The Importance of InSAR Data in Mapping Subduction Zone: The example of the Coupling over the Hikurangi Subduction Zone

Louise Maubant*

William Frank*, Laura Wallace[1], Charles Williams[1], Ian Hamling[1]

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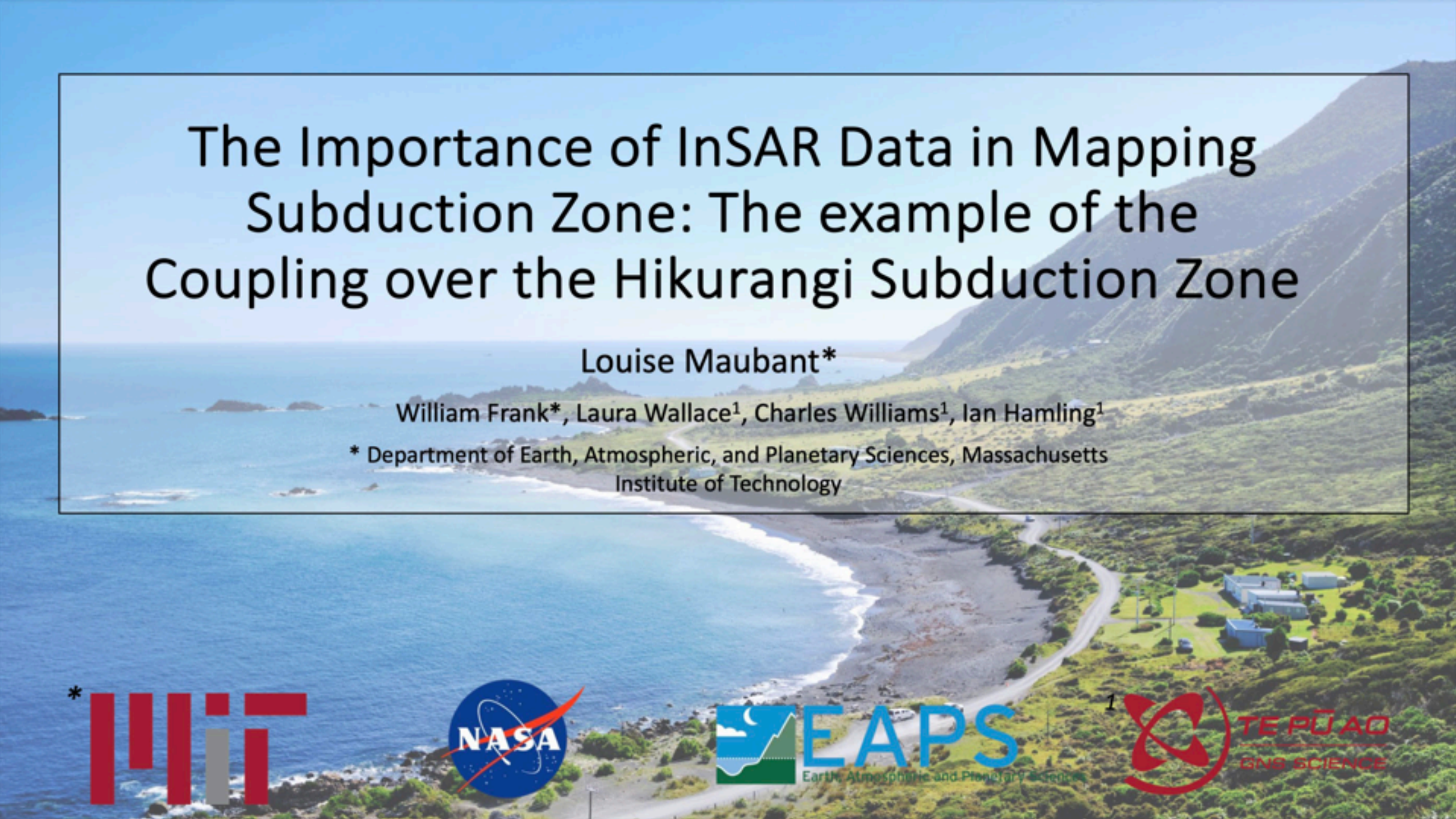
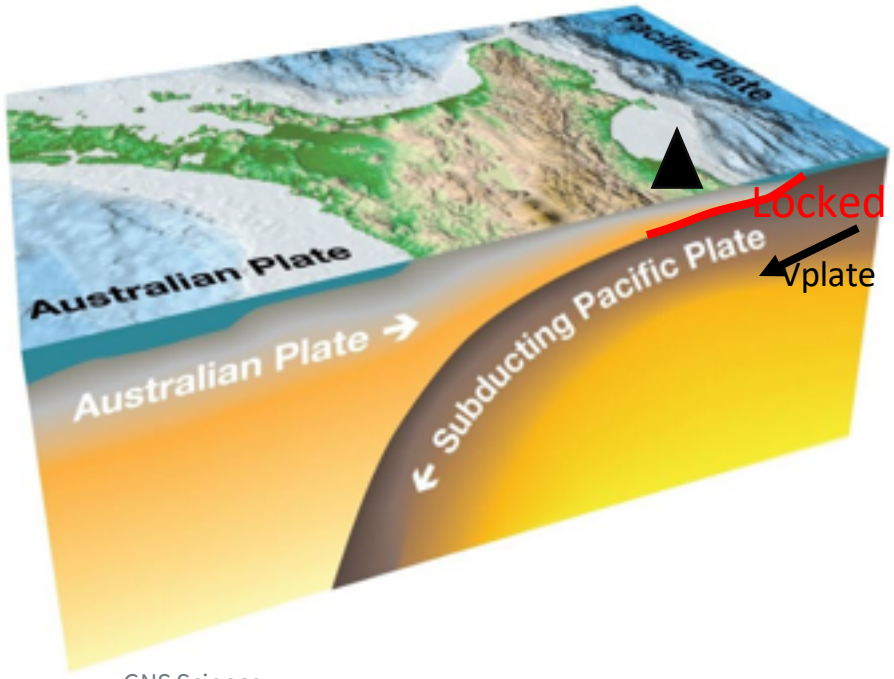


Observing the seismic cycle with geodesy

➢ Loading phase: interseismic



GNS Science

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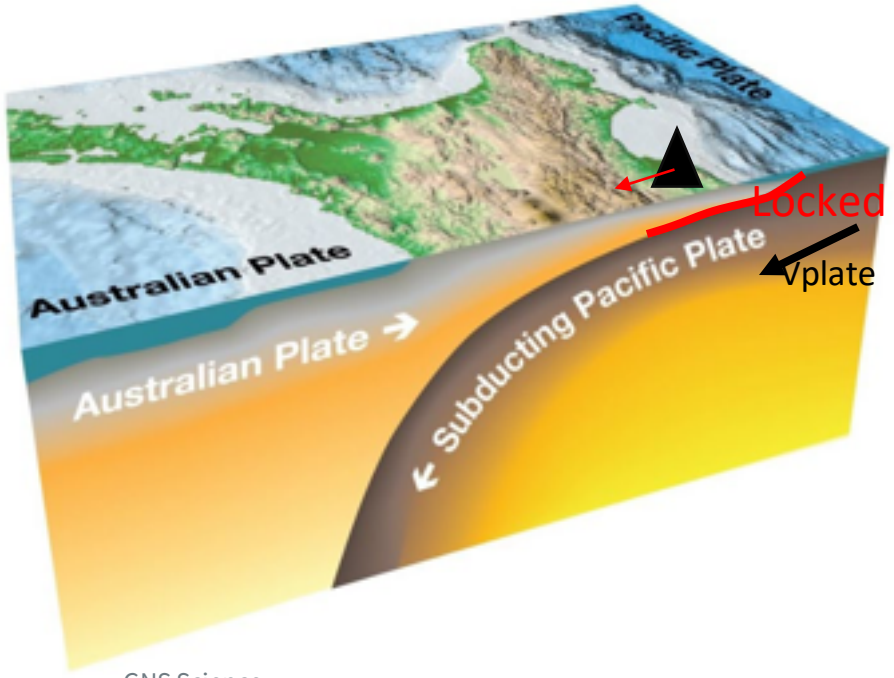

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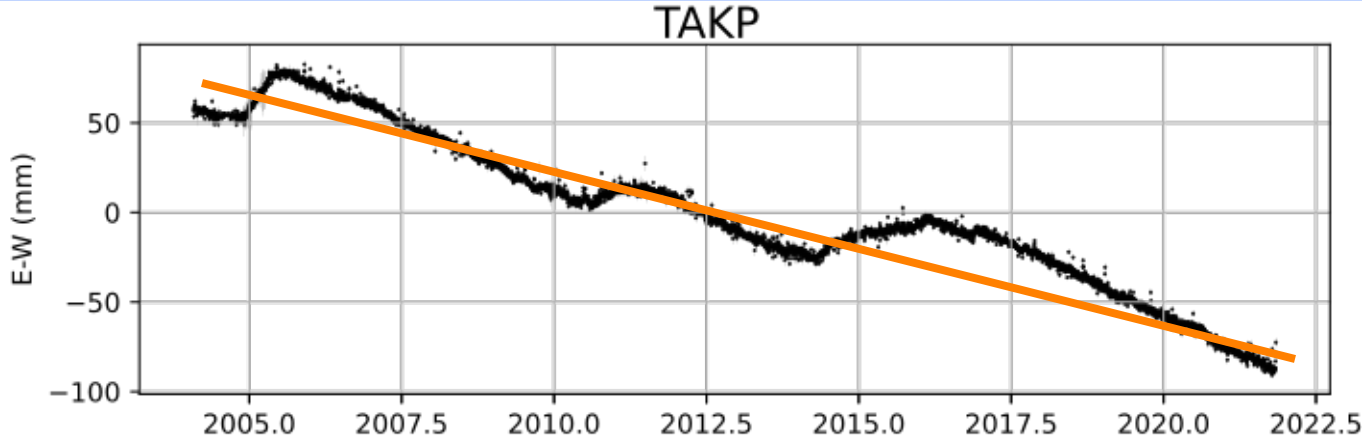

Observing the seismic cycle with geodesy

- Loading phase: interseismic
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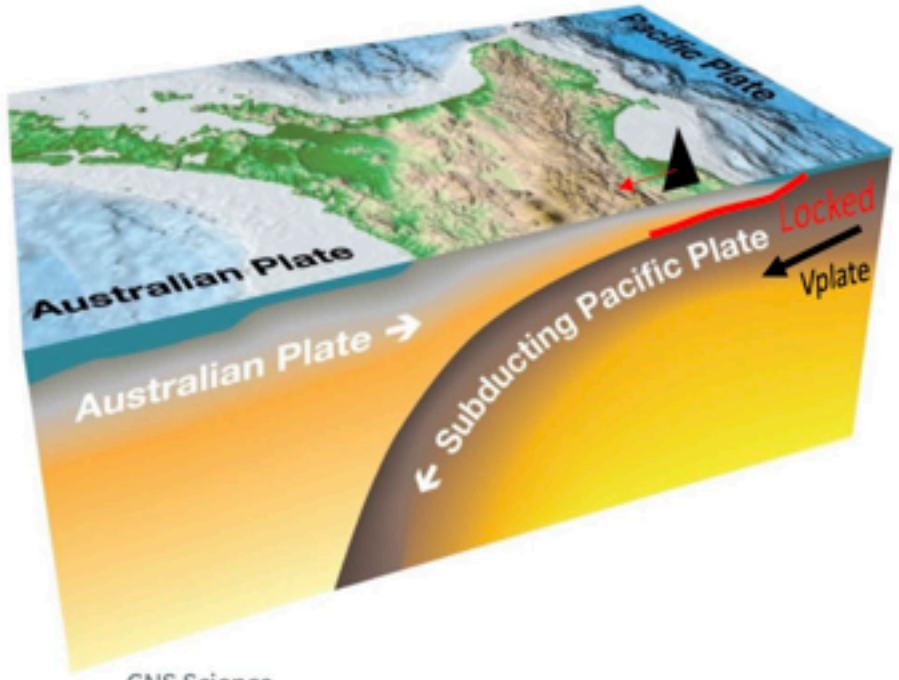

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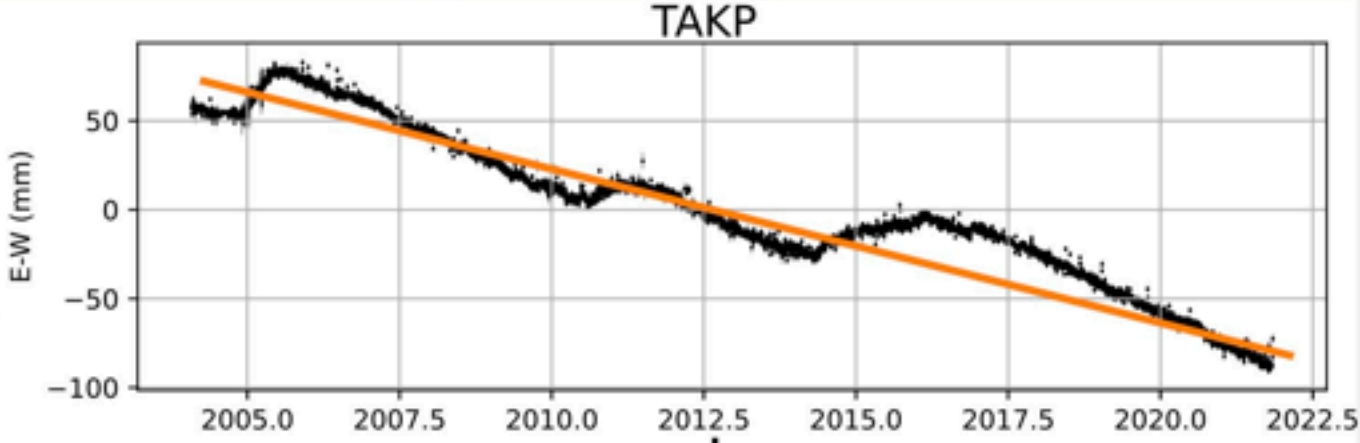
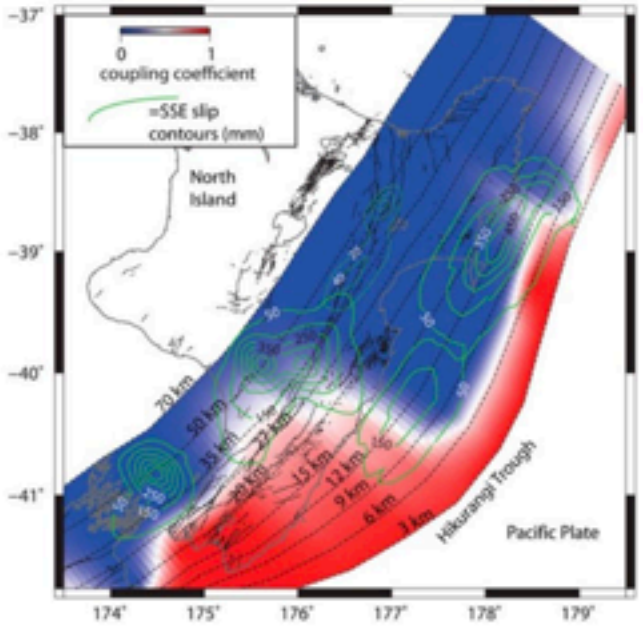


$$\text{Coupling: } \gamma = 1 - \frac{V_{interface}}{V_{plate}}$$

Power et al, 2016



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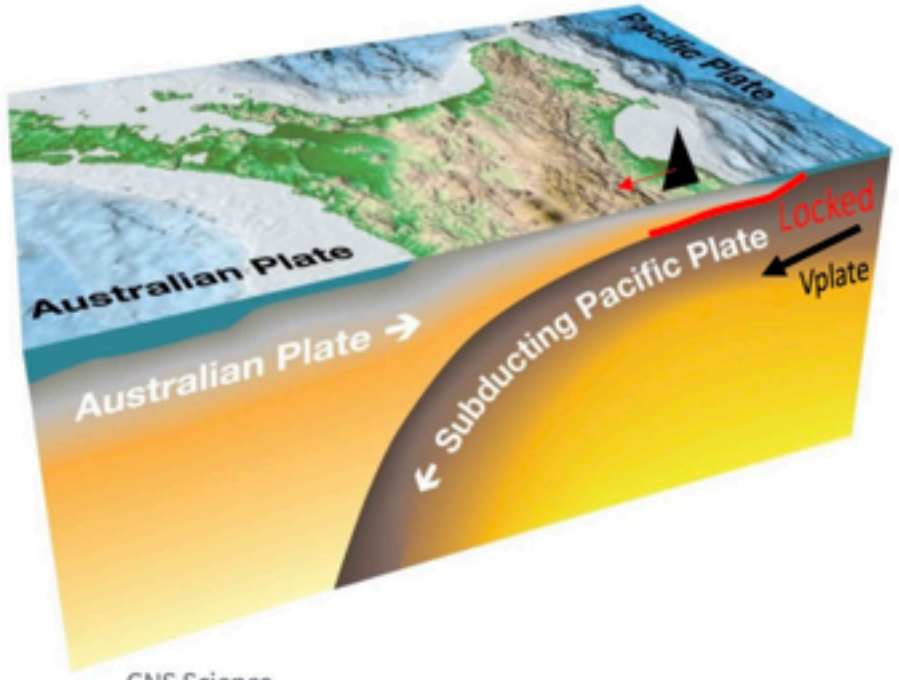

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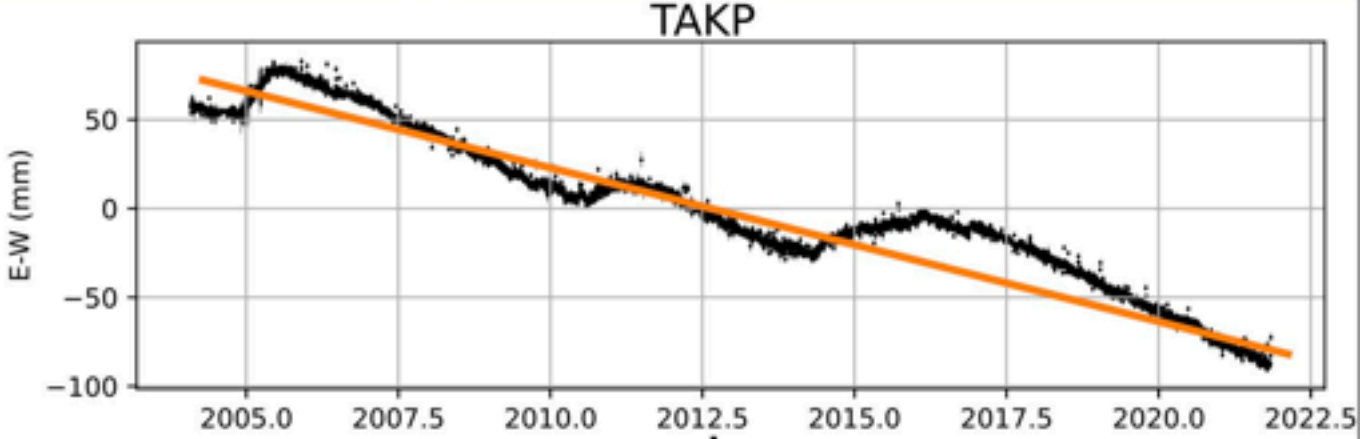

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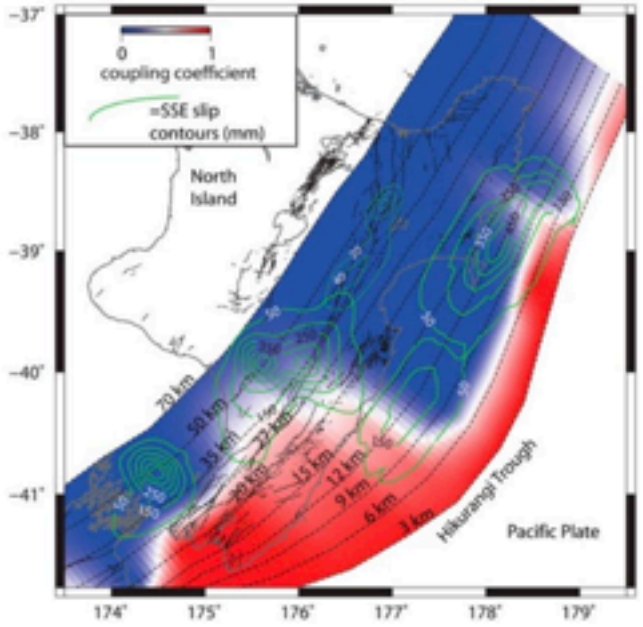

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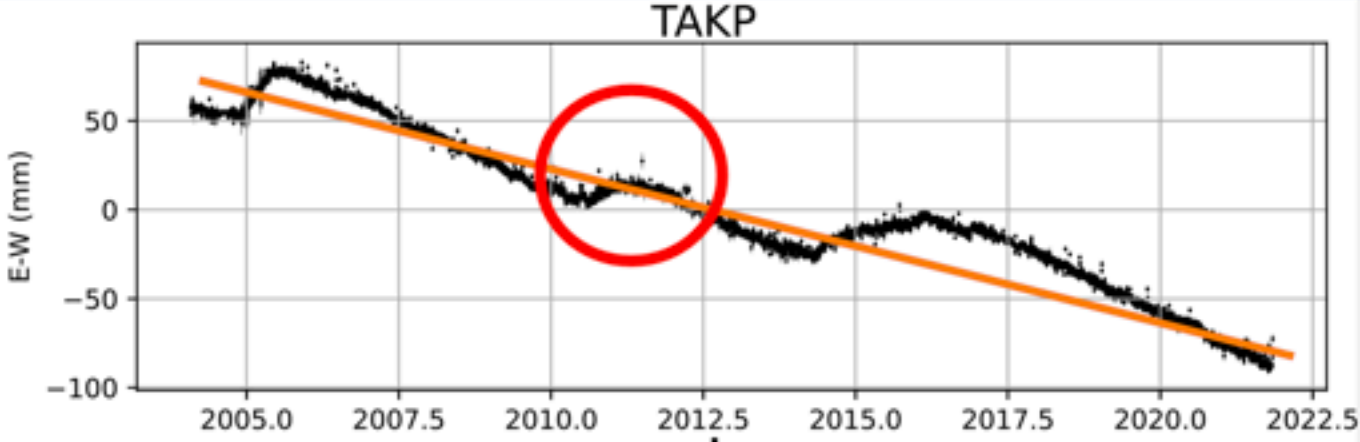
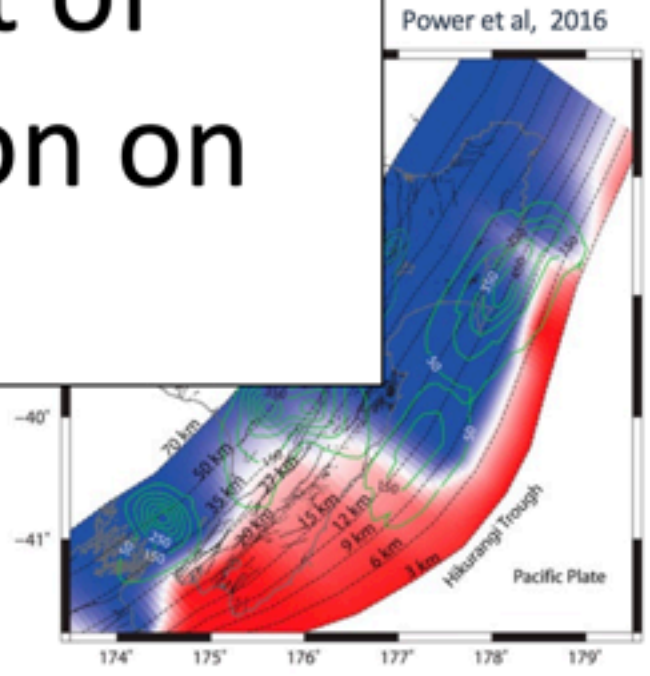


GNS Science

What is the impact of transient deformation on plate coupling?



Scientific motivation

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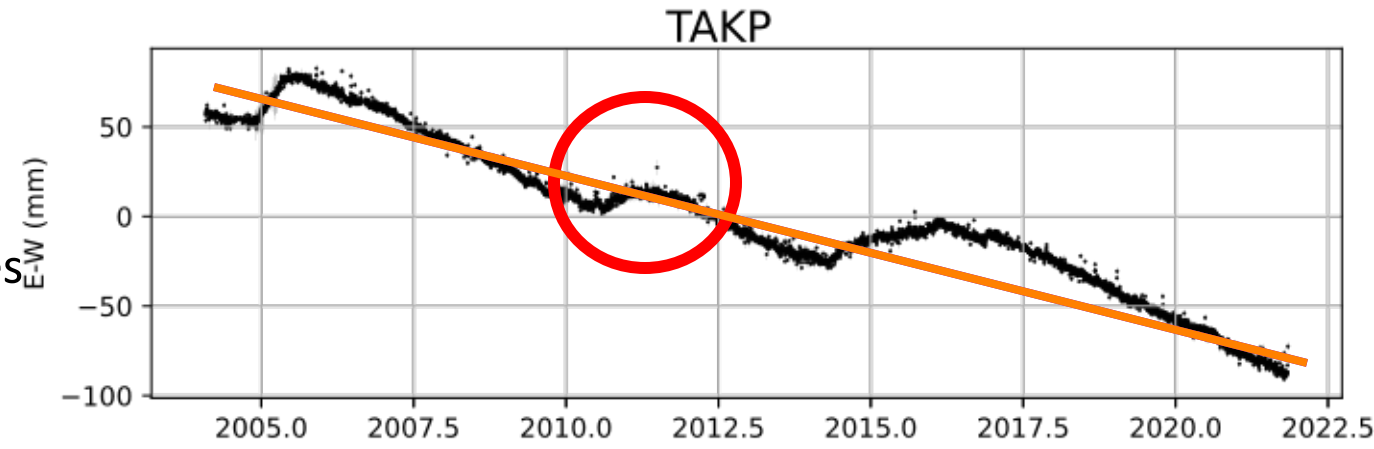

○ If the deformation evolves through time, which observational period should we choose to recover plate coupling?

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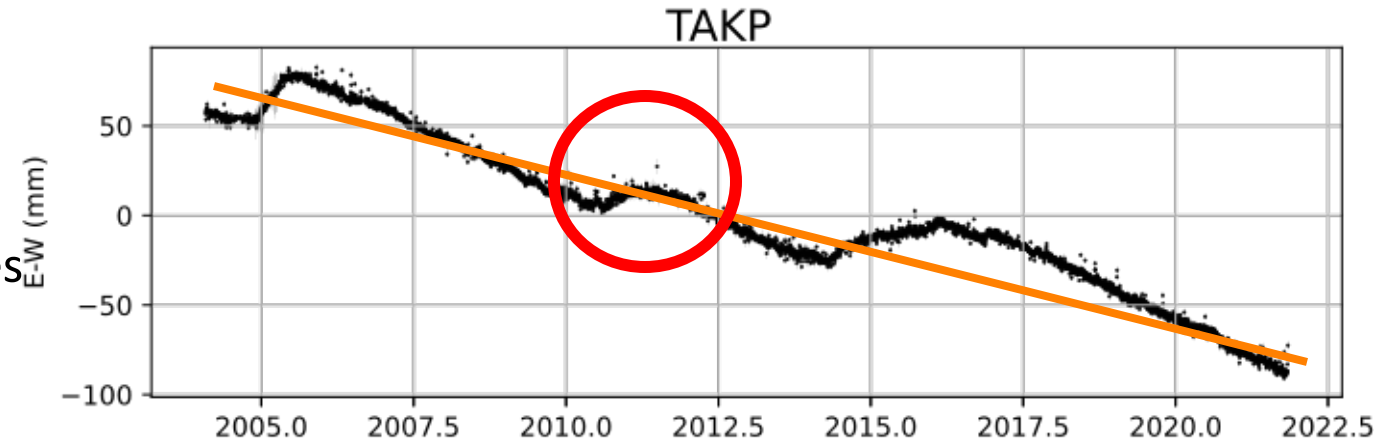

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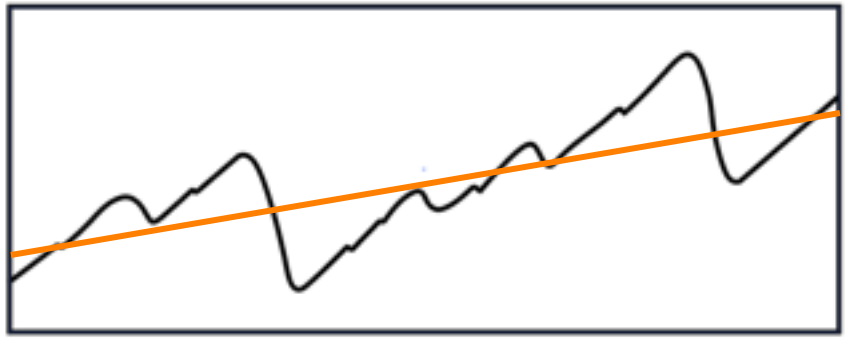
Long-term



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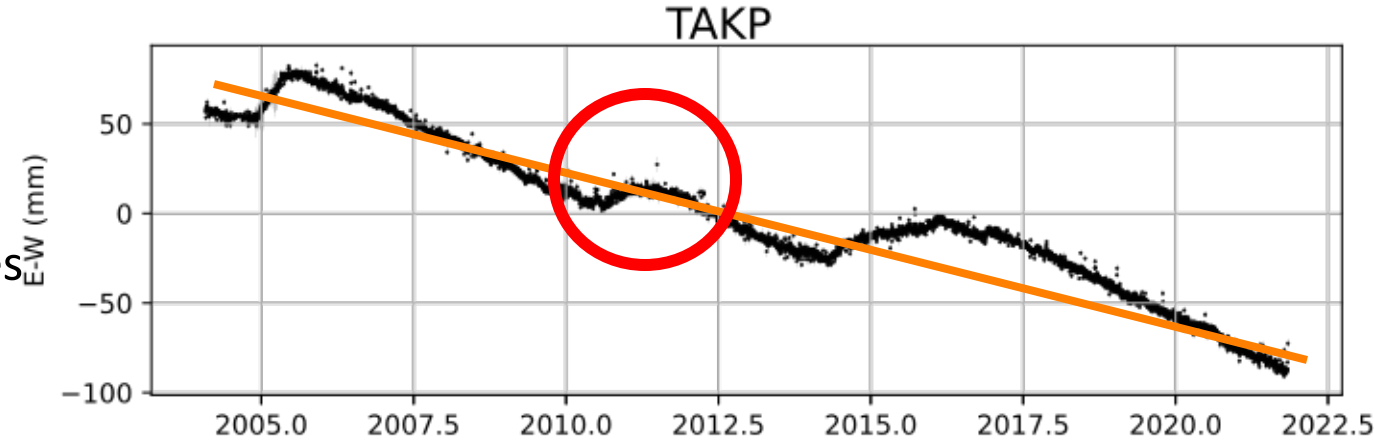

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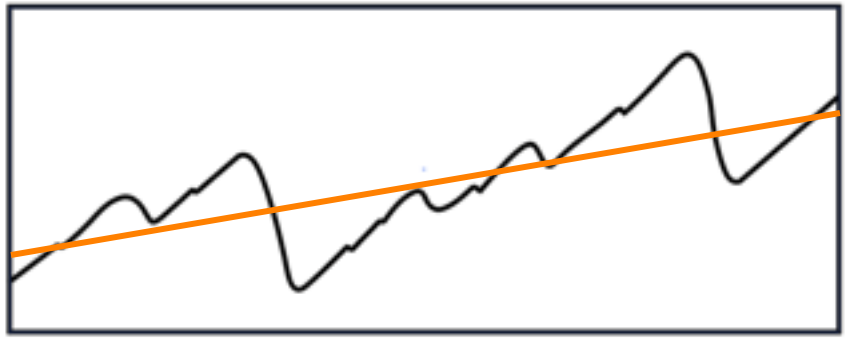
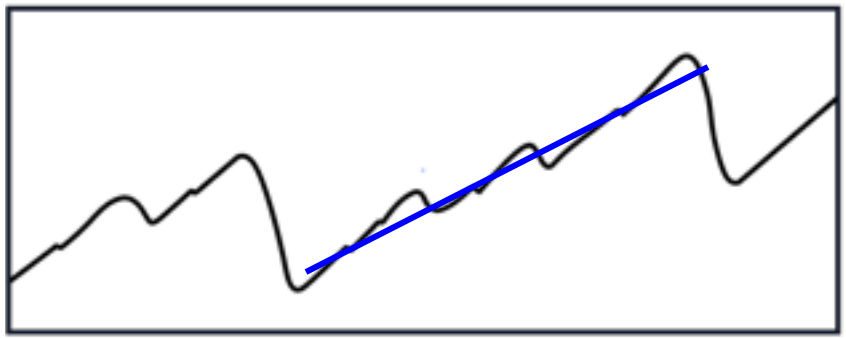


Between long-term slow slip events



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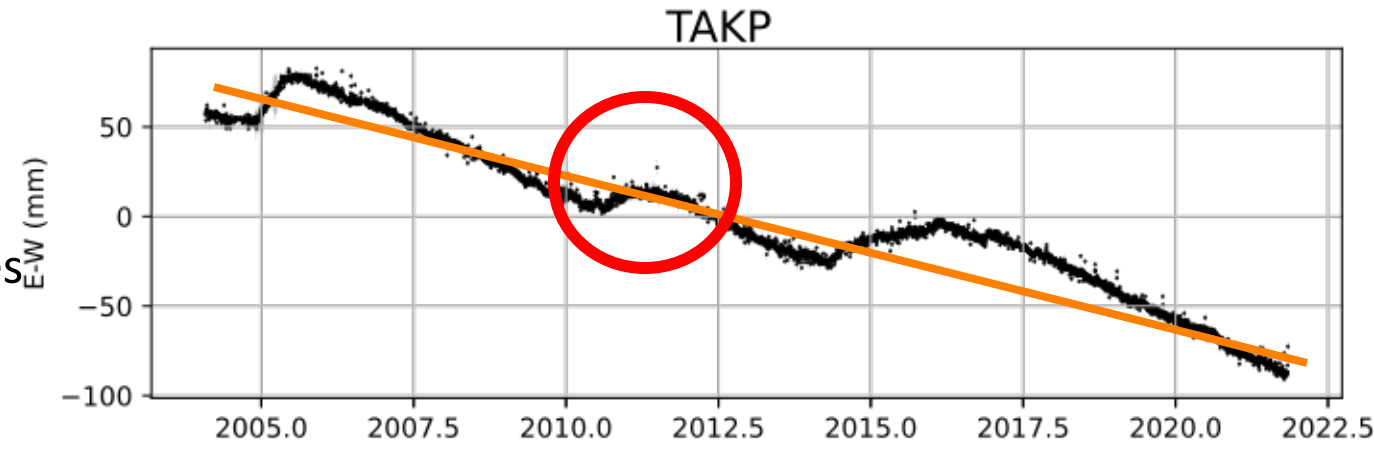

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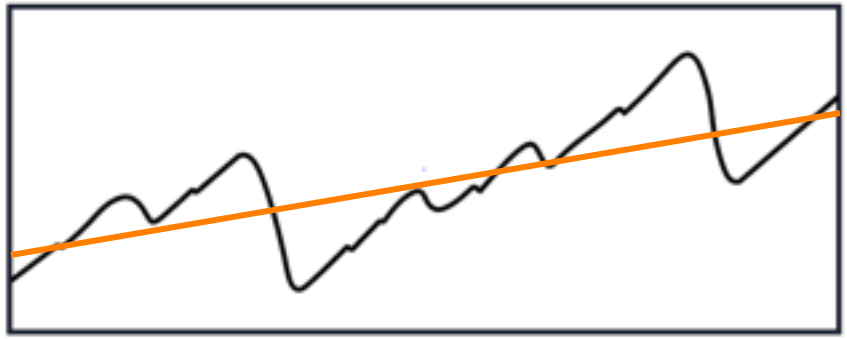

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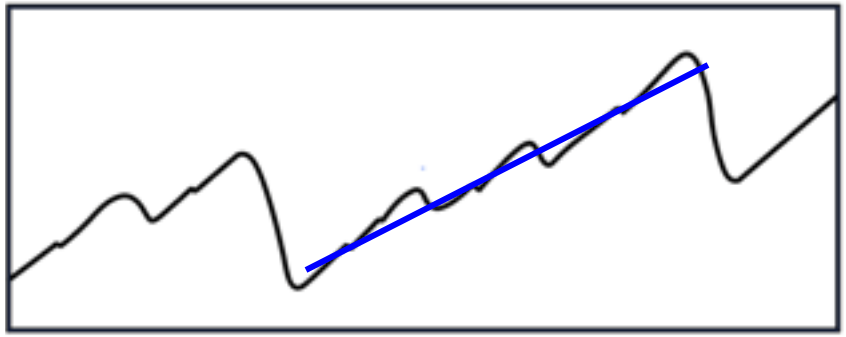
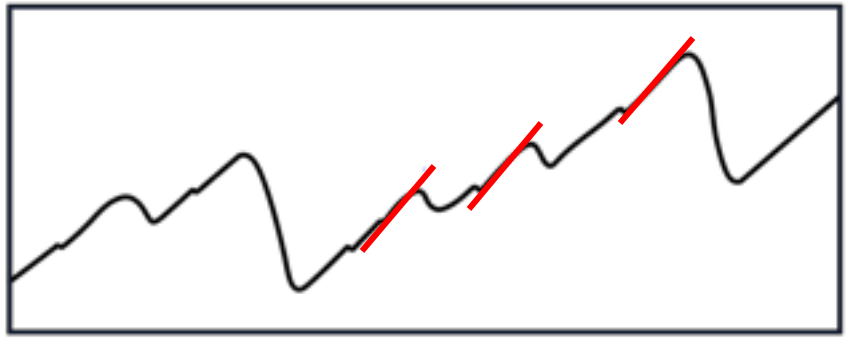


Between every slow slip event



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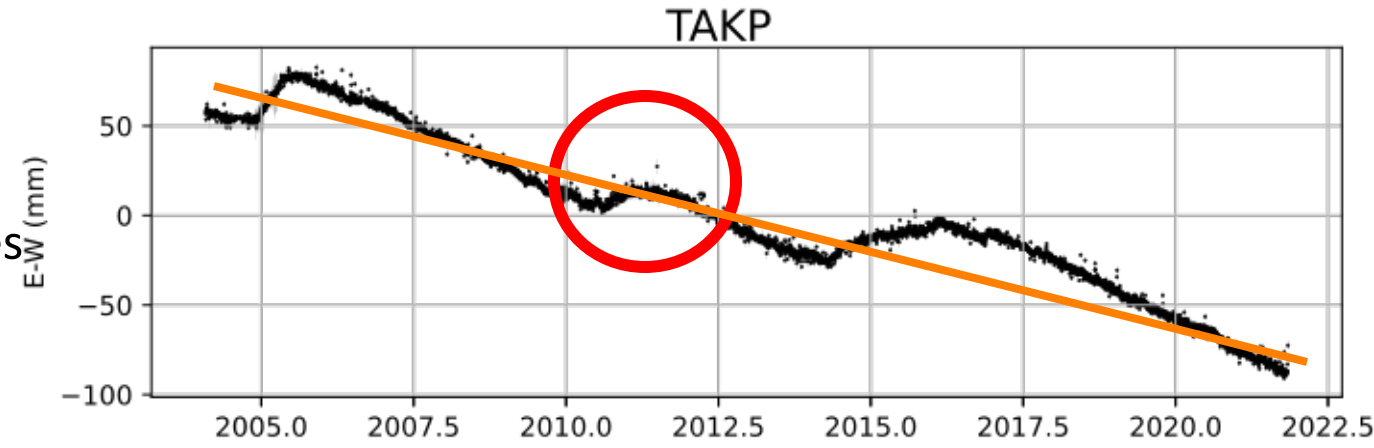

- If the deformation evolves through time, which observational period should we choose to recover plate coupling?
- By looking at different time periods, can we determine kinematic coupling?

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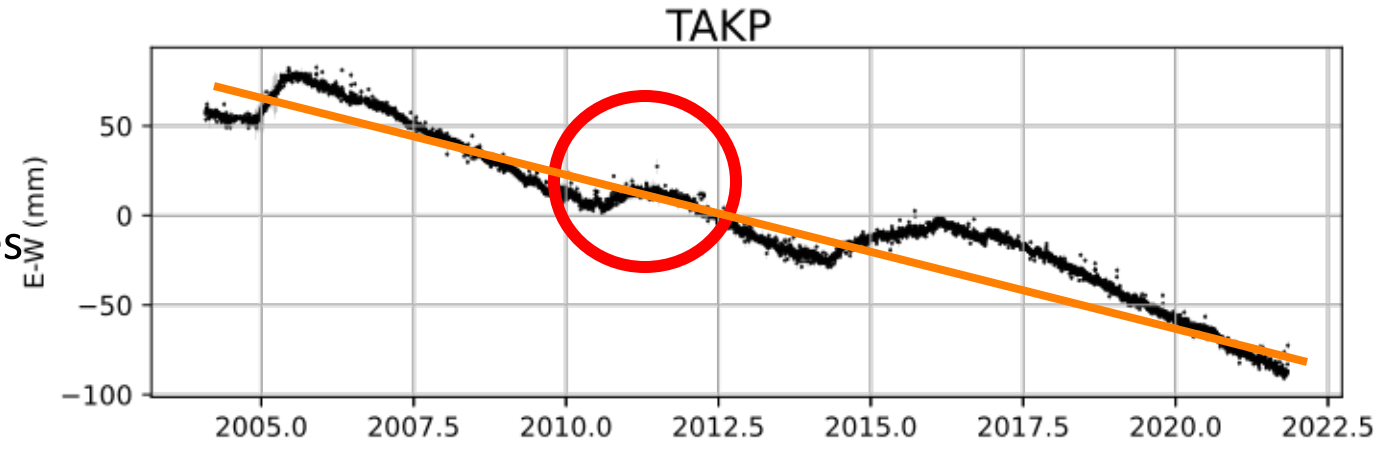


- If the deformation evolves through time, which observational period should we choose to recover plate coupling?
- By looking at different time periods, can we determine kinematic coupling?
- Spatial extent of coupling is directly linked to future seismic hazard; does GNSS provide sufficient resolution to accurately recover coupling?

Scientific motivation

- If the deformation evolves through time, **which observational period should we choose** to recover plate coupling?
- By looking at different time periods, can we determine **kinematic coupling**?
- The spatial extent of coupling is directly linked to future seismic hazard; **does GNSS provide sufficient resolution** to accurately recover coupling?

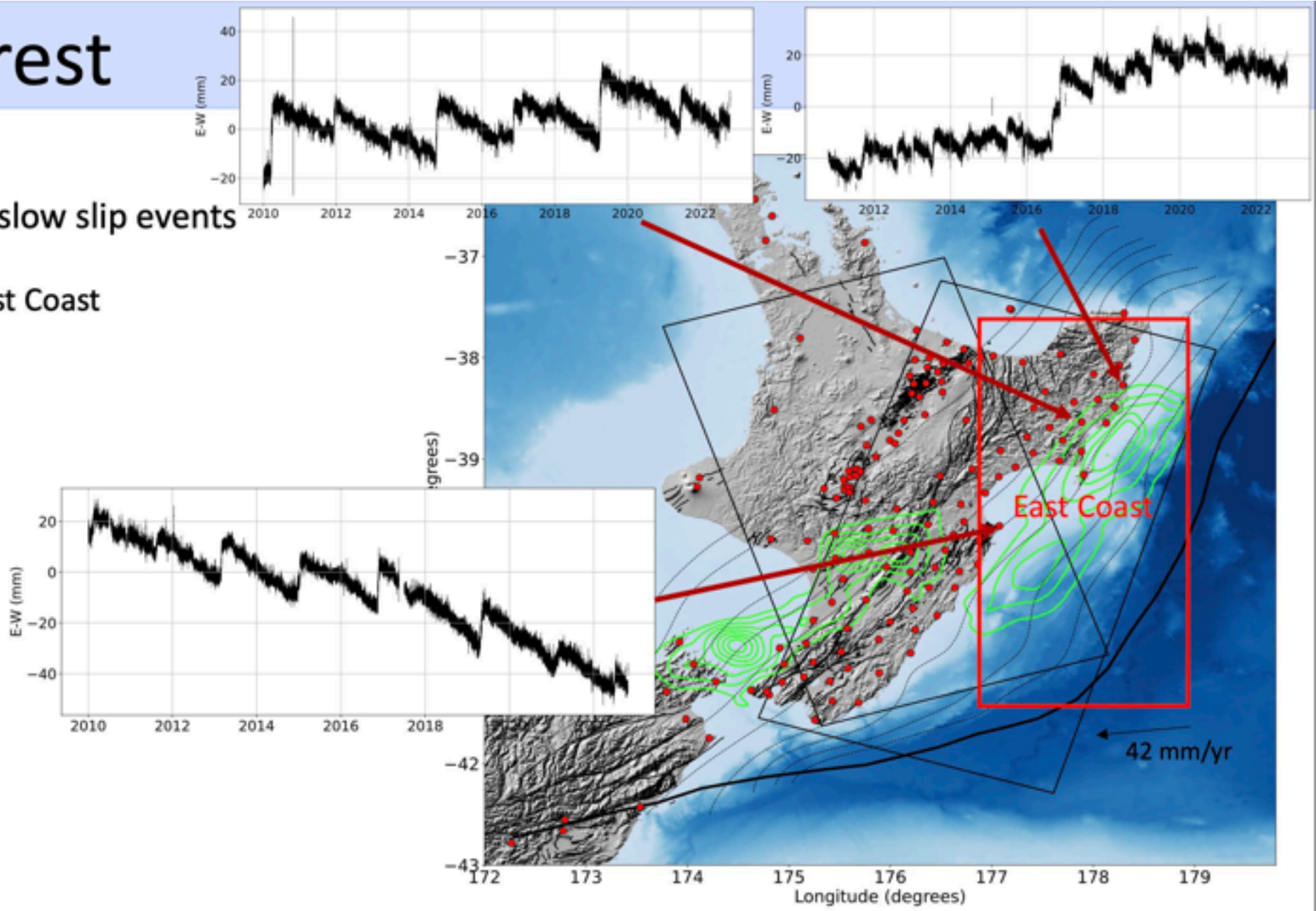
Practical approach:

- **Geodetic study**: Using GNSS and InSAR time series (Sentinel-1) → to enhance the spatial coverage of the GNSS network
- **Geodetic inversion** of slip deficit on the interface ⇒ Plate coupling of the interface

Region of Interest

- Hikurangi subduction:
  - Shallow and short-term slow slip events
    - East Cape
    - Gisborne
    - Hawke Bay

East Coast



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- Hikurangi subduction:
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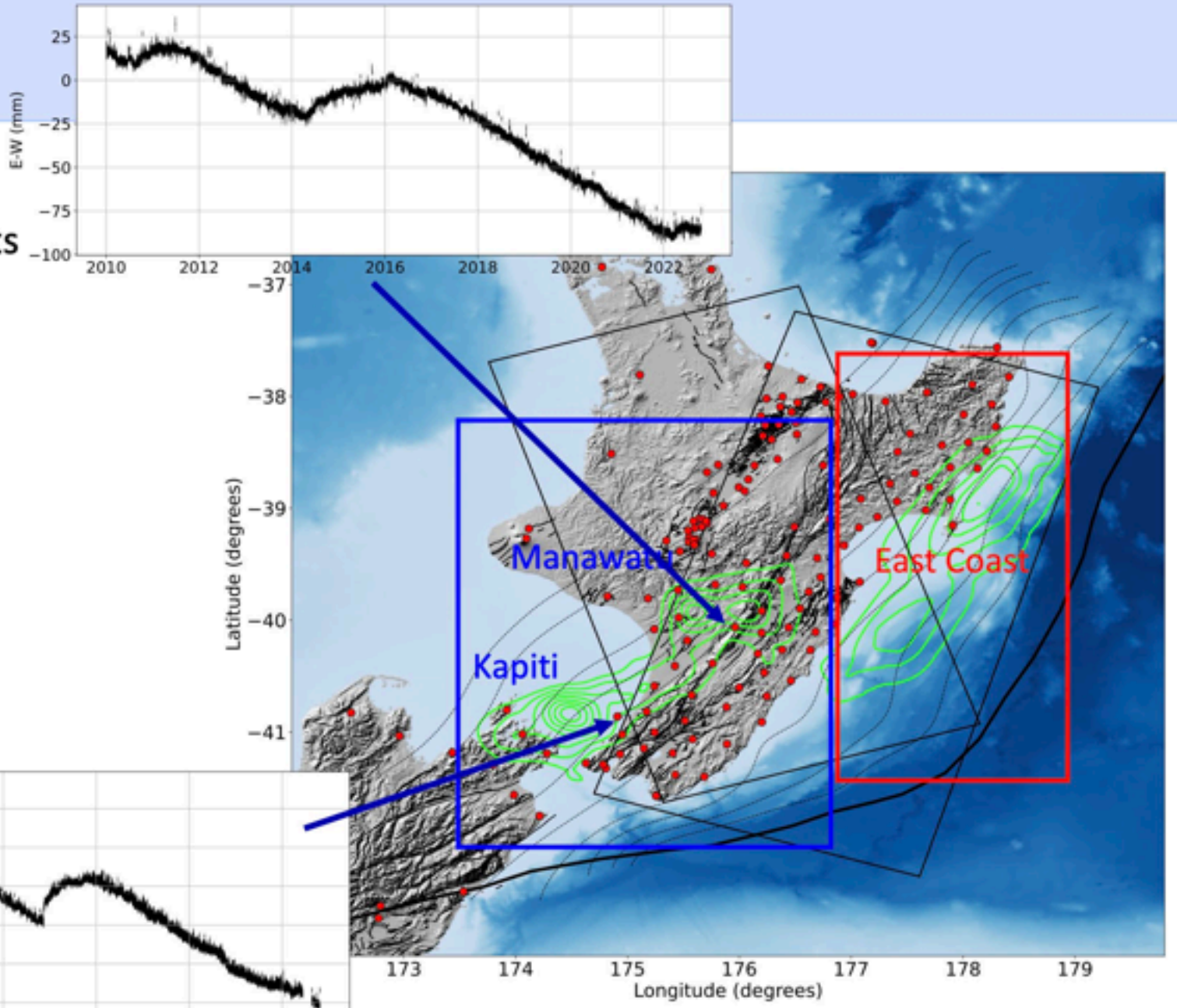
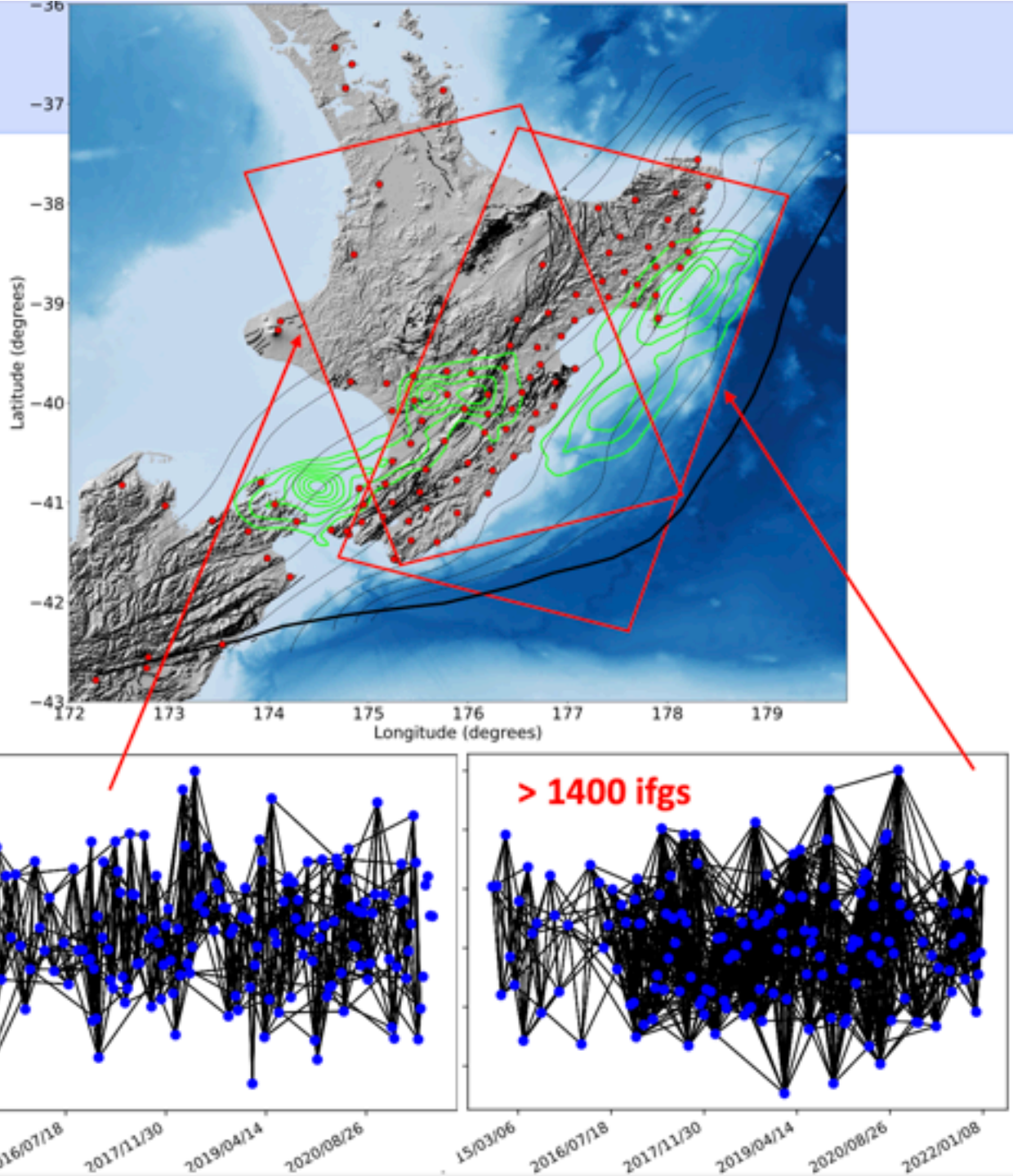
    - East Cape
    - Gisborne
    - Hawke Bay

    East Coast
  - Deep and long-term slow slip events
    - Kapiti
    - Manawatu



Geodetic dataset

- GNSS: 92 stations
- InSAR Time series (Sentinel-1):
  - 1 image every 6 - 12 days since Nov. 2014
  - Long temporal baseline to mitigate biases
  - Atmospheric mitigation: ERA5
  - Time series construct using a Small baseline approach with NSBAS *(Doin, et al. 2011)*



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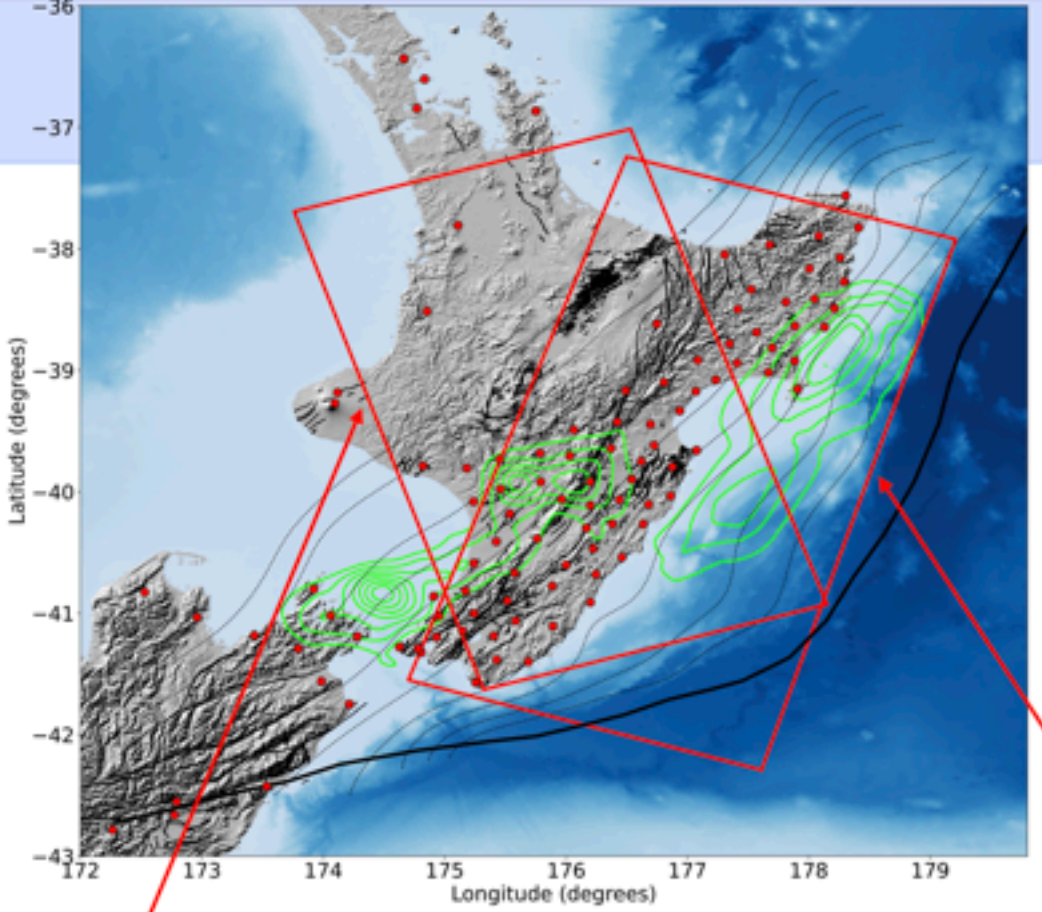
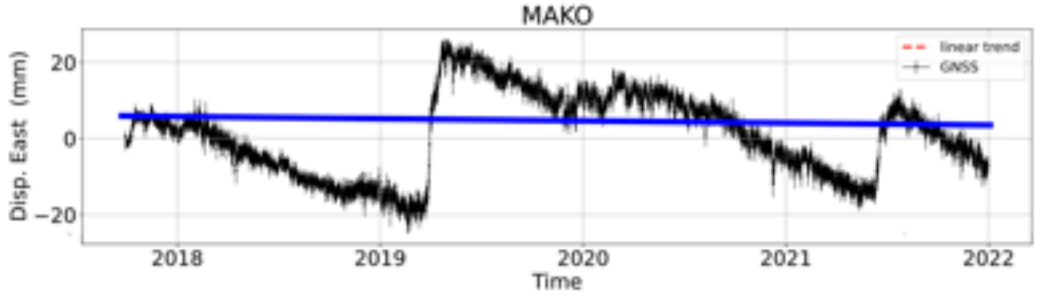
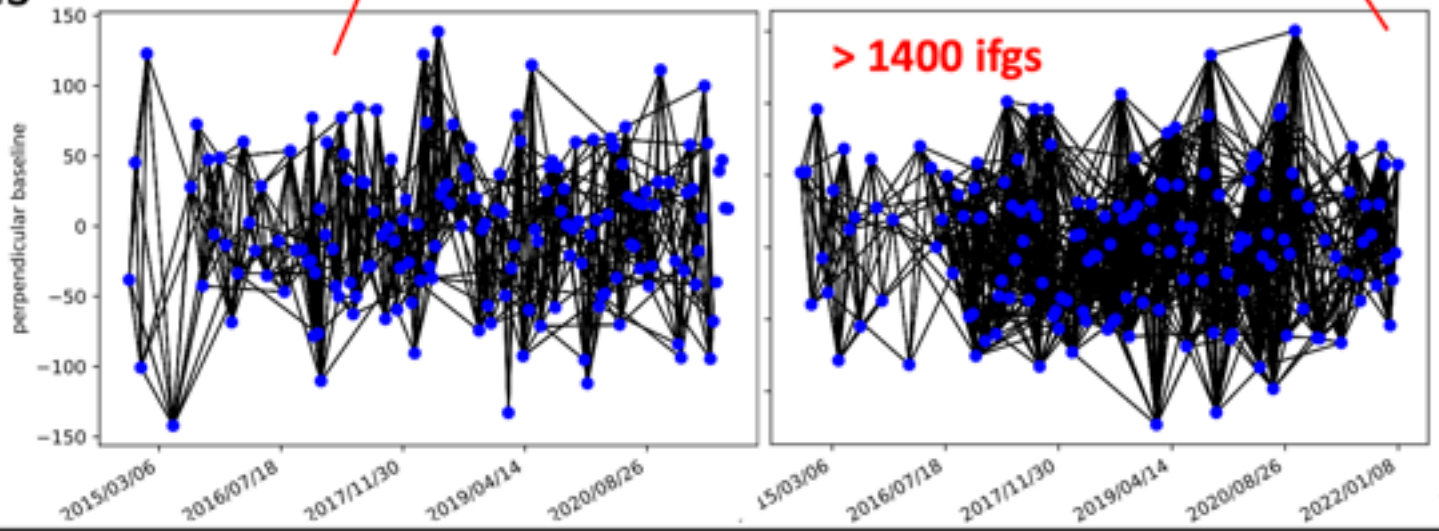


- Trajectory model to obtain the velocities
  - Least squares approach

$$u(t) = Vt + u_0$$



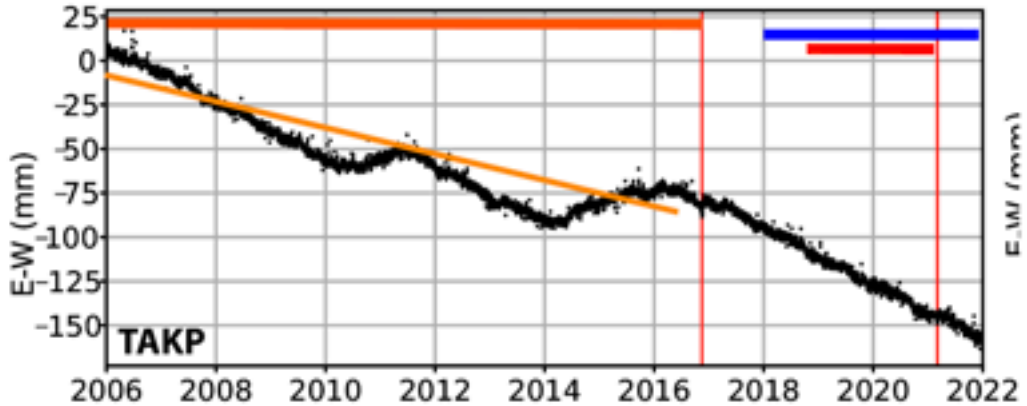


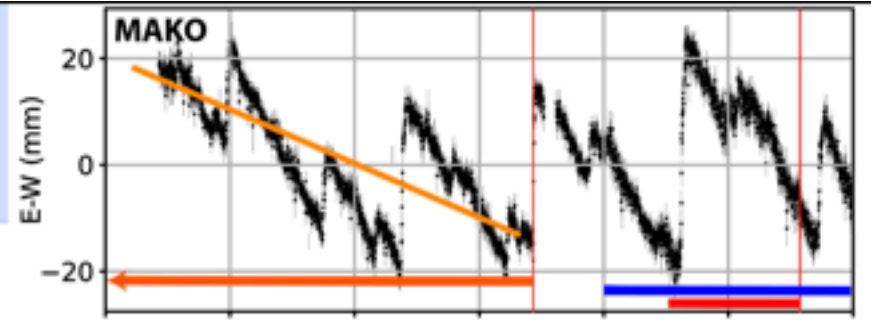
What period shall we study?

a. **Long-term**

Observation period: 2006 – 2016

- Before Kaikōura Earthquake (Nov 2016, Mw 7.8)





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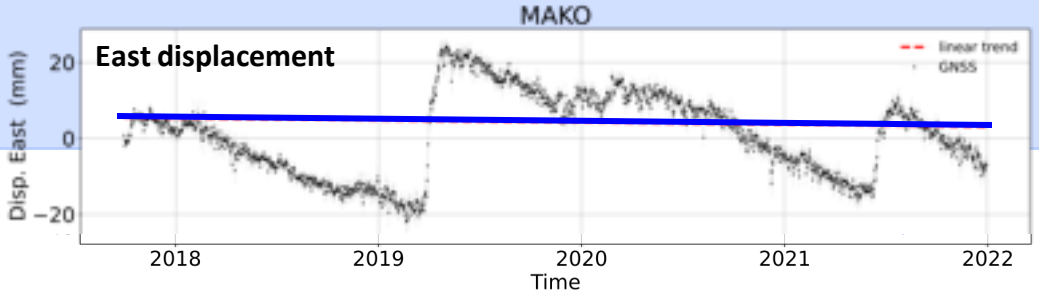
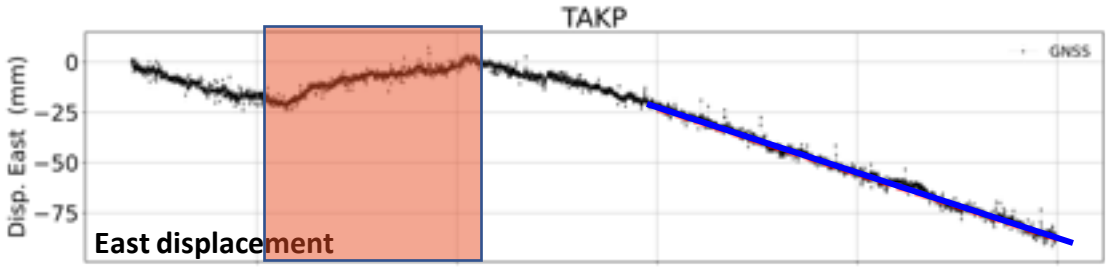
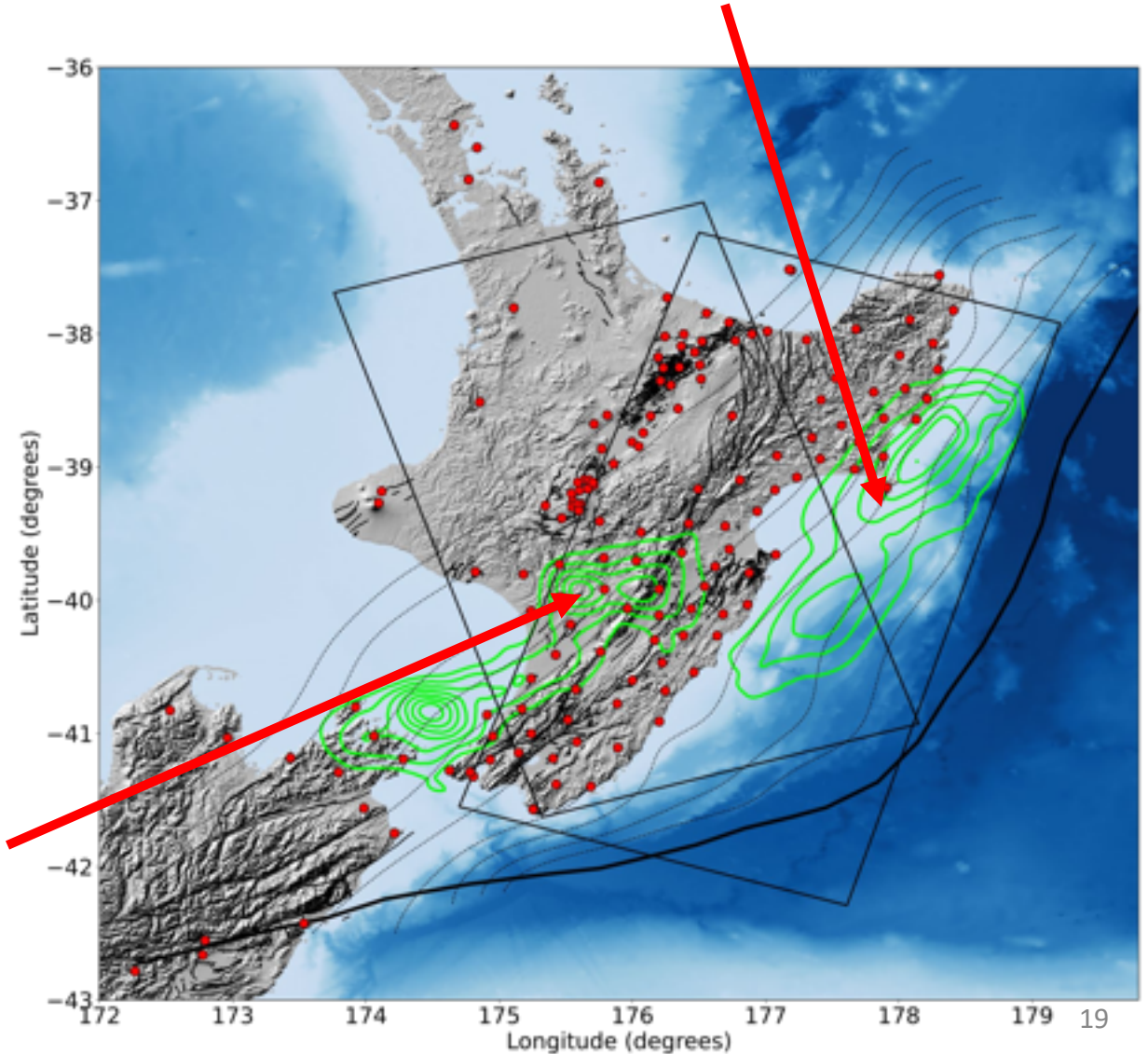


b. Inter-deep-SSE (between Manawatu and Kapiti SSEs)
Observation period: 2018 – 2022

- Impacted by shallow transient deformation





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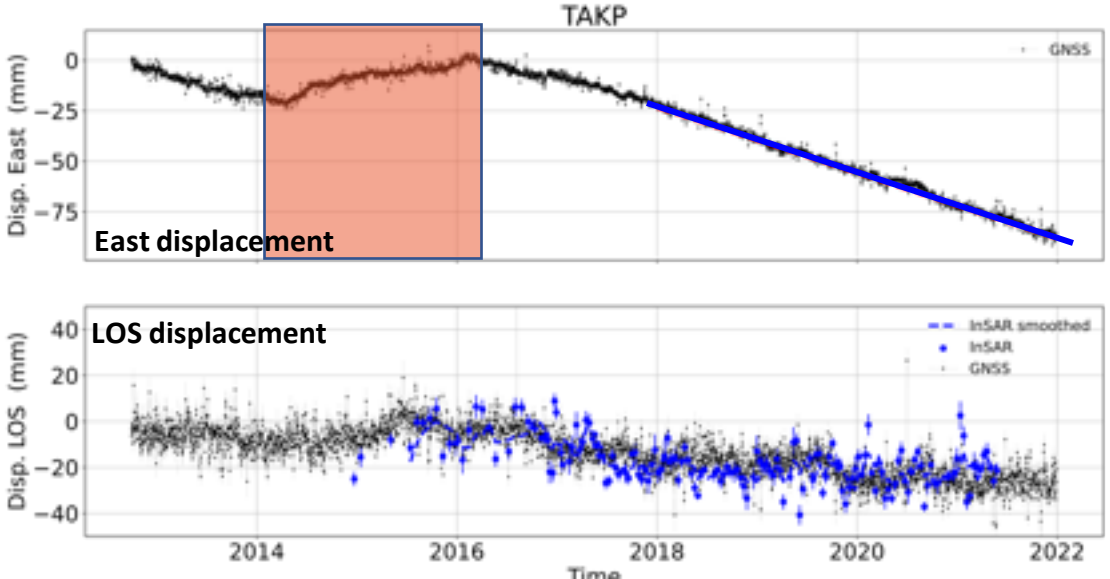

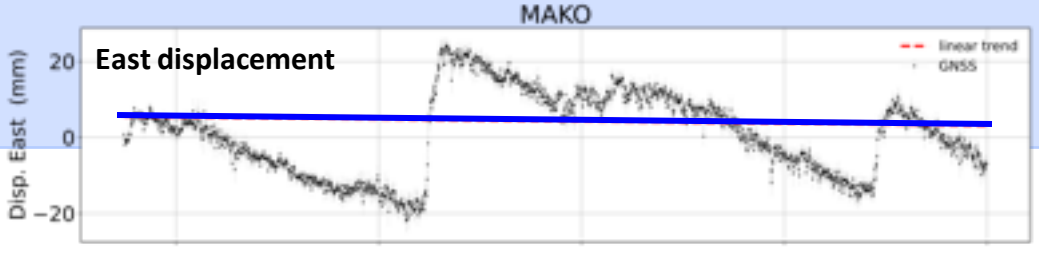

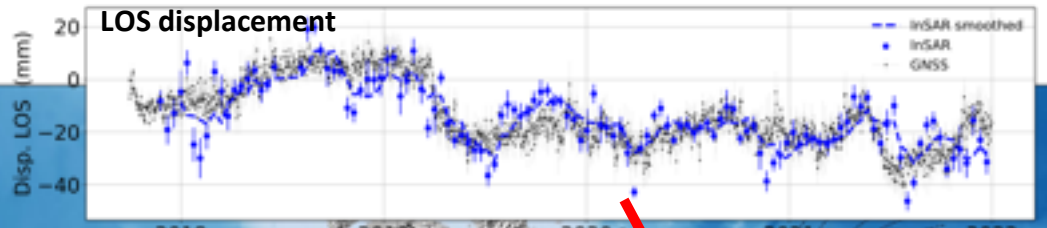

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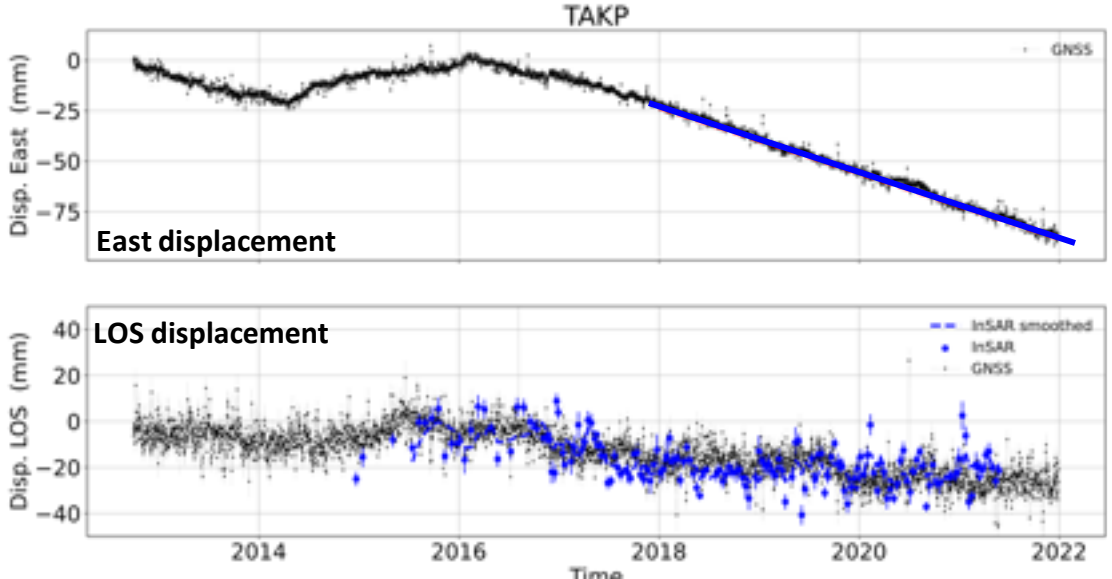
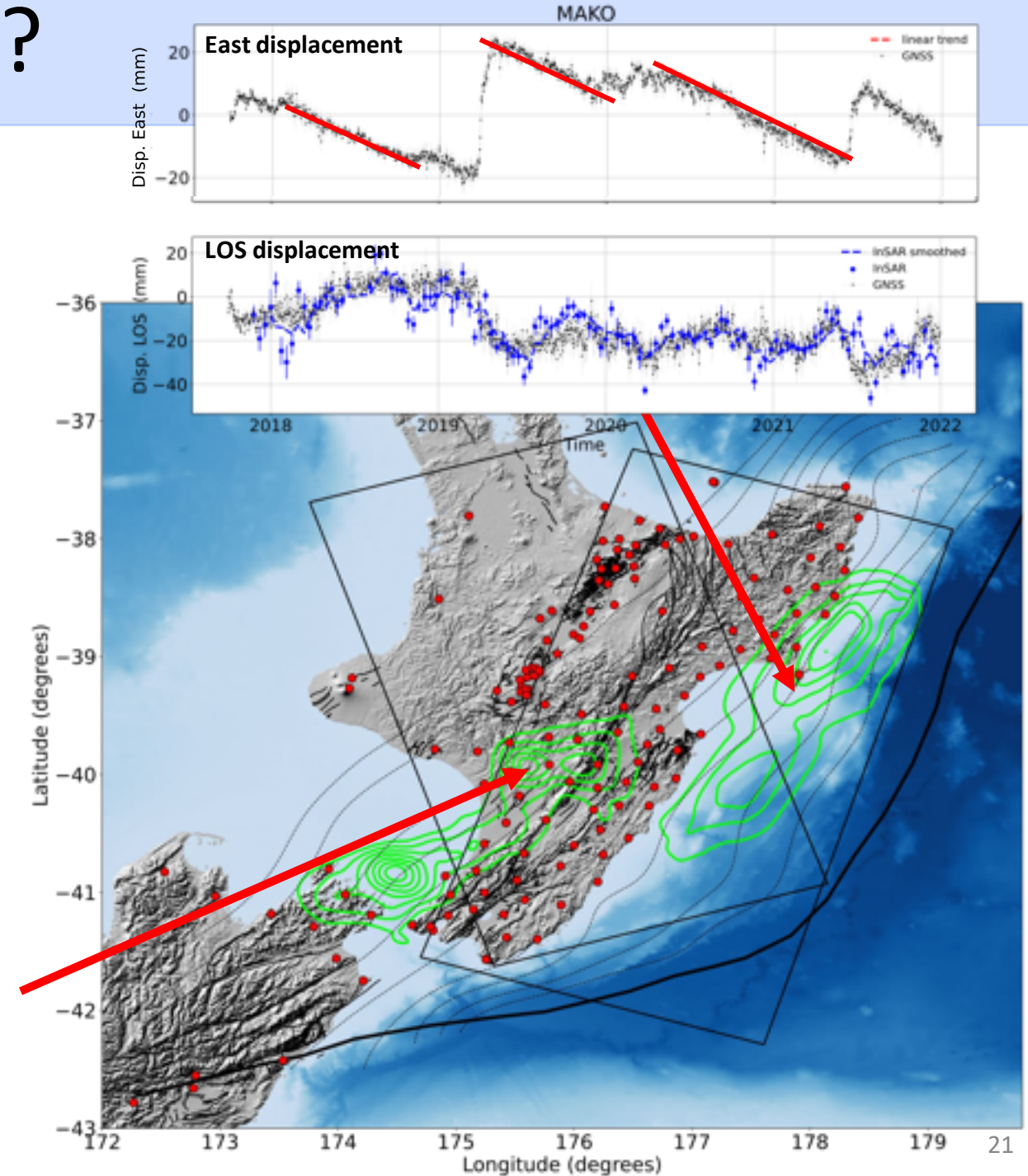
- Impacted by shallow transient deformation
- Robust estimation of the velocities over InSAR time series

c. **Inter-SSE** (between every SSEs)

- Different period windows needed for every region
- Difficult to estimate velocities in regions with short-term SSEs using InSAR data





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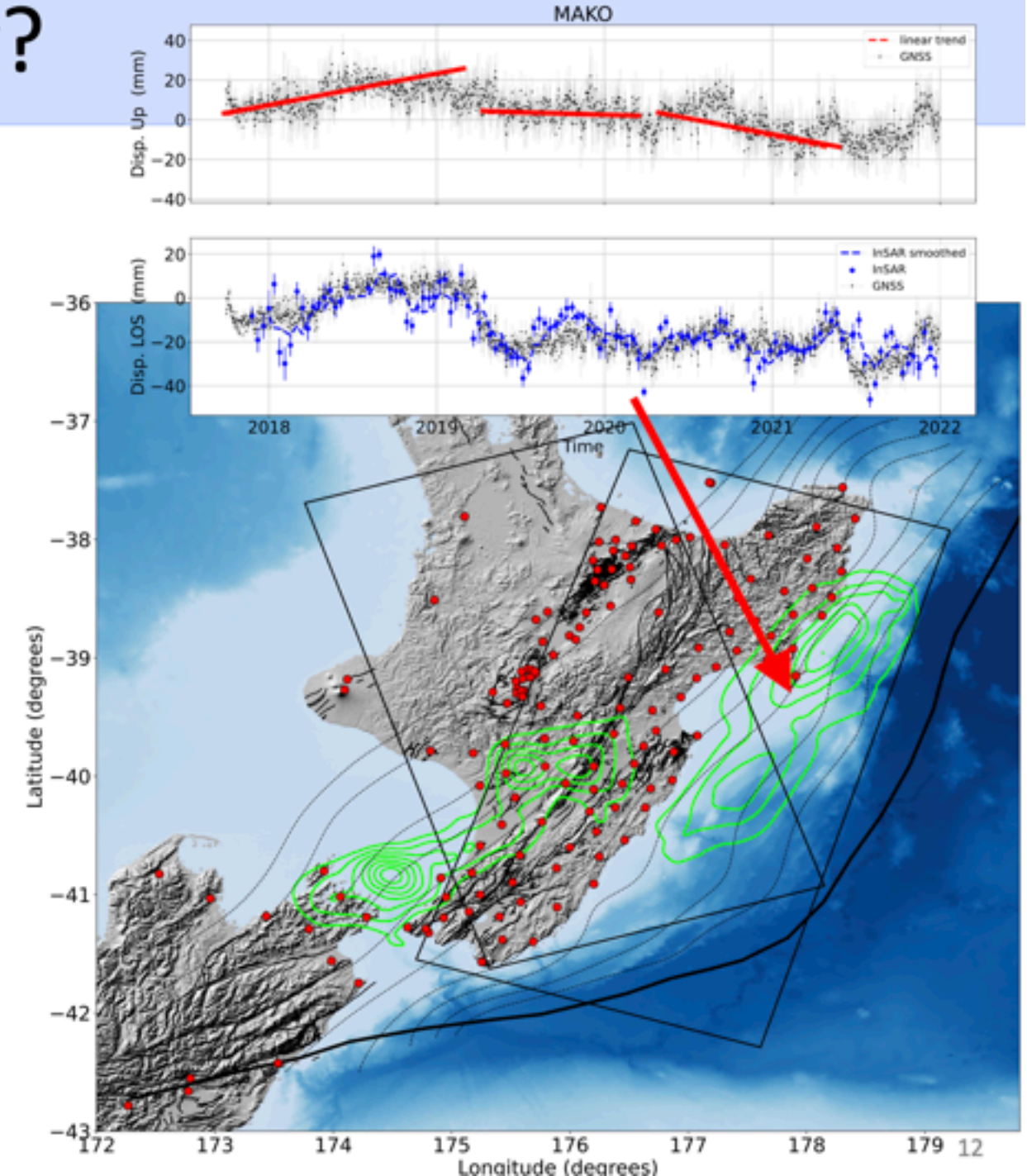
- Impacted by shallow transient deformation
- Robust estimation of the velocities over InSAR time series

c. **Inter-SSE** (between every SSEs)

- Different period windows needed for every region
- Difficult to obtain an estimation of the velocities in short-term SSEs regions using InSAR data
- Impossible to obtain coherent velocities on vertical displacements due to seasonal signals



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b. Inter-deep-SSE (between Manawatu and Kapiti SSEs)
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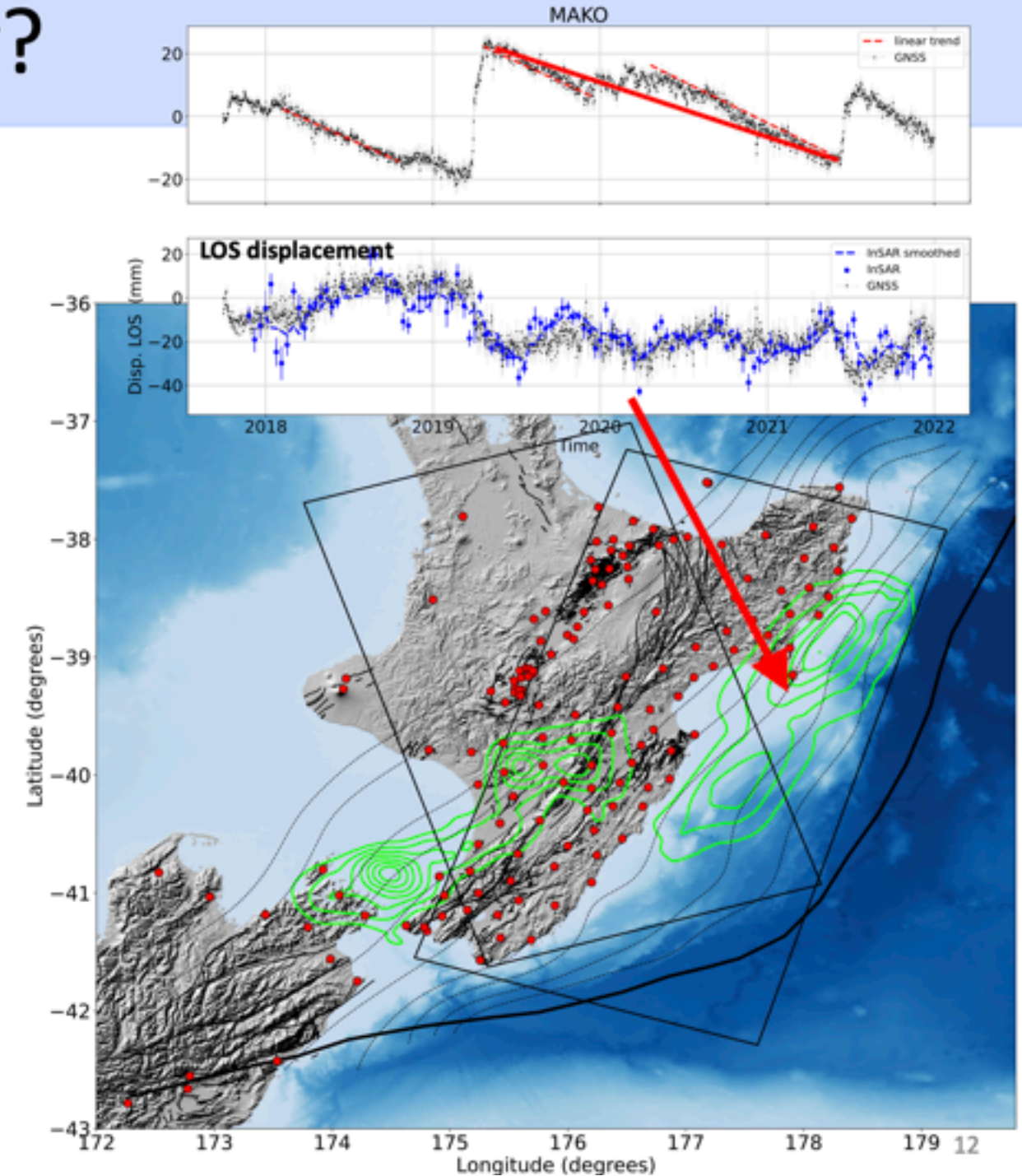
c. ~~Inter-SSE (between every SSEs)~~

- Different period windows needed for every region
- Difficult to obtain an estimation of the velocities in short-term SSEs regions using InSAR data
- Impossible to obtain coherent velocities on GNSS vertical displacements

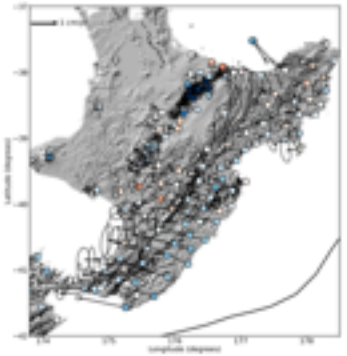
Inter-major-SSE

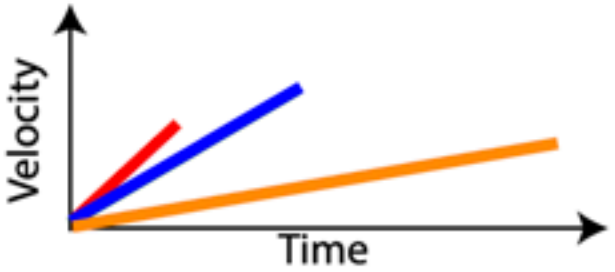
Observation period: 2019.4 – 2021.3



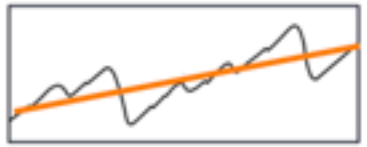
What period shall we study?

- Three options:

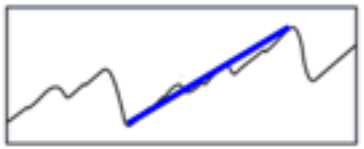


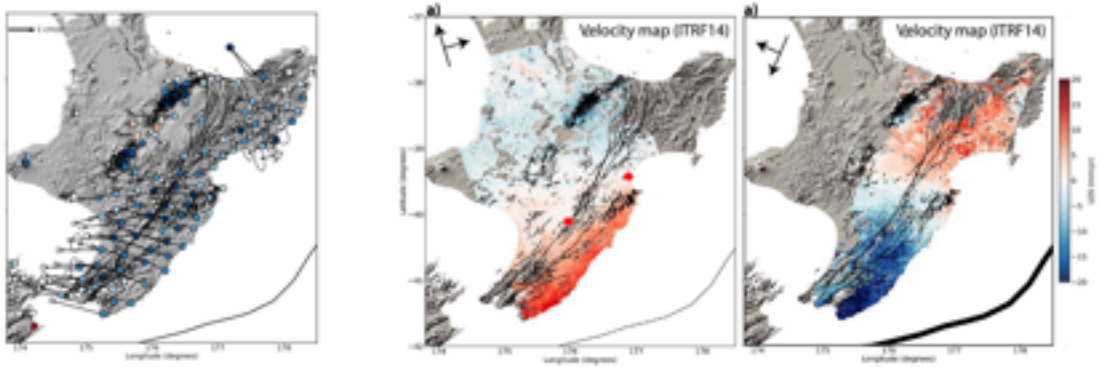


a) 10yr: over 2006.0 – 2016.0: **only GNSS**

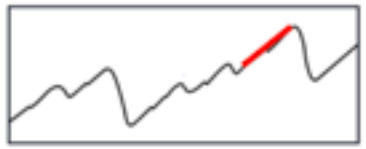


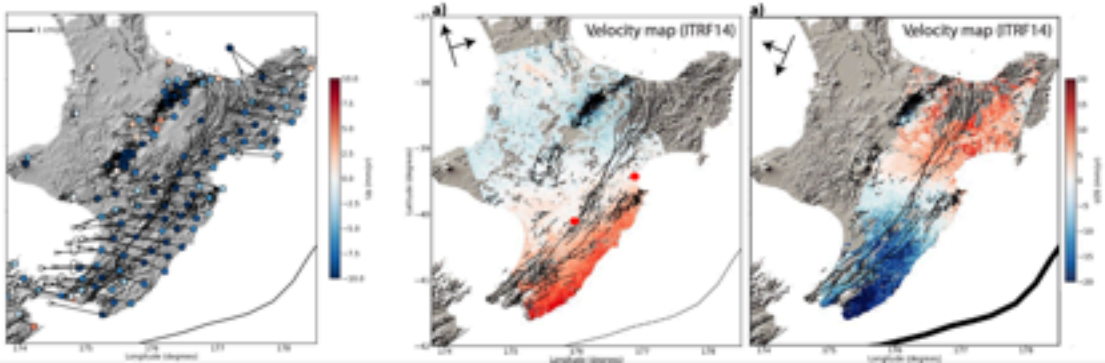
b) 4yr: over 2018.0 – 2022.0 Between deep SSEs: **GNSS + InSAR**





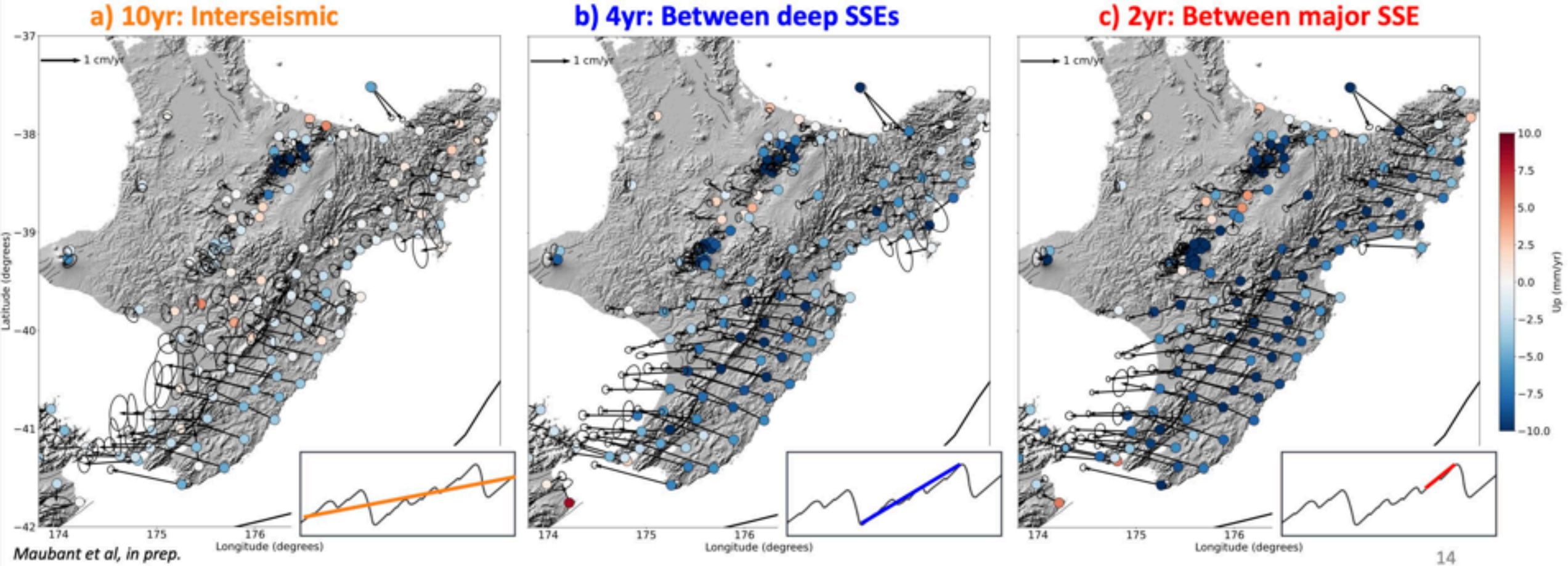
c) 2yr: over 2019.4 – 2021.3 Between major SSEs**: GNSS + InSAR**





GNSS data

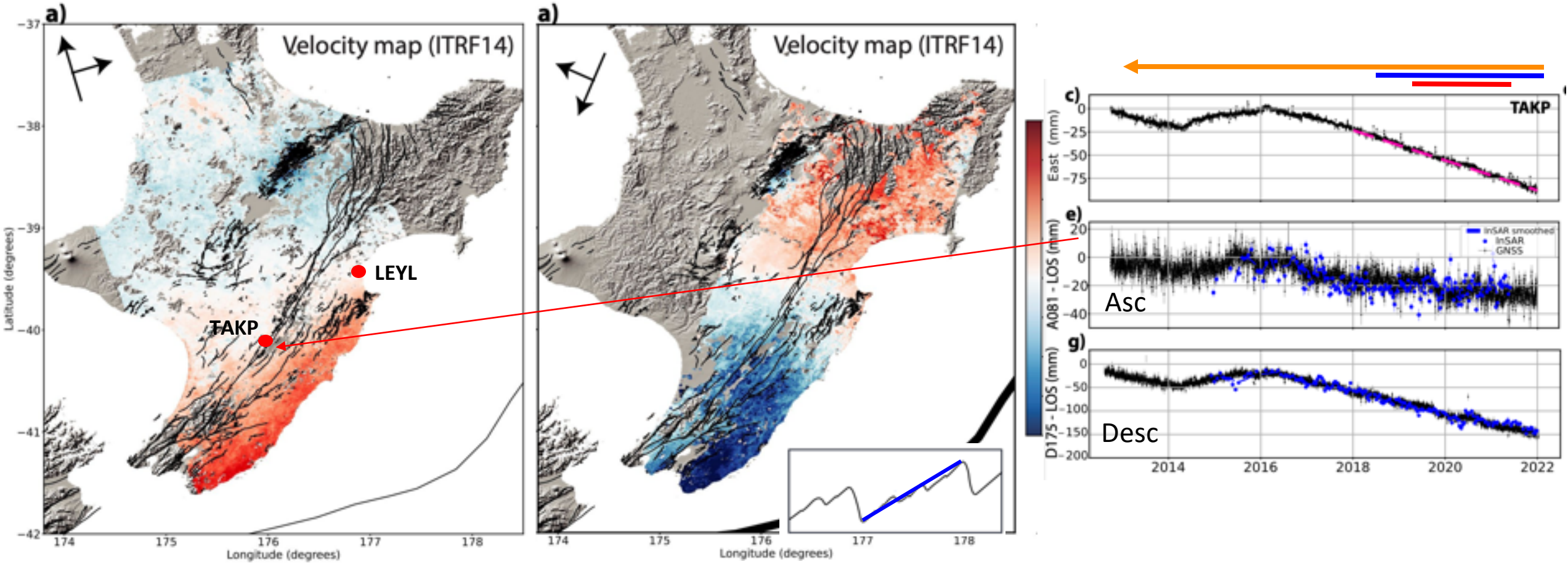
- Three options:
  a. 10 years; over 2006 – 2016: only GNSS
  b. 4 years; over 2018 – 2022; between **deep** SSEs: GNNS + InSAR
  c. 2 years; over 2019 – 2021; between **major** SSEs: GNSS + InSAR



Maubant et al, in prep.

InSAR data 4yr: Between deep SSEs

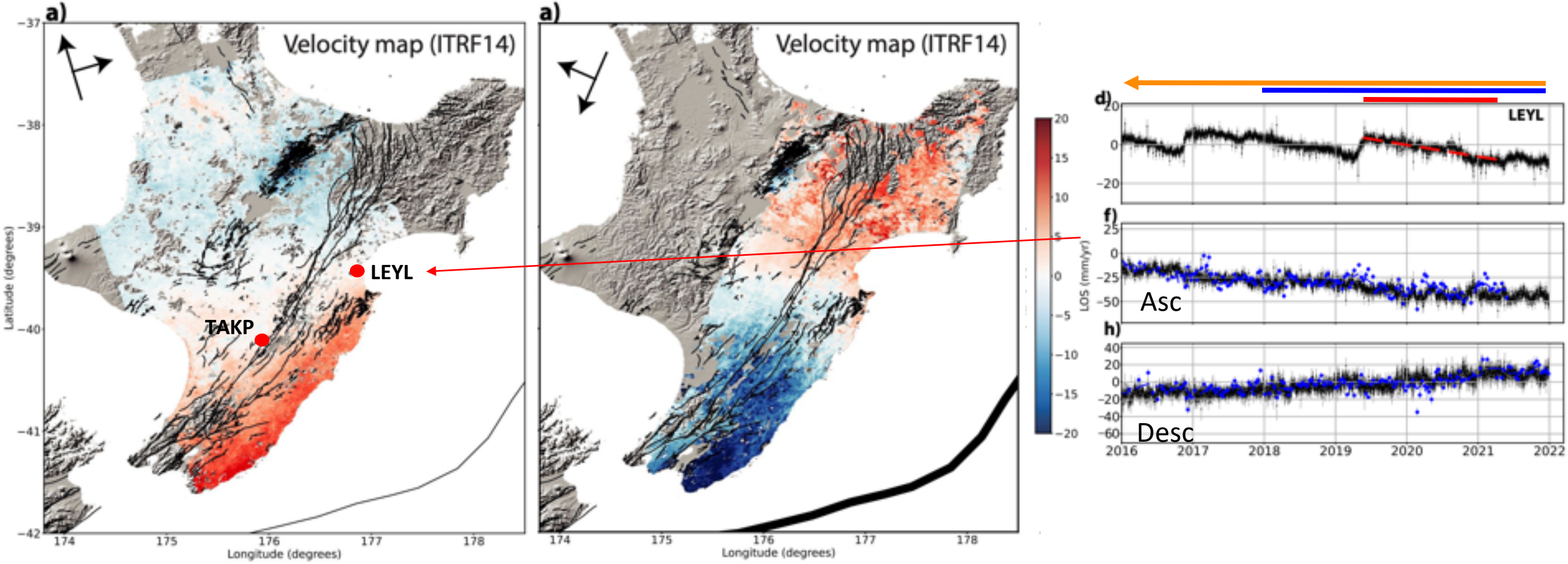
- **InSAR time series correlated with GNSS time series converted in LOS**
- **InSAR can detect deep slow slip events**



Maubant et al., under review

InSAR data 4yr: Between deep SSEs

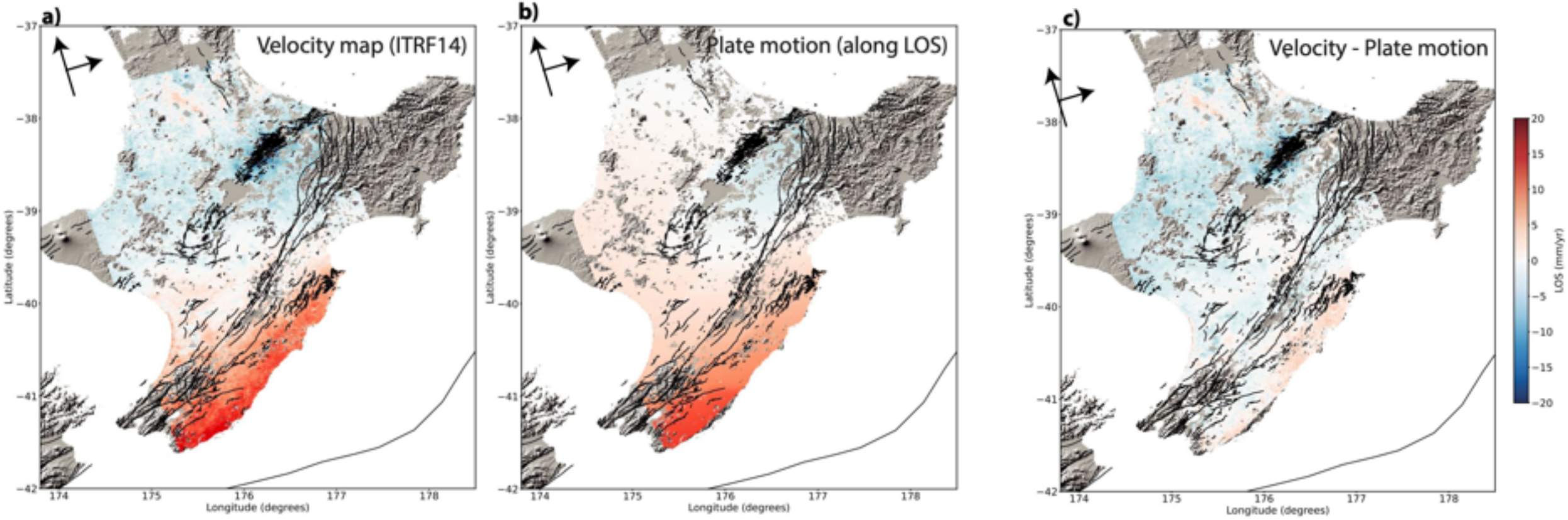
- **InSAR time series correlated with GNSS time series converted in LOS**
- **InSAR cannot detect the shallow slow slip events**
  - **Small vertical displacements, orbit geometries, fault geometry**



Maubant et al., under review

InSAR data: plate motion correction

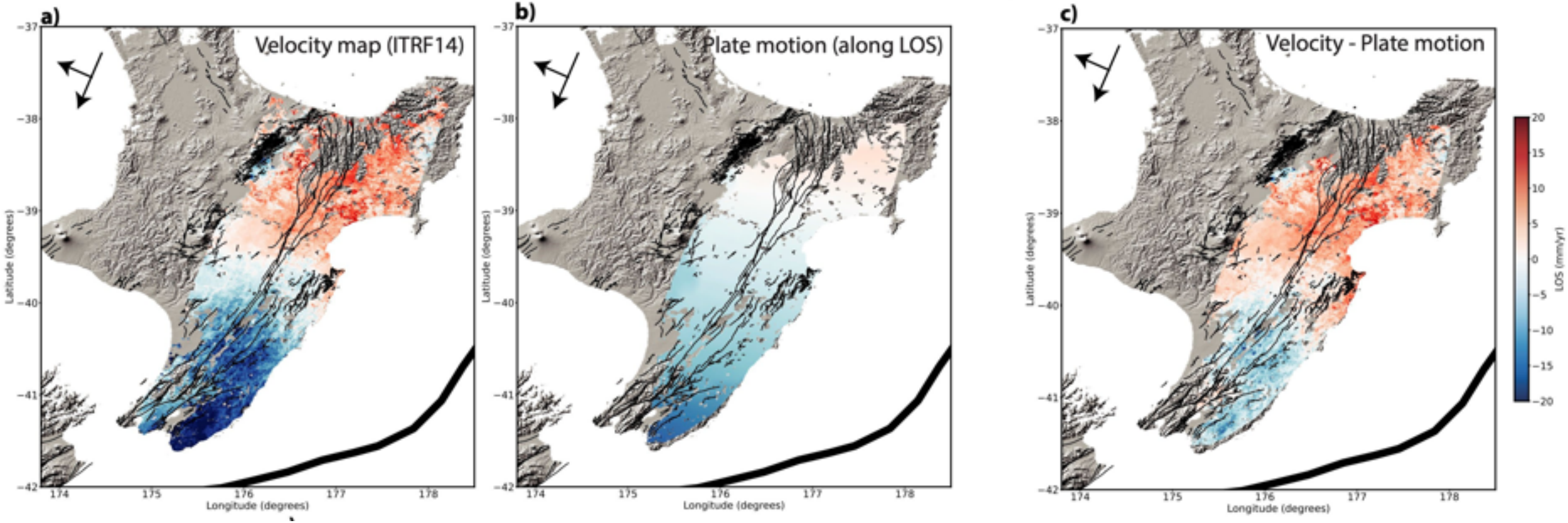
- **InSAR data are converted using a block model (*Wallace et al., 2010*)**
- Ascending track is more sensitive to horizontal displacements



Maubant et al., under review

InSAR data: plate motion correction

- **InSAR data are converted using a block model (*Wallace et al., 2010*)**
- Descending correction are smaller because this track is more sensitive to vertical displacements



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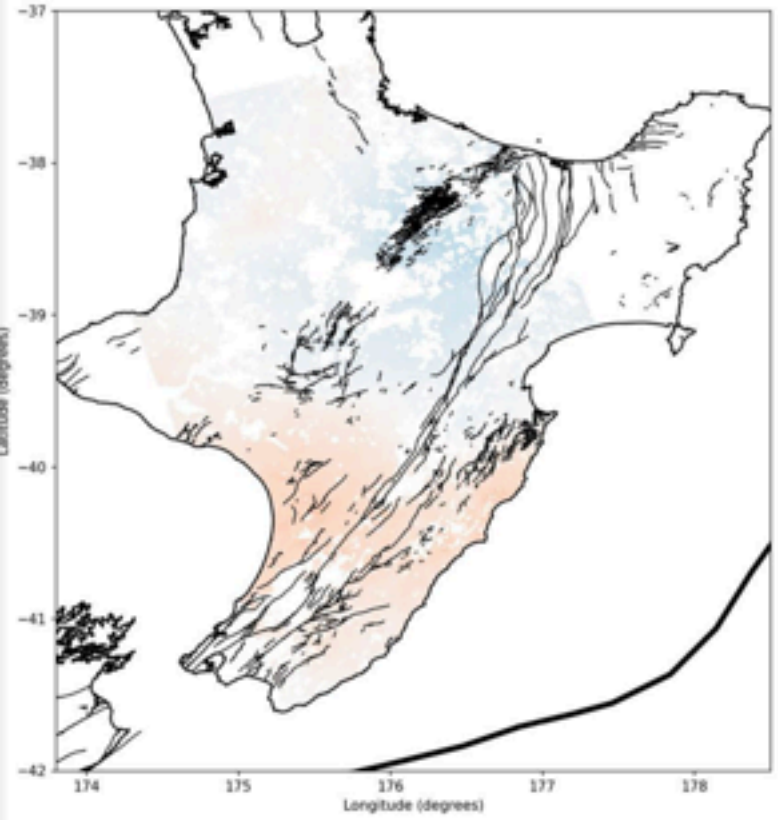
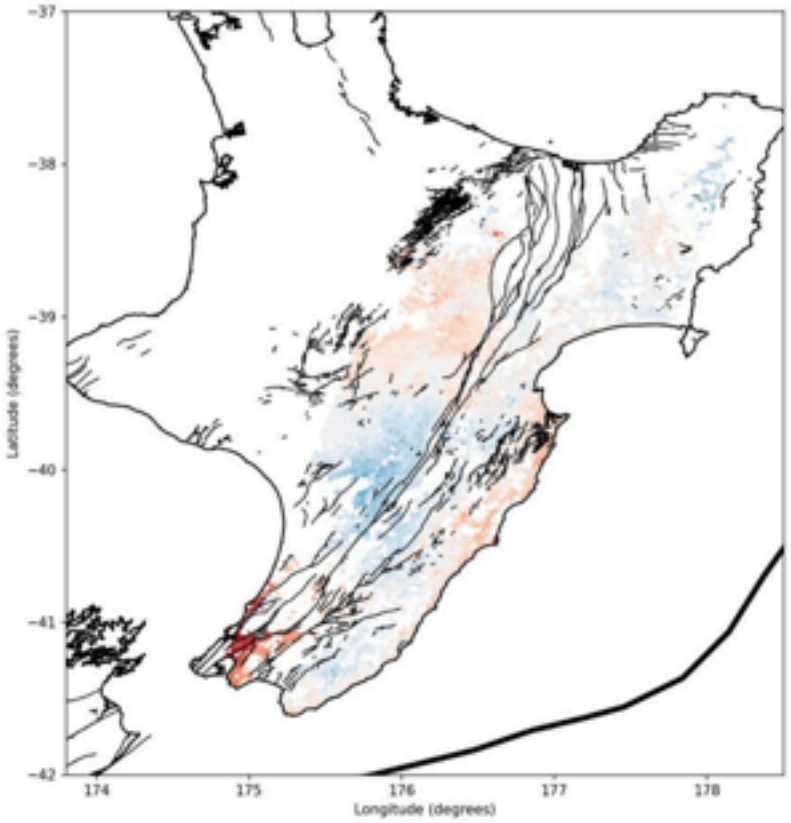
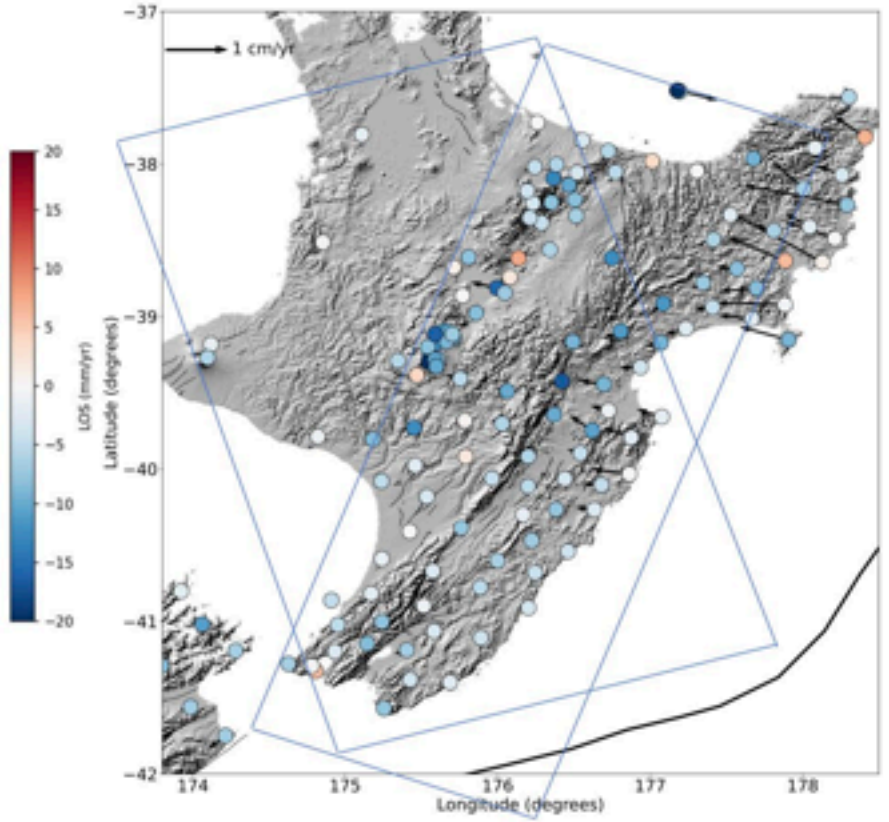
Inter-deep-SSE vs Inter-"major"-SSEs

- Errors are smaller in East Cape region
- Less robust estimation of velocities on vertical components
- Only East Cape/Gisborne region is impacted by the shallow SSEs

Difference: c - b







Maubant et al, under review

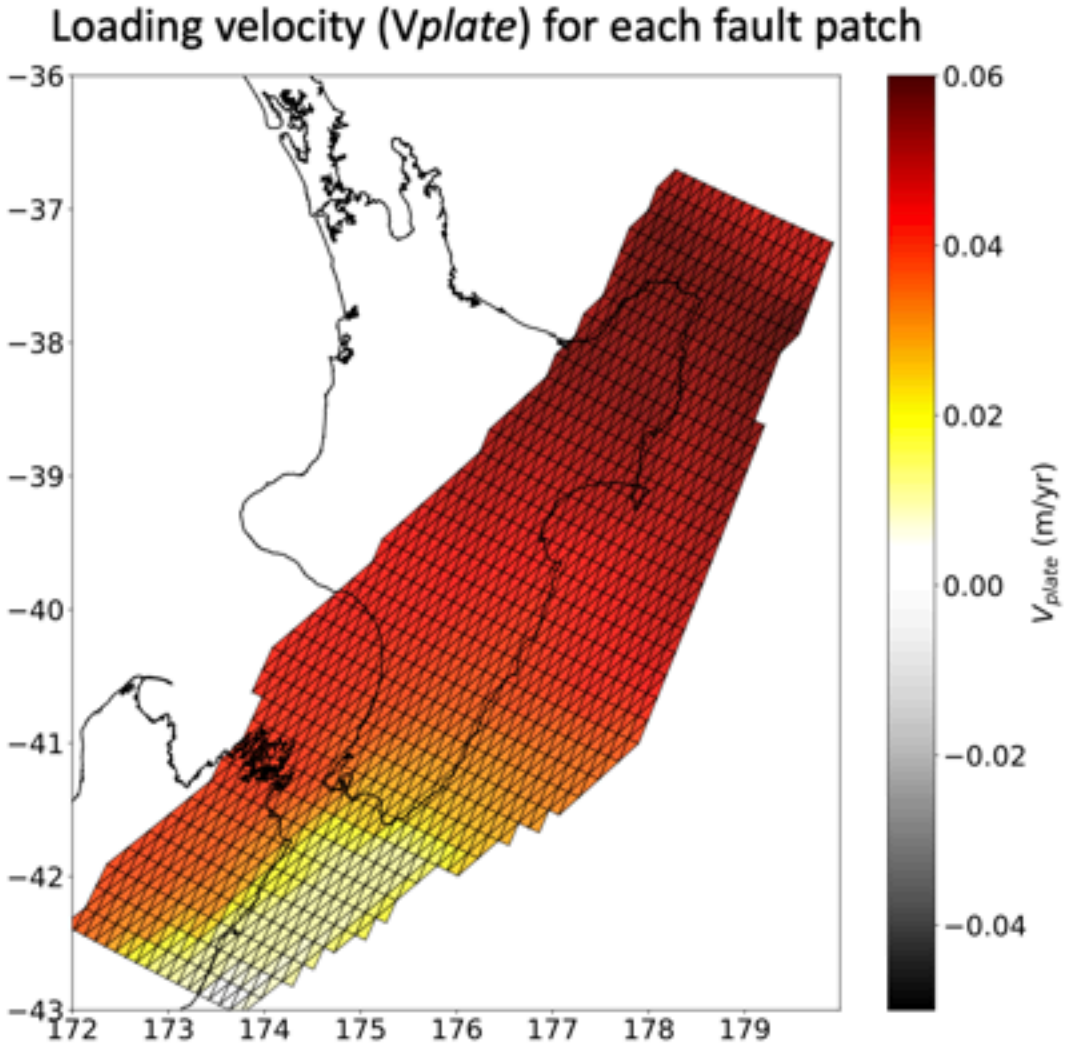
Inversion

- Okada dislocation $\boldsymbol{G}$:
  - Elastic half-space medium
- Linear inversion (Tarantola 2005)

$$m = m_0 + C_m G^t (G C_m G^t + C_d)^{-1} (d - G m_0)$$

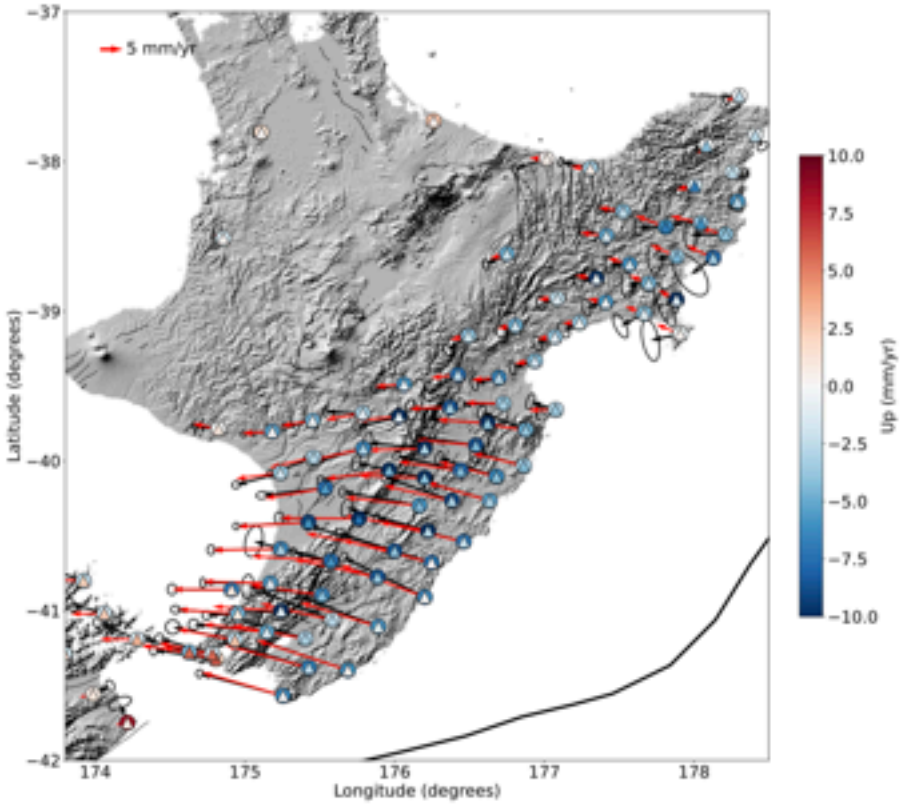
- Parameters define using the best compromise between χ^2 (errors) and model roughness
  (weight, damping value, correlation length)
- Imposed slip direction using *Wallace et al, 2010* plate model

- **Initial assumption: $\boldsymbol{m_0}$** is defined as coupled between 0 and 20 km
- Coupling obtain by using the V*plate* for each patch

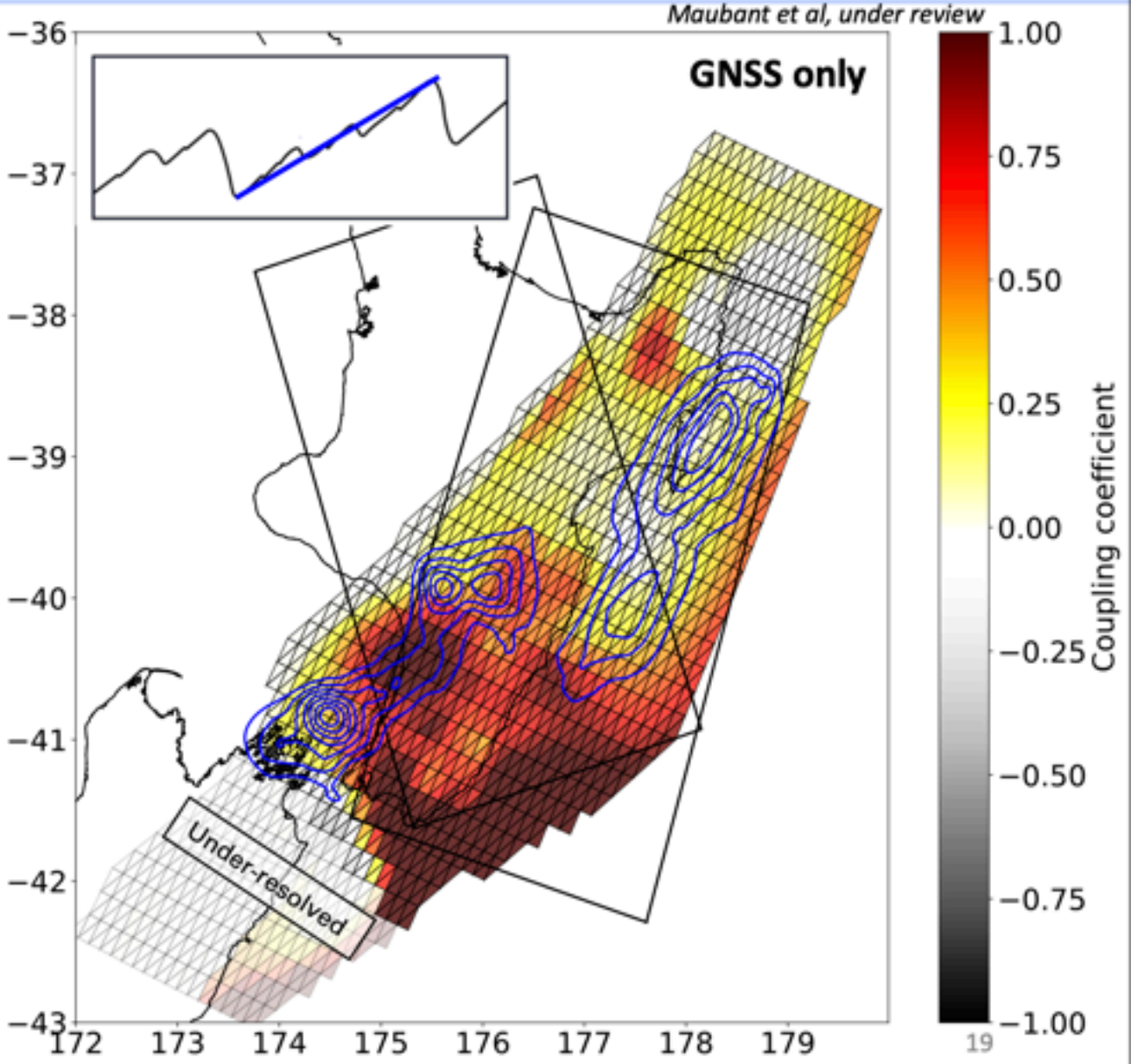


GNSS only: Coupling map over **deep** SSEs (2018 – 2022)

- W_{GNSS}=1
- Coupled region between deep SSEs regions
- Slip in shallow SSEs region

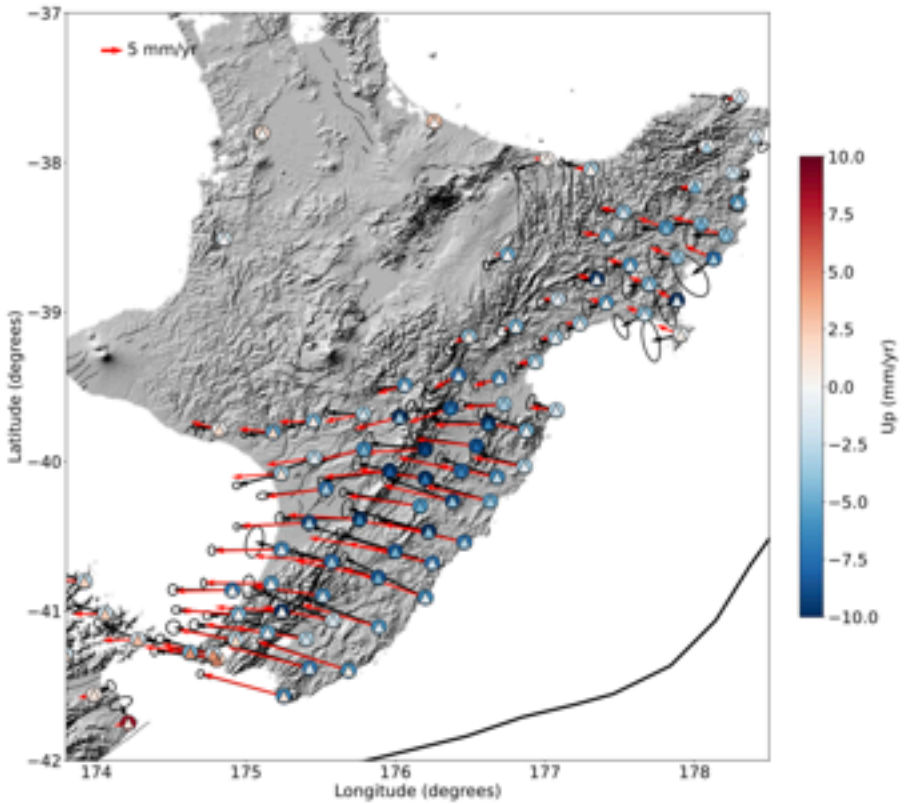


Maubant et al, under review

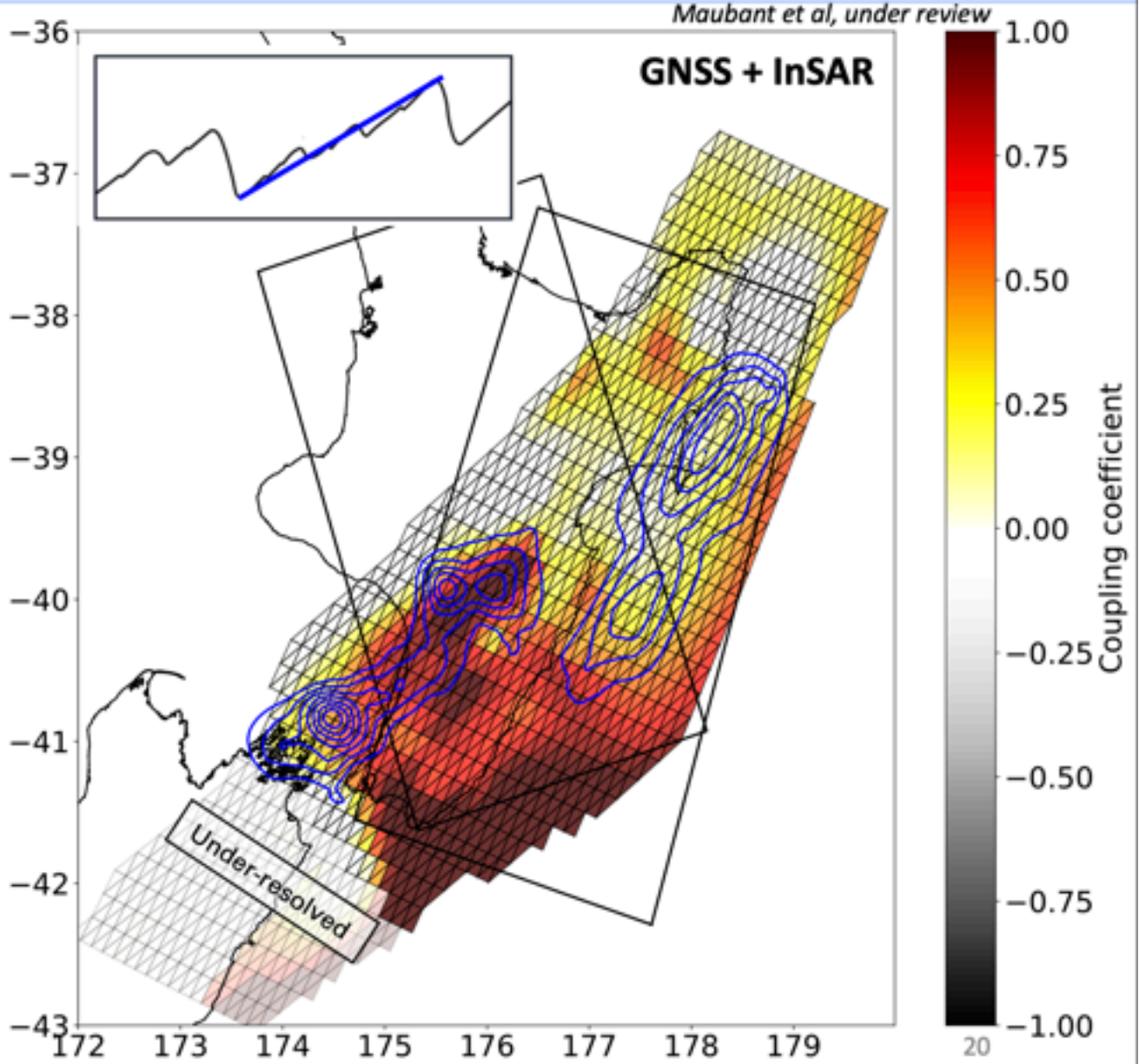


GNSS + InSAR: Coupling map over **deep** SSEs (2018 – 2022)

- W_{GNSS}= 0.6
- Coupled region in deep SSEs regions
- Slip in shallow SSEs region
- Using InSAR allow to obtain more details

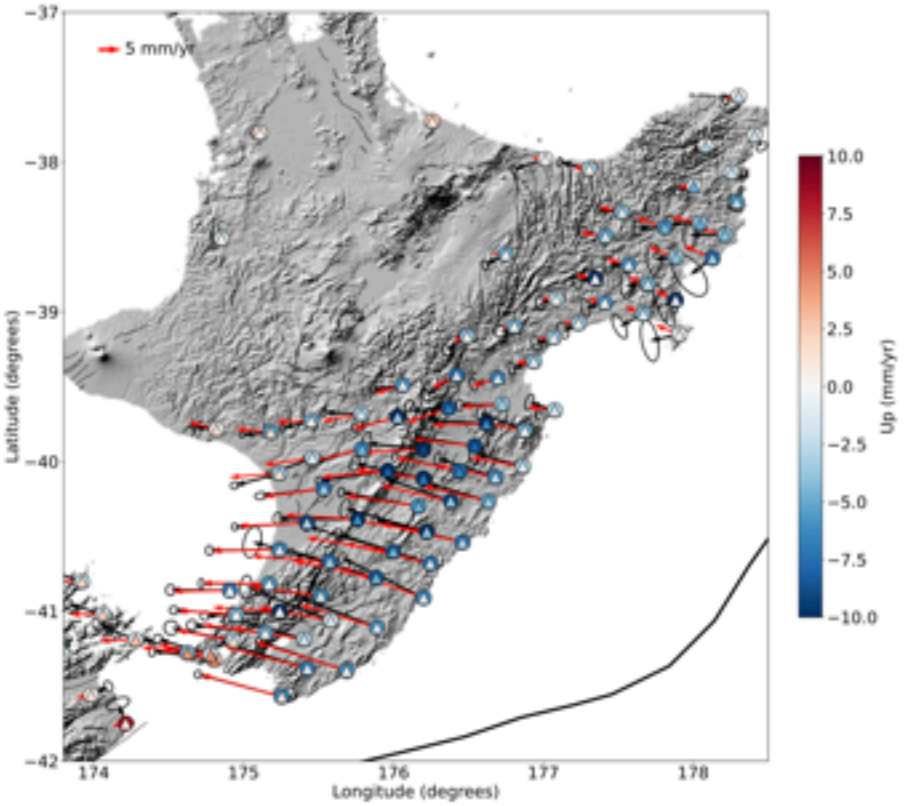


Maubant et al, under review

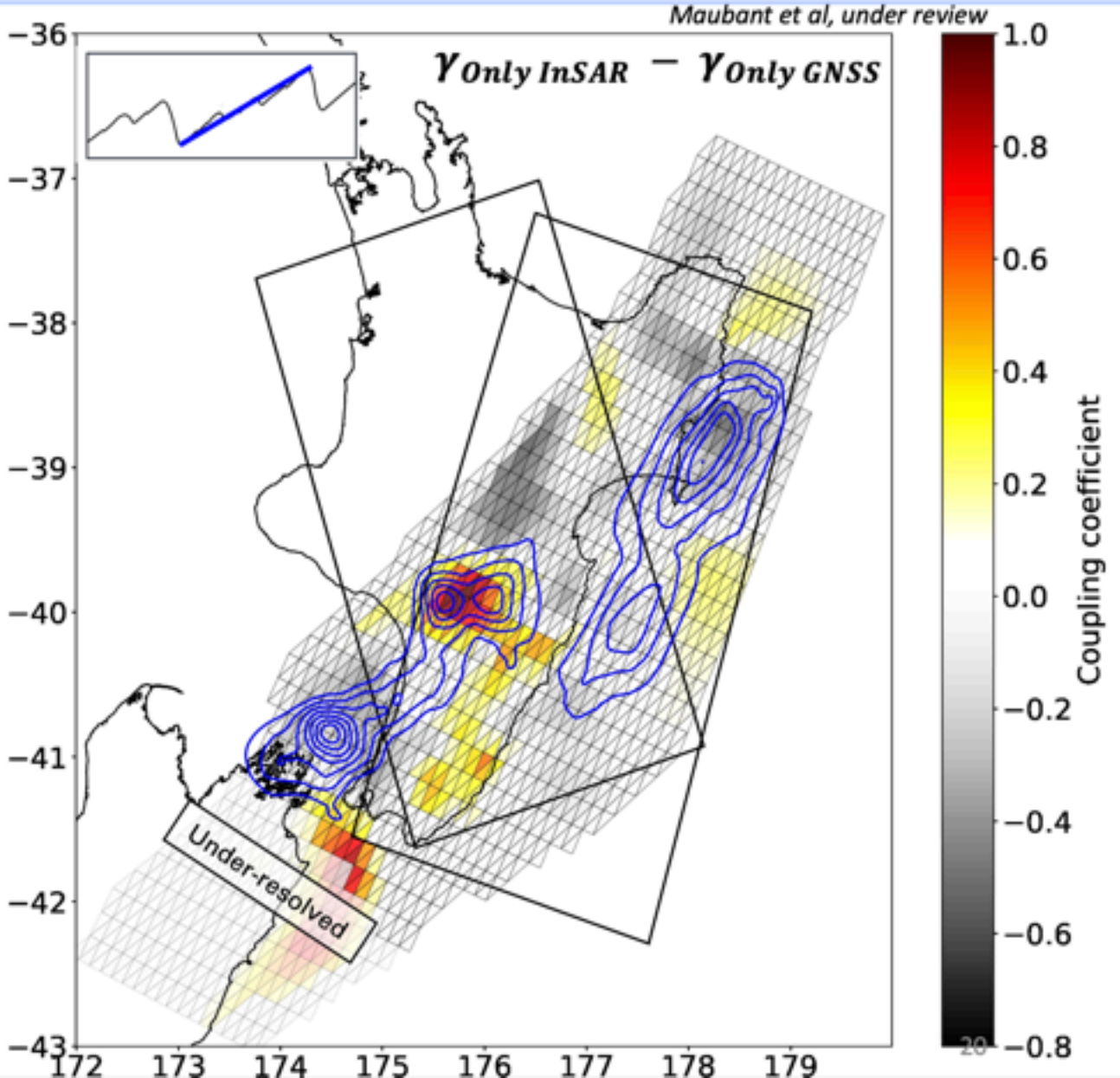


GNSS vs InSAR: Coupling map over **deep** SSEs (2018 – 2022)

- W_{GNSS}= 0.6
- Coupled region in deep SSEs regions
- Slip in shallow SSEs region
- Using InSAR allow to obtain more details

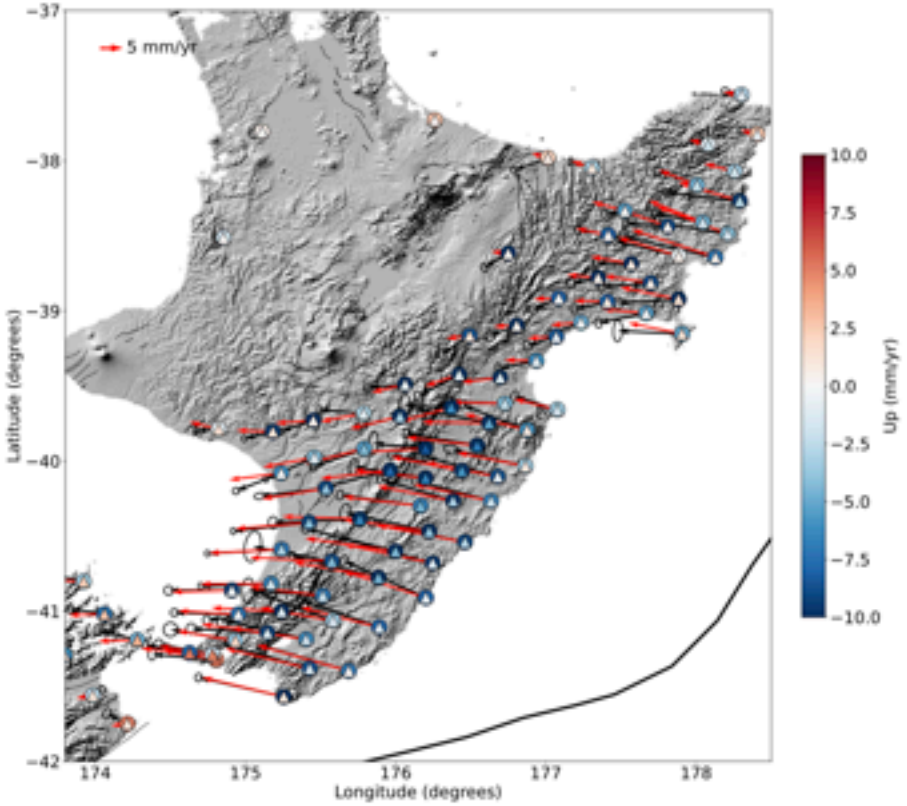


Maubant et al, under review

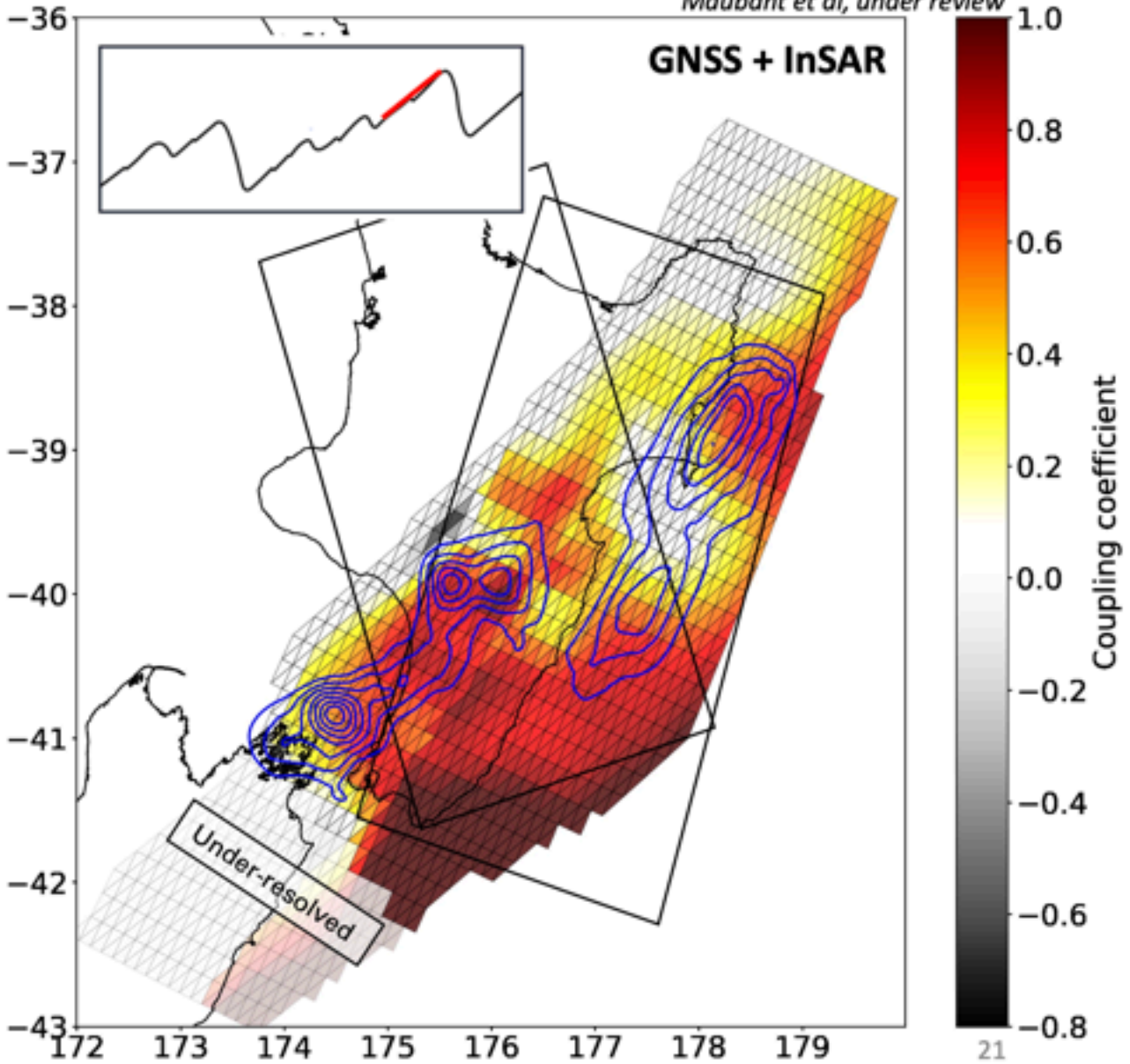


GNSS + InSAR: Coupling map over **major** SSEs (2019 – 2021)

- **W_{GNSS}= 0.6**
- Coupled region in Manawatu SSE region
- Coupled region in East Coast “major” SSEs



Maubant et al, under review



GNSS + InSAR: Coupling map over **major** SSEs (2019 – 2021)

- W_{GNSS}= 0.6
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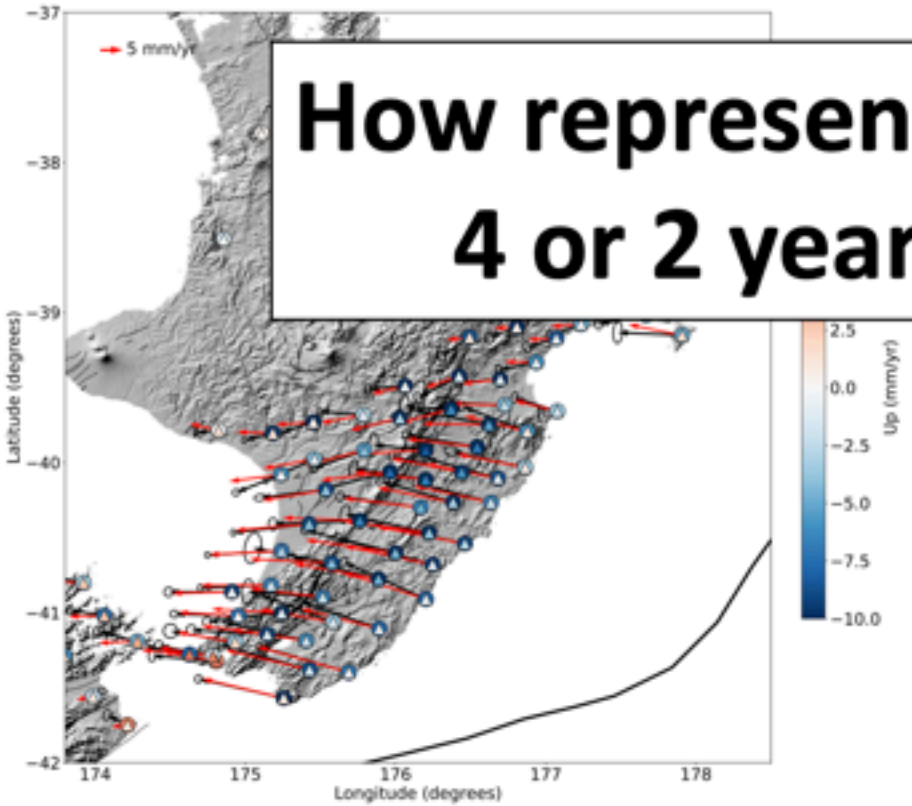
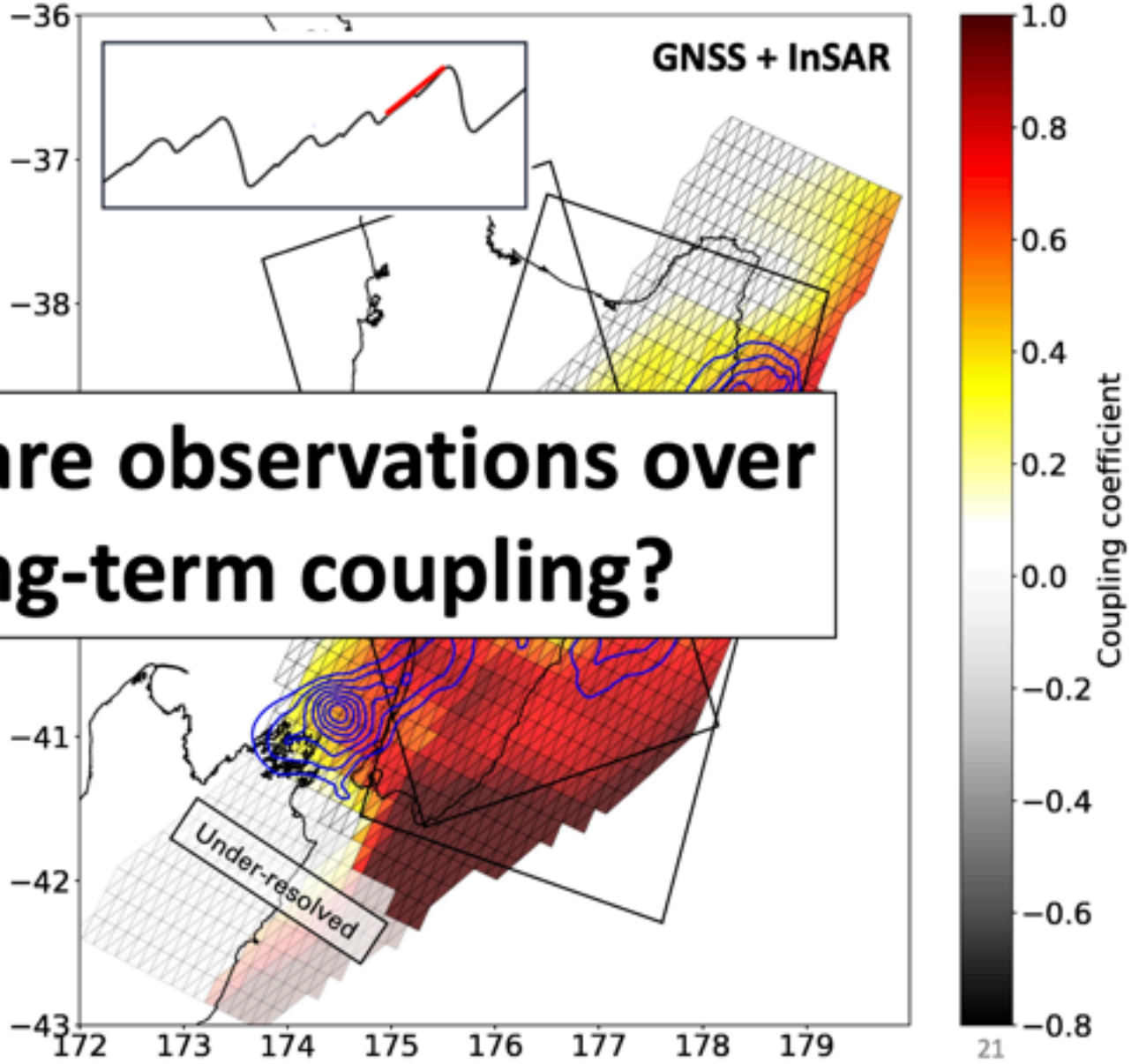
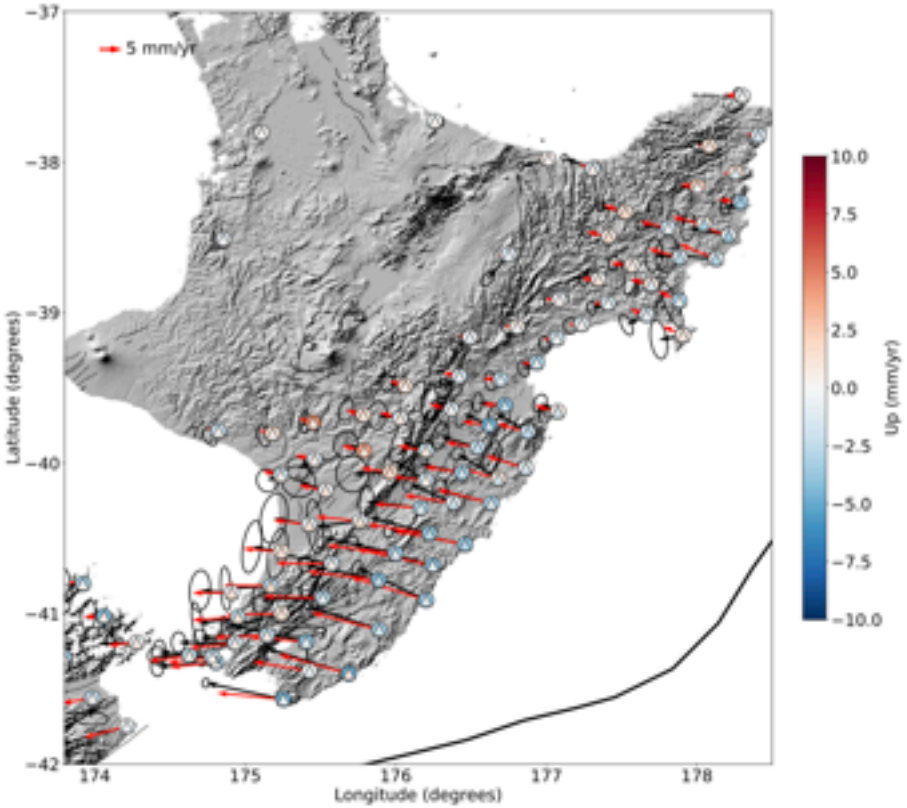


How representative are observations over 4 or 2 years of long-term coupling?



Coupling map over interseismic period (2006 – 2016)

- **Only GNSS available in this period**
- **Uncoupled** region in deep SSEs region and in shallow SSEs region



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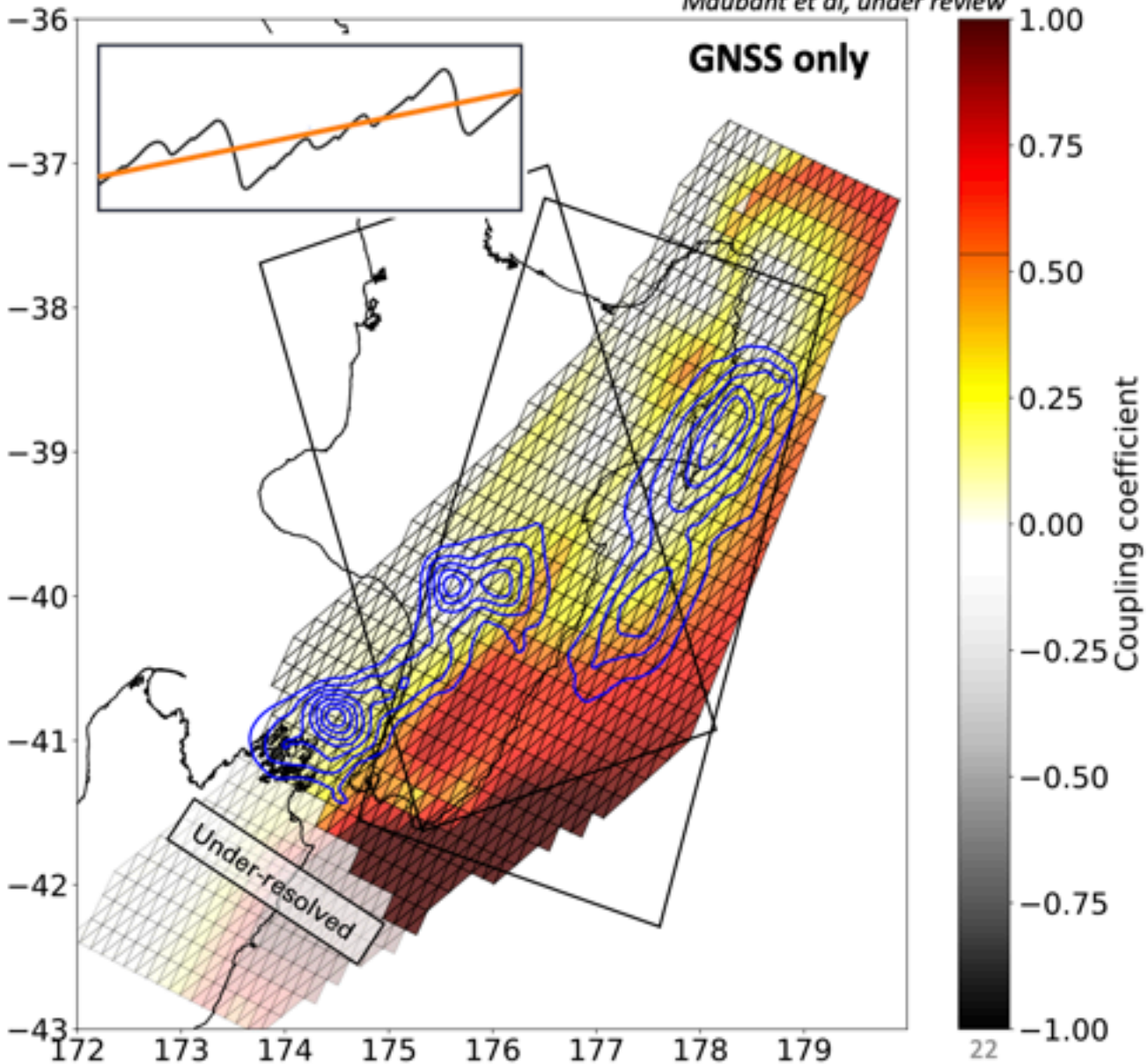
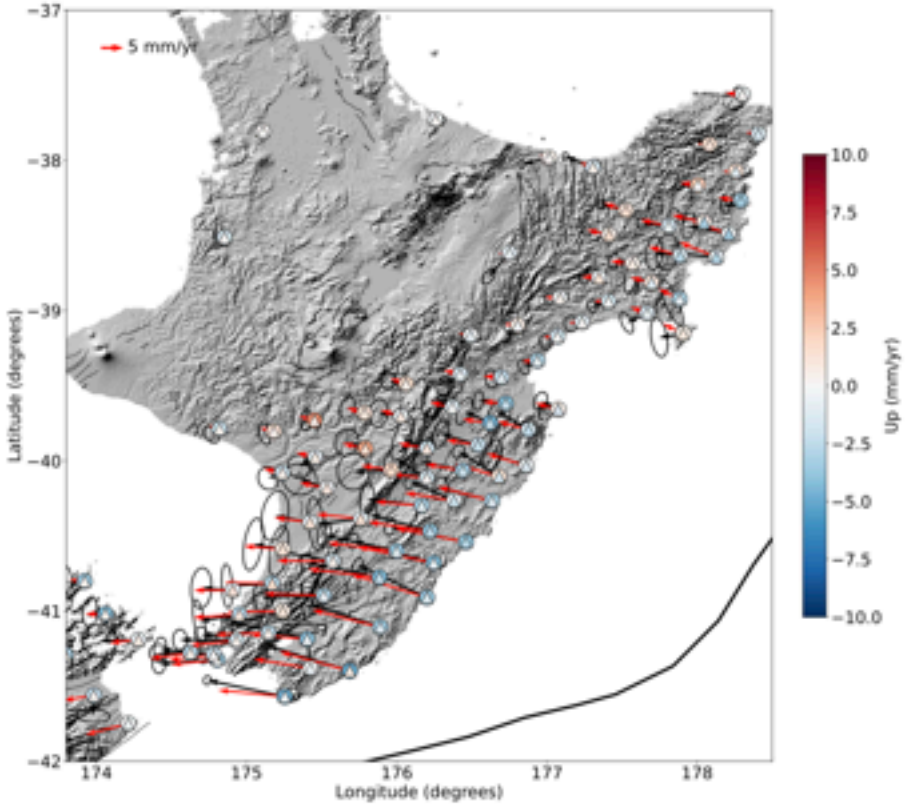


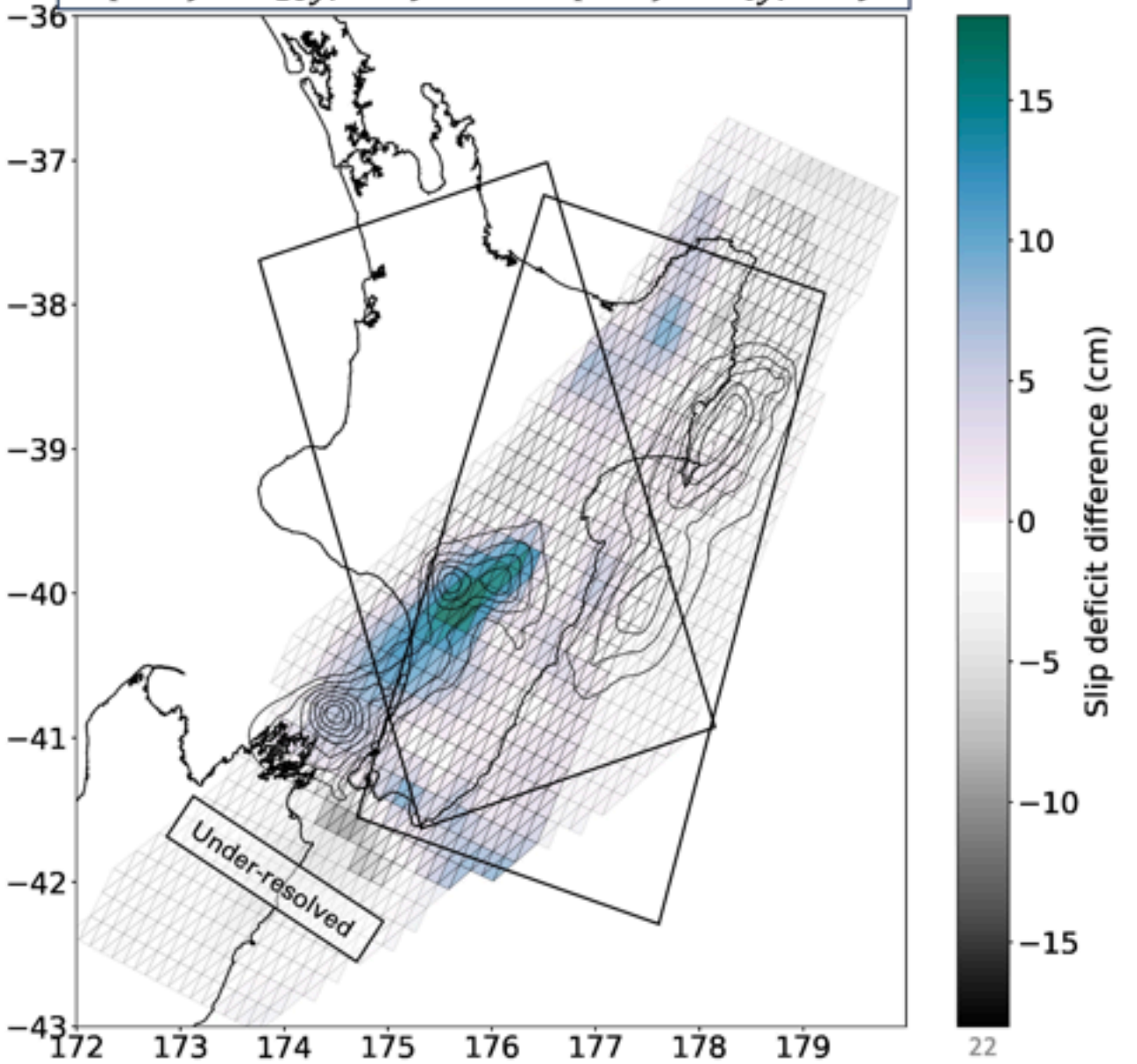
Slow slip events

- Slow slip events can be **retrieved** by comparing the slip deficit over different time periods
- Maximum slip of 18 cm corresponding well to past deep Slow slip events



Maubant et al, under review

$$Slip\ deficit_{10yr} * 4yr - Slip\ deficit_{4yr} * 4yr$$



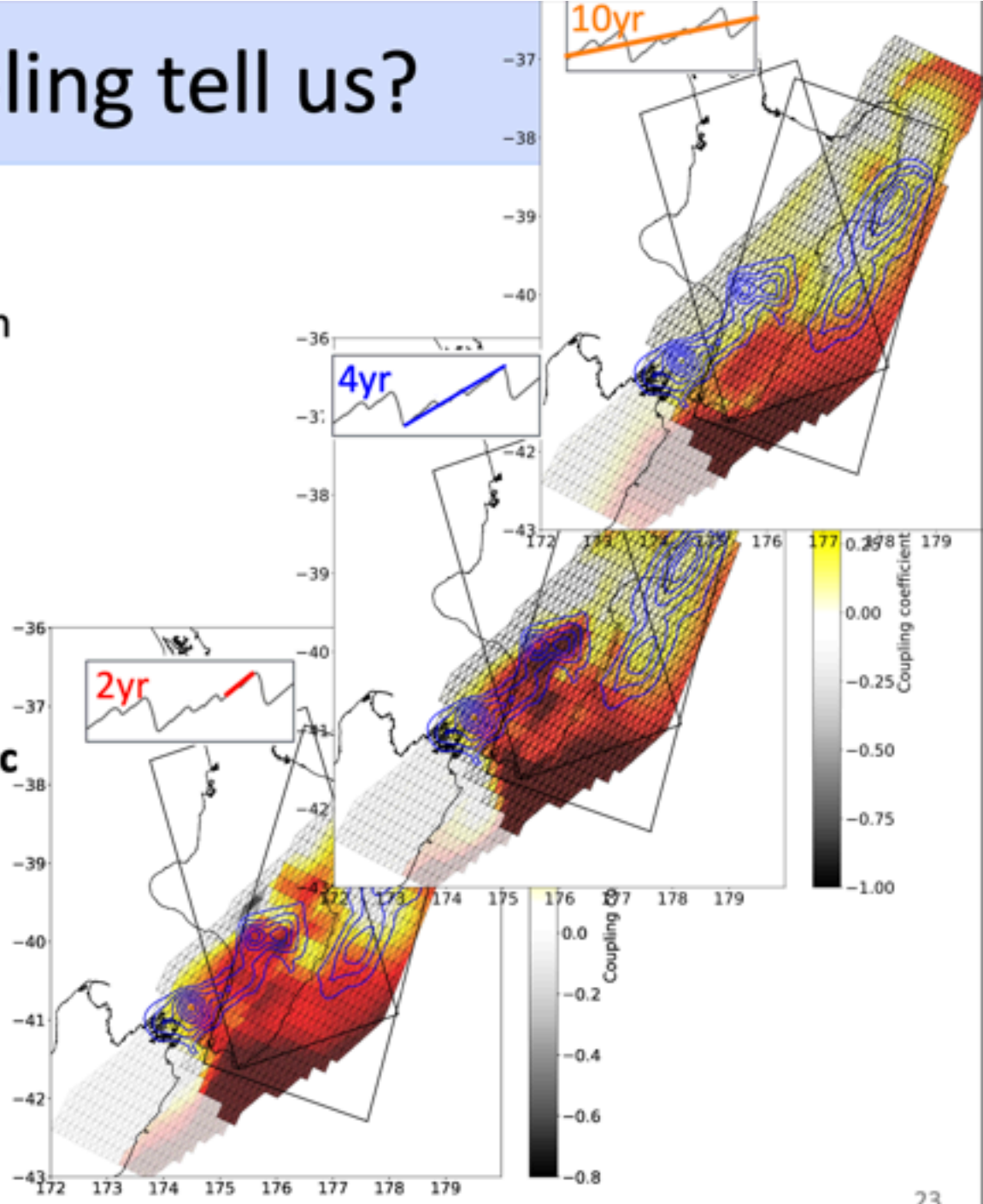
What do estimates of plate coupling tell us?

1. **If the deformation evolves through time, which observational period should we choose to recover plate coupling?**
   No good answer! The interseismic period is not **stationary** in **time and space**.

2. **By looking at different time periods, can we determine a kinematic coupling?**
   Comparing different time periods can help us tease out which regions release built-up stress aseismically or seismically

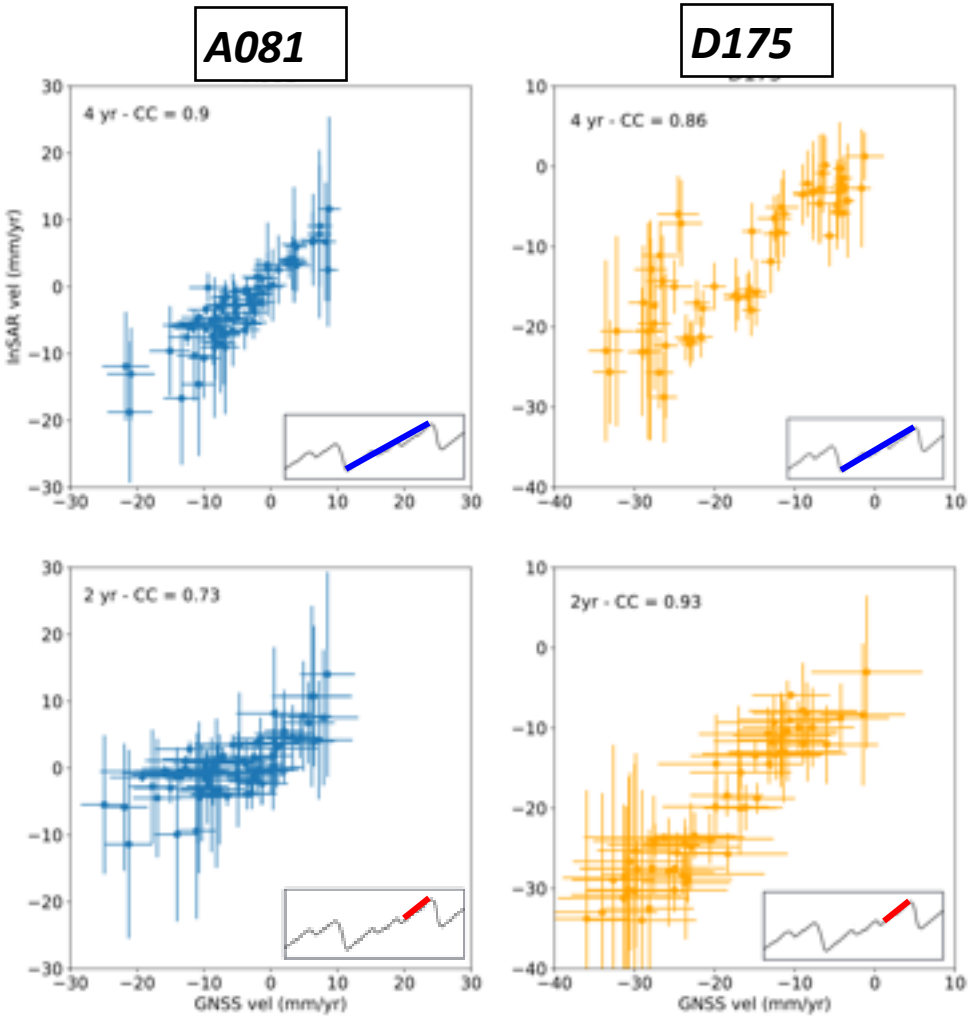
3. **Spatial extent of coupling is directly linked to future seismic hazard; does GNSS provide sufficient resolution to accurately recover coupling?**
   Probably not with current networks!
   InSAR won't replace GNSS networks but provides spatially **complementary** and **important** information

4. Slow slips signal can be recovered by comparing coupling over different observational period



InSAR data vs GNSS

- $V_{InSAR} \propto V_{GNSS}$
- InSAR velocities calculated over 2 years have higher errors
- InSAR must be corrected from plate motion



Maubant et al., under review