Postglacial stress – strain rate paradox, example of the Western Alps : Coupling geodetical strain rate and numerical modeling

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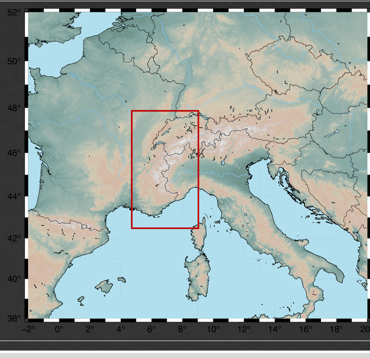
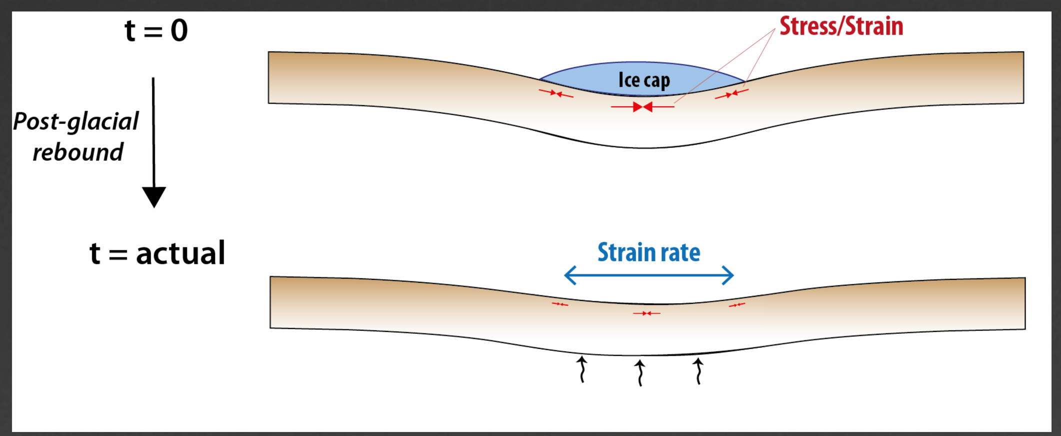
Introduction

In the Western Alps, strain rate derived from GNSS study and seismicity strain presents similar patterns, in shape and amplitude. These similarities tend to indicate that most of the deformation is seismic. This presumed link between deformation rate and seismicity also suggest that GNSS provide information for seismic study and natural hazard.

Here we use a numerical modeling approach to test Glacial Isostatic Adjustment (GIA) as a process of both deformation rate and seismicity. We show that behind the apparent consistency between GNSS signal and seismicity hiding a stress-strain rate paradox link to glacial unloading.





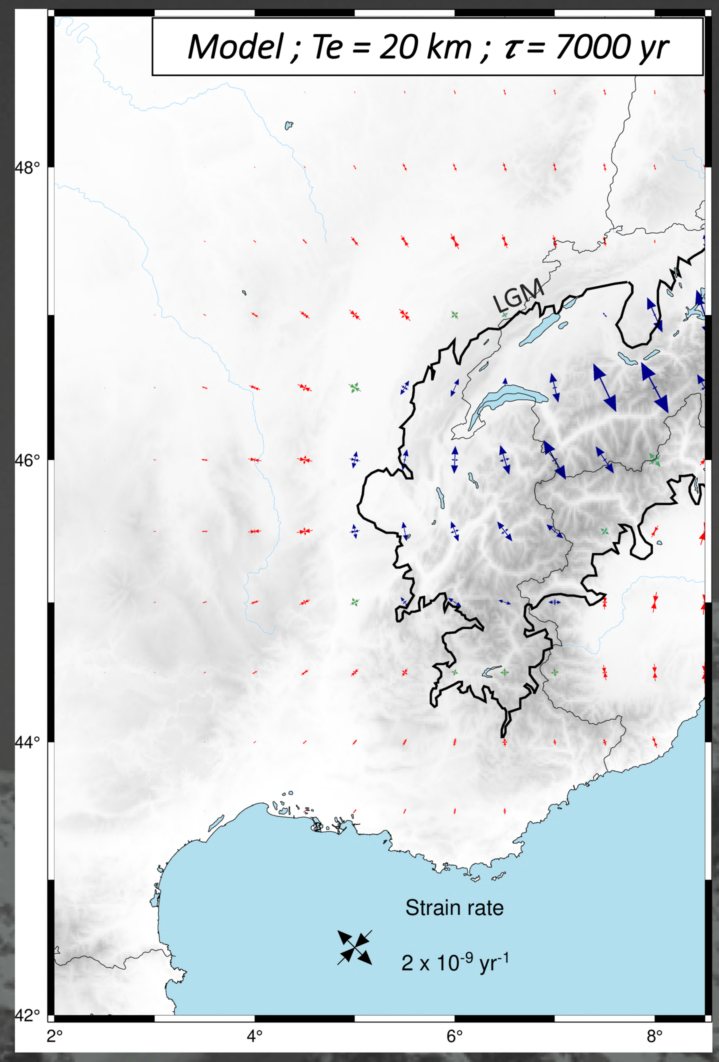
Schematic representation of the flexural response of a thin plate to glacial unloading. The stress and strain rate in the upper part of the plate is respectively represented in red and blue.

Strain rate

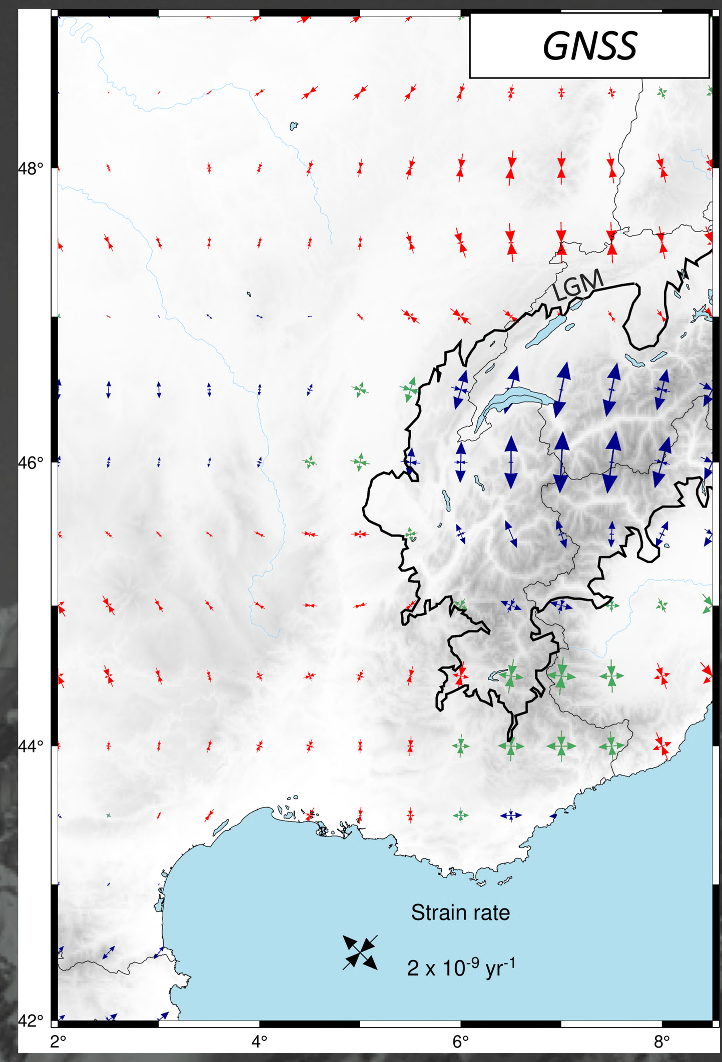
The diminution of the stress amplitude triggers an extension rate on the top of the plate at the maximum flexure. In the alpine icecap case, an extension rate is modeled on the central part of the Alps. The tectonic influence of the Adriatic plate is relatively low in this area, but could eventually explain the difference in vector azimuth on both fields, and induce a strike-slip area in the southern Alps region (D'agostino et al., 2008).

Models predict a shortening rate radially around the former ice cap. Even if such small deformation rates are hard to extract from the GNSS signal, a similar shortening rate is seen on the observed strain rate field in Rhine graben. The amplitude of the GNSS strain vector is twice bigger than modeled one: GIA alone can't explain all the shortening signals in Rhine graben and should be amplified by other local processes, such as Eiffel volcanic field (Kreemer et al., 2020).

Modeled



Observed



Modeled (left) and GNSS (right) strain rate on Western Alps. Strain rate is computed with a Gaussian smoothing method (Smoothing distance : 180 km). For models, strain rate is computed on the top of the plate. Blue : Extension rate ; Red : Shortening rate ; Green : Strike-slip rate.

GNSS strain rate field

The original velocity field has been computed from Nevada Geodetic Laboratory (NGL) dataset (Blewitt et al., 2018). GNSS strain rate is computed from the velocity field with a Gaussian smoothing method (results are weighted by square uncertainties). The Smoothing distance of 180 km induces uncertainties around 1 nstrain.yr^{-1}. The strain rate field shows a robust extension rate of 2 nstrain.yr^{-1} in southern Switzerland, also seen in previous studies on GNSS strain rate made with permanent GNSS network in France (Masson et al., 2019).

Stress

GIA induces compressive stress on the top of the plate. Models show that all the central Alps are NW-SE compressive (4 MPa).
Seismicity presents normal focal mechanisms in the inner Alps. As all central Alps are in compression, predicted rakes lead to inverse focal mechanisms. Despite the values of projected perturbation stress on fault high enough to triggers seismicity, modeled seismicity rakes are incompatible with observed ones.

This incompatibility is also seen for Jura's faults and Belledonne's fault, where regional stress is orthogonal to fault structures. For faults where stress is in parallel to the structure, predicted rakes are far more dispersed: As an example, part of observed rakes on Durance's fault could be explained by GIA.
In a general way, GIA alone fails to explain observed seismicity in the Western Alps. and even tends to inhibit.

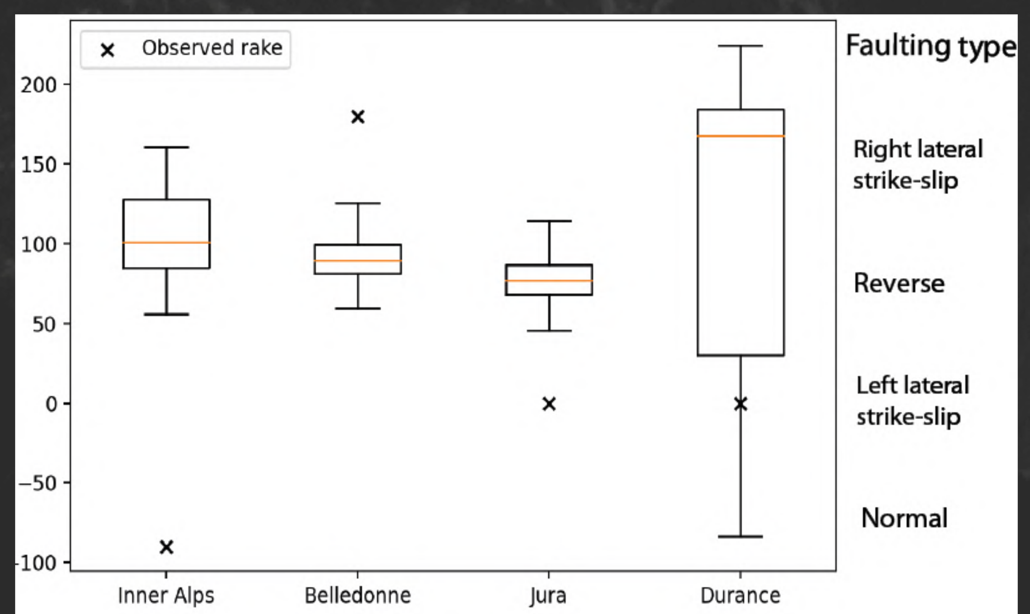
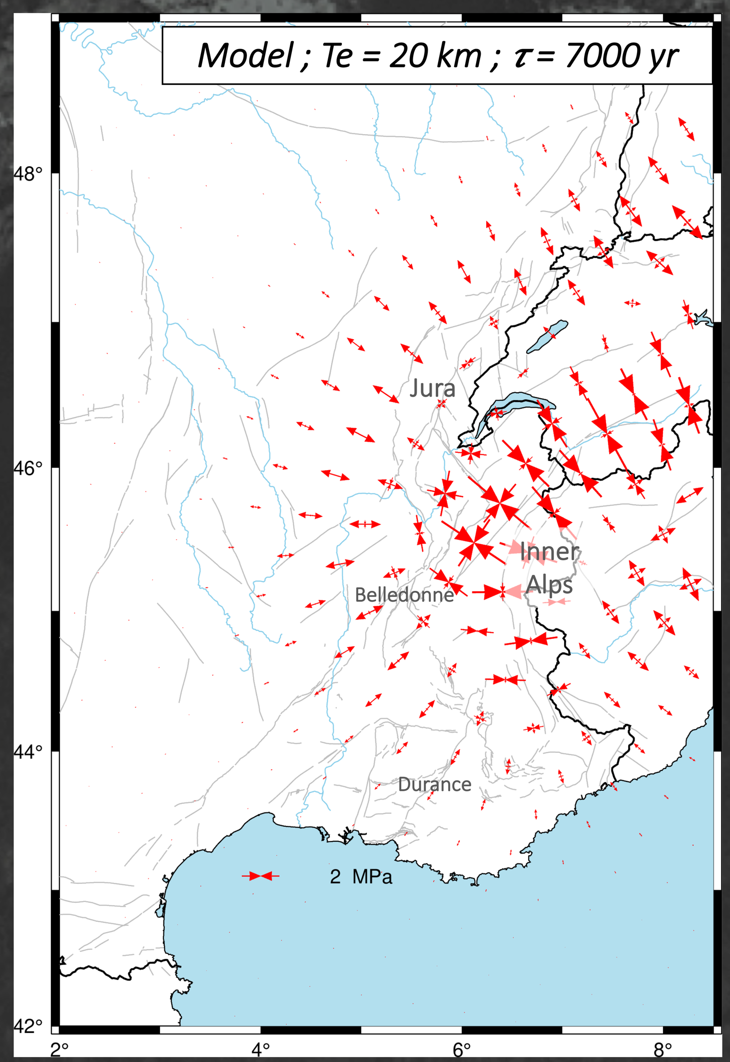
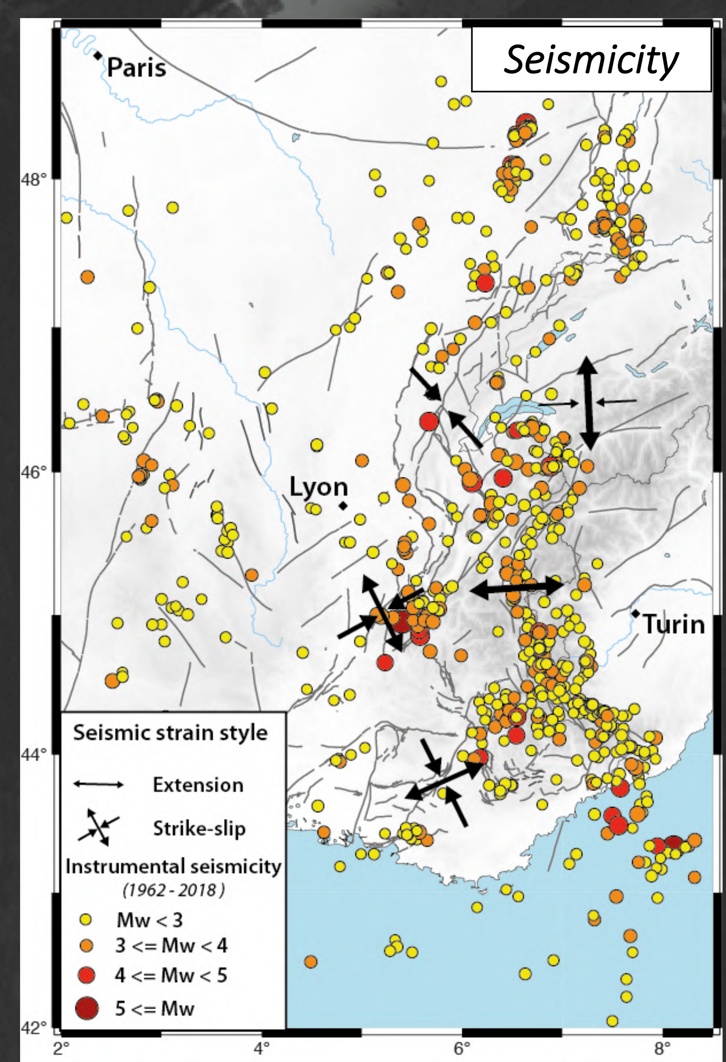


Diagram of predicted rake on active faults. Rake is computed from Coulomb perturbation failure projected on faults geometry. Variability depends on the parameterization range (flexural models and fault geometry)



Modeled stress, computed on the top of the plate, on Western Alps. Grey line : Active faults (BDFA).



Instrumental seismicity (1962 – 2018) and associated seismic strain style (SI-HEX - FMHex20) .

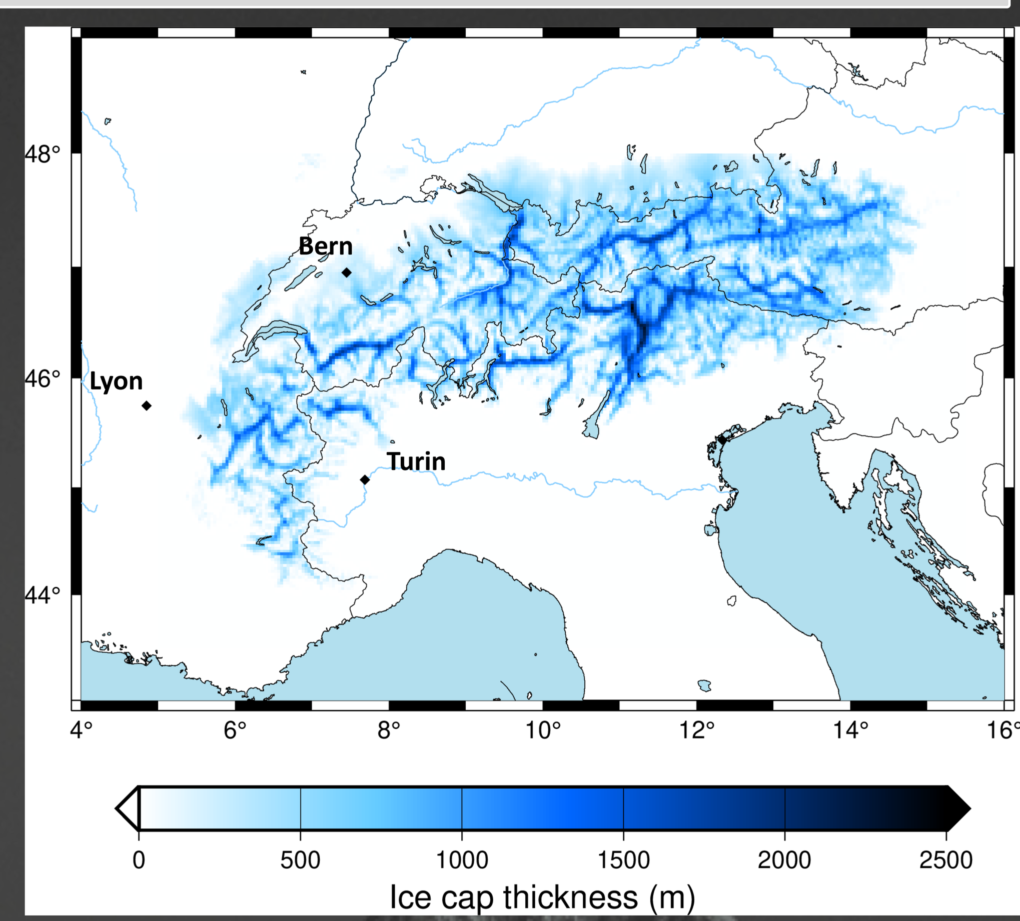
Seismicity

The Alps is one of the most seismically active regions in France, with several destructive earthquakes recorded in instrumental (ex: Annecy, 1996, Mw=4.9) and historical (Bale, 1356, Mw=6.5) seismicity. The seismic derived strain patterns (Delacou et al., 2004; Sue et al., 1999) show a range axis perpendicular extension within the inner regions and strike-slip or range axis normal shortening at the periphery.

Flexural Modeling. Input and parameterization

Flexural response to Glacial Isostatic Adjustment is studying here with numerical modeling. The thin plate bending in response to the last glacial maximum load is represented with gFlex code (Wickert, 2016). The initial flexure is dependant on elastic thickness (**Te**) and load. We use here an alpine ice cap model, from Mey et al. (2016). We have added the visco-elastic response (Turcotte and Schubert, 2014), depending on characteristic time (**τ**). Variability range tested for both parameters are :

- 10 km < Te < 34 km
- 4500 yr < τ < 8000 yr



Icecap thickness model, from Mey et al. (2016). Used as an input in flexure models

Stress and strain rate are computed admitting Kirchhoff-Love plate theory (infinitesimal deformation, no vertical shear, low tilting). We used the stress and strain rate computed on the top of the elastic plate, considering that it is representative of the seismogenic crust state.

Conclusion and Perspective

To conclude …

- A part of the present-day GNSS strain rate could be explained by GIA, especially the extension rate in southern Switzerland. Nevertheless, the difference in vectors angle and amplitude (in shortening area) between both fields suggest that the strain rate field is influenced by others processes.
- Incompatibility between observed seismicity and modeled stress shows that GIA can not trigger seismicity in the Alps. Computed rake from the stress perturbation projected on faults suggests that glacial unloading tends to inhibit seismic activity.
- In regions where GIA is a major process, GNSS can't be directly included in natural hazard models.

… And to go further !

A large part of the strain field remains not explained. To try to give a better picture of active processes in the region, the goal is to :

- provide an accurate GNSS strain rate field, especially on integrating the Swiss dataset
- quantify the part of each deformation factor in the Alps (such as erosion and Adriatic tectonic)

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