Geodetic monitoring of the surface deformation in Latin America

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SIRGAS: Sistema de Referencia Geocéntrico para Las Américas

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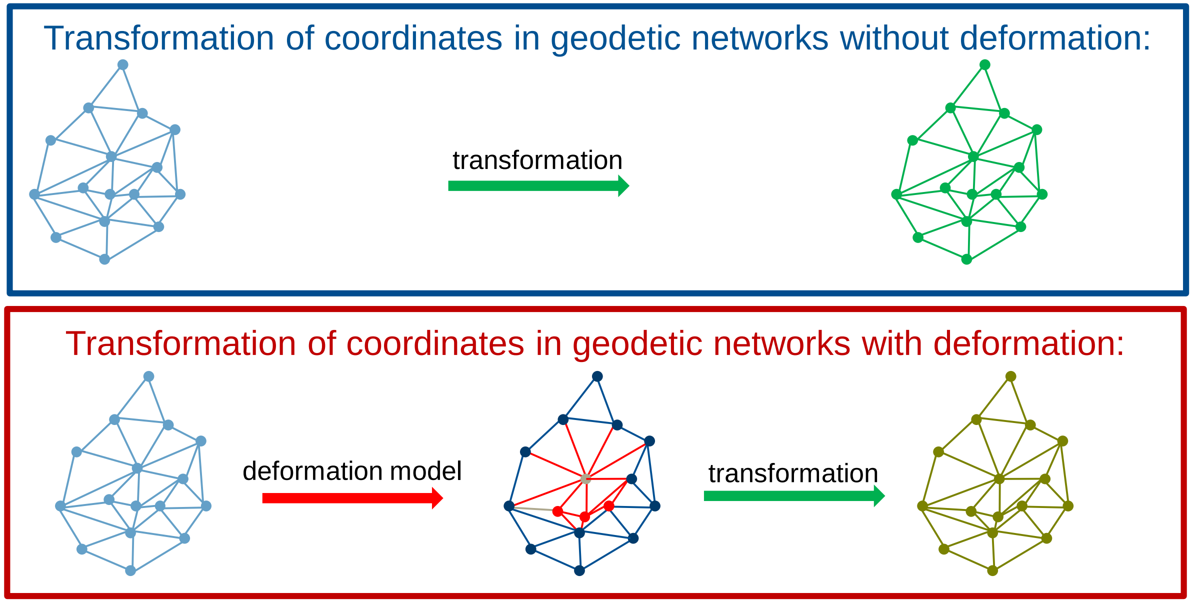
Motivation

Surface deformation models are needed in geodetic applications

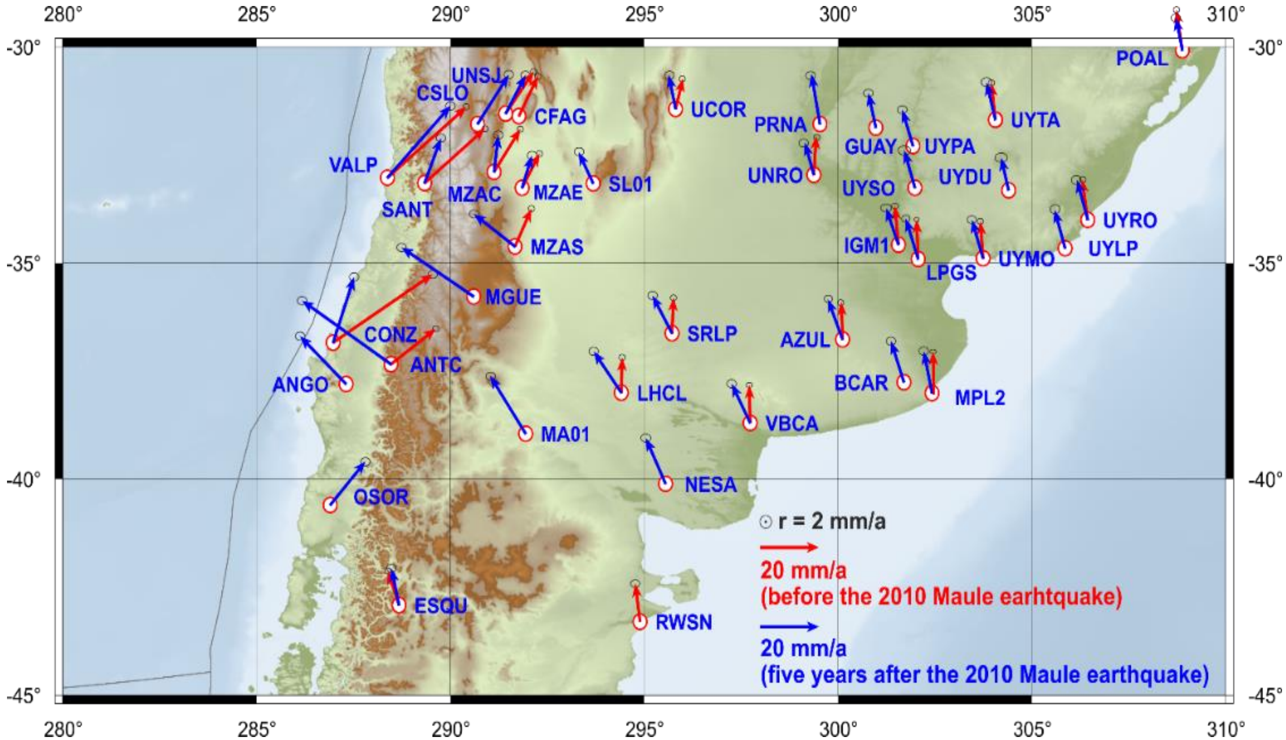
- To monitor the kinematics of geodetic reference frames;
- To provide an appropriate transformation between pre-seismic and post-seismic (deformed) coordinates (specially in official maters like legal borders, cadastre, land management, etc.);
- To interpolate surface motions arising from plate tectonics or crustal deformations in areas where no geodetic stations are established.



Motivation

The surface deformation models used in geodesy should

- mirror the present-day surface kinematics;
- provide a high-spatial resolution;
- consider deformation patterns and not only plate tectonic motions;
- be updated after strong earthquakes.

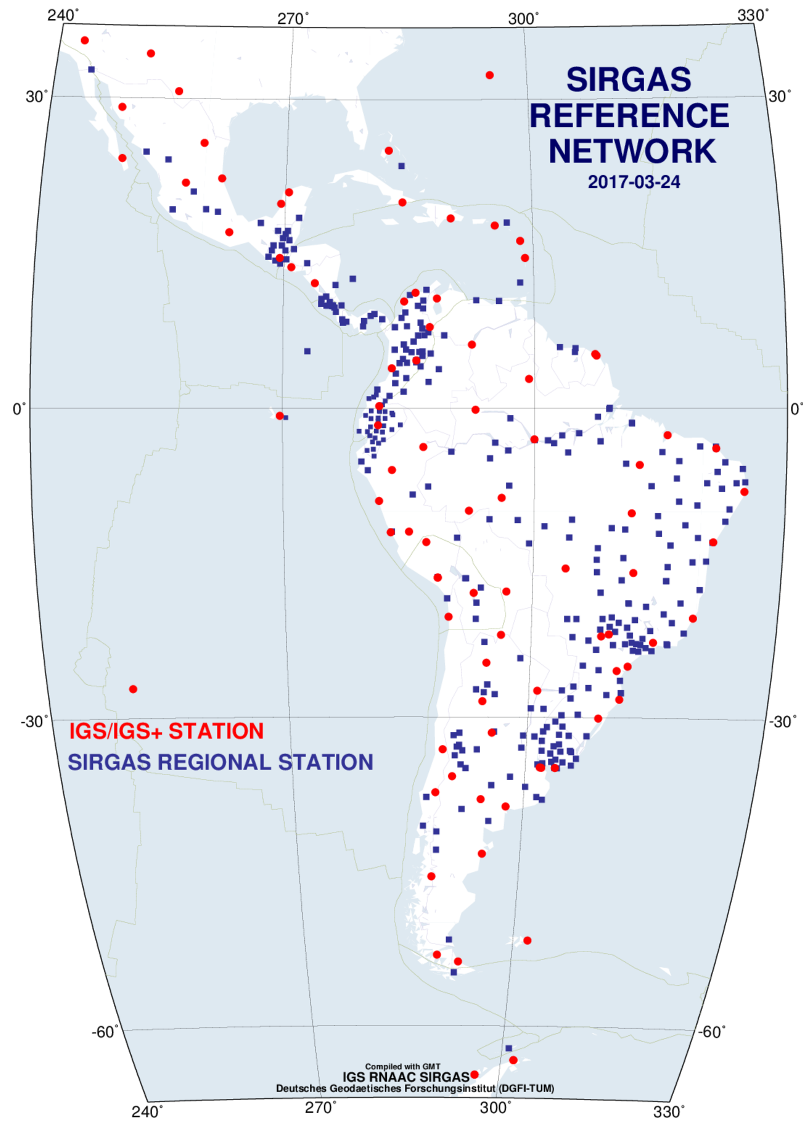


Station velocities determined before and five years after the 2010 Maule earthquake. In the Andes region the velocity vectors were oriented about N45°E before the event, now they are directed around N40°W (about 20 mm/a).

Geodetic reference frame in Latin America

SIRGAS: Sistema de Referencia Geocéntrico para Las Américas

- It is composed of about 420 continuously operating GNSS stations;
- It is routinely processed by 10 analysis centres generating weekly solutions for station positions;
- Each station is computed by three analysis centres applying the most recent standards and processing strategies;
- Accuracy of weekly station positions is about ± 1.0 mm horizontal and ± 2.5 mm vertical;
- Weekly normal equations are accumulated for the estimation of multi-year solutions including station positions referring to a certain epoch and constant stations velocities.



Kinematics of the SIRGAS reference frame

2000.0 ... 2010.1

Stations: 230

Accuracy positions

Hor.: ±1.5 mm

Ver.: ±2.4 mm

Accuracy velocities

Hor.: ±0.7 mm/a

Ver.: ±1.1 mm/a

2010.2 (2012.2) ... 2015.2

Stations: 456

Accuracy positions

Hor.: ±0.8 mm

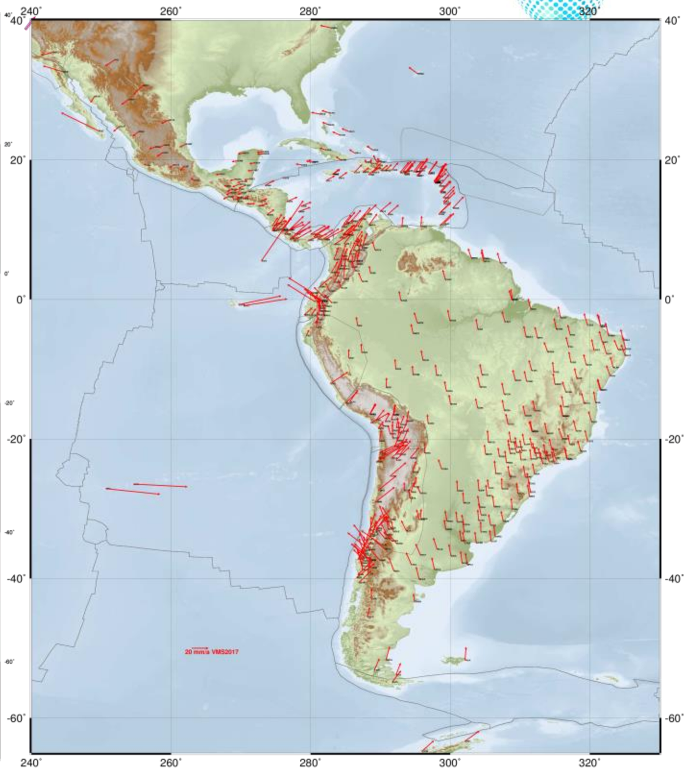
Ver.: ±3.5 mm

Accuracy velocities

Hor.: ±0.7 mm/a

Ver.: ±1.6 mm/a

2014.0 ... 2017.1



Stations: 515

Accuracy positions

Hor.: ±0.8 mm

Ver.: ±2.5 mm

Accuracy velocities

Hor.: ±0.7 mm/a

Ver.: ±1.1 mm/a

Surface deformation models inferred from cumulative solutions of GNSS weekly normal equations

Input data — Precise station velocities from reference frame multi-year solutions

Remove plate motions — Removal of plate tectonic motions from the input (observed) velocities

Tectonic settings from Seismology — Identification of tectonic blocks and deformation zones based on seismology studies

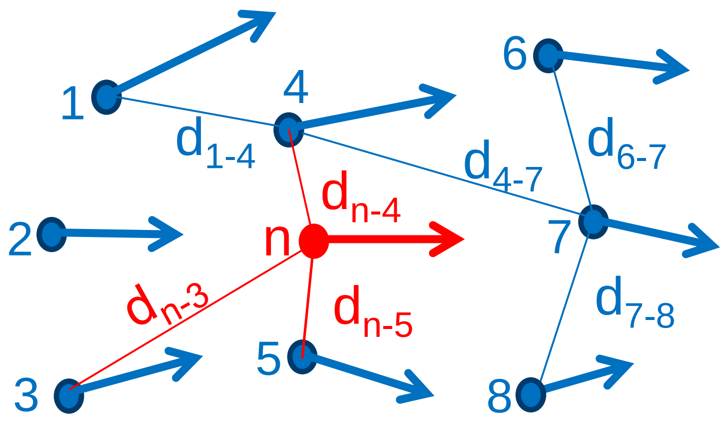
LSC prediction — Interpolation of the residual velocities to a regular grid using a geodetic Least Squares Collocation approach (LSC)

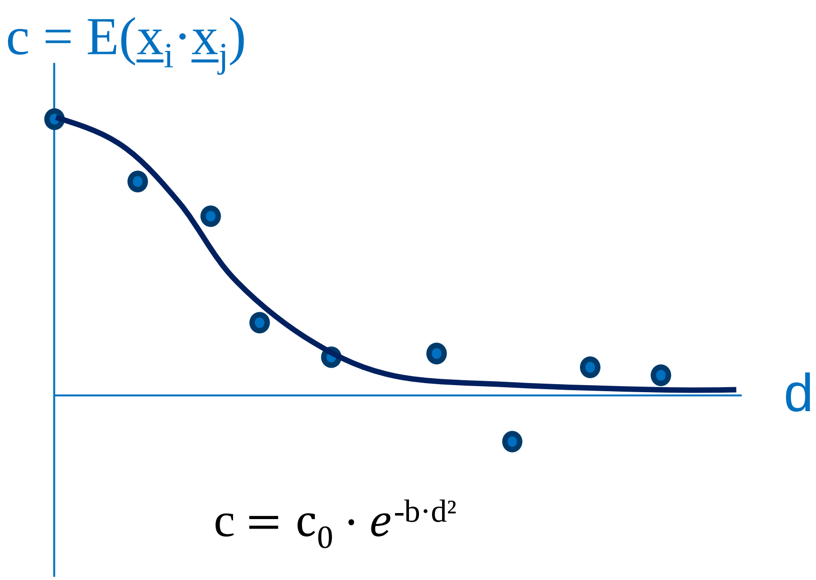
Deformation model

Restore plate motions — Addition of plate motions to the interpolated residual velocities

Velocity (kinematics) surface model

Modelling of deformations based on the geodetic Least Squares Collocation approach (LSC)





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 regular grid

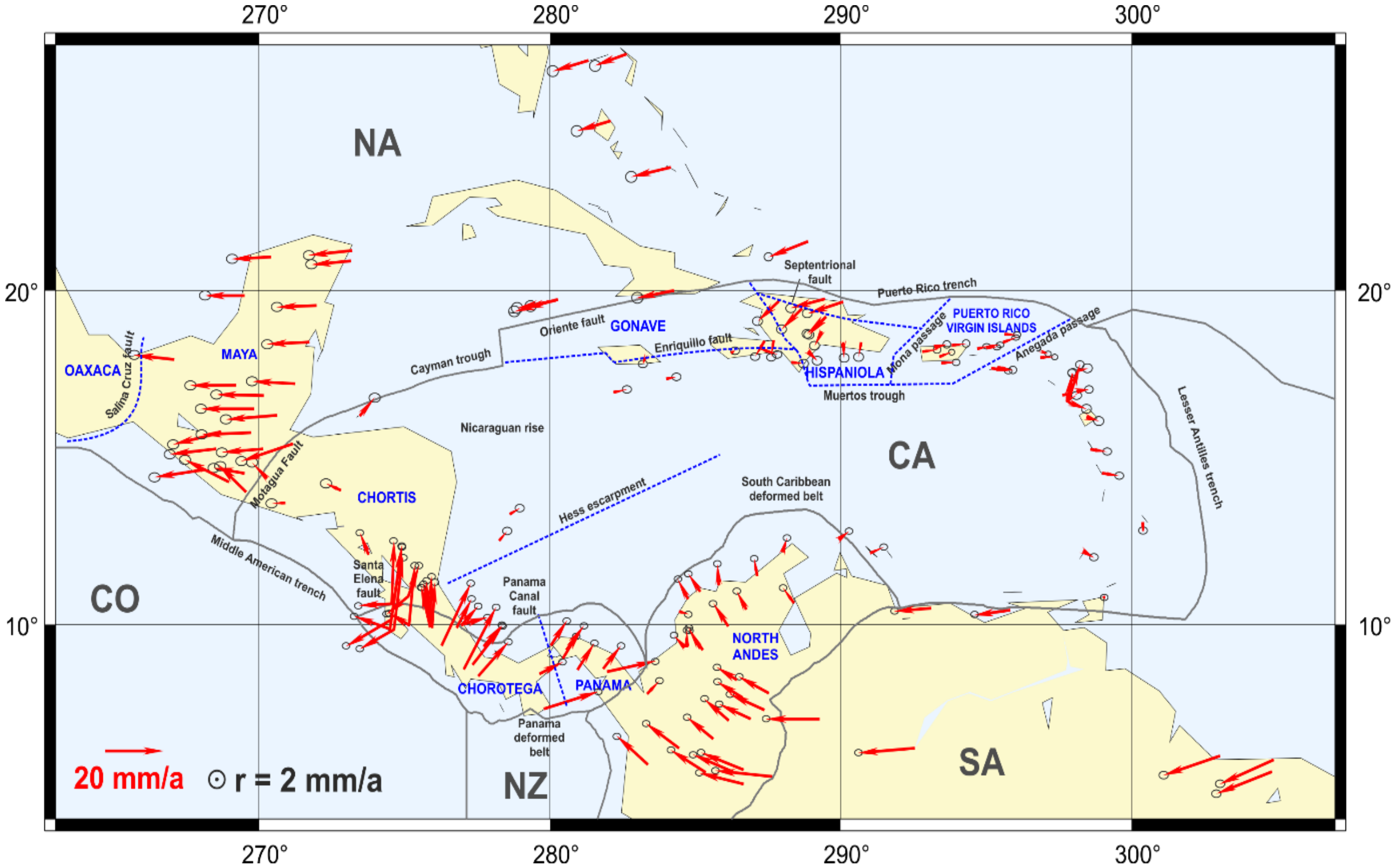
$\underline{\mathbf{v}}_{obs}$ = observed velocities (v_N, v_E) in geodetic stations

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

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

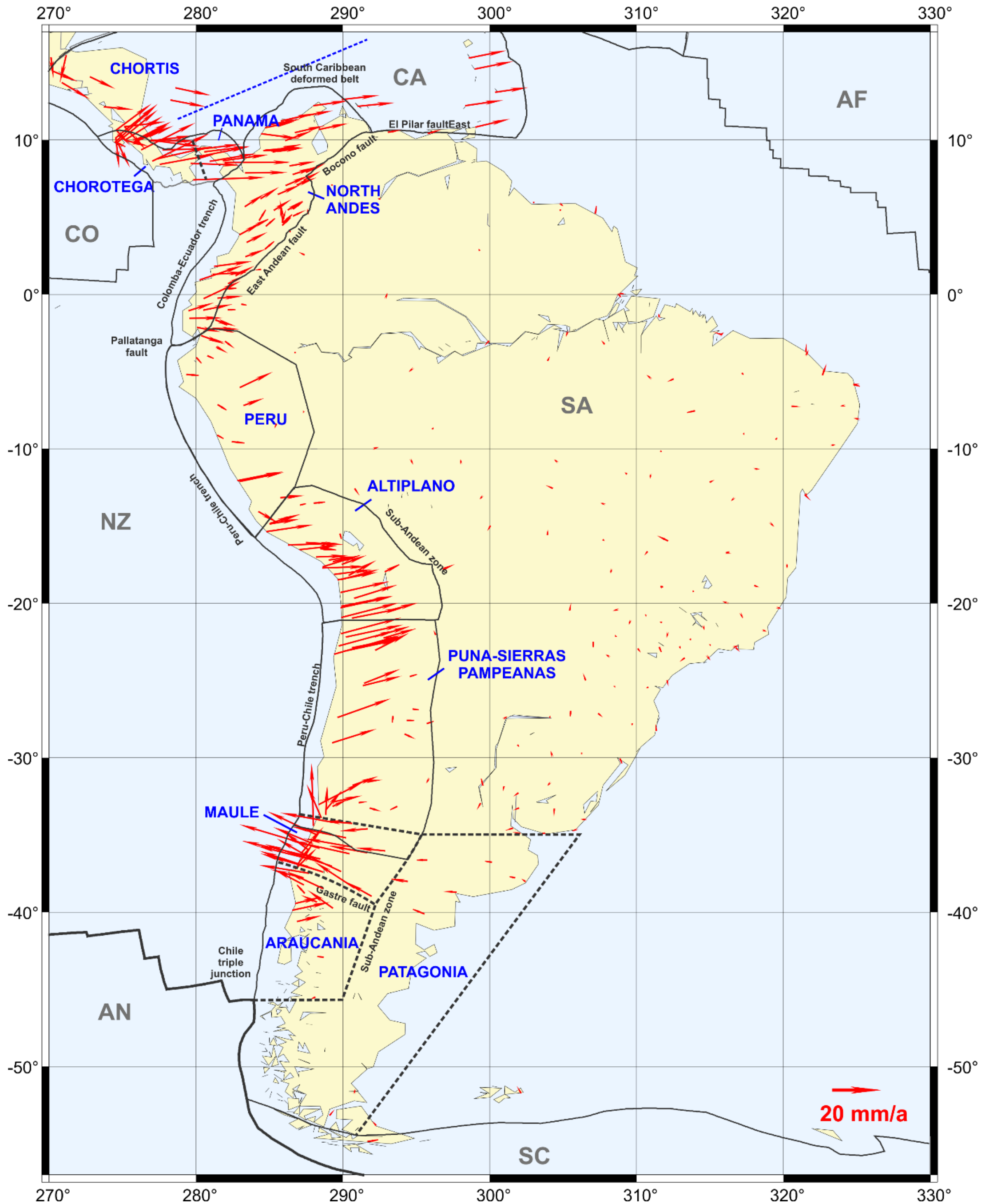
$\underline{\mathbf{C}}$ matrices are built from empirical isotropic, stationary covariance functions.

Tectonic settings in the Caribbean



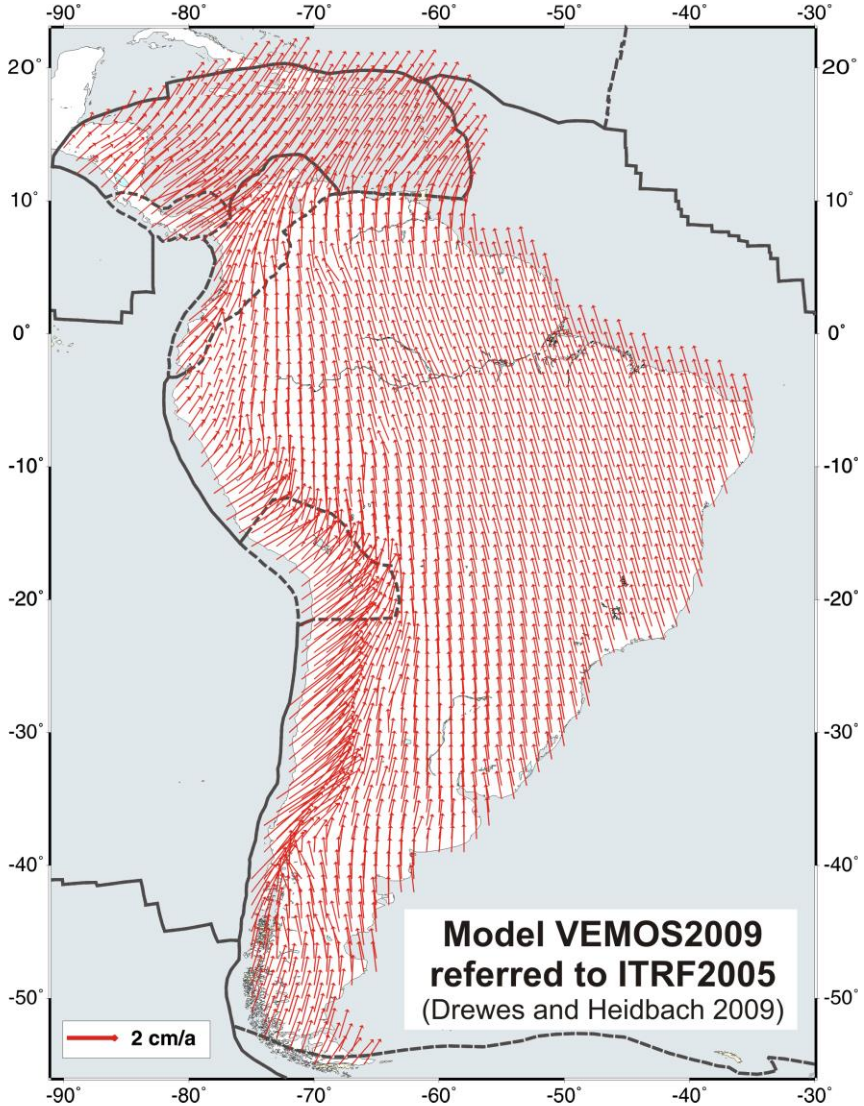
Geodetic station velocities relative to the Caribbean plate and block geometry used for the computation of the deformation model. Plate boundaries (in black) after Bird (2003), additional main tectonic blocks (in blue) after Boschmann et al. (2014), James (2007), Symithe et al. (2015) and Calais et al. (2016). CA: Caribbean, CO: Cocos, NA: North America, NZ: Nazca, SA: South America.

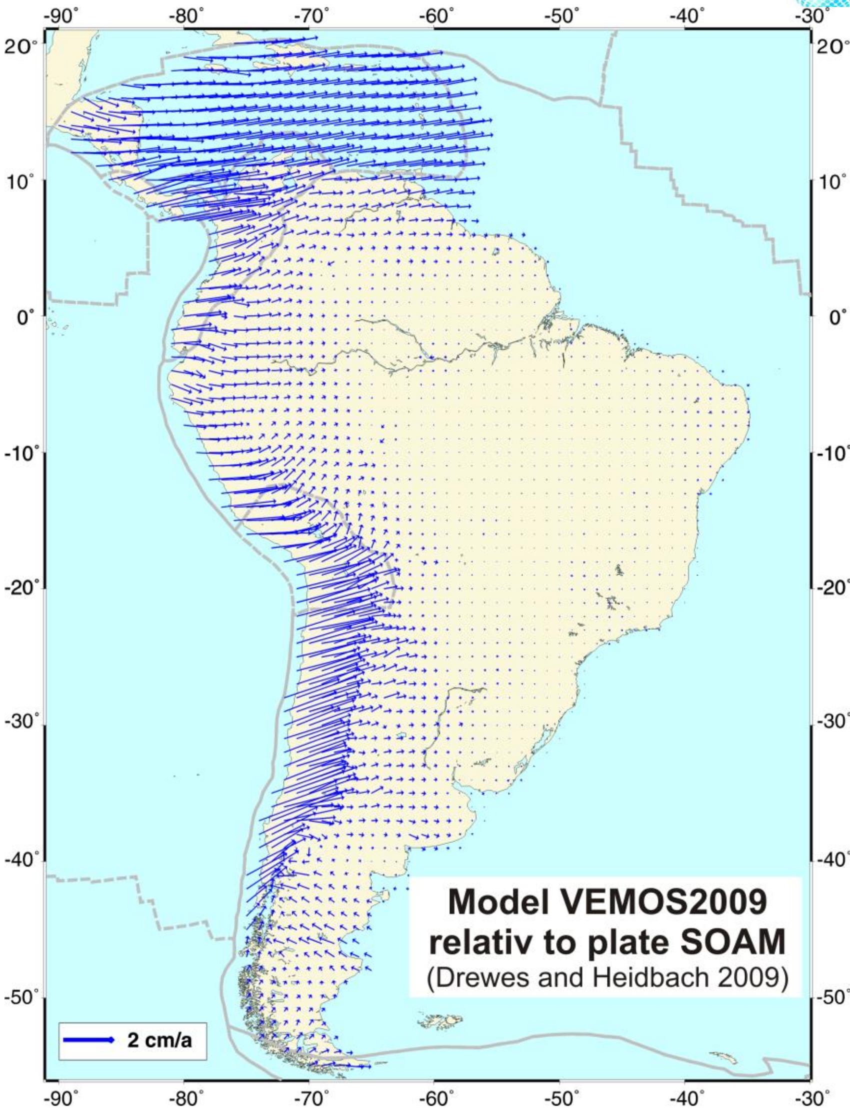
Tectonic settings in South America



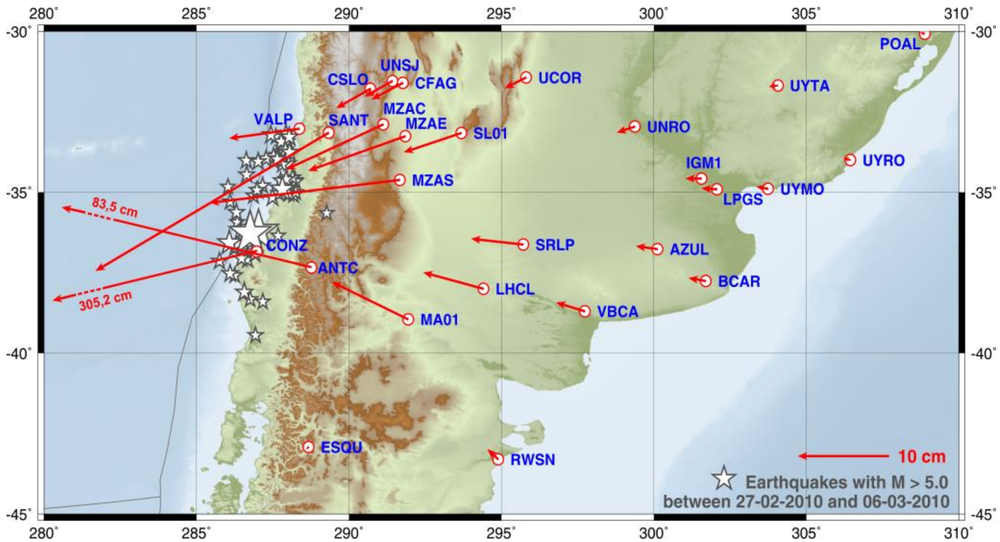
Geodetic station velocities relative to the South American plate and block geometry used for the computation of the deformation model. Plate boundaries (solid black lines) after Bird (2003), additional tectonic blocks (dashed lines) inferred from the station velocity behaviour. Plates: AF: Africa, AN: Antarctica, CA: Caribbean, CO: Cocos, NZ: Nazca, SA: South America, SC: Scotia..

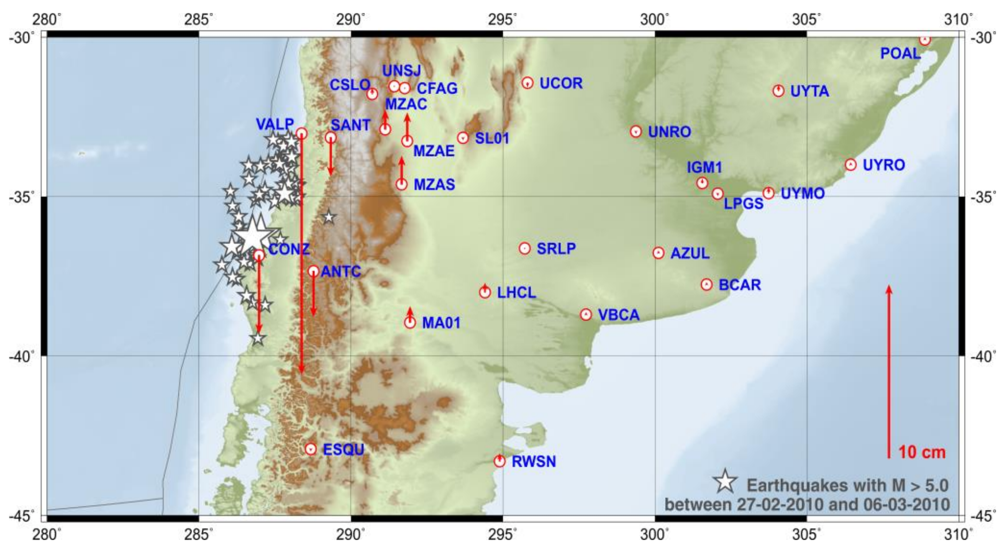
Surface kinematics and deformation model previous to the 2010 Maule earthquake: VEMOS2009 (2000.0 ... 2009.6)

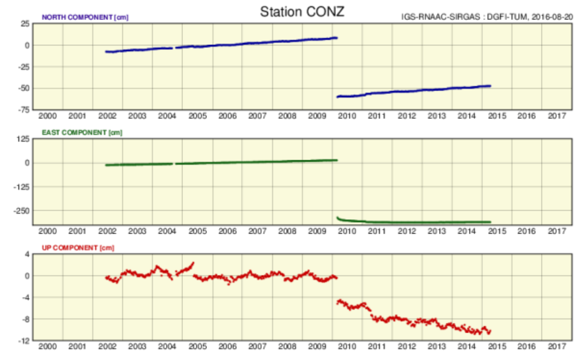


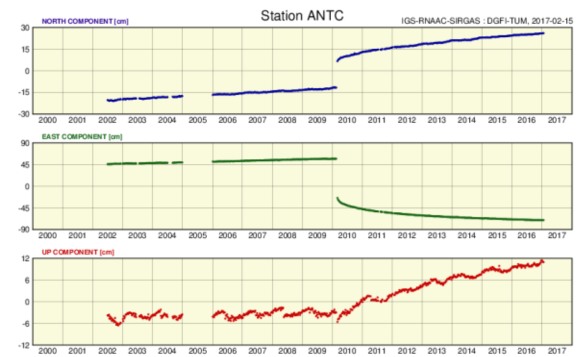


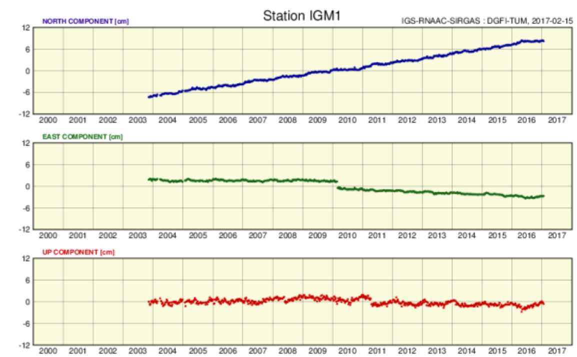
Co-seismic impact of the 2010 Maule earthquake the SIRGAS reference frame



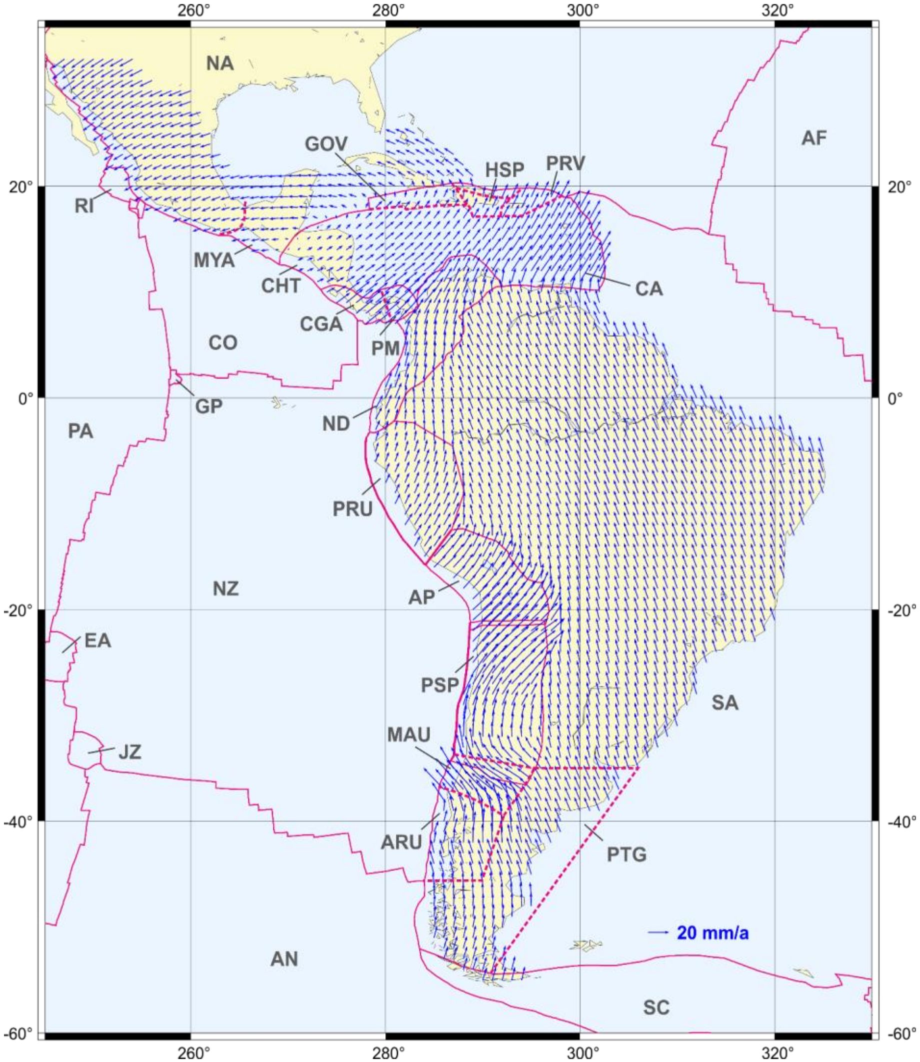


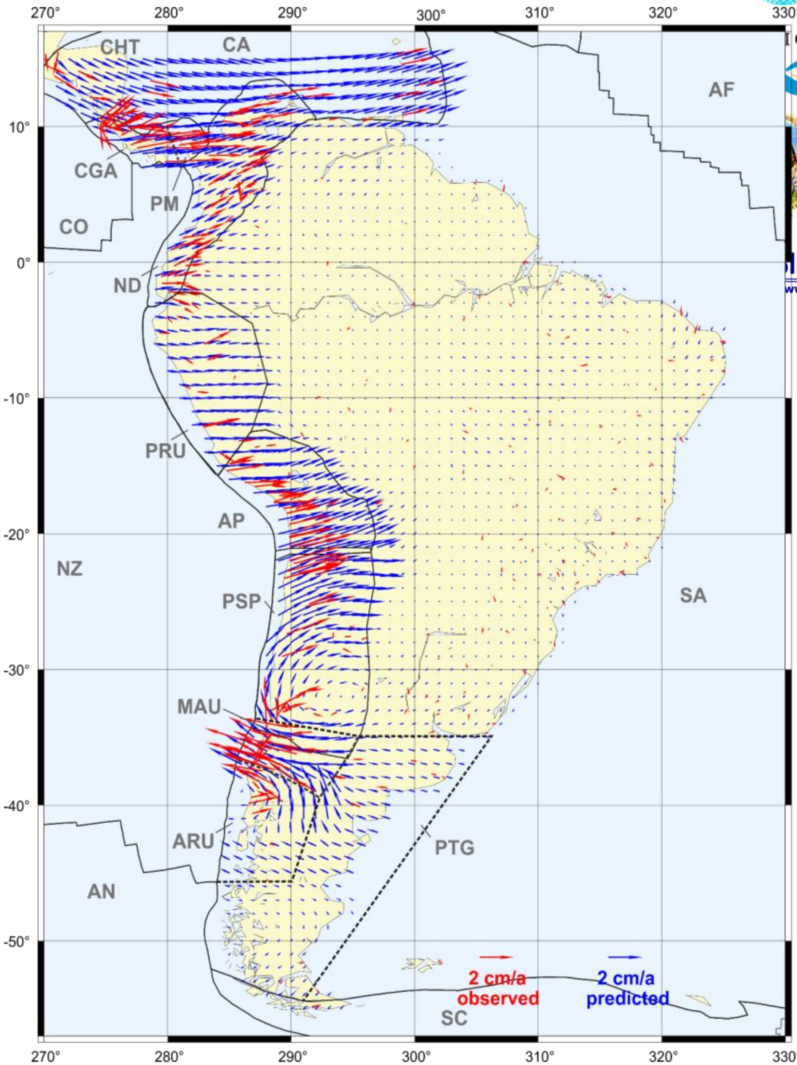




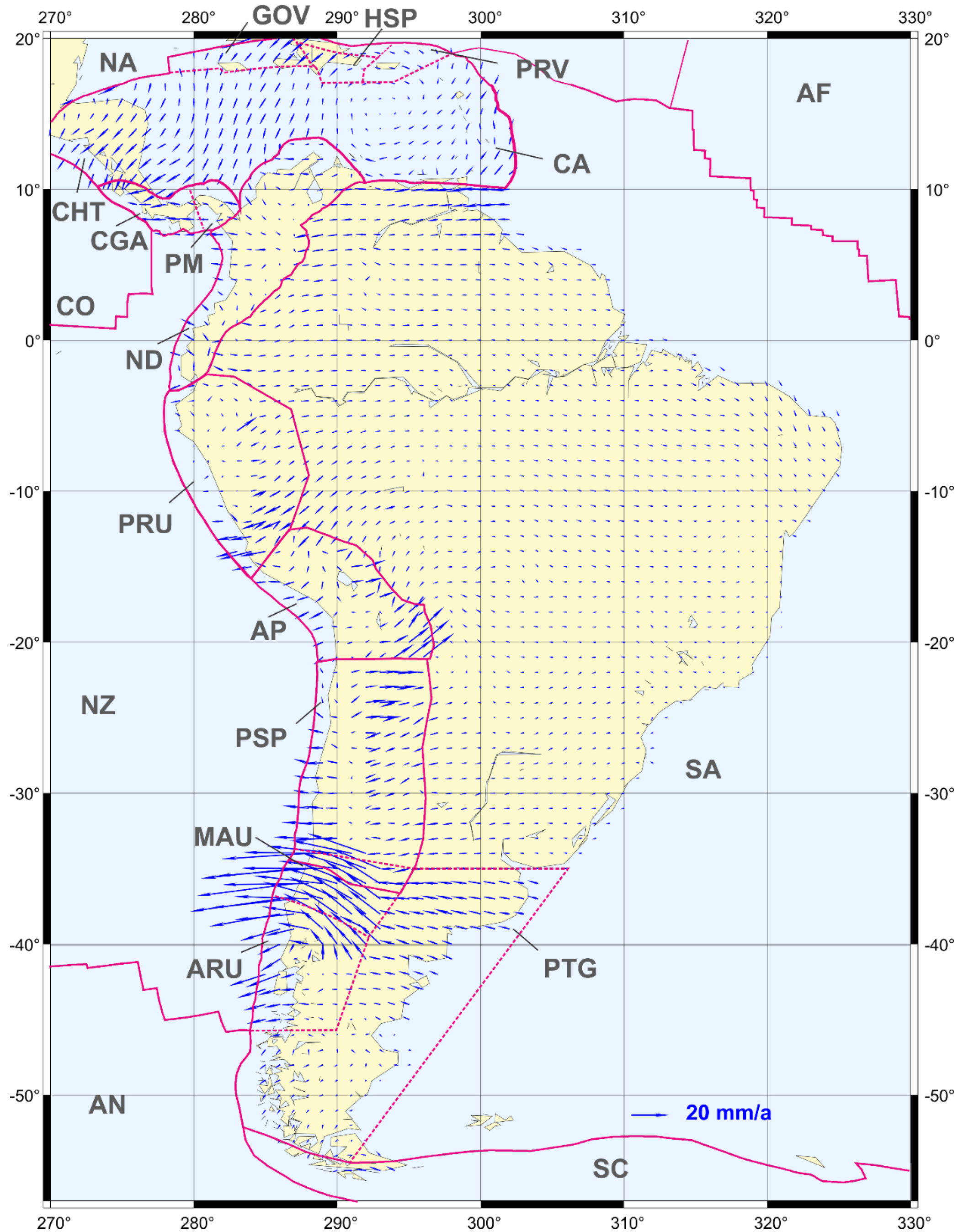


Surface kinematics and deformation model within 5 years after the 2010 Maule earthquake: VEMOS2015 (2010.2 ... 2015.2)

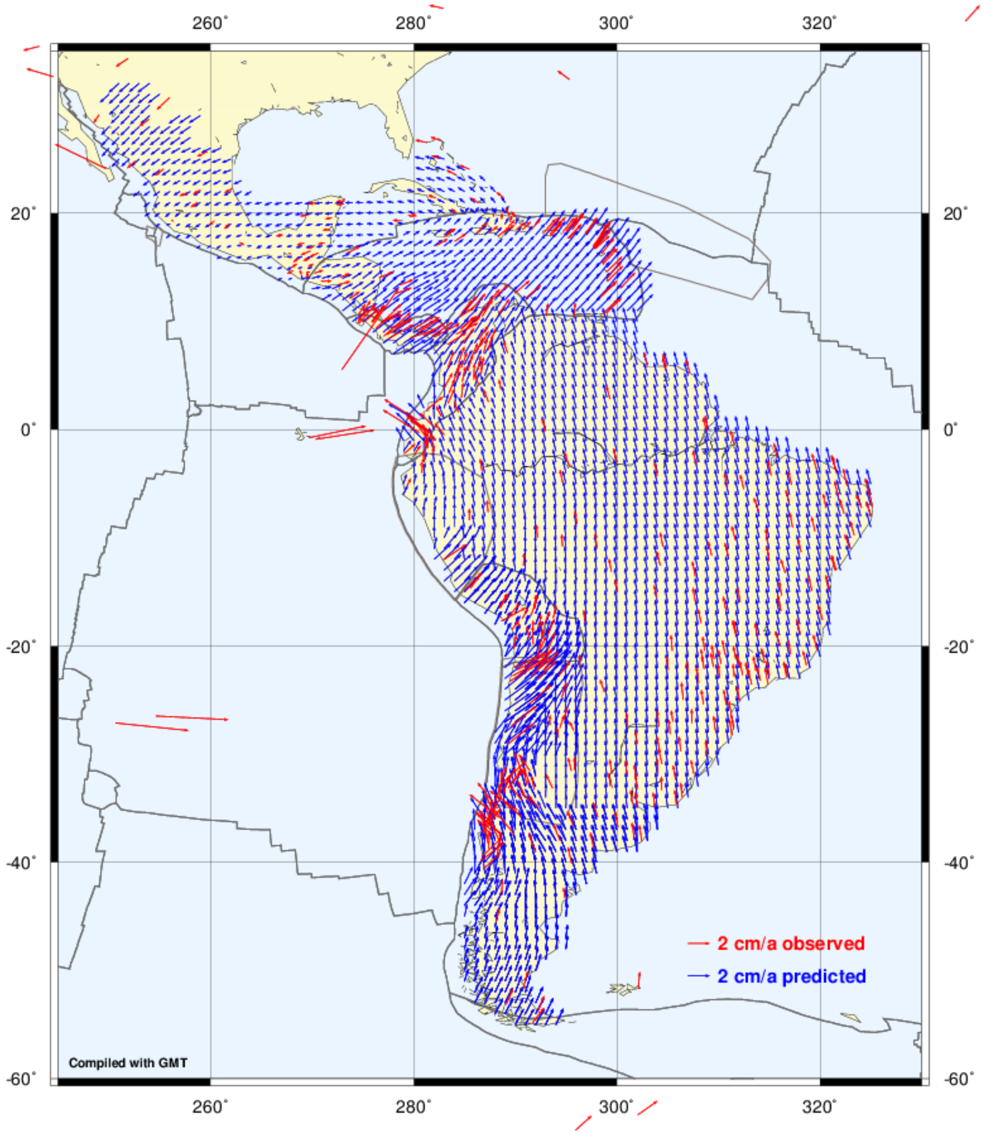


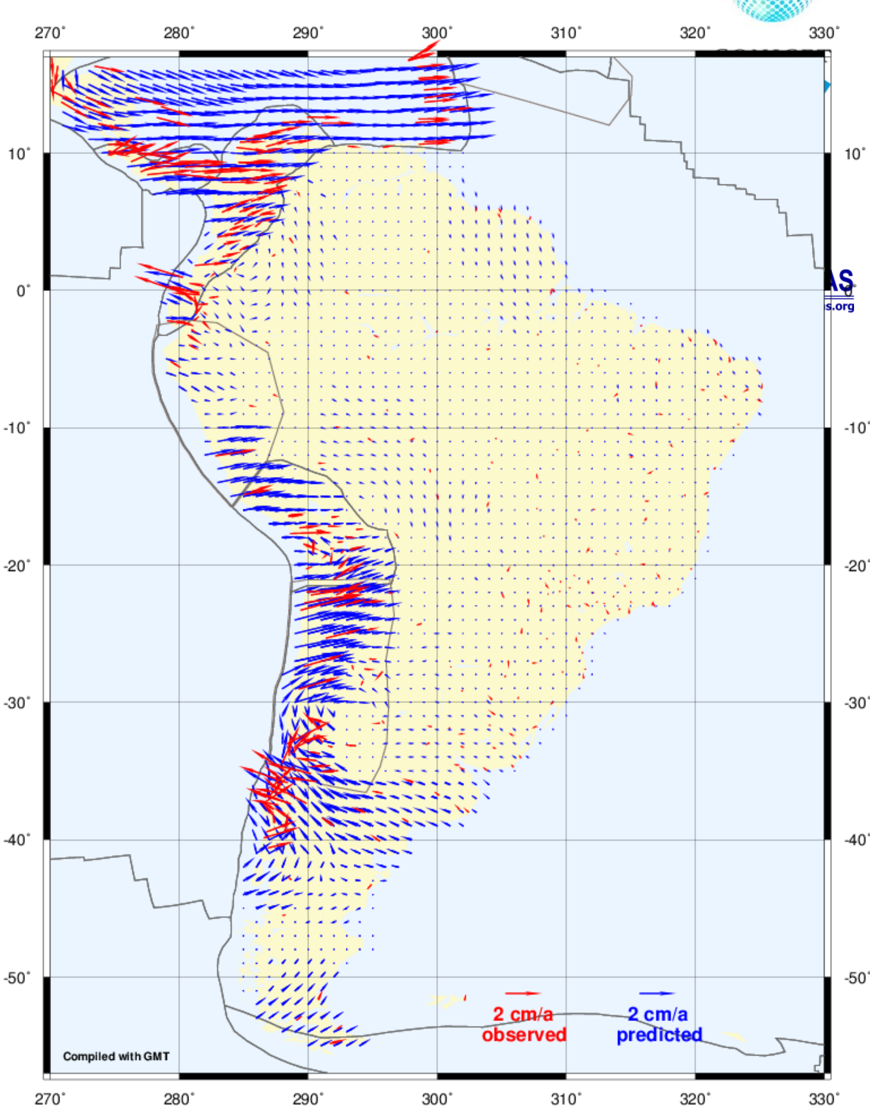


VEMOS2015 vs VEMOS2009

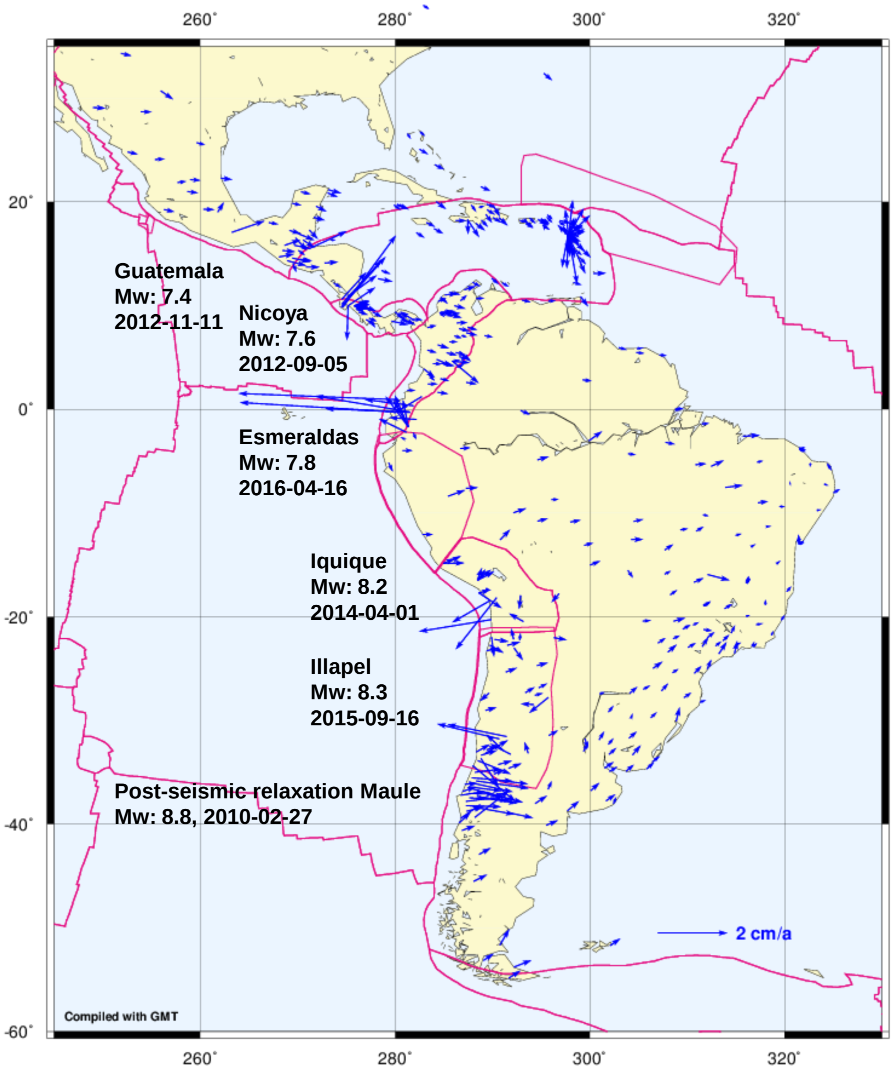


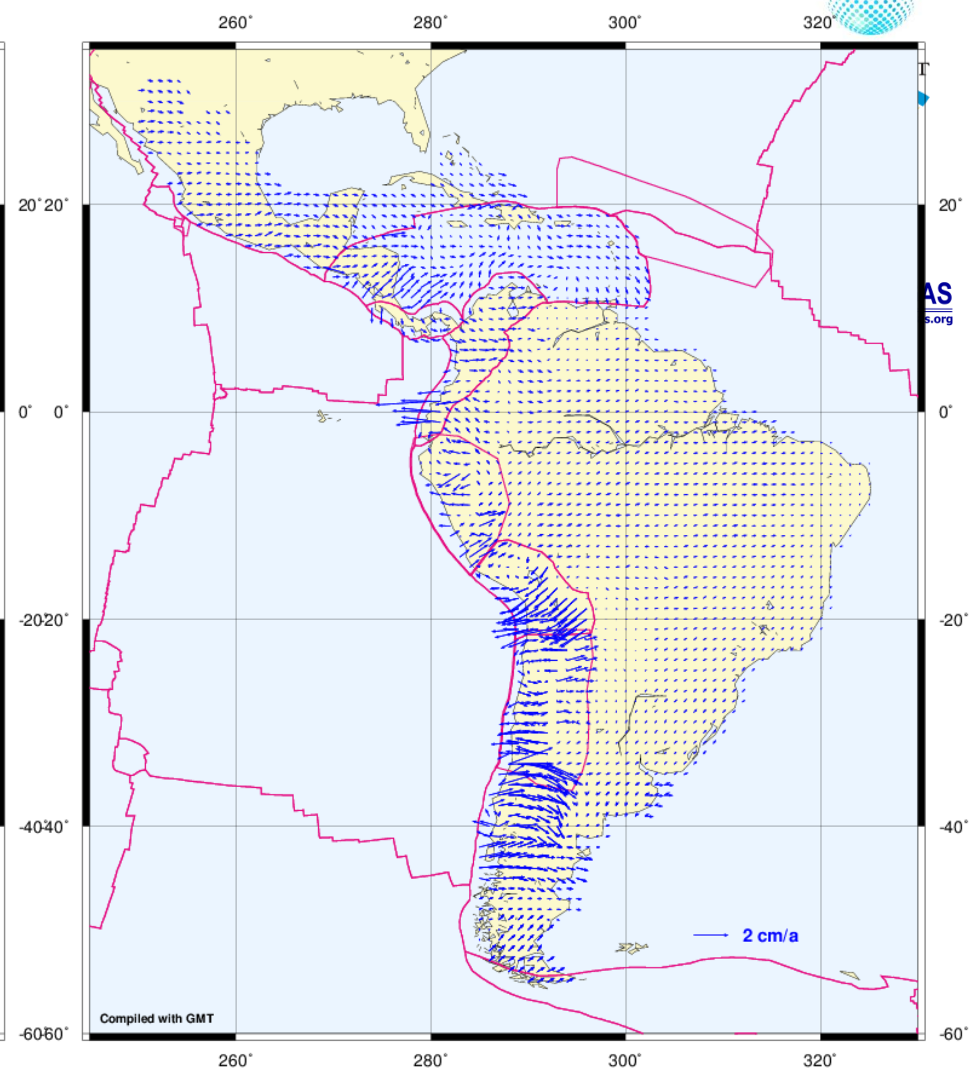
Surface kinematics and deformation model from January 2014 to January 2017: VEMOS2017





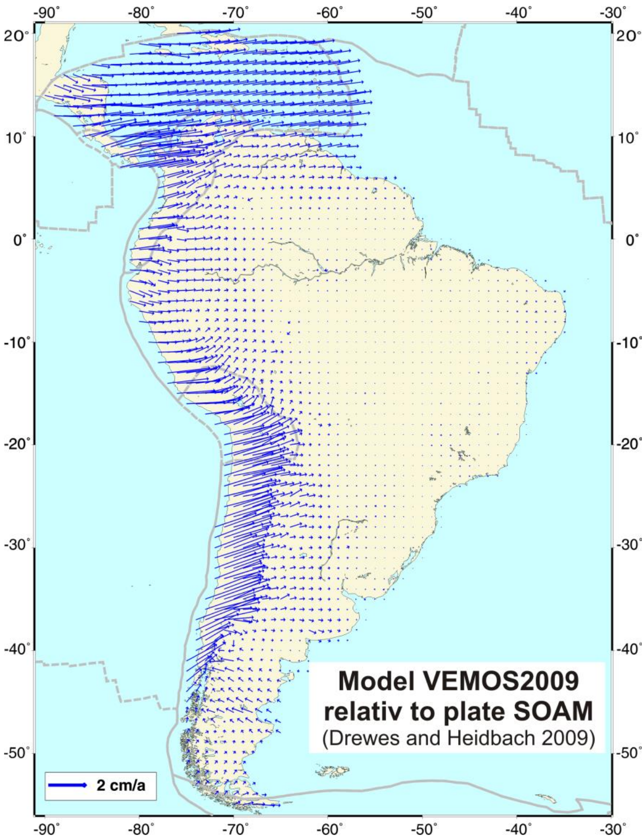
VEMOS2017 vs VEMOS2015



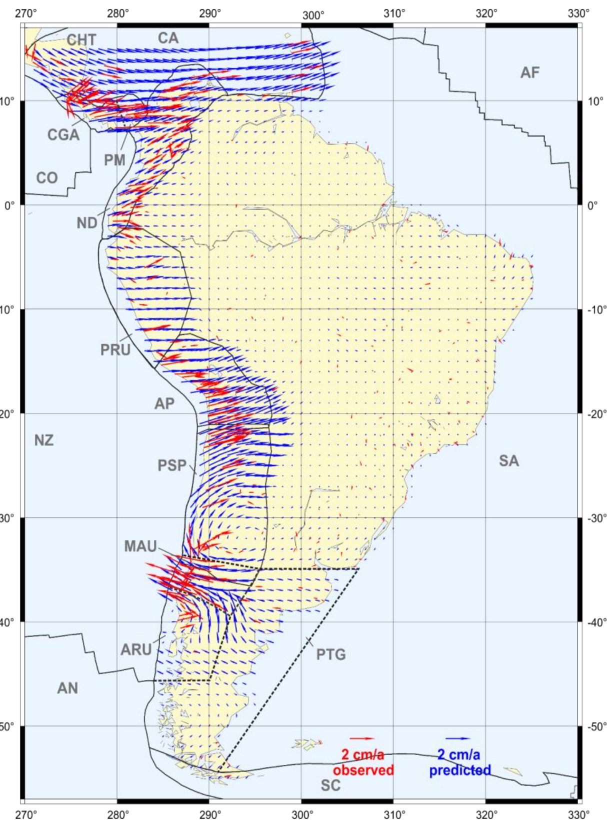


Recent surface deformation in Latin America

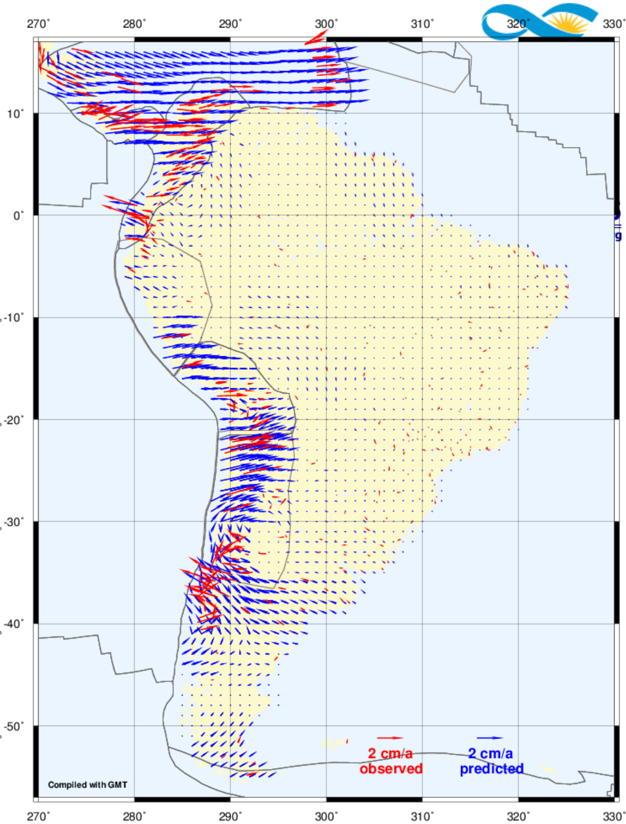
2000.0 ... 2009.6



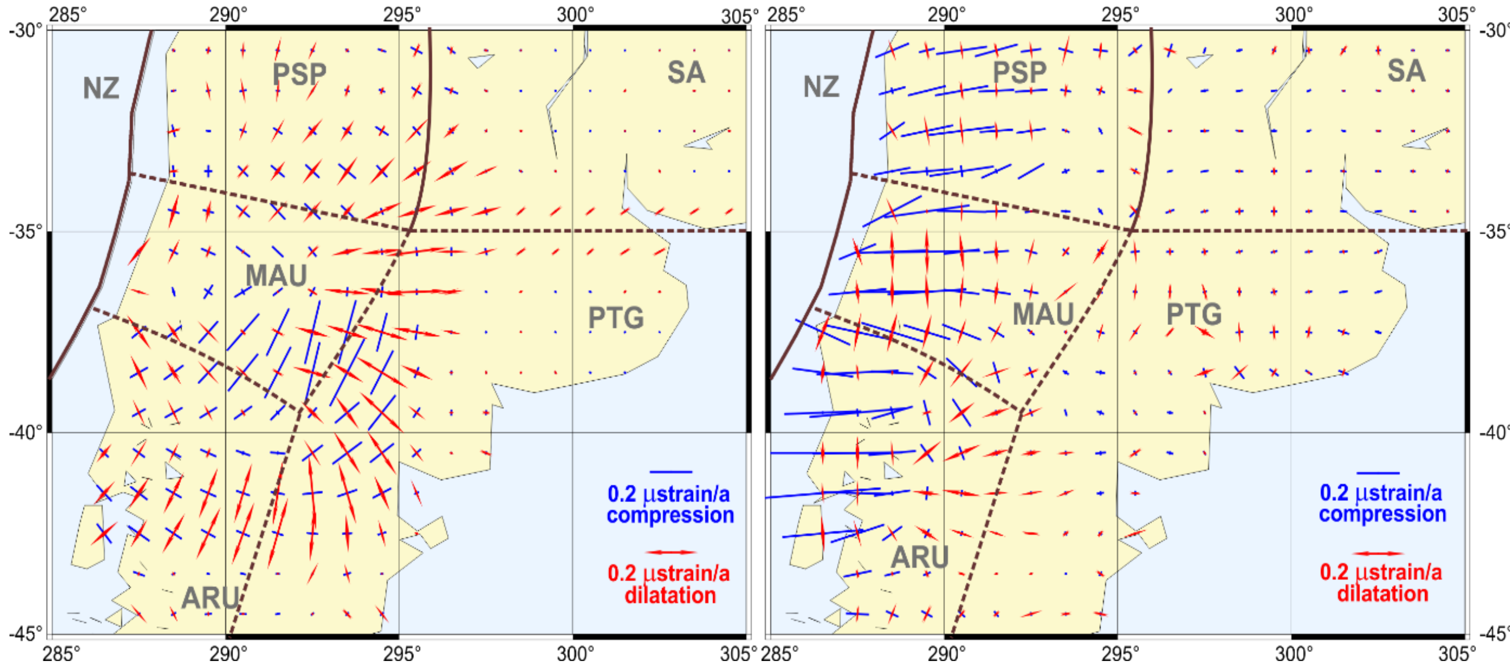
2010.2 (2012.2) ... 2015.2



2014.0 ... 2017.1



Strain field after (left) and before (right) the 2010 Maule earthquake



Before the earthquake:

- strong west-east compression (0.40 µstrain/a) between the latitudes 38°S and 44°S;
- extensional strain rates oriented in the north-south direction with magnitudes around 0.10 µstrain/a.

After the earthquake:

- maximum extensional strain rate (0.20 to 0.35 µstrain/a) southern of latitude 40°S;
- northern of latitude 35°S, the extension directed to the Maule zone (S45°W) with quite smaller rates (< 0.06 µstrain/a);
- largest compression (0.25 µstrain/a) in the boundary between Maule (MAU) and Patagonia (PTG) .

Closing remarks

- The modelled surface kinematics was inferred from GNSS velocities only; i.e. physical properties or dynamical environments were not included.
- Station velocities as well as the inferred deformation models represent the mean displacements (deformation) along the defined periods (VEMOS2009: 2010.0 to 2009.6; VEMOS2015: 2010.2 to 2015.2; VEMOS2017: 2014.0 to 2017.1)
- The tectonic settings in the Caribbean and Central America are founded on the combination of geophysical and geological interpretations/models with GNSS results.
- The deformation zones in the southern part of South America are defined in accordance with the geometry given by the GNSS station velocities obtained in this study.
- The deformation caused by the 2010 Maule earthquake extends up to latitude 45°S and to the Atlantic coast in Argentina. One could therefore conclude that the southern part of Patagonia is also deformable and does not belong to the stable part of the South American plate.
- The computation of the velocity field for SIRGAS has to be repeated until the velocities have come to a “normal” behaviour. This may take some more years.