Deformation pattern of the Western Alps from two decades of campaign and permanent GNSS measurements

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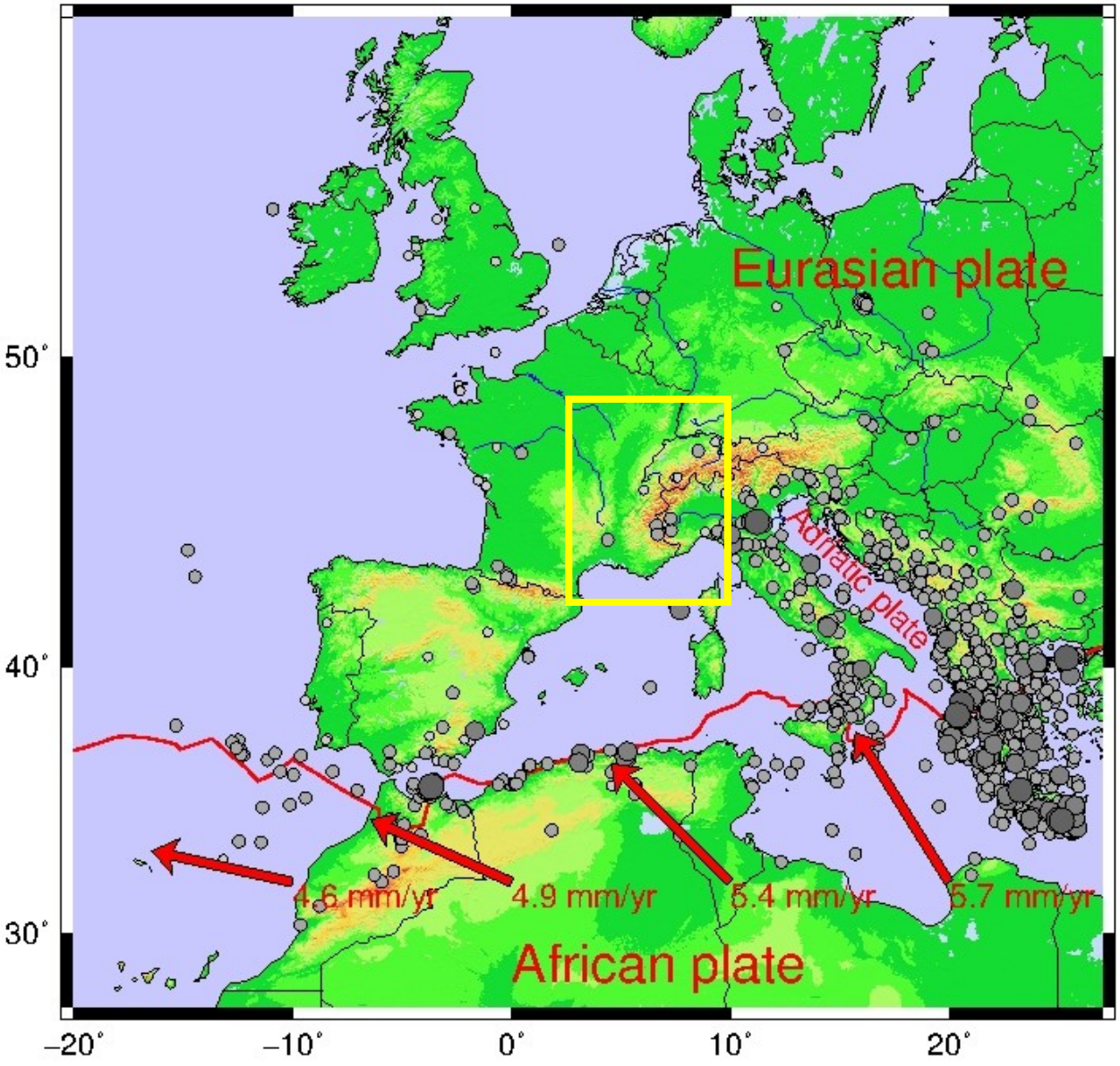
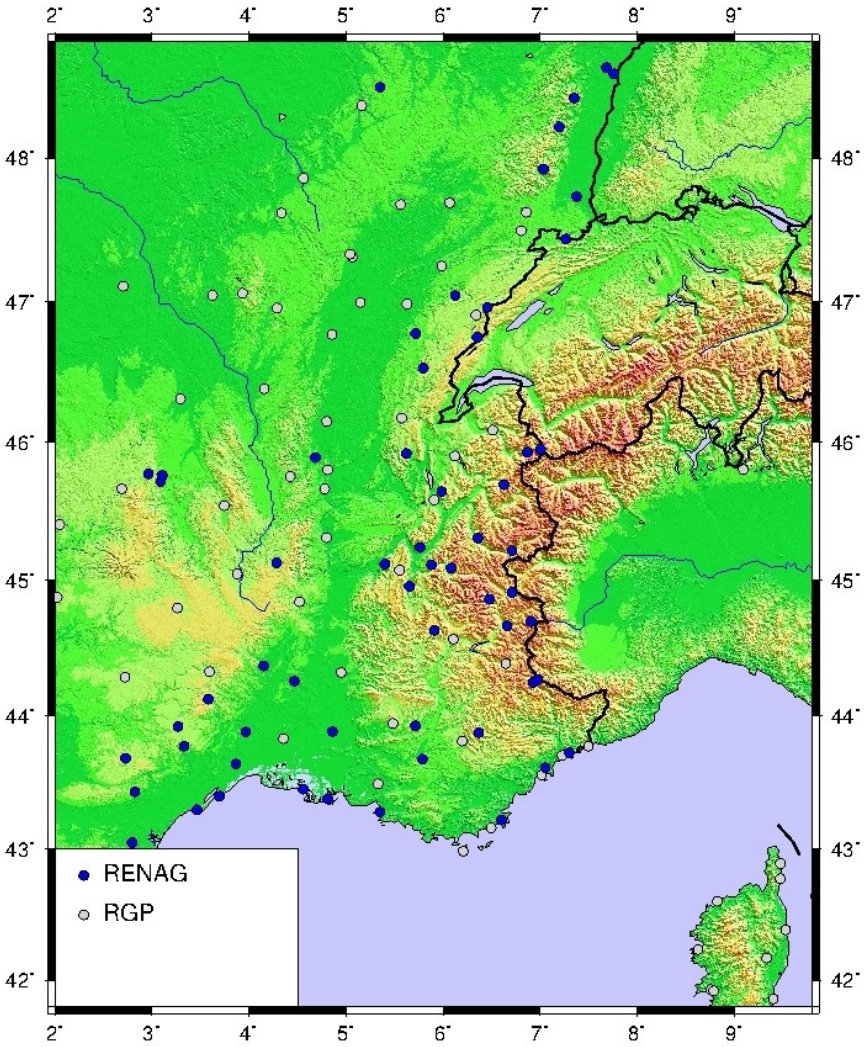
Western Alps: Tectonic settings and seismicity

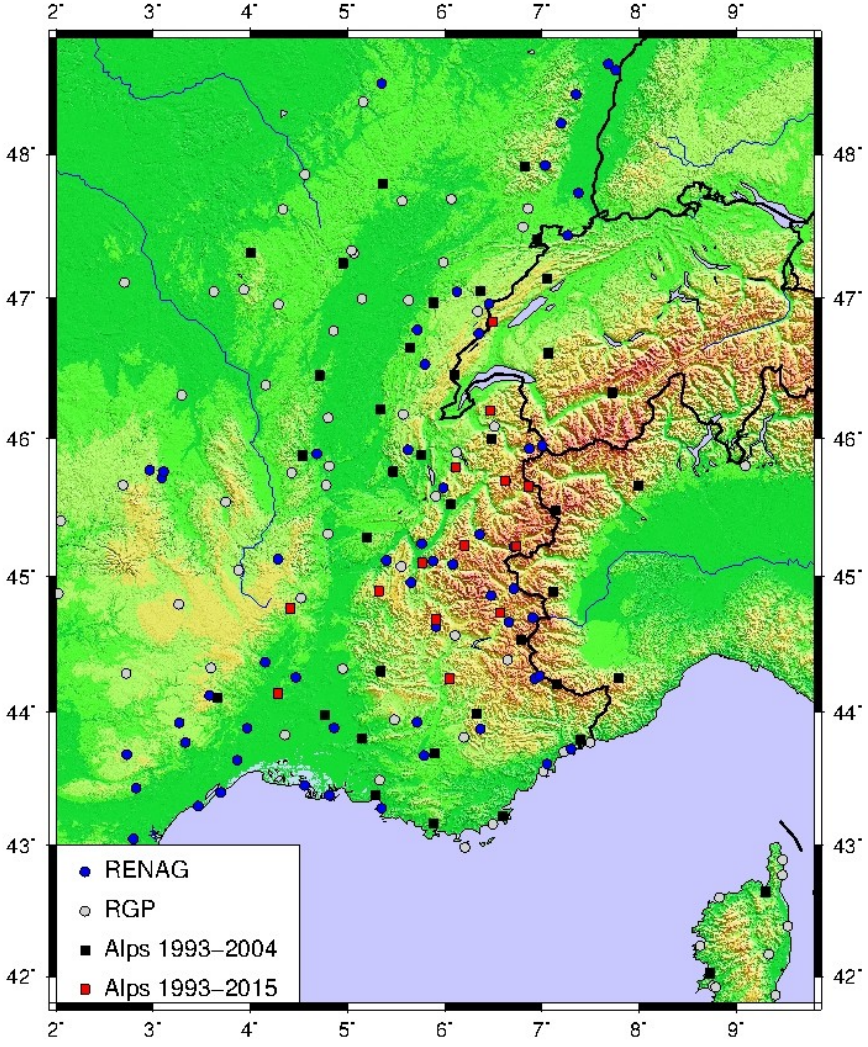


USGS seismicity > M=2.5
2011-2016

Plate velocities from
Serpelloni et al., 2011

Western Alps: GPS data

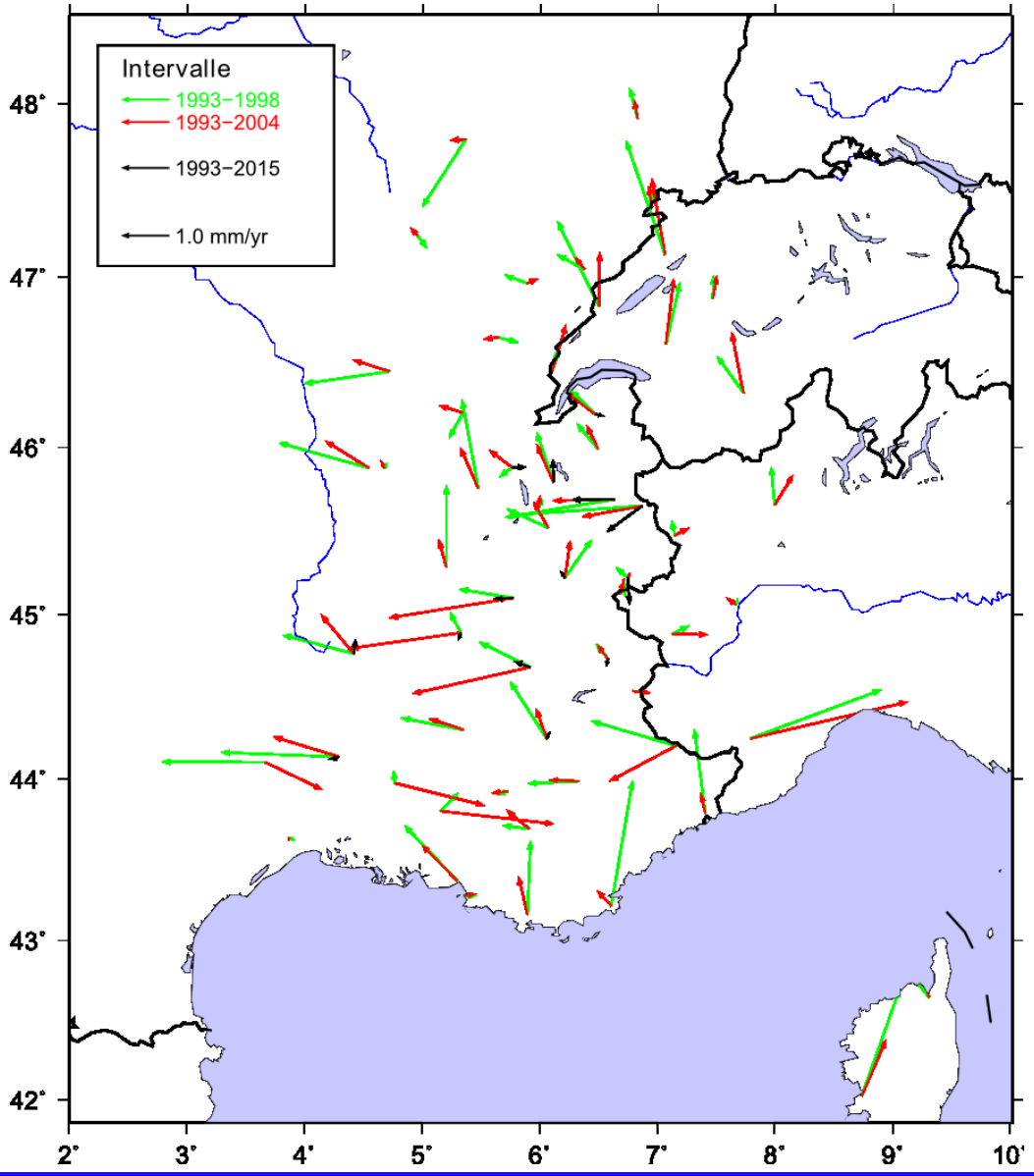




http://renag.resif.fr
http://rgp.ign.fr

Vigny et al., 2002

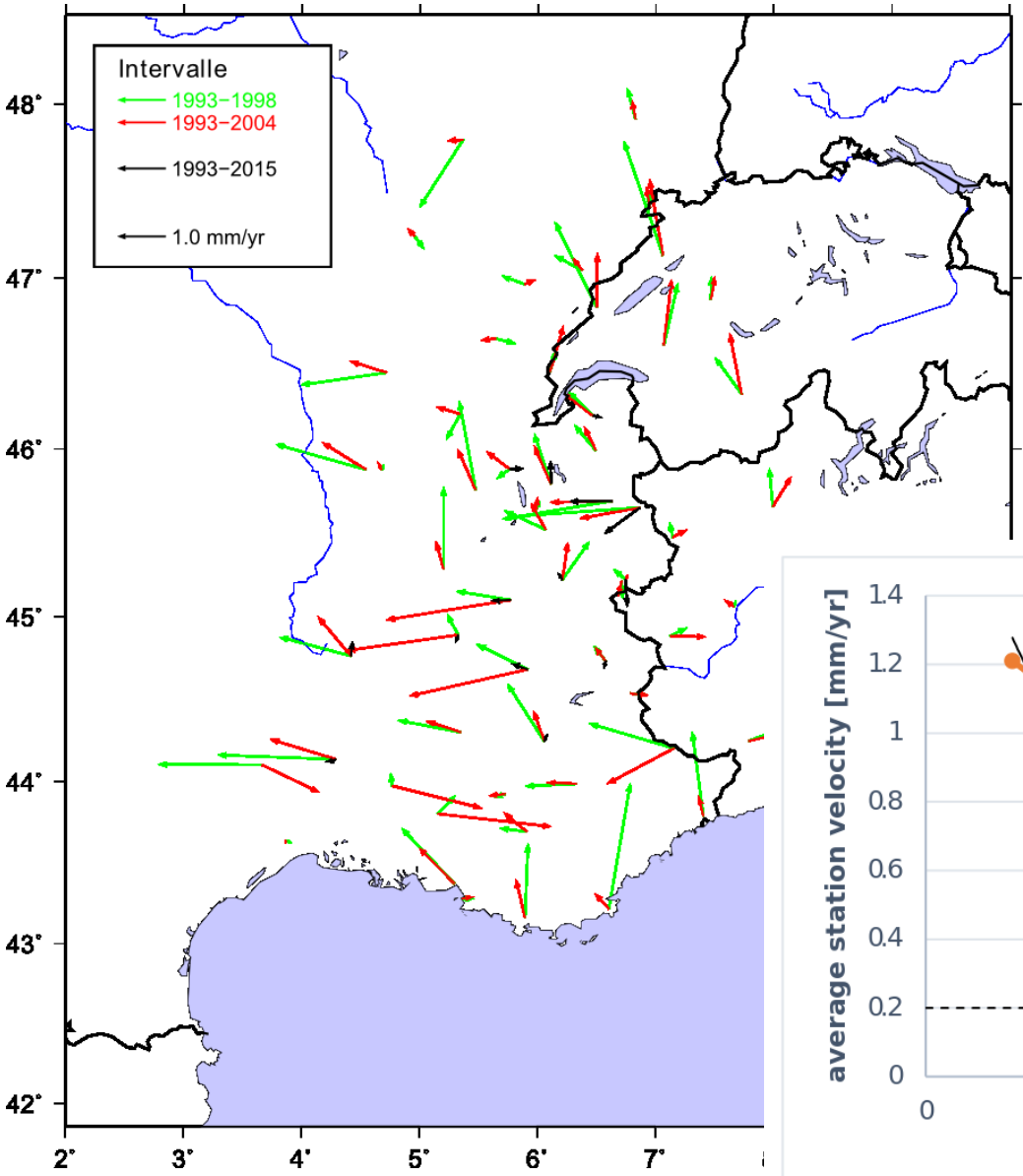
GPS velocity convergence over decennial time spans



Example: Alps campaign measurements

- 1993
- 1998 (5 years span)
- 2004 (11 years span)
- 2015 (22 years span)

GPS velocity convergence over decennial time spans



Example: Alps campaign measurements

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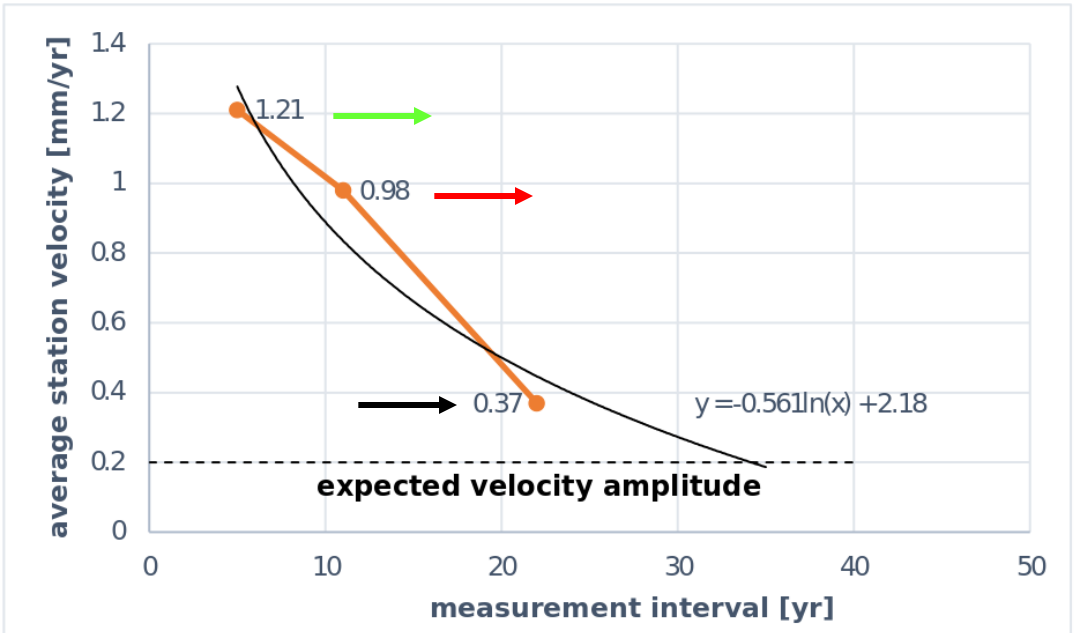
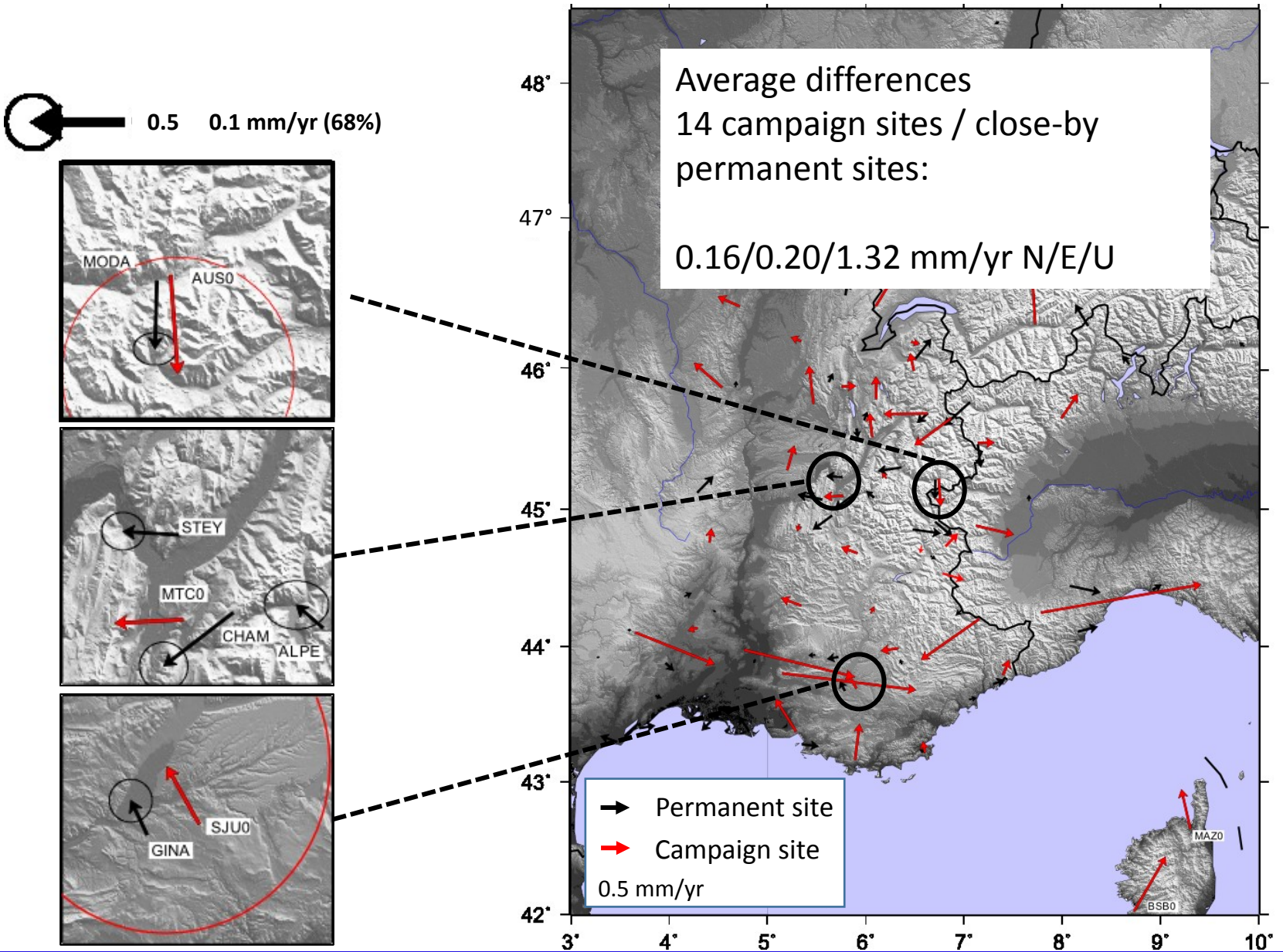


Comparison of campaign and permanent GPS velocities

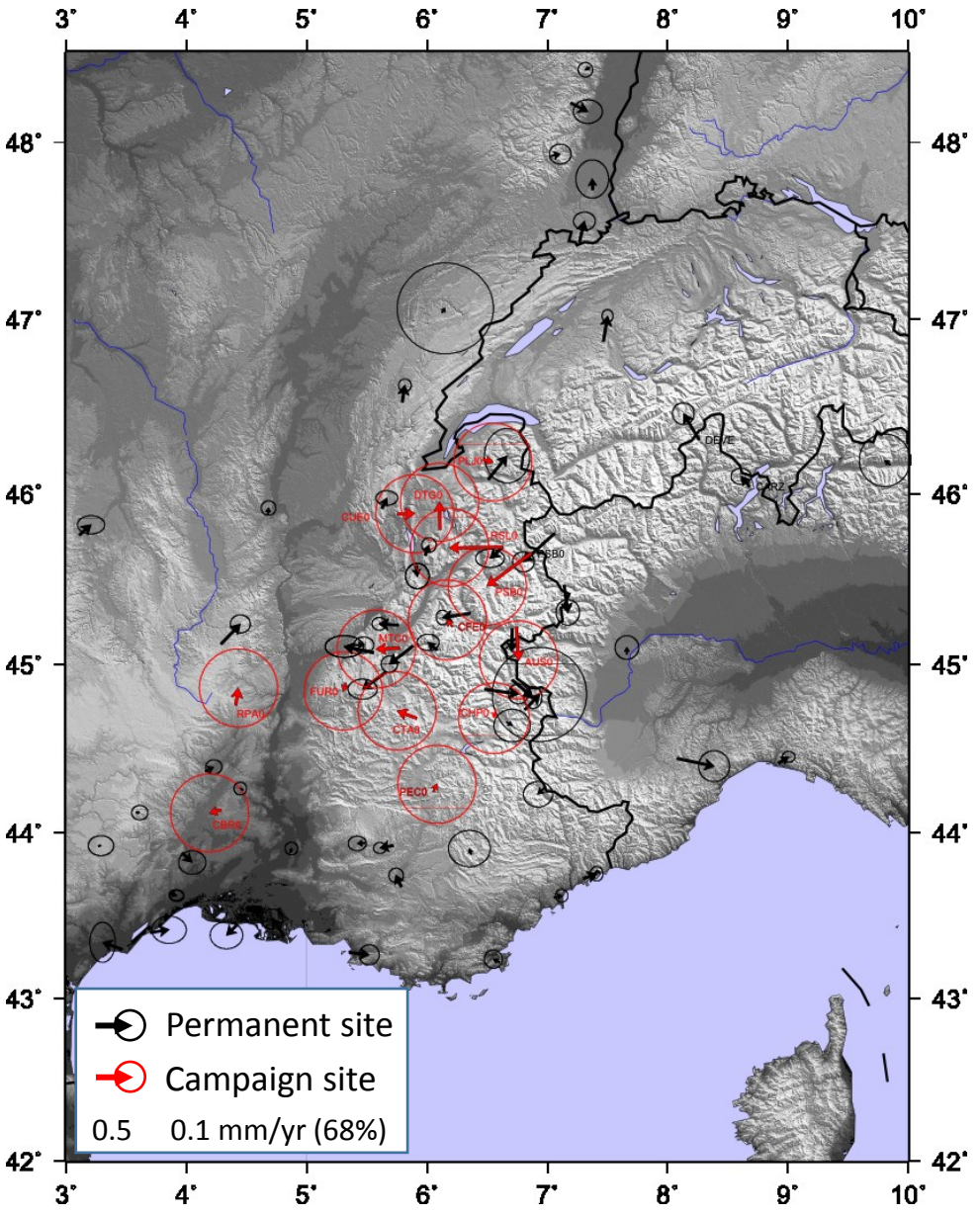


Final ISTerre GPS velocity solution over the Western Alps

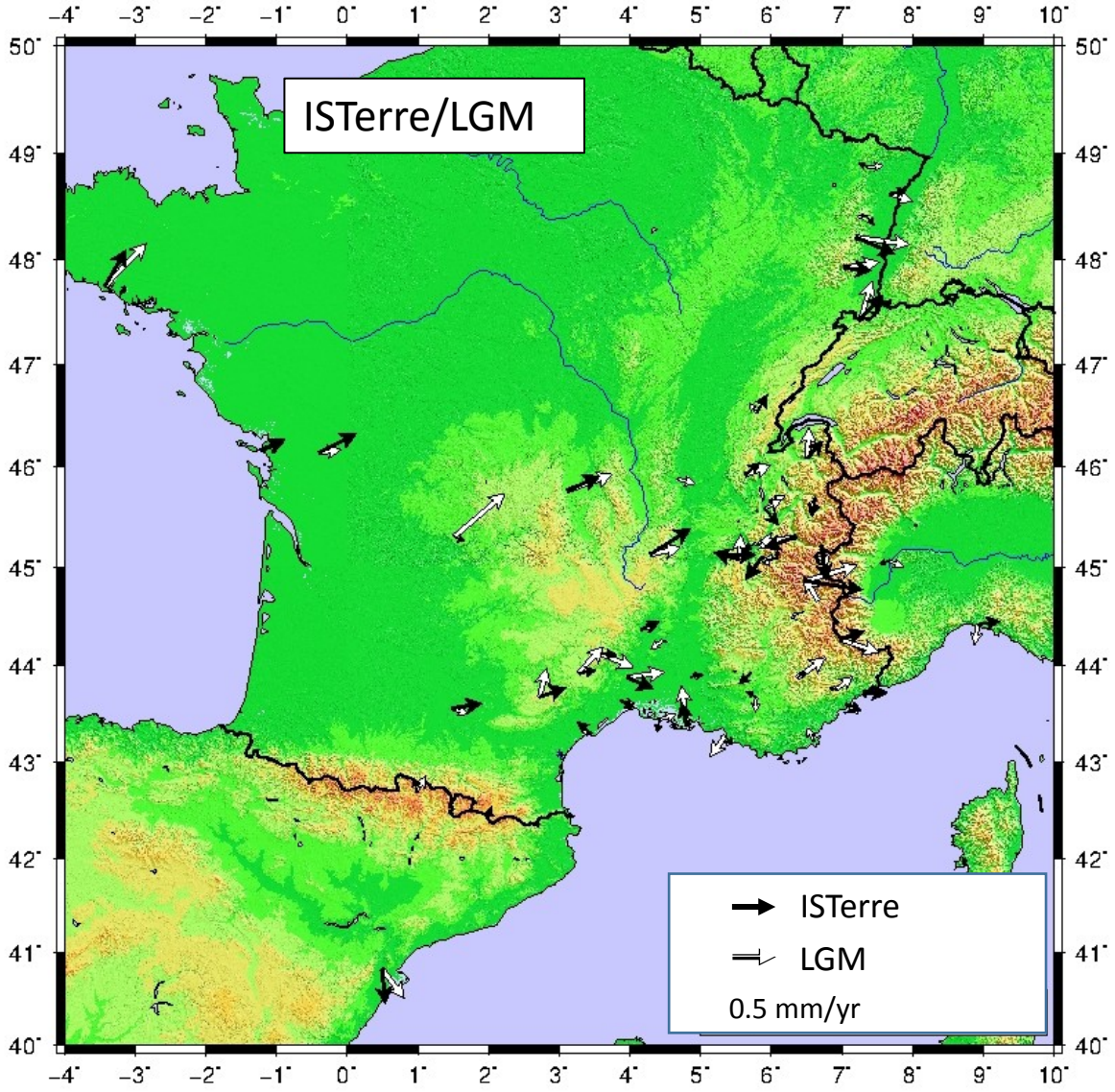
RENAG 1998-2014.5
Alps 1993-2015
MIT's GAMIT/GLOBK 10.6 (DD)

Independent solutions:
- Laboratoire Géosciences Montpellier (LGM):
RENAG 2000-2013
RGP 2000-2013
Natural Resources Canada CSRS (PPP)

- Nevada Geodetic Laboratory (NGL):
RENAG 1998-2016.5
GIPSY/OASIS (PPP)



Comparison of independent velocity solutions



ISTerre: GAMIT (DD)
LGM: CSRS (PPP)
NGL: GIPSY (PPP)

	ISTerre /LGM	ISTerre /NGL
# stations	53	55
Horizontal (mm/yr)	0.13	0.18
Vertical (mm/yr)	0.44	0.75

ISTerre /LGM	> 8 yrs	> 10 yrs
# stations	37	24
Horizontal (mm/yr)	0.29	0.12
Vertical (mm/yr)	0.40	0.37

Results comparison of velocity solutions

Comparison 22 years **campaign** solution with up to 16.5 years **permanent** solution:

- Difference of 14 campaign sites with close-by permanent sites:
  0.16/0.20/1.32 mm/yr on the N/E/U components
- Encouraging result for long term campaigns

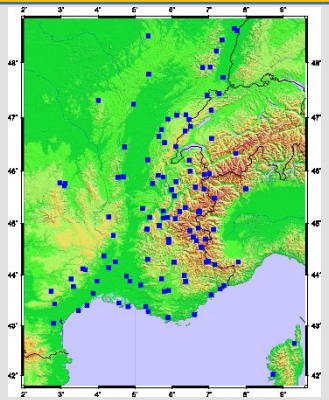
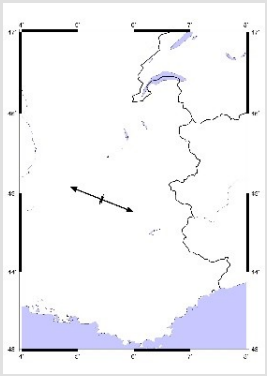
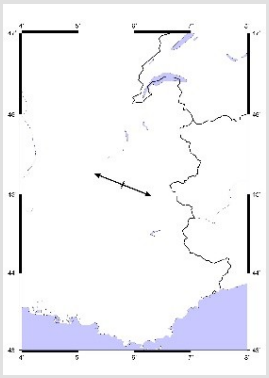
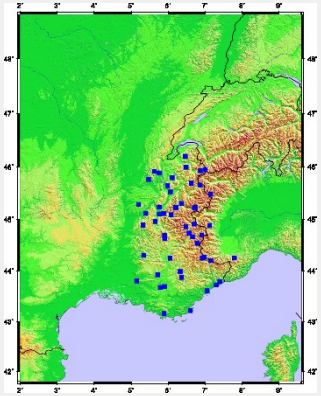
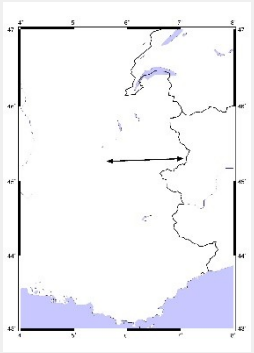
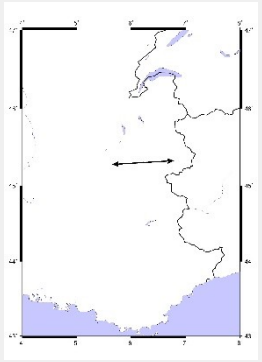
Comparison of **3 independent solutions** on up to 14-18 years of permanent data (DD and PPP):

- Minimizing differences of velocity fields yields 0.13-0.18 mm/yr on the horizontal and 0.44-0.75 mm/yr on the vertical component

0.2 mm/yr horizontally: for individual stations at the level of the tectonic signal !

➔ Search for redundancy between close-by stations or independent solutions to enhance the signal-to-noise level

Large scale deformation (ISTerre solution)

		RENAG	RENAG + Alps (all)
Extension / Compression / Azimuth : **(nanostrain/yr) / (nanostrain/yr) / °**		**0.67 / -0.11 / 111 °**	**0.62 / -0.08 / 112°**
Large			
Extension / Compression / Azimuth :		**3.23 / -0.09 / 87 °**	**2.25 / -0.05 / 87°**
Restricted to the arc			

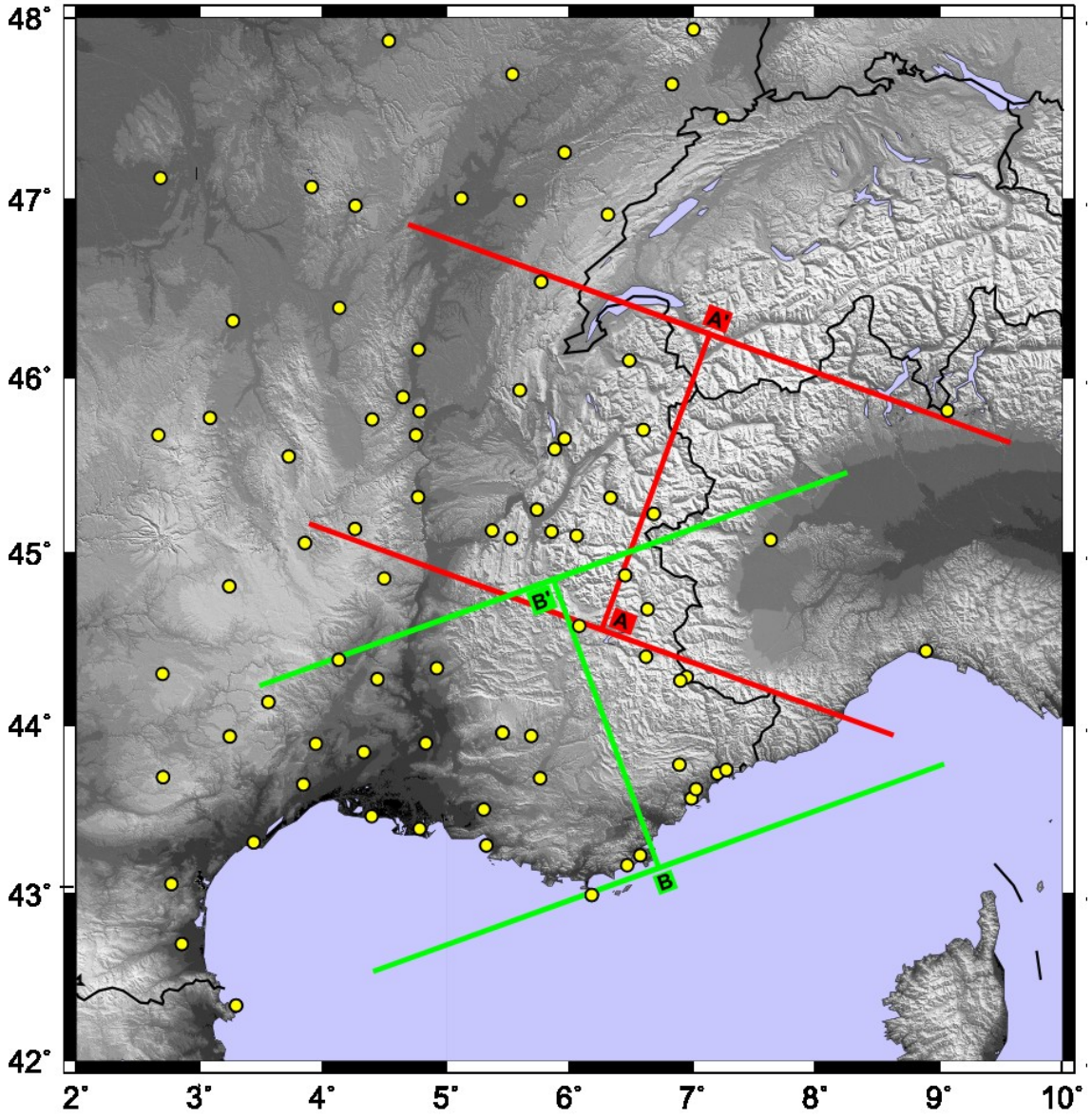
1 nanostrain/yr

= 1 mm/yr / 1000 km

= 0.1 mm/yr / 100 km

Scale change !

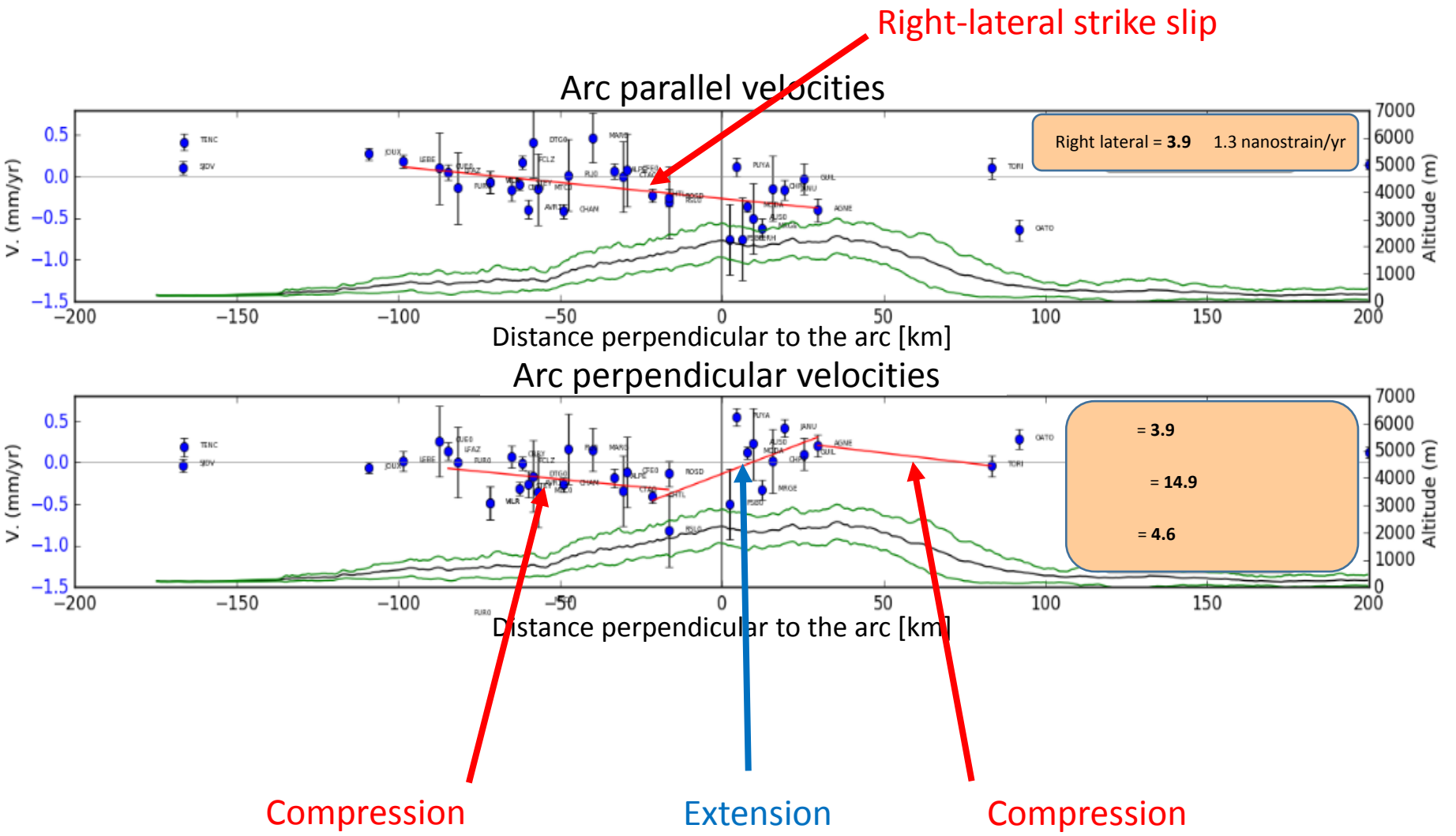
Velocity profiles



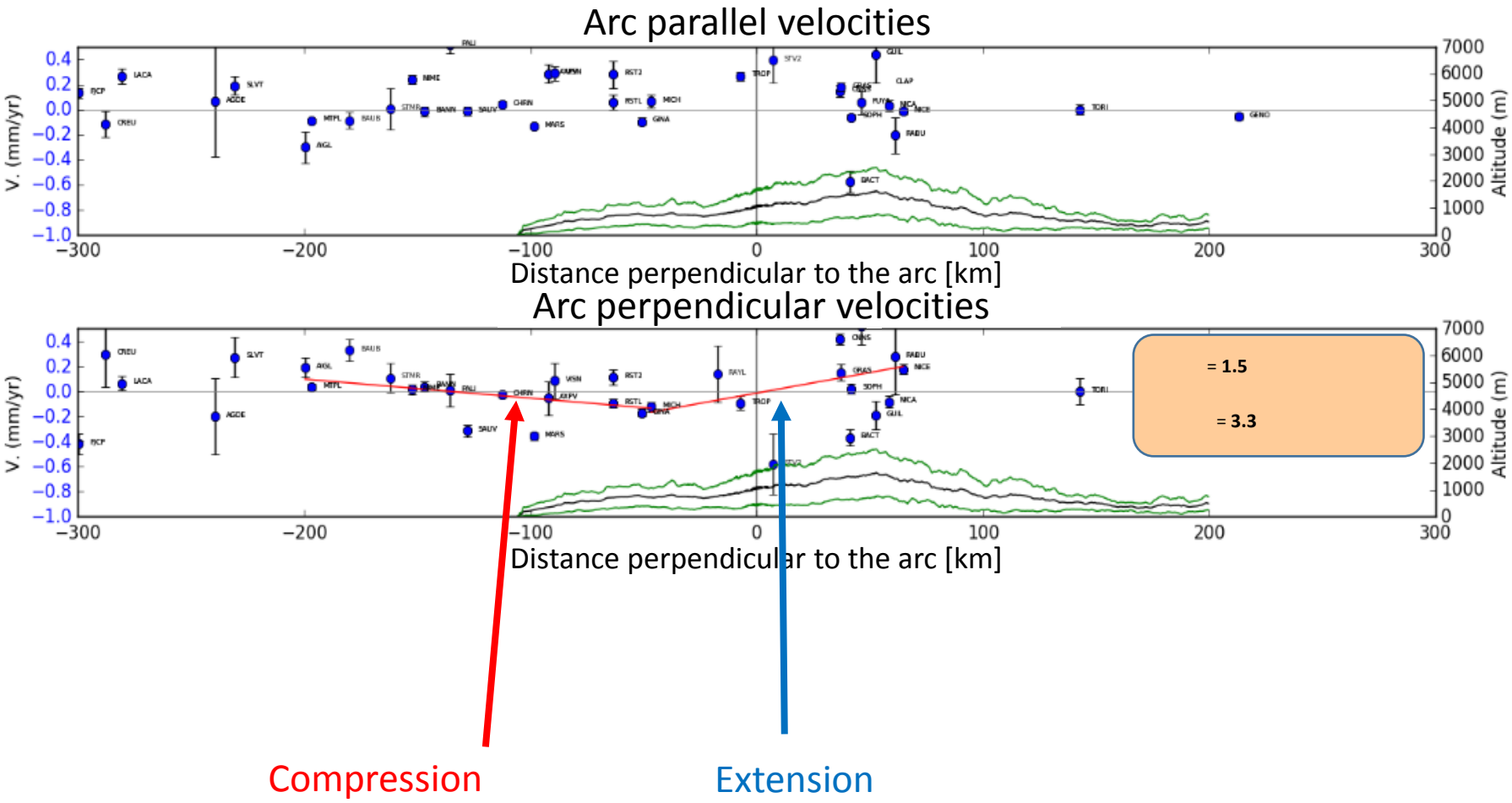
Profiles A (Northern Alps) and B (Southern Alps)

- Perpendicular to the arc
- Plot arc perpendicular velocity components ➔ extension/compression
- Plot arc parallel velocity components ➔ strike-slip

Velocity profiles: Northern Alps (ISTerre solution)



Velocity profiles: Southern Alps (ISTerre solution)



Velocity profiles: Comparison solutions ISTerre / LGM

	solution	West (nanostrain/yr)	Center (nanostrain/yr)	East (nanostrain/yr)
North parallel	ISTerre		-3.9 (RL)	
	LGM		-4.6 0.8 (RL)	
North perpendicular	ISTerre	-3.8 2.8 (SH)	14.9 6.1 (EX)	-4.6 (SH)
	LGM	-5.3 1.5 (SH)	23.3 6.2 (EX)	-2.4 2.1 (SH)
South perpendicular	ISTerre	-1.3 0.9 (SH)	3.1 1.5 (EX)	No sites
	LGM	-1.5 0.6 (SH)	3.3 0.5(EX)	No sites

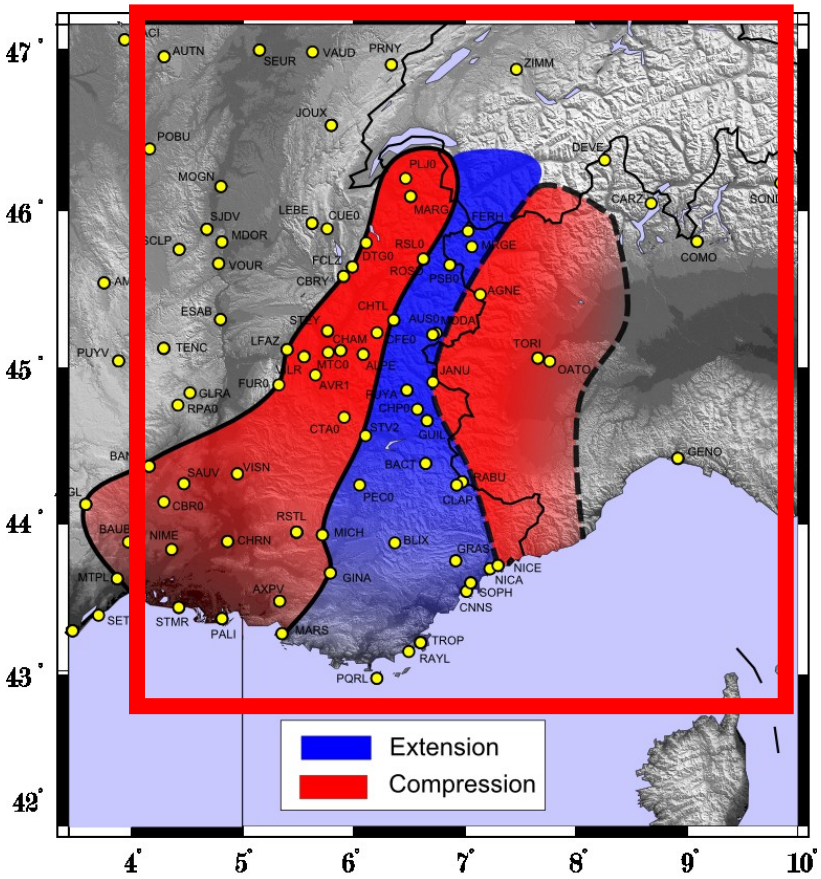
Profiles established with the independent solution LGM yield the same tendencies:

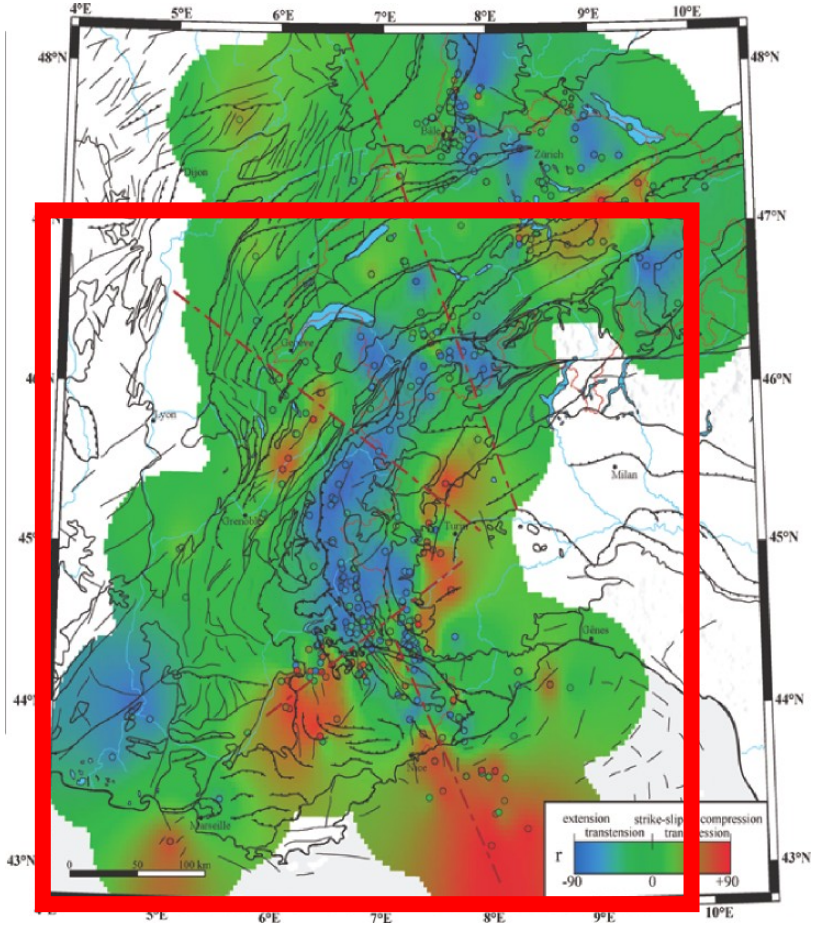
- Compression/extension/compression
- Right lateral strike-slip

qualitatively and quantitatively within uncertainties

Schematic geodetic deformation map

Interpolation between the arc perpendicular velocity profiles

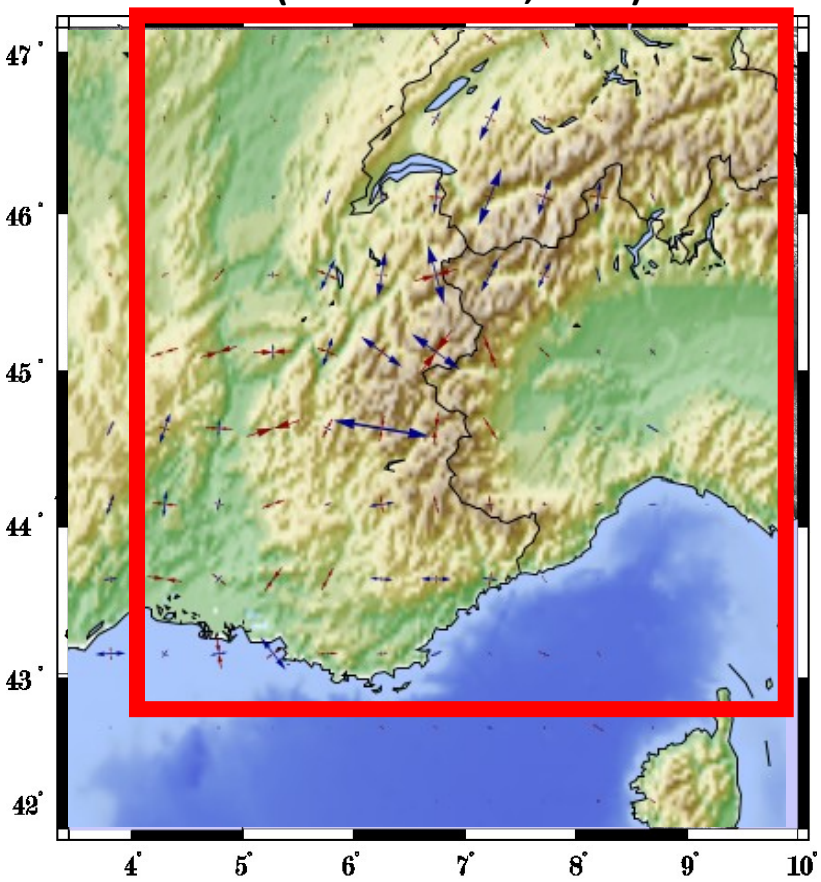


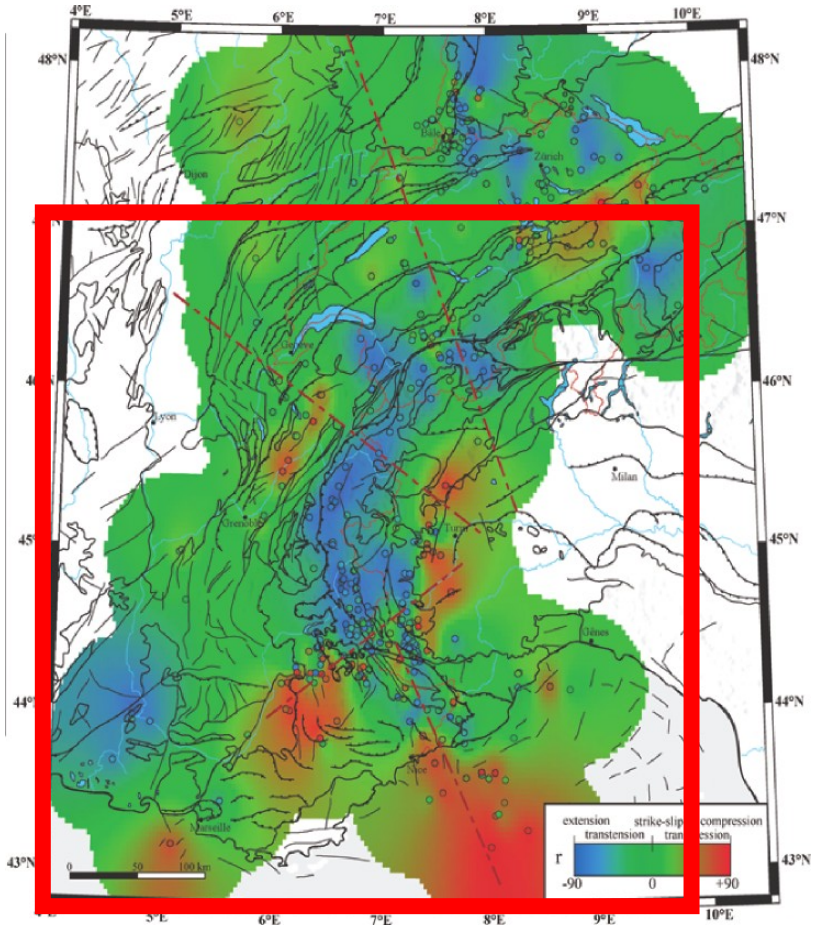


Comparison with localisation of deformation from focal mechanisms (*Delacou et al., 2004)*

Geodetic deformation map on regular grid

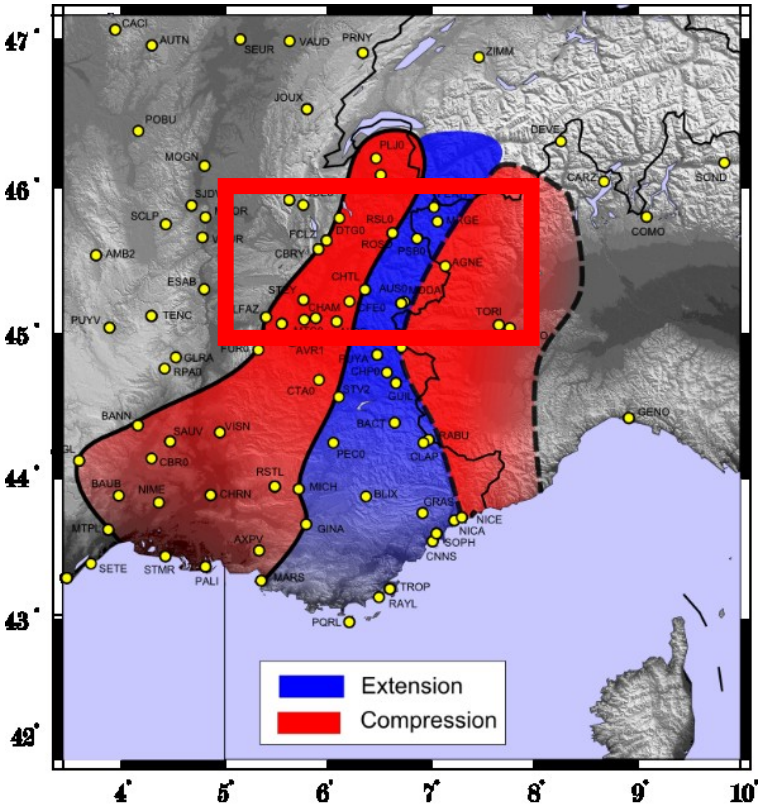
Strain rates from inversion of GPS baseline changes in regular grid elements (Masson et al., 2014)

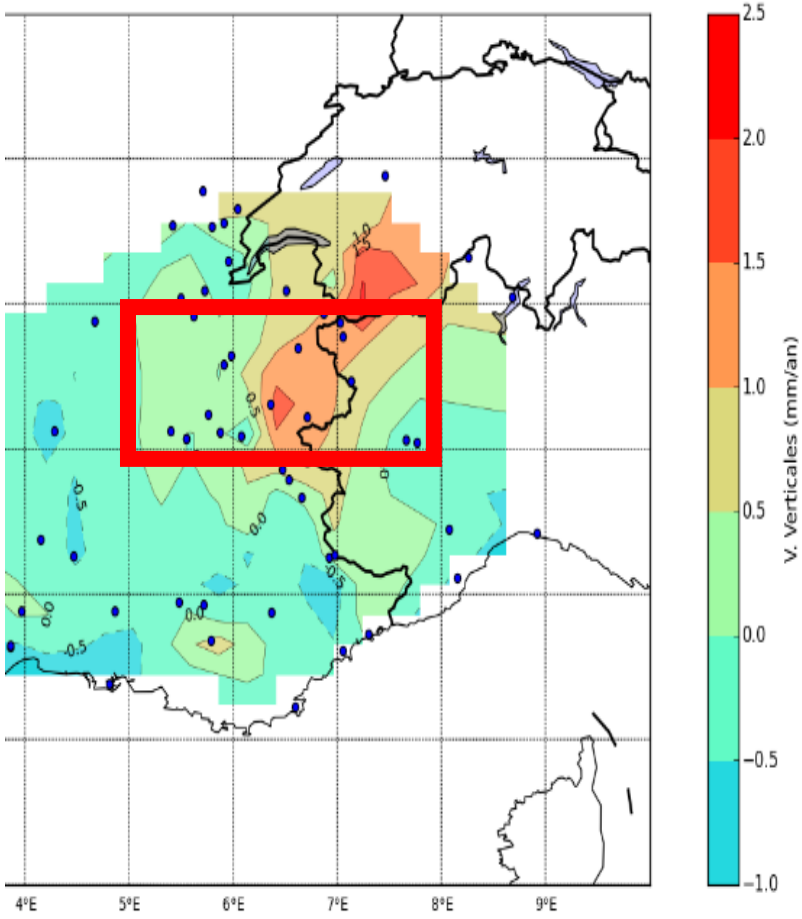




Comparison with localisation of deformation from focal mechanisms (*Delacou et al., 2004)*

Comparison horizontal and vertical deformation fields





➔ Maximum extension at maximum uplift (Vernant et al., 2013, Nocquet et al., 2016):

- Erosional unloading (model also predicts shortening at the borders)
- Glacial isostatic adjustment (short and long term)
- Low viscosity zone (Lippisch, 2003, Fox et al., 2015): dynamic topography by more buoyant mantle material

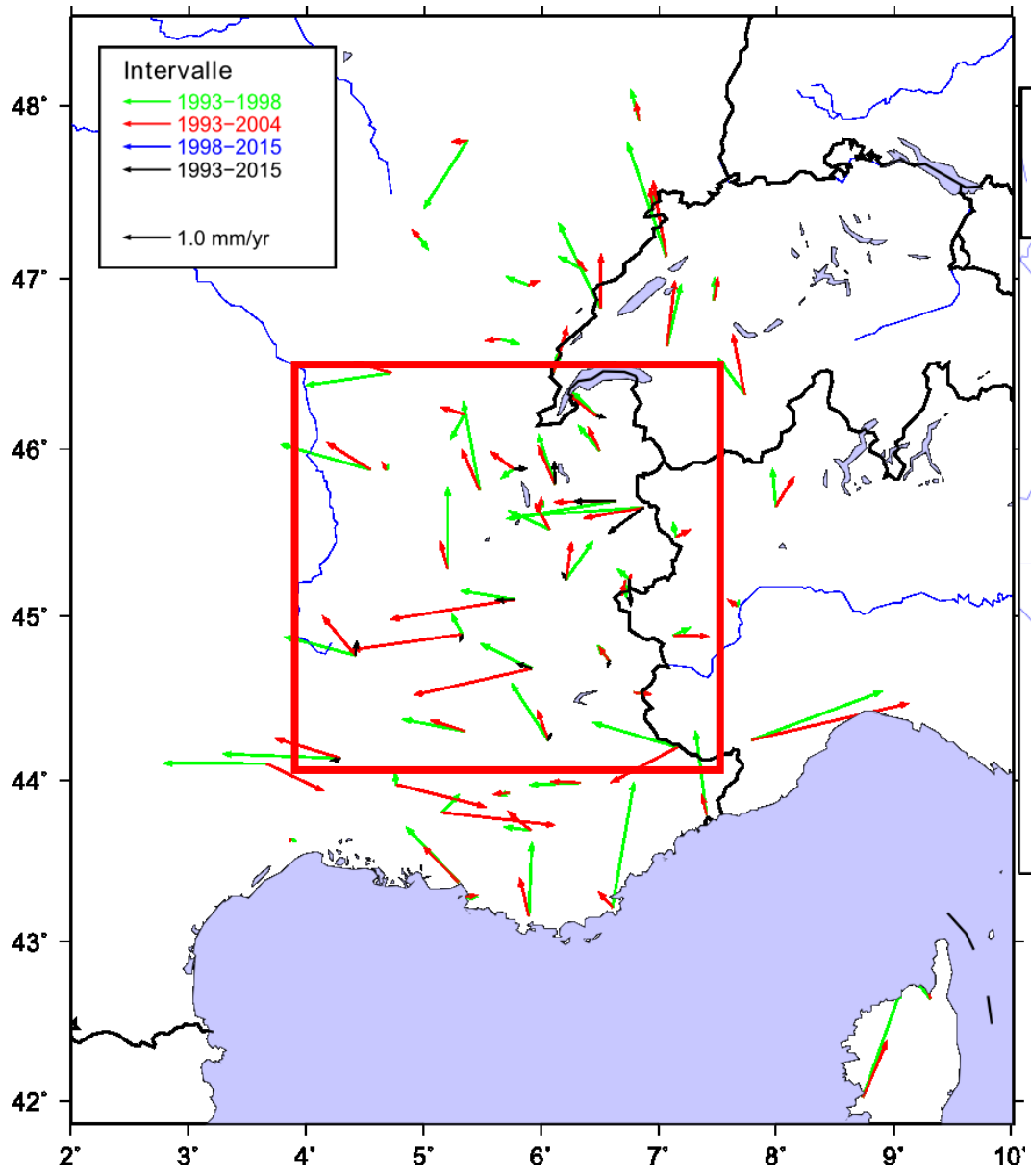
Summary

- Western Alps deformation predicted by seismicity now quantified by long term geodesy:
  - Extension in the center of the arc, from 15 to 3 nanostrain/yr from North to South
  - Compression at the borders of the arc, from 8 to 1.5 nanostrain/yr from North to South
- Right lateral strike-slip in the North of 0.5 mm/yr over 130 km compatible with anti-clockwise rotation of the Adriatic plate
- Uplift confirmed, from 2 to 0.3 mm/yr from North to South

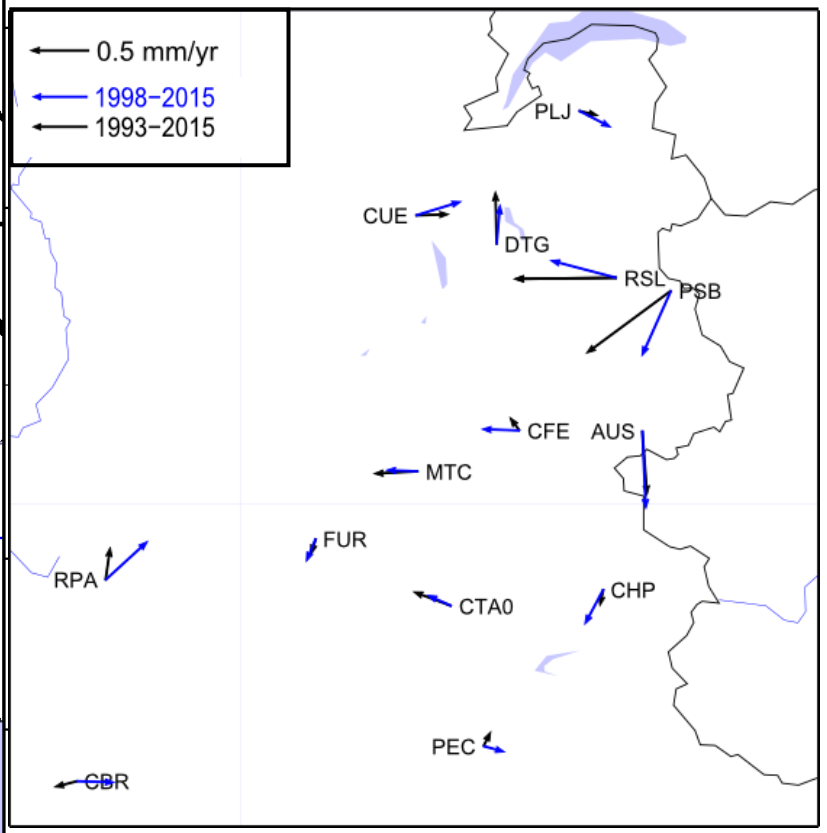
➔ New quantitative 3D constraints on geodynamic models of the Alps, thanks to **redundancy** between **permanent and campaign GPS measurements** and between **independent geodetic solutions**, **enhancing the weak signal to noise ratio** in the Western Alps

Many thanks for your attention !

GPS velocity convergence over decennial time spans

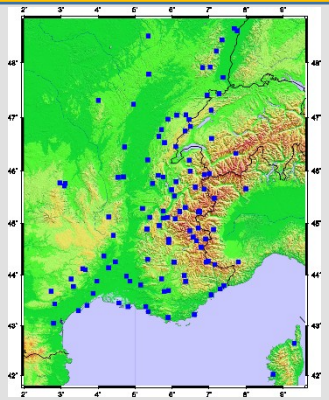
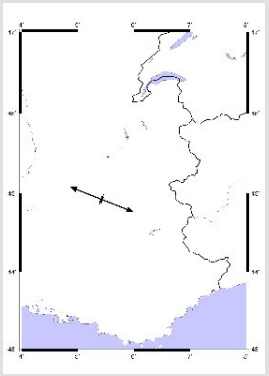
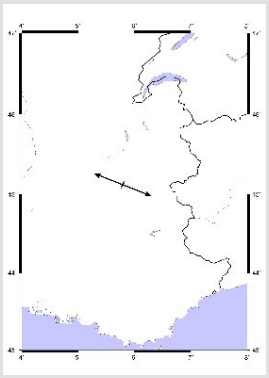
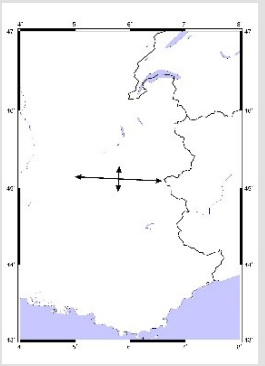
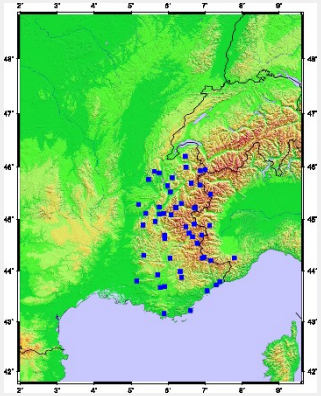
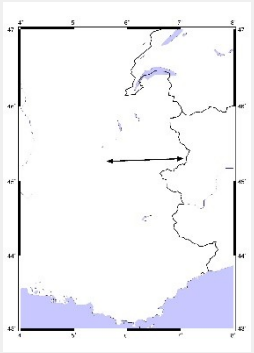
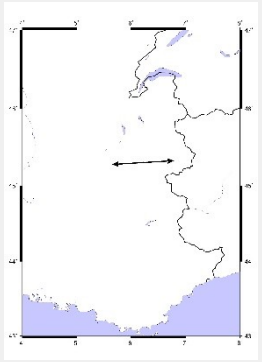
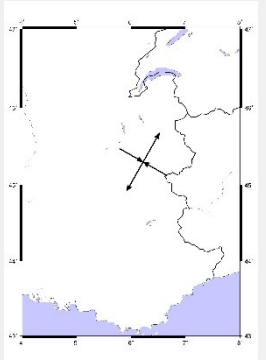


With or without the 1993 campaign



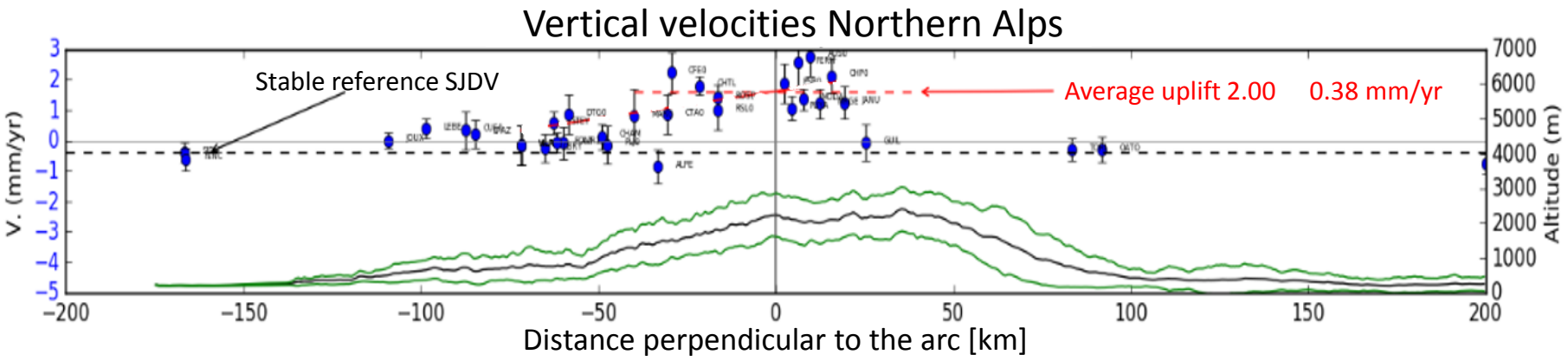
Note scale change !

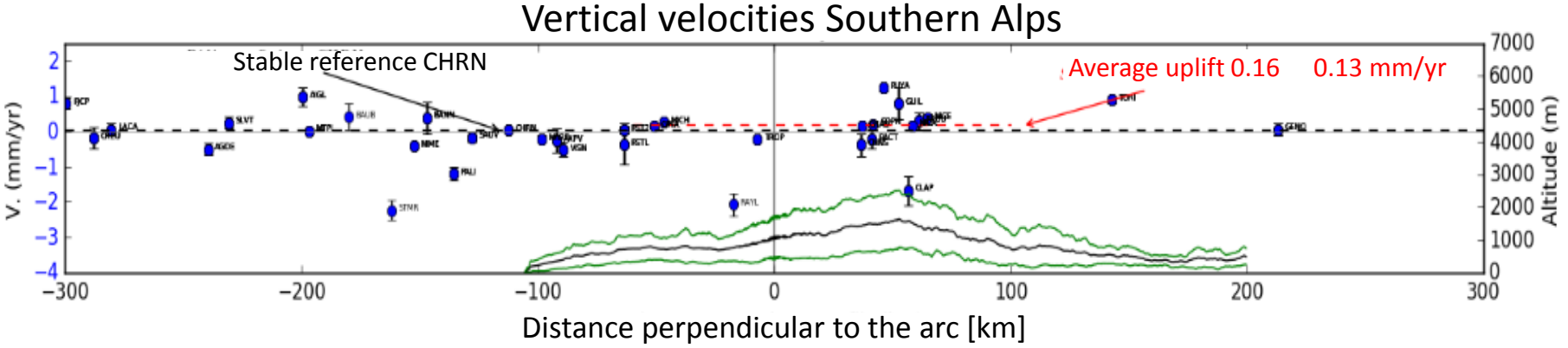
Large scale deformation (ISTerre solution)

		RENAG	RENAG + Alps (all)	RENAG + Alps equal weight
Extension / Compression / Azimuth : **(nanostrain/yr) / (nanostrain/yr) / °**		**0.67 / -0.11 / 111 °**	**0.62 / -0.08 / 112°**	**0.89 / 0.26 / 93°**
Large				
Extension / Compression / Azimuth :		**3.23 / -0.09 / 87 °**	**2.25 / -0.05 / 87°**	**0.69 / -0.56 / 29°**
Restricted to the arc				

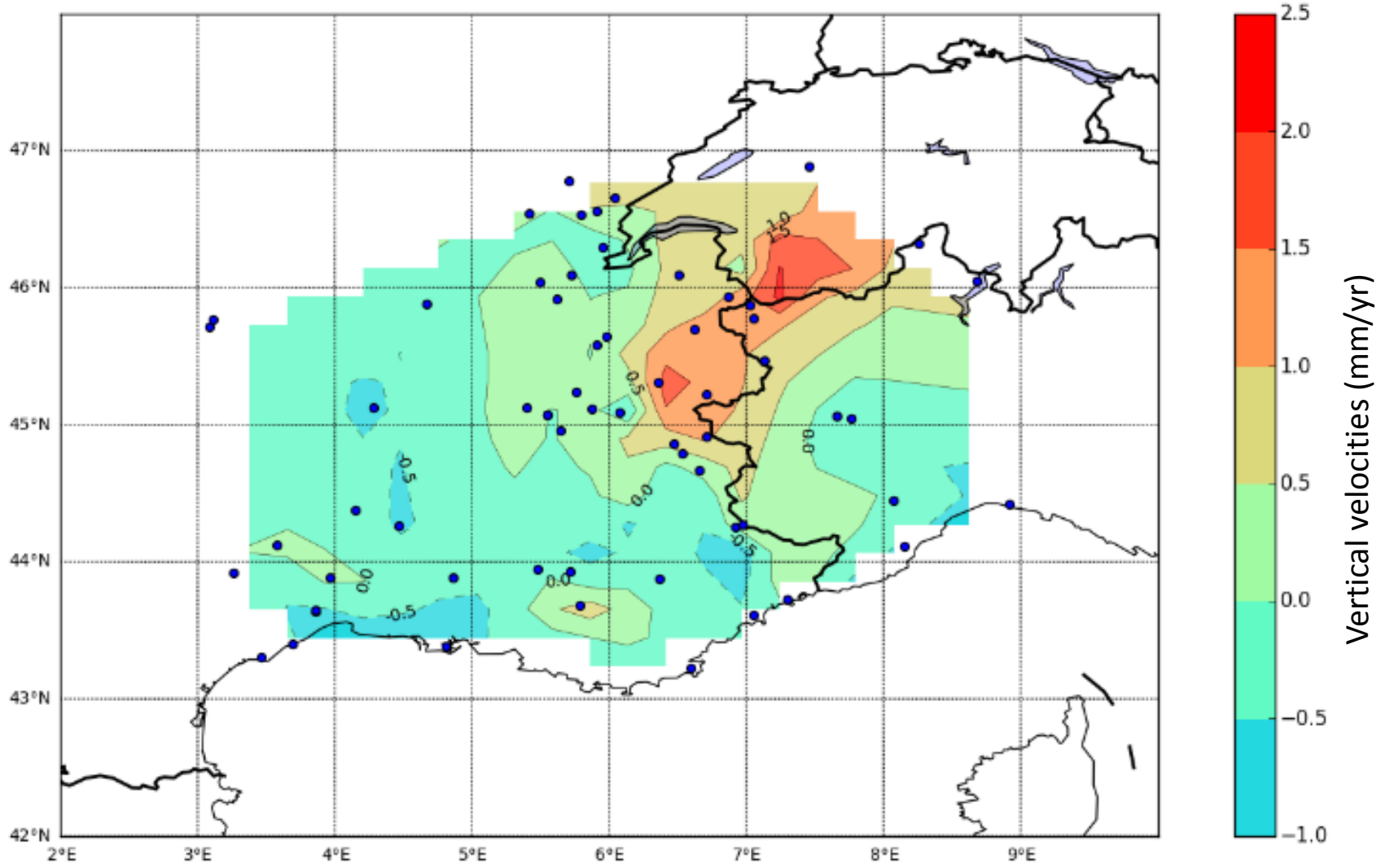
➔ East-West extension ▪ **0.6 nanostrain/yr (**large) ▪ **2 - 3 nanostrain/yr** (restricted to the arc)

Vertical velocity profiles



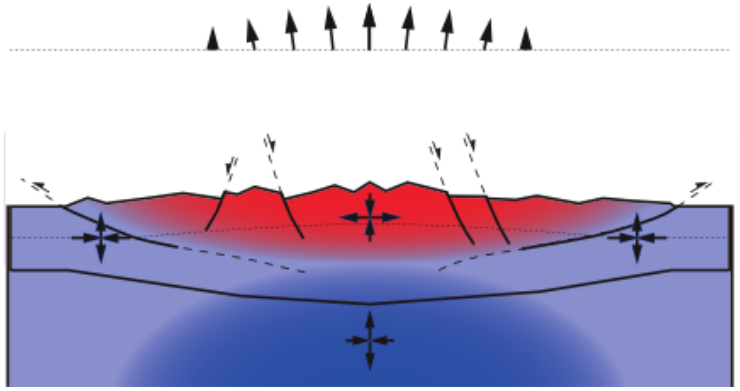


Vertical velocity field

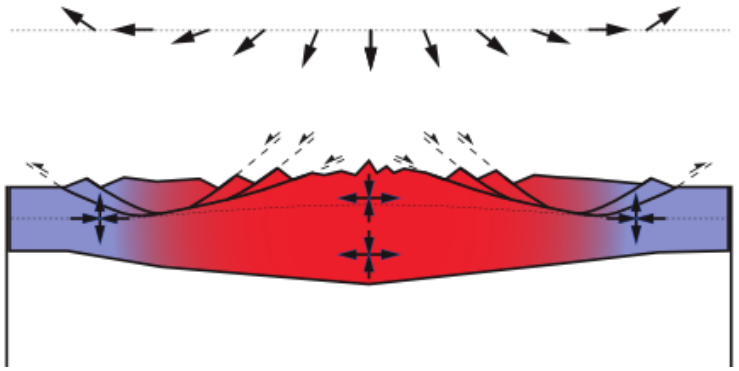


Models of Alpine horizontal and vertical deformation

Vernant et al., 2013

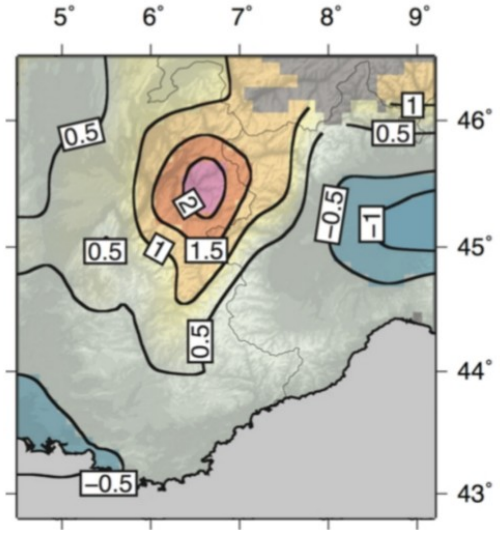


Extension induced by erosion

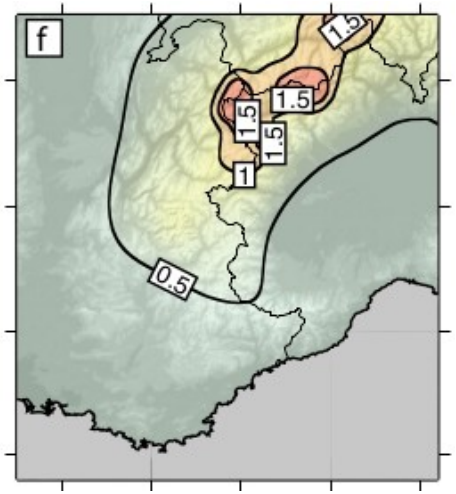


Extension induced by gravitational collapse

Nocquet et al., 2016 and authors herein



Measured uplift



Model predicted uplift

Summed effect of isostatic adjustment due to deglaciation and erosion

+ low viscosity zone
+ deep forces (dynamic topography by upwelling hot mantle material)