Continuous deformation in place of rigid plates for representing the kinematics of the Earth’s surface in geodetic applications

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Current status: Crustal kinematics based on plate tectonics

Plate tectonic models are based on geophysical data over geologic times.

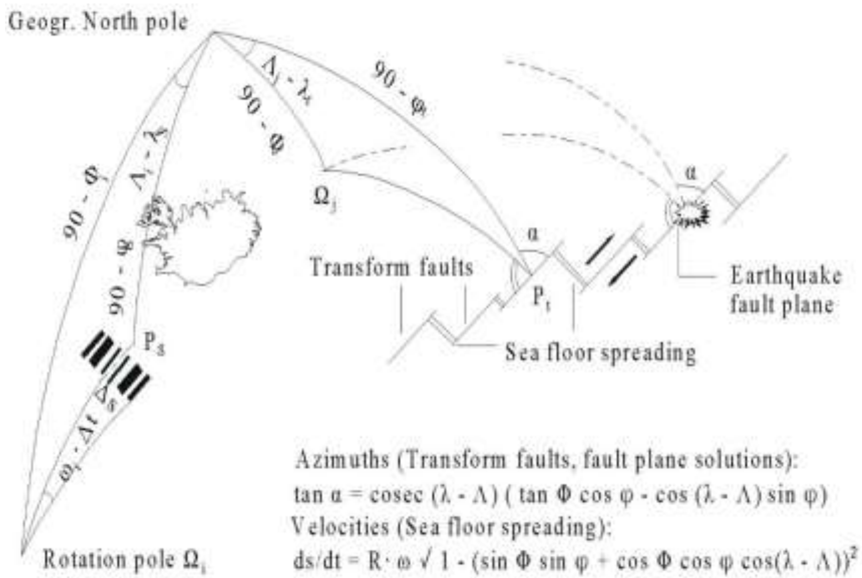


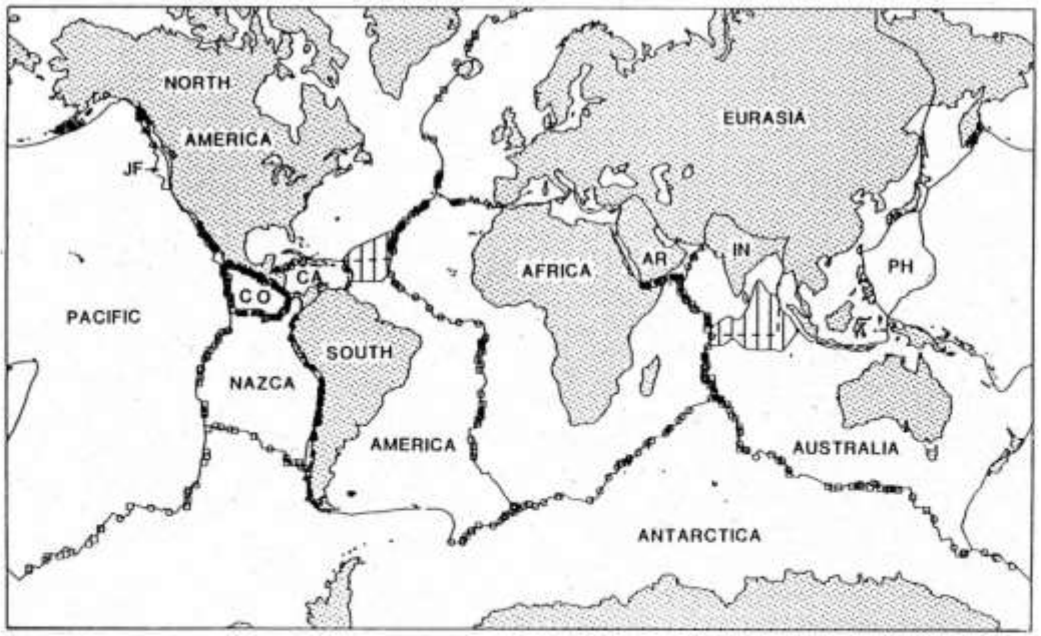
Plate kinematics is derived geophysically from three observation types:

- **Sea floor spreading** rates (velocities),
- **Transform faults** azimuths (directions),
- **Earthquake slip** vectors (directions).

The result are plate rotation vectors on a sphere (Theorem of Euler)

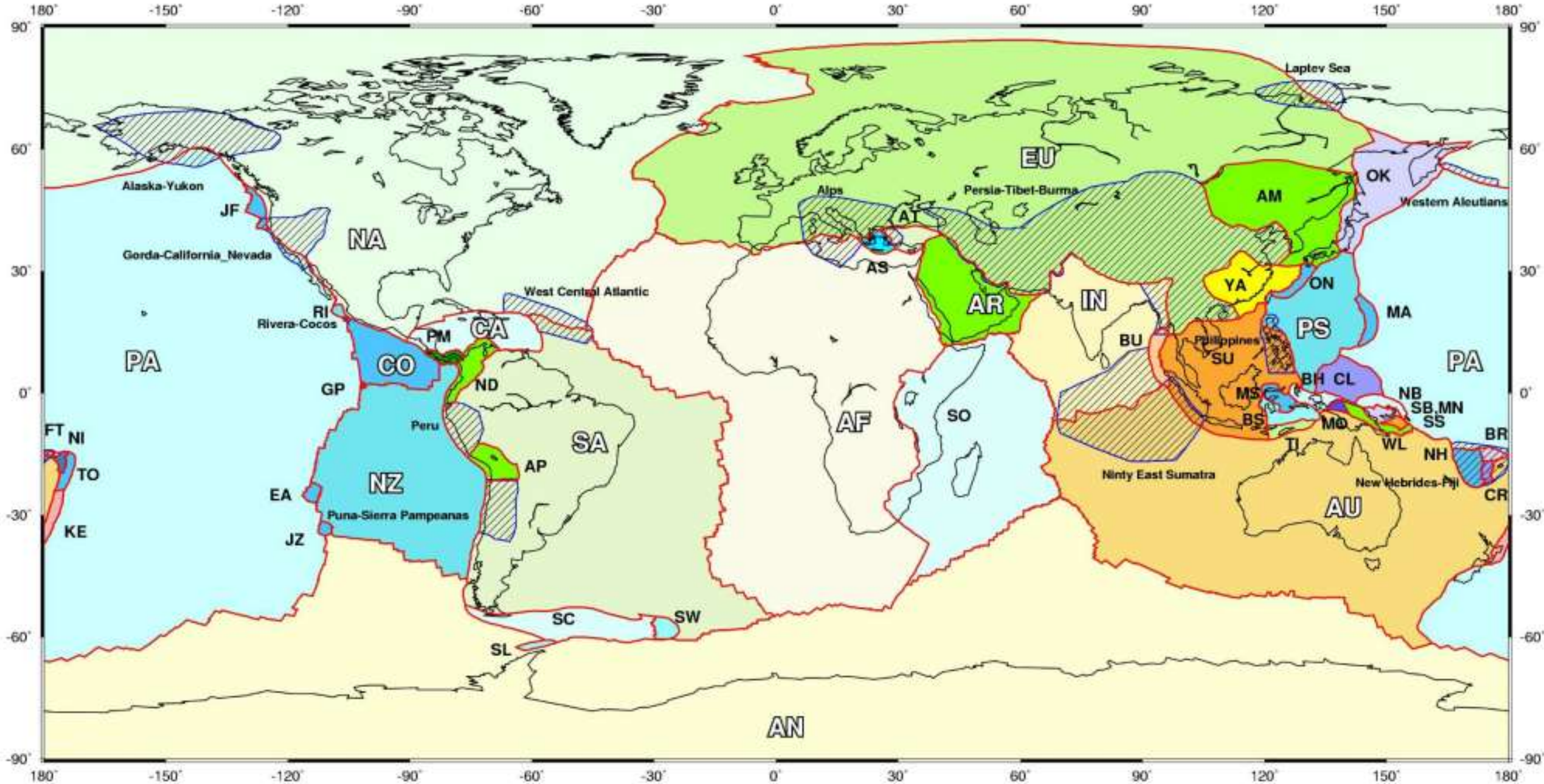
Such a model of rigid plates is NUVEL-1A (DeMets et al. 1994). Station velocities of the **ITRF** are based on this model defining the kinematic datum.

NUVEL-1A does **not** include any non-rigid crustal deformation.



Considering more plates and crustal deformation zones

The plate model PB2002 (Bird 2003) includes 13 deformation zones within and between 52 plates, the 10 larger ones identical with NUVEL-1A.



The observation data cover a period of 3 Million years. Valid for today?

Plate kinematics based on geodetic observations

- **Present day** plate kinematic models are only feasible since space geodetic observations allow **measuring global position changes** (velocities).
- Geodetic Actual Plate Kinematic Models (APKIM) are computed since 1988.
- The latest APKIM2014 is based on the ITRF2014 (Altamimi et al. 2016).

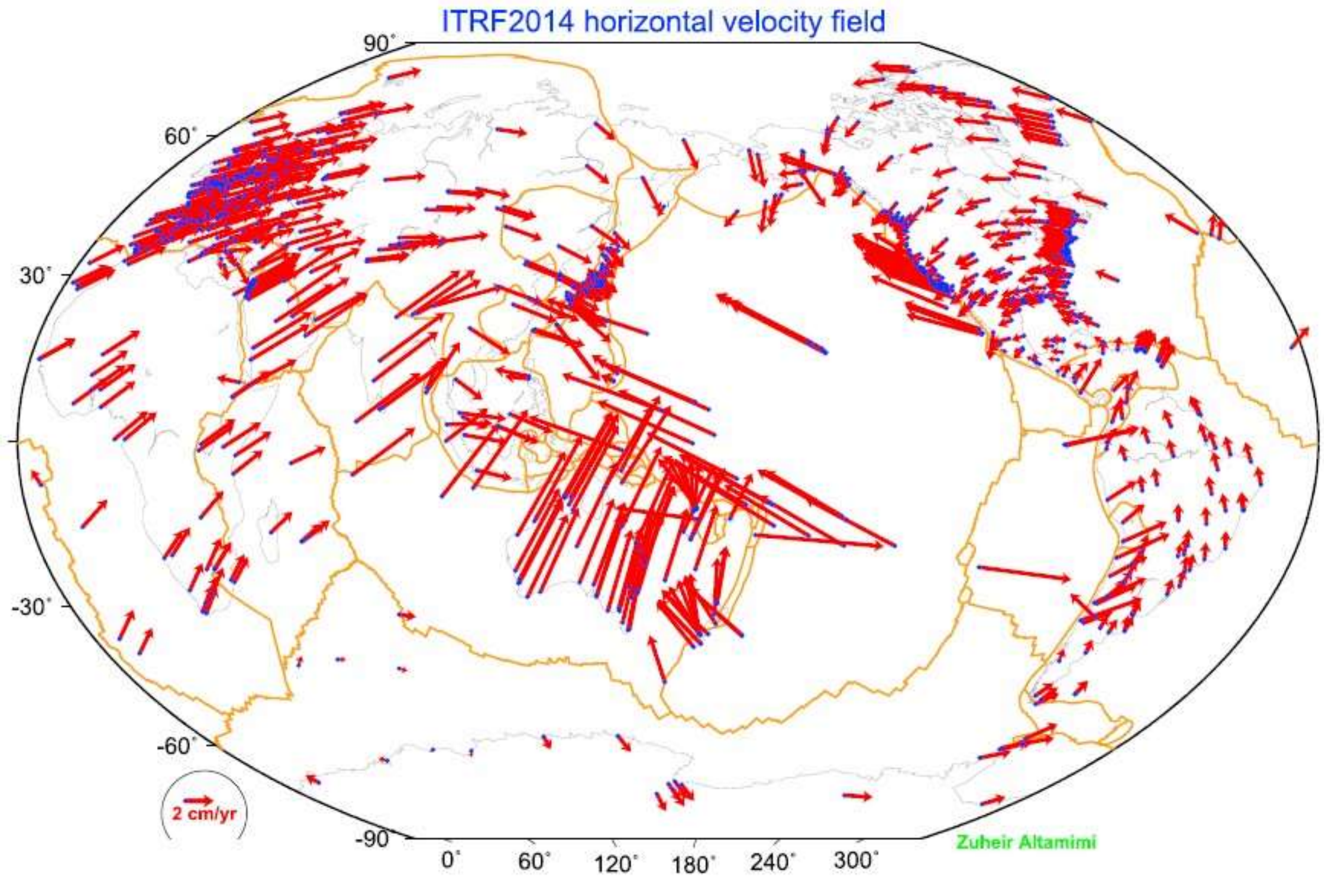


Figure 11. ITRF2014 horizontal site velocities with formal error less than 0.2 mm/yr. Major plate boundaries are shown according to *Bird* [2003].

Velocities used for APKIM 2014

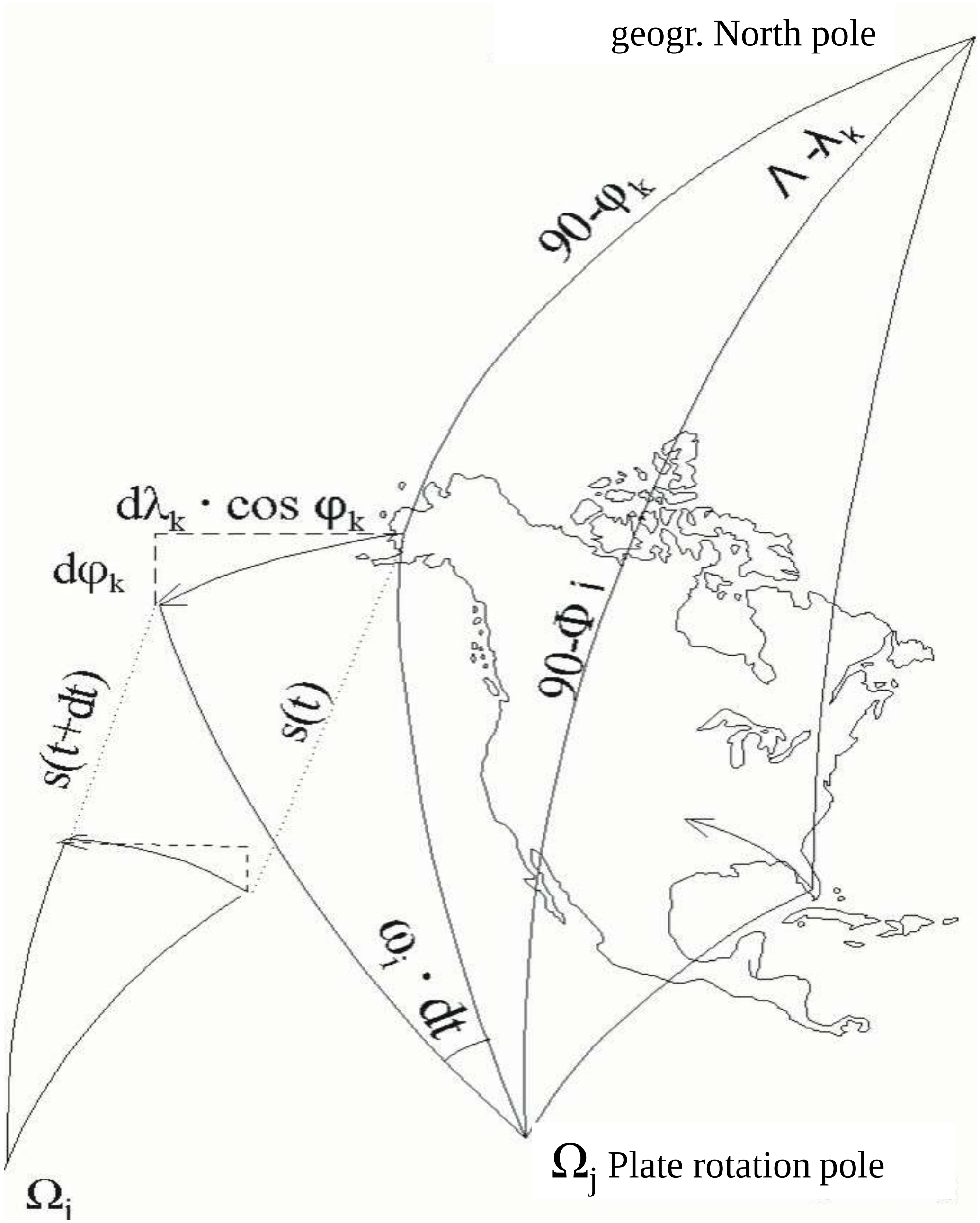
- only the latest periods in ITRF

Techniques

- GNSS 657
- Laser 46
- VLBI 54
- Doris 28

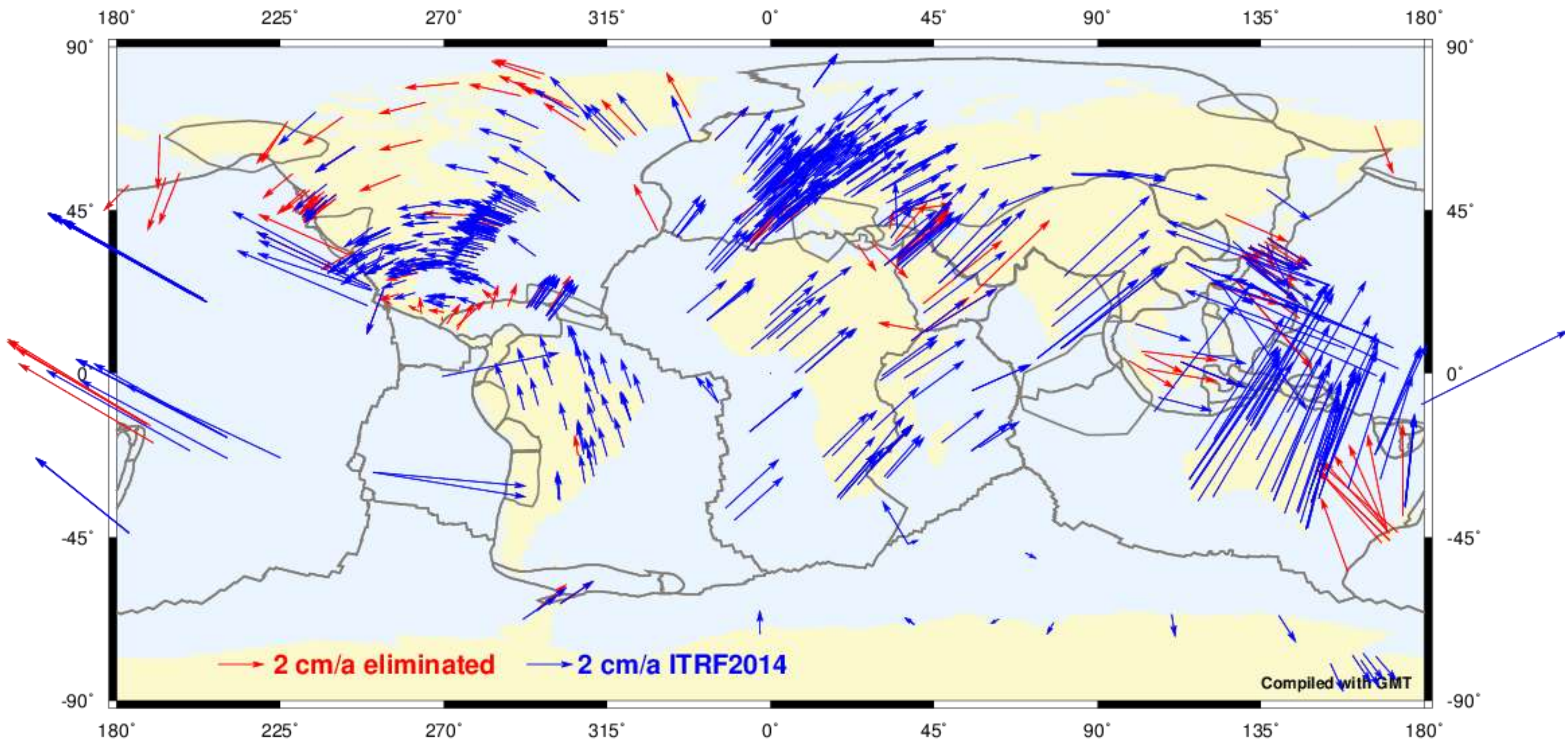
Total 785

Summary of the processing procedure



- ITRF includes point coordinates and velocities of consecutive periods (solutions). A new period starts at any discontinuity.
- Only the latest periods are taken for the estimation of the plate rotation vectors (Ω(Φ,Λ,ω)).
- A two-dimensional adjustment is done (by spherical geometry) to avoid the effect of less precise vertical velocities.
- Iterative adjustments were done eliminating “non-fitting” ITRF velocities after the 3-sigma-criterion.

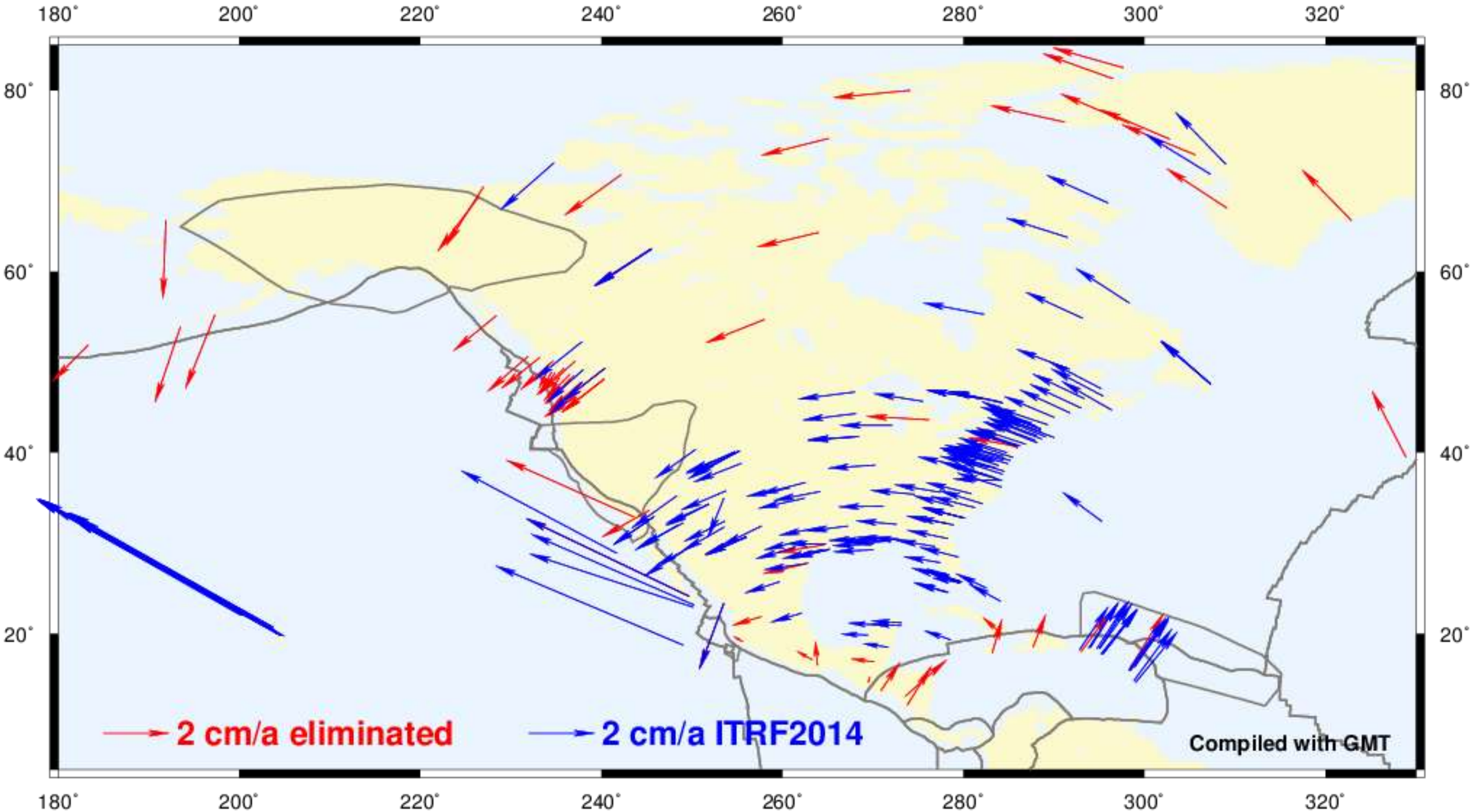
Available & eliminated velocities (outliers / deformations)



ITRF2014 latest period: 785 velocity vectors; used: 636; eliminated: 149;
Reasons: ITRF estimation uncertainties **or** intra-plate deformations

Eliminated velocities (outliers / deformation-rigid plates)

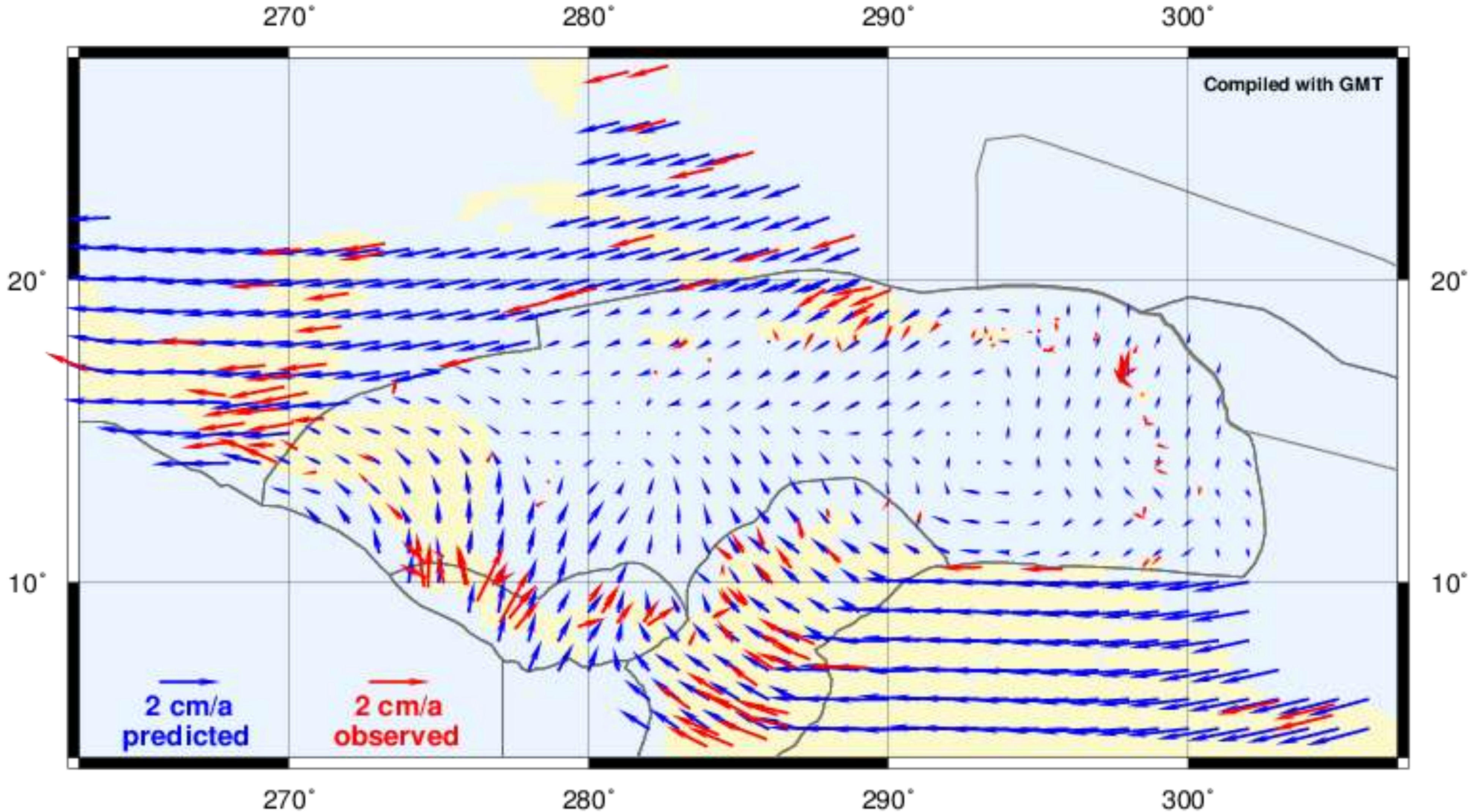
North American plate ITRF2014 available and eliminated velocity vectors



Most velocities are given in the southern part that dominates the estimation.
Northern velocities do obviously not correspond to the same rigid plate!

Deformable (non rigid) plates)

Caribbean plate deformation (from the SIRGAS velocity model VEMOS2017)

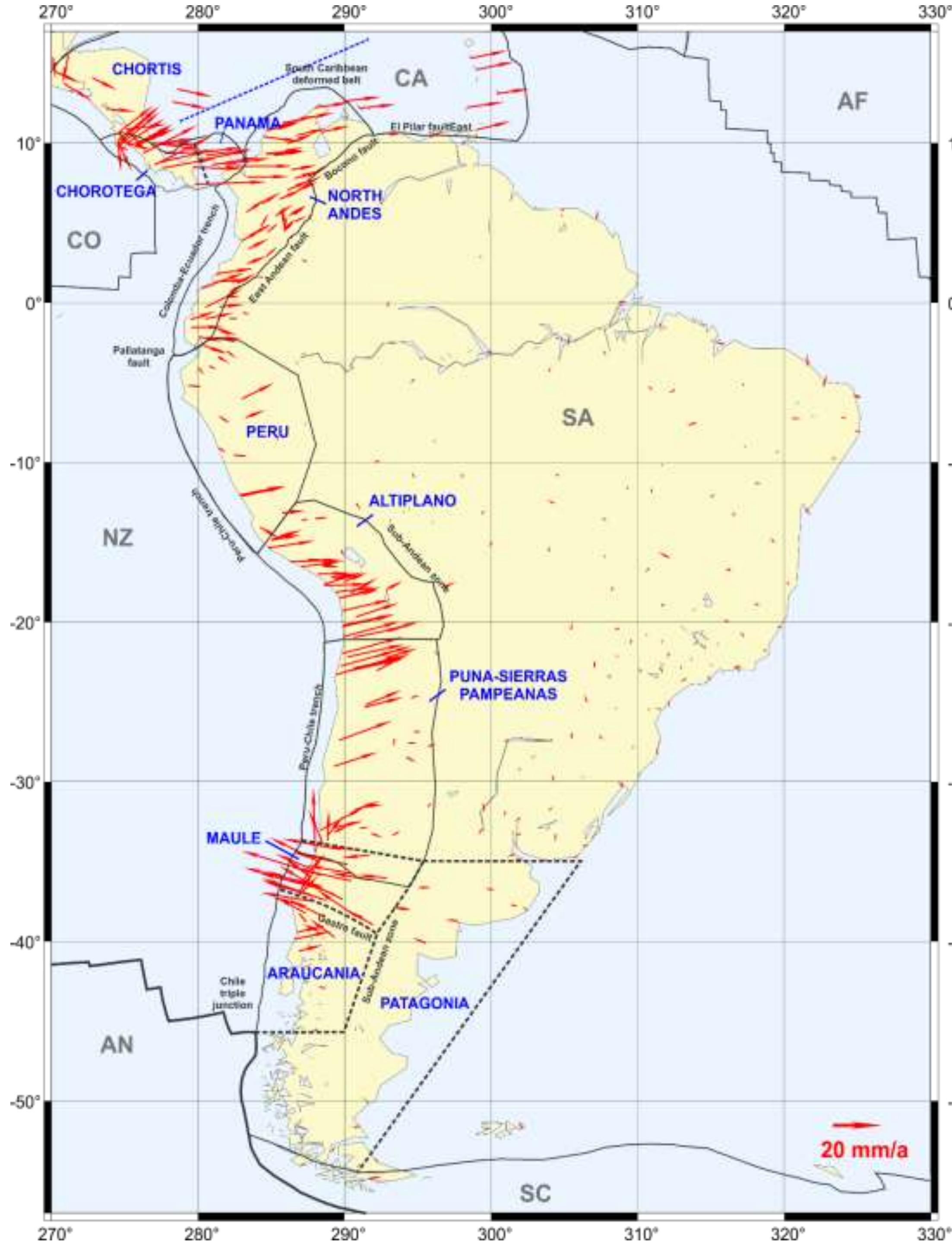


The Caribbean plate is obviously not a rigid plate!

Deformable (non rigid) plates)

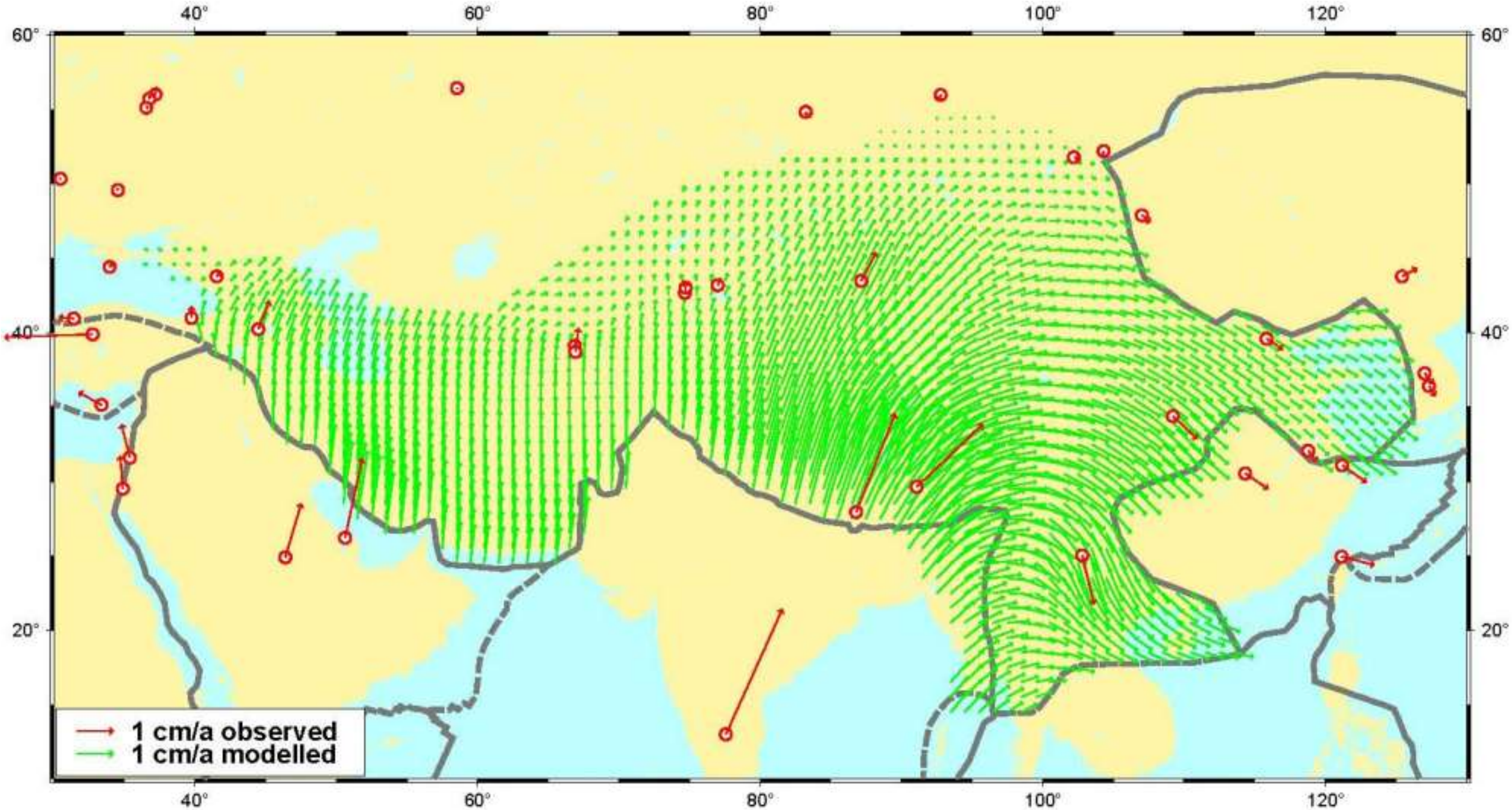
South American plate deformation (from VEMOS2017)

The South American plate is not a rigid plate. There is deformation greater than the precision of the estimated velocities (< 1 mm/a), in particular in the south-eastern area (Patagonia).



Deformable (non rigid) plates)

Eurasian plate deformation (from all the APKIM velocities since 2005)



The Eurasian plate is obviously not a rigid plate!

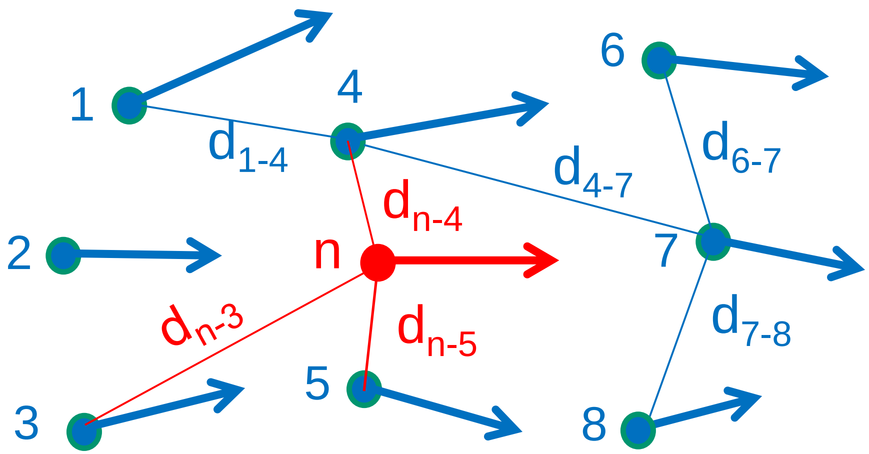
Comparison of estimated plate rotation poles (Φ, Λ, ω)

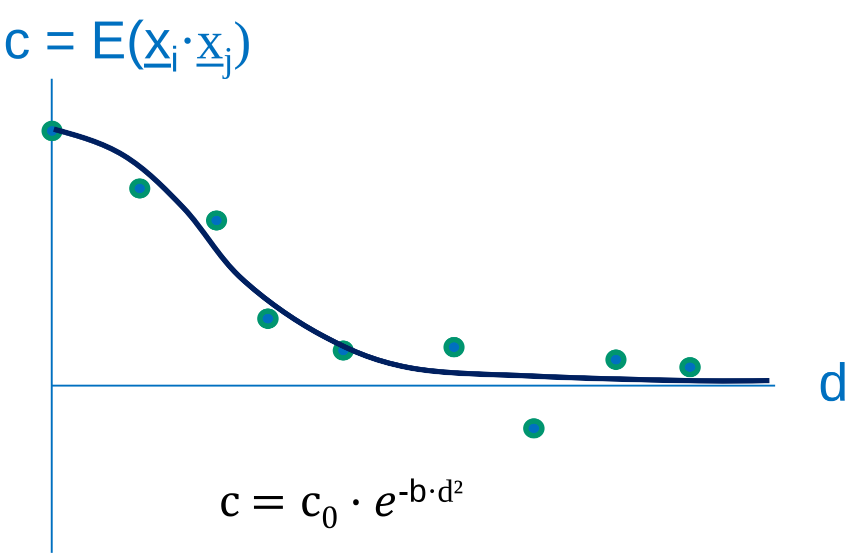
(red numbers are different to APKIM2014 after the 3-sigma-criterion)

Plate	APKIM2014			APKIM2008			NNR NUVEL-1A		
	Φ [°]	Λ [°]	Ω [°/Ma]	Φ [°]	Λ [°]	Ω [°/Ma]	Φ [°]	Λ [°]	Ω [°/Ma]
Africa	49.57	278.71	0.267	49.80	278.54	0.268	50.57	286.04	0.291
	±0.19	±0.54	±0.001	±0.26	±0.70	±0.001			
Antarctica	59.32	234.04	0.216	58.83	231.91	0.214	62.99	244.24	0.238
	±0.39	±0.56	±0.003	±0.33	±0.59	±0.003			
Arabia	49.62	3.54	0.582	50.00	3.45	0.570	45.23	355.54	0.546
	±0.31	±1.05	±0.010	±0.36	±1.33	±0.012			
Australia	32.29	37.91	0.630	32.46	37.88	0.633	33.85	33.17	0.646
	±0.10	±0.20	±0.001	±0.14	±0.31	±0.002			
Caribbean	31.48	269.32	0.337	28.00	250.93	0.208	25.00	266.99	0.214
	±1.16	±3.01	±0.032	±1.32	±2.68	±0.018			
Eurasia	54.45	259.66	0.255	55.13	260.58	0.256	50.62	247.73	0.234
	±0.22	±0.33	±0.001	±0.28	±0.40	±0.001			
India	51.51	1.71	0.523	50.20	11.75	0.552	45.51	0.34	0.545
	±0.31	±4.33	±0.009	±0.66	±4.27	±0.013			
N. America	-4.82	272.10	0.193	-5.76	272.50	0.189	-2.43	274.10	0.207
	±0.30	±0.13	±0.001	±0.45	±0.22	±0.001			
Nazca	45.60	257.75	0.632	45.88	257.61	0.682	47.80	259.87	0.743
	±0.91	±0.39	±0.006	±0.63	±0.33	±0.001			
Pacific	-62.50	110.42	0.680	-62.57	110.93	0.634	-63.04	107.33	0.641
	±0.08	±0.34	±0.001	±0.08	±0.36	±0.005			
S. America	-18.68	231.31	0.122	-19.35	237.84	0.127	-25.35	235.58	0.116
	±0.51	±1.30	±0.001	±1.02	±1.51	±0.002			

Alternative to plate models: continuous deformation model

An alternative to rigid plate kinematics for modeling global deformation is a continuous deformation model. We use a least squares collocation approach.





2D-vector prediction:

$$\underline{\mathbf{v}}_{pred} = \underline{\mathbf{C}}_{new}^{T}\, \underline{\mathbf{C}}_{obs}^{-1}\, \underline{\mathbf{v}}_{obs}$$

$\underline{\mathbf{v}}_{pred}$ = predicted velocities (v_N, v_E) in a 1°× 1° grid

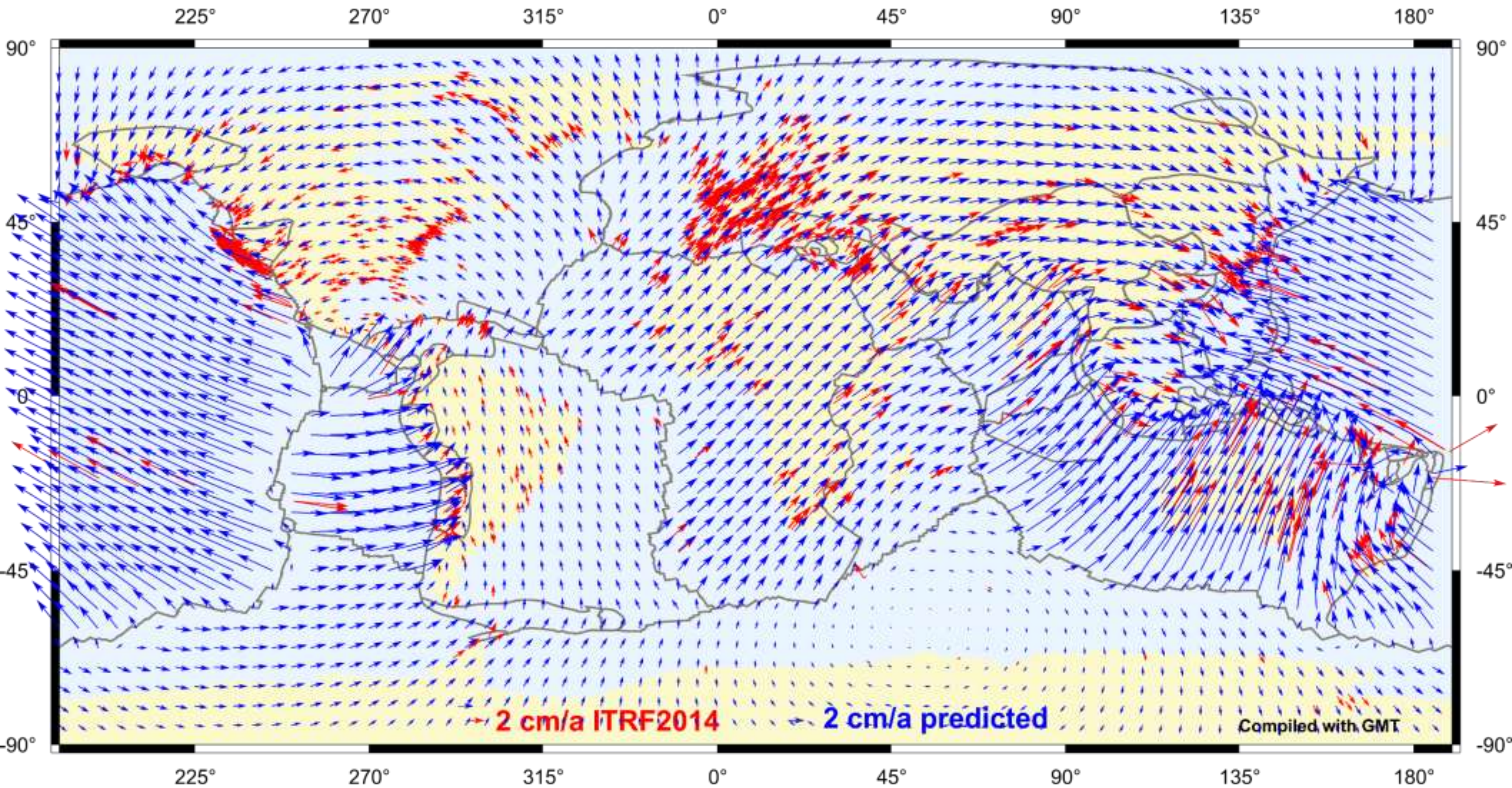
$\underline{\mathbf{C}}_{obs}$ = correlation matrix between observed vectors (C_{NN}, C_{EE}, C_{NE})

$\underline{\mathbf{C}}_{new}$ = correlation matrix between predicted & observed vectors

$\underline{\mathbf{v}}_{obs}$ = observed velocities (v_N, v_E) in geodetic stations

$\underline{\mathbf{C}}$ matrices are built from empirical isotropic, stationary covariance functions $c = E(x_i \cdot x_j)$.

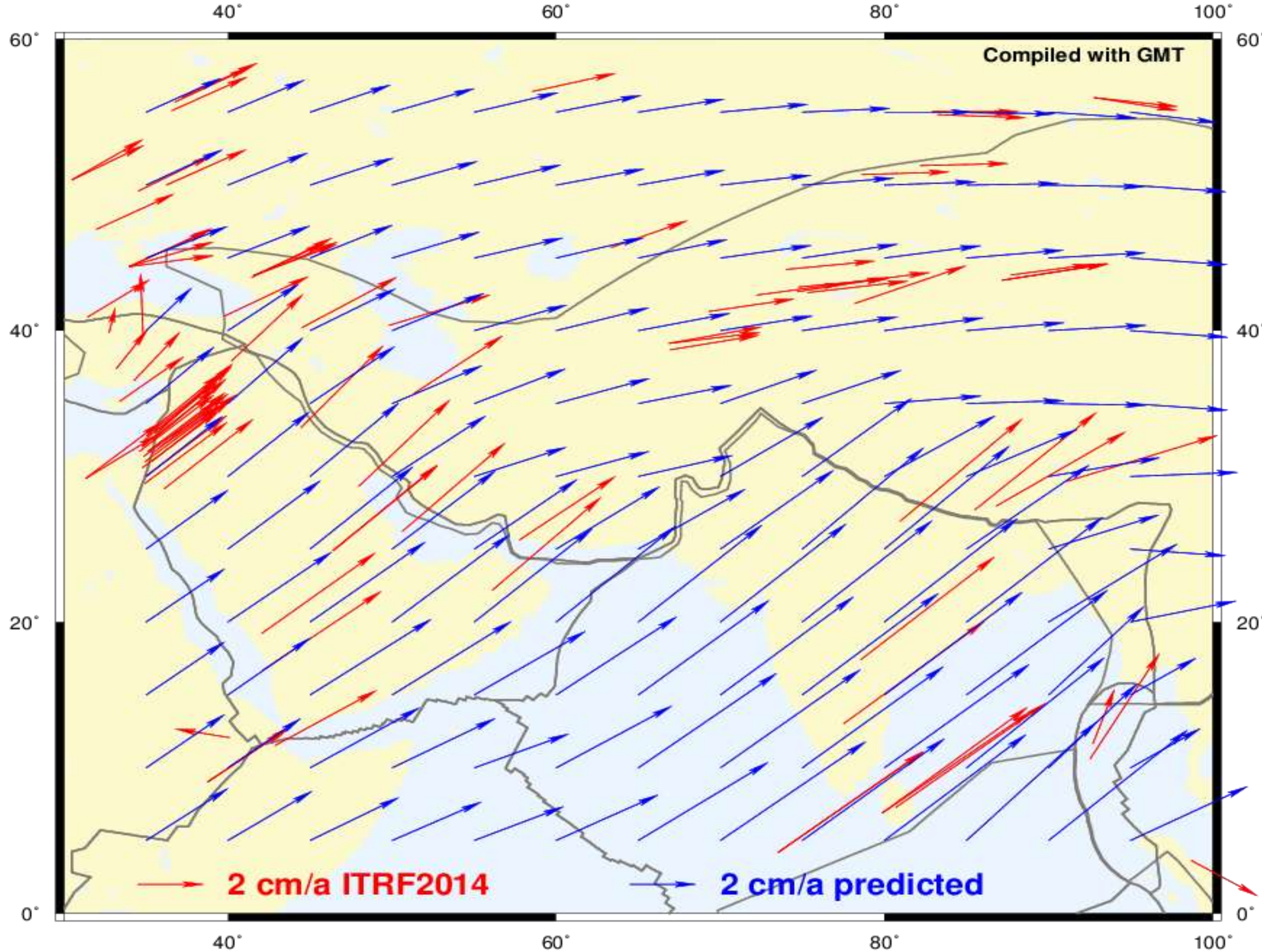
Continuous crustal deformation model from ITRF2014



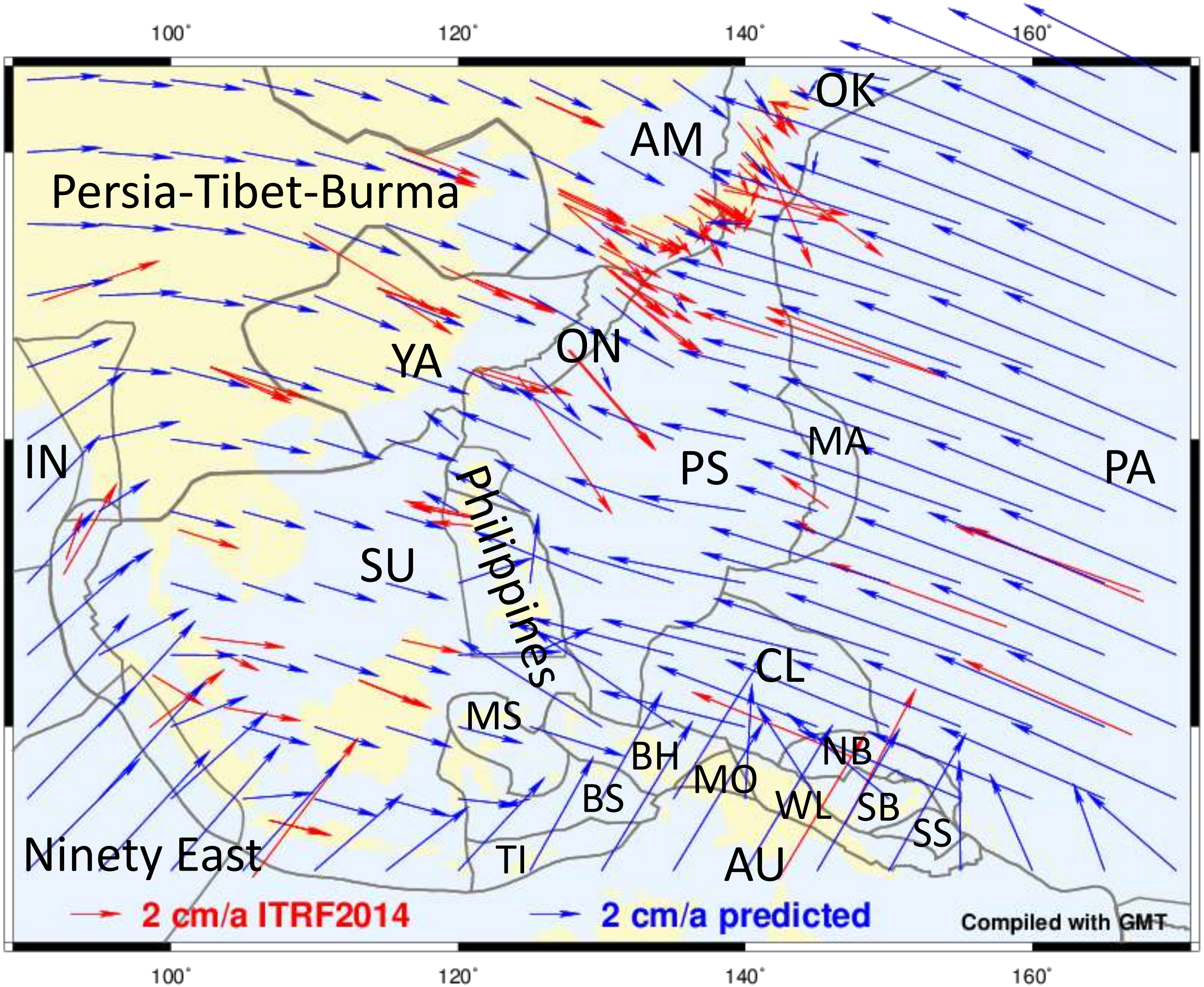
The collocation approach includes station velocities up to 500 km from the grid point to be predicted. If a sufficient number of station velocities (> 3) is not available, the used plate model (APKIM2014) is considered.

Example of continuous deformation zones

The Persia-Tibet-Burma orogen (Bird 2003) between Eurasia and India plates



Example of extreme deformation zones



East Asia is a complicated tectonic area (extremely difficult for prediction)

Plates (e.g. PA) and orogens (deformation zone names) are according to Bird (2003)

Conclusions

- Plate tectonics is a good model for geology, in particular paleo geology.
- It can very well be used in geophysics for many modelling purposes.
- It may be used in geodesy as a basis for preliminary studies and models, but not for representing the global crustal deformation, which is needed in time-dependent global and continental reference frames (e.g. ITRF, AFREF, APREF, EUREF, NAREF, SIRGAS).

Thank you very much for your attention!