Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

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Ministerio de Minería
Gobierno de Chile

Research funding: IDeA I+D_ID23I10147

IGS INTERNATIONAL GNSS SERVICE

Nonlinear Displacement Models in Regional Reference Frames:

*A Case Study of the **REDGEOMIN** (Chile) and **SIRGAS** GNSS Networks*

*Tarrío Mosquera, José Antonio (1); **Marten A., Miguel (1)**; Giglio, Juan (1); Caceres, Catalina (1); Vasquez, Valeria (1); Vivanco, Diana (1); Isla, Fernando (1); Caverlotti, Marcelo (1)*
Jeldres, Gabriel (2); Urrutia, Rodrigo (2)

Organization(s): 1: USC Geodetic Processing and Analysis Center, University of Santiago of Chile (USACH)
; 2: Servicio Nacional de Geología y Minería (SERNAGEOMIN), Santiago, Chile

Presenter: Miguel Marten A.
Date: 02-07-2024

IGS Symposium & Workshop
July 1 to 5, 2024 Bern, Switzerland
Session 3: Giving Access To The Reference Frame Through GNSS

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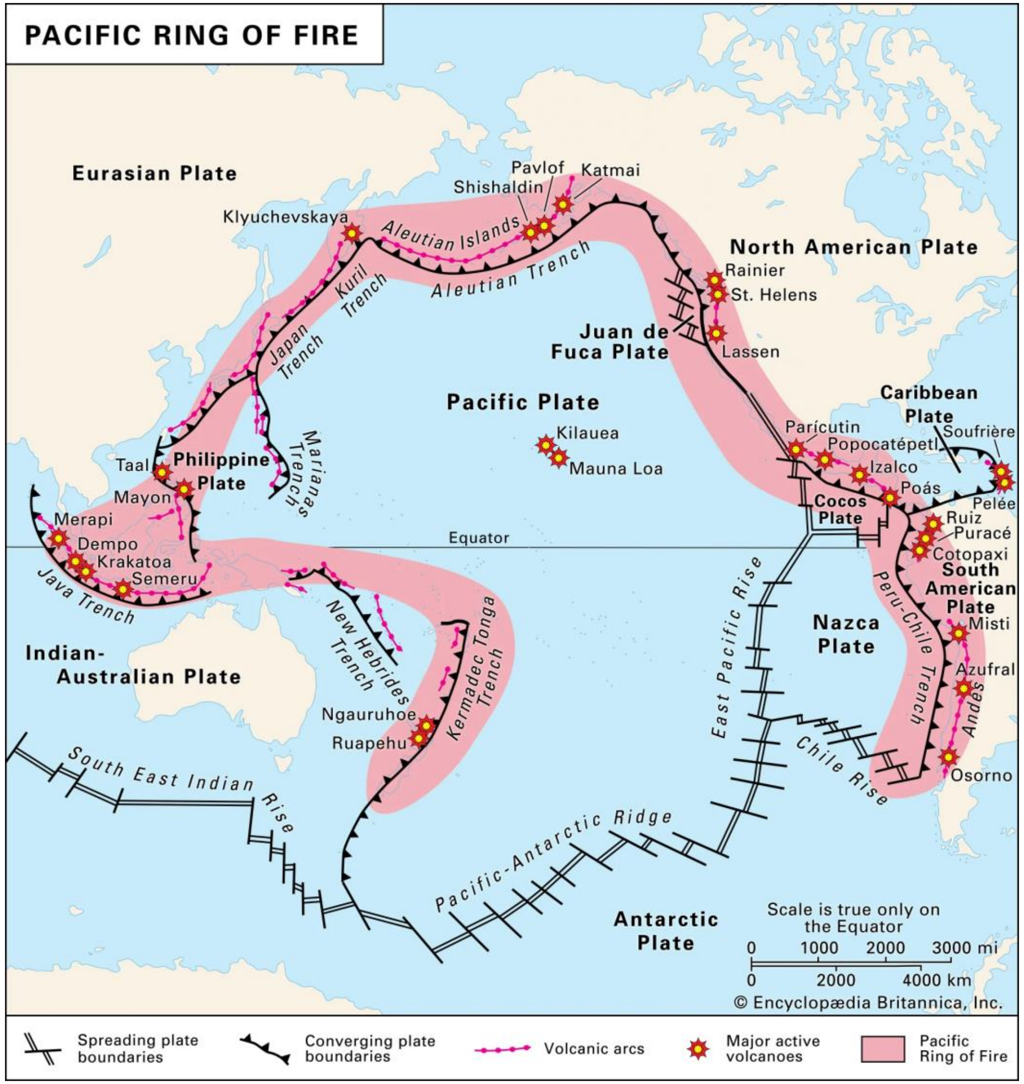
Context

- The Pacific Ring of Fire is a center of significant interest for geosciences due to its geodetic dynamics.

- The REDGEOMIN network (KRF), located in this region, along with the SIRGAS network(KRF), face fundamental challenges regarding the kinematics of geodetic reference frames.

- These frames exhibit significant variations, ranging from centimeters to meters, attributable to large-magnitude earthquakes.



Source: https://www.britannica.com/place/Ring-of-Fire

Context

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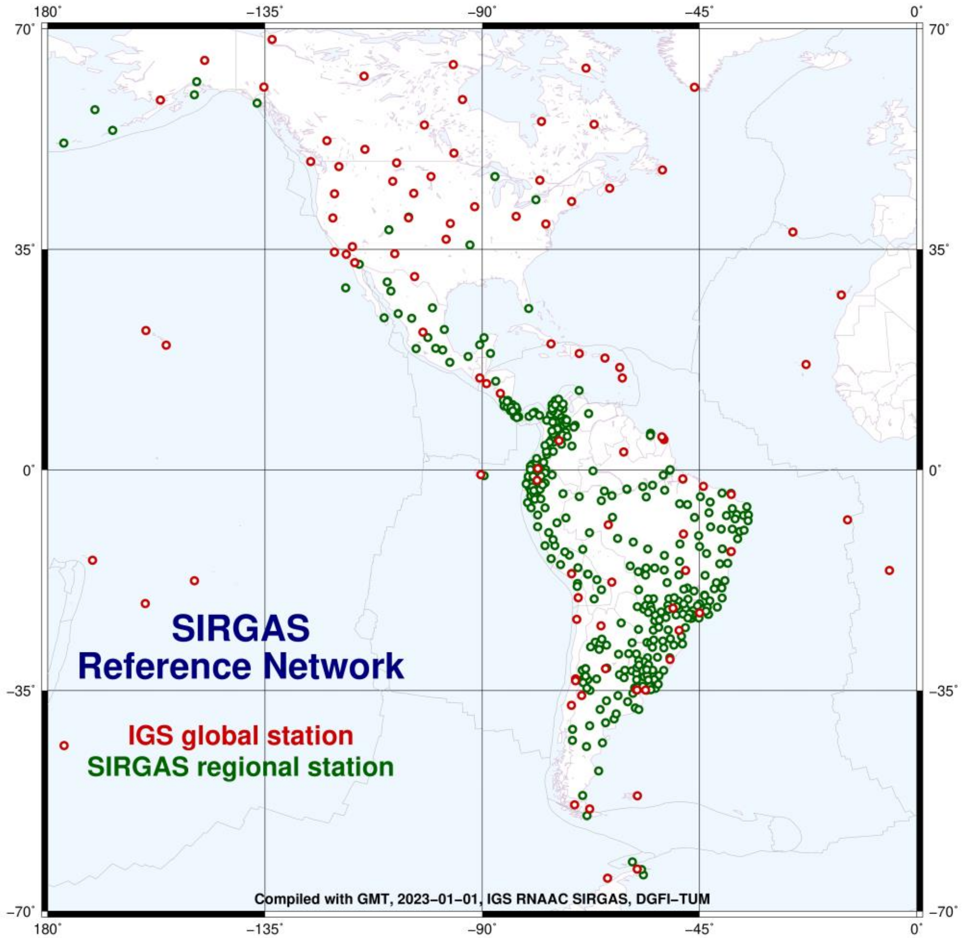

Source: https://sirgas.ipgh.org/realizaciones/sirgas-con/

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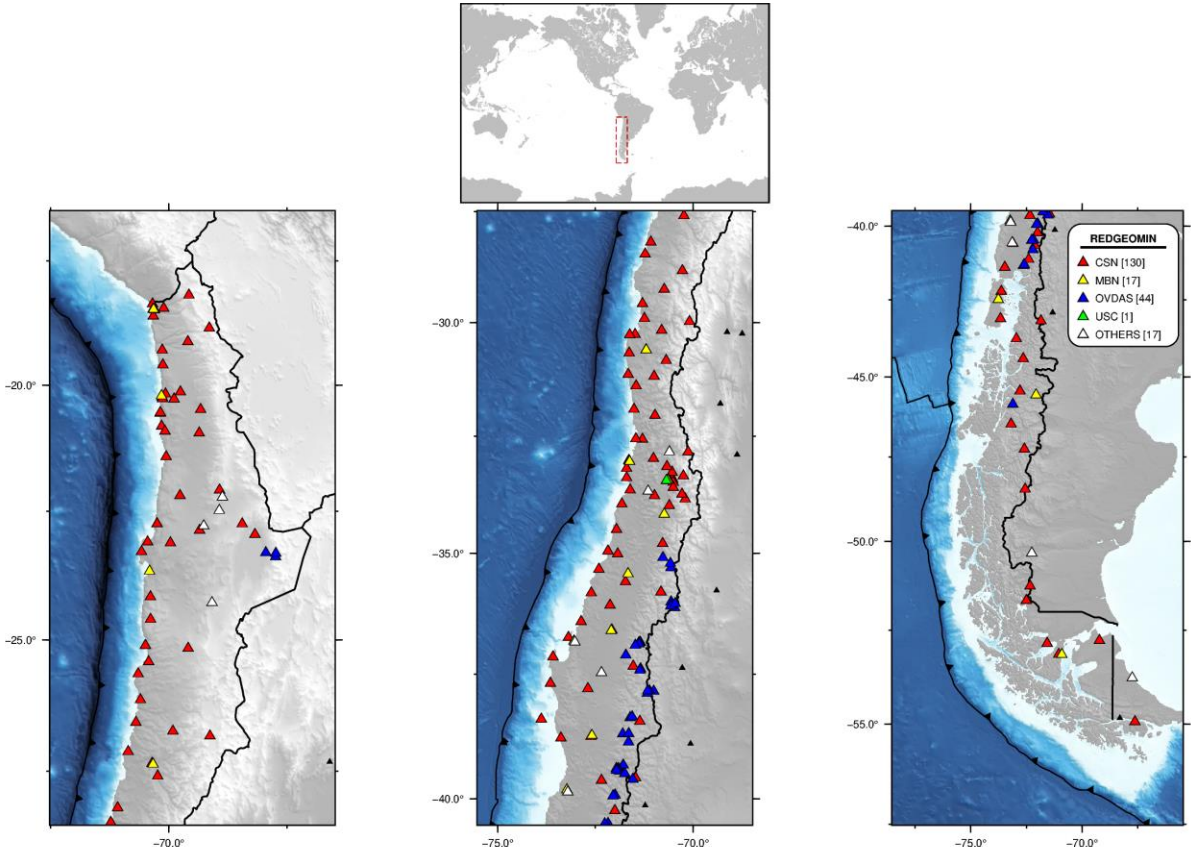
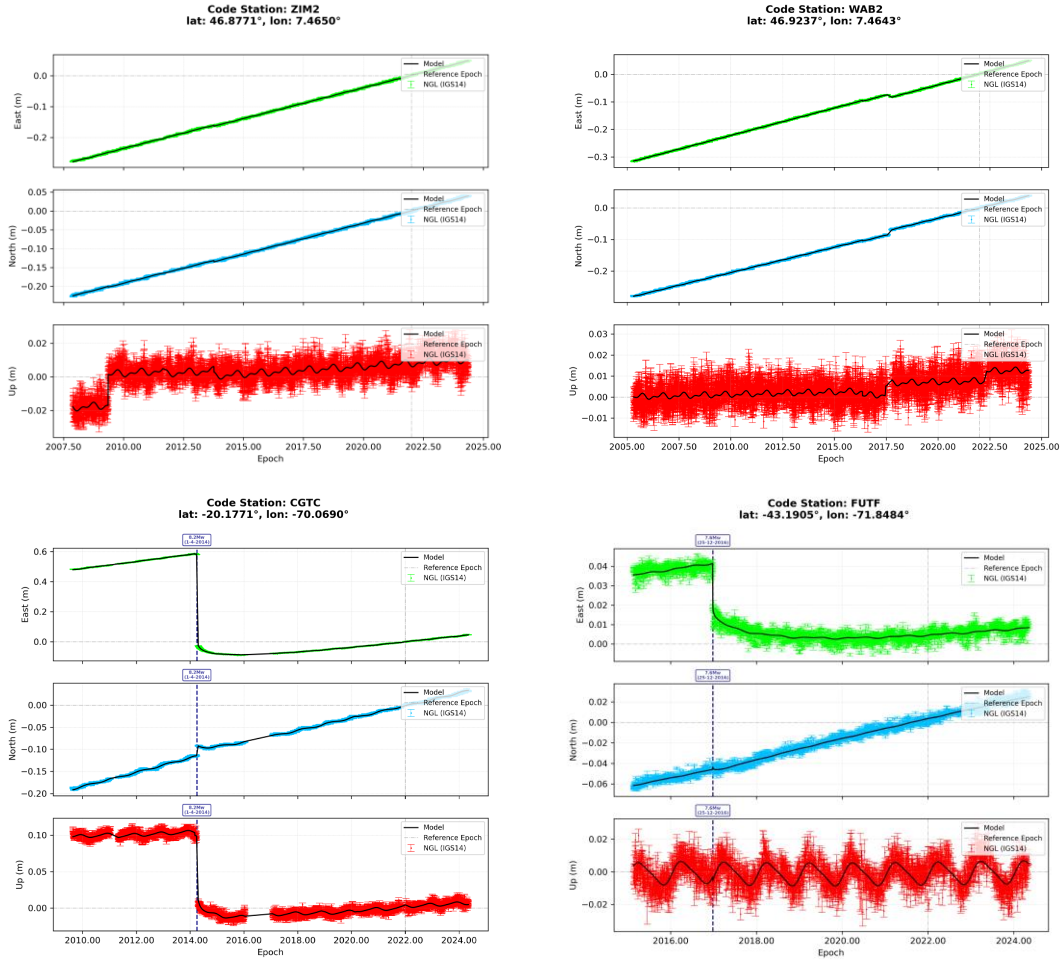


Source: USC Geodetic Processing and Analysis Center

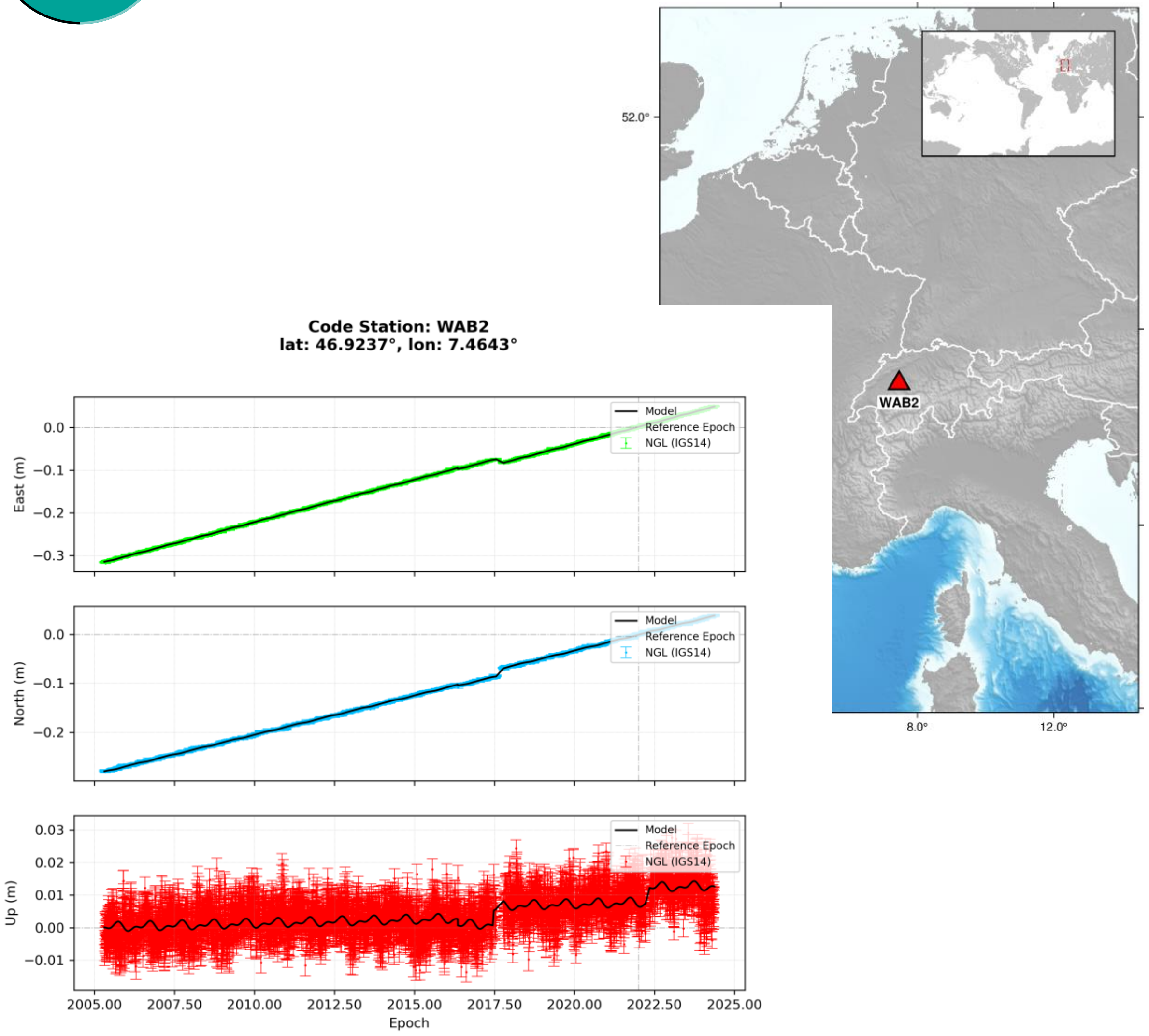
Problem Statement



Source: USC Geodetic Processing and Analysis Center

- The primary problem addressed in this study is the kinematics of geodetic reference frames in a highly seismic region.
- Seismic activity causes significant variations in the frames, complicating precise geodetic measurements.
- Accurate measurement and modeling are essential for understanding these variations*(over benchmarks)*.

Problem Statement



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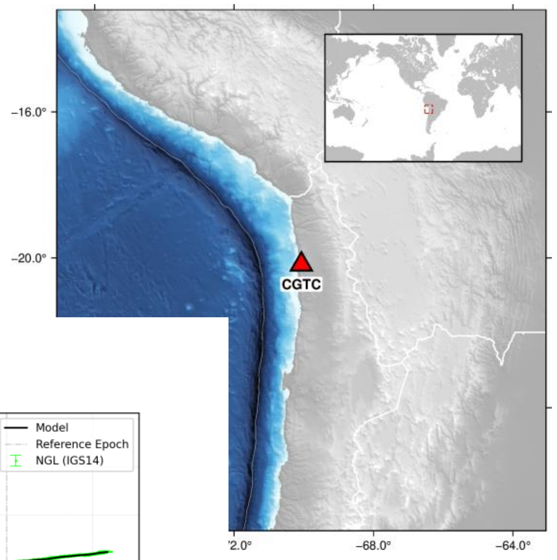

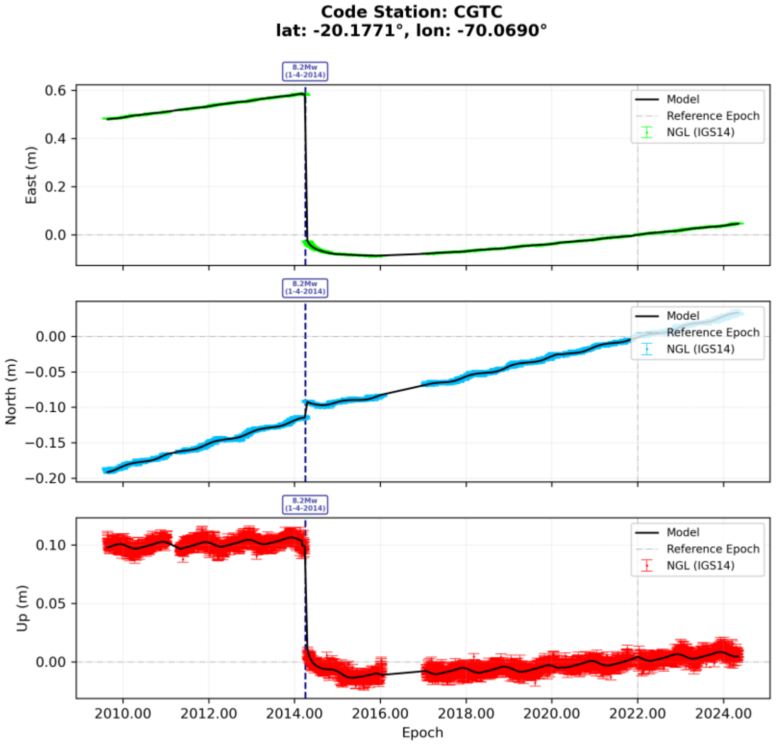

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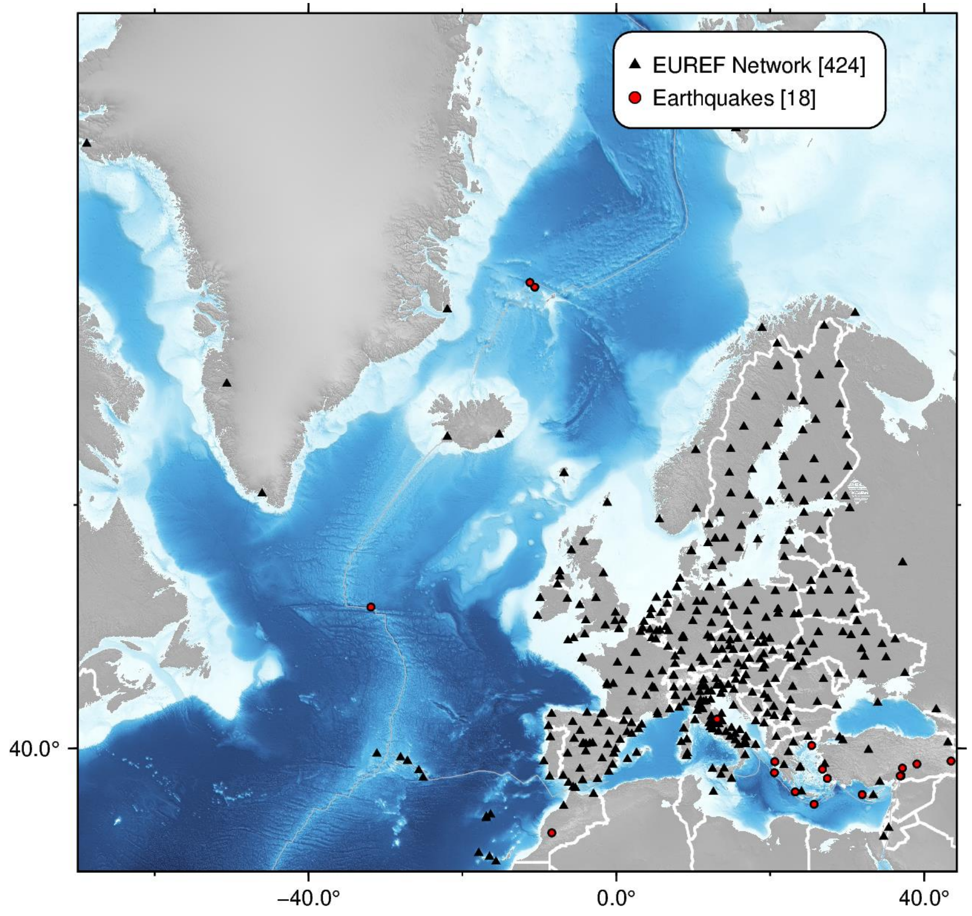
Objectives

- **Main Objective**
    - Characterizing deformation patterns from GNSS data in the context of seismic and non-seismic events.

- **Specific Goals**
    - Model nonlinear displacements
    - Analyse both seismic and non-seismic events affecting these displacements.
    - Incorporate existing deformation patterns in the study area to cluster stations for interpolation in data-sparse zones.



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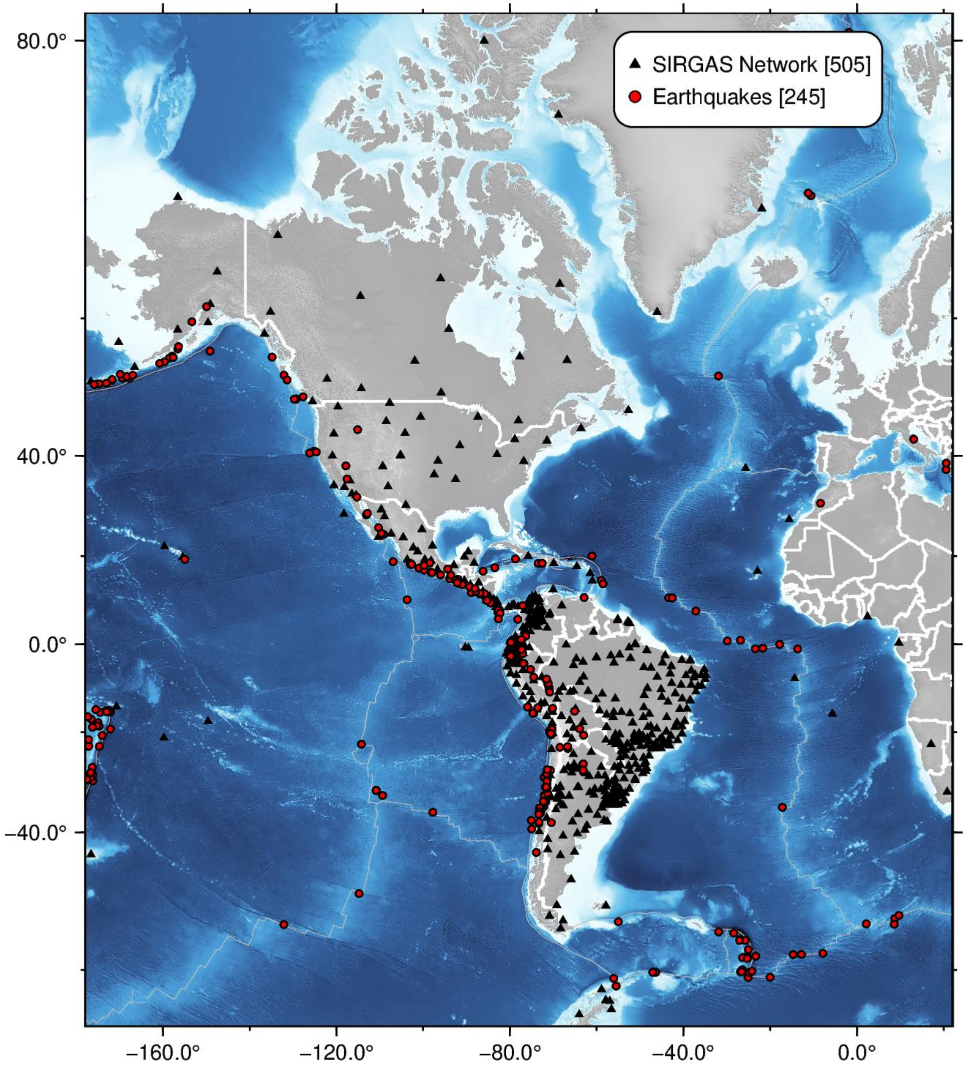
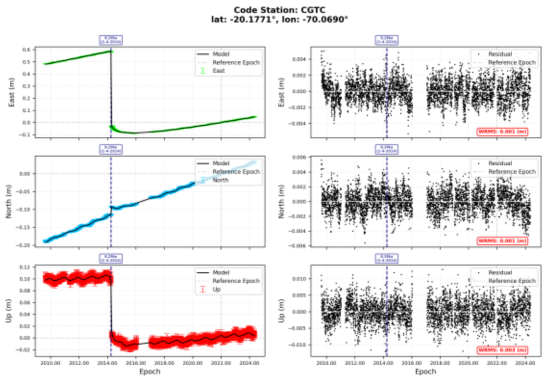


Source: USC Geodetic Processing and Analysis Center

Methodology



Data Download

SIRGAS

- Weekly GNSS solution from REPRO2 SIRGAS network (IGb14)

(Sánchez, L. et al., 2022)

IGS products for processing:

- Orbit file (.SP3)
- BIAS file (.BIA)
- Rotation parameters (.ERP)
- IGS coordinates (.SNX)
- Antenna corrections (.PCV)

- Weekly GNSS solution for the REDGEOMIN (Chile).

Supplemented with NGL

REDGEOMIN

Data Modelling

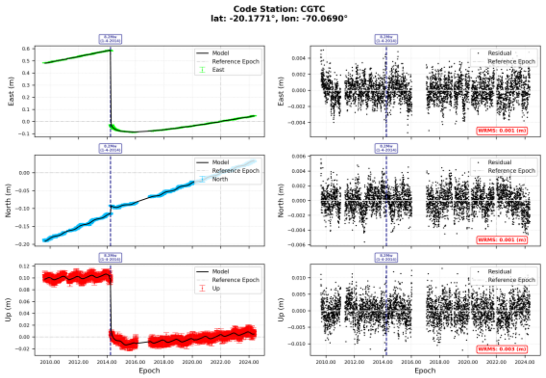
- Update time series of all available GNSS stations.
- Apply nonlinear displacement models to the processed data.
- Ensure residuals with millimetre precision for accurate modelling of displacements.

Information Extraction

- Obtain model parameters associated with the seismic cycle.
- Use machine learning tools to cluster GNSS stations based on their behaviour.

- Employing the k-means method to group stations with similar deformation patterns (horizontal velocities)

Modelling Techniques



- **Nonlinear Displacement Models**
  - Post-seismic, co-seismic, and inter-seismic modelling

Secular movement | Instrumental offset | Stational oscilation

$$x(t) = \boxed{x_0 + v(t - t_R)} + \boxed{\sum_{j=1}^{n_j} A_j H(t - t_j)} + \boxed{\sum_{s=1}^{n_s} \left[B_s \cos\left(2\pi \frac{t}{t_s}\right) + C_s \sin\left(2\pi \frac{t}{t_s}\right) \right]} +$$

$$\boxed{\sum_{eq=1}^{n_{eq}} D_{eq} H(t - t_{eq}) + \sum_{eq=1}^{n_{eq}} E_{eq} \log\left(1 + \left(\frac{t - t_{eq}}{\tau_{eq}}\right) H(t - t_{eq})\right) + \sum_{eq=1}^{n_{eq}} F_{eq} \left(1 - e^{-\frac{t - t_{eq}}{\tau_{eq}}}\right)}$$

Coseismic and **Postseismic** Deformation

Modelling Techniques

- Machine Learning to cluster GNSS stations based on their behaviour

Deformation patterns (strain) + geolocation

data

Preprocessing

normalized data

Clustering algorithms

station cluster

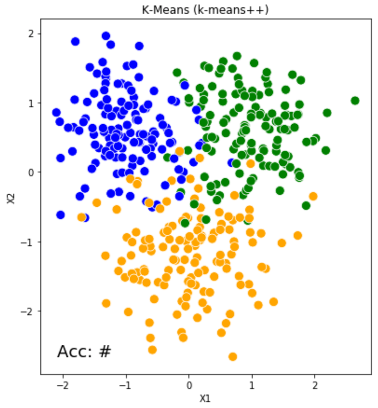
Deformation model ADELA

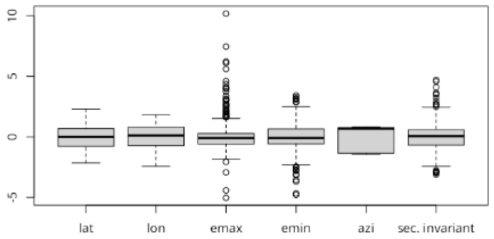
coordinates

Evaluation

Others CORS data (PPP)

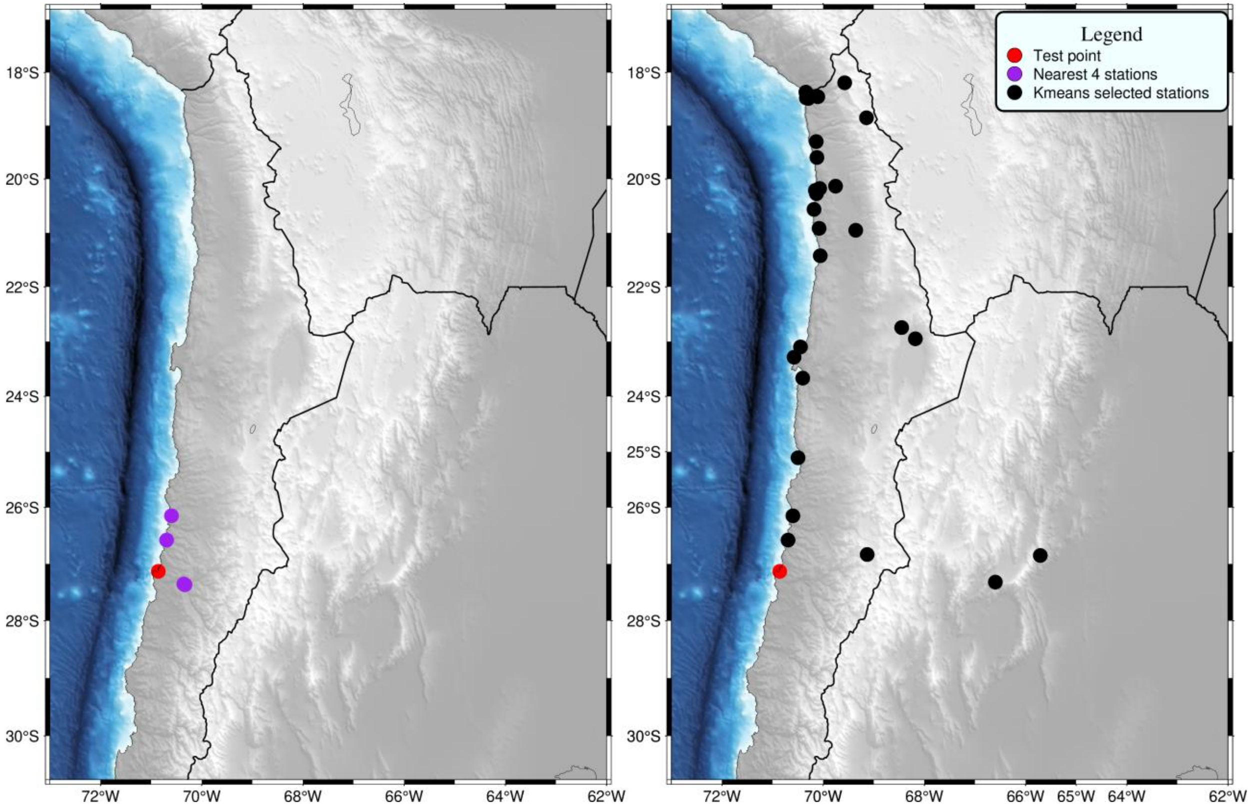
coordinates





Modelling Techniques

- **Machine Learning to cluster GNSS stations based on their behaviour**



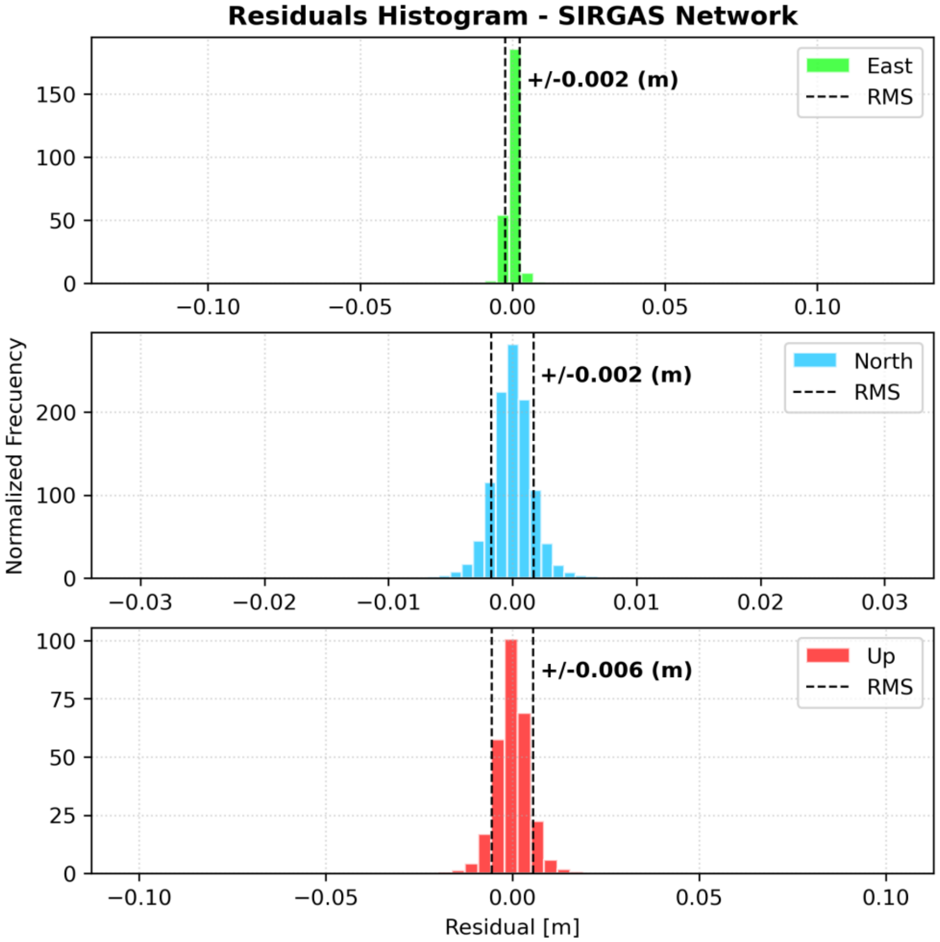
Source: USC Geodetic Processing and Analysis Center

In the image, a point is shown where coordinates are to be calculated for a specific epoch. The map on the left uses displacement interpolation with the 4 nearest stations. The map on the right uses the k-means method to cluster the stations and generate interpolation with the entire corresponding group.

Results – SIRGAS

The residuals for the SIRGAS network, which are the differences between the model and the observed data, are compiled in a histogram that shows the residuals for the entire network. Key points to highlight:

- Millimetre-level precision in the East, North and Up coordinates with RMS values of 2 mm, 2 mm and 6 mm, respectively.



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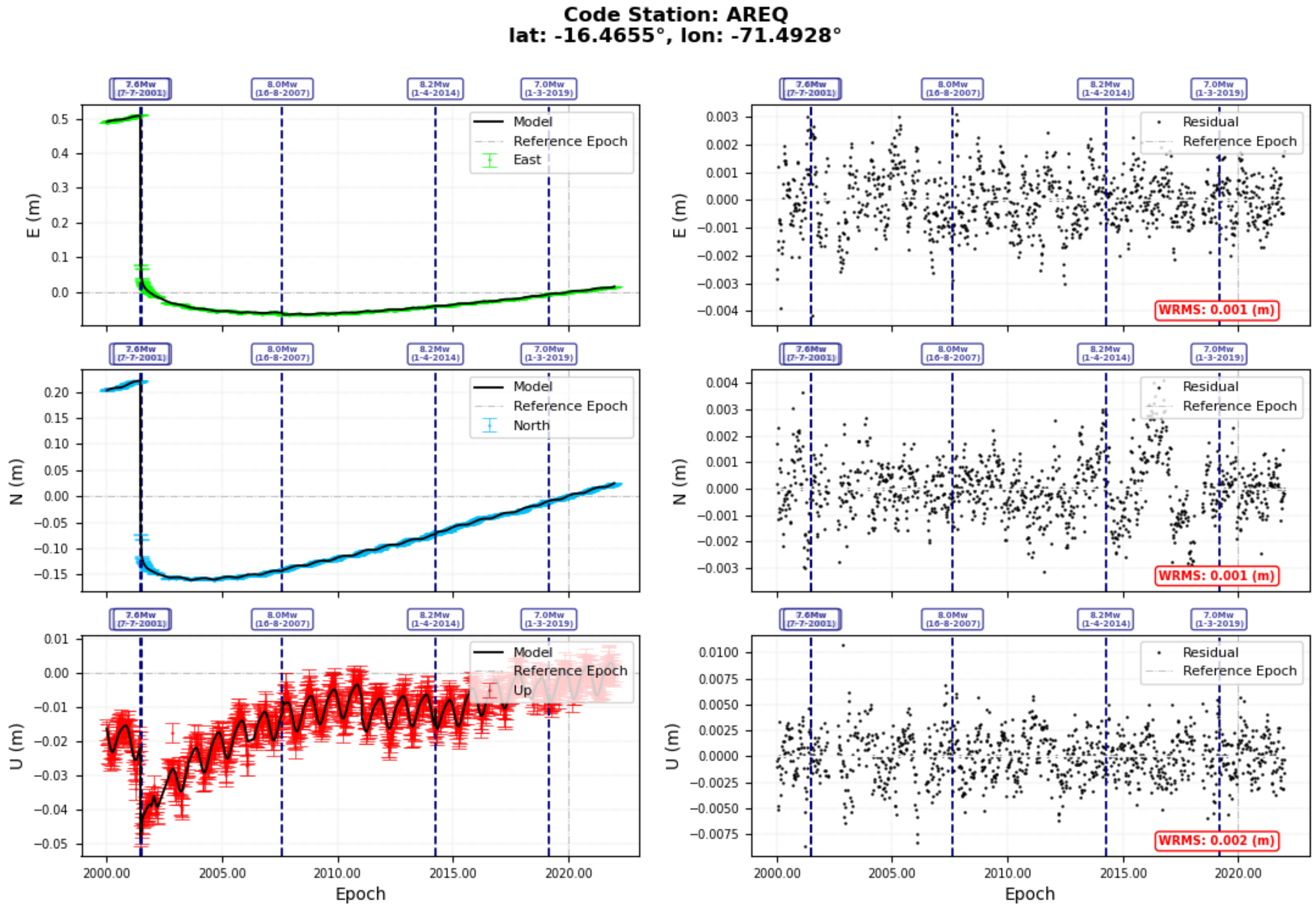
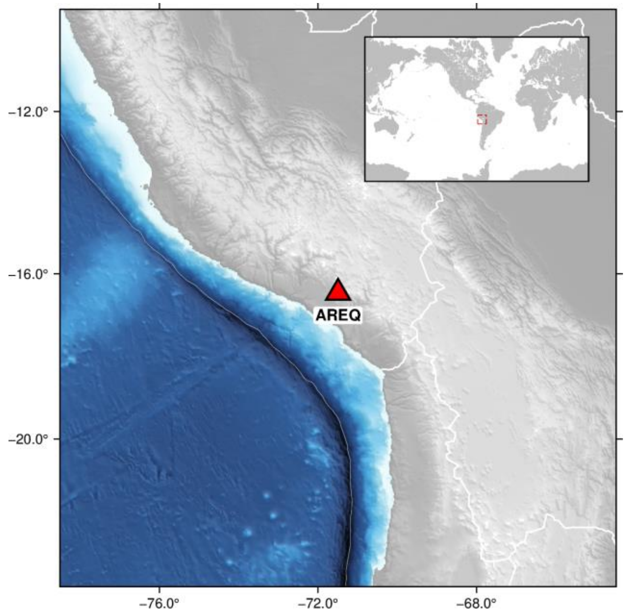
Results – SIRGAS

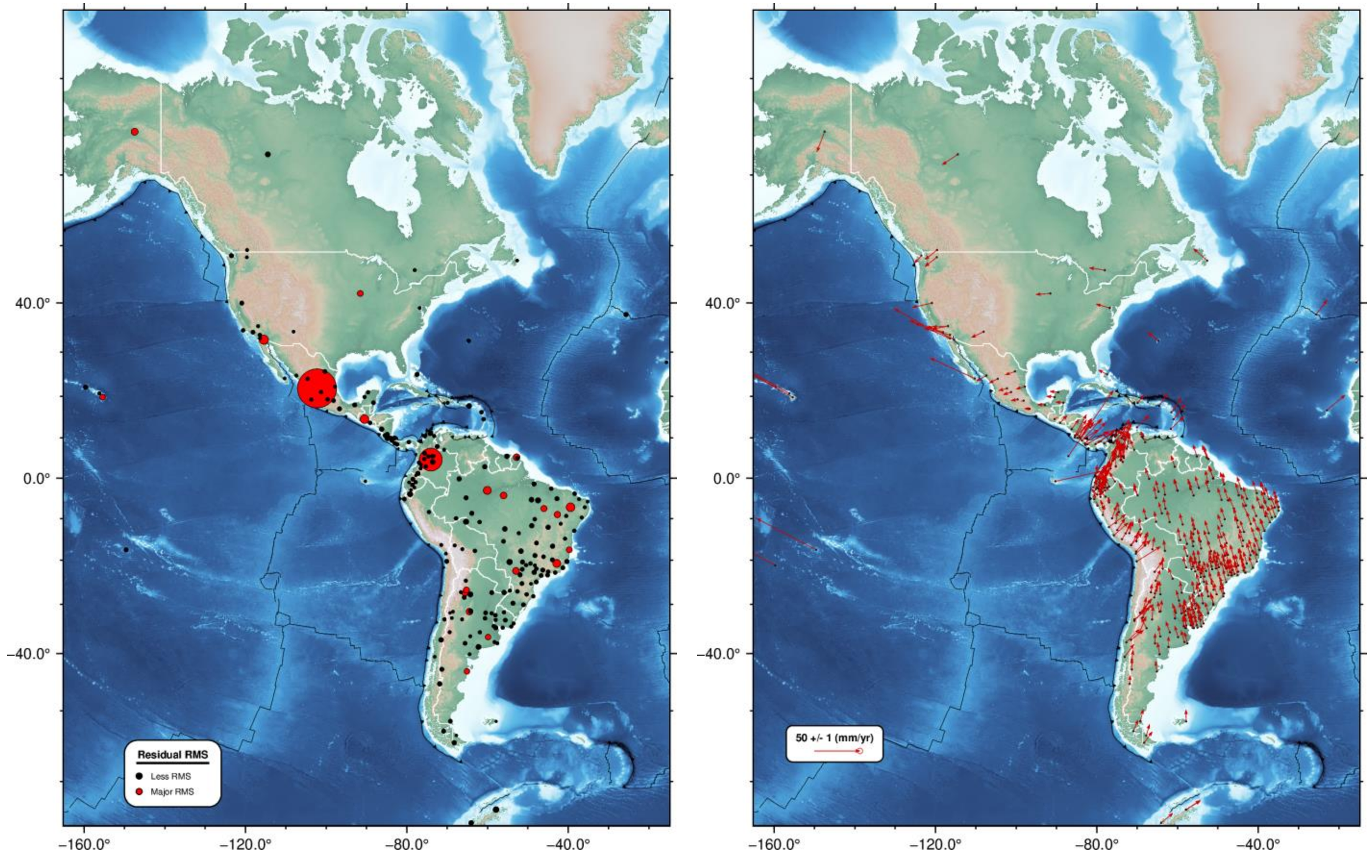




Source: USC Geodetic Processing and Analysis Center

Results – SIRGAS

- **Regional Observations**
  - Differential behaviors resulting from the complex tectonic interaction in the region.
  - Deformation patterns that align with the different plate boundaries.



Source: USC Geodetic Processing and Analysis Center

Results – REDGEOMIN

The residuals for the REDGEOMIN network, which are the differences between the model and the observed data, are compiled in a histogram that shows the residuals for the entire network. Key points to highlight:

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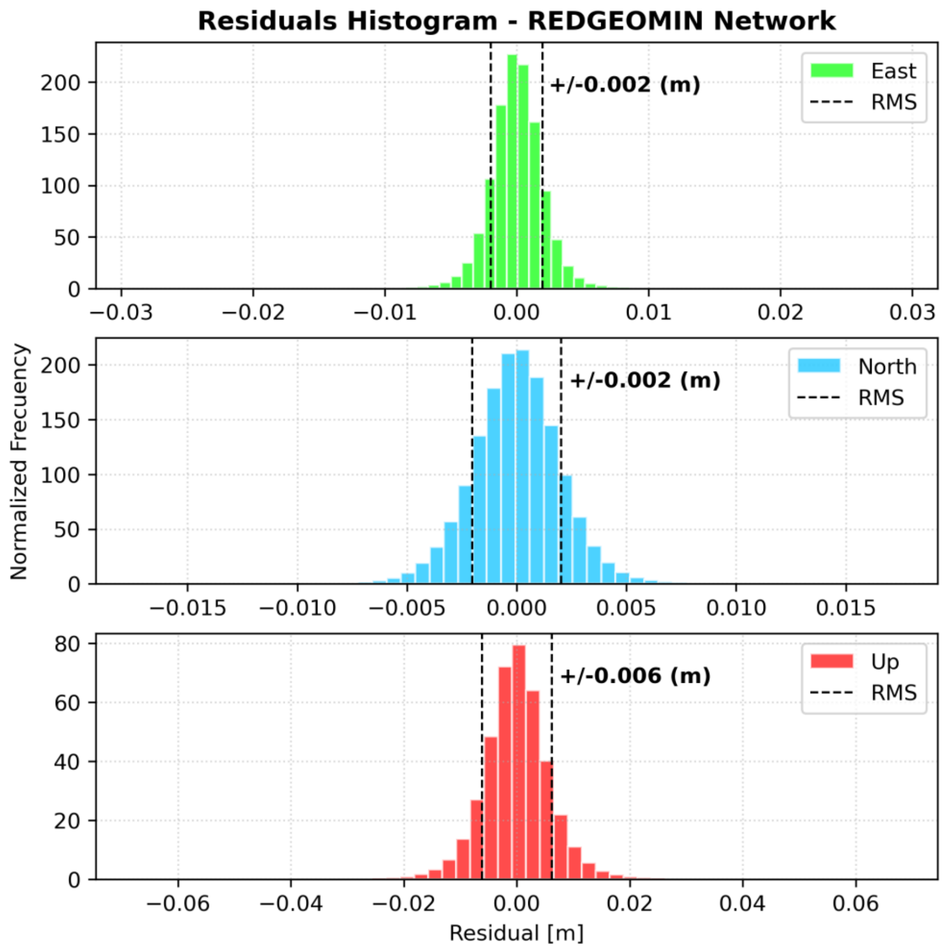
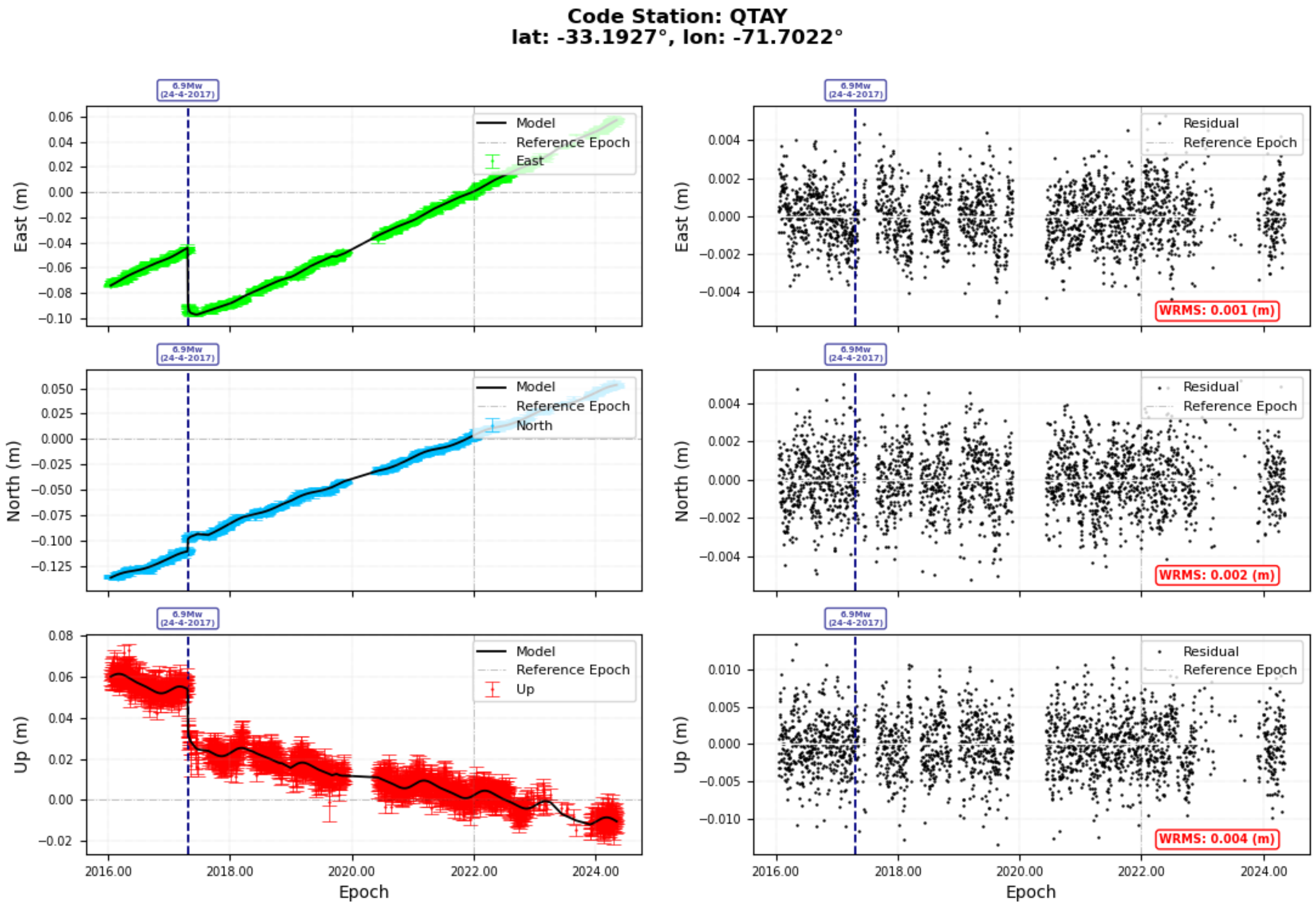
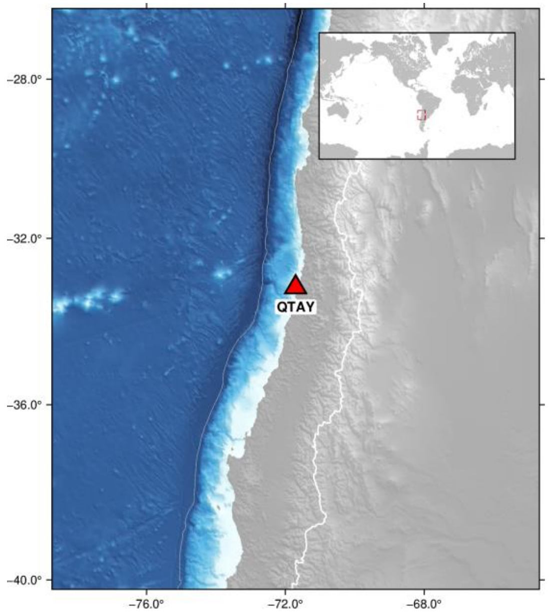


Source: USC Geodetic Processing and Analysis Center

Results – REDGEOMIN



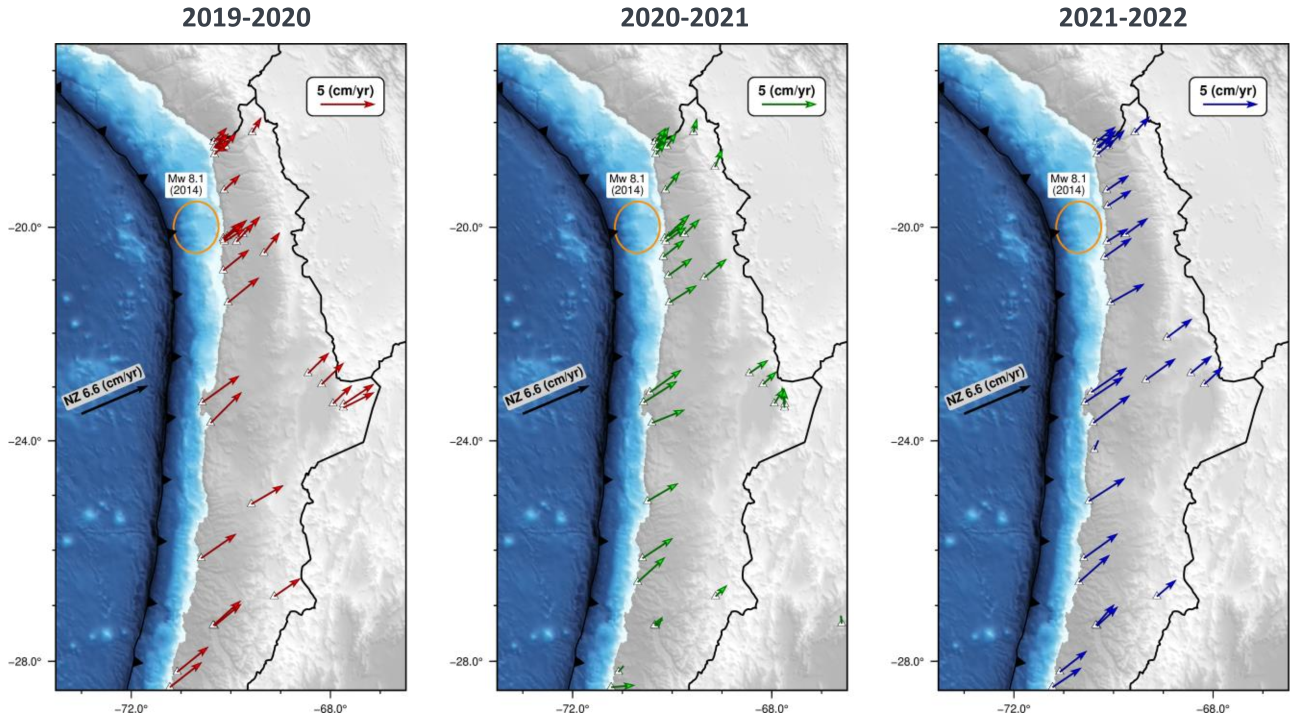


Source: USC Geodetic Processing and Analysis Center

Results – REDGEOMIN

- **Regional Observations**
  - Differential behaviours observed in Northern, Central, and Southern Chile.

- **Key Seismic Events**
  - 27th February 2010 (8.8 Mw)
  - 1st April 2014 (8.2 Mw)
  - 16th September 2015 (8.4 Mw)



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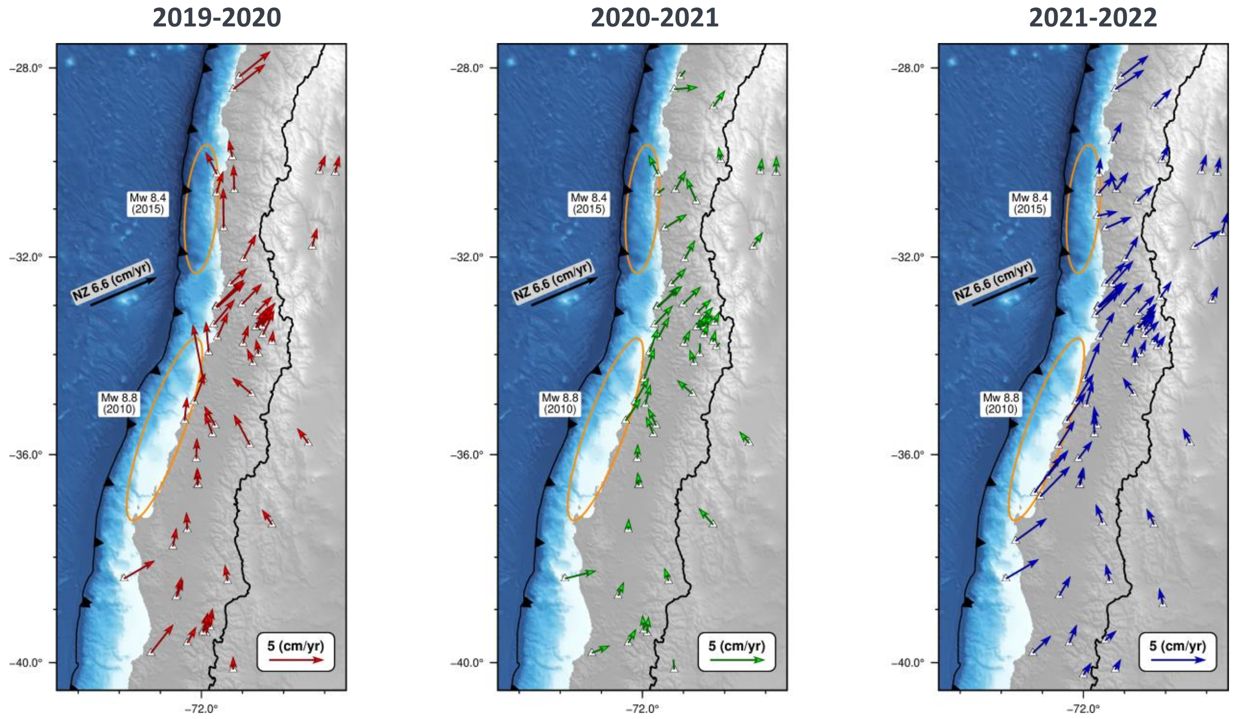

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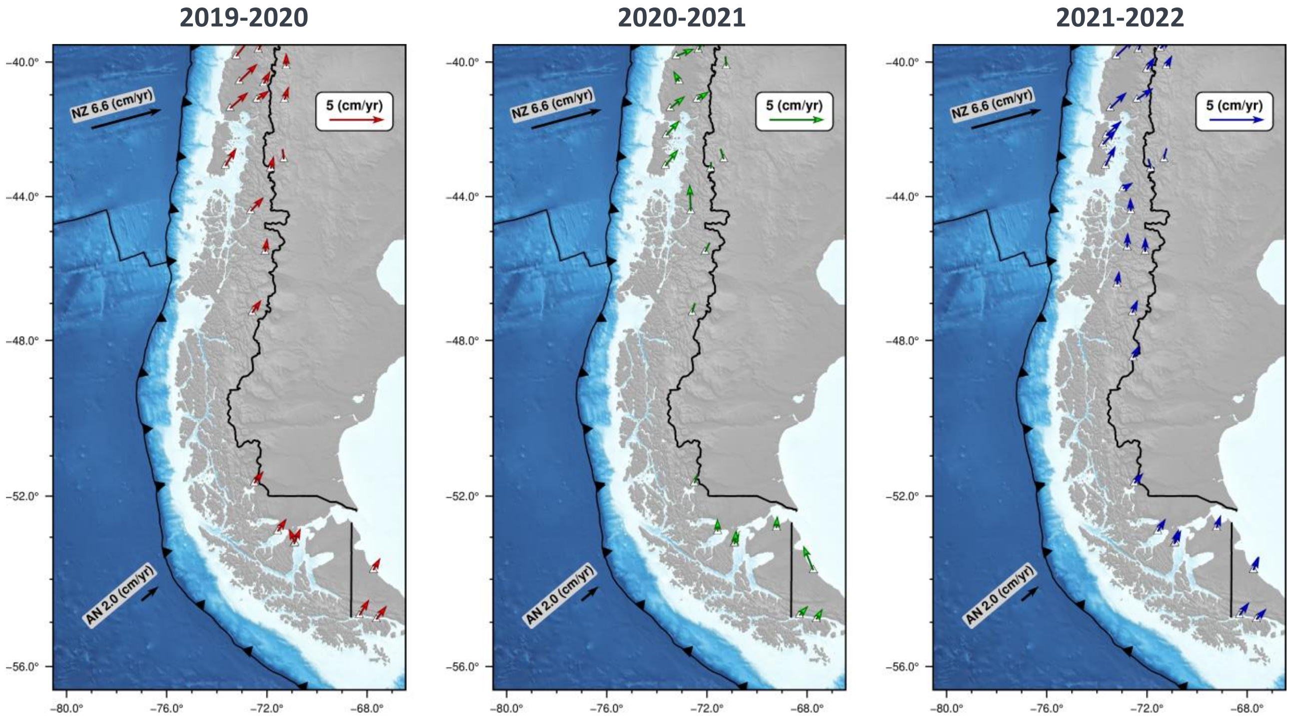
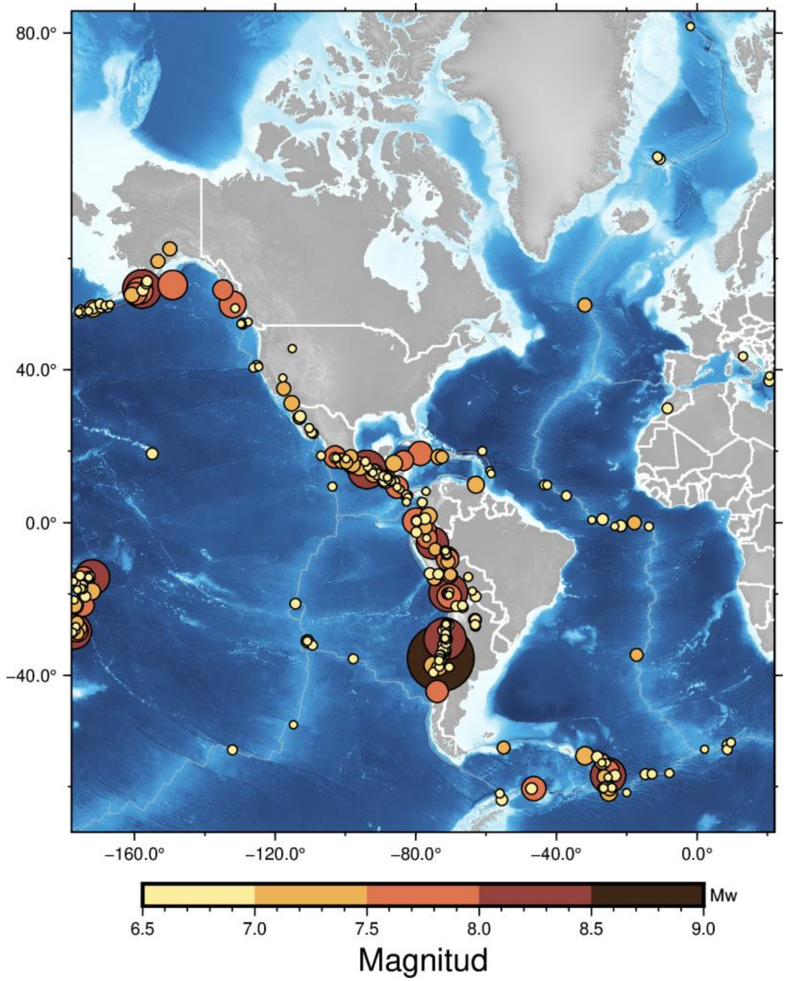


Source: USC Geodetic Processing and Analysis Center

Analysis and Interpretation

- **Deformation Rates**
  - Analysis of Earth's surface changes
  - Accurate fitting of GNSS time series enhances understanding of surface deformation, especially in regions with complex tectonic contexts.
- **Behavioral Differentiation**
  - Areas affected by significant seismic events
  - REDGEOMIN and SIRGAS exhibit deformation patterns influenced by seismic activity and major earthquakes.



Source: USC Geodetic Processing and Analysis Center

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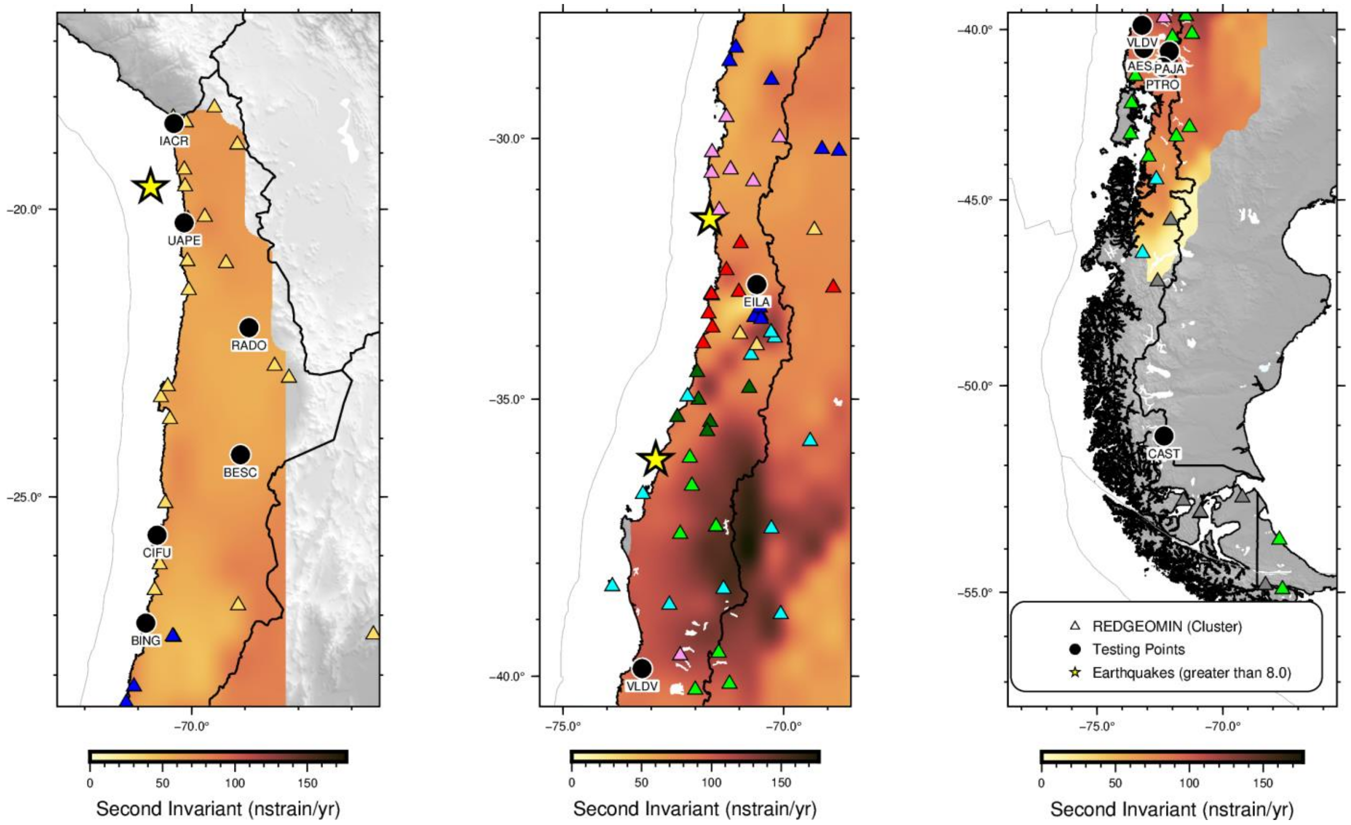
Practical Implications



Source: USC Geodetic Processing and Analysis Center

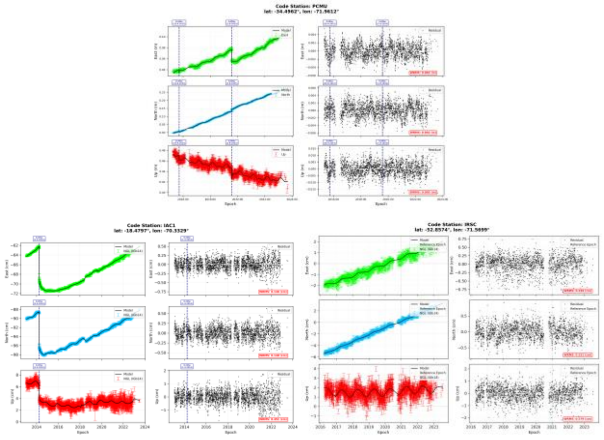
- **Sectorization of the region**
  - Improved precision in regional reference frames.
- **Application of GNSS Data Analysis**
  - Impact on updating and modifying geodetic reference systems for enhanced precision and reliability.

STATISTICS	Nearest – 4	K-mean
MIN (m)	0.002	0.002
MAX (m)	0.021	0.013
MEAN (m)	0.006	0.005
MEDIAN (m)	0.004	0.004
STD_DEV (m)	0.005	0.003

Products

Time series coordinates

USC Geodetic Processing and Analysis Center



PSD files

Testing stage at BSW

```
...
*------------------------------------------------------------------------------
+SOLUTION/ESTIMATE
*INDEX _TYPE_ CODE PT SOLN _REF_EPOCH__ UNIT S  ___ESTIMATED_VALUE___ __STD_DEV__
...
    56 ALOG_N ATJN  A ---- 14:091:85607    m 2 -4.406326577737000e-01 2.08592e-05
    57 TLOG_N ATJN  A ---- 14:091:85607    y 2  1.000000000000000e+00 6.41314e-02
    58 ALOG_U ATJN  A ---- 14:091:85607    m 2  1.529800026174000e+00 3.53868e-04
    59 TLOG_U ATJN  A ---- 14:091:85607    y 2  1.000000000000000e+00 6.41314e-02
    60 ALOG_E CAL9  A ---- 15:259:82472    m 2  6.752164231148000e+00 8.07070e-04
    61 TLOG_E CAL9  A ---- 15:259:82472    y 2  2.737850787132000e-03 3.18203e-03
    62 ALOG_N CAL9  A ---- 15:259:82472    m 2 -1.348084723577000e+00 9.89225e-04
    63 TLOG_N CAL9  A ---- 15:259:82472    y 2  2.737850787132000e-03 3.18203e-03
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    65 TLOG_U CAL9  A ---- 15:259:82472    y 2  2.737850787132000e-03 3.18203e-03
...
```

Deformation Model

ADELA (Analysis of Deformation beyond Los Andes)

Products

Geodetic innovation in Chilean mining: The evolution from static to kinematic reference frame in seismic zones

José Antonio Tarrío.[1]*, Catalina Cáceres., Valeria Vásquez., Miguel Marten., Jesarella Inzunza., Fernando Isla., Marcelo Caverlotti., Gabriel Jeldres., Rodrigo Urrutia., Cristian Mardones. and Rui Fernandes.

1 USC Geodetic Processing and Analysis Center. University of Santiago of Chile (USACH), Chile

Published
https://www.degruyter.com/document/doi/10.1515/jogs-2022-0173/html

Open Access Published since January 24, 2011

Journal of Geodetic Science

ISSN: 2081-9943
Editor-in-chief: Mehdi Eshagh

Call for Papers

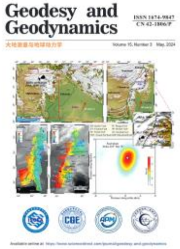
Integrating geodetic infrastructures for GNSS displacements analysis in Chile: A case study with REDGEOMIN (2019-2022)

José Antonio Tarrío.[1]*, Valeria Vásquez. [1], Catalina Cáceres. [1], Miguel Marten. [1], Fernando Isla. [1], Marcelo Caverlotti. [1], Gabriel Jeldres., Rodrigo Urrutia., Cristian Mardones.

1 USC Geodetic Processing and Analysis Center. University of Santiago of Chile (USACH), Chile

2 Servicio Nacional de Geología y Minería de Chile (SERNAGEOMIN), Chile

Accepted (in press)



Journal of Geodesy and Geodynamics

Conclusions

- **Summary of Findings**
  - In continental Chile, there is a pressing need to transition from a static to a kinematic reference frame, given the considerable magnitude of surface deformation caused primarily by seismic activity.
  - Non-linear modeling of GNSS time series is crucial in study regions like SIRGAS and REDGEOMIN due to the complex geodynamic context and high seismic activity.
- **Future Work**
  - To fully utilize the potential of ML tools (clustering), it is necessary to incorporate relevant information such as active fault systems and the diverse geological contexts prevailing in different regions of the country.
  - Apply clustering techniques with machine learning tools to distinguish areas with similar deformation behaviors and analyze these variations over time, observing how they evolve.
  - Work on densifying the GNSS station network to improve the surface deformation model and explore more clustering methods to describe surface deformation behavior with greater precision.

Research funding: IDeA I+D_ID23I10147

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