Geodetic monitoring of the variable surface deformation in Latin America

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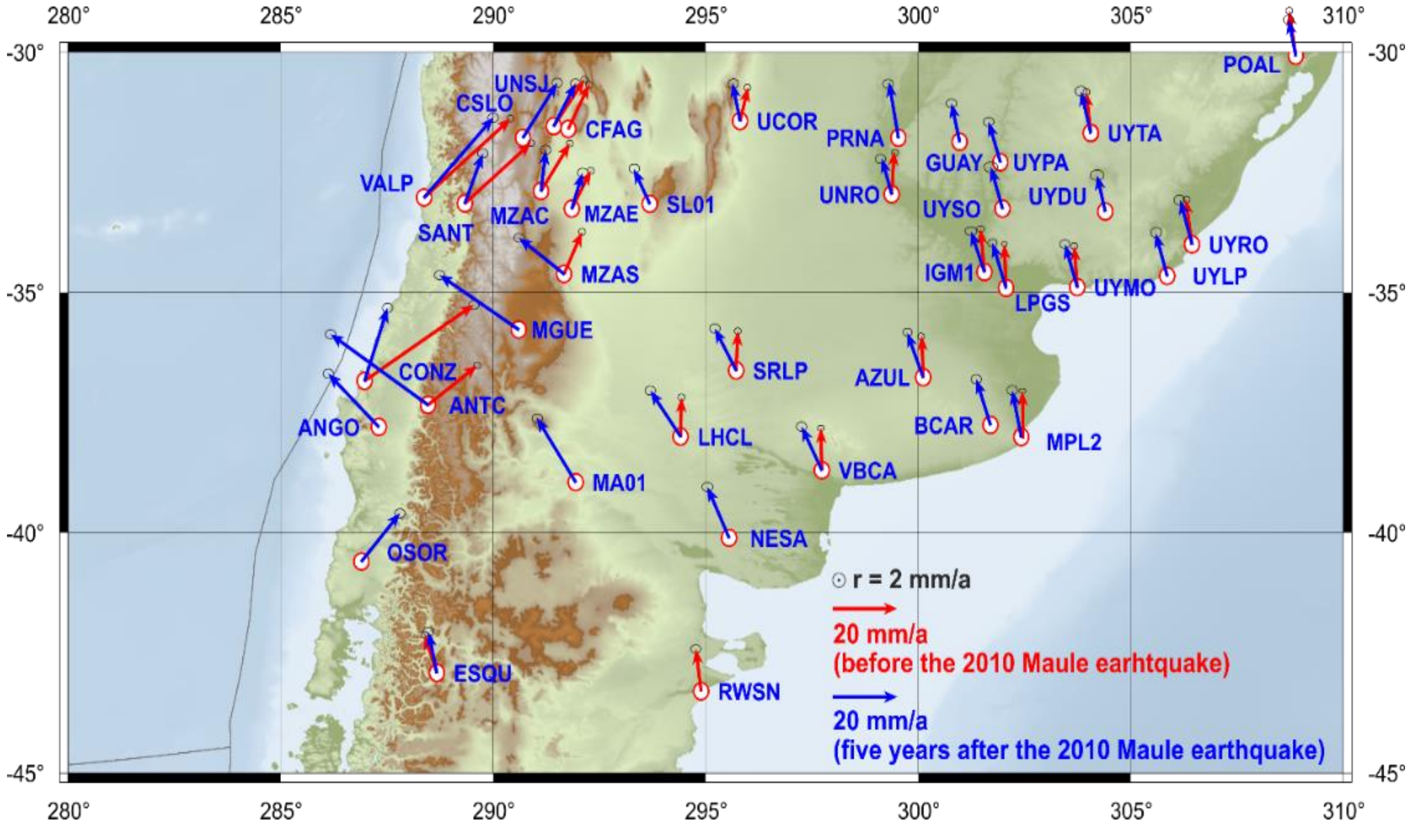
Motivation

Surface deformation models are the basis for computing coordinates of any point at any time from a time-dependent reference frame (positions and velocities). They must

- provide a high-spatial resolution in order to reflect all regional effects;
- consider regional deformation patterns and not only global (plate tectonic) models;
- be updated after any major abrupt deforming event (e.g. 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).

Tectonics in Latin America

Standard tectonic models distinguish plates and deformation zones (orogens).

Plates:

NA	N America	AF	Africa
RI	Rivera	CA	Caribbean
PM	Panama	ND	North Andes
CO	Cocos	GP	Galapagos
PA	Pacific	EA	Easter Island
NZ	Nazca	AP	Altiplano
SA	S America	JZ	Juan Fernandez
AN	Antarctica	SC	Scotia

Orogens:

GCN	Gorda-California-Nevada
PRU	Peru
PSP	Puna-Sierras Pampeanas
RCO	Rivera-Cocos
WCA	West Central Atlantic

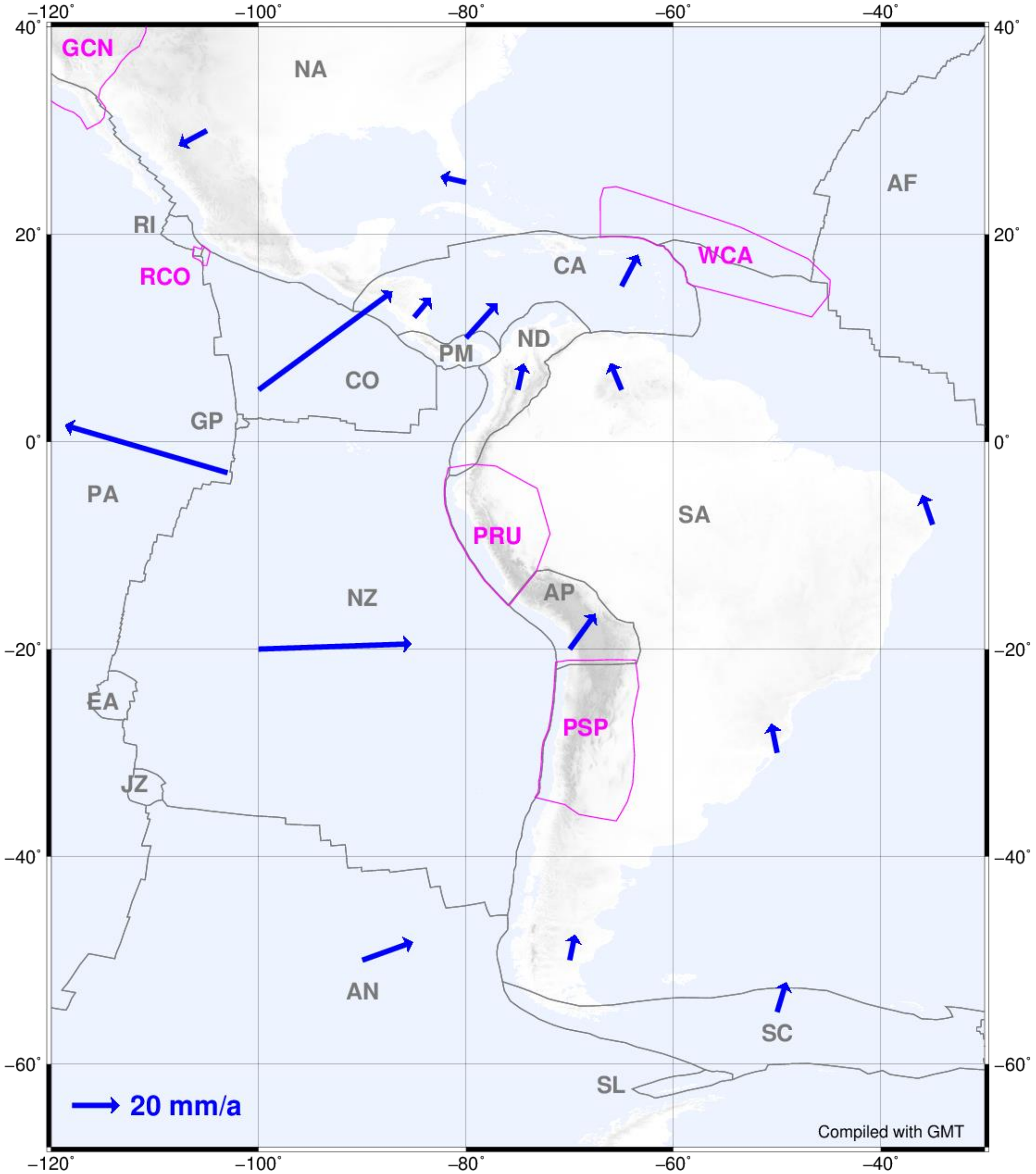
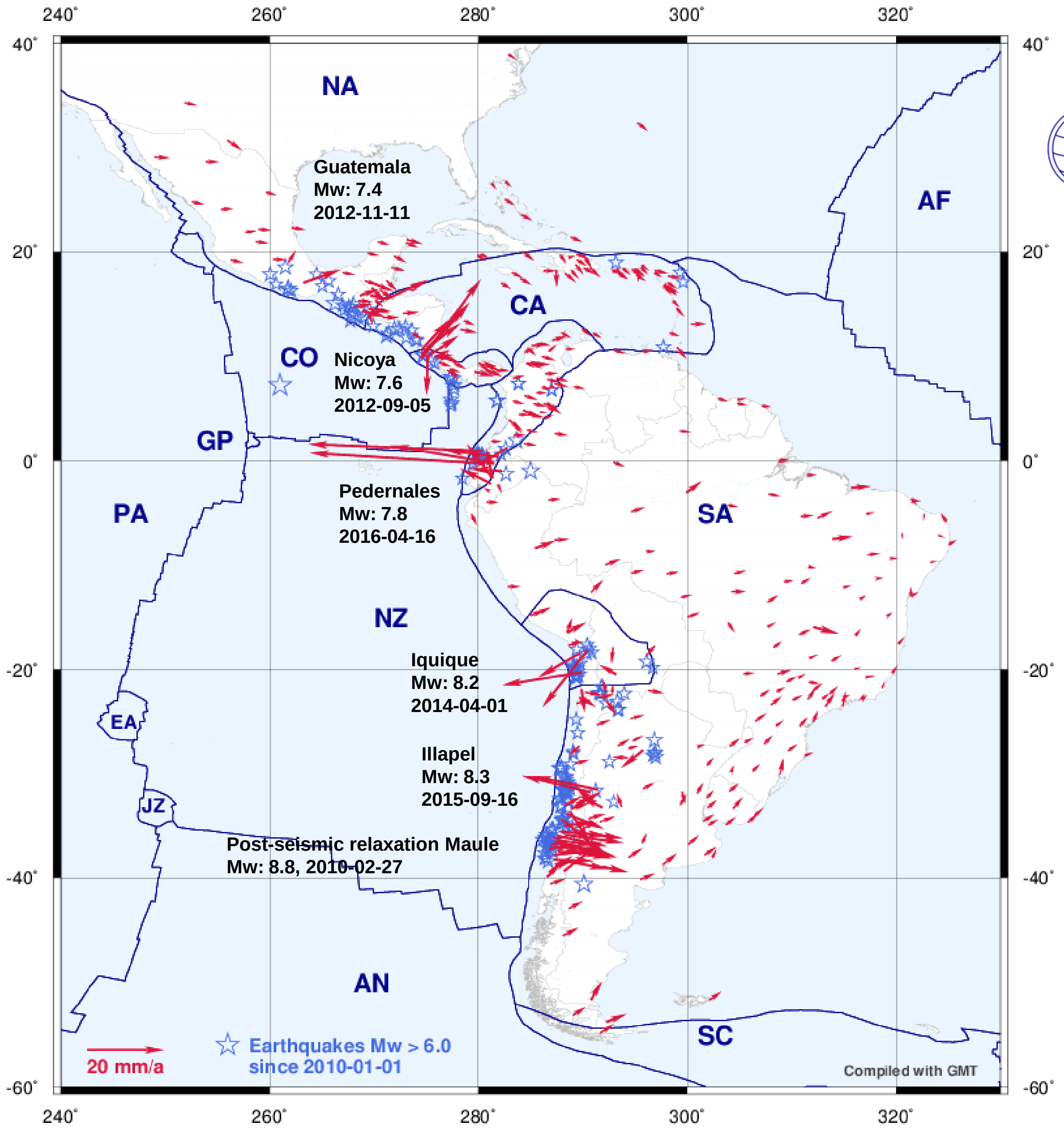


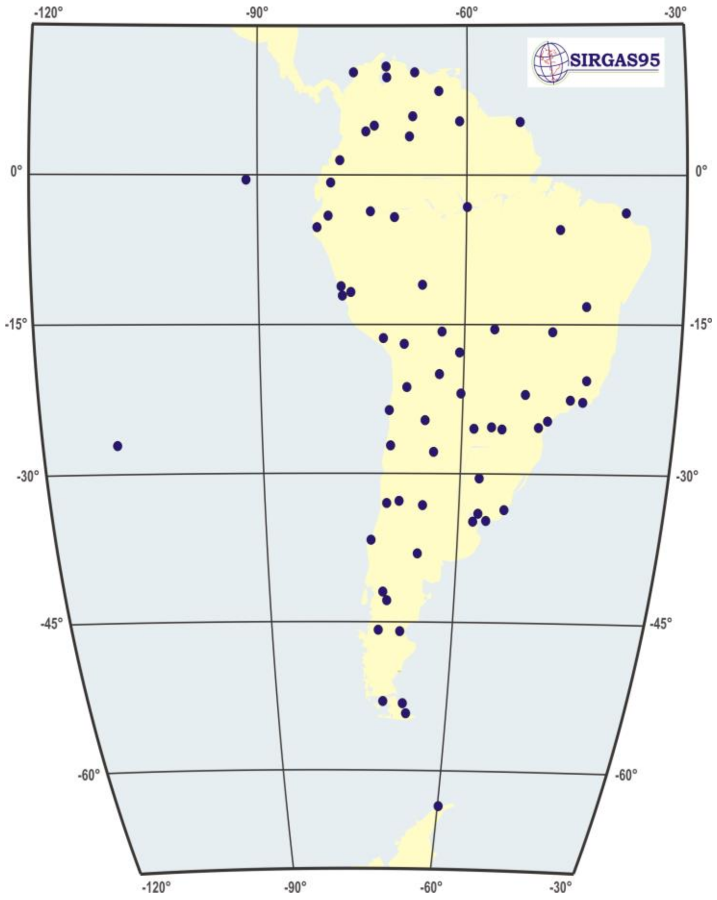
Plate boundaries and orogens after (Bird 2003); plate motions after (Drewes 2017)

Impact of strong earthquakes on geodetic reference stations

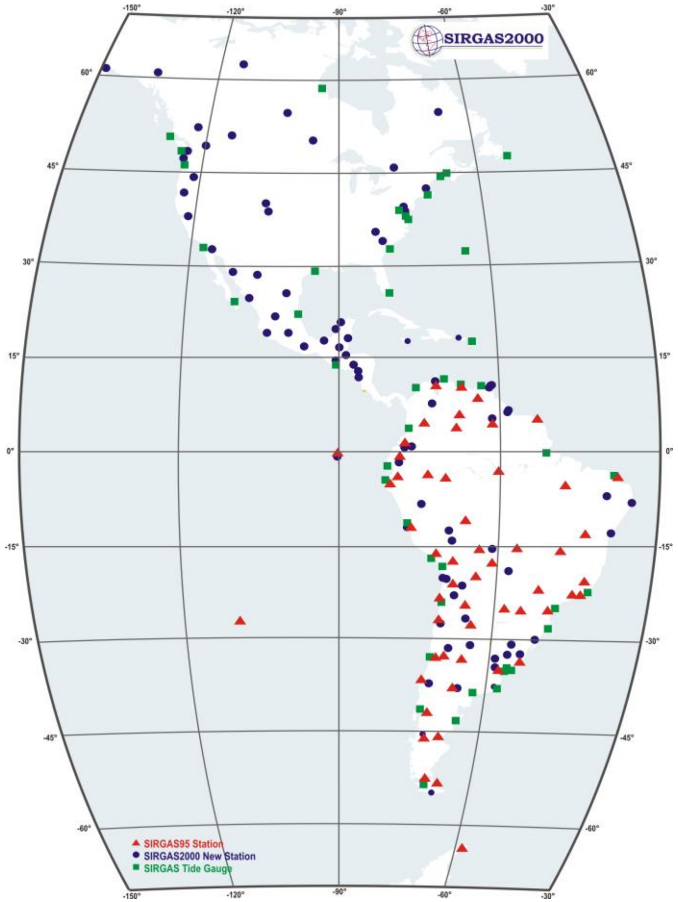
The interaction of these moving plates causes an extremely high seismic activity in this area, generating episodic station movements and deformations in the geodetic reference frames (like ITRF and its regional densification SIRGAS).



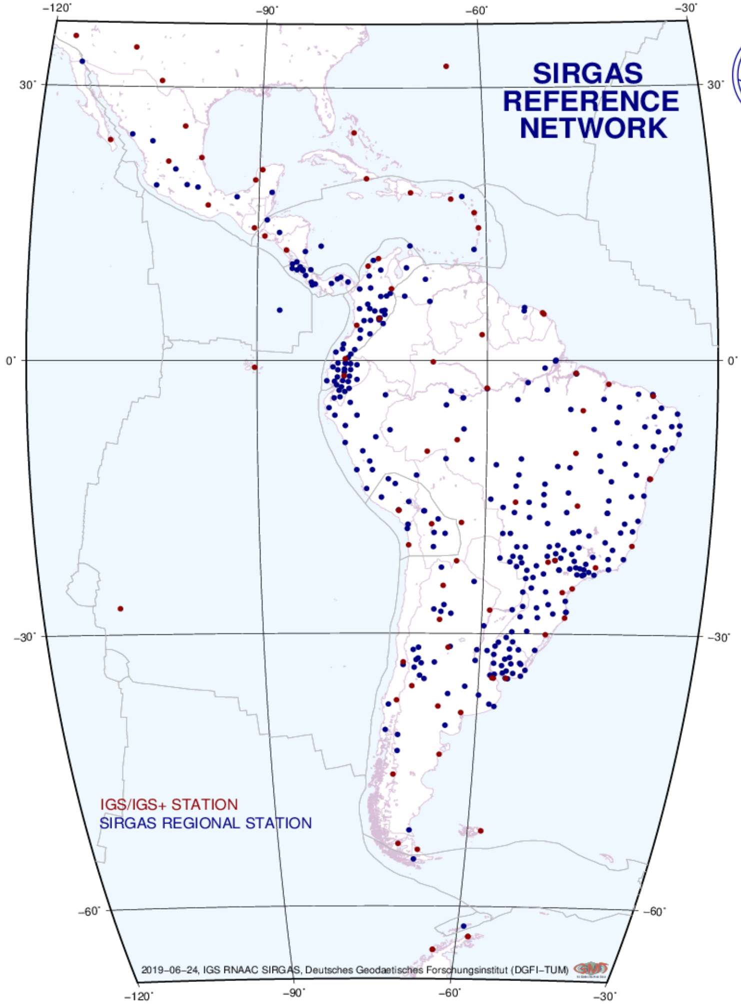
Geodetic reference frame in Latin America: SIRGAS



SIRGAS1995
GPS campaign
58 stations



SIRGAS2000
GPS campaign
184 stations



Today: ≈ 400 continuously operating GNSS (CO-GNSS) stations

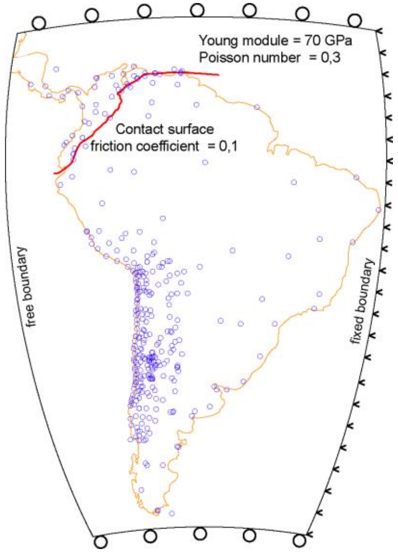
Geodetic surface deformation models for SIRGAS: VEMOS

To support the maintenance of the SIRGAS reference frame, surface deformation models are regularly computed. New versions are released only when strong changes are detected.

- VEMOS2003 (Drewes and Heidbach, 2005)
  - 329 input station velocities (campaigns and continuously operating GPS stations)
  - Finite Element Model (FEM) and Least-Squares Collocation (LSC)
  - Time span: 1993.0 to 2002.0
- VEMOS2009 (Drewes and Heidbach, 2012)
  - 496 input station velocities (campaigns and continuously operating GPS stations)
  - FEM and LSC
  - Time span: 2000.0 to 2009.6
- VEMOS2015 (Sánchez and Drewes, 2016)
  - 456 input station velocities (continuously operating GNSS stations only)
  - LSC
  - Time span: 2010.2 to 2015.2
- VEMOS2017 (Drewes and Sánchez, 2017)
  - 500 input station velocities (continuously operating GNSS stations only)
  - LSC
  - Time span: 2014.0 to 2017.1

Modelling surface deformation using FEM and LSC

Finite Element Model (FEM)



- Homogeneous isotropic elastic (Hooke) material

  $\varepsilon_N = 1/E\ (\sigma_N - \nu\sigma_E)$

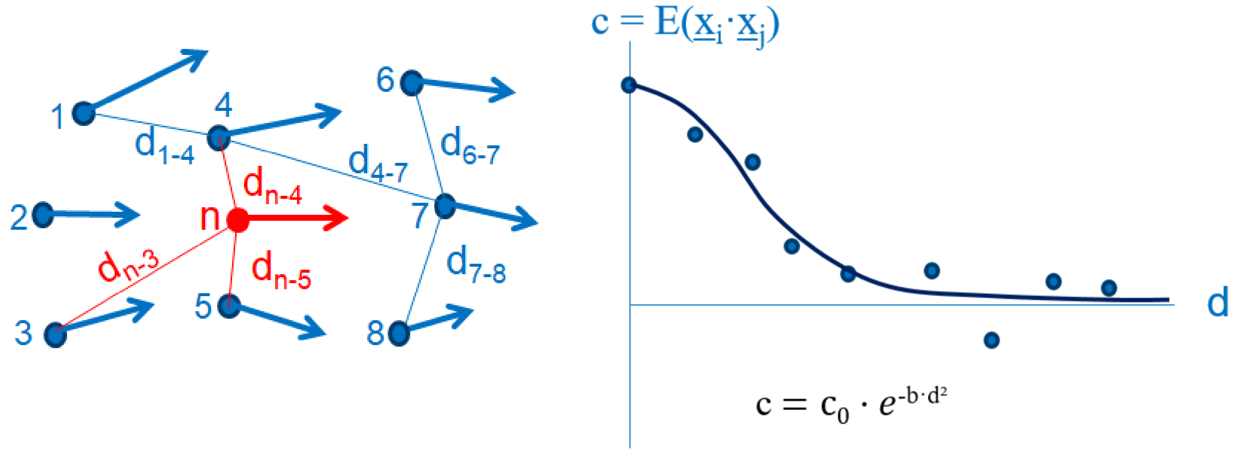
  $\varepsilon_E = 1/E\ (\sigma_E - \nu\sigma_N)$

  Young modulus E = 70 GPa

  Poisson number v= 0.25

- Linear elements adopted to geographical station distribution (500,000)
- Constraints: Geodetically observed station velocities

Least-squares Collocation (LSC)



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

$\underline{\mathbf{v}}_{pred}$ = predicted velocities in a regular grid

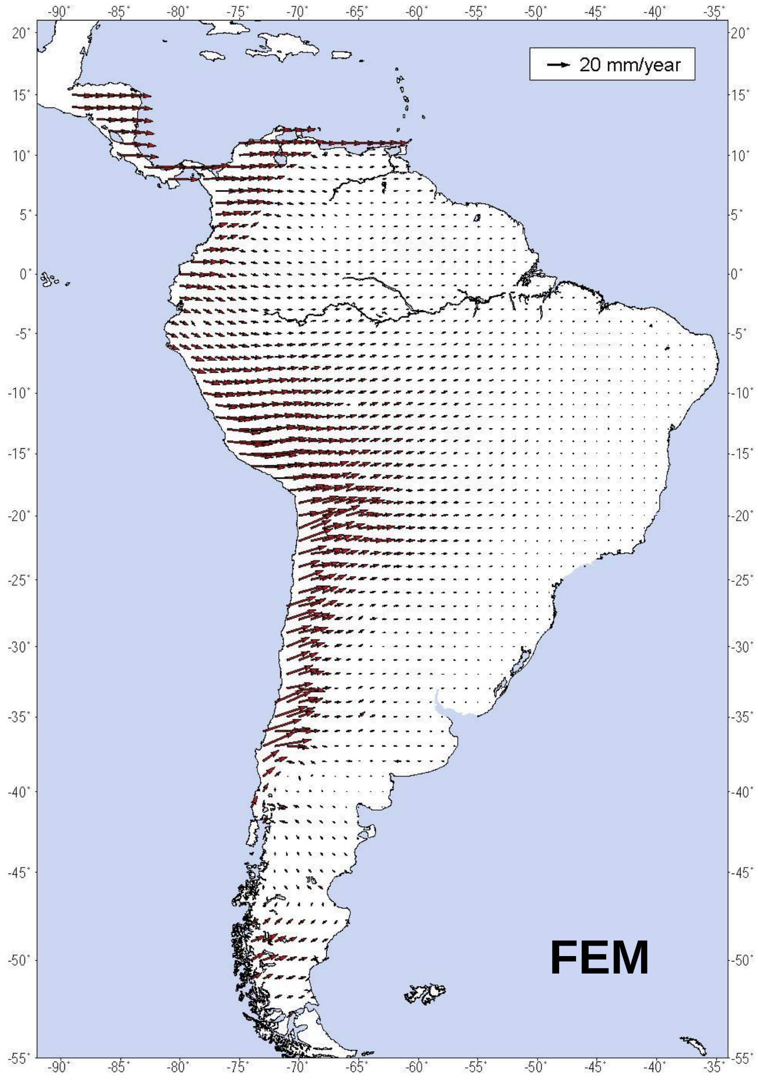
$\underline{\mathbf{v}}_{obs}$ = observed velocities at geodetic stations

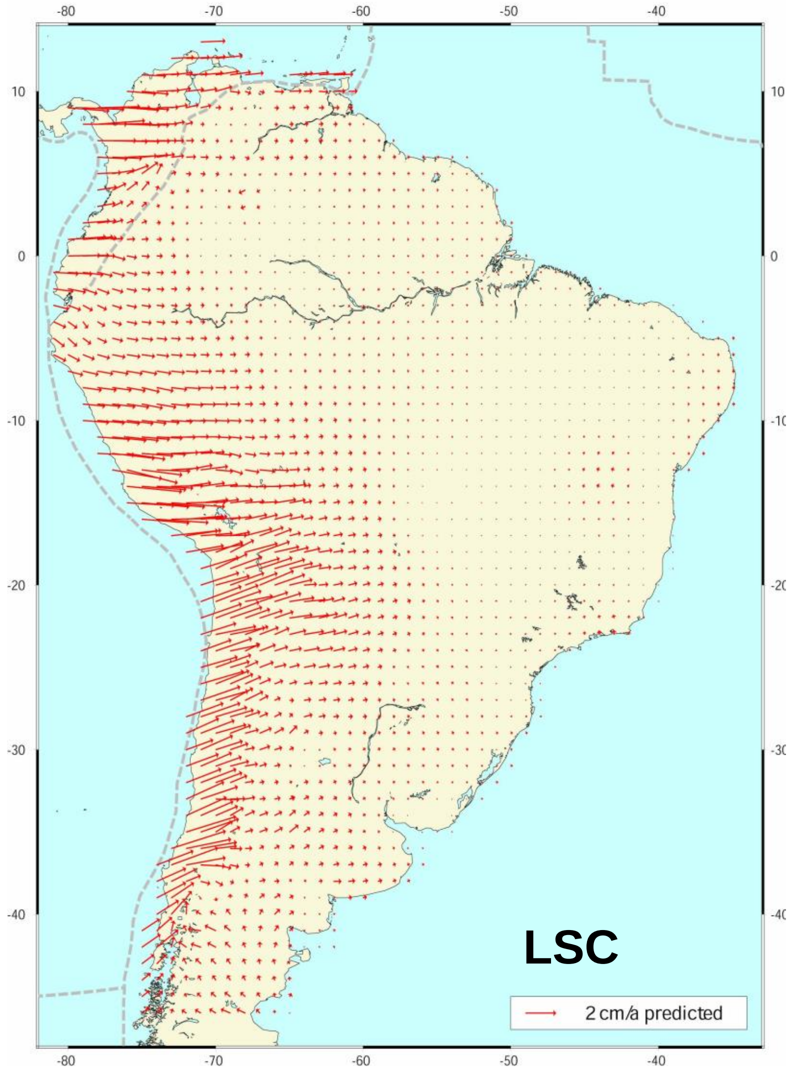
$\underline{\mathbf{C}}_{new}$= correlation matrix between predicted and observed vectors

$\underline{\mathbf{C}}_{obs}$= correlation matrix between observedvectors

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

VEMOS2003 [1993.0 to 2002.0]

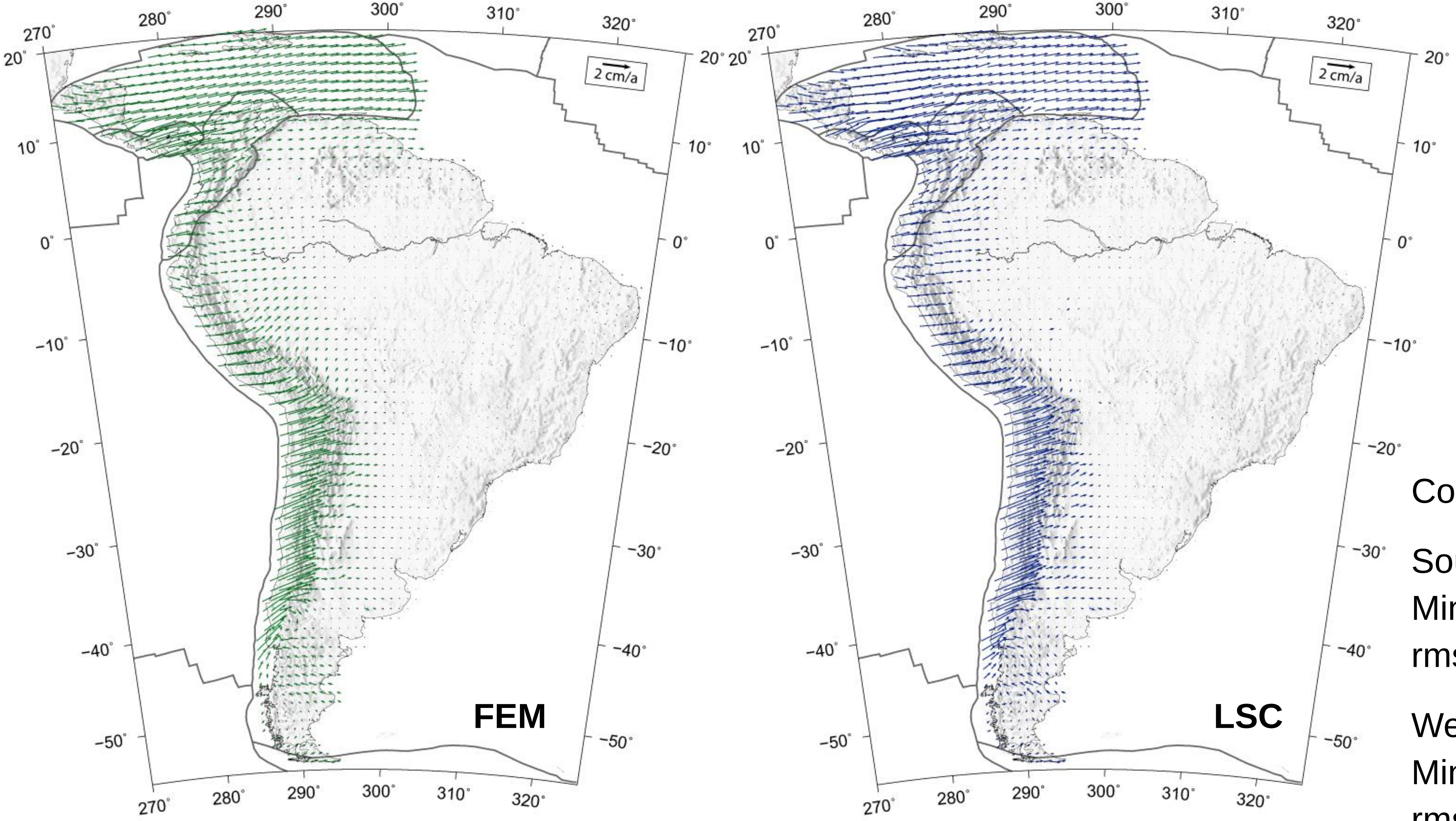




Comparison LSC-FEM:

- South – North: ± 1,0 mm/a
- West – East: ± 1,7 mm/a

VEMOS2009 [2000.0 to 2009.6]

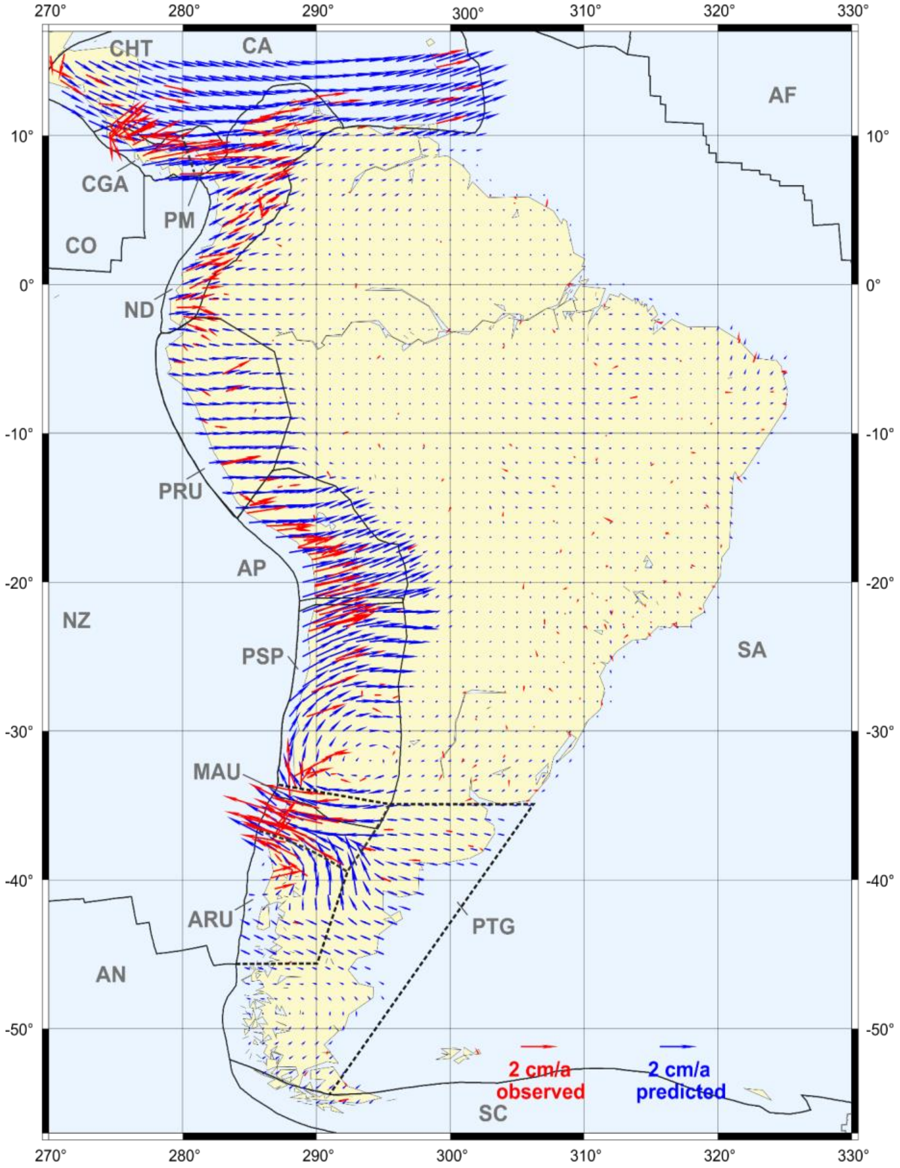


Comparison LSC-FEM:

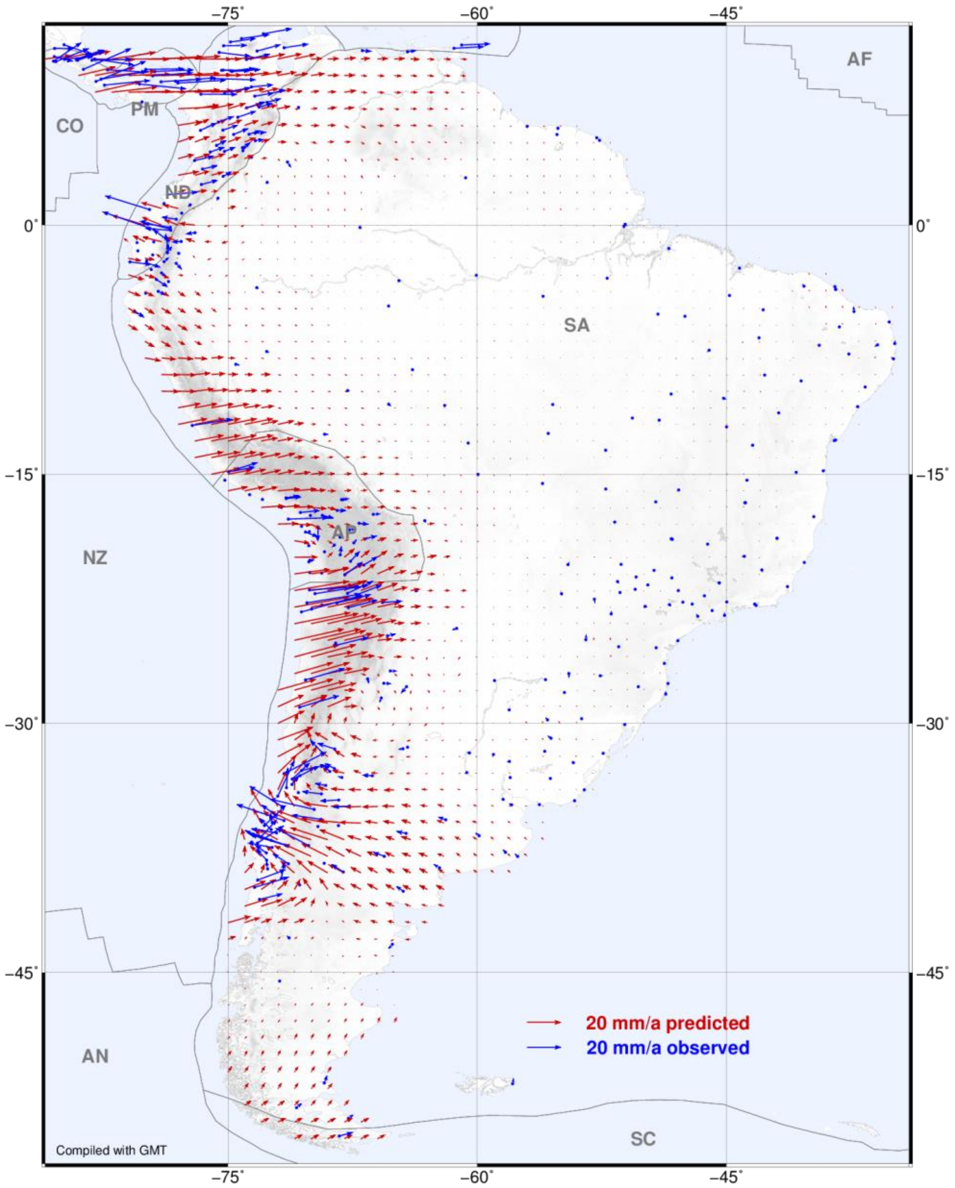
South – North:
Min./max.: - 5 … 3,5 mm/a
rms: ± 0,8 mm/a

West – East:
Min./max.: - 6 … 6,3 mm/a
rms: ± 1,4 mm/a

VEMOS2015 [2010.2 to 2015.2]



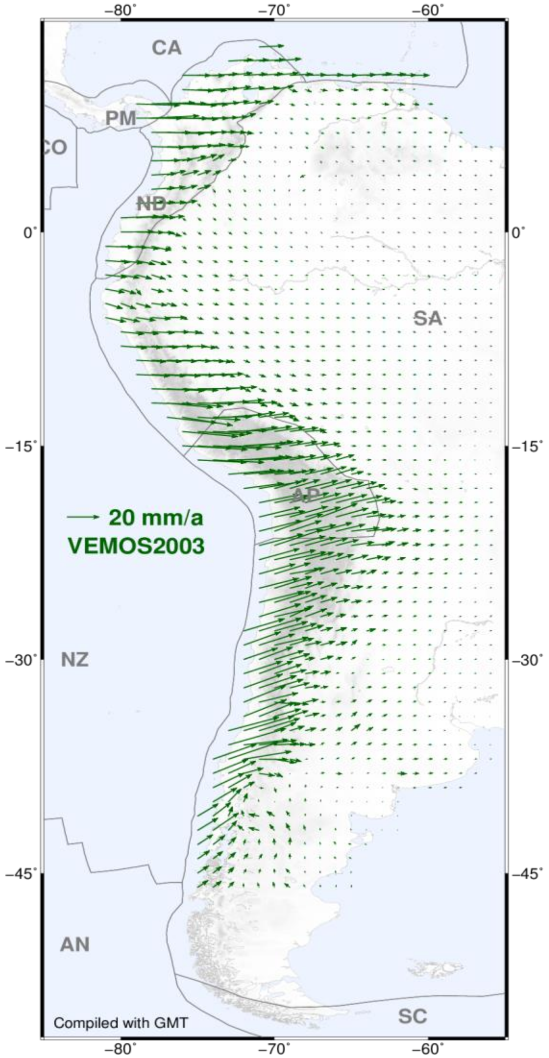
VEMOS2017 [2014.0 to 2017.1]



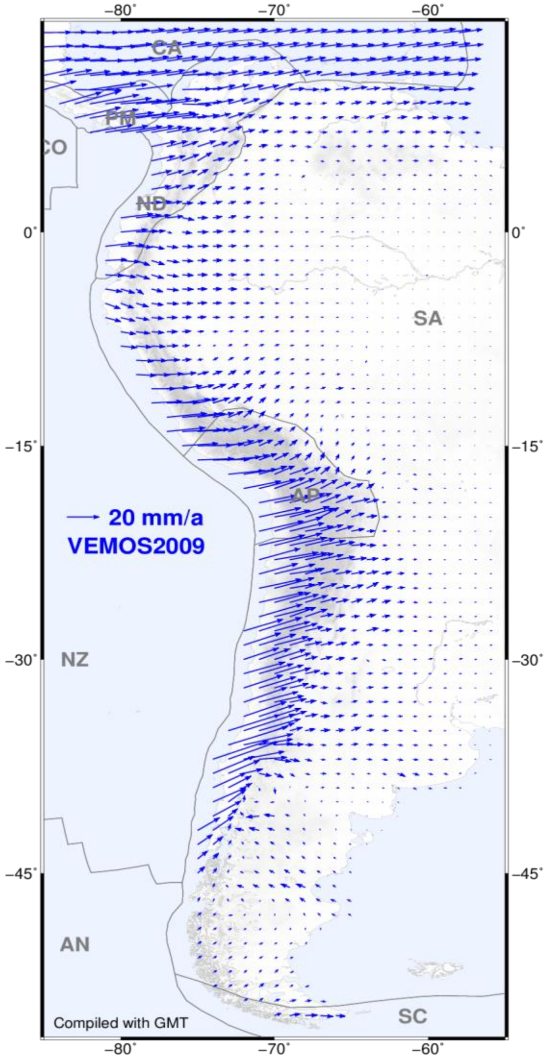
SIRGAS
www.sirgas.org

Deformation model series in Latin America

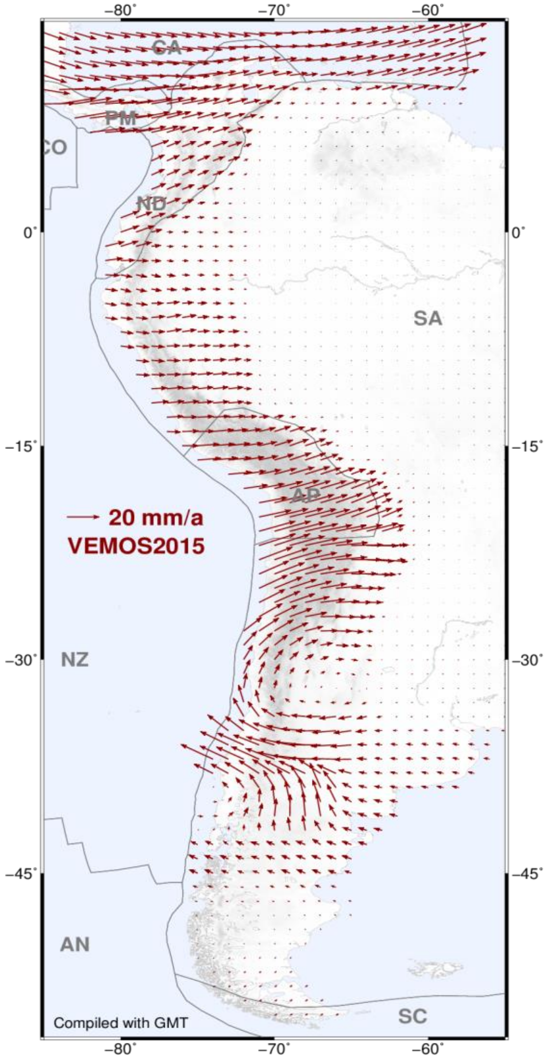
VEMOS2003
[1993.0 to 2002.0]



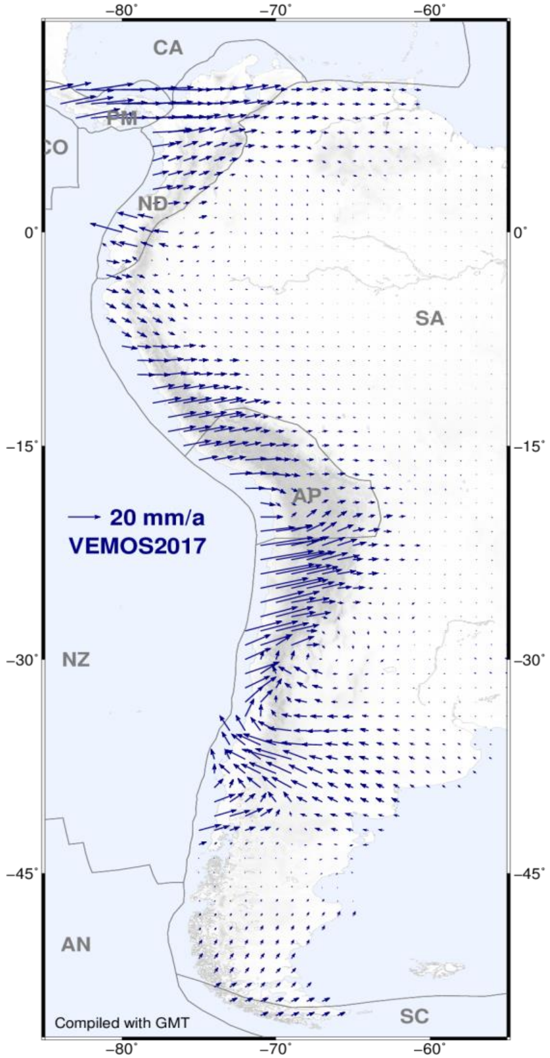
VEMOS2009
[2000.0 to 2009.6]



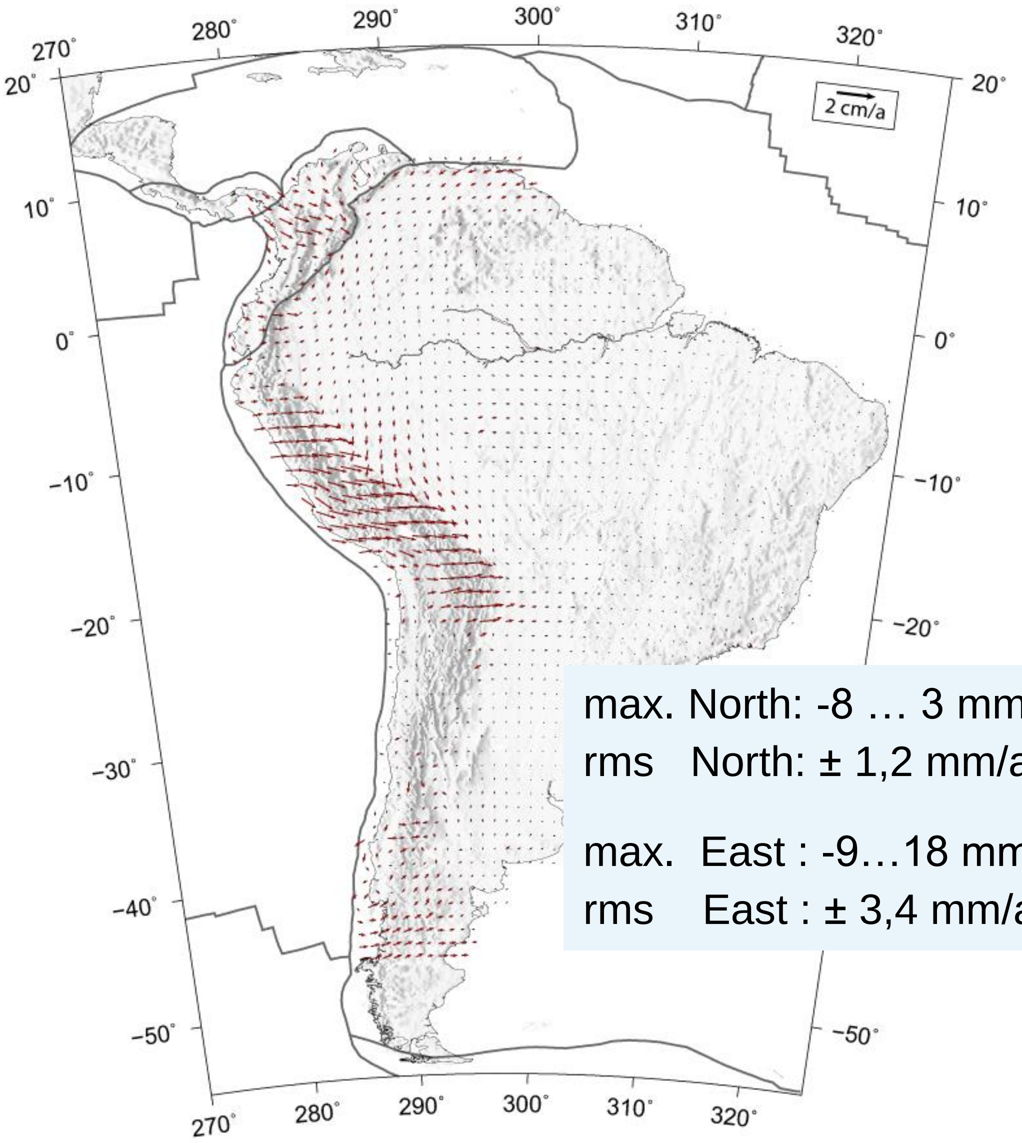
VEMOS2015
[2010.2 to 2015.2]



VEMOS2017
[2014.0 to 2017.1]



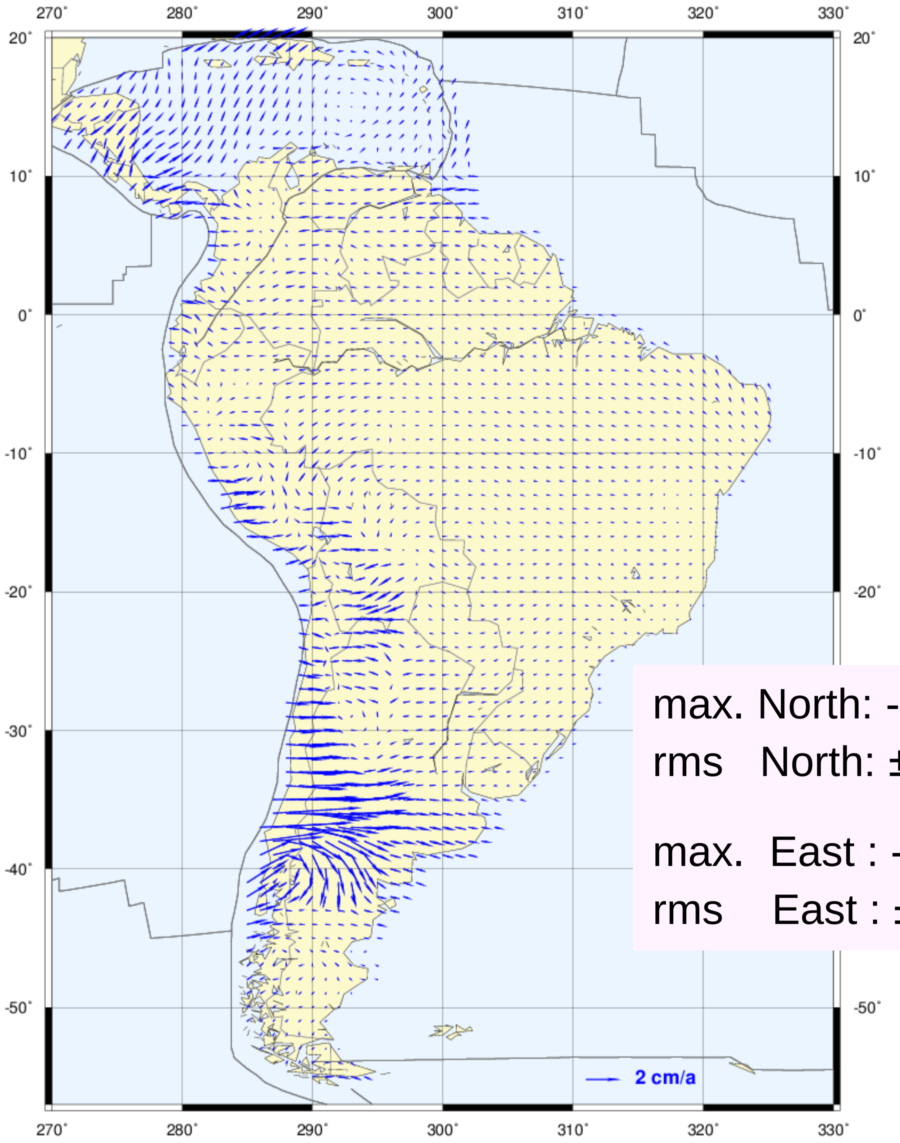
VEMOS2009 [2000.0 to 2009.6] minus VEMOS2003 [1993.0 to 2002.0]



max. North: -8 … 3 mm/a
rms North: ± 1,2 mm/a

max. East : -9…18 mm/a
rms East : ± 3,4 mm/a

VEMOS2015 [2010.2 to 2015.2] minus VEMOS2009 [2000.0 to 2009.6]



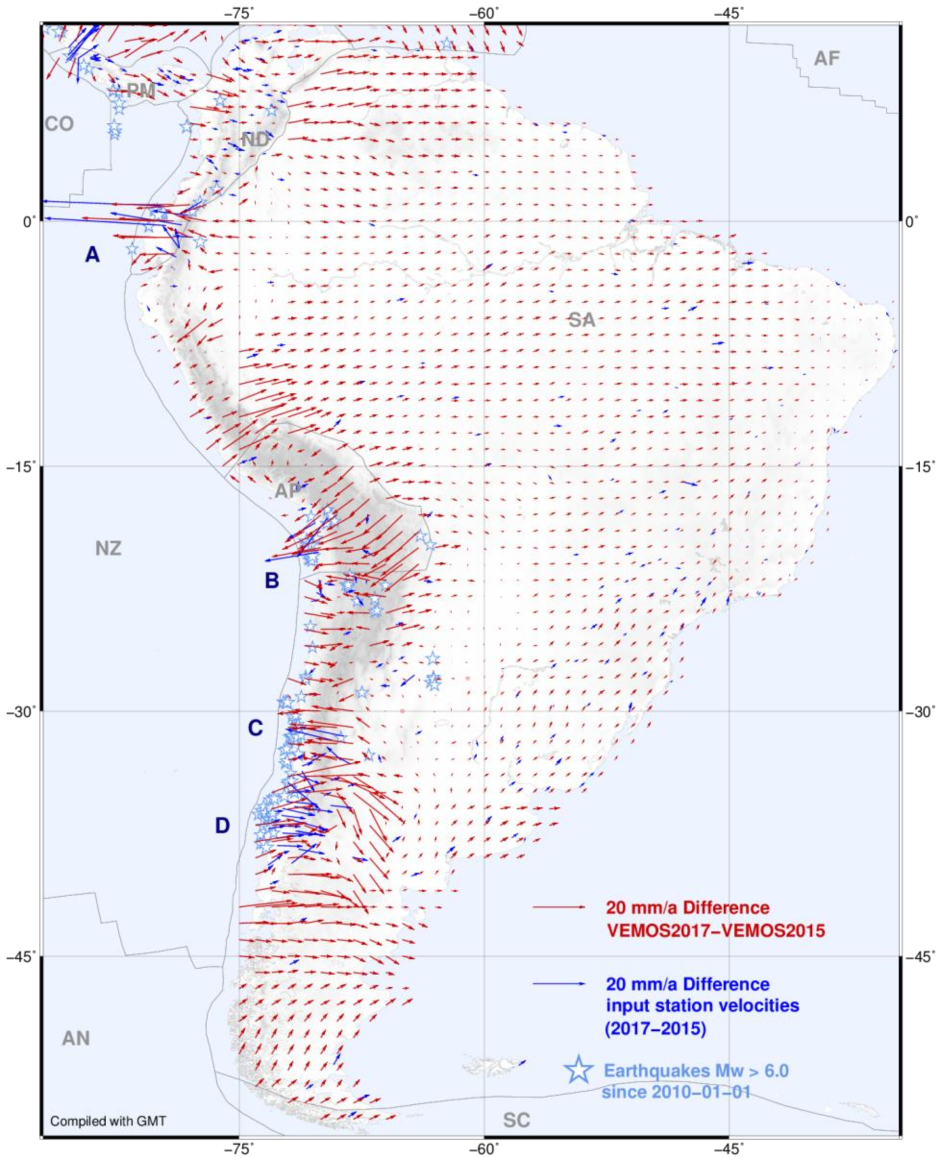
max. North: -16 … 10 mm/a
rms North: ± 2,3 mm/a

max. East : -14…54 mm/a
rms East : ± 5.2 mm/a

VEMOS2017
[2014.0 to 2017.1]

minus

VEMOS2015
[2010.2 to 2015.2]

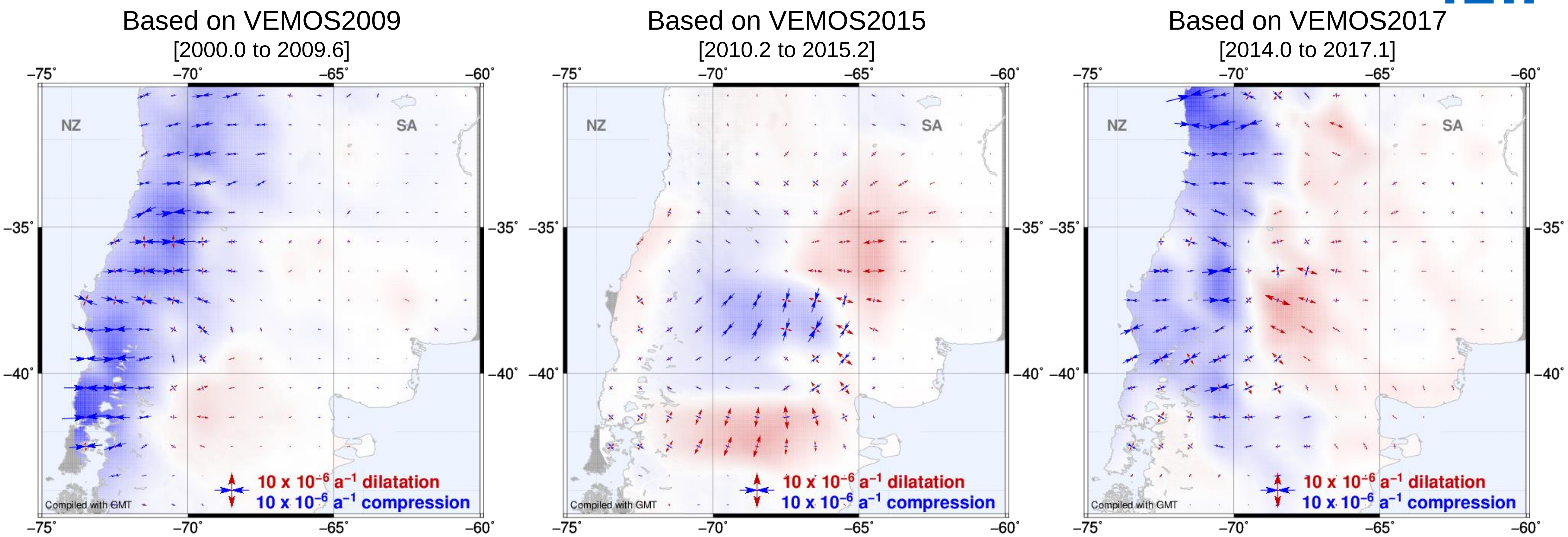


max. North: -10 … 9 mm/a
rms North: ± 1,1 mm/a

max. East : -29…28 mm/a
rms East : ± 2,3 mm/a

A. Pedernales Mw7.8, Apr 16, 2016
B. Pisagua Mw8.2, Apr 1, 2014,
C. Illapel Mw8.3, Sep 16, 2015,
D. Maule Mw8.8, Feb 27, 2010.

Strain field series in the South Andes



Before the Maule earthquake:

– strong west-east compression between the latitudes 38°S and 44°S;

– extensional strain rates in the north-south direction.

After the Maule earthquake:

– maximum extensional strain rate south of latitude 40°S;

– north of 35°S extension to Maule zone (S45°W) with smaller rates;

– largest compression between Maule and Patagonia; it returns to the *usual* motion.

Closing remarks

- The surface deformation models VEMOS are inferred from GNSS velocities only; i.e. physical properties or dynamical environments are not included.
- For the prediction of the deformation vectors, the boundaries of the major plates are considered before the interpolation. In deformation zones (e.g. the Andes, Central America), we assume a continuous lithosphere deforming under the kinematic conditions imposed by the GNSS station velocities.
- 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.
- 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 computation of the velocity model for SIRGAS (VEMOS) has to be repeated until the velocities have come to a “normal” behaviour. This may take some more years.