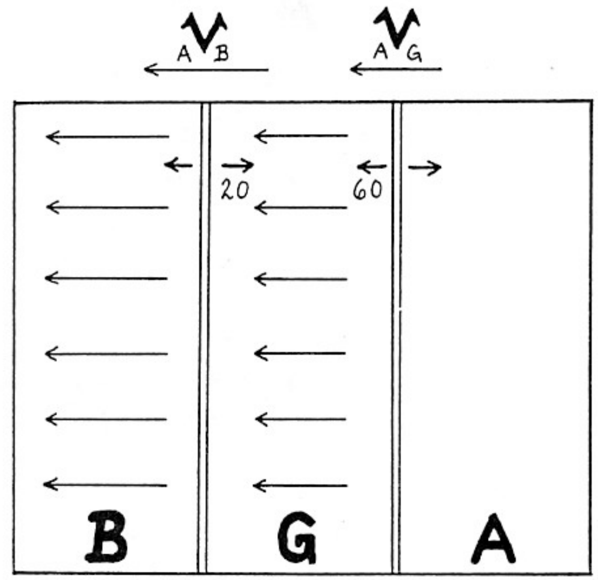


Plate motions: fundamentals



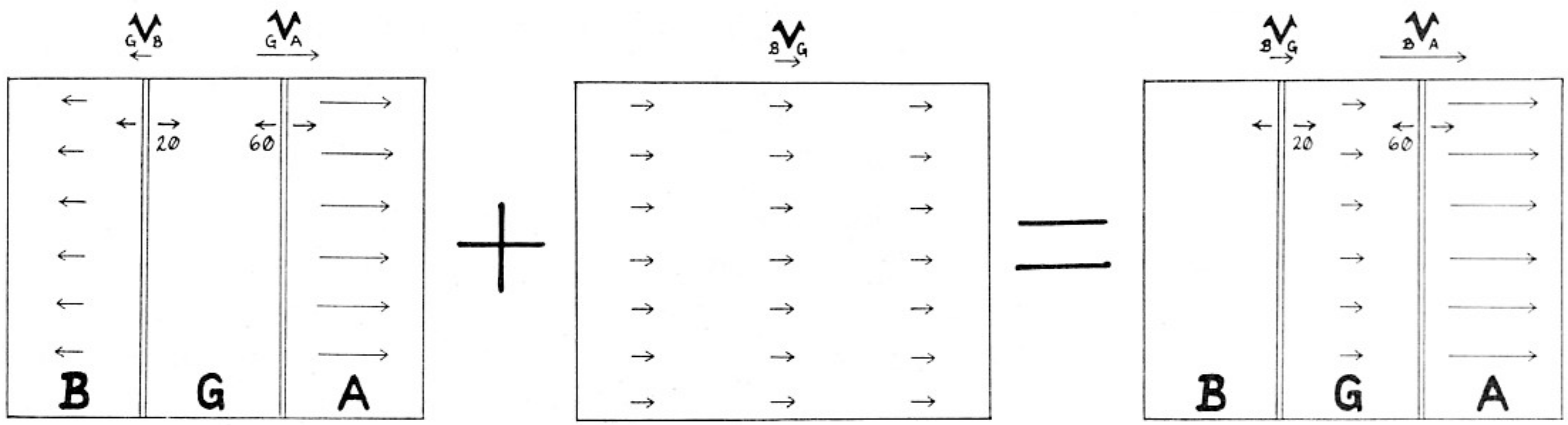
Assuming plate B fixed and 2 spreading centers at 20 and 60 mm/yr



Same, assuming plate A fixed

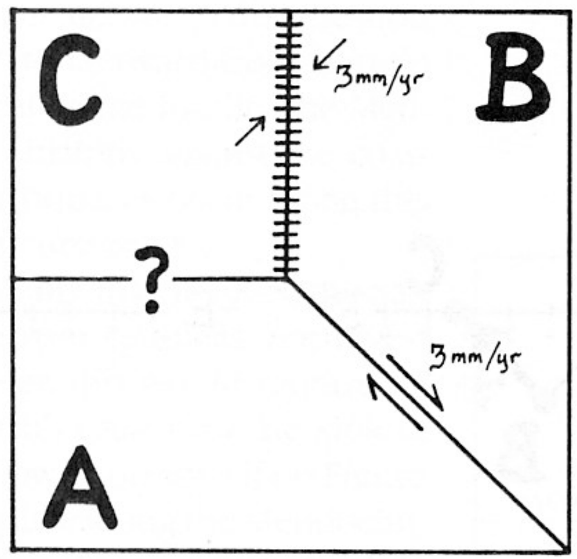
- Velocities are relative (to a reference plate)
- Reference plate can be changed

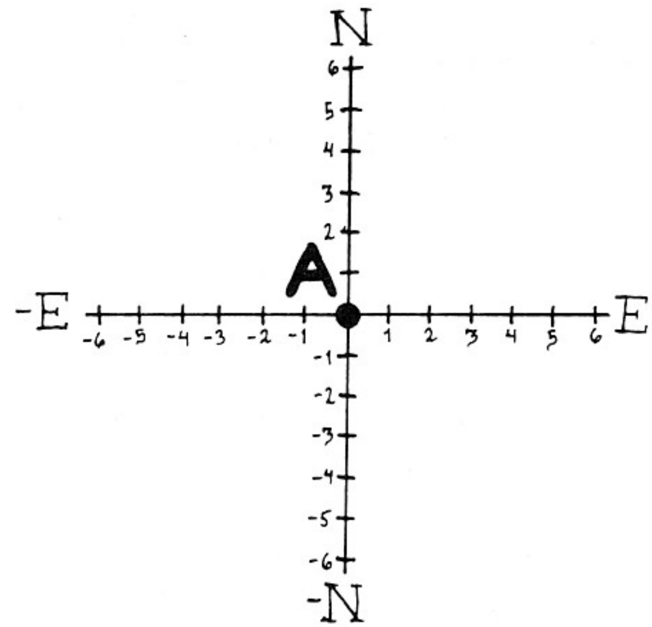
Plate motions: fundamentals



- Changing the reference plate = subtracting a constant velocity field to all plates (the velocity field of the new reference plate)
- What about "real life" rotations…?

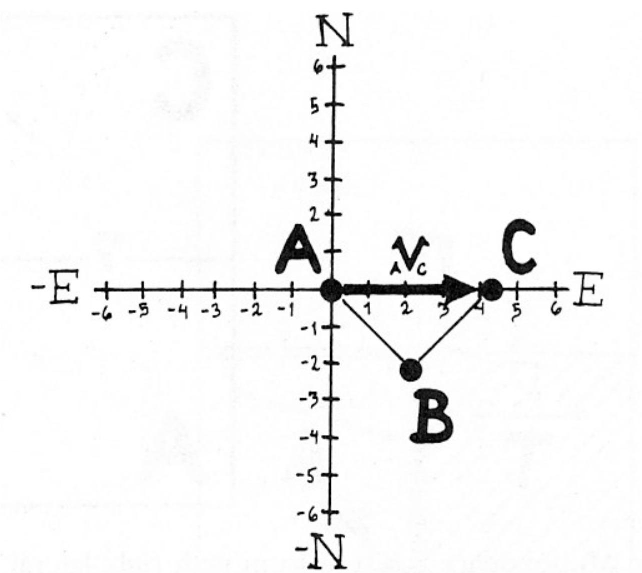
Plate motions: fundamentals

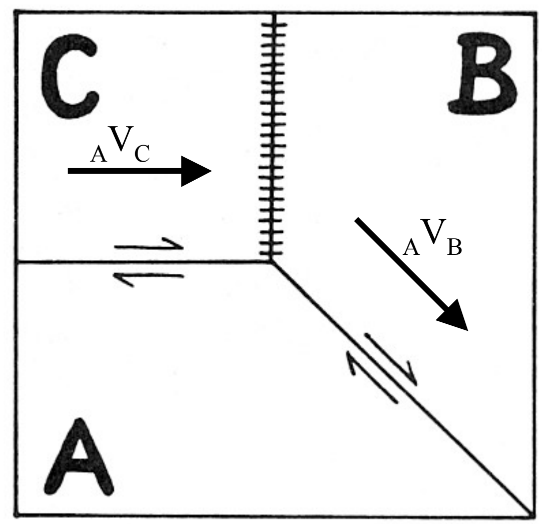




- 3 plates A, B, C
- AB boundary = transform, 3 mm/yr in N135E direction
- BC boundary = subduction trench, 3 mm/yr N45E direction
- Problem:
  - Calculate the velocity of C with respect to A
  - What should the nature of the AC plate boundary be?
  - Plot the velocity vector of plates B and C with respect to A

Plate motions: fundamentals



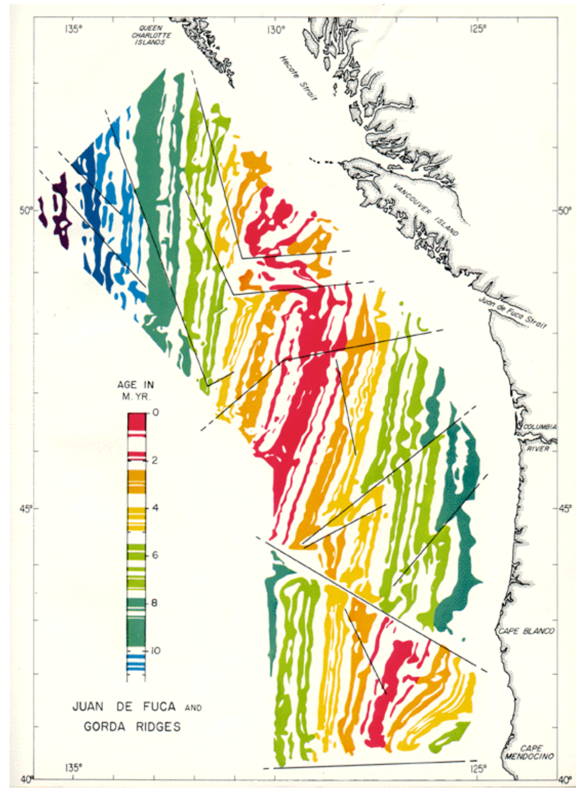


- ~ 4 mm/yr, N90E
- A/C = transform plate boundary

Plate motions: fundamentals

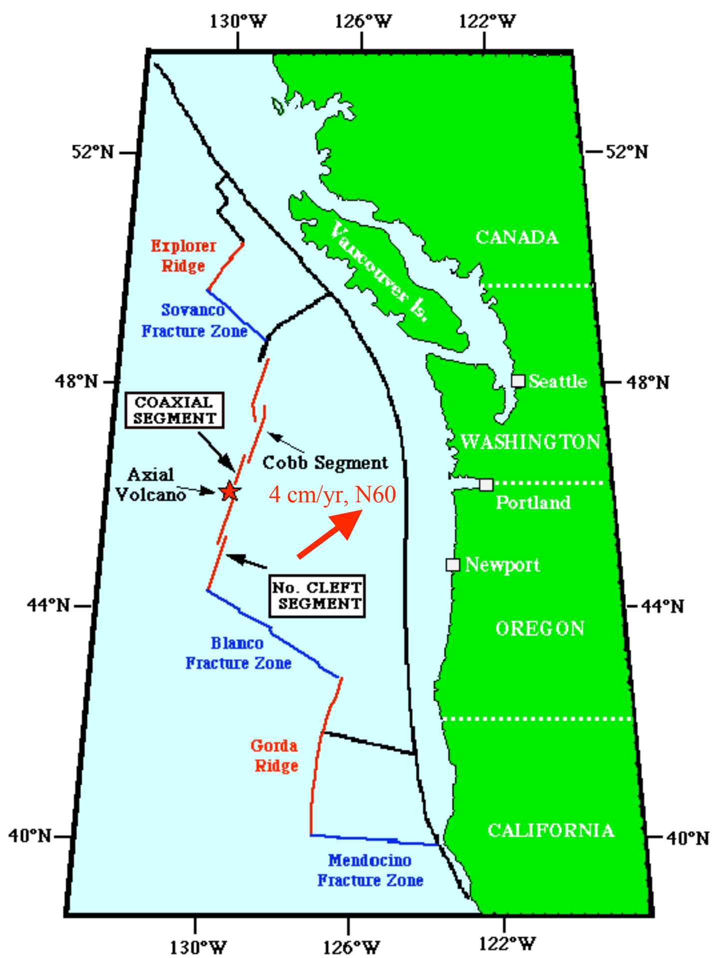
Location map of Juan de Fuca plates

(Modified from Washington Post)



- Nature of the boundary between the Juan de Fuca plate and North America? (is there a Juan de Fuca plate?)
- Given (at 44N/126W):
  - Most recent magnetic isochron across Juan de Fuca ridge + transform fault azimuth => JUFU/PCFC: ve=53.9 mm/yr / vn=-22.7 mm/yr / v=58.5 mm/yr in 112.8 azim
  - Geodetic measurements across the San Andreas fault => NOAM/PCFC: ve=20.3 mm/yr / vn=-42.6 mm/yr / v=47.2 mm/yr in 154.6 azim
- Juan de Fuca w.r.t. North America?

Plate motions: fundamentals



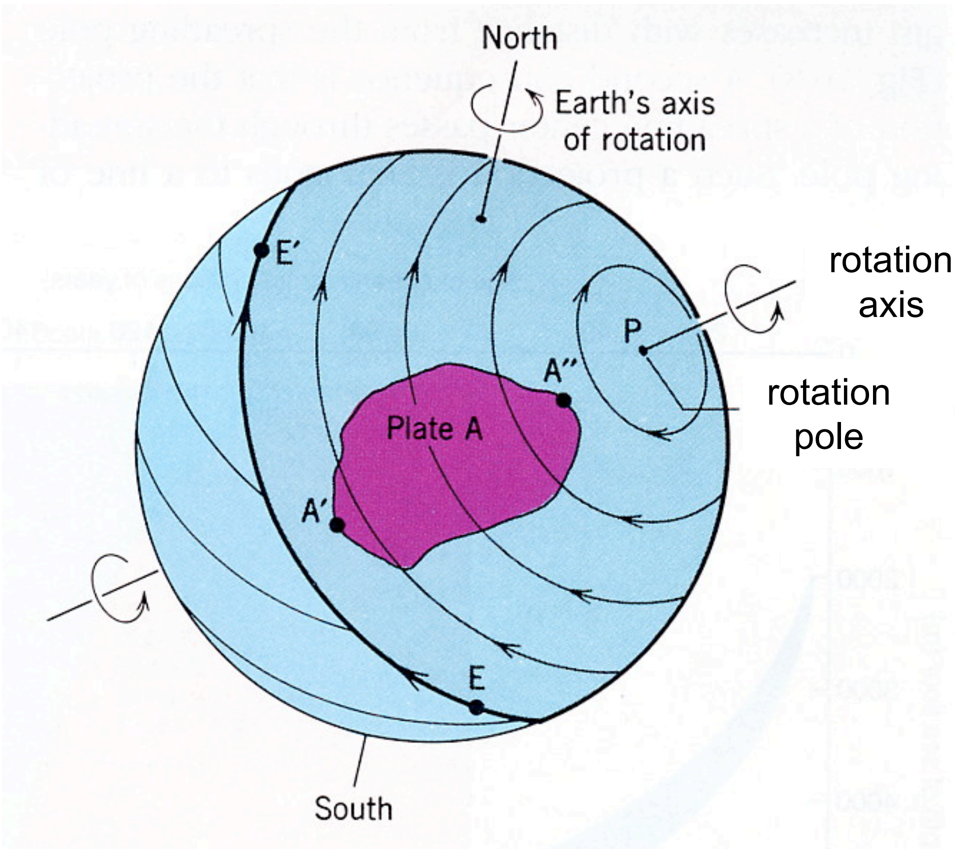
- ${}_{J}V_{P} + {}_{P}V_{N} = {}_{J}V_{N} \Leftrightarrow {}_{J}V_{P} - {}_{N}V_{P} = {}_{J}V_{N}$
  - JUFU/NOAM: ve=33.6 / vn=20.0 / v=39.1 in N59.3 azim
  - Oblique convergence between Juan de Fuca and North America
- No clear trench and no clear Benioff zone, but andesitic volcanoes (Cascade range: Rainier, St Helens, Baker, Shasta)
- Marine surveys later showed clear evidence for compression in small accretionary wedge at the F/N boundary
- Lack of deep earthquakes may be due to slow subduction => subducted lithosphere heats up before descending very far => less and shallower earthquakes
- Recent discovery: “silent earthquakes” or “creep events” => something different is happening…

What have we learned?

- Main arguments:
  - Continental drift
  - Sea floor spreading
  - Seismicity distribution and focal mechanisms
- Concept of “rigid lithospheric plates”
- Plate tectonics = a **kinematic** theory
  - **Rigid** plates (no intraplate deformation)
  - Deformation concentrated at infinitely **narrow plate boundaries**
    - Divergent = spreading centers (“ridges”)
    - Convergent = subductions (“trenches”)
    - Strike-slip = transform faults
- Plate tectonics describes the current motion of rigid lithospheric caps (= plates) on a sphere.

  (anything beyond that is your responsibility…)

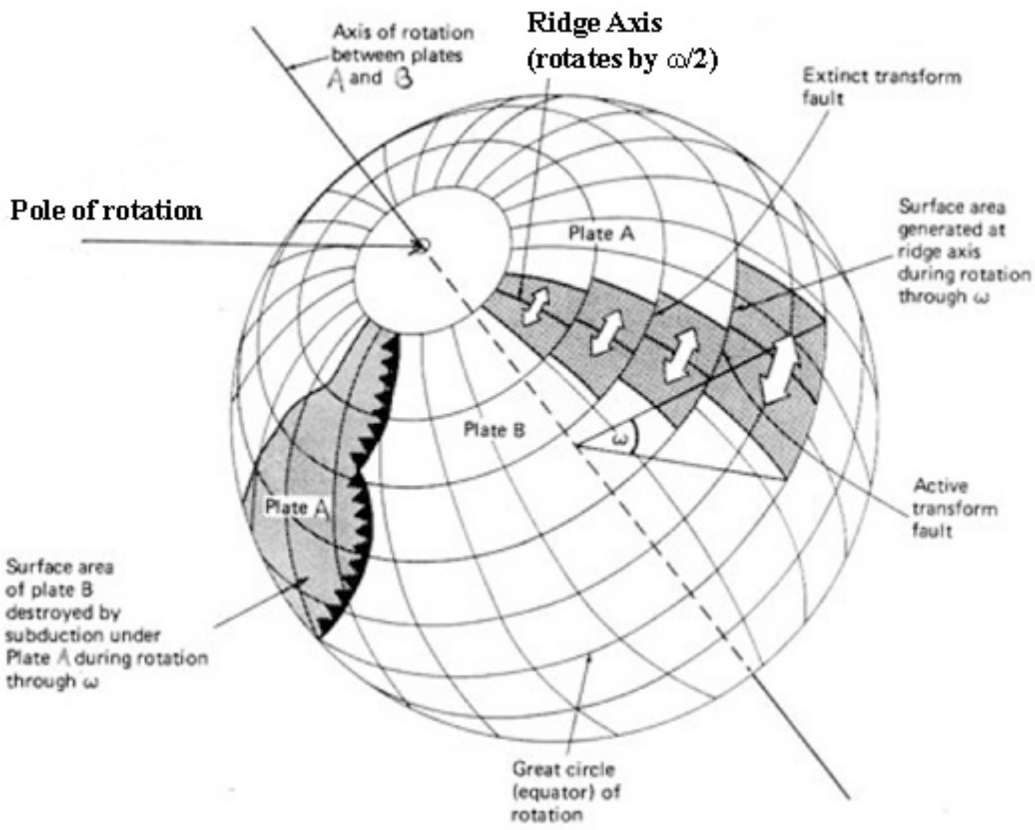
Plate motions on a sphere



- Euler theorem: the motion of a rigid body can be described by a translation + a rotation
- On the Earth surface: translation = 0 => (rigid) plate motions are rotations about axis passing through the center of the Earth
- Rotation fully described by:
  - The location of the intersection of the plate rotation axis wirh the Earth's surface = rotation pole, or **Euler pole** [latitude, longitude]
  - The angular velocity of the rotation about the pole

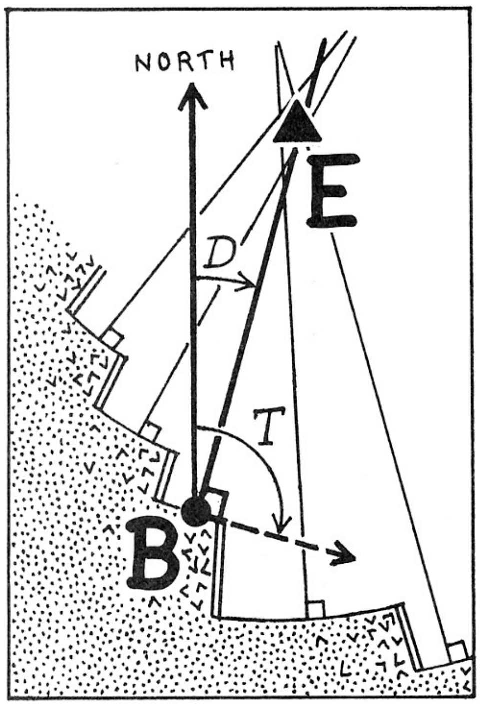
[Euler poles are virtual…]

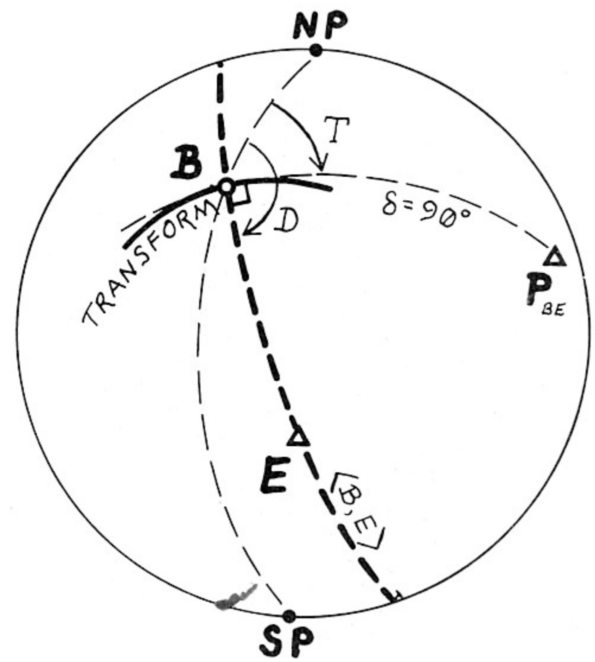
Plate motions on a sphere



- Relative plate motion direction given by transform directions
  - Transform faults = small circles about the rotation pole
  - Conversely, rotation pole located on great circle perpendicular to transform direction
- Relative plate motion rate given by sea-floor magnetic isochron.
- Relative plate motion direction also given by earthquake slip vectors

Plate motions on a sphere





- Observation of transform direction around site B = azimuth T => Euler pole located on great circle 90° from the transform direction
- Similar observation at *n* sites = the intersection of *n* sites gives the location of the Euler pole.
- Observational errors + transforms not always exactly parallel to plate motion => great circles intersection = confidence area.

Plate motions on a sphere

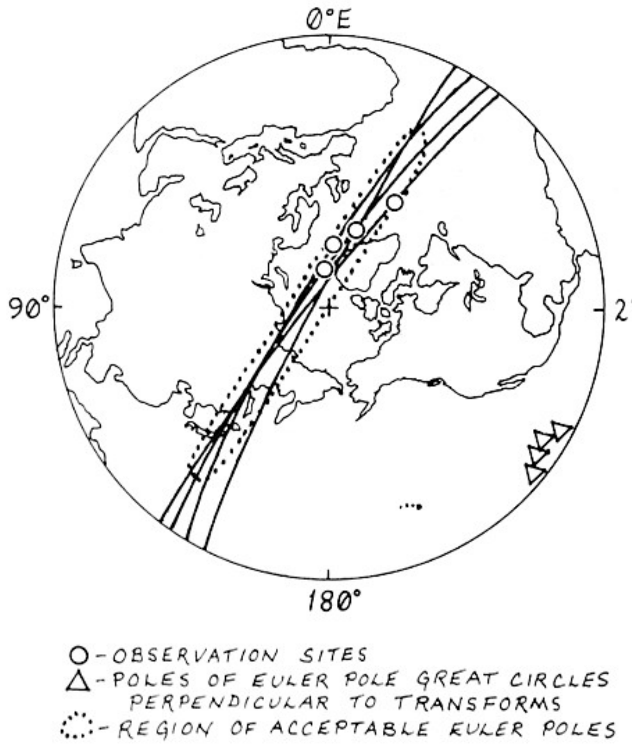


Table 4-1. Trends of transforms along Mid-Atlantic Ridge.

Site **T**		D_T	$\mathbf{P}_{<T, E>}$	
λ	ϕ		λ	ϕ
79.0°	2.5°	308°	6.7°	235.0°
71.0°	352.0°	295°	7.9°	238.2°
66.5°	340.0°	278°	3.2°	242.7°
52.5°	326.5°	275°	3.0°	232.5°

D_T, trend of transform; $\mathbf{P}_{<T, E>}$, pole of great circle from transform to expected Euler pole.

- Example in the central Atlantic ocean
- Transform faults well expressed in bathymetry
- Euler pole great circle nearly parallel => intersect at small angle => large uncertainty

Plate motions on a sphere

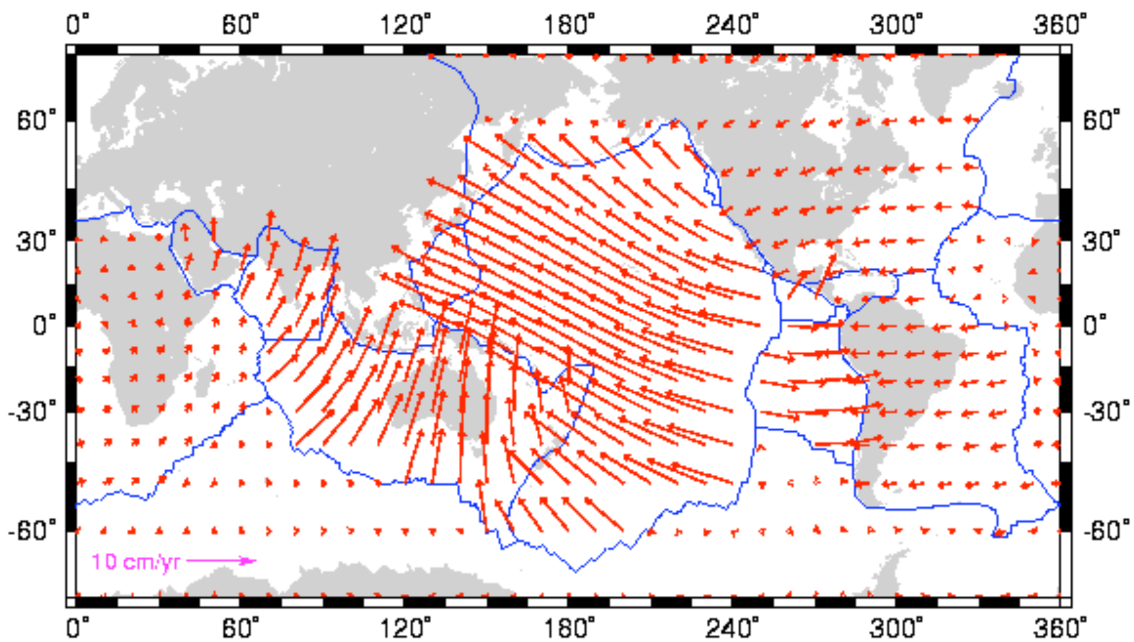


Table 2. Angular Velocities Describing Plate Motion

Plate Pair	Angular Velocity Lat. °N	Lon. °E	ω °/m.y.	Pole Error Ellipse σ_{max} °	σ_{min} °	ζ_{max} °	σ_ω °/m.y.
Eurasia–N. Amer.	78.5	122.0	.23	8.2	4.9	−8	.03
N. Amer.–Pacific	49.1	−73.0	.79	4.1	2.2	−83	.03
Africa–N. Amer.	80.9	16.7	.22	14.5	11.1	15	.04
Pacific–Australia	−57.2	−173.5	1.13	2.6	2.4	43	.04
Australia–Eurasia	9.9	47.4	.72	4.9	4.0	−53	.05
Africa–Eurasia	−11.7	−27.3	.07	41.7	36.1	36	.03
Eurasia–Pacific	60.2	−74.4	.95	3.3	2.2	−88	.05
Australia–Africa	11.2	52.6	.71	6.1	4.3	−22	.04
N. Amer.–S. Amer.	6.5	−55.6	.28	8.3	7.4	−55	.12
Africa–S. Amer.	39.9	−49.3	.38	16.2	7.4	−7	.10

The first plate moves counterclockwise relative to the second plate. The uncertainty in pole position is described by the one-sigma error ellipse, which is given by the angular lengths of the semi-principal axes (σ_{max} and σ_{min}) and azimuth of the semi-major axis (ζ_{max}, in degrees clockwise of North). The uncertainty in rotation rate is σ_ω.

- Systematic measurement of all transform fault directions
- Systematic identification of the most recent magnetic isochron (3.16 My)
- Plate-circuit closure condition

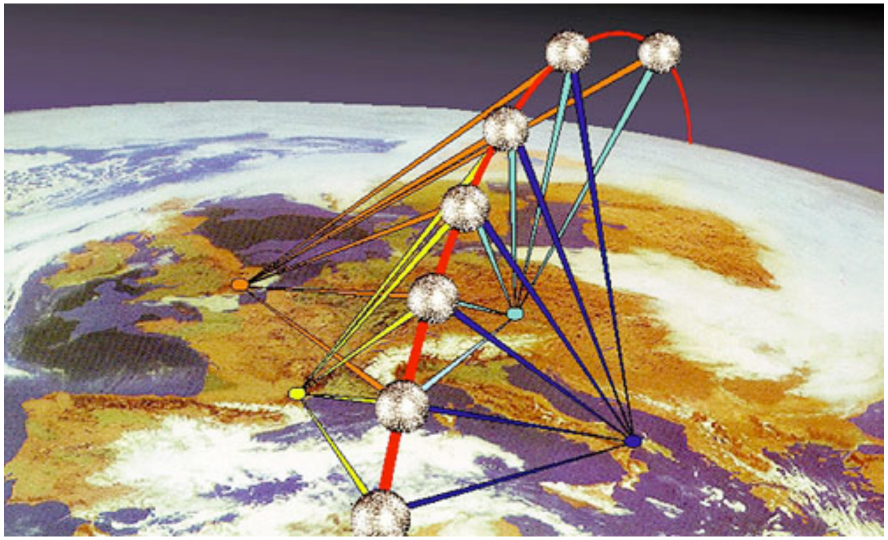
⇒ **Global plate motion model** = e.g. NUVEL1

Space geodesy and plate motions

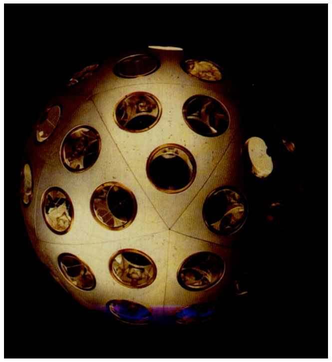
- 1980's/1990's = development of space geodesy
- Space geodesy = measuring (relative) position of sites on Earth using space-based observations

Space geodesy and plate motions

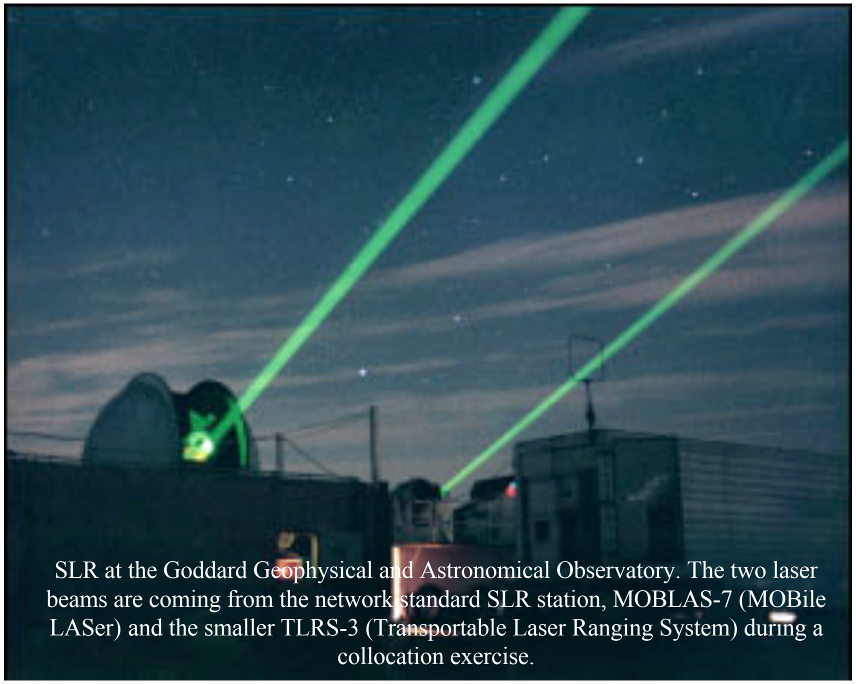
- Measurement of distance (=range) between a ground station and a satellite = *Satellite Laser Ranging* (SLR)
- Ground station transmits a very short laser pulse from a telescope to a satellite
- The laser pulse is retro-reflected by corner cube reflectors on the satellite back to the ground telescope
- Very precise clock at the ground station measures the round trip time $t_{emission} - t_{reception}$
- Time measurement accuracy < 50 picoseconds, or < 1 centimeter in range
- 3 stations, 1 satellite => position of the satellite (if station position known)
- 3 satellites, 1 station => position of the station (if satellite orbit known)



Tracking a satellite with a network of SLR stations



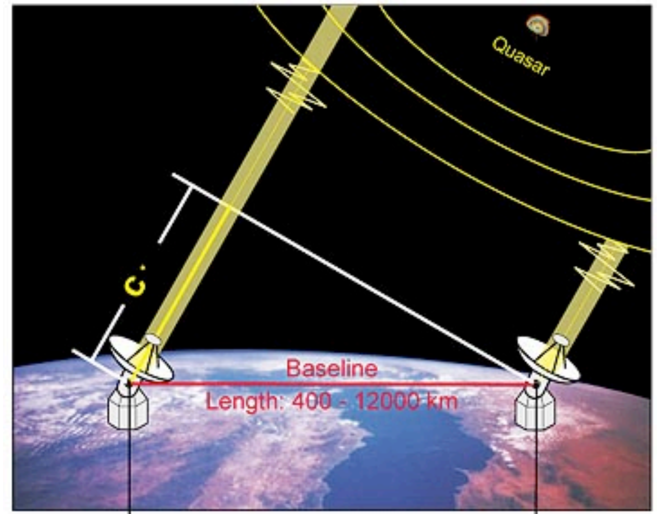
Starlette, a geodetic satellite
Launched in 1975
48 cm diameter, 47 kg



SLR at the Goddard Geophysical and Astronomical Observatory. The two laser beams are coming from the network standard SLR station, MOBLAS-7 (MOBile LASer) and the smaller TLRS-3 (Transportable Laser Ranging System) during a collocation exercise.

Space geodesy and plate motions

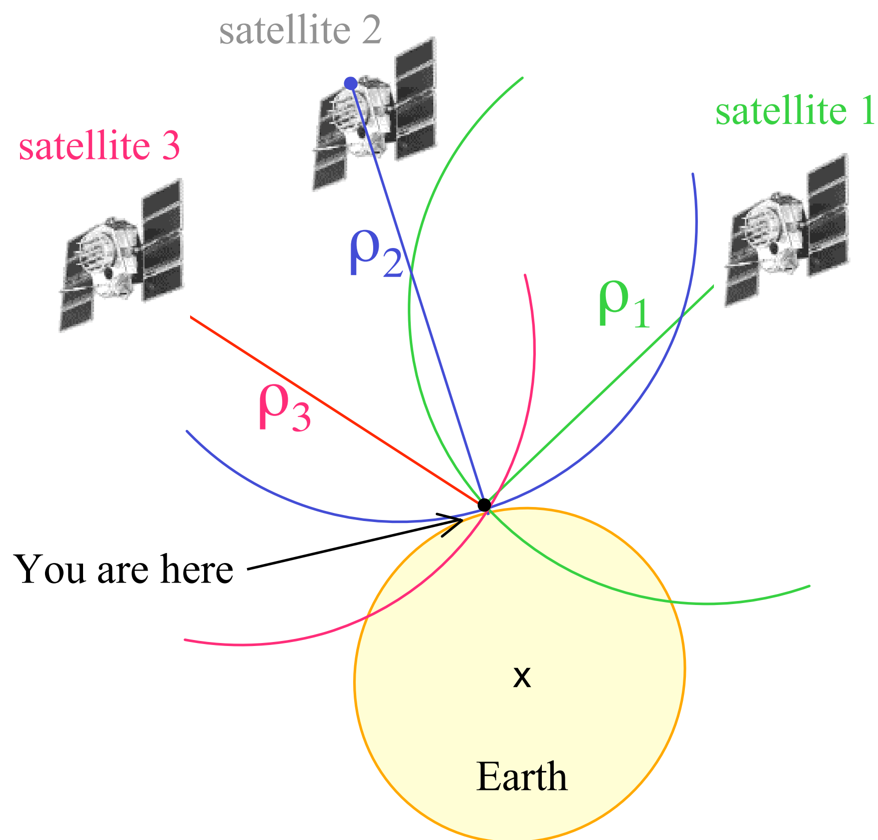
- *Very Long Baseline Interferometry*
- Radio-astronomy technique, used to locate and map stars, quasars, etc = "sources"
- Wavelength = 1-20cm
- Measures the time difference between the arrival at two Earth-based antennas of a radio wavefront emitted by a distant quasar
- If the source positions are known => ground baseline => "geodetic" VLBI
- Time measurements precise to a few picoseconds, => relative positions of the antennas to a few millimeters

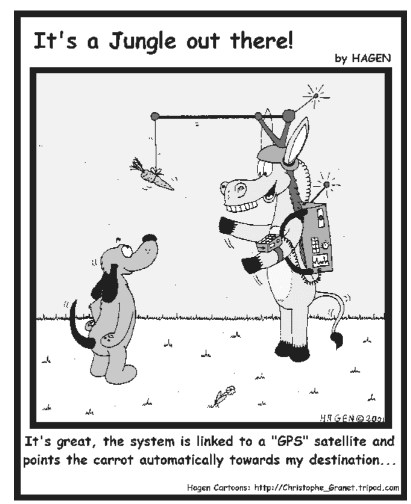


VLBI antenna at Algonquin, Canada

Space geodesy and plate motions

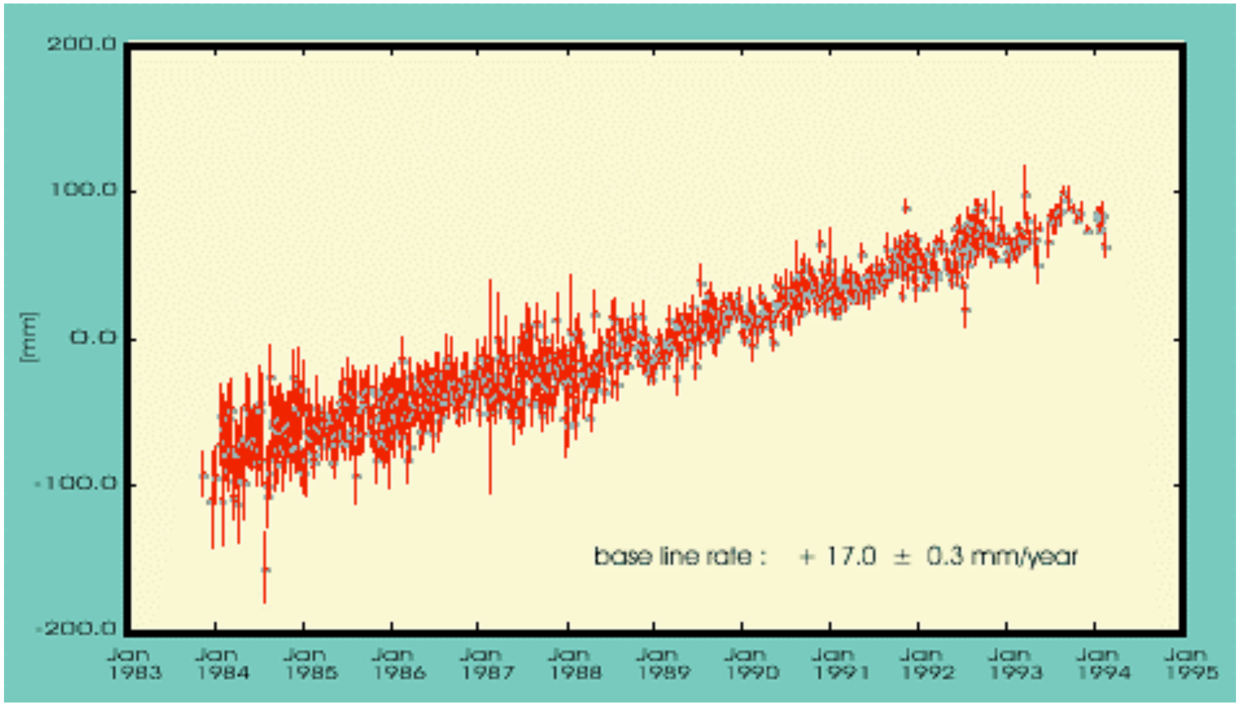
- A constellation of satellites broadcasting a radio signal towards the Earth
- GPS antenna and receivers record and decode the radio signal into satellite-antenna distances
- Three distances => solve for latitude, longitude, elevation
- A fourth satellite is needed to solve for the time difference between the receiver and satellite clocks
- Precision:
  - \$100 receiver ⇒ 100 m
  - \$10,000 receiver ⇒ 1 mm (with sophisticated data post-processing…)





Space geodesy and plate motions

Wegener's dream…



The "famous" Westford (Ma) – Wetzell (Germany) VLBI baseline

Space geodesy and plate motions

Smith et al., 1993

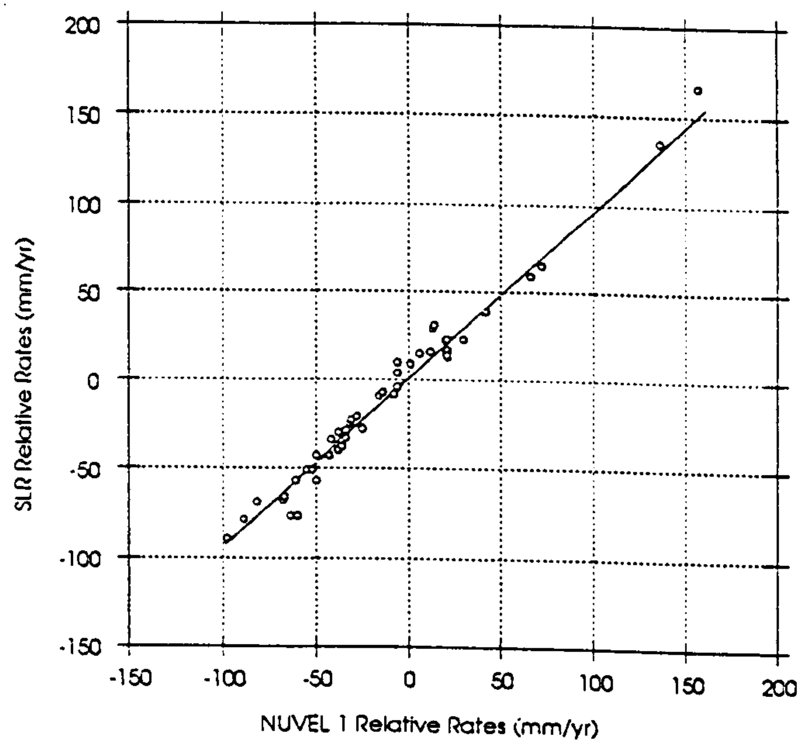
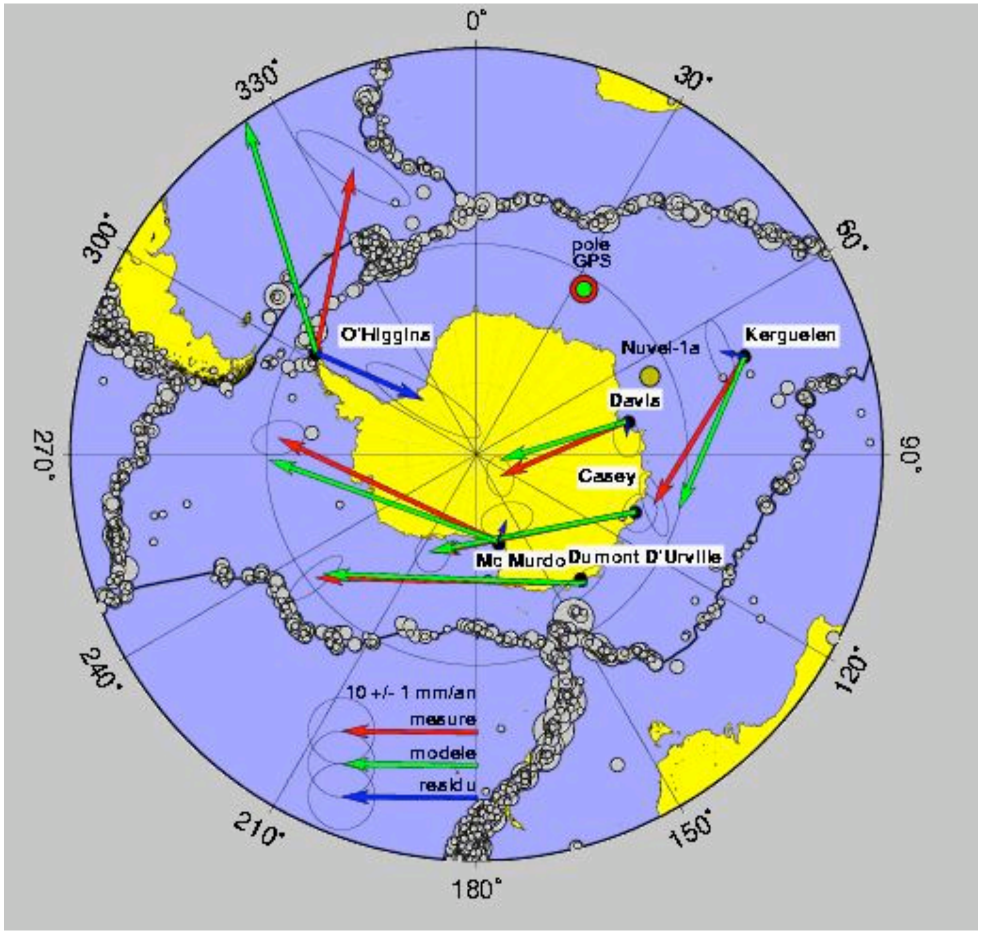


Fig. 11. Comparison of SLR determined geodesic rates with those implied by the NUVEL 1 geologic plate motion model for 54 lines connecting stations on five plates that are well within plate interiors and crossing at least one plate boundary. The slope of the line is 0.949 ± 0.019.

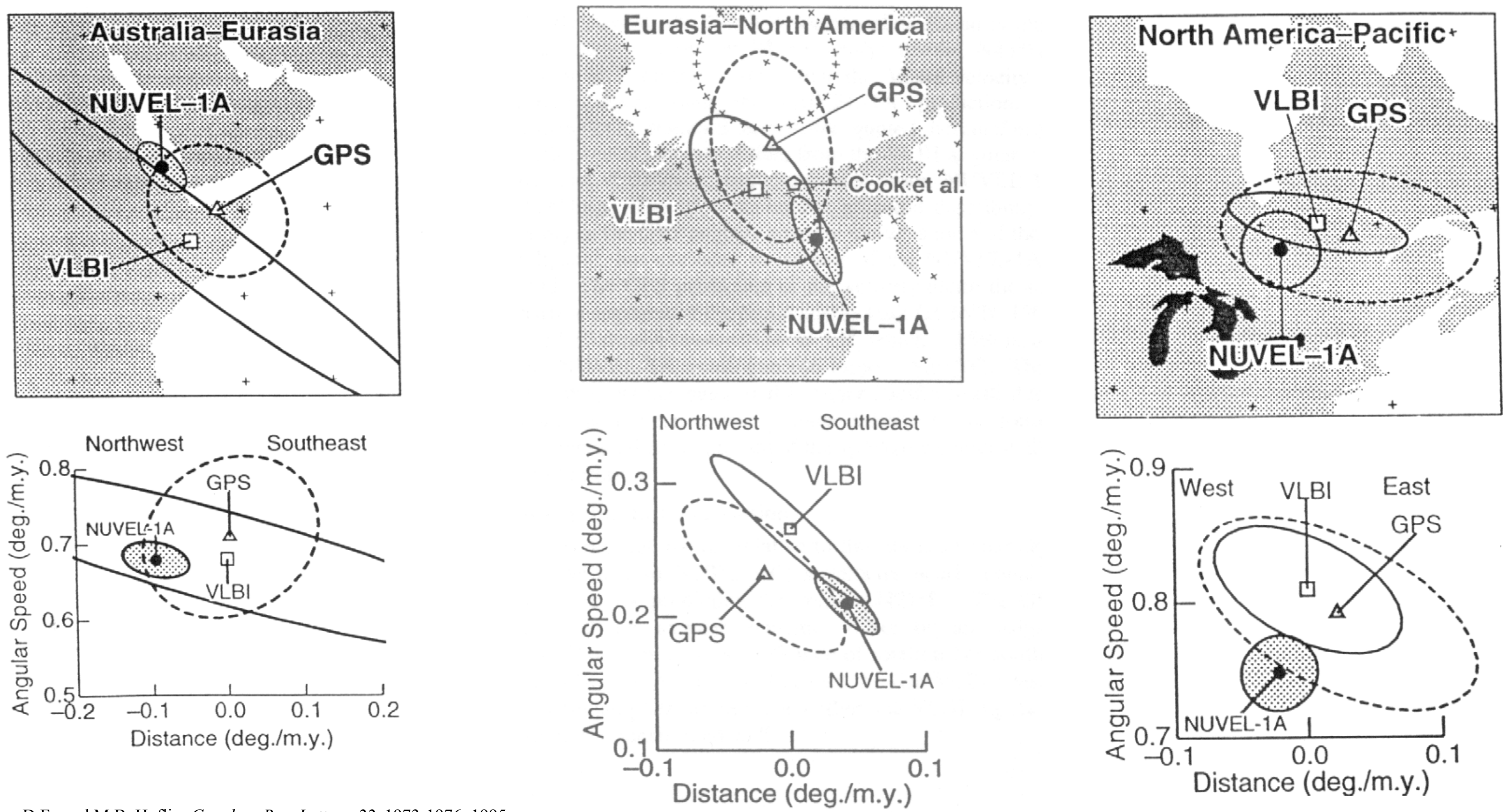
- Comparison between SLR observations and Nuvel1 plate motion mode
- Plate motions are steady (over the past 3 My)
- Validation of the geological model
- Validation of the geodetic measurements

Space geodesy and plate motions



- GPS measurements in Antarctica (red arrows)
- Used to estimate the rotation of Antarctica w.r.t Africa
- Comparison with NUVELA: OK except O'Higgins

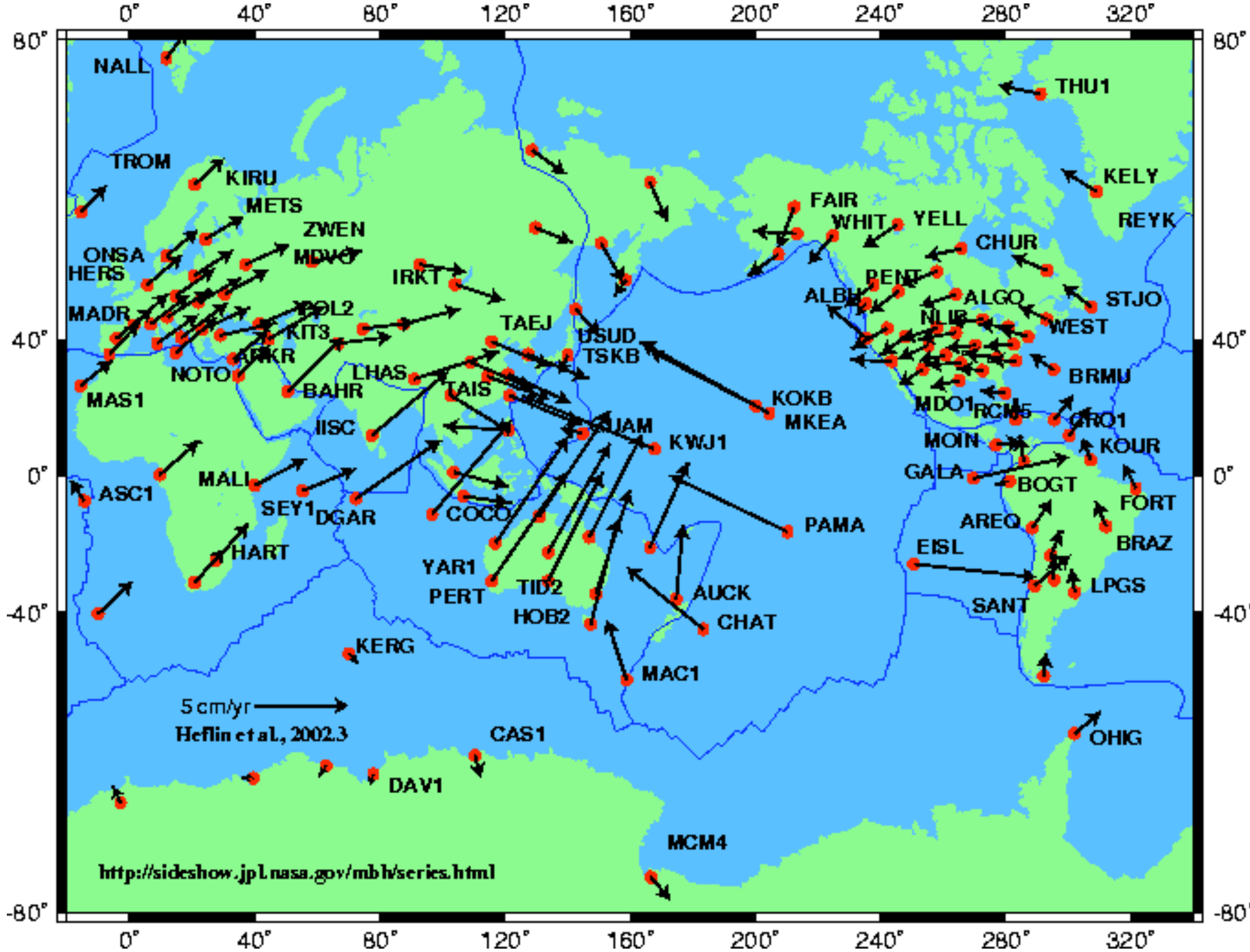
Space geodesy and plate motions



Argus, D.F., and M.B. Heflin, *Geophys. Res. Letters, 22*, 1973-1976, 1995

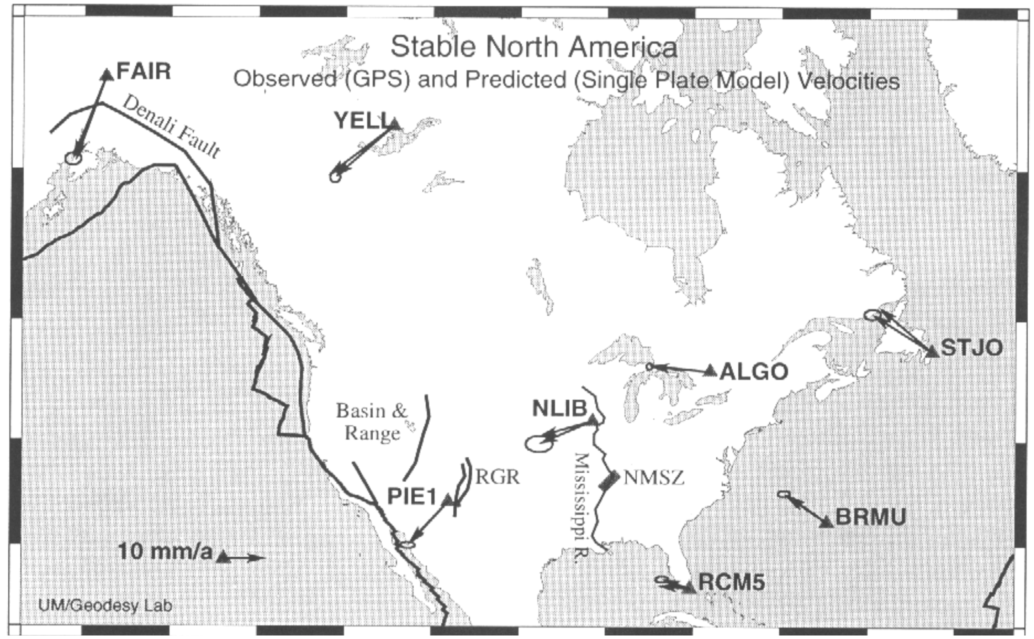
For most major plates, instantaneous motion measured with space geodesy = 3 My average from NUVEL1 geological model

Space geodesy and plate motions



Intraplate deformation?

- Dixon et al., GRL, 1996: *"How rigid is the stable interior of the North American plate?"*
- Answer = 2 mm/yr over the entire North American plate



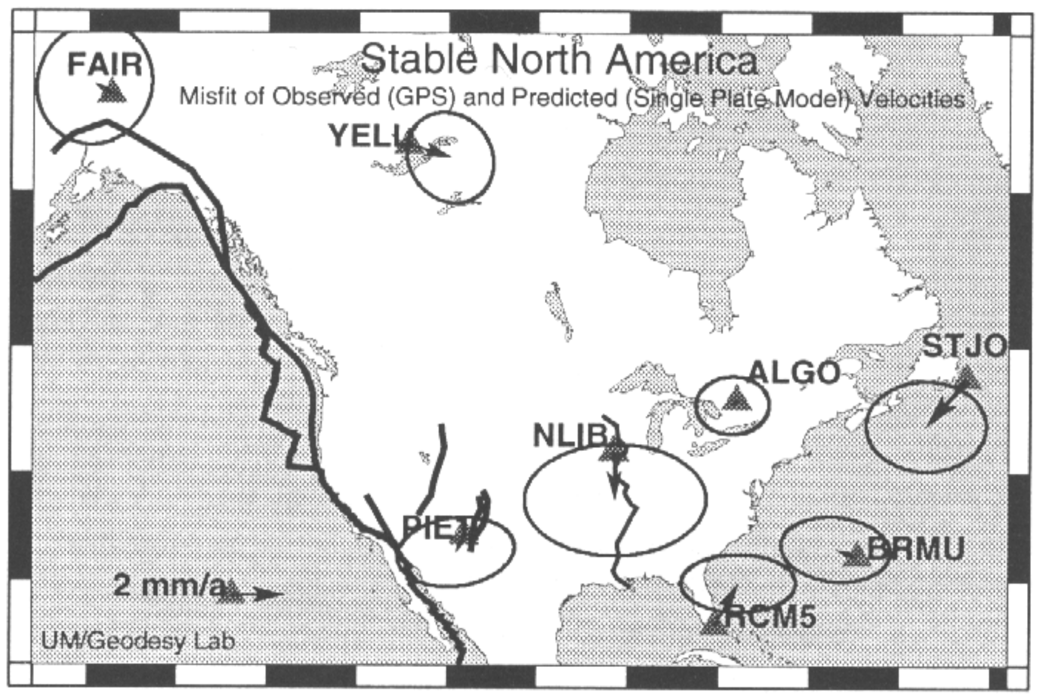
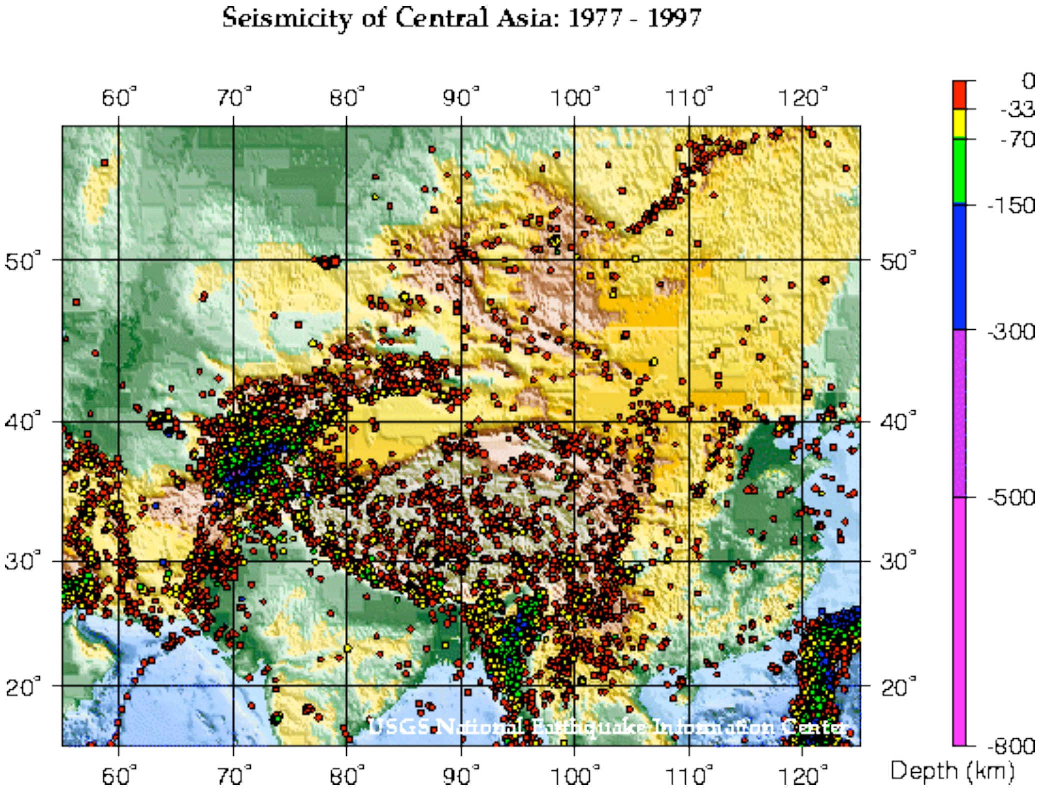


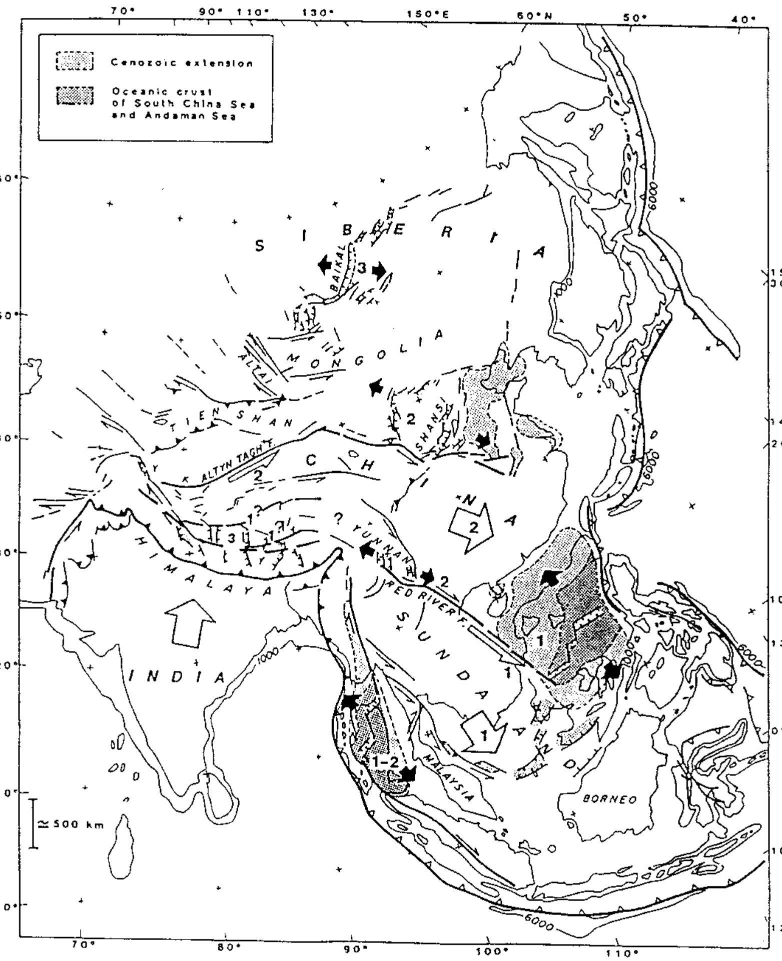
Table 1. Observed[1], Predicted[2] and Residual[3] GPS Site Velocities (mm/yr)

	North Velocity		West Velocity		Residual
	Observed[1]	Predicted[2]	Observed[1]	Predicted[2]	Vector Magnitude[3]
ALGO	1.3 ± 0.3 (3.9)	1.5	14.4 ± 0.3 (4.5)	14.2	0.2
BRMU	6.9 ± 0.3 (3.5)	6.6	10.1 ± 0.6 (6.6)	9.3	0.9
FAIR	-19.9 ± 0.6 (4.1)	-20.3	7.9 ± 0.8 (5.1)	7.3	0.7
NLIB	-5.6 ± 0.8 (3.0)	-3.8	12.7 ± 1.3 (5.5)	12.8	1.8
PIE1	-10.5 ± 0.3 (3.6)	-9.9	9.5 ± 0.7 (6.9)	9.2	0.7
RCM5	2.2 ± 0.3 (3.3)	0.6	6.5 ± 0.6 (6.6)	7.4	1.9
STJO	9.1 ± 0.5 (3.9)	10.9	14.2 ± 0.8 (6.3)	12.7	2.3
YELL	-12.5 ± 0.5 (3.9)	-12.0	13.9 ± 0.5 (5.0)	15.5	1.7

1. Relative to ITRF-94. Numbers in parentheses are weighted root mean square scatter of daily position estimates (mm).
2. Based on a rigid plate model with pole at 6.3°N, 278.2°E, ω=0.202°/my.
3. $(R_n^2+R_w^2)^{1/2}$ where $R_{n,\ w}$ are the north or west Residuals (Observed - Predicted) (mm/yr).

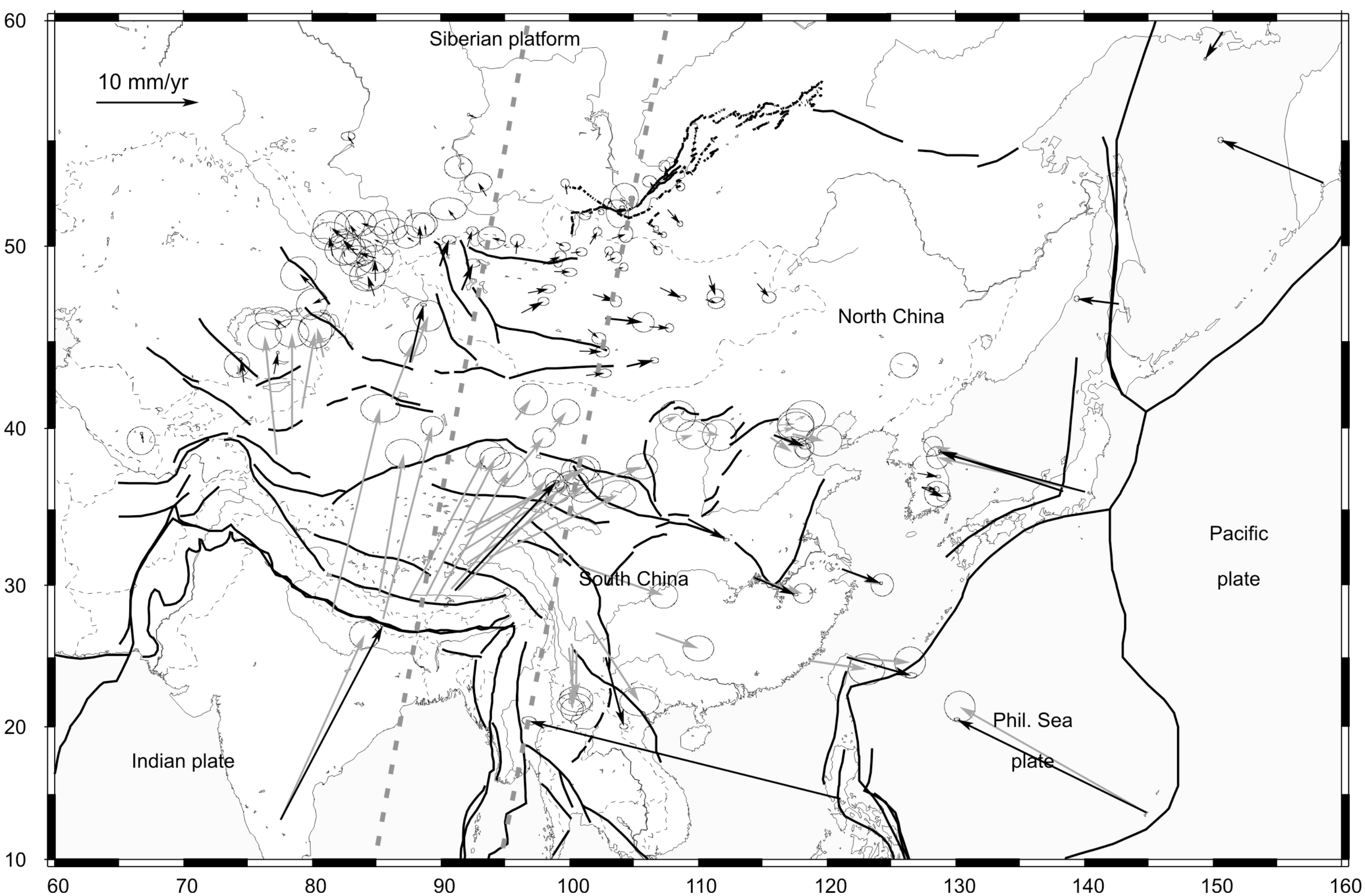
Intraplate deformation?





- Large active faults, from the Himalayas to the Baikal rift zone, limit major crustal blocks
- Seismicity concentrated along the Himalayas, Tien Shan, and in Tibet.
- But significant seismicity all the way north to the Baikal rift.

Intraplate deformation?



What have we learned?

- The motion of (rigid) plates can be described by a rotation about a Euler pole
- Plate rotations can be estimated from data:
  - Oceanic data: transform fault azimuths, sea-floor magnetic anomalies, earthquake slip vectors => NUVEL1 global plate kinematic model
  - Geodetic data: velocity of VLBI, SLR, or GPS sites
- Nuvel1/geodesy comparison => plate motions have been constant over the past 3 My
- Intraplate deformation < 2 mm/yr, with some notable exceptions such as Asia…