The Plate Tectonic Approximation After 50 Years*

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and many colleagues:

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Key collaborators**: Jean-Yves Royer, Stephen Zatman, Corné Kreemer, Gregory Houseman, & Seth Stein.**

**With apologies, I am deferring "Cenozoic True Polar Wander and the Origin of the Hawaiian-Emperor Bend" for the Fall AGU meeting*

Summary: The Plate Tectonic Approximation after 50 years

Plate tectonics originally assumed narrow plate boundaries, but we now recognize many wide or diffuse plate boundaries

DPBs recog. early in continents but later in oceans. Cover 10% to 15% of Earth surface

Outstanding example of DOPB: Boundary between India, Capricorn, & Australia plates

In oceans → component plates (e.g., Capricorn) and plate composites (e.g. **Indo**-Capricorn-**Australia**-Macquarie).

Poles of rotation of DOPBs tend to lie in their mutual boundary—now understood to be a consequence of both plate geometry and rheology

Vertically integrated rheology of deforming oc. lithosphere→ thin sheet of power-law fluid, exp. n =~30. n >> than typical estimated for deforming continental lithosphere.

Plate rigidity (excluding plate boundary deformation) is an excellent, but not perfect, approximation

Small, signif. non-rigidity: thermal contraction & nonspherical Earth

Transform faults are not parallel to plate motion, but it's still a good approx.

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Space Geodesy quantifies signif. short-term non-rigidity due to deglaciation

Challenge to rigid plate hypothesis: 15 ± 4 mm/yr non-closure about the Galapagos TJ

It's not the plate boundaries, but the existence of nearly rigid plate interiors that is the essence of plate tectonics

Space geodesy → expand scope & explore steadiness of plate motion & measure plate nonrigidity

Space geodesy → include plates not bounded by mid-ocean ridges

  Analyze Basin & Range, San Andreas Fault System, other distr. dfmn.

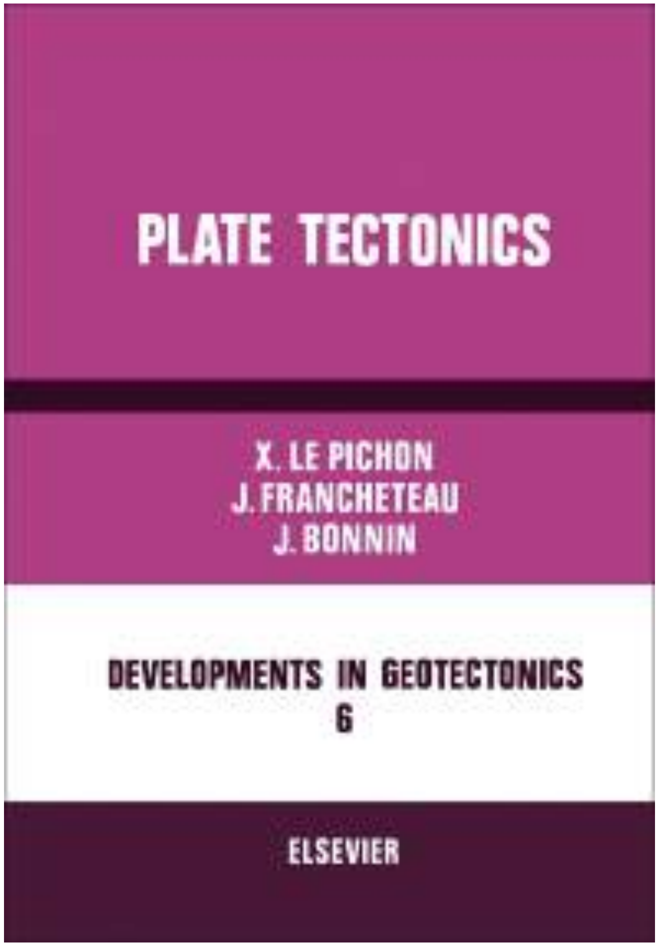
Mainly steady, but some signif. diff''s between geologic & geodetic rates

1960-1968: The plate tectonics revolution

Fall 1973: As a university student, I take my 1st course in Earth Science. ”Plate tectonics” is not mentioned in the textbook (but we are assigned Scientific American offprints to read)

Spring 1974: I take a course in Marine Geophysics and use Prof. Le Pichon’s new book as a textbook. →

I soon decide to change my major from Physics to Earth Science.



ORIGINAL TENETS OF PLATE TECTONICS

Explicit:

Boundaries are Narrow

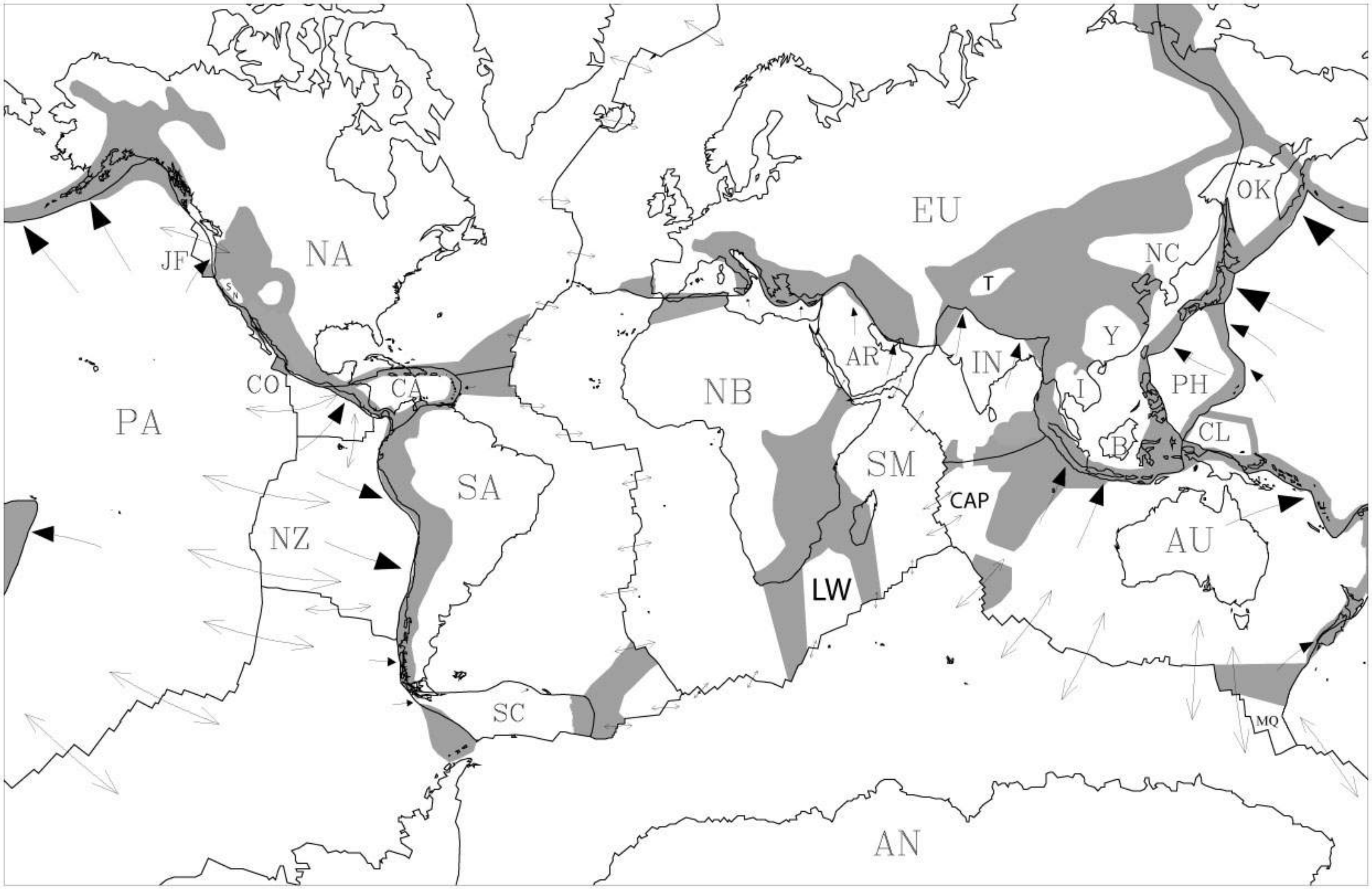
Plates are Rigid

Implicit:

Plate Motion Is Steady

World Plate Boundary Map

(After Gordon & Stein 1991)



Shaded regions are wide plate boundary zones (a.k.a. “diffuse plate boundaries”); narrow boundaries are shown by black curves. Poles of rotation across DOPBs tend to lie in the DOPBs themselves. [Gordon, 1998; Zatman et al., 2001, 2005]

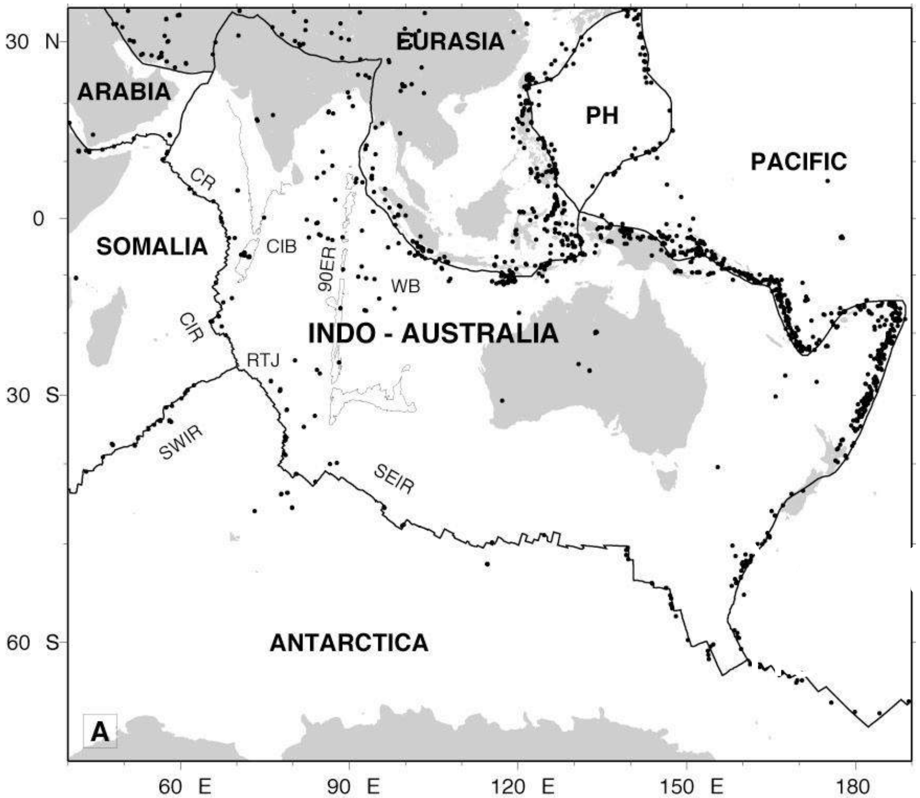
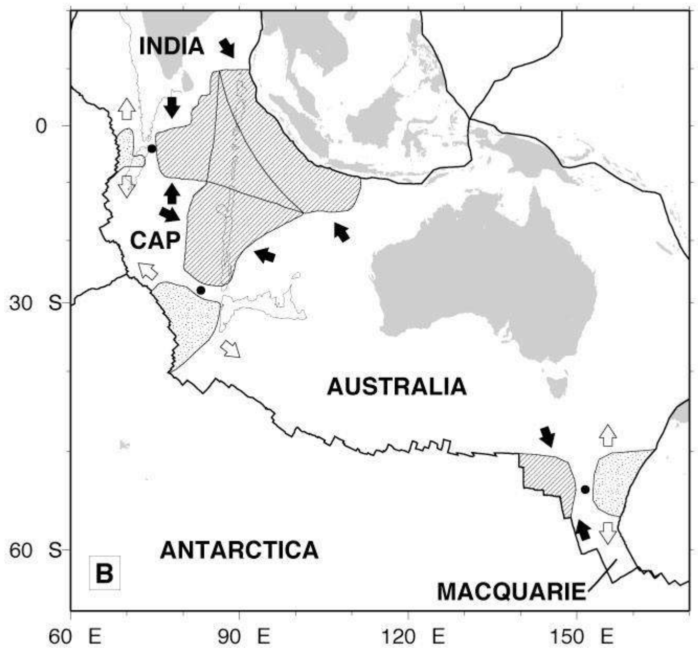


Plate Composite: Indo-Australia

-bounded by traditional narrow boundaries

Insofar as a plate is nearly rigid, **"component plates" are plates** and "composite plates" are not.



Component Plates: India, Capricorn, Australia, & Macquarie

Royer & Gordon 1997;
Gordon, Royer, & Argus 2008
Wiens et al. 1985
Cande & Stock, 2004

Thin viscous sheet model applied to deforming oceanic lithosphere

- Horizontal stress is balanced within a thin spherical sheet

- Finite element formulation based on a triangular mesh

- Plane-stress formulation; buoyancy forces due to variations in deformation-induced thickening are assumed negligible (*Ar* = 0)

- Deformation rates obey a power-law rheology:

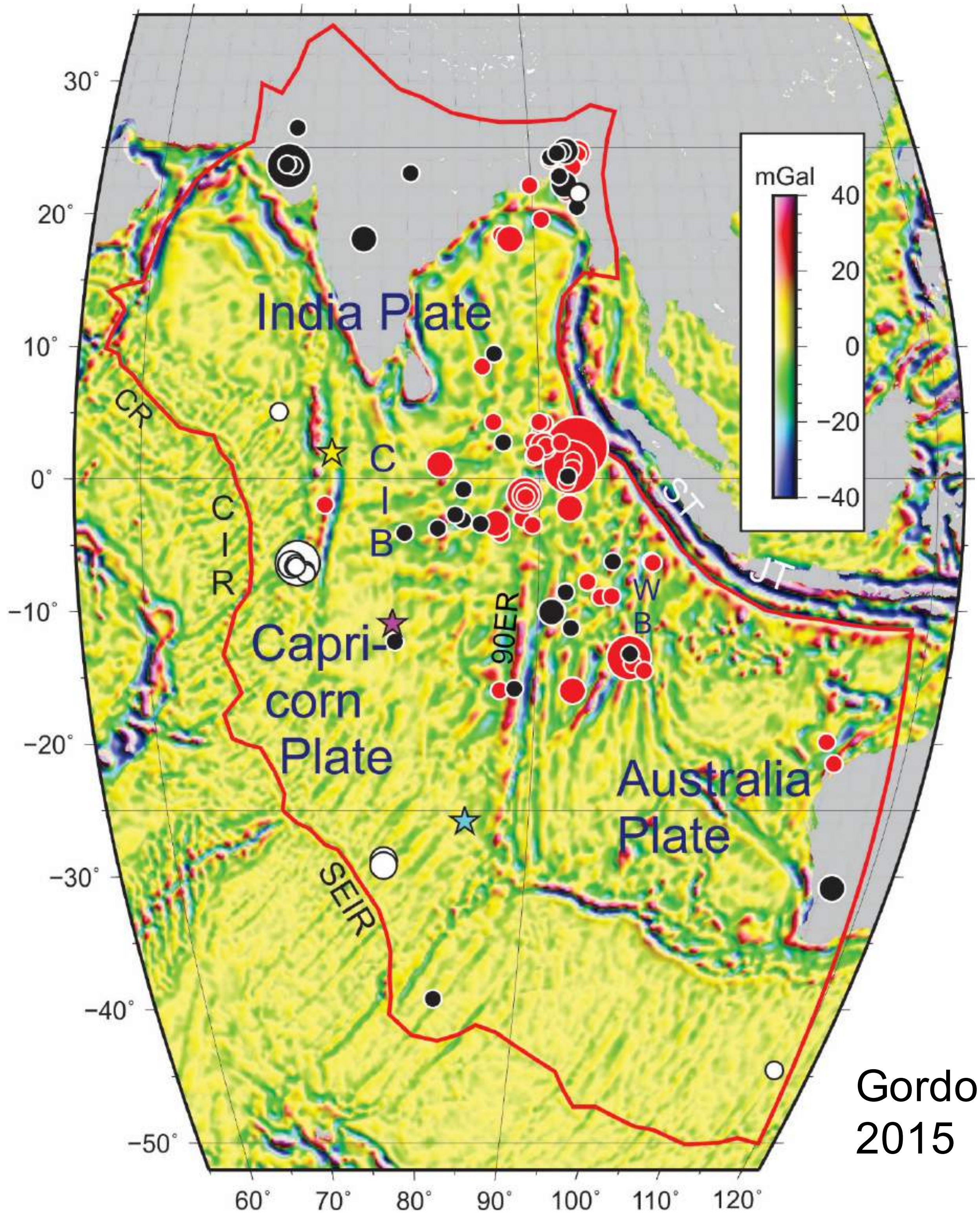
$$\tau_{ij} = B\dot{E}^{\frac{1}{n}-1}\dot{\varepsilon}_{ij}$$

where *n* is power-law exponent

- Current displacement-rate and strain-rate fields are calculated

Applying thin viscous sheet models to diffuse oceanic plate boundaries;

Kinematic boundary conditions from MORVEL relative plate angular velocities.



Domain of finite-element analysis, location map, & earthquake locations

Normal

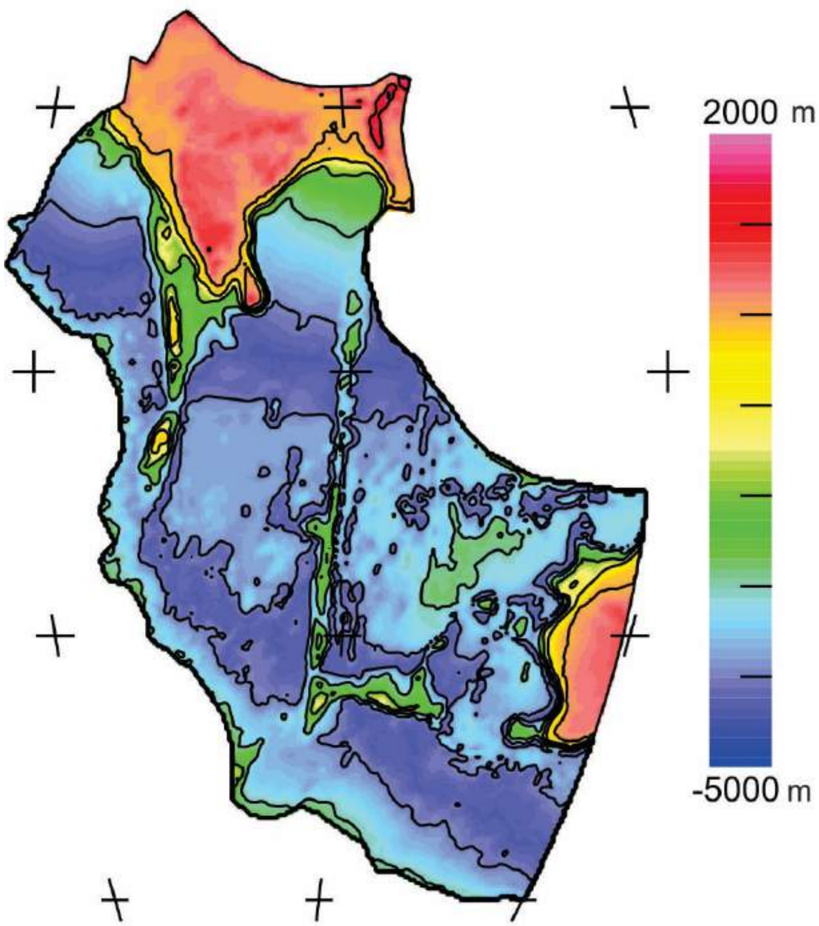
Strike Slip

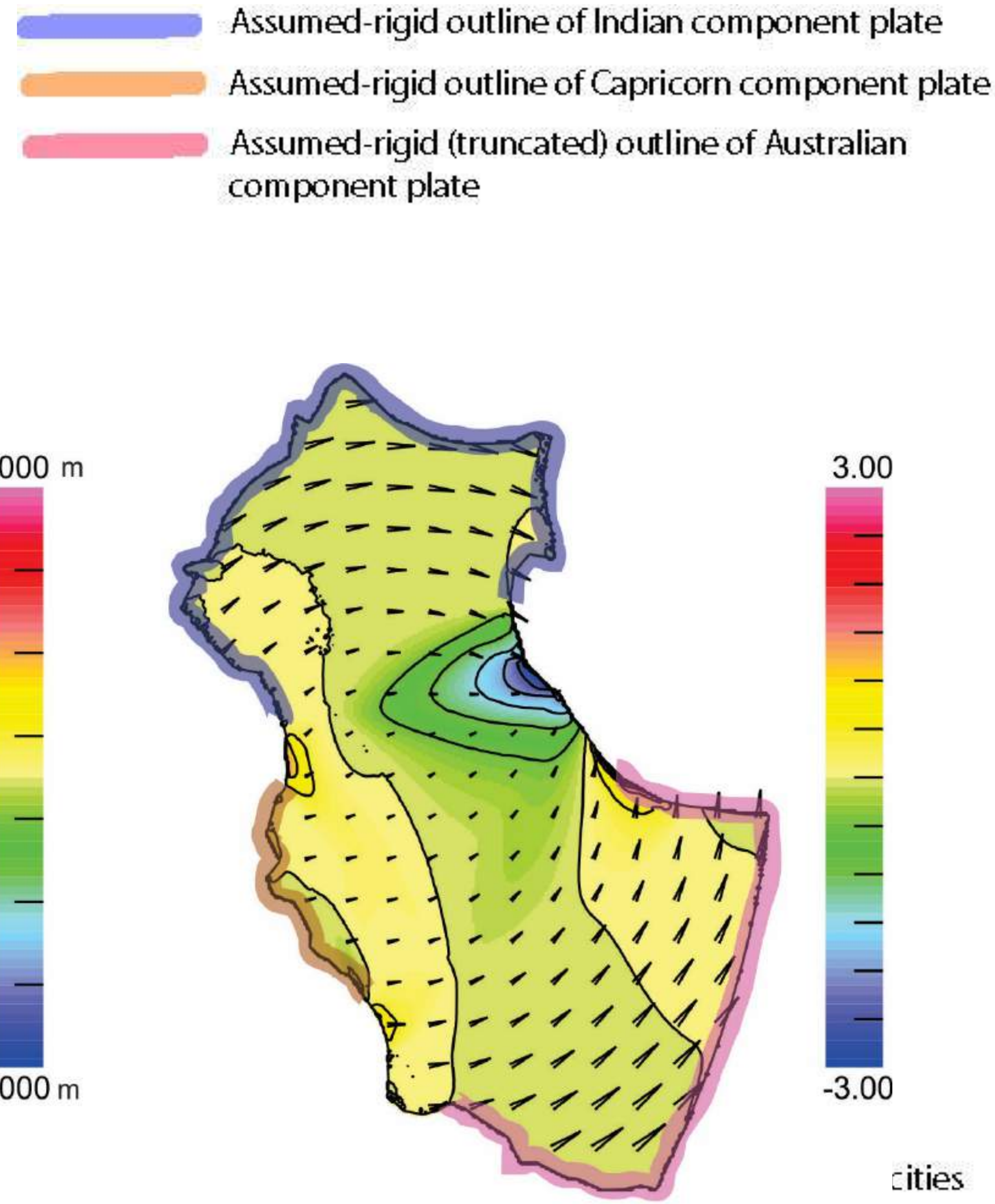
Thrust

Gordon & Houseman 2015

Kinematic B.C.'s:
Relative angular velocities are applied to the rigid outlines of 3 component plates.

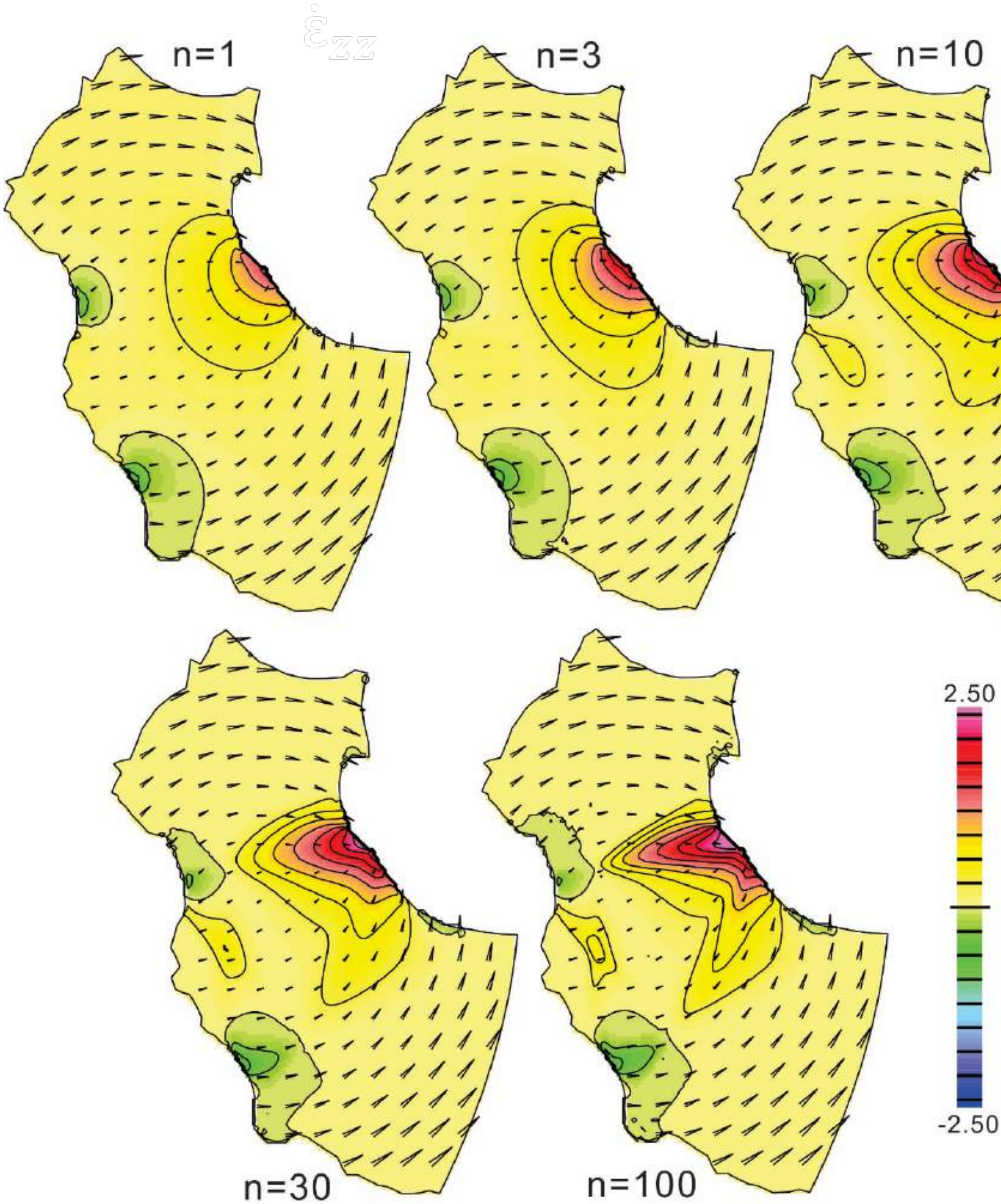
Velocity of outline smoothly interpolated between rigid outlines.

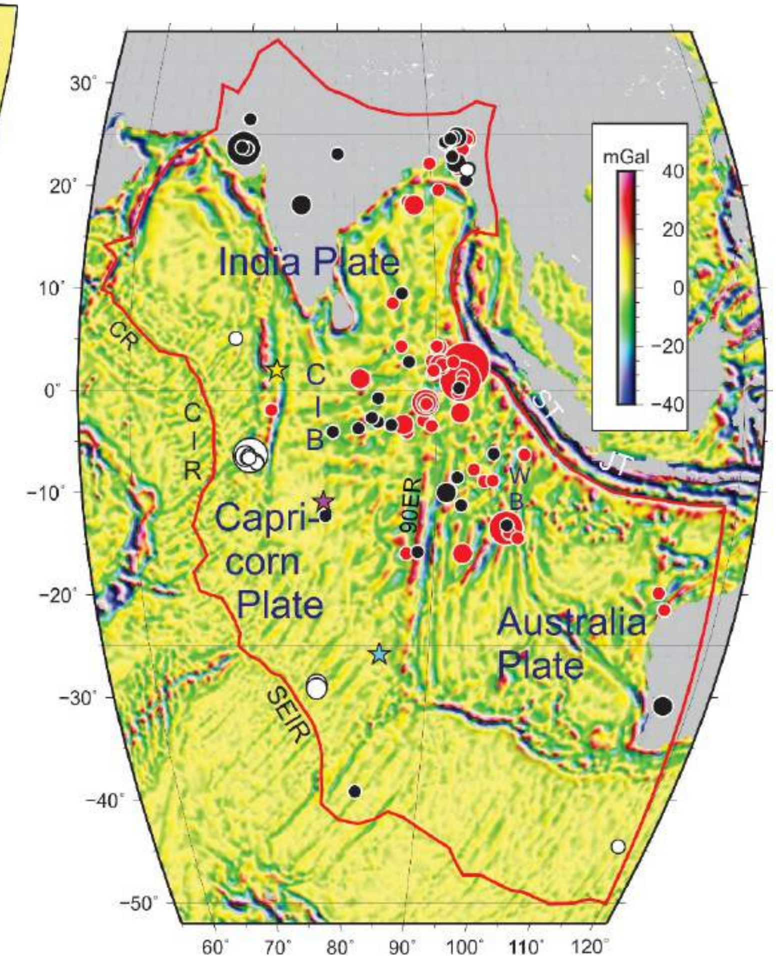




Reference frame: India and Australia have equal and opposite angular velocities.

Variation of distribution of modeled vertical strain rate with power-law exponent *n*.
n ~ 30 best fits the distribution of observed deformation.

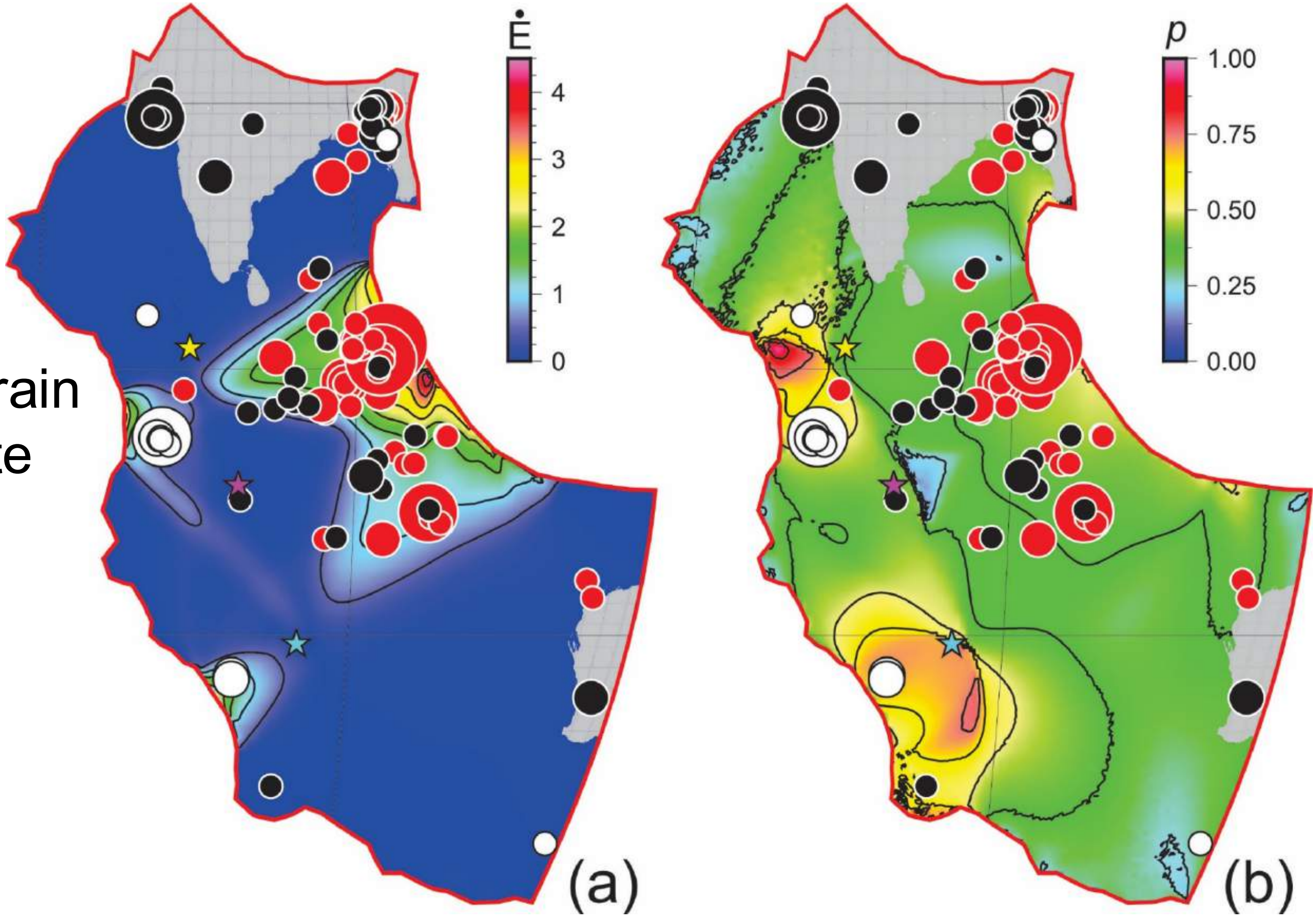




Gordon & Houseman 2015

Comparison of Model with Earthquake Locations & Mechanisms

Strain rate



Predicted Types of Focal Mech.

White: Mainly normal faulting
Red: Mainly strike-slip faulting
Black: Mainly thrust faulting

Gordon & Houseman 2015

The **central tenet of plate tectonics:**

Plates are rigid

Questions:

How fast do they deform/strain?

How do these strain rates compare with those in diffuse plate boundaries?

With those in narrow plate boundaries?

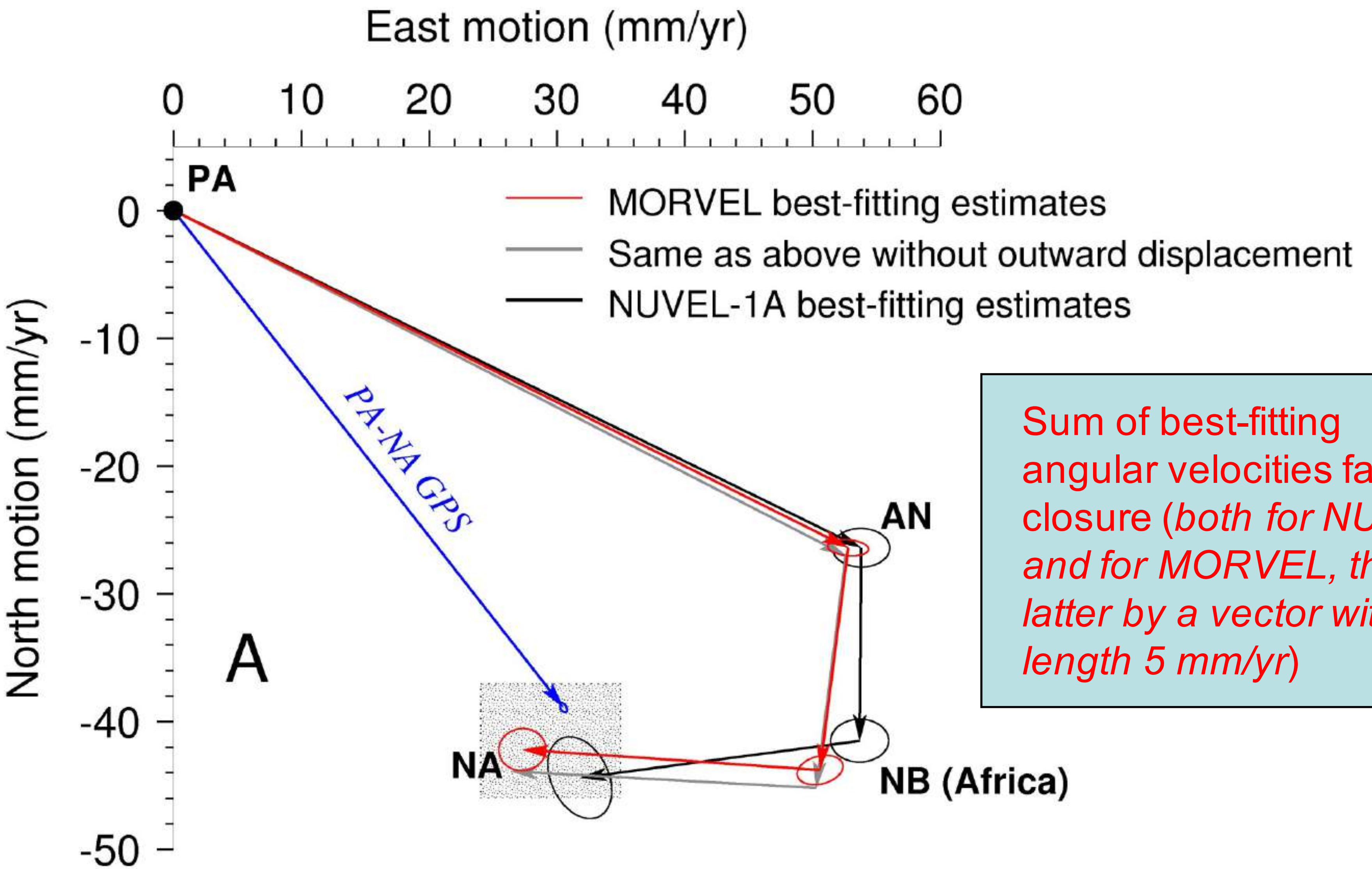
How is the straining distributed spatially?

What are the main processes by which they deform?

Key evidence for plate non-rigidity: Plate circuit nonclosure from DeMets et al. 2010

- No. America-Nubia-Antarctica-Pacific plate circuit:
  - 5 ± 3 mm/yr (95% conf. limit)
- Bouvet triple junction
  - 3 ± 2 mm/yr (95% conf. limit)
- Galapagos triple junction
  - **14 ± 5 mm/yr** (95% conf. limits)
    - Tuo Zhang at Rice University has new work that reduces, but does not eliminate, this misfit
    - Still too large to explain by known processes of intraplate deformation

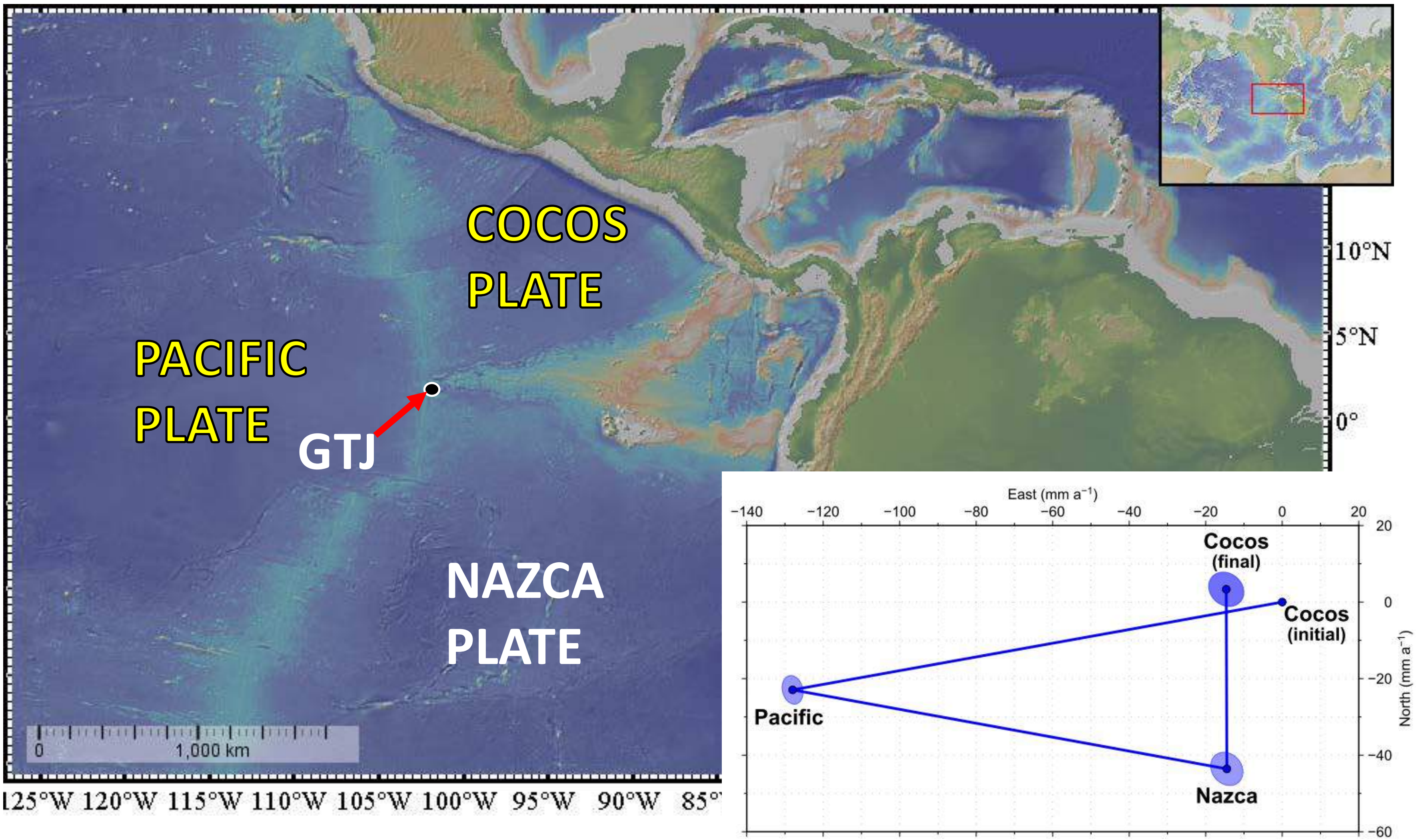
Test of Plate Circuit Closure: Pacific-Antarctic-Nubia-North America (*Velocity Space near Coastal Calif.*)



Sum of best-fitting angular velocities fails closure (*both for NUVEL and for MORVEL, the latter by a vector with length 5 mm/yr*)

DeMets, Gordon, & Argus 2010

Cocos-Nazca-Pacific Plate Circuit Non-Closure about the Galapagos TJ



Zhang, Gordon, & Wang 2017

Thus, plates are NOT rigid. What could cause the non-rigidity?

Two possibilities we've explored:

(1)Plate movement over a nonspherical Earth [McKenzie 1972; Turcotte & Oxburgh 1973]

(2)(2) Horizontal thermal contraction of oceanic lithosphere [Collette 1974; Kumar & Gordon 2009] *--will discuss on next slide*

Horizontal contraction of oceanic lithosphere due to cooling

Vertically averaged horizontal normal strain rate of brittle upper lithosphere due to isotropic thermal contraction is given by

$$\dot{\varepsilon} \propto \frac{1}{t + t_0}$$

where t is age and $t_0 \approx 0.1$ Ma

Kumar & Gordon 2009 JGR

Straining and Displacements of a Cooling Shrinking Pacific Plate

Strain rate: Contours of log of the 2nd invariant of the strain rate tensor. Black=contractional white=extensional

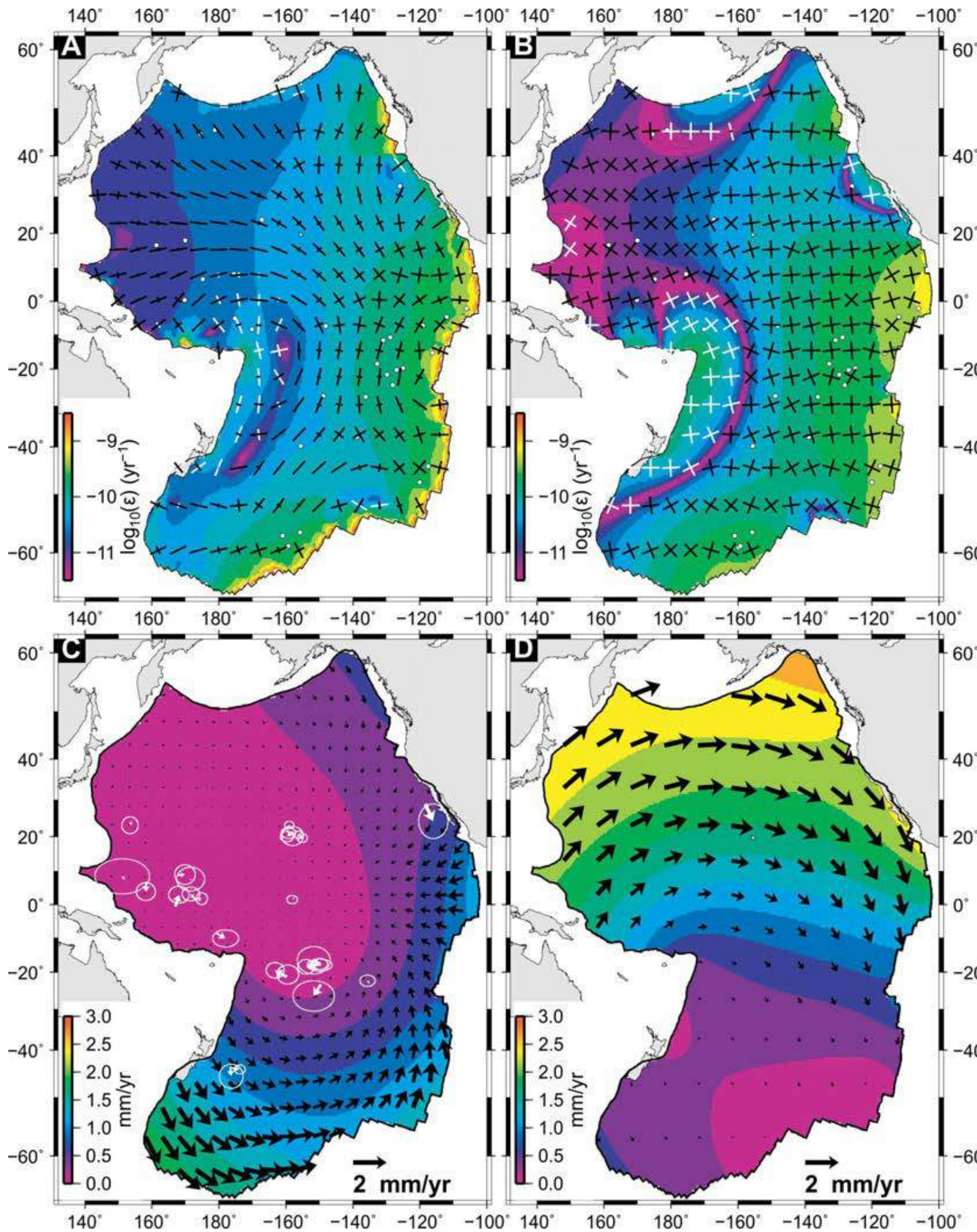
A: optimized to match expected areal changes.
B: optimized to preserve shape

Velocities: Contour of speed. Black arrows=predicted. White arrows=residual observed.

C: In a frame of reference that minimizes the motion of the region of oldest oceanic lithosphere.
D: In a frame of reference that minimizes the motion of lithosphere near the Pacific-Antarctic Rise

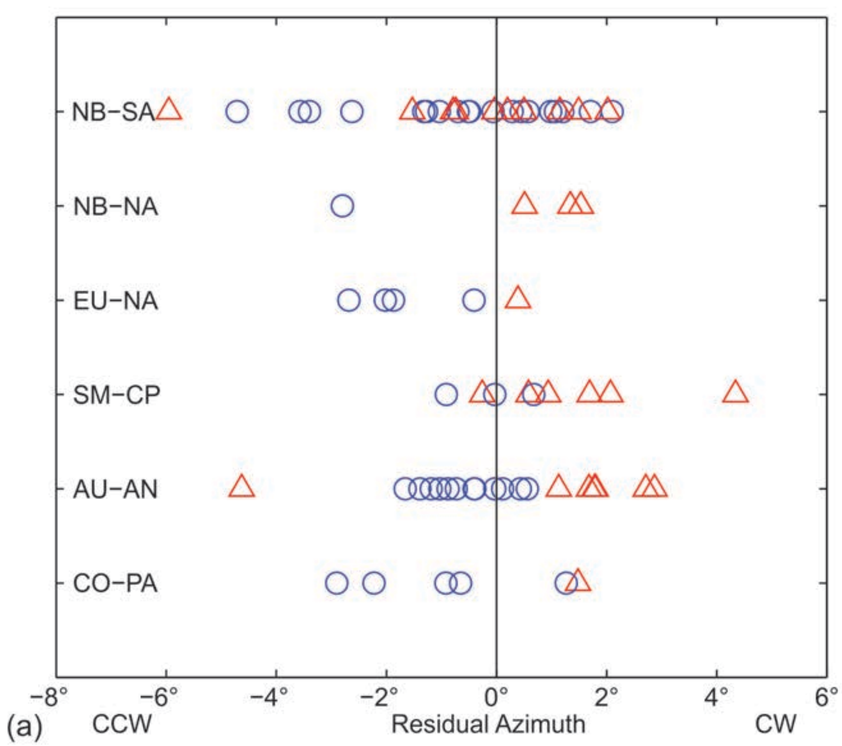
Analysis uses ~200,000 cells.

Kreemer & Gordon, Geology, 2014

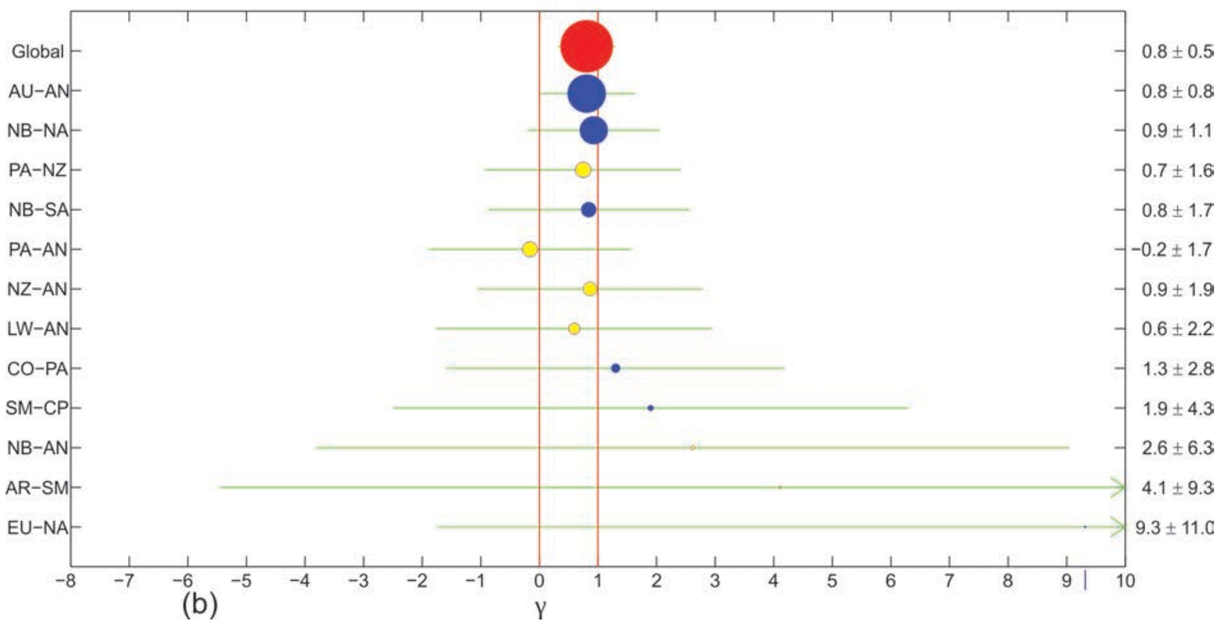


How can we further test the predictions of the shrinking plate hypothesis?

- GPS? No---Sites neither dense enough nor in the right locations (which would be on young oceanic lithosphere)
- ***Azimuths of transform faults***

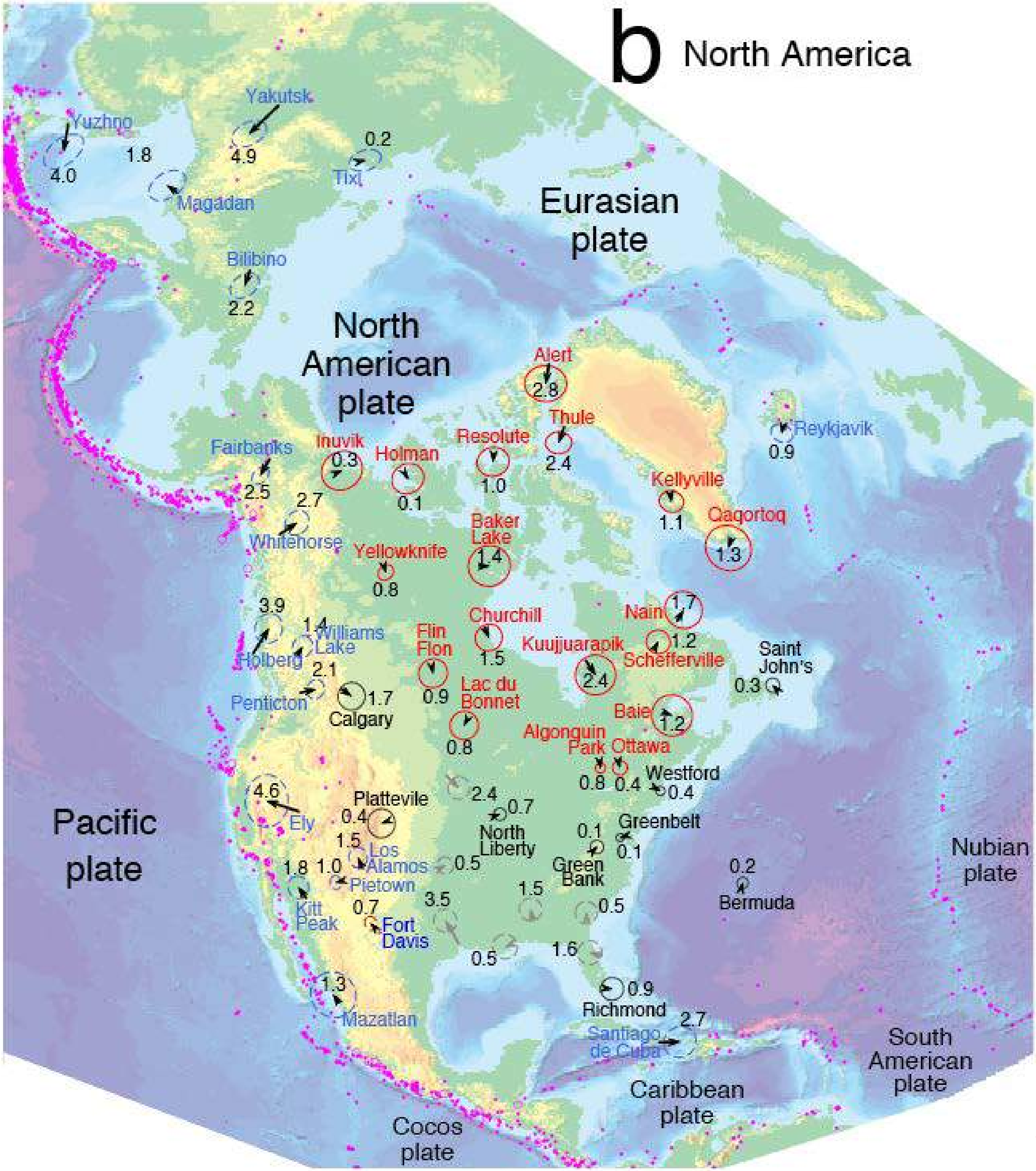


Residuals of transform fault azimuths with respect to best-fitting calculated values for plate boundaries with both LL (red triangles) and RL (blue circles) slipping transform faults. Rigid plate hypothesis predicts zero difference between RL and LL. Shrinking plate hypothesis predicts that LL tend to be CW of LL. ***In 6 out of 6 cases, the mean LL residual is CW of the mean RL residual, consistent with the shrinking plate hypothesis.***



Best constrained estimates of t parameter γ that best fit the data. Red, global best fit. Blue, best fit to a plate pair with both LL and RL slipping faults. Yellow, best fit to a plate with transforms that slip in just one sense. γ =0 is predicted if the plates are rigid. γ=1 is predicted by the shrinking plate hypothesis.

Mishra & Gordon 2016



Intra-plate deformation on short and long time scales illustrated by space geodetic sites on North America.

Reference frame is that which minimizes the velocities of sites on stable NA plate

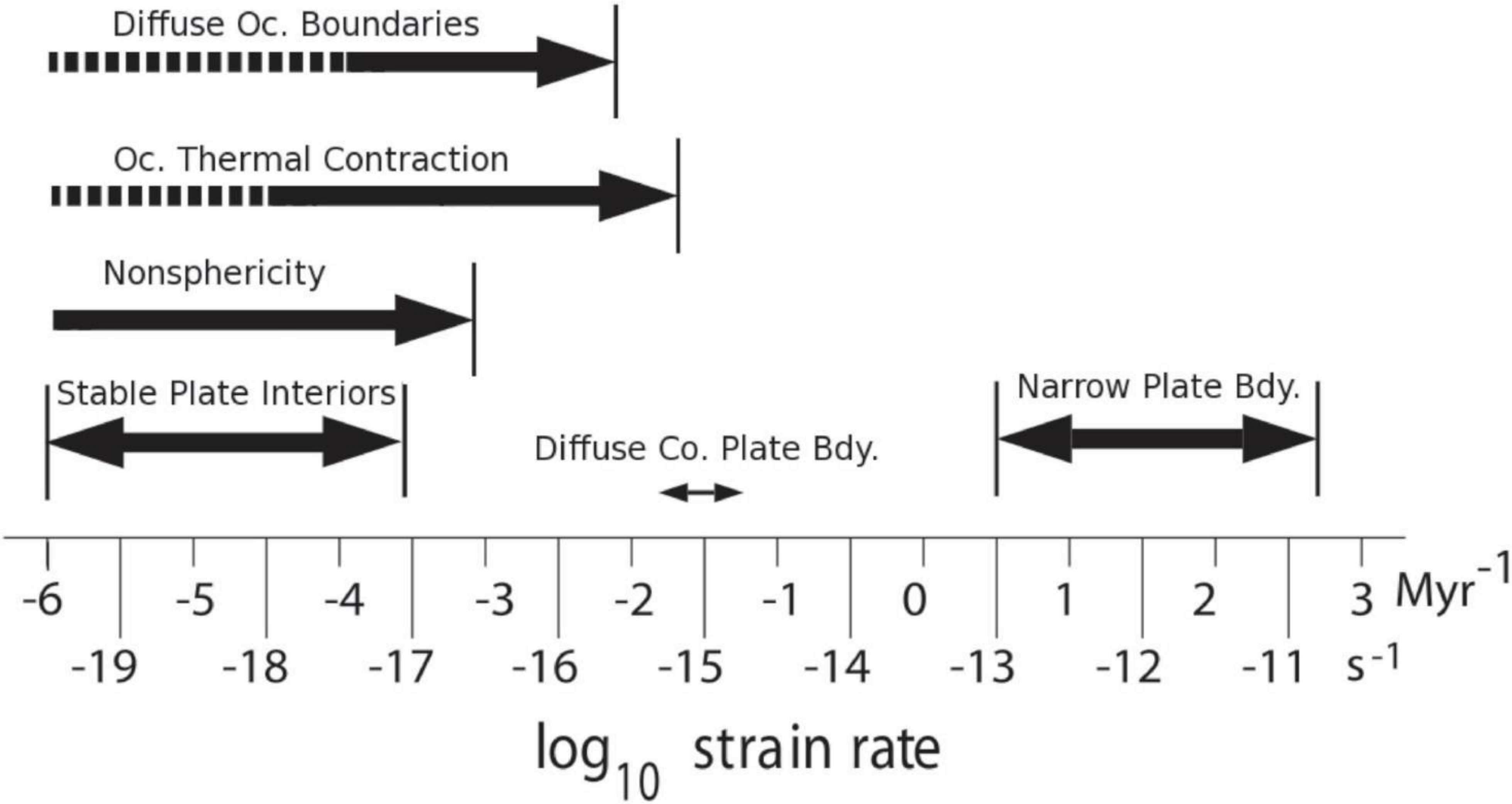
Black: Assumed to be on stable NA plate

Blue: Diffuse plate boundary sites

Red: Sites significantly affected by post-glacial rebound

Argus et al. GJI, 2010

Tectonic Strain Rates

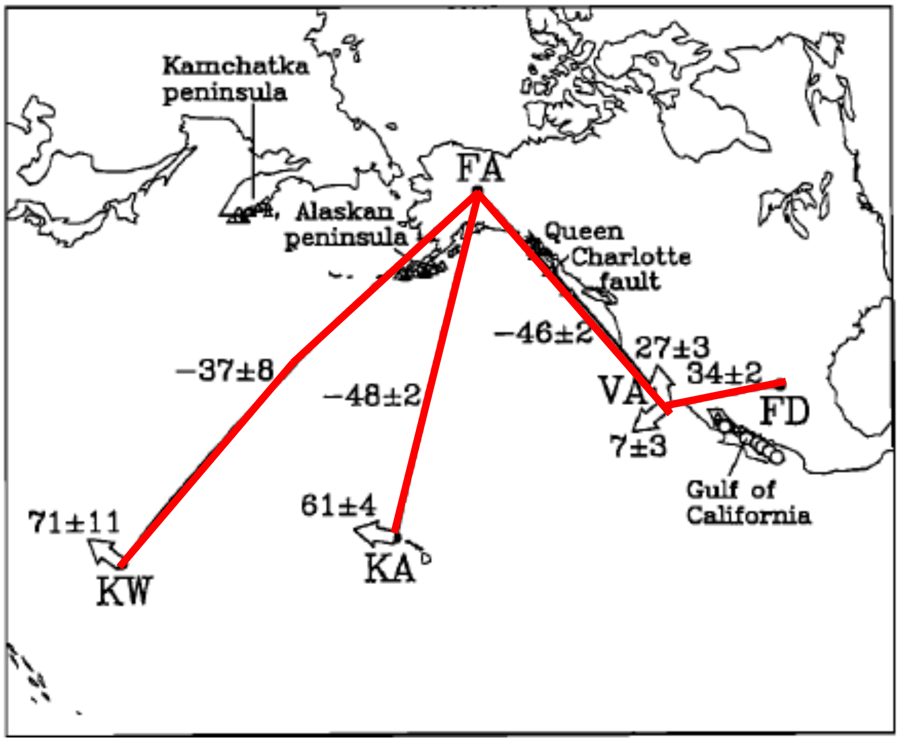


Steadiness of Plate Motion ca 1990

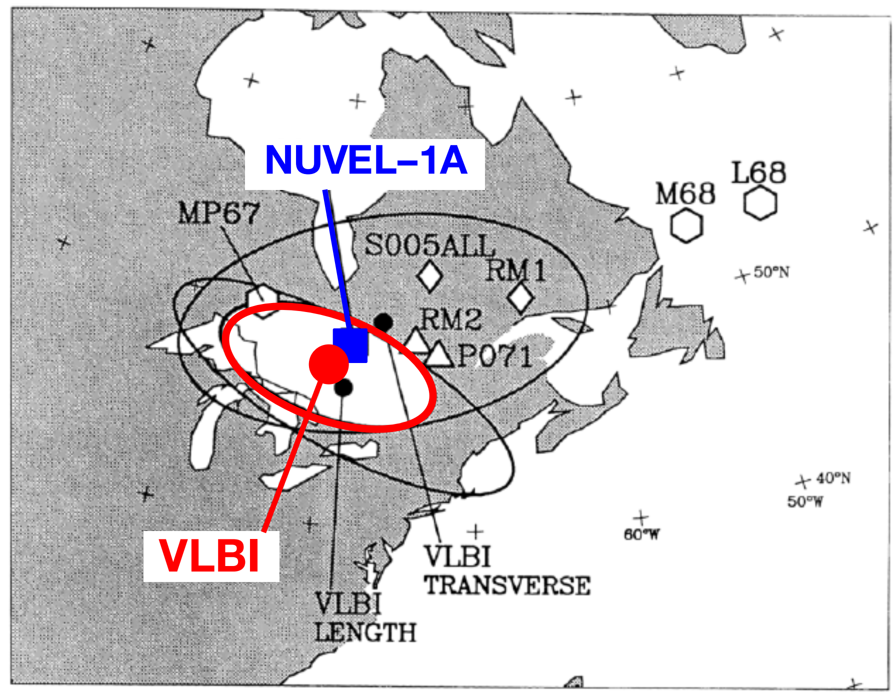
Pacific–North America plate motion

Geology/Marine Geophysics vs. Space Geodesy

VLBI baselines



Rotation poles

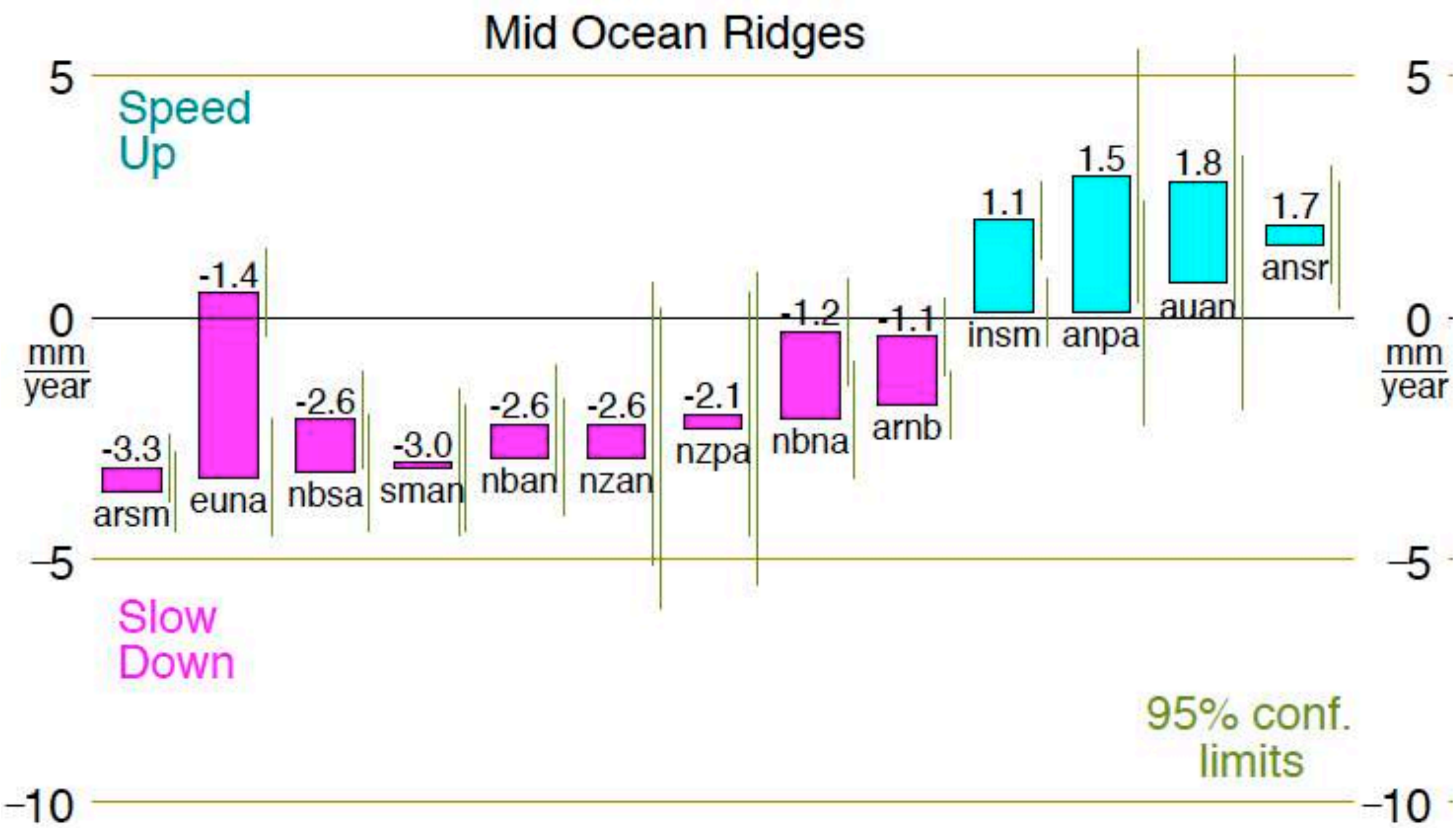


1st published plate angular velocity from space geodesy. Shows the high degree of steadiness of decade versus million year time scales.

Argus & Gordon JGR 1990;
also see Ward 1990, and work of scientists at NASA Goddard Space Flight Center

Speed differences
GEODVEL(space geodesy) vs MORVEL (marine geophysics)

range MOR's
9 slowed down
4 sped up
transition width



Work of D. Argus; MORVEL (DeMets et al., 2010); GEODVEL (Argus et al. 2010)

Speed differences
GEODVEL(space geodesy) vs
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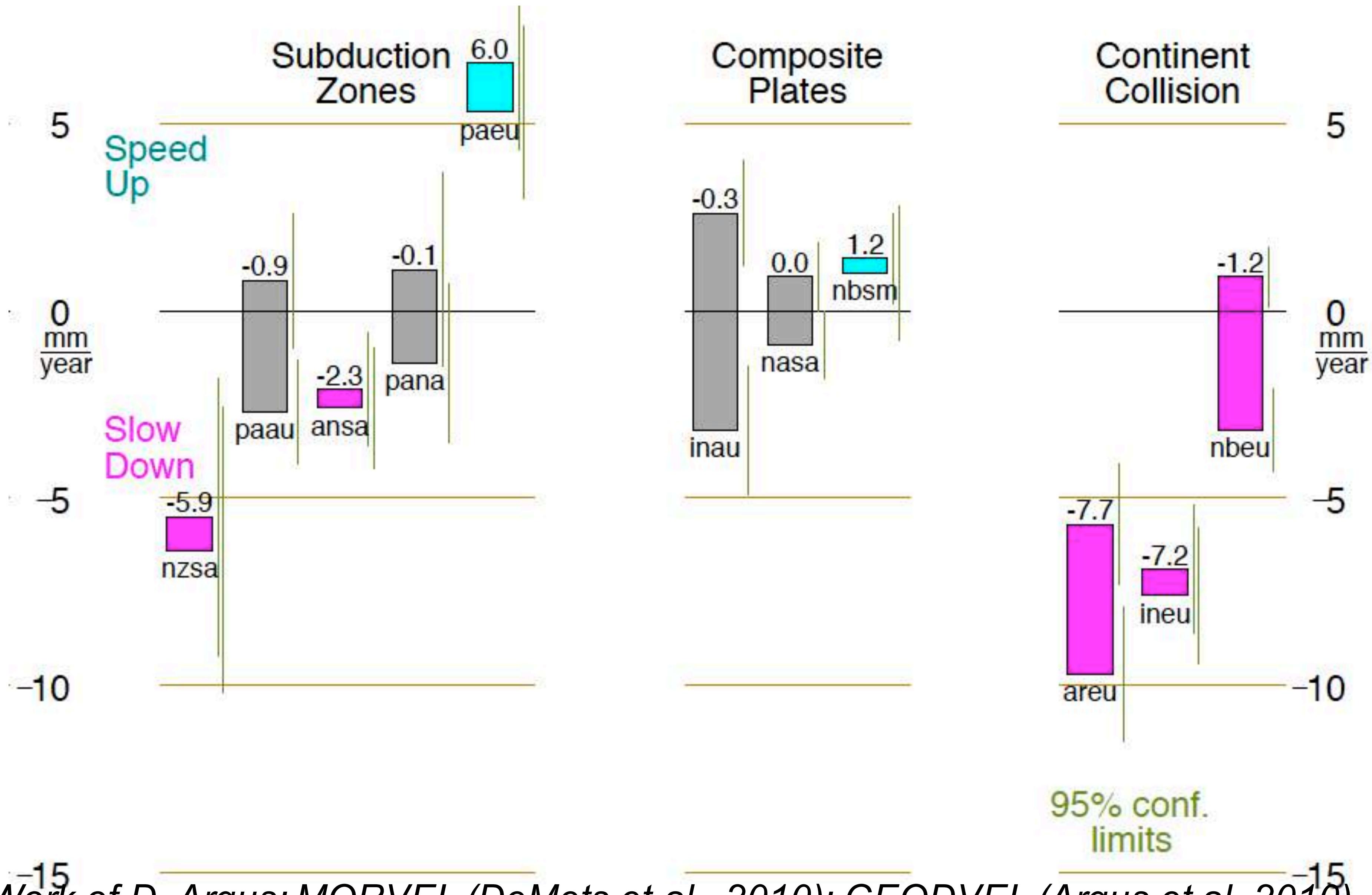
range other
no speed change
for composite
north component
rel. to Eurasia



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The End