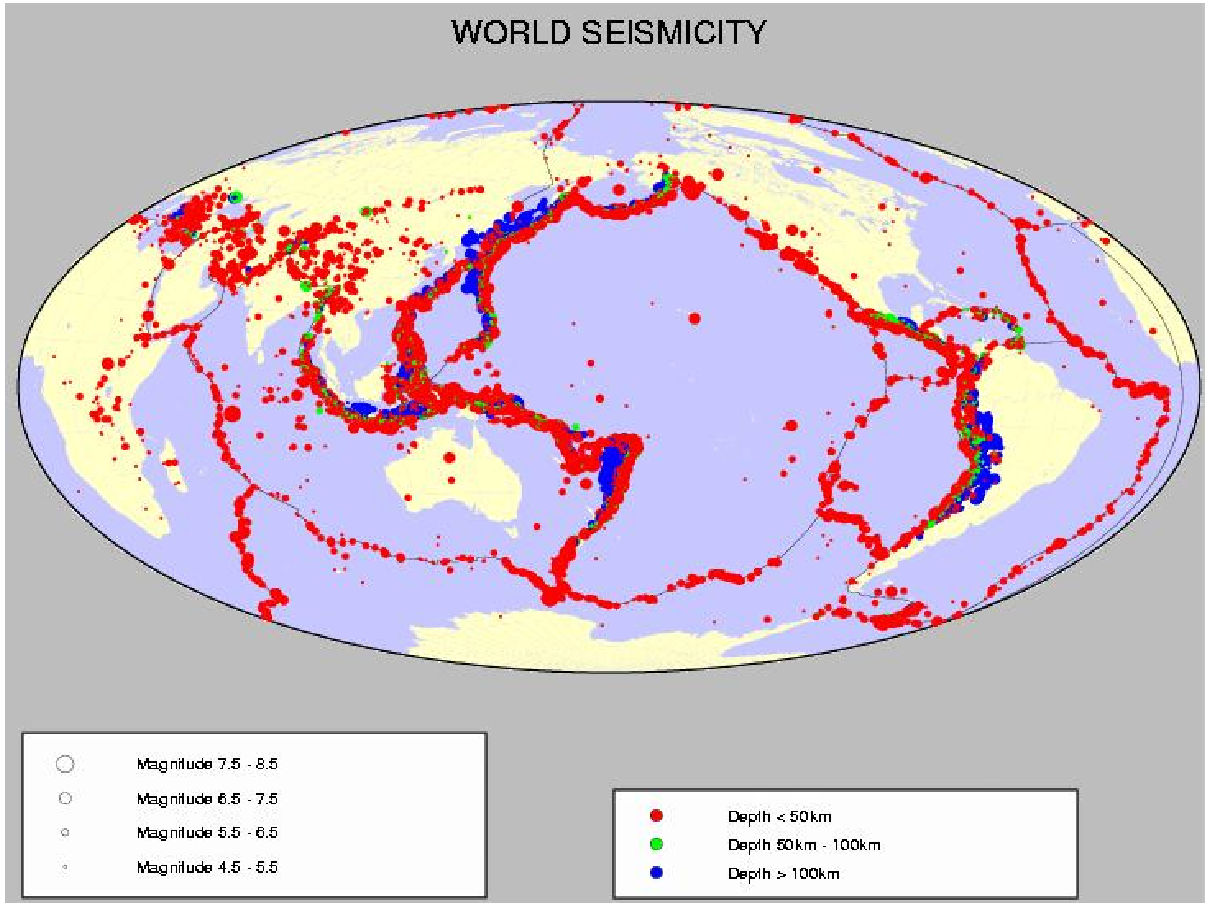
RIGID PLATE TECTONICS

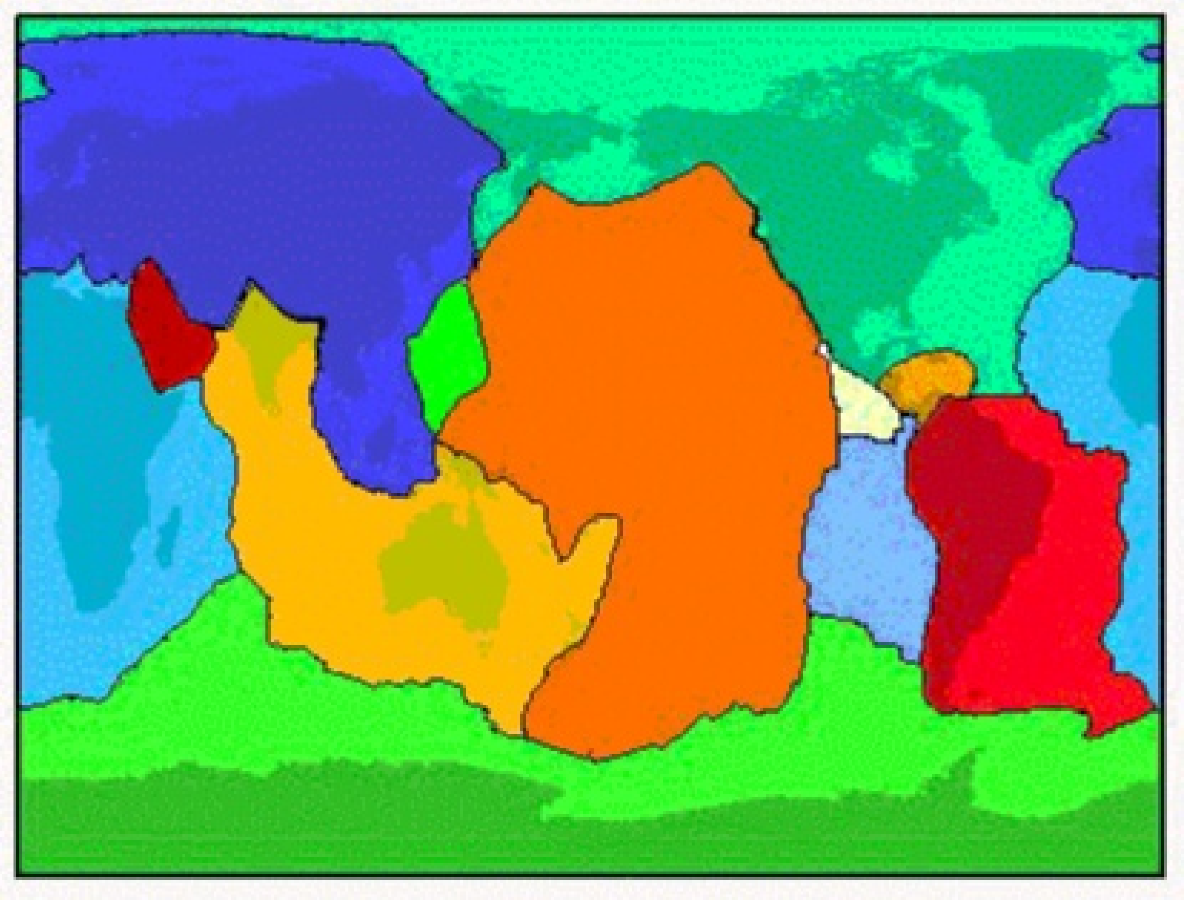
- Plate definition
- Plate motion : Euler pole
- Geological model : Nuvel-1A
- Geodetic model : ITRF
- Rigid plate rotations
- Plate deformation : strain and rotation tensors

World seismicity



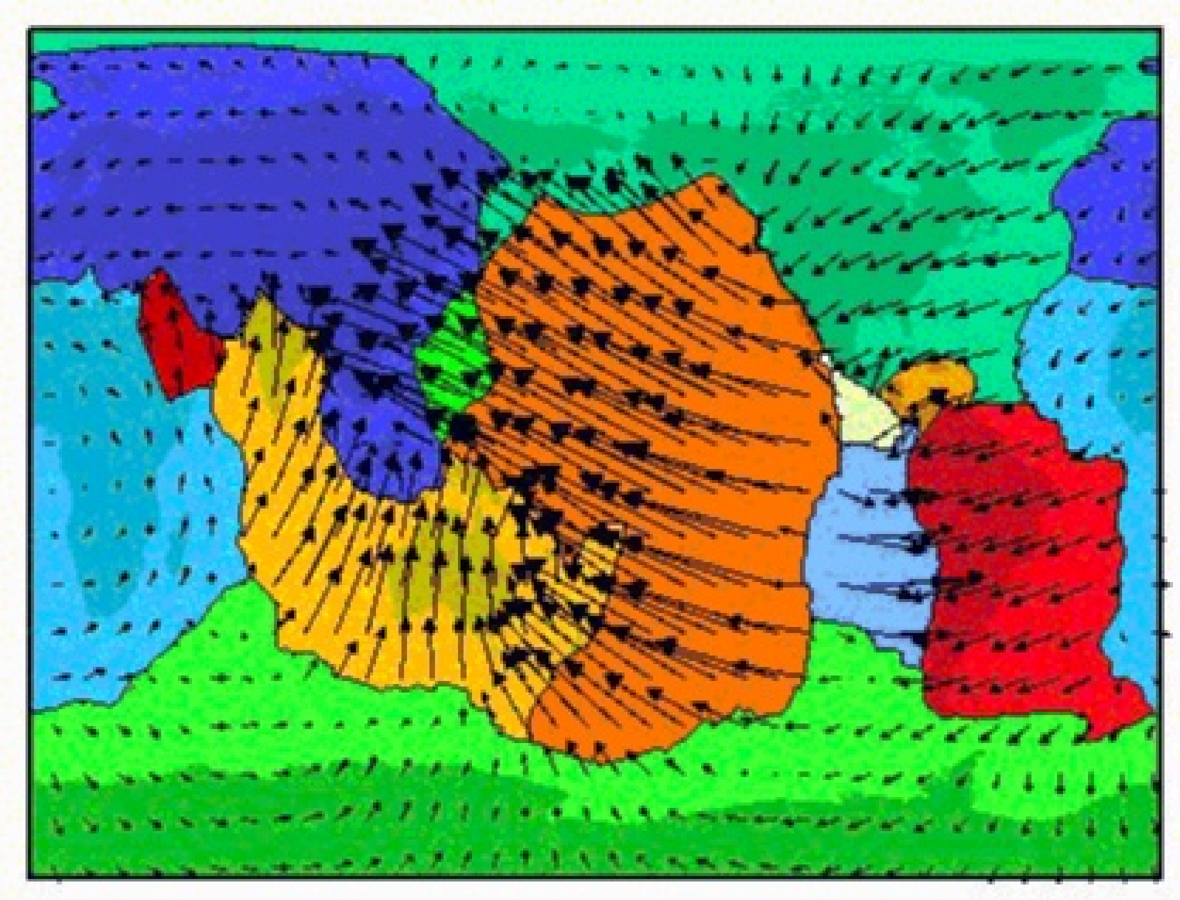
The Earth surface is cut by seismic « lines », separting quite areas, i.e. plates.

Plate geometry



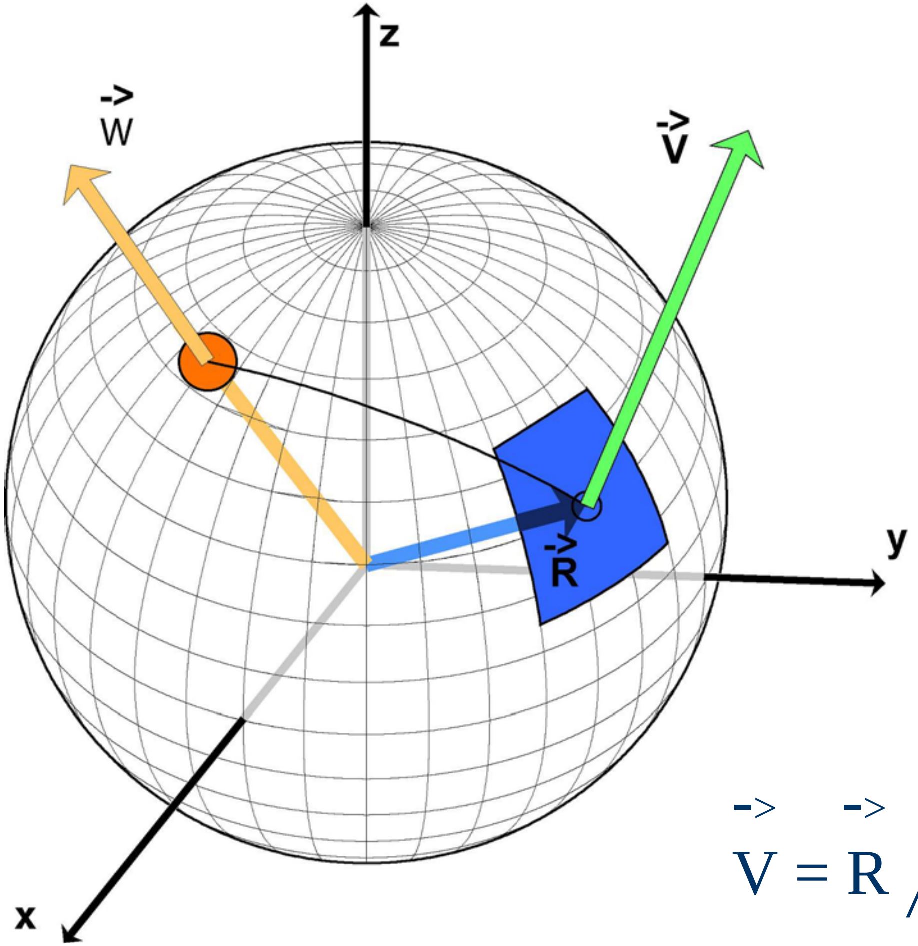
There are 12 main plates

Plate motion



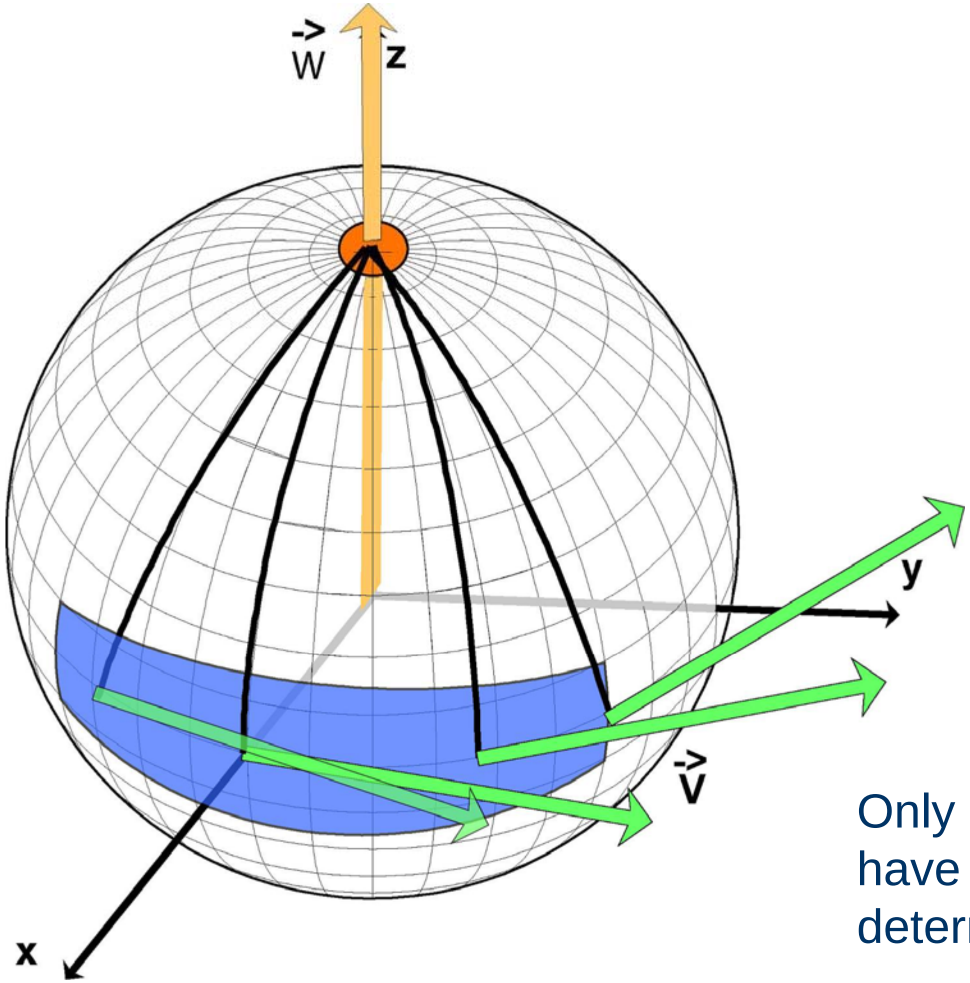
Plates move : it is plate tectonics

Rotation on a sphere



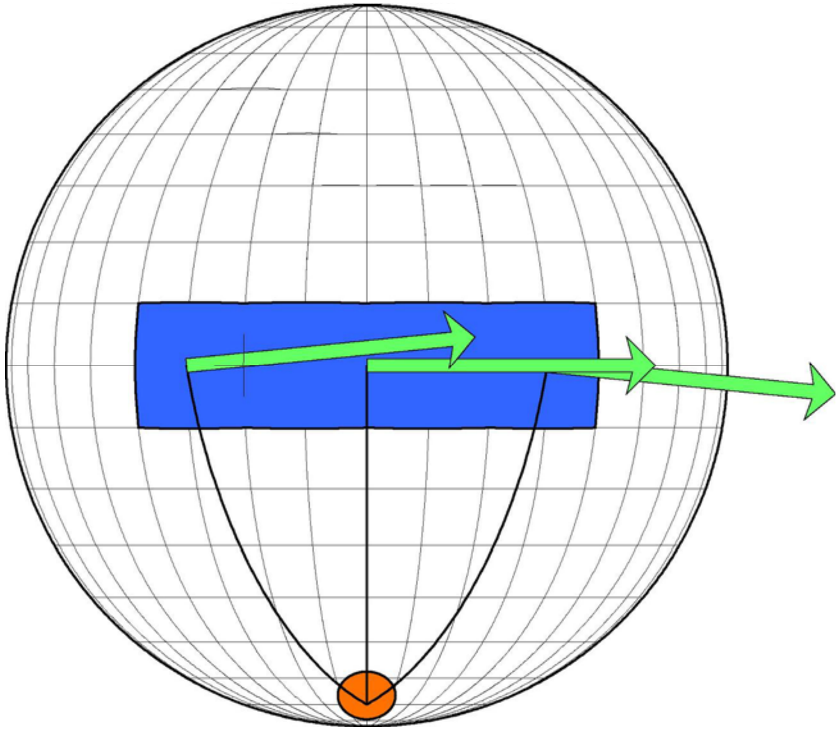
$$\vec{V} = \vec{R} \wedge \vec{W}$$

Finding a pole



Only large plates have well determined poles

Effect of velocity uncertainty



Slightely different velocities can give

very different poles

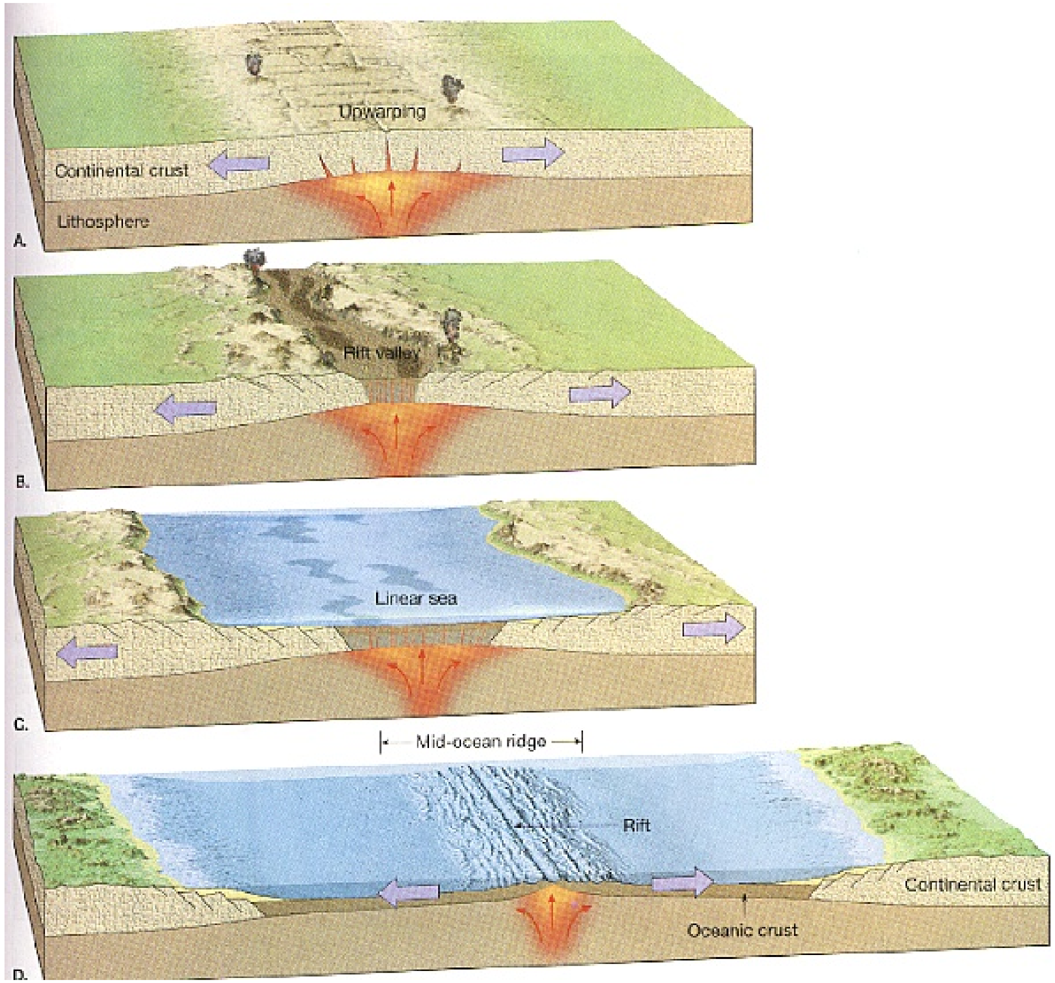
Or reverse :

Very different poles can give quite similar velocities

Pole positions don't matter.
only velocities do !!!!

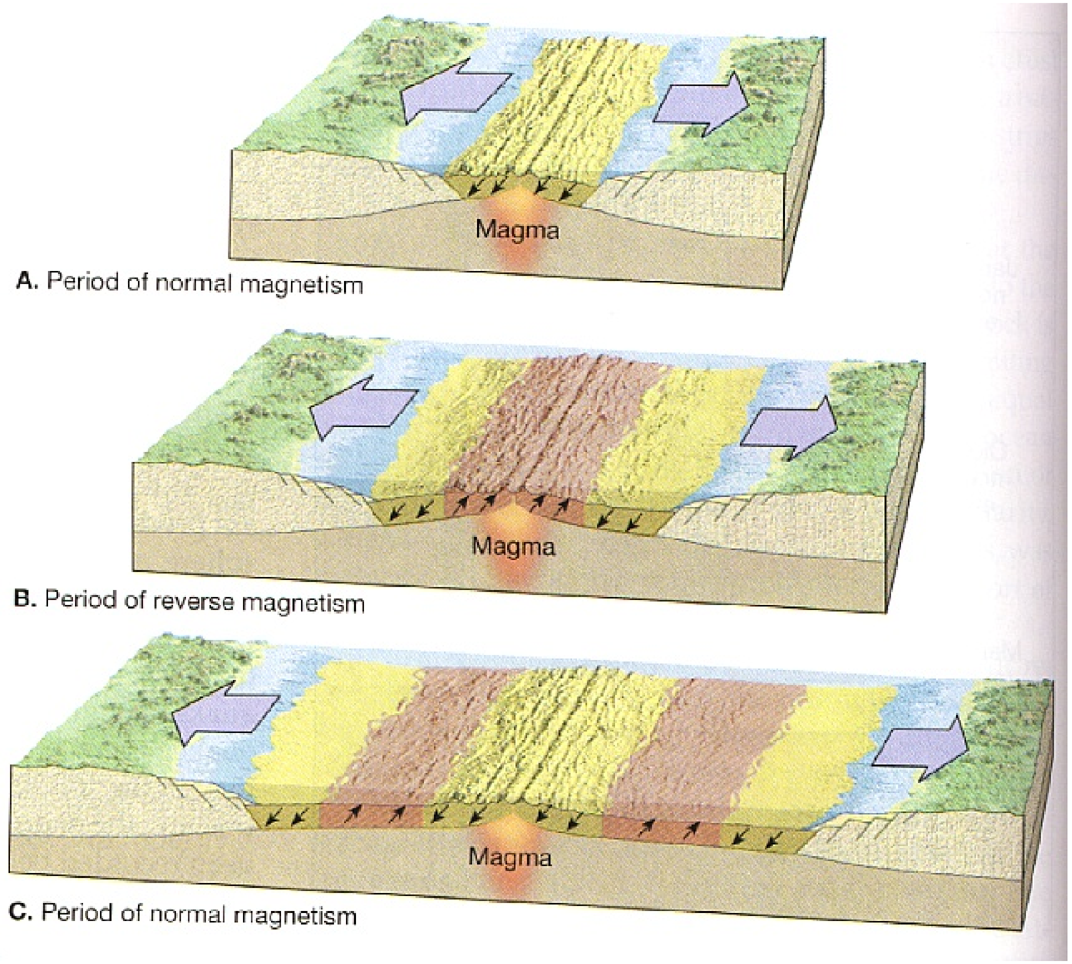
Geological model : how it works

Rates : continental drifting



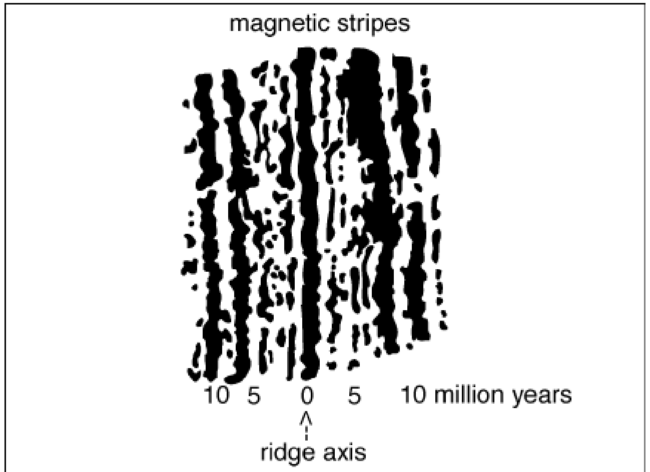
Geological model : how it works

Rates : generation of oceanic crust and sea floor magnetic anomalies

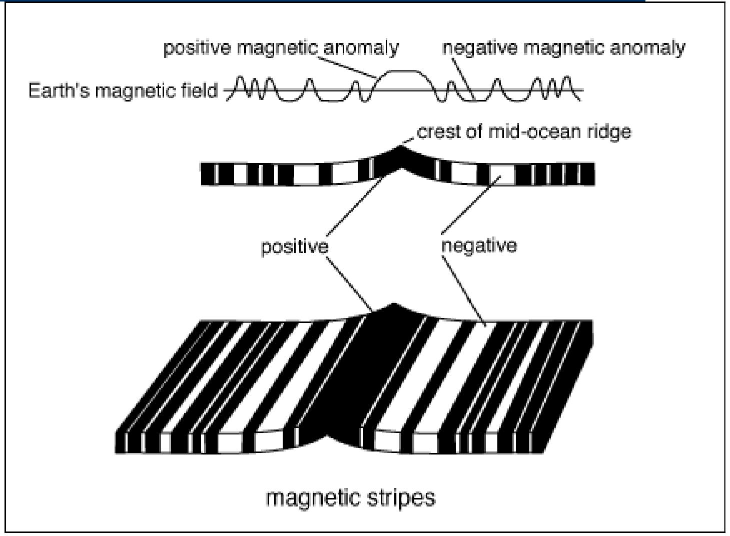


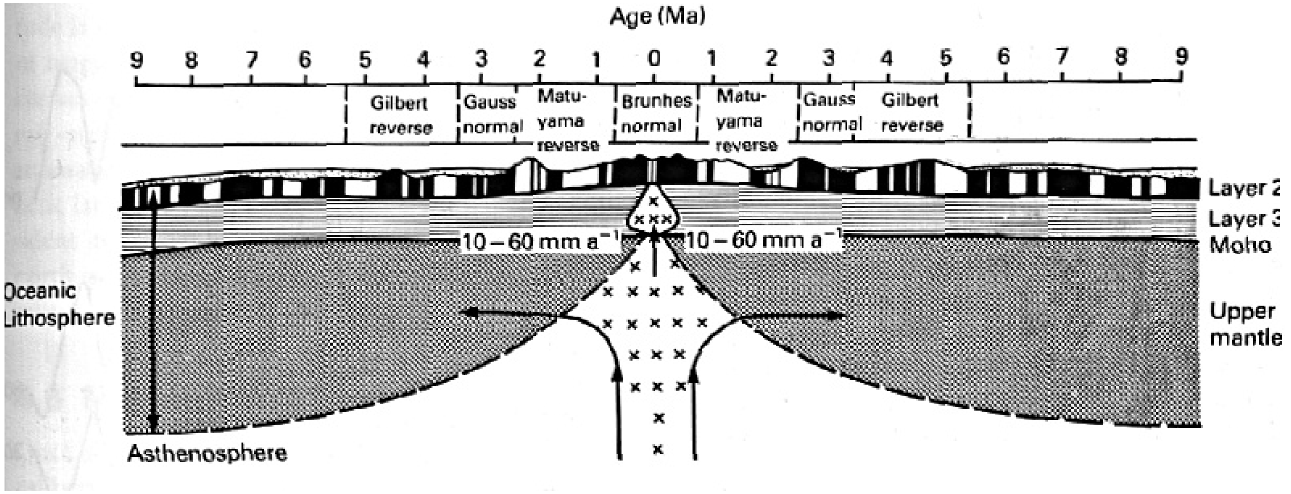
Geological model : how it works

Rates : Vine and Matthews hypothesis



Pattern created by magnetic stripes along the Mid-Atlantic Ridge south of Iceland.





Geological model : how it works

Rates : unecrtainties from magnetic time scale

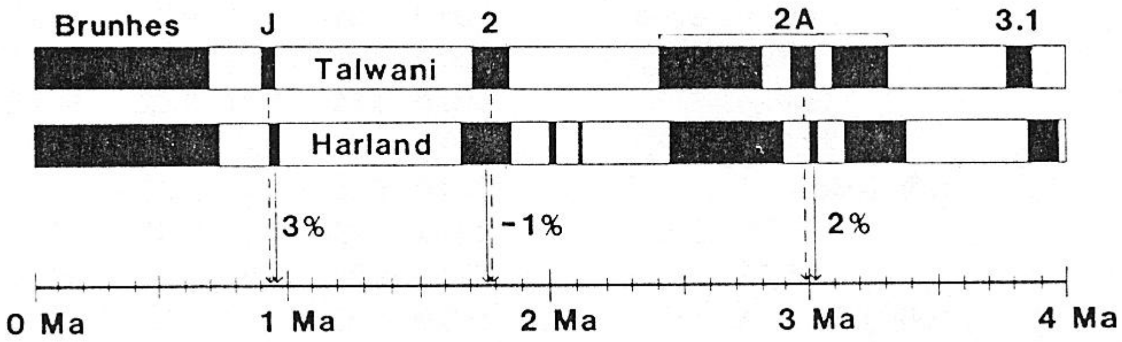


Figure 1. Comparison since 4.0 Ma of the geomagnetic reversal time-scale used here (Harland *et al.* 1982) with the time-scale used by Chase (1978) and Minster & Jordan (1978) (Talwani *et al.* 1971). We determined rates by seeking the best fit to the centre of anomaly 2A, which is 2 per cent older in the Harland *et al.* time-scale than in the Talwani *et al.* time-scale.

Geological model : how it works
directions

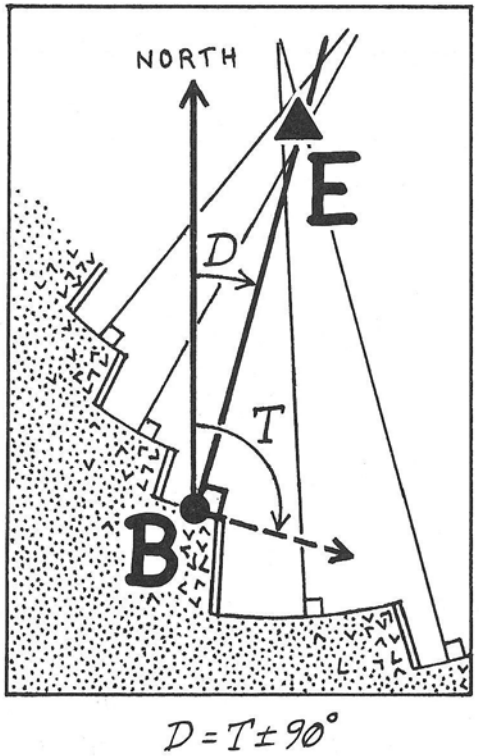


Figure 4-1.
Locating an Euler pole **E** from the trends *T* of transforms. Lines nearly intersecting at **E** are great circles perpendicular to the transforms.

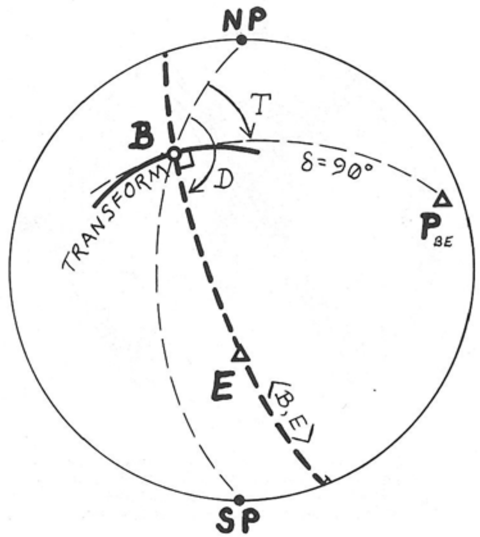


Figure 4-2.
Euler pole **E** is on the great circle perpendicular to the trend of the transform. $\mathbf{P}_{BE}$ is the pole of the great circle <**B**, **E**>.

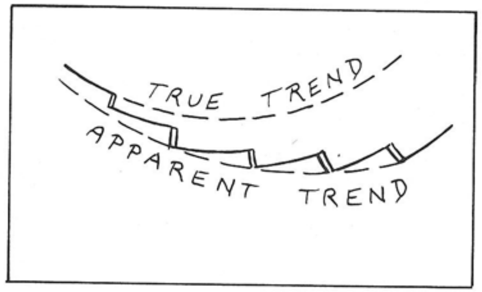
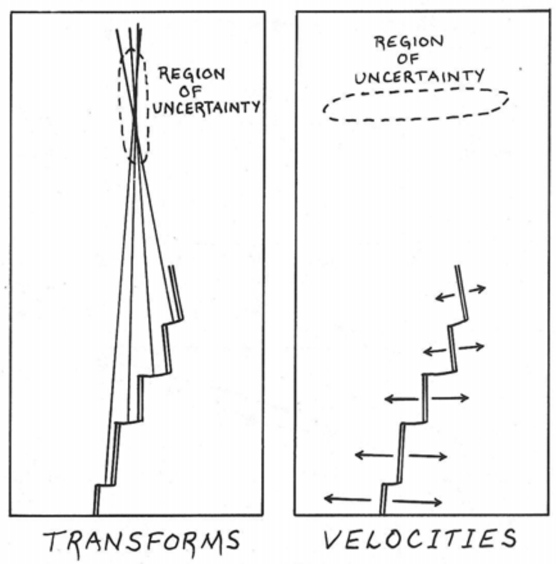
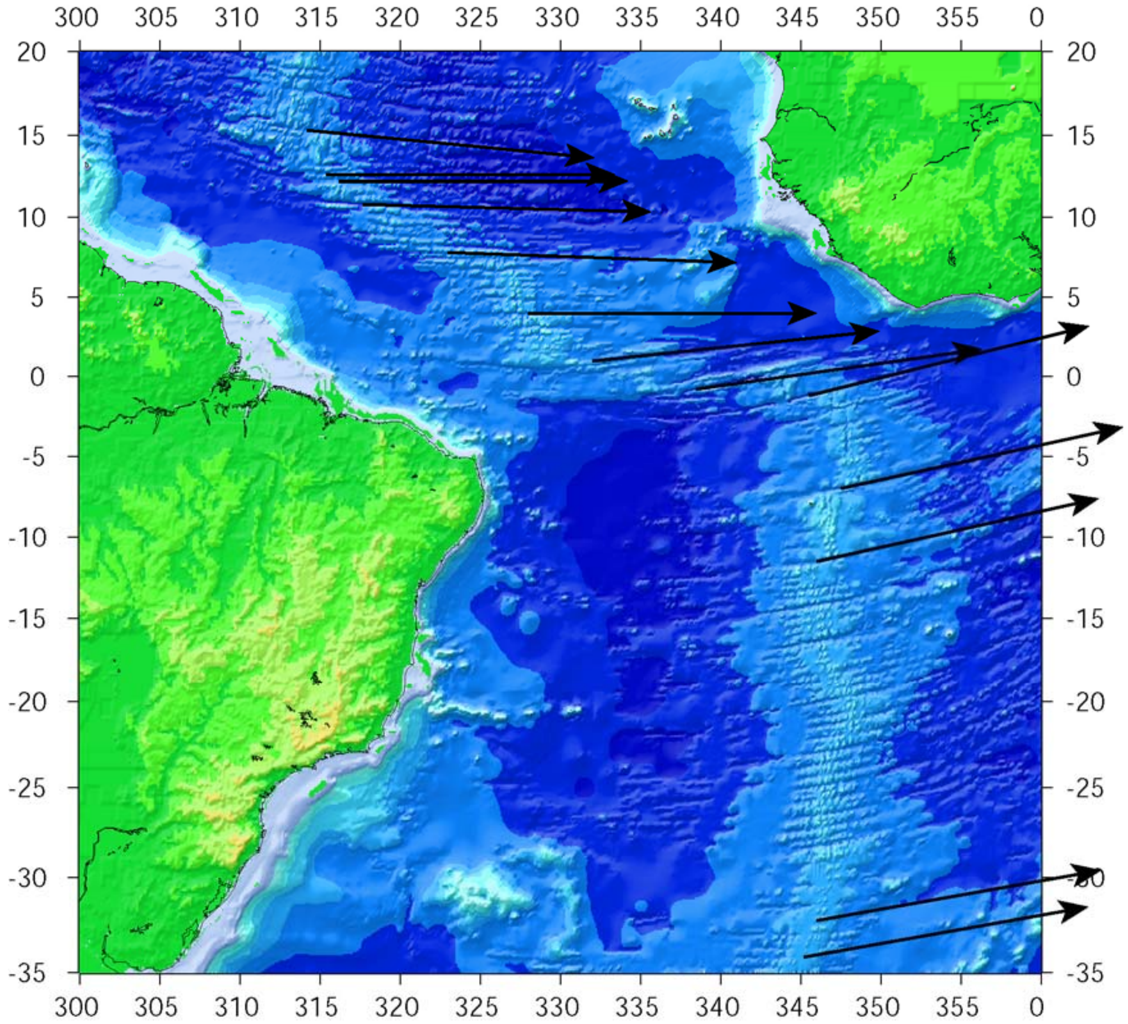


Figure 4-3.
Apparent and true trends of transform system offset by short ridge segments.



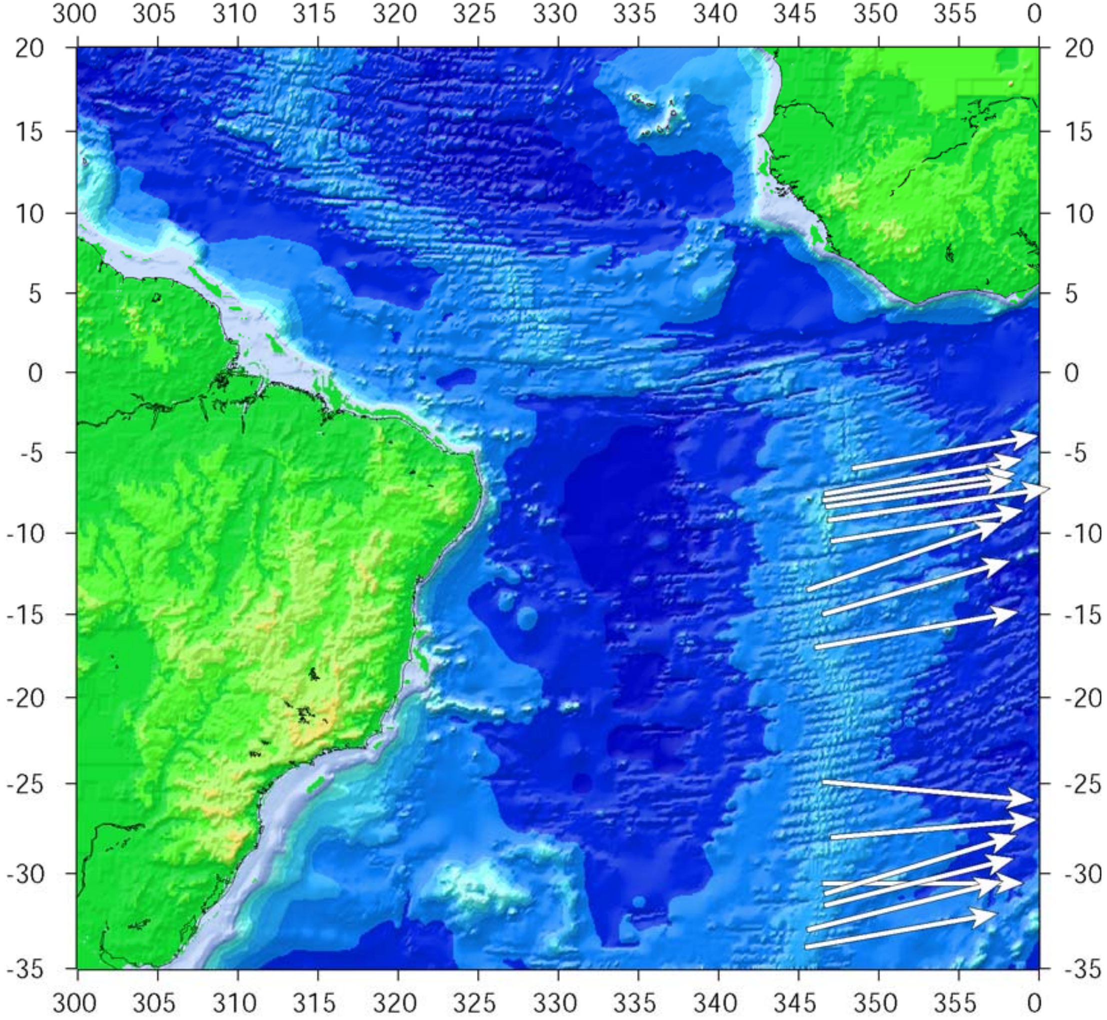
Geological model : real data
Transform faults azimuths

Lon	lat	azimuth
15.3	-45.8	95.5
12.6	-44.6	90.0
12.2	-43.8	90.0
10.8	-42.3	91.5
7.8	-37.0	92.0
4.0	-32.0	90.0
1.0	-28.0	84.0
-0.8	-21.5	82.0
-1.2	-14.5	76.0
-7.0	-12.5	77.7
-11.5	-14.0	77.5
-32.3	-14.0	80.0
-34.2	-14.8	80.0
-54.2	-2.0	65.0



Geological model : real data
Spreading rates

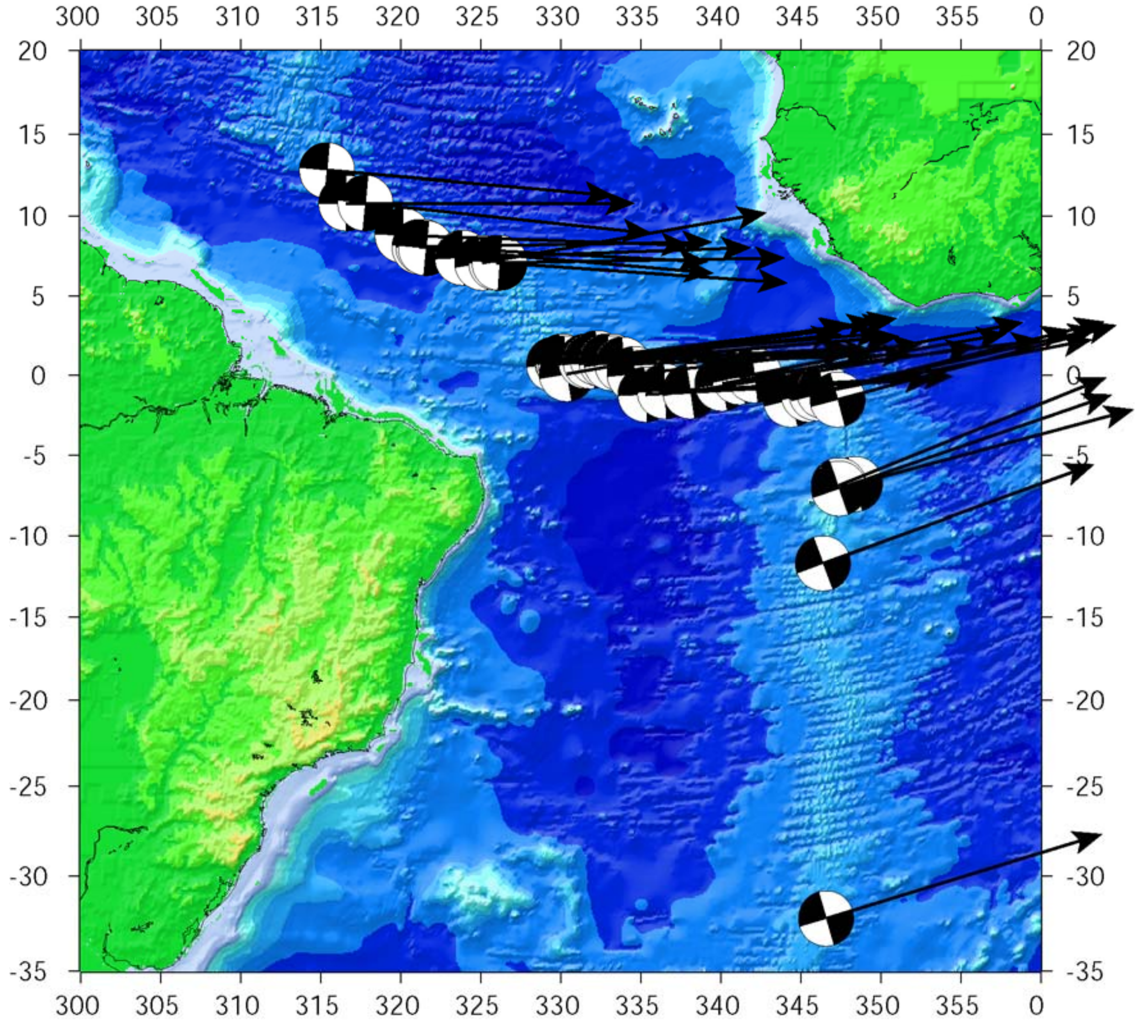
lon, lat, rate, az			
-6.0	-11.7	33	10
-7.6	-13.4	35	10
-8.0	-13.5	34	8
-8.4	-13.3	33	8
-9.2	-13.2	39	8
-10.5	-13.0	34	9
-13.5	-14.5	36	19
-15.0	-13.5	34	16
-17.0	-14.0	36	10
-24.9	-13.5	37	-5
-28.0	-13.0	36	5
-30.5	-13.5	35	0
-31.1	-13.4	35	17
-31.7	-13.4	34	14
-33.0	-14.5	35	14
-33.9	-14.6	34	10
-38.5	-17.0	36	10
-40.0	-16.0	36	5
-42.0	-16.0	32	5
-43.0	-16.0	35	5
-54.2	-1.3	28	25
-54.5	-1.1	30	25



Geological model : real data
Slip vector azimuths

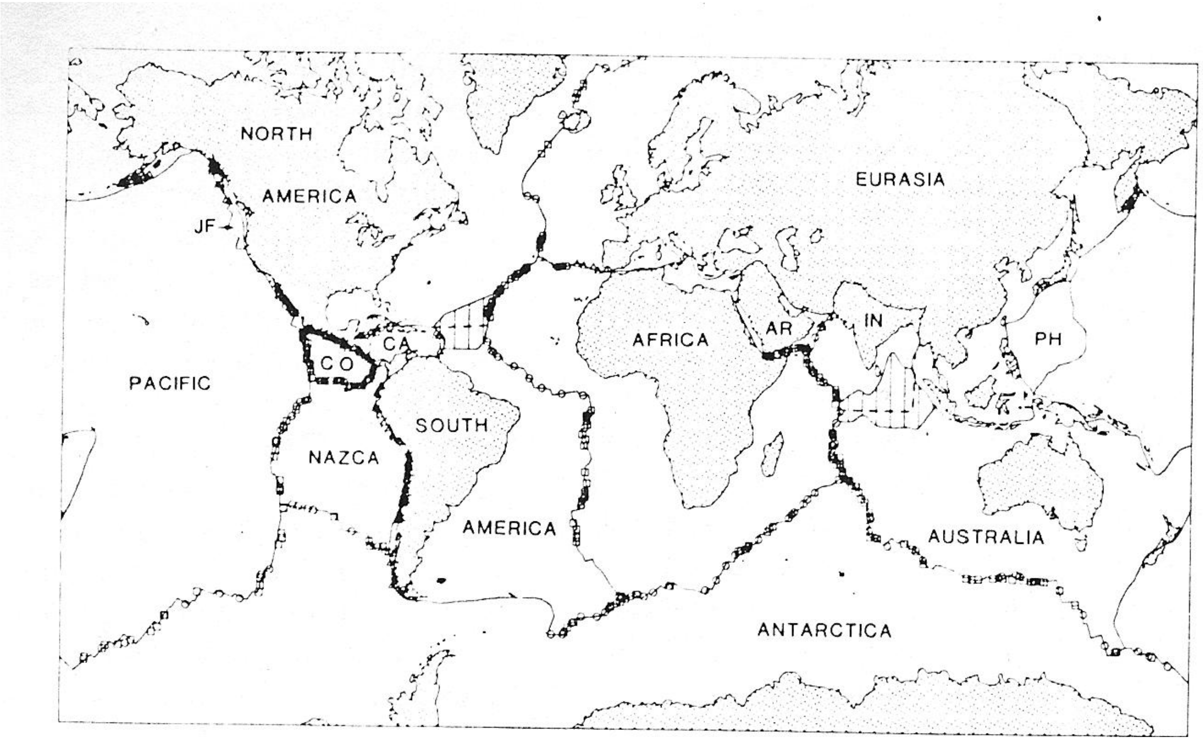
Lon	lat	azimut
12.8	-44.6	95.0
10.8	-43.4	90.0
10.8	-42.2	96.0
8.8	-39.9	92.0
8.1	-38.8	93.0
8.1	-38.5	89.0
8.0	-38.4	95.0
7.4	-36.1	88.0
7.1	-34.9	80.0
7.1	-34.0	89.0
7.1	-33.8	94.0
0.7	-30.4	84.0
0.9	-29.9	83.0
0.8	-29.8	88.0
0.8	-29.7	87.0
0.1	-29.6	80.0
0.9	-28.4	88.0
0.9	-28.1	82.0
1.1	-27.7	85.0
0.9	-27.1	85.0
0.9	-27.1	82.0
0.9	-26.8	85.0
0.8	-26.8	81.0
0.7	-26.1	88.0
0.1	-25.3	84.0
-1.2	-24.7	87.0
-1.0	-23.5	87.0
-1.0	-21.9	81.0

Lon	lat	azimut
-0.5	-19.9	80.0
-0.1	-18.8	79.0
-0.0	-17.9	83.0
-1.5	-15.6	76.0
-1.2	-14.5	79.0
-1.1	-14.0	77.0
-1.0	-13.5	76.0
-1.5	-12.7	75.0
-6.8	-11.6	75.0
-6.9	-12.6	68.0
-7.1	-12.6	71.0
-11.7	-13.6	70.0
-32.2	-13.4	73.0
-35.8	-16.0	76.0
-35.5	-16.1	81.0
-47.6	-12.9	76.0
-46.9	-10.8	85.0



Geological model : Nuvel-1A, Demets et al., 1990

Current plate motions, Geophys. Journal. Int., 101, 425-478, 1990



Around 1200 slip vector azimuth, transform fault orientations and spreading rates are compiled in one model for plate motion

Geological model : data table

Table 3. *(continued)*

26.90	-44.50	26	4	24.5	0.022	n16e	*Rabinowitz & Schouten* (1985)
26.20	-44.80	22	3	23.5	0.037	n30e	*McGregor et al.* (1977)
25.70	-45.00	24	4	24.2	0.022	n24e	*Rabinowitz & Schouten* (1985)
25.30	-45.40	22.5	2	24.4	0.089	n24e	*Rabinowitz & Schouten* (1985)
25.10	-45.40	24.5	2	24.4	0.090	n24e	*Rona & Gray* (1980)
24.50	-46.10	23	4	24.6	0.023	n23e	*Rabinowitz & Schouten* (1985)
24.20	-46.30	24.5	2	25.1	0.097	n15e	*Rona & Gray* (1980)
23.00	-45.00	25	4	25.2	0.025	n08e	*Rabinowitz & Schouten* (1985)
22.80	-45.00	25	2	25.1	0.100	n04e	*Rabinowitz & Schouten* (1985)
Africa-North America: Transform Azimuths							
35.20	-35.60	104.5	2	103.6	0.203		*Roest et al.* (1984)
33.70	-38.70	104.5	2	103.4	0.216		*Roest et al.* (1984)
30.00	-42.40	101.5	3	102.9	0.100		*Roest et al.* (1984)
23.70	-45.70	98.0	2	102.2	0.220		*Roest et al.* (1984) & *Pockalny et al.* (1988)
Africa-North America: Slip Vectors							
35.43	-36.03	102.0	20	103.6	0.002		CMT 4.29.85
35.41	-36.01	101.0	10	103.7	0.008		CMT 6.06.82
35.35	-36.08	100.0	10	103.7	0.008		*Bergman & Solomon* (1988)
35.14	-35.45	101.0	15	103.6	0.004		CMT 7.14.80
33.79	-38.64	101.0	10	103.4	0.009		*Bergman & Solomon* (1988)
33.78	-38.46	102.0	15	103.4	0.004		CMT 5.07.84
33.69	-38.60	103.0	15	103.4	0.004		CMT 5.03.84
28.74	-43.58	91.0	20	102.8	0.002		*Engeln et al.* (1986)
23.83	-45.94	100.0	10	102.2	0.009		*Bergman & Solomon* (1988)
23.86	-45.57	100.0	10	102.2	0.009		*Bergman & Solomon* (1988)
23.81	-45.44	106.0	15	102.2	0.004		CMT 11.28.81
23.74	-45.17	102.0	15	102.2	0.004		CMT 3.12.77
Africa-Eurasia: Transform Azimuths							
36.90	-23.50	257.0	5	260.2	0.187		*Laughton et al.* (1972)
37.00	-22.60	265.0	3	263.3	0.399		*Laughton et al.* (1972)
37.10	-21.70	265.0	3	266.3	0.384		*Laughton et al.* (1972)
37.10	-20.50	-90.0	7	270.4	0.098		*Laughton et al.* (1972)
Africa-Eurasia: Slip Vectors							
37.75	-17.25	-89.0	25	-79.2	0.022		CMT 10.17.83
37.22	-14.93	-50.0	25	-71.5	0.042		*Grimison & Chen* (1986)
36.96	-11.84	267.0	25	-62.0	0.066		*Grimison & Chen* (1986)
36.01	-10.57	-35.0	25	-57.0	0.092		*Fukao* (1973)
35.99	-10.34	-60.0	25	-56.3	0.098		*Grimison & Chen* (1986)
36.23	-7.61	-35.0	25	-49.8	0.104		*Grimison & Chen* (1986)
Africa-South America: Spreading Rates							
-6.00	-11.70	33	6	34.1	0.018	n10w	*van Andel et al.* (1973)
-7.60	-13.40	35	6	34.4	0.018	n10w	*van Andel et al.* (1973)
-8.00	-13.50	34	2	34.4	0.160	n08w	*Brozena* (1986)
-8.40	-13.30	33	6	34.5	0.018	n08w	*van Andel et al.* (1973)
-9.20	-13.20	39	6	34.6	0.017	n08w	*van Andel et al.* (1973)
-10.50	-13.00	34	3	34.8	0.068	n09w	*Brozena* (1986)
-13.50	-14.50	36	4	35.0	0.034	n19w	*Brozena* (1986)
-15.00	-13.50	34	2	35.4	0.136	n16w	*Brozena* (1986)
-17.00	-14.00	36	3	35.6	0.061	n10w	*Brozena* (1986)
-24.90	-13.50	37	6	34.5	0.013	n05e	*Dickson et al.* (1968)
-28.00	-13.00	36	3	35.7	0.053	n05w	*Dickson et al.* (1968)
-30.50	-13.50	35	3	35.1	0.051	n00e	*Dickson et al.* (1968)
-31.10	-13.40	35	5	35.7	0.019	n17w	*Welch et al.* (1986)
-31.70	-13.40	34	3	35.7	0.052	n14w	*Welch et al.* (1986)
-33.00	-14.50	35	3	35.6	0.051	n14w	*Welch et al.* (1986)
-33.90	-14.60	34	4	35.6	0.029	n10w	*Welch et al.* (1986)
-38.50	-17.00	36	6	35.1	0.013	n10w	*Dickson et al.* (1968)
-40.00	-16.00	36	3	34.7	0.051	n05w	*Loomis & Morgan* (1973)
-42.00	-16.00	32	4	34.4	0.029	n05w	*Dickson et al.* (1968)
-43.00	-16.00	35	3	34.2	0.052	n05w	*Loomis & Morgan* (1973)
-54.20	-1.30	28	5	30.9	0.023	n25w	NGDC *Chain* 115-4
-54.50	-1.10	30	3	30.8	0.064	n25w	NGDC *Chain* 115-4
-54.60	-1.00	30	5	30.8	0.023	n25w	NGDC *Chain* 115-4
Africa-South America: Transform Azimuths							
15.30	-45.80	95.5	3	94.0	0.128		*Roest et al.* (1984)
12.60	-44.60	90.0	3	93.1	0.108		*Collette et al.* (1979)
12.20	-43.80	90.0	3	92.6	0.101		*Collette et al.* (1979)
10.80	-42.30	91.5	2	91.7	0.197		*Macdonald et al.* (1986)
7.80	-37.00	92.0	8	88.6	0.008		*Emery & Uchupi* (1984)
4.00	-32.00	90.0	5	86.0	0.016		*Emery & Uchupi* (1984)
1.00	-28.00	84.0	5	84.1	0.015		*Emery & Uchupi* (1984)
-0.80	-21.50	82.0	2	81.0	0.110		*Belderson et al.* (1984)
-1.20	-14.50	76.0	3	77.8	0.069		*Emery & Uchupi* (1985)
-7.00	-12.50	77.7	2	77.3	0.150		*Brozena* (1986)
-11.50	-14.00	77.5	3	78.2	0.056		*Brozena* (1986)
-32.30	-14.00	80.0	2	78.5	0.098		D. Forsyth (personal communication, 1985)
-34.20	-14.80	80.0	3	78.8	0.042		D. Forsyth (personal communication, 1985)
-54.20	-2.00	65.0	10	71.0	0.006		*Sclater et al.* (1976a)
Africa-South America: Slip Vectors							
15.34	-45.92	97.0	10	94.1	0.012		*Bergman & Solomon* (1988)
15.30	-45.78	98.0	10	94.0	0.011		*Bergman & Solomon* (1988)
15.25	-45.15	97.0	10	93.6	0.011		*Bergman & Solomon* (1988)
14.14	-45.18	100.0	20	93.6	0.003		*Engeln et al.* (1986)
12.84	-44.57	95.0	15	93.1	0.004		CMT 6.09.87
12.05	-43.79	101.0	20	92.6	0.002		*Engeln et al.* (1986)
10.79	-43.51	92.0	10	92.4	0.009		*Bergman & Solomon* (1988)
10.83	-43.43	90.0	10	92.4	0.008		CMT 1.10.85
10.83	-43.23	96.0	20	92.2	0.002		*Engeln et al.* (1986)
10.77	-43.11	92.0	10	92.2	0.008		*Bergman & Solomon* (1988)
10.79	-42.23	96.0	15	91.7	0.003		CMT 3.20.84
10.72	-42.02	97.0	20	91.5	0.002		*Engeln et al.* (1986)
10.72	-41.68	87.0	10	91.3	0.008		*Bergman & Solomon* (1988)
8.80	-39.87	92.0	15	90.3	0.003		CMT 8.13.80
8.05	-38.79	102.0	20	89.6	0.001		*Engeln et al.* (1986)
8.15	-38.76	93.0	10	89.6	0.006		CMT 11.01.84
8.10	-38.55	89.0	15	89.5	0.003		CMT 11.05.78
8.04	-38.39	95.0	15	89.4	0.003		CMT 12.06.81
8.11	-38.09	90.0	10	89.3	0.006		*Engeln et al.* (1986)
7.39	-36.10	88.0	15	88.1	0.002		CMT 4.22.81
7.30	-34.86	85.0	10	87.4	0.005		*Engeln et al.* (1986)
7.08	-34.87	80.0	15	87.5	0.002		CMT 12.24.85
7.10	-34.04	89.0	15	87.0	0.002		CMT 7.26.80
7.07	-33.85	94.0	20	86.9	0.001		CMT 8.30.84
0.67	-30.39	84.0	15	85.3	0.002		CMT 6.22.84
0.86	-29.88	83.0	10	85.0	0.004		CMT 10.12.85
0.83	-29.82	88.0	10	85.0	0.004		CMT 3.20.78
0.77	-29.69	87.0	10	84.9	0.004		CMT 3.20.78
0.11	-29.60	80.0	20	84.9	0.001		CMT 7.24.80
0.82	-28.98	90.0	20	84.6	0.001		*Engeln et al.* (1986)
0.95	-28.43	88.0	10	84.3	0.004		CMT 6.06.85
0.97	-28.29	89.0	20	84.2	0.001		*Engeln et al.* (1986)
0.93	-28.09	82.0	15	84.1	0.002		CMT 9.19.84
1.14	-27.71	85.0	15	83.9	0.002		CMT 6.22.78
0.89	-27.11	85.0	15	83.6	0.002		CMT 11.14.79
0.95	-27.08	82.0	15	83.6	0.002		CMT 11.02.81
0.93	-26.83	85.0	15	83.5	0.002		CMT 7.01.85
0.80	-26.77	81.0	15	83.5	0.002		CMT 6.15.86
0.90	-26.77	88.0	20	83.4	0.001		*Engeln et al.* (1986)
0.87	-26.50	88.0	20	83.3	0.001		*Engeln et al.* (1986)
0.75	-26.14	88.0	20	83.1	0.001		CMT 3.23.86
0.81	-25.45	89.0	20	82.8	0.001		*Engeln et al.* (1986)
0.11	-25.35	84.0	10	82.8	0.004		CMT 11.01.80
-1.19	-24.68	87.0	10	82.5	0.004		CMT 8.12.82
-1.30	-24.30	99.0	20	82.4	0.001		*Engeln et al.* (1986)
-0.99	-23.48	87.0	15	81.9	0.002		CMT 12.08.84
-0.85	-22.13	85.0	20	81.3	0.001		*Engeln et al.* (1986)
-0.97	-21.86	81.0	10	81.2	0.004		CMT 1.03.82
-0.84	-21.81	77.0	10	81.1	0.004		CMT 10.13.83
-0.51	-19.92	80.0	15	80.2	0.002		CMT 12.29.86
-0.50	-19.90	80.0	20	80.2	0.001		*Engeln et al.* (1986)
-0.52	-19.86	77.0	10	80.2	0.005		CMT 4.22.84
-0.58	-19.77	83.0	15	80.1	0.002		CMT 10.09.84
-0.38	-19.55	80.0	15	80.0	0.002		CMT 6.04.85
-0.22	-19.19	79.0	15	79.8	0.002		CMT 6.07.87
-0.32	-19.17	83.0	20	79.8	0.001		*Engeln et al.* (1986)
-0.04	-19.14	77.0	10	79.8	0.005		CMT 5.05.87
-0.13	-18.83	79.0	10	79.6	0.005		CMT 7.07.81
-0.30	-18.60	88.0	20	79.6	0.001		*Engeln et al.* (1986)
-0.14	-18.24	74.0	15	79.4	0.002		CMT 3.12.87
-0.19	-18.03	89.0	20	79.3	0.001		*Engeln et al.* (1986)
-0.02	-17.88	83.0	10	79.2	0.005		CMT 6.24.86

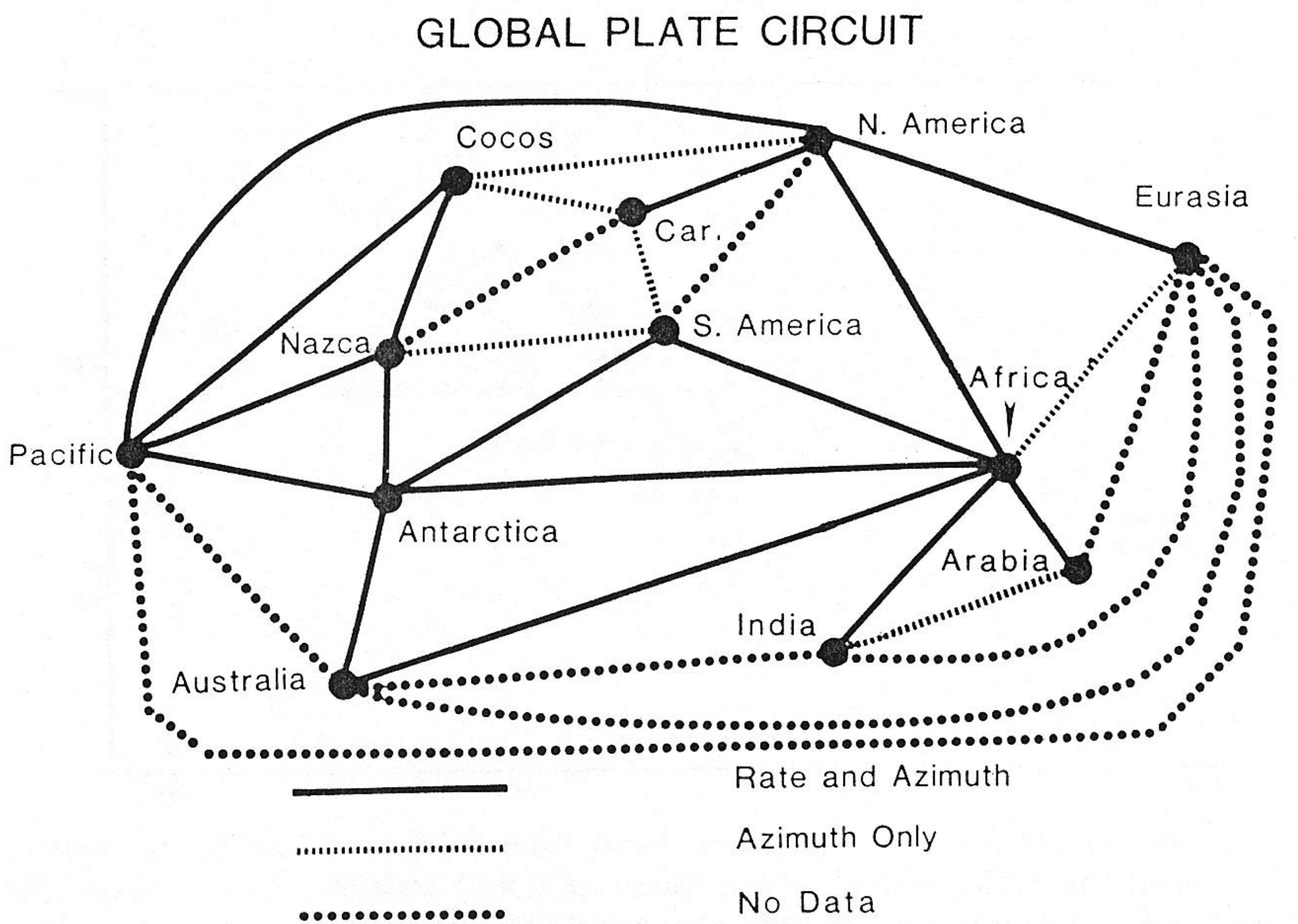
Arabia-India: Fault Trends

21.00	61.80	30.0	5	27.8	0.459	*Matthews* (1966)
18.00	60.20	23.0	5	22.3	0.534	*Matthews* (1966)

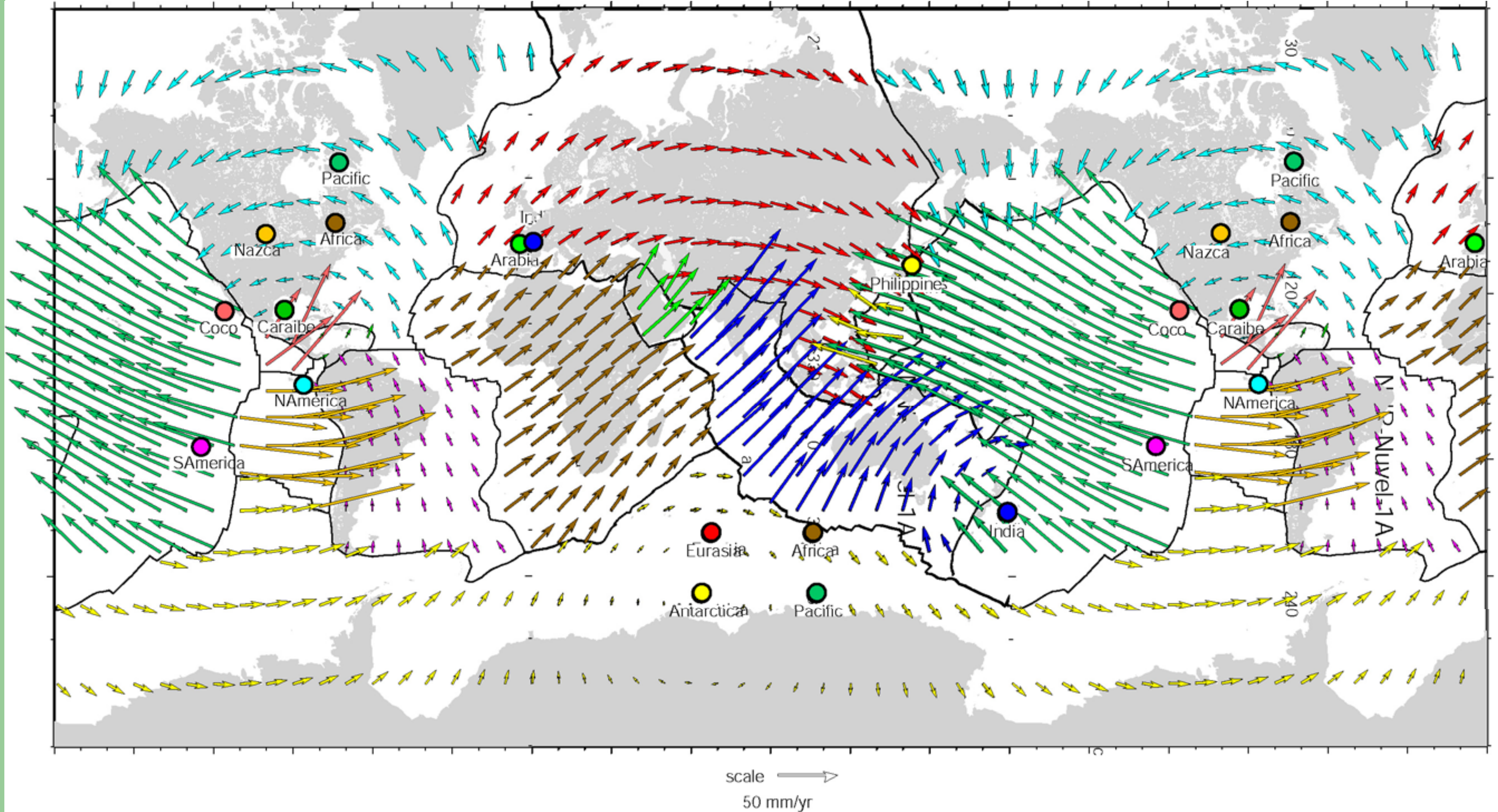
Arabia-India: Slip Vectors

24.58	66.23	41.0	15	37.5	0.270	*Quittmeyer & Kafka* (1984)
23.79	64.73	28.0	15	34.6	0.176	*Quittmeyer & Kafka* (1984)
21.87	62.32	12.0	15	29.5	0.067	*Quittmeyer & Kafka* (1984)
20.91	62.44	26.0	15	28.3	0.055	CMT 4.7.85
14.94	57.96	23.0	15	16.4	0.171	CMT 12.14.85
14.57	58.09	10.0	15	16.0	0.188	CMT 12.5.81

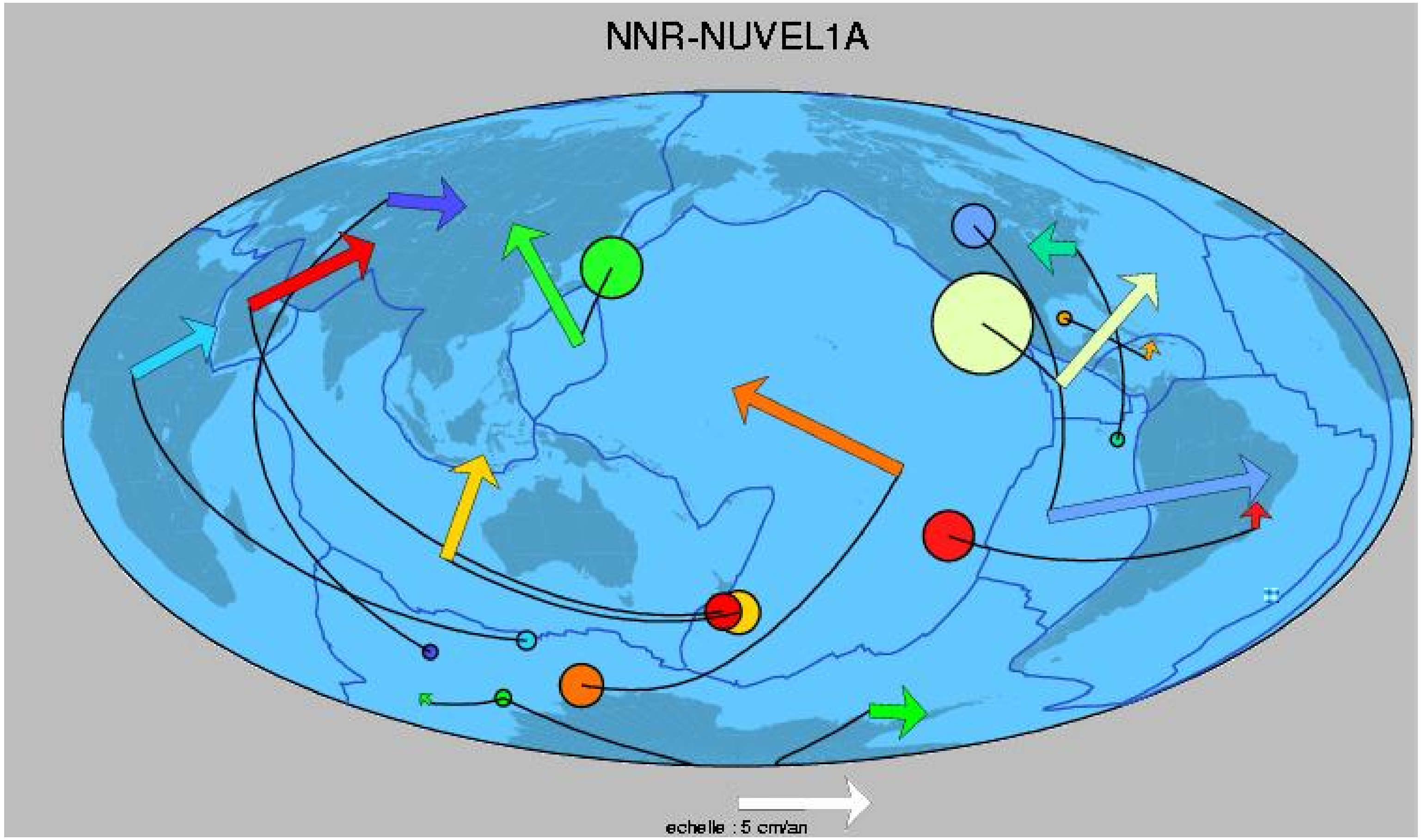
Geological model : closure circuit



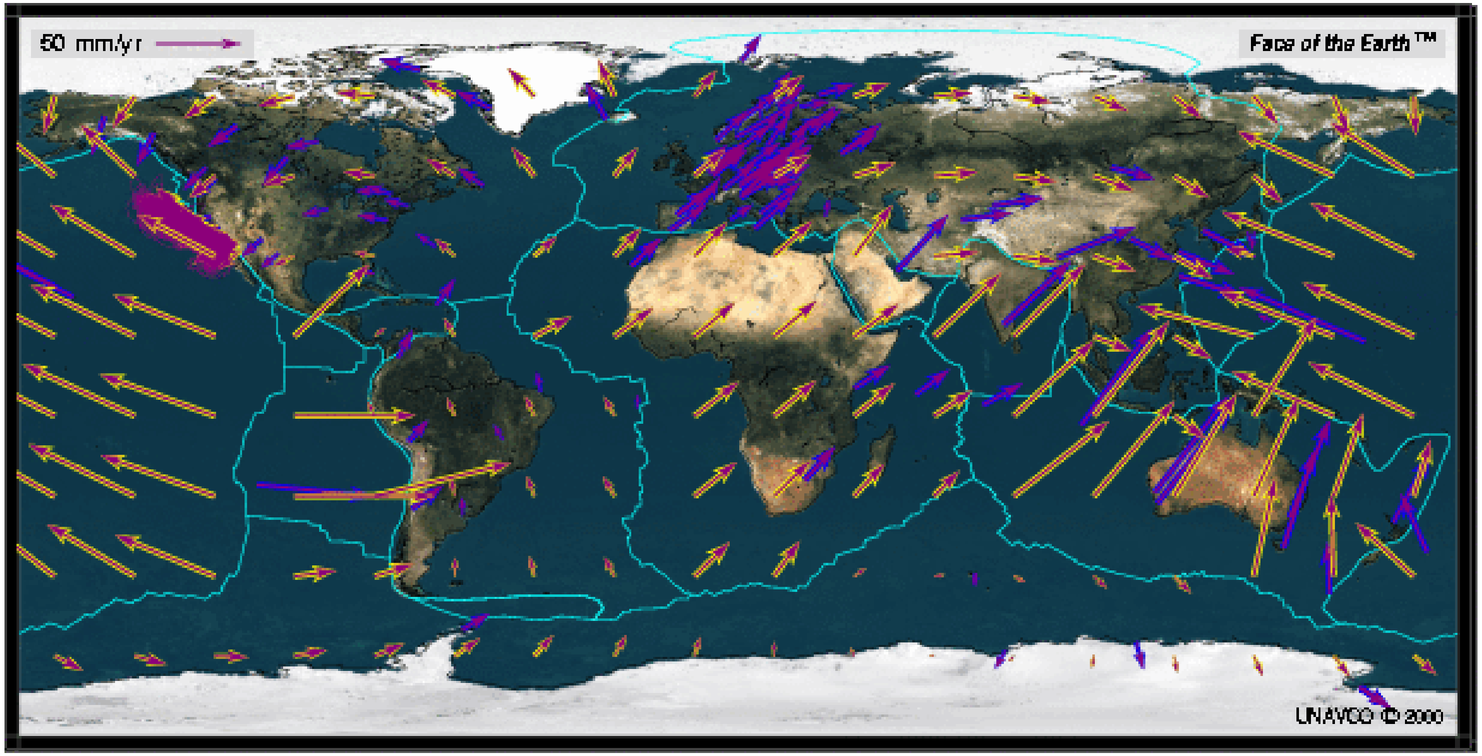
NNR-Nuvel-1A : velocities



NNR-Nuvel-1A : poles



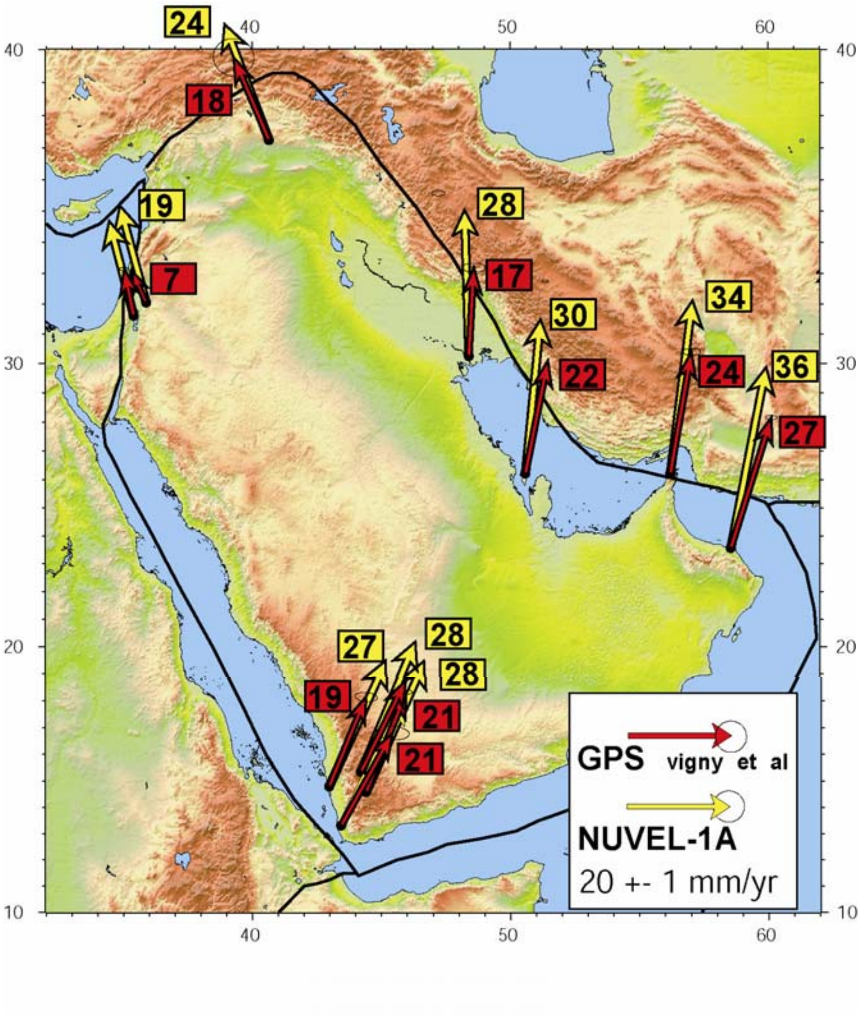
GPS VEL solution

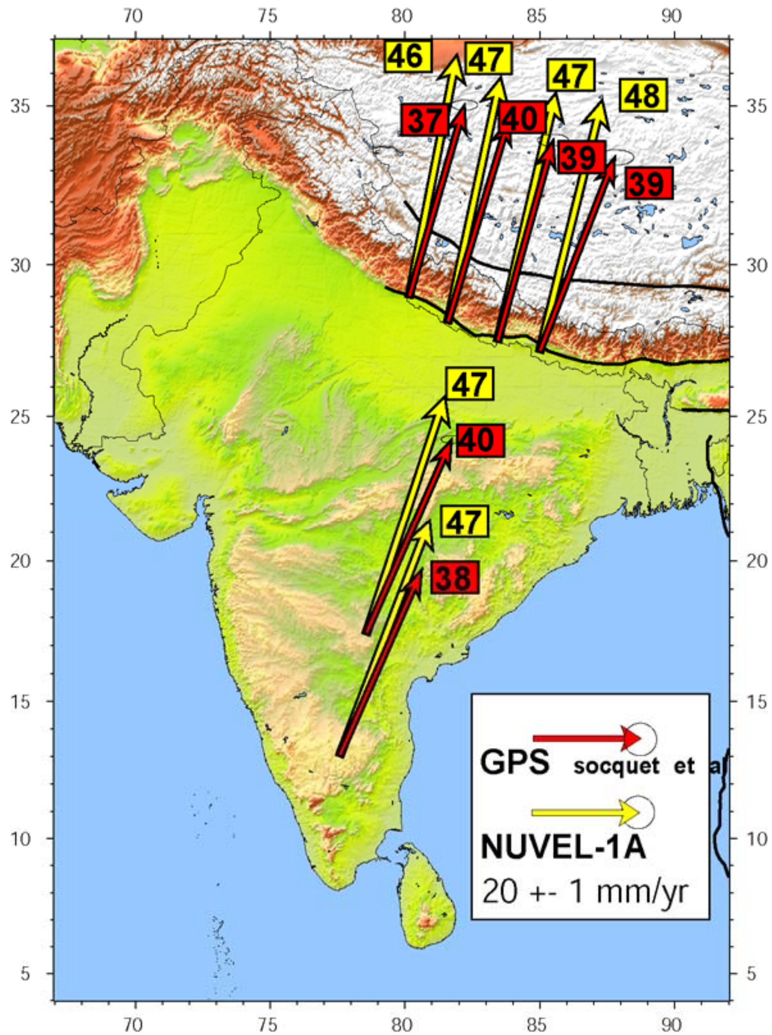


Nuvel-1A (yellow) – GPSVEL (violet)

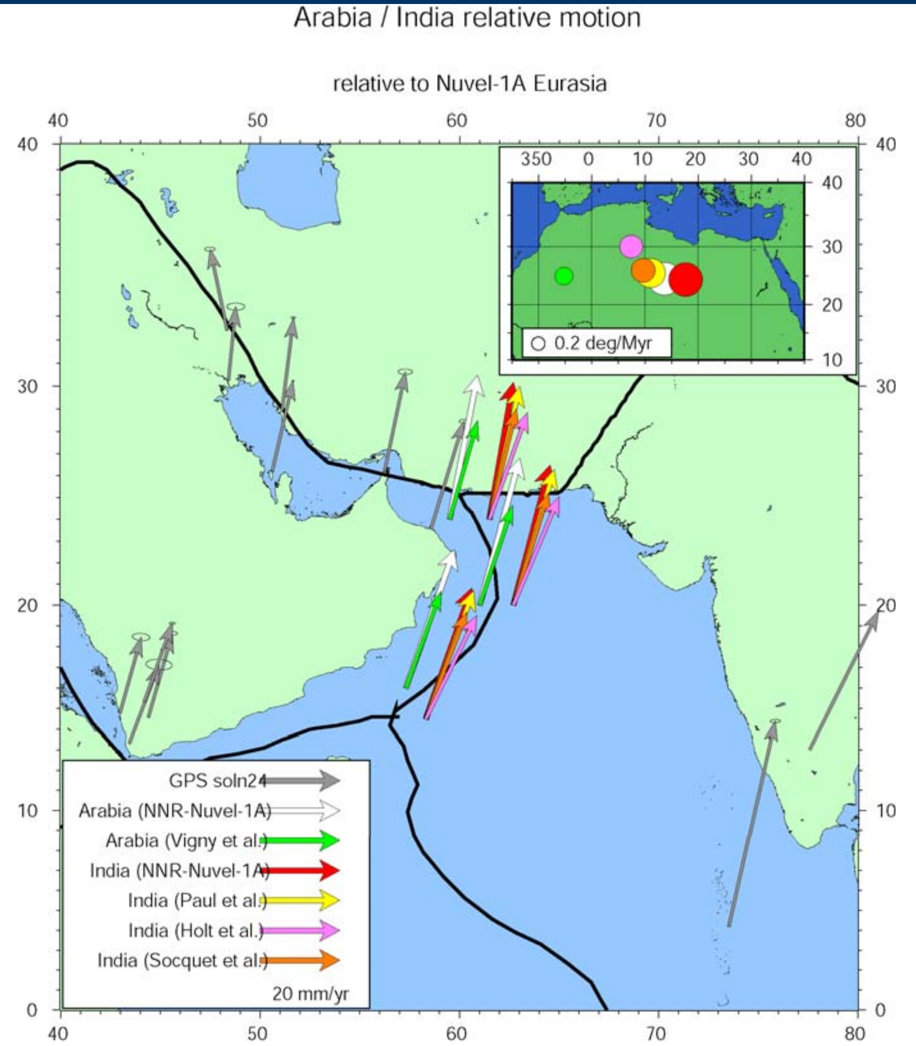
Good match with "geological" velocities: 1 cm/yr = 10 km in 1 million year), but…

GPS finds Arabia and India are slower than expected

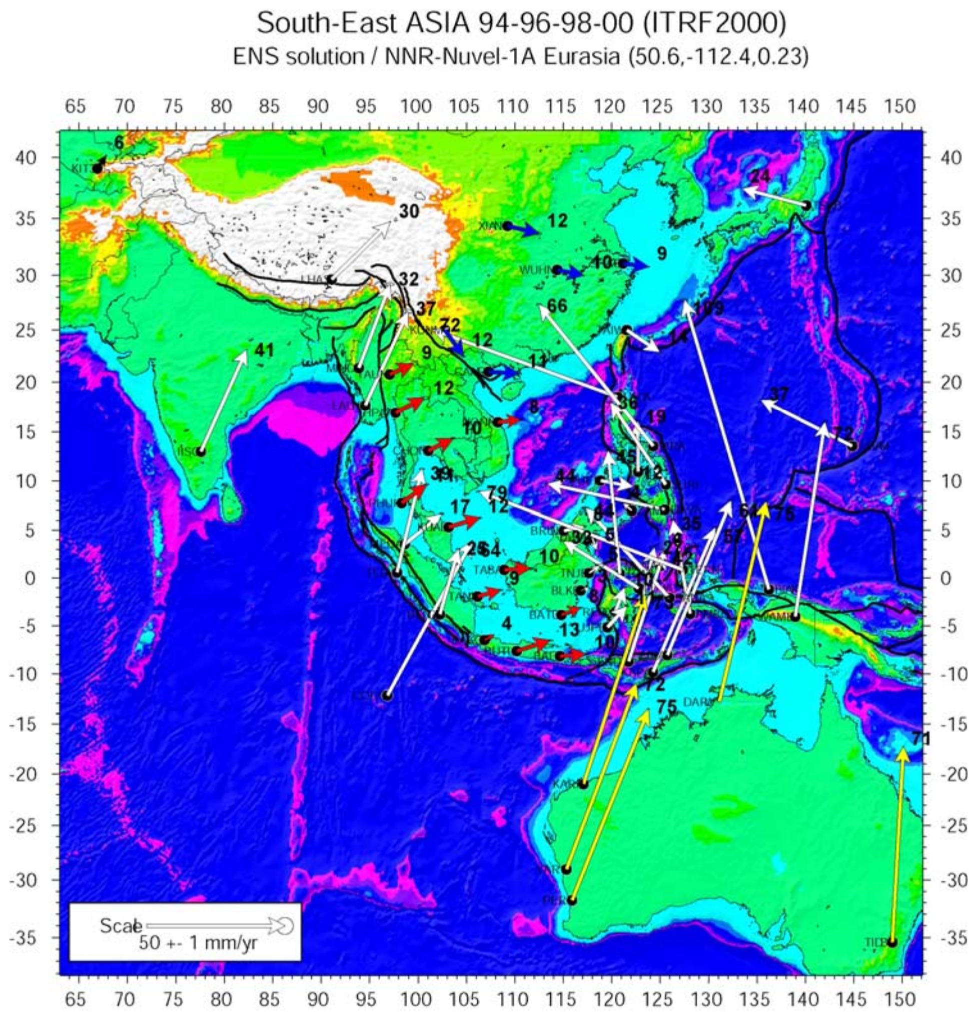




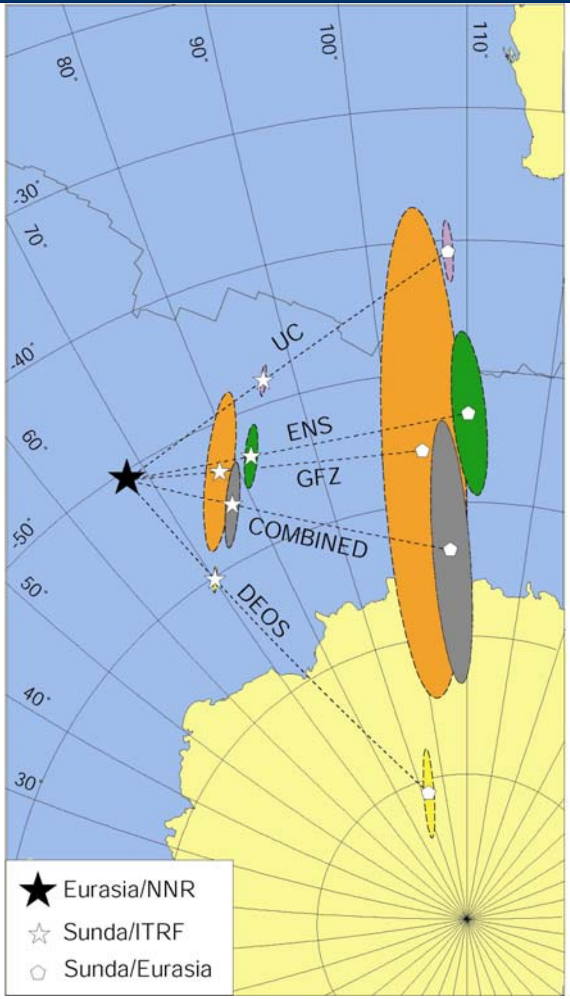
Arabia India relative motion

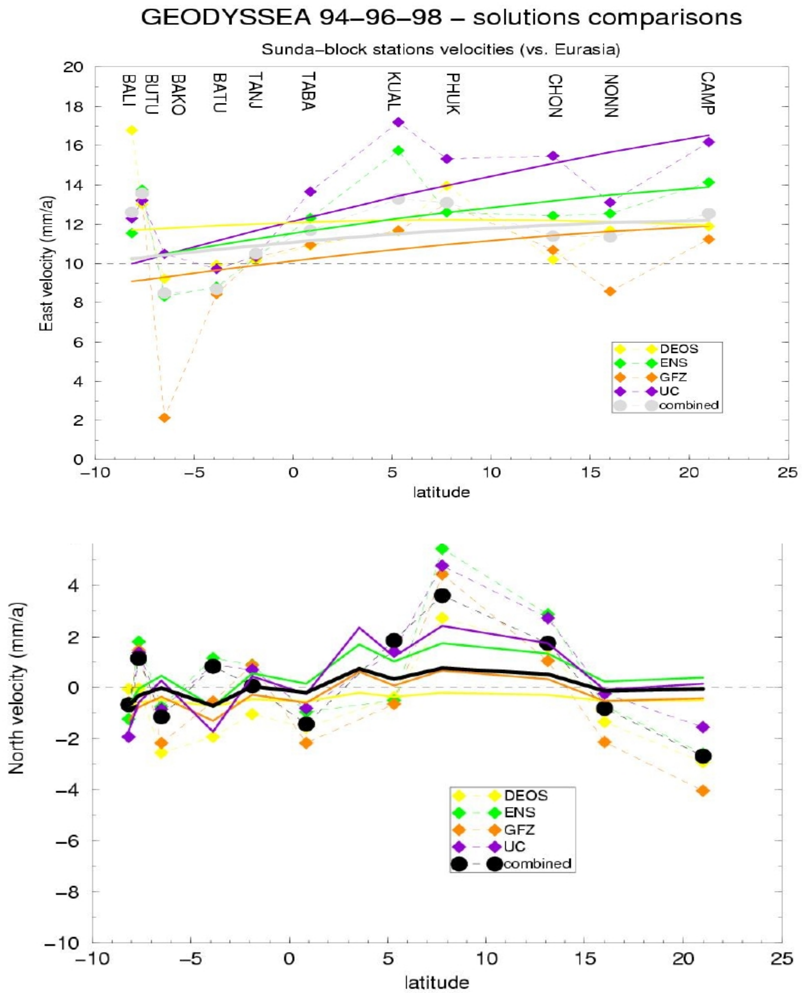


Rigid Sundaland

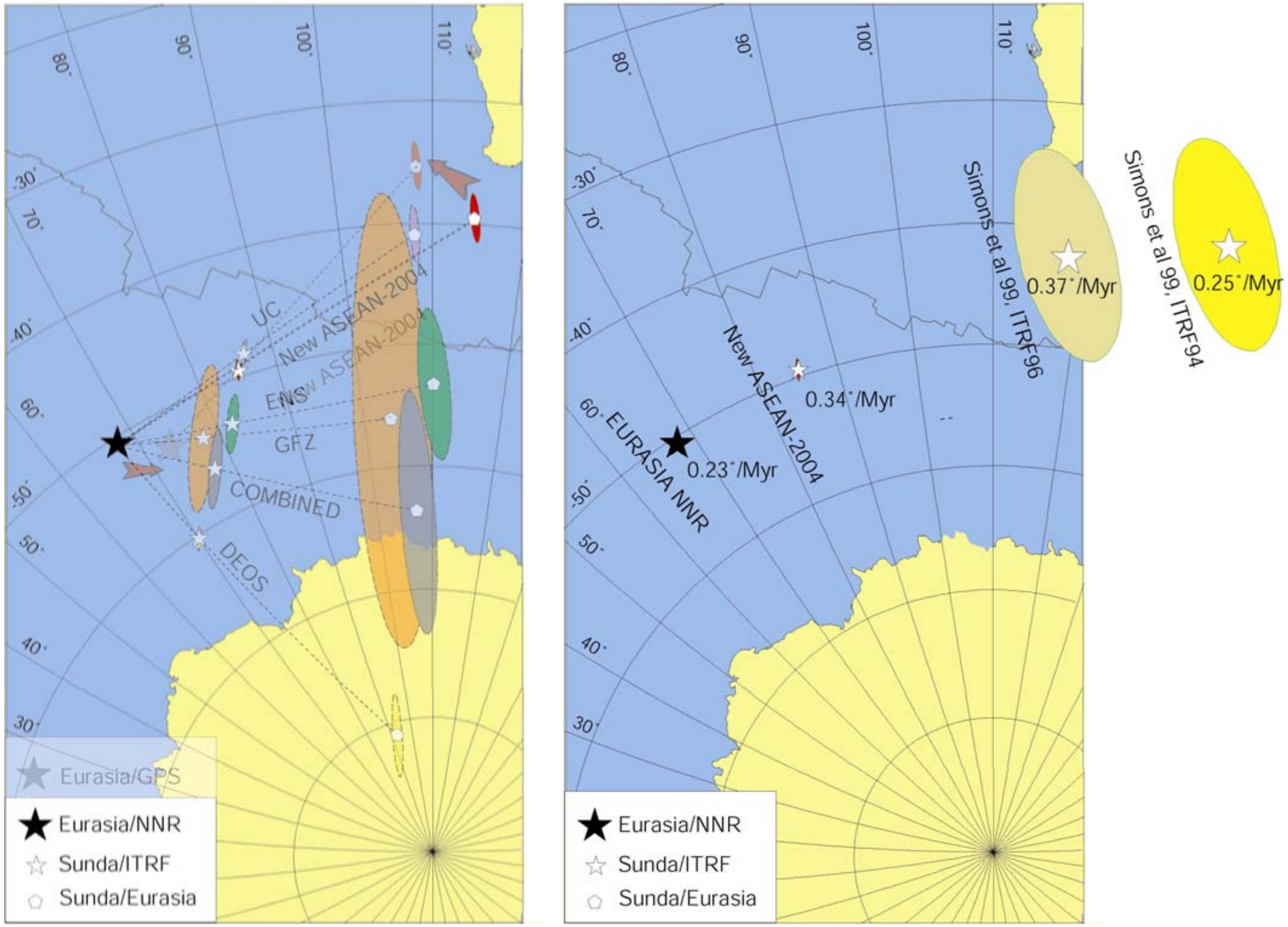


GEODYSSEA poles

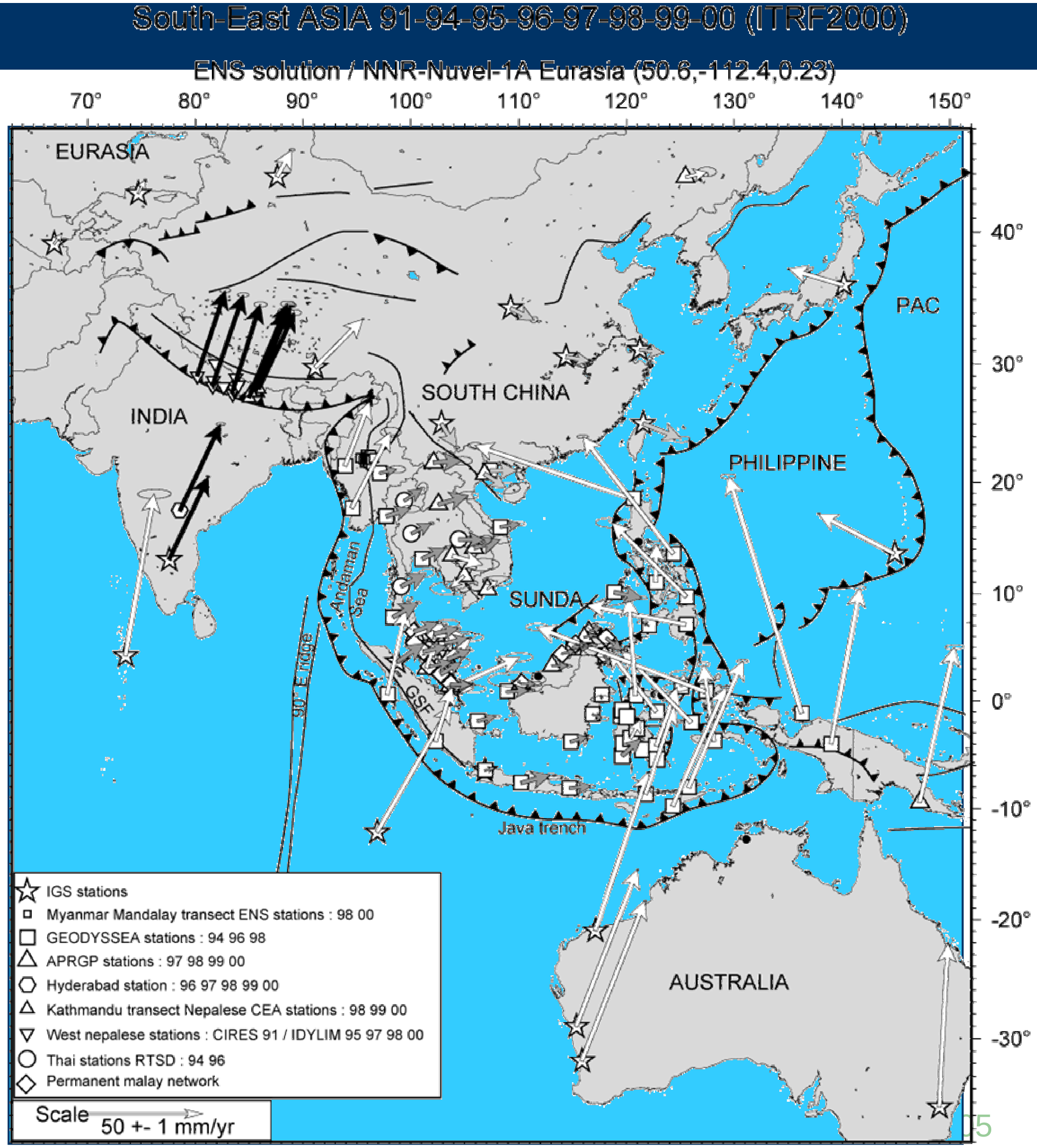




Older GEODYSSEA poles

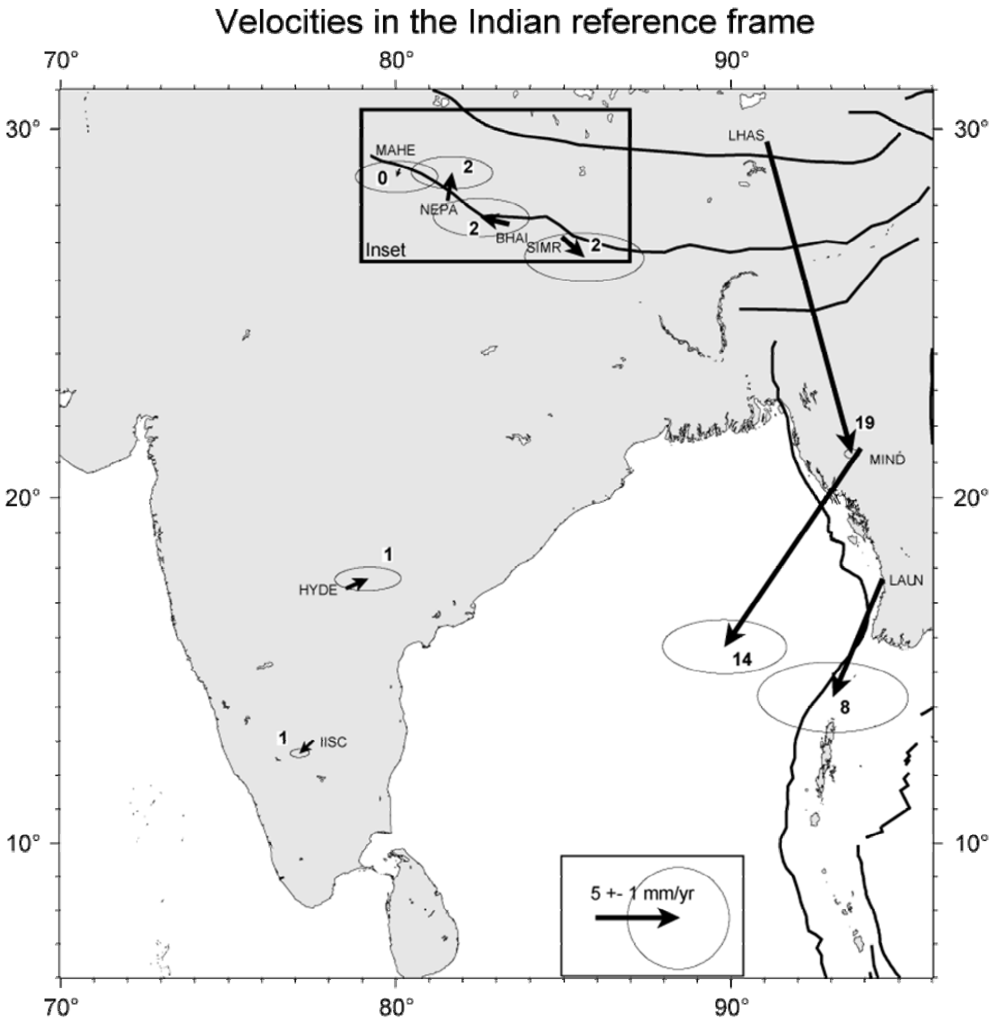


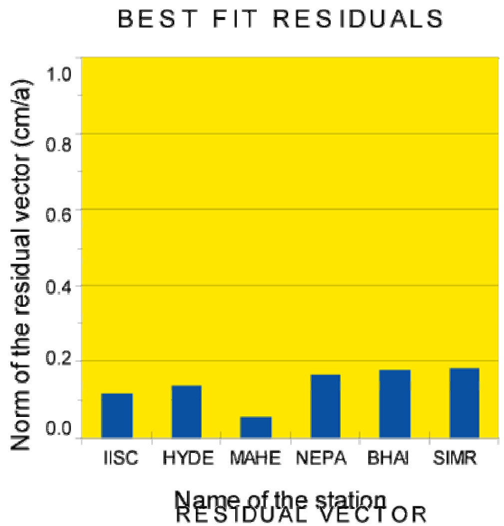
New ASEAN solution (Simons and Socquet, submitted)

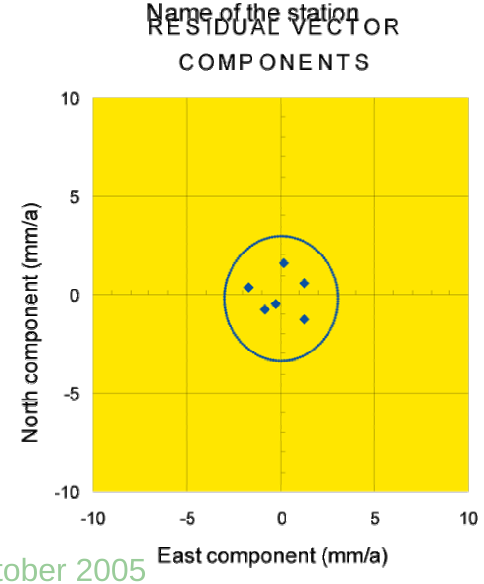


120 sites measured over a decade

Rigidity of India

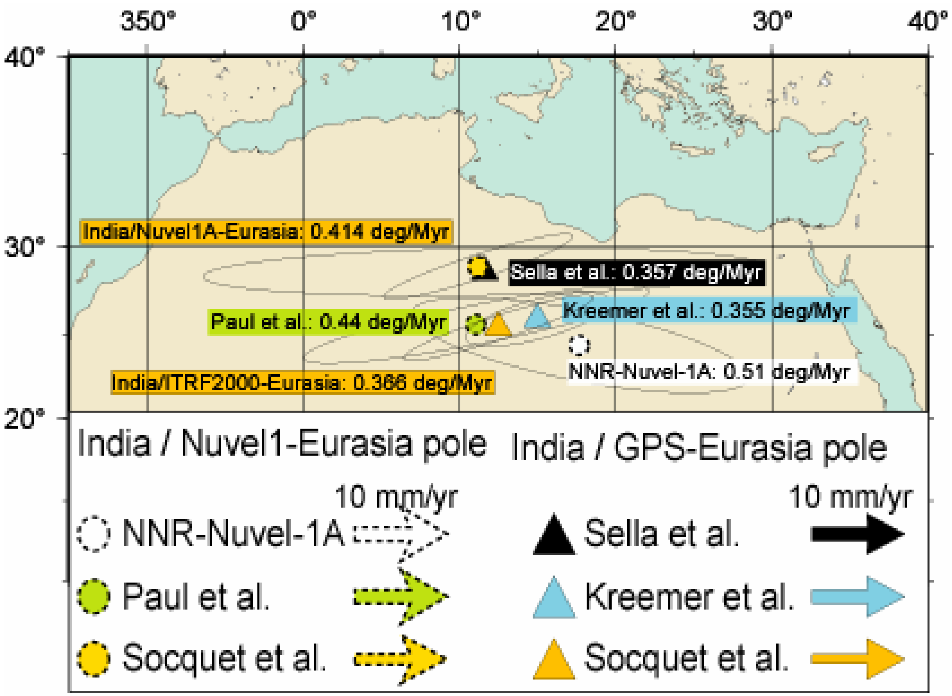


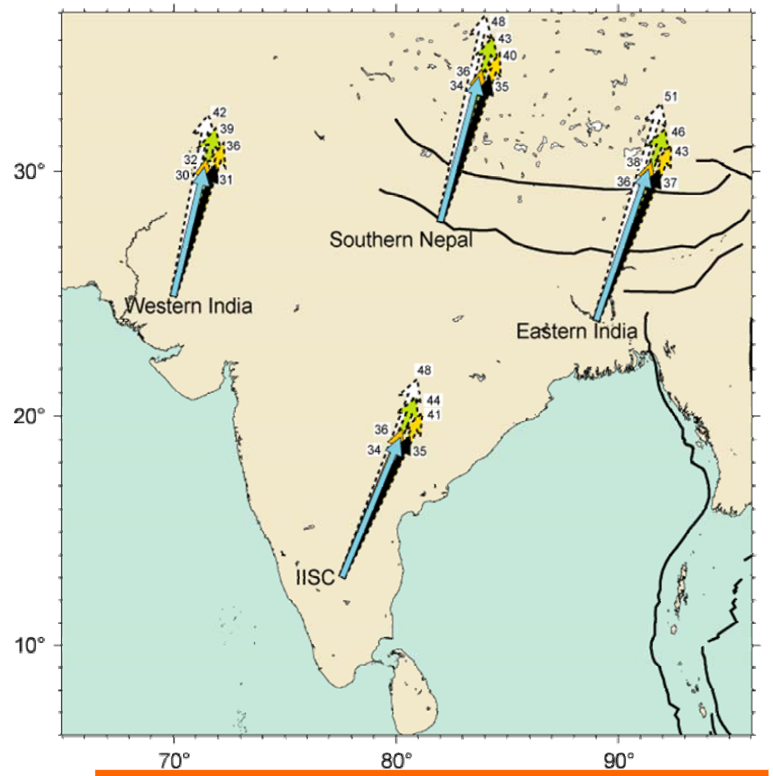




India-Eurasia motion

motion from different studies



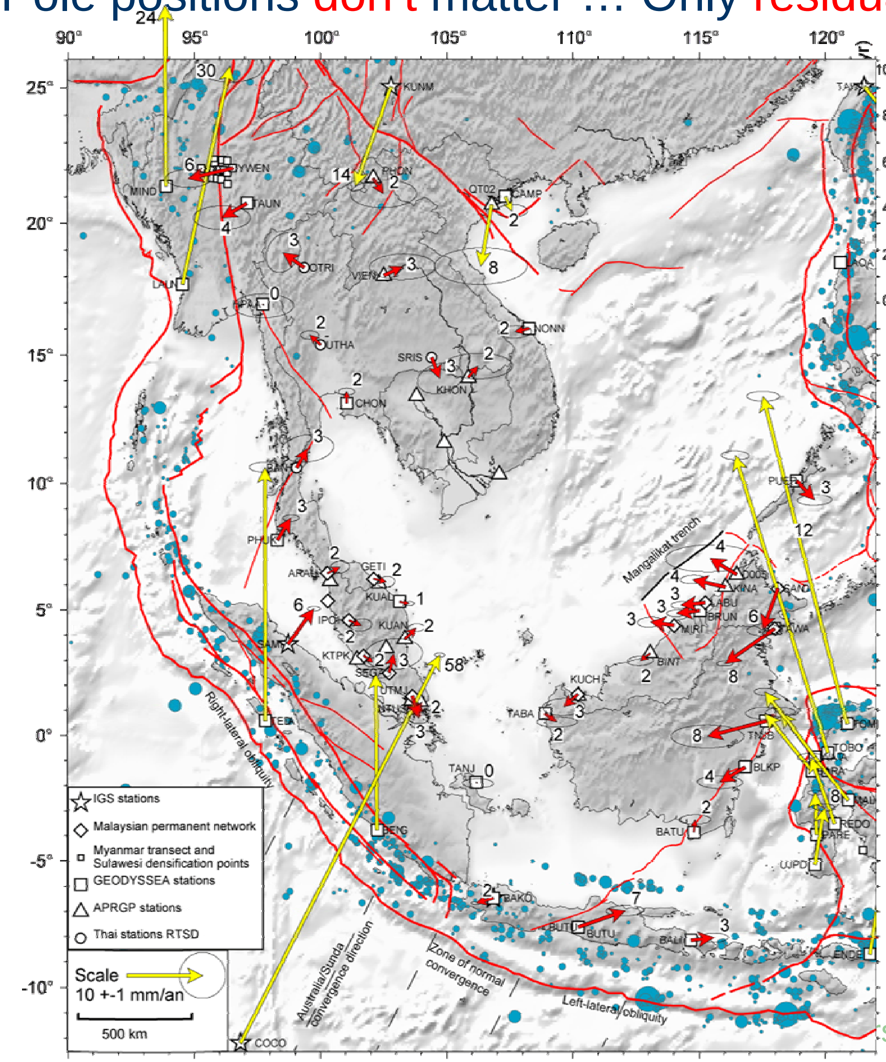


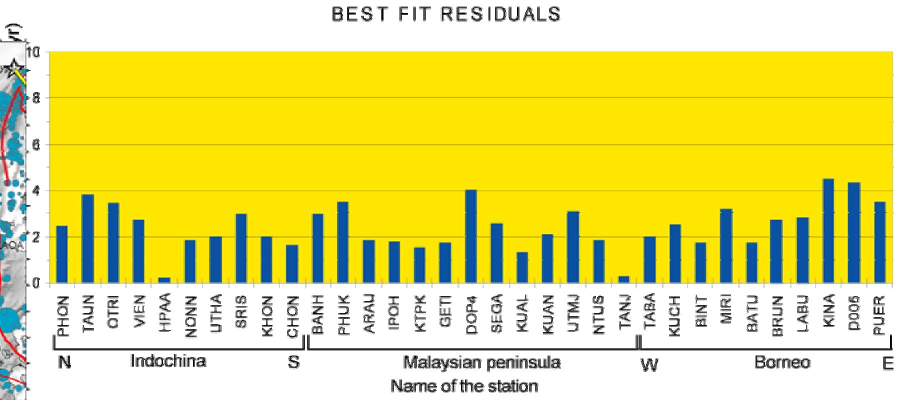
3.5 cm/yr

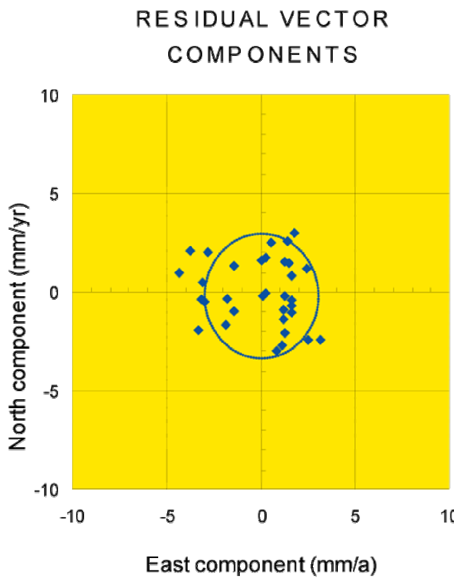
Instead of **5 cm/yr**
we thought 10 years ago

ASEAN Residual velocities

Pole positions don't matter … Only residual velocities do

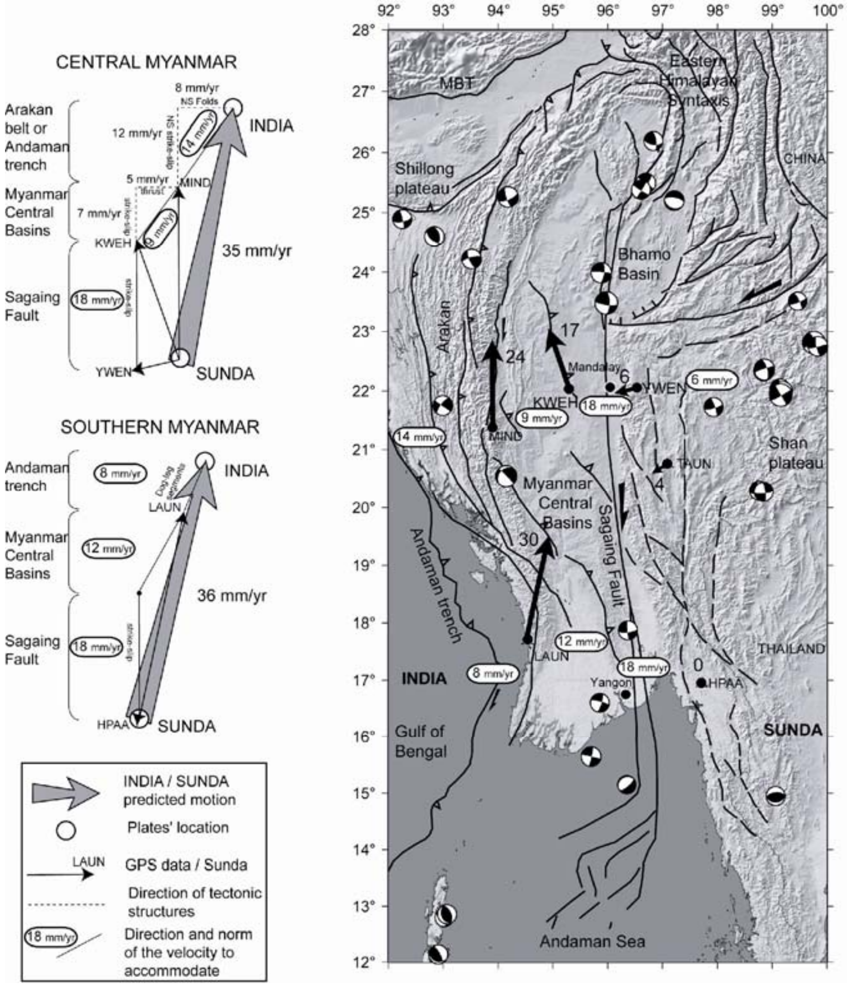






India/Sunda relative motion

Pole positions don't matter….only predicted motions on plate boundary do



Strain rate and rotation rate tensors (1)

To asses plate deformation :

1. Look at station velocity residuals
2. Compute strain rate and rotation rate tensors

$$\text{Strain} = \frac{\text{Velocity}}{\text{Distance}} = \frac{\text{mm/yr}}{\text{km}} = \%\ /\ \text{yr}$$

$$\text{Matrix tensor notation : } S_i^j = d(V_i) / d(x_j) = \begin{vmatrix} d(V_x) / d(x) & d(V_x) / d(y) \\ d(V_y) / d(x) & d(V_y) / d(y) \end{vmatrix}$$

Theory says : [S] = [E] + [W]

Symetrical Strain rate — Antisymetrical rotation rate

Strain rate and rotation rate tensors (2)

$$[E] = \frac{1}{2}\left([S] + [S]^T\right) = \begin{vmatrix} E_{11} & E_{12} \\ E_{12} & E_{22} \end{vmatrix} \qquad [W] = \frac{1}{2}\left([S] - [S]^T\right) = \begin{vmatrix} 0 & W \\ -W & 0 \end{vmatrix}$$

[E] has 2 Eigen values : ε_1, ε_2

ε_1 and ε_2 are extension/compression along principal direction defined by angle θ (defined as angle between ε_2 direction and north)

$$\varepsilon_1 = E_{11}\cos^2\theta + E_{22}\sin^2\theta - 2\,E_{12}\sin\theta\,\cos\theta$$

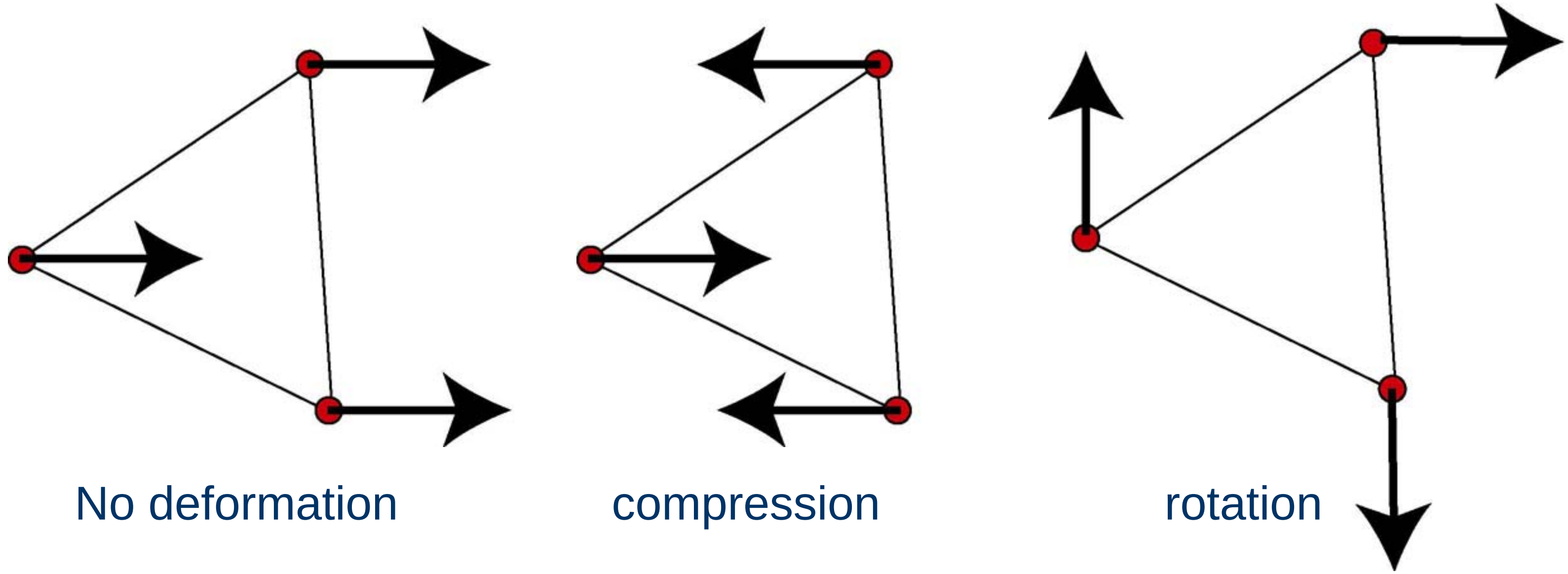
$$\varepsilon_2 = E_{11}\sin^2\theta + E_{22}\cos^2\theta - 2\,E_{12}\sin\theta\,\cos\theta$$

Strain rate and rotation rate tensors (3)

Minimum requirement to compute strain and rotation rates is :

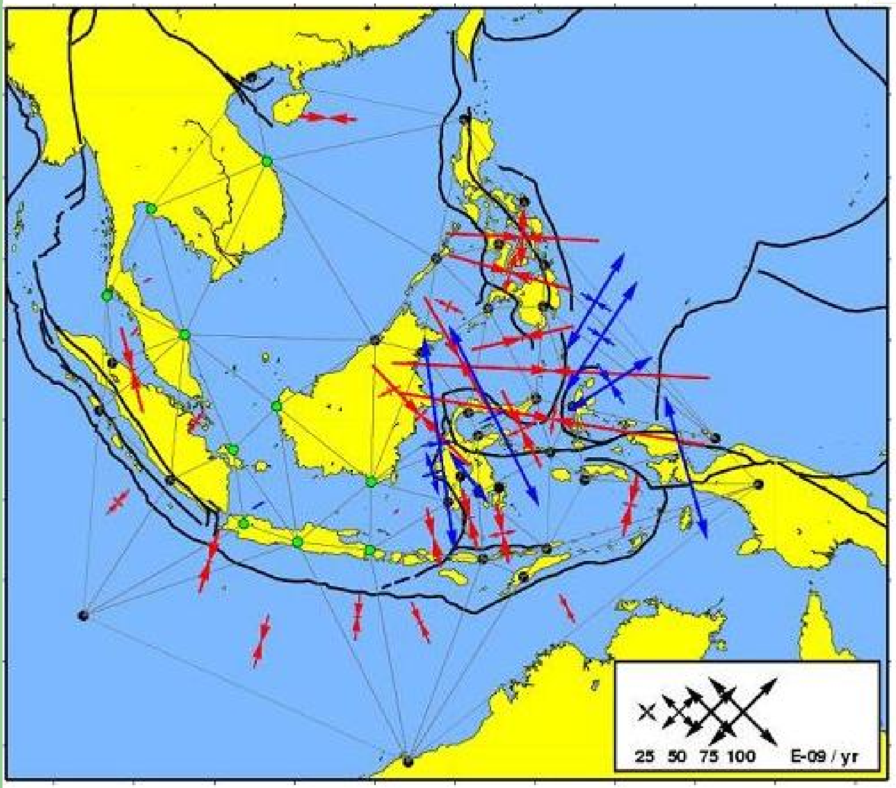
3 velocities (to allow to determine 3 values ε_1, ε_2, and W)

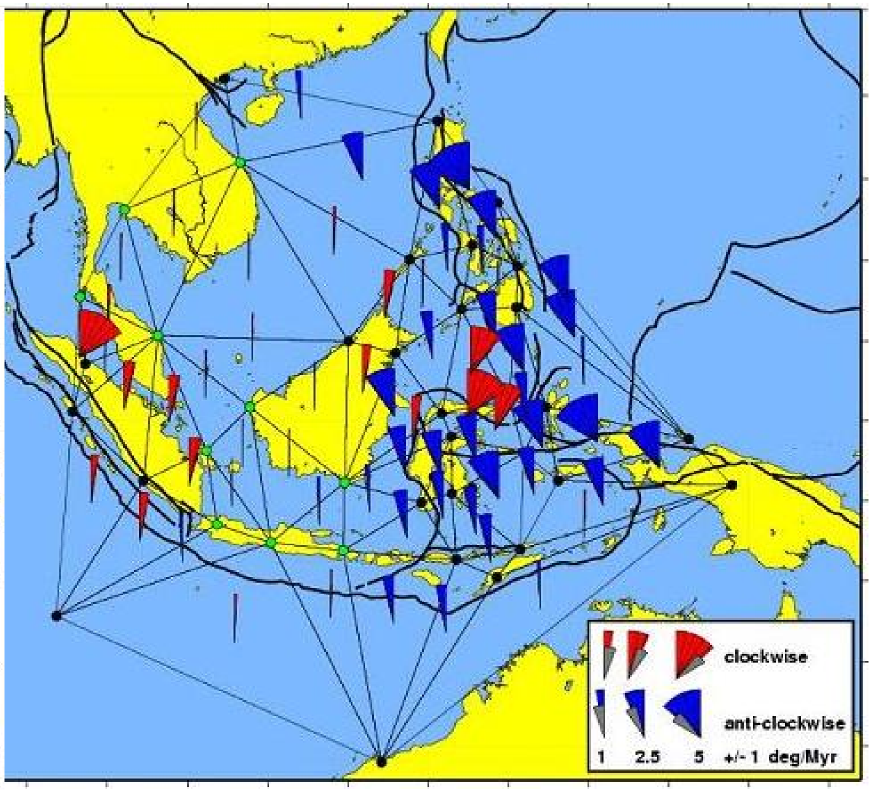
Therefore we can compute strain rate and rotation rate within any polygon, the minimum polygon being a triangle



Strain and rotations are unsensitive to reference frame

Strain and rotation in GEODYSSEA network





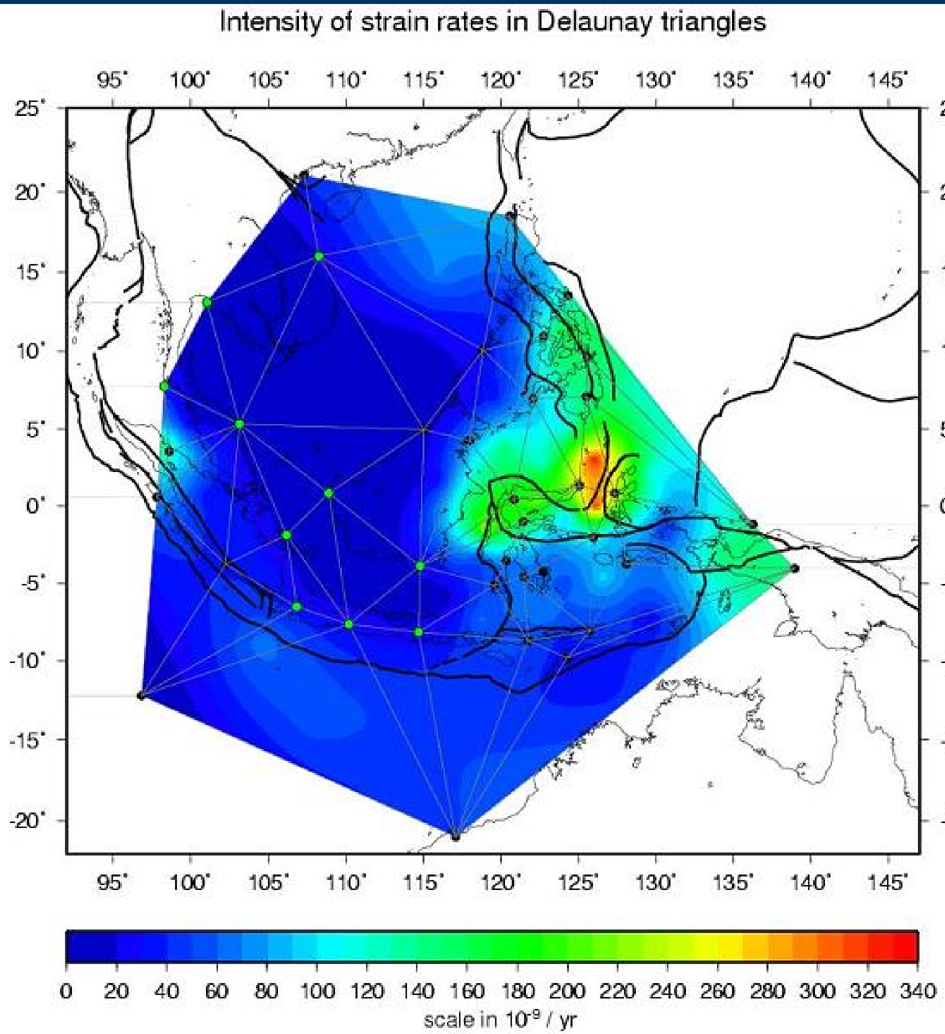
Strains :

extension/compression/strike-slip

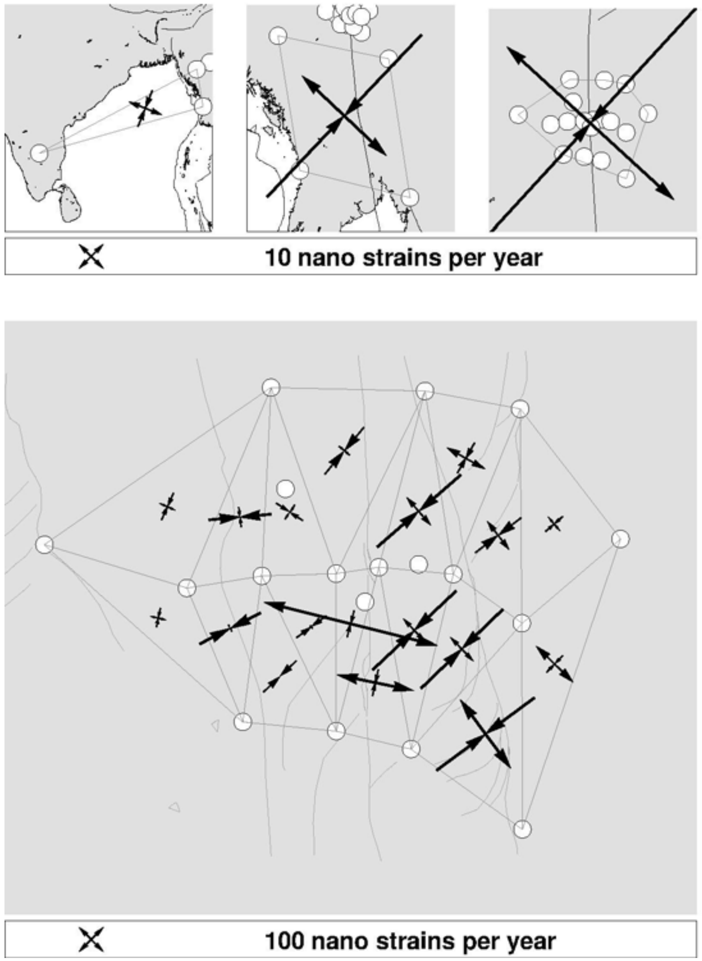
Rotations :

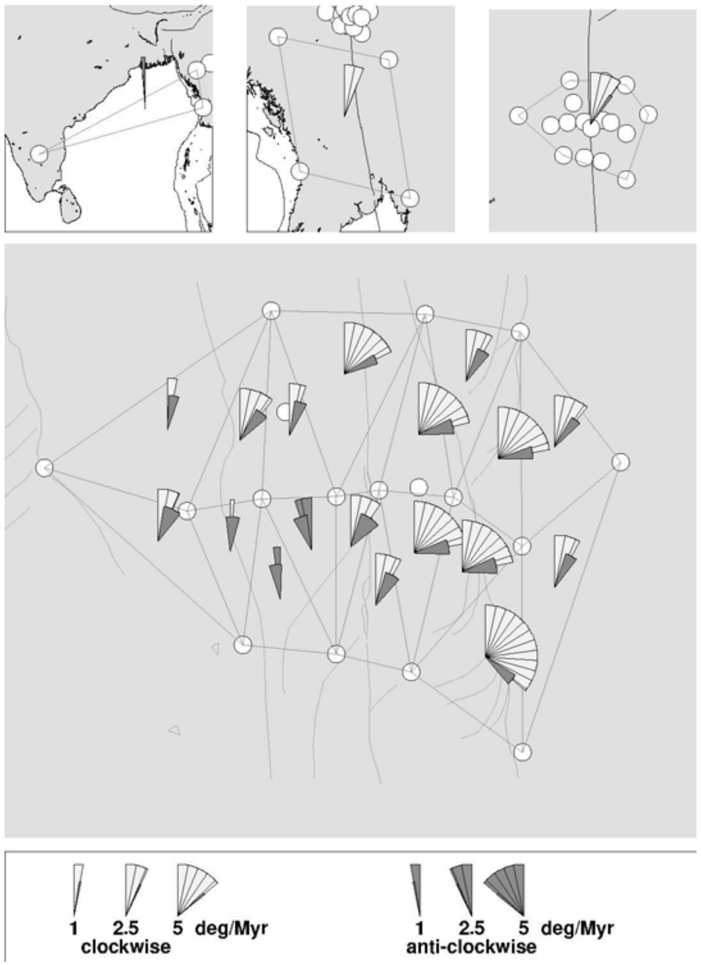
Anti-clockwise/clockwise

Intensity of strain in GEODYSSEA network

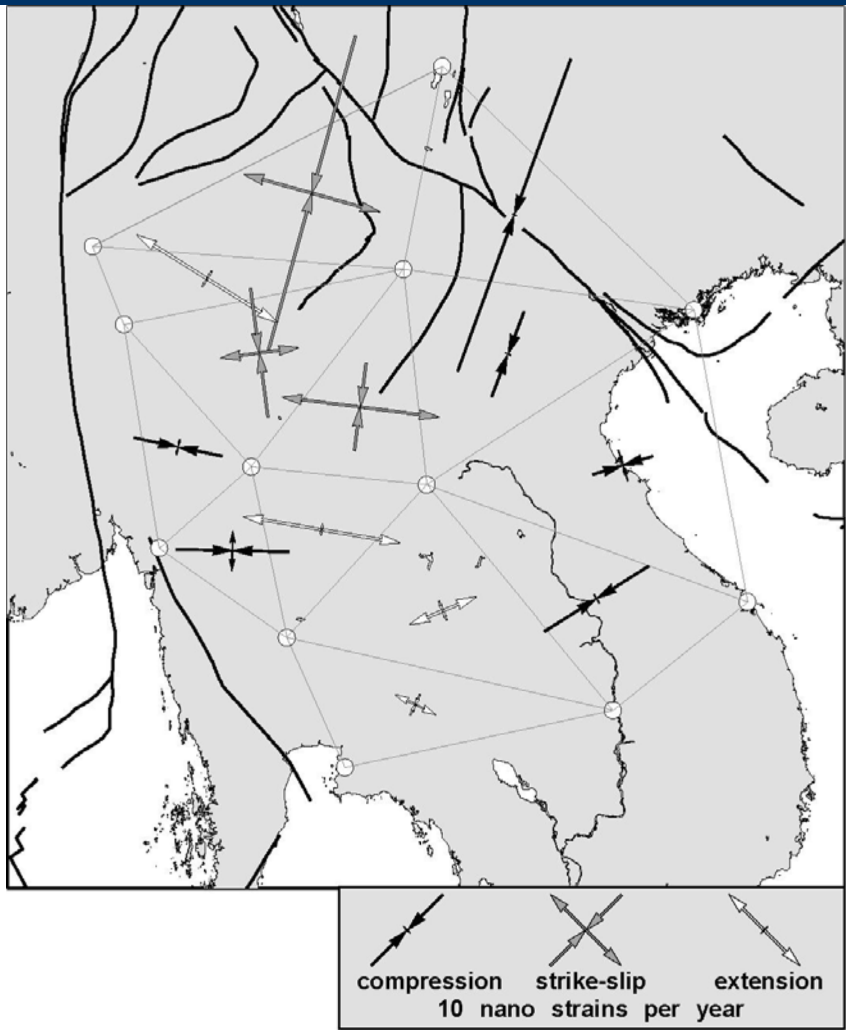


Strain and rotation in Myanmar

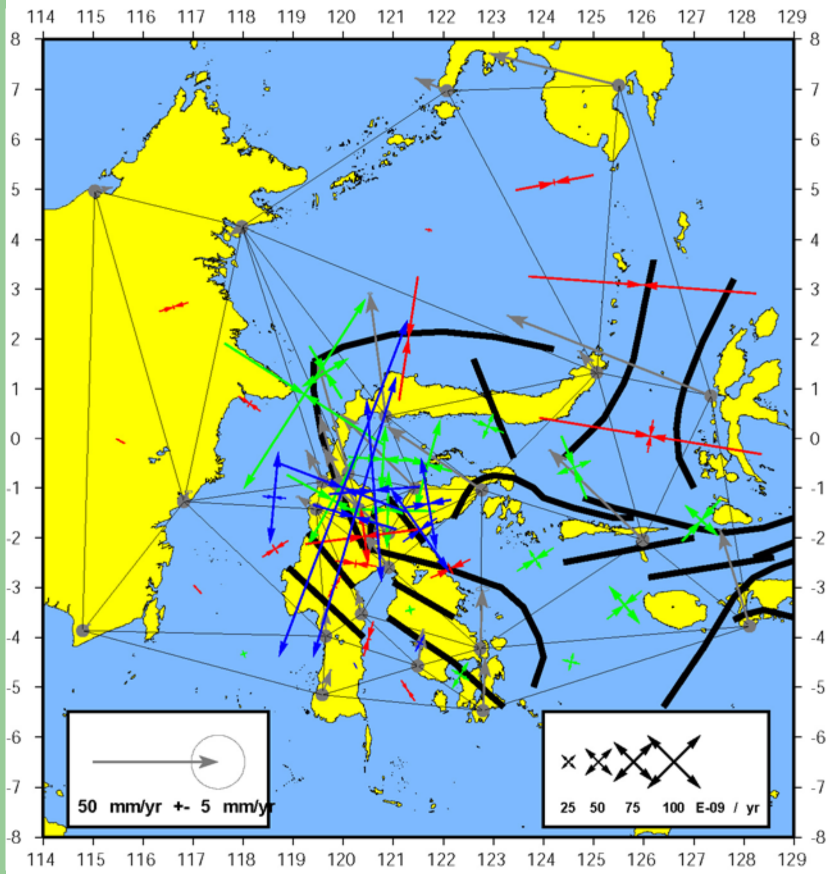


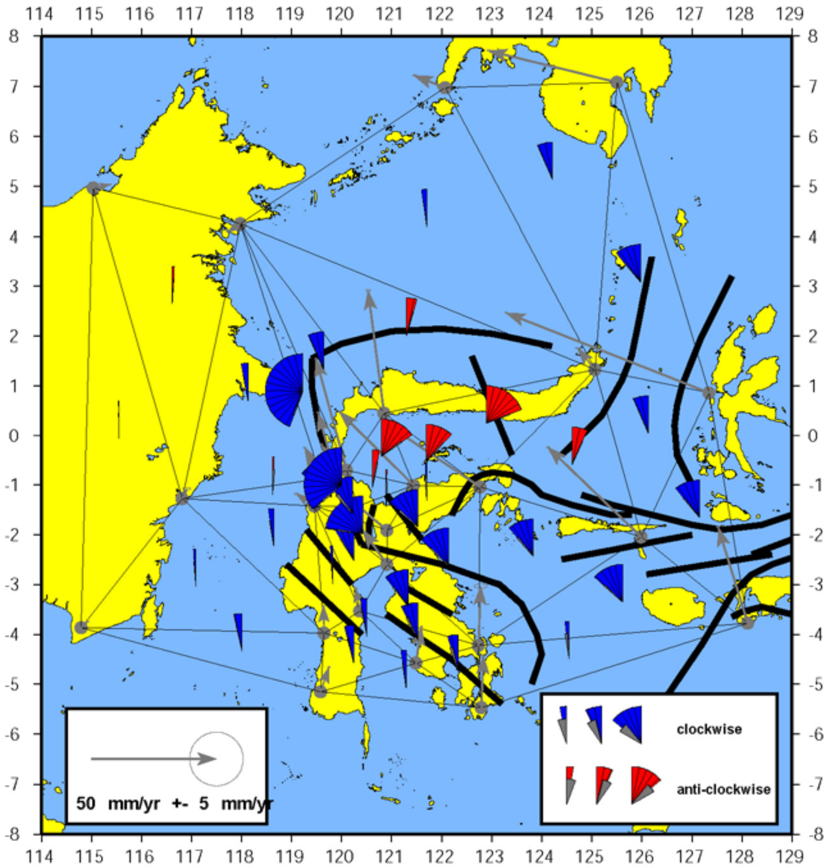


Strain in Northern Sundaland (Thailand)



Strain and rotation in Sulawesi network





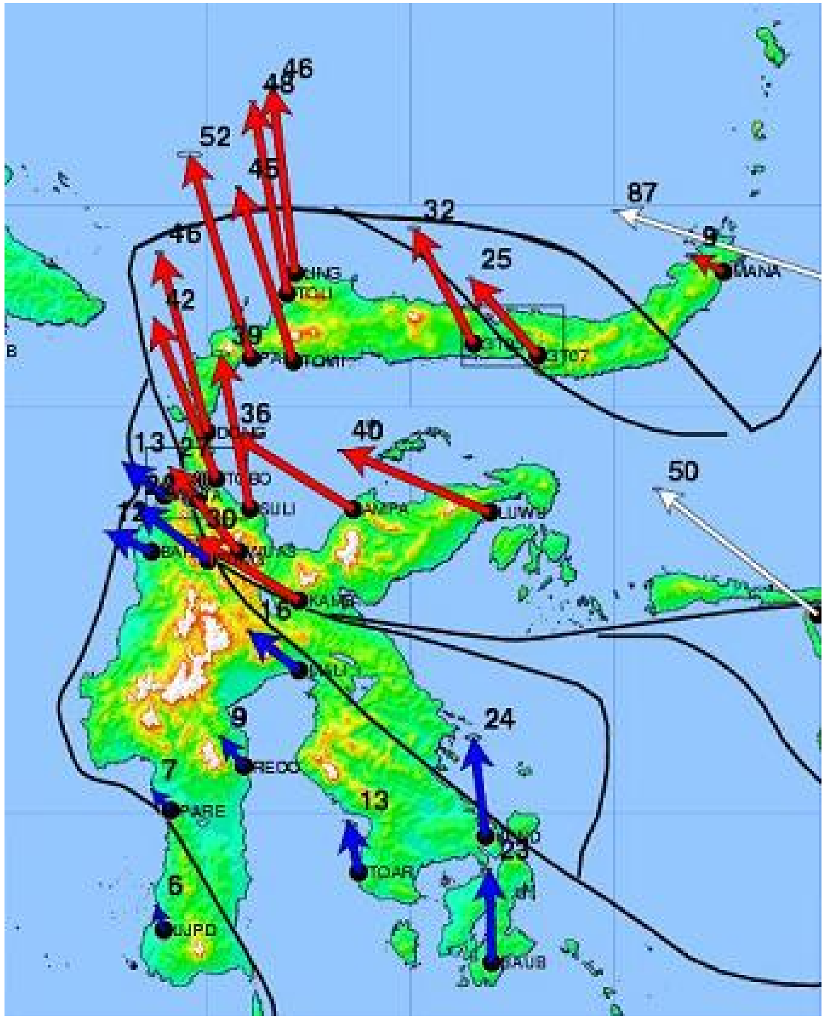
Strains :

extension/compression/strike-slip

Rotations :

Anti-clockwise/clockwise

Blocks and Internal deformation in Sulawesi



Blocks and Internal deformation in Sulawesi