Sentinel-1 InSAR Reveals Complex Strain Accumulation at the Southwestern Caribbean-South America Transform Plate Boundary

Machel Higgins, Shimon Wdowinski, Omar Perez, James Kellog

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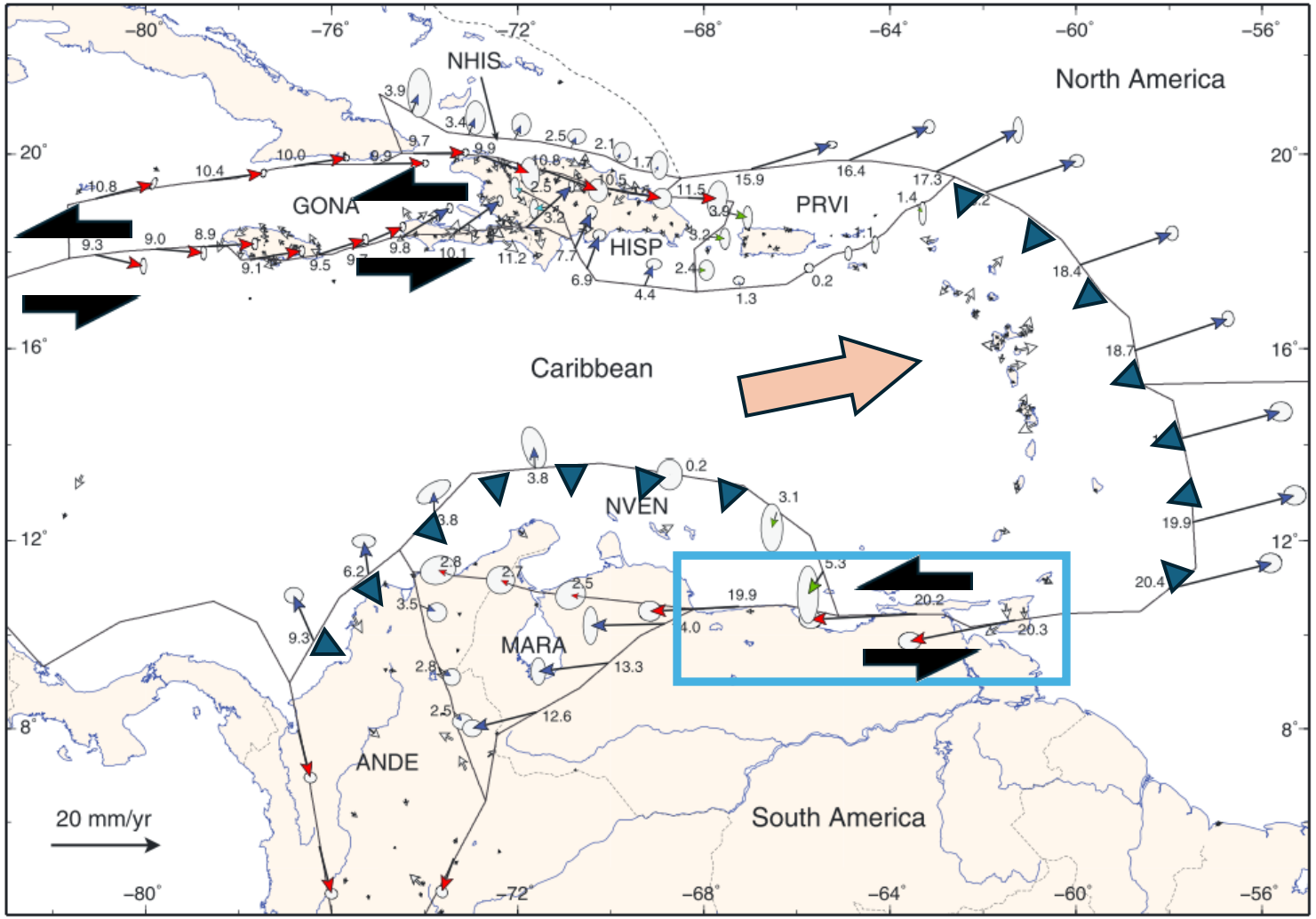
Caribbean Tectonic Setting



Circum-Caribbean Tectonic Block Model from Symithe et al., 2016.
The southern Caribbean-South American transform plate boundary takes up 20 mm/yr to 22 mm/yr left-lateral motion.

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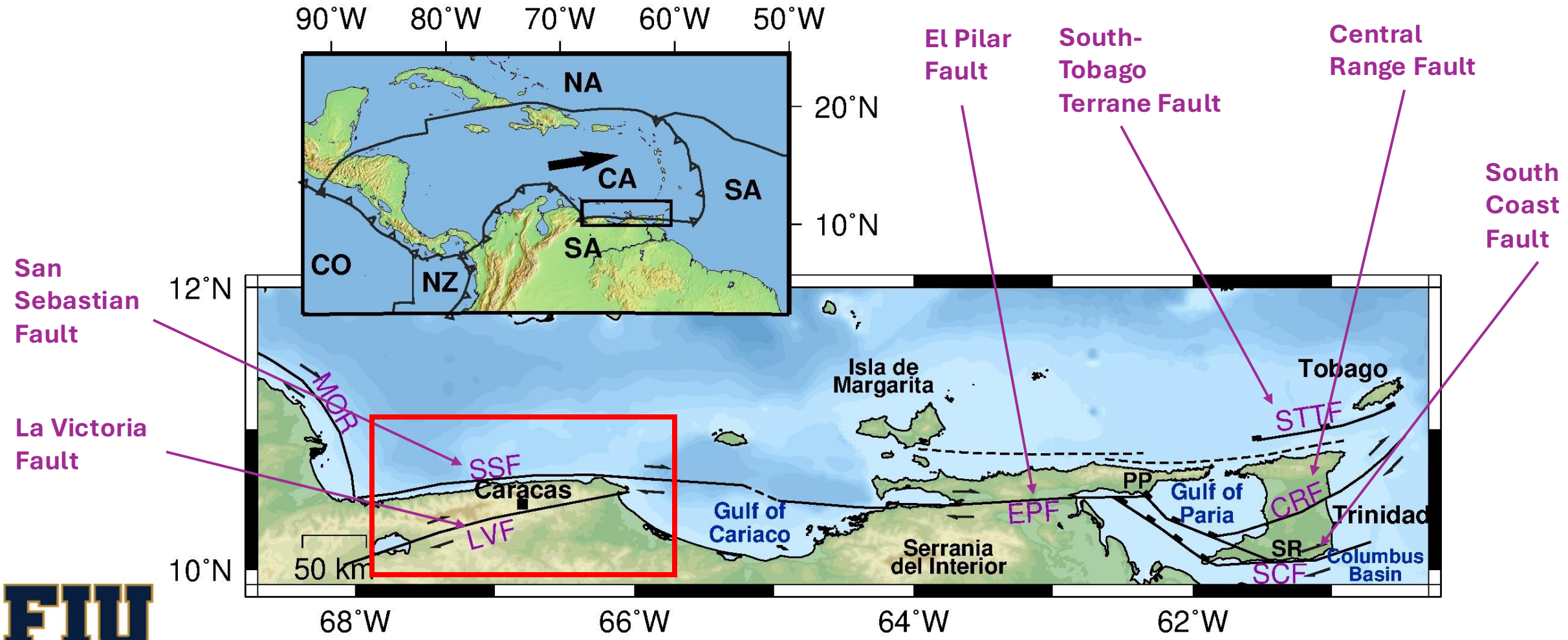
Southern Caribbean-South American Transform Plate Boundary



Strain partitioned over sub-parallel fault systems in northern **Venezuela** and the islands of **Trinidad and Tobago**.

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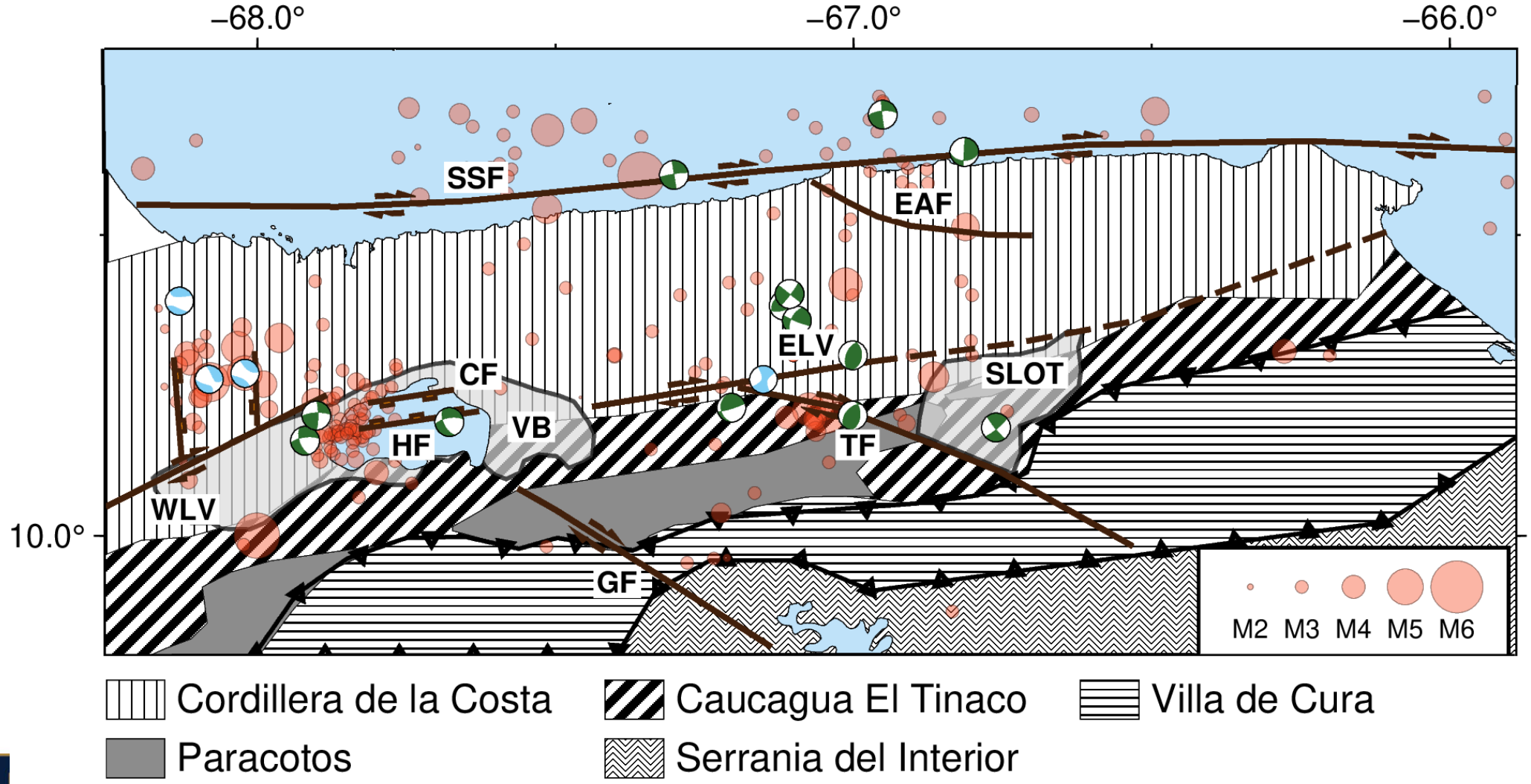
Northern Venezuela Faults, Seismicity, and Terranes



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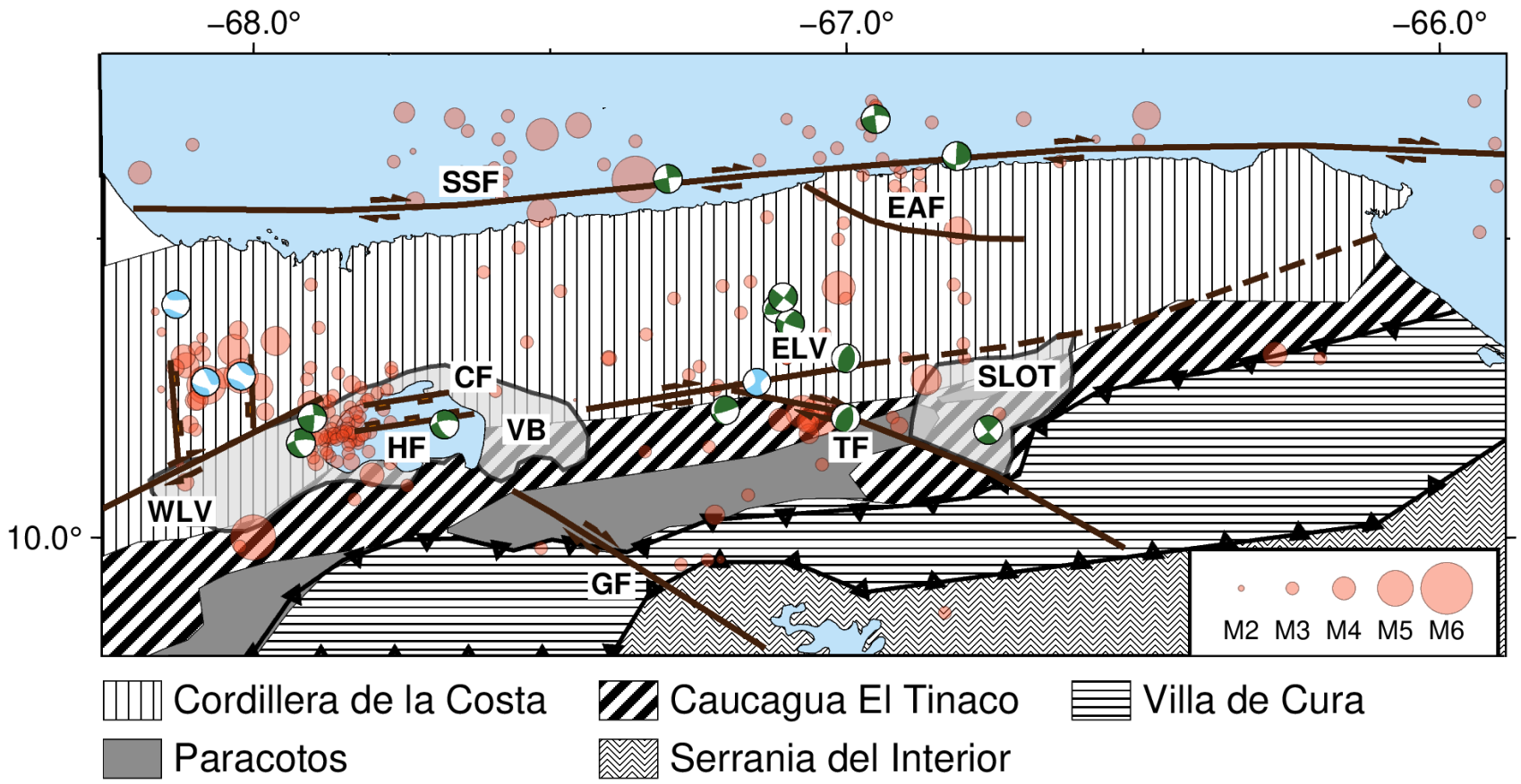
SSF – San Sebastian Fault **WLV** – Western La Victoria Fault **ELV** – Eastern La Victoria Fault

EAF – Al Avila Fault **GF** – Rio Guárica Fault **TF** – Tácata Fault

HF – El Horno Fault **CF** – Cabrera Fault

Northern Venezuela Faults, Seismicity, and Terranes

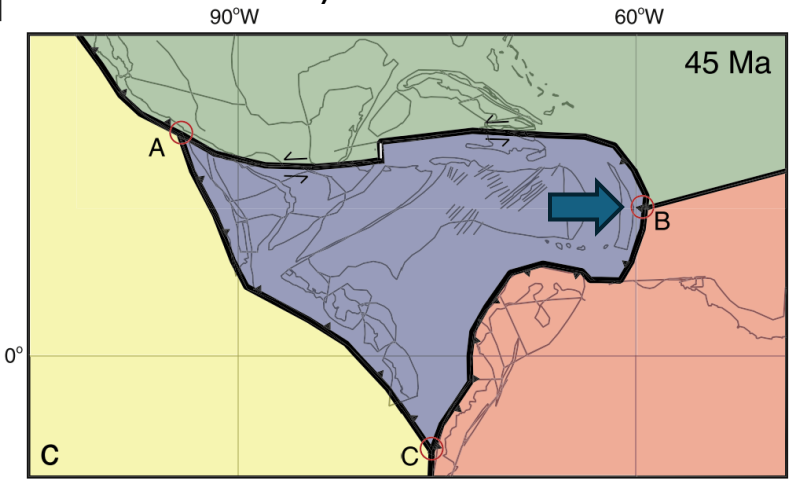


Caribbean Plate Eastward Migration.

WSW-ENE trending accreted and emplaced terranes.

South to North:

- Late Jurassic rifting of Pangea (Villa de Cura)
- Early Cretaceous Great Caribbean Arc (Cuacagua El Tinaco)
- "Bulldozed" remnants of the Eastern Caribbean arc (Cordillera de la Costa).



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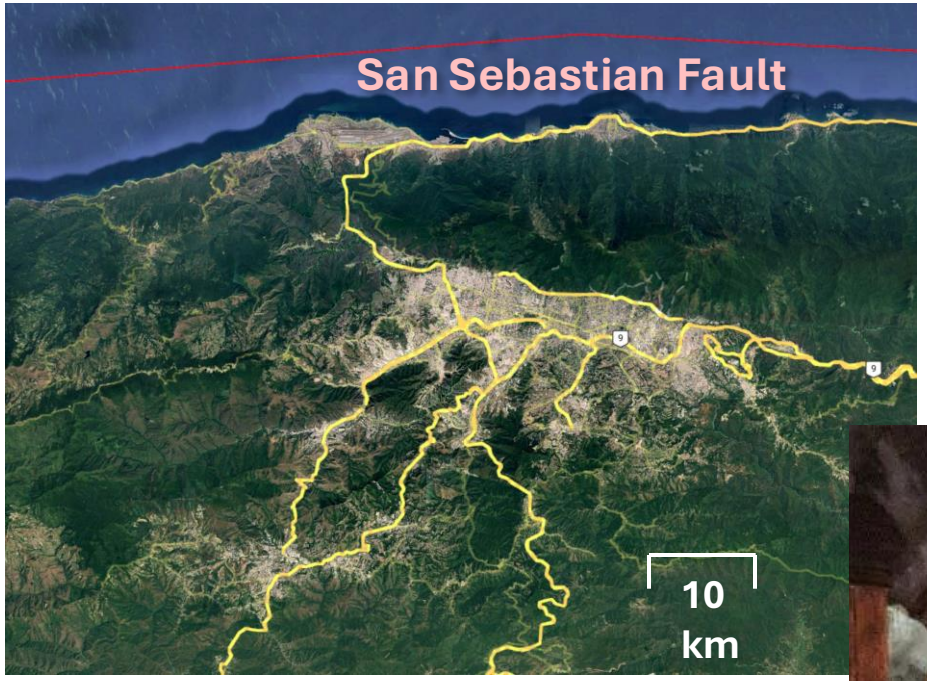
Source: Boschman et al. 2016.

Caracas Historical Seismicity



Aerial Image of Caracas from Google Earth

1812 M7.7 Caracas Earthquake

Damage and collapse structures following 1967 M6.7 Caracas earthquake.

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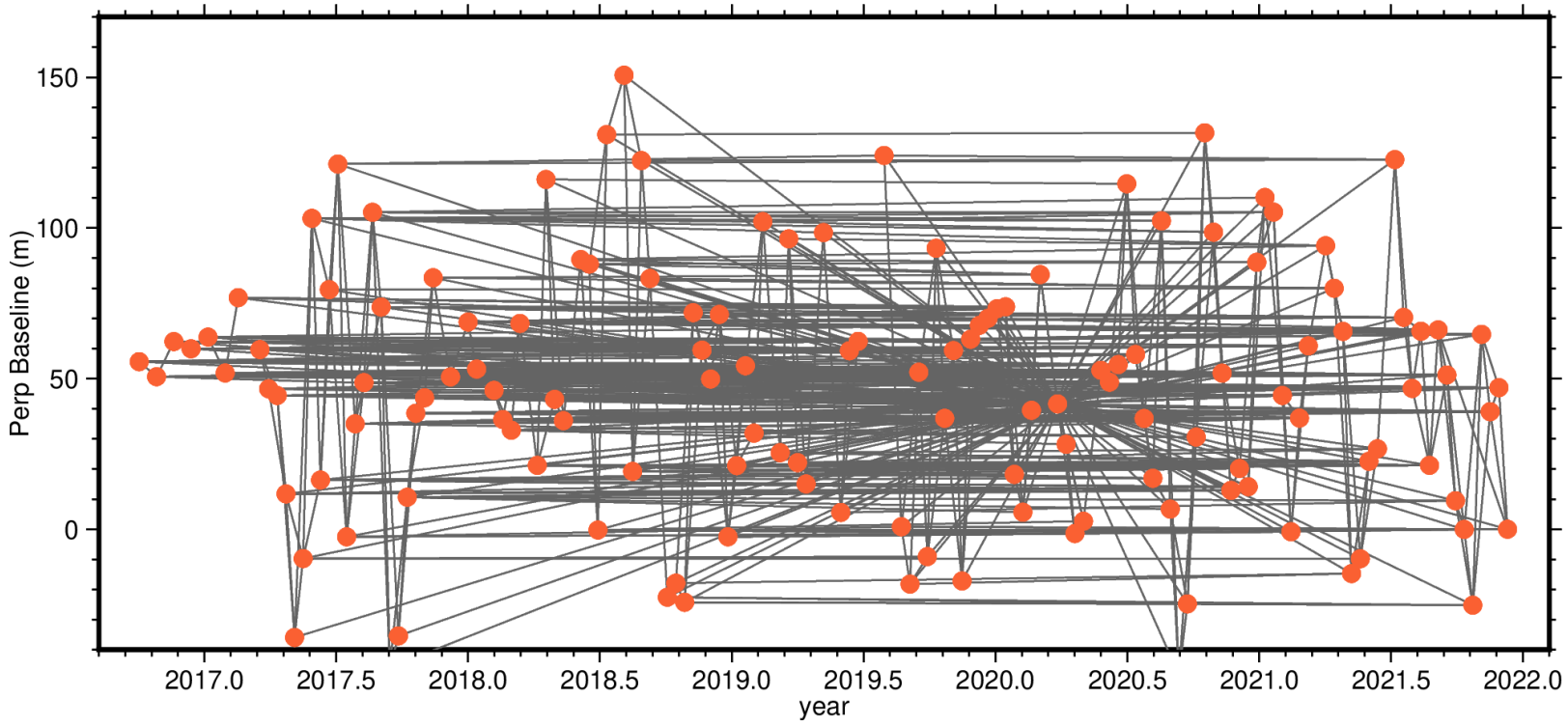
InSAR Data

Sentinel-1 (Path 133 Frame 1213)



Interferograms created with GMTSAR. Permanent Scatter pixels selection and processing done with the StaMPS code. For time series, seasonal signals, steps due to unwrapping errors, and secular LOS velocity were estimated using equation below,

$$x(t) = A_i H_i(t) + B\sin(ht + \gamma_{annual}) + C\sin(2ht + \gamma_{semi-ann}) + v(t)$$

625 interferograms were created using the **Long Temporal Short Perpendicular Baselines** strategy.

SBAS complemented with pairs using criteria of 800 days to 1500 days temporal and <5 m perpendicular baselines.

Differential phase for >800 days baselines exceeds atmospheric noise and reduces unwrapping error outliers for sum-of-squares minimization during SBAS least squares inversion. **Able to detect 2 -3 mm/yr (Higgins & Wdowinski, 2025).**

PS baselines are not needed but were included to ensure connected subnetworks.

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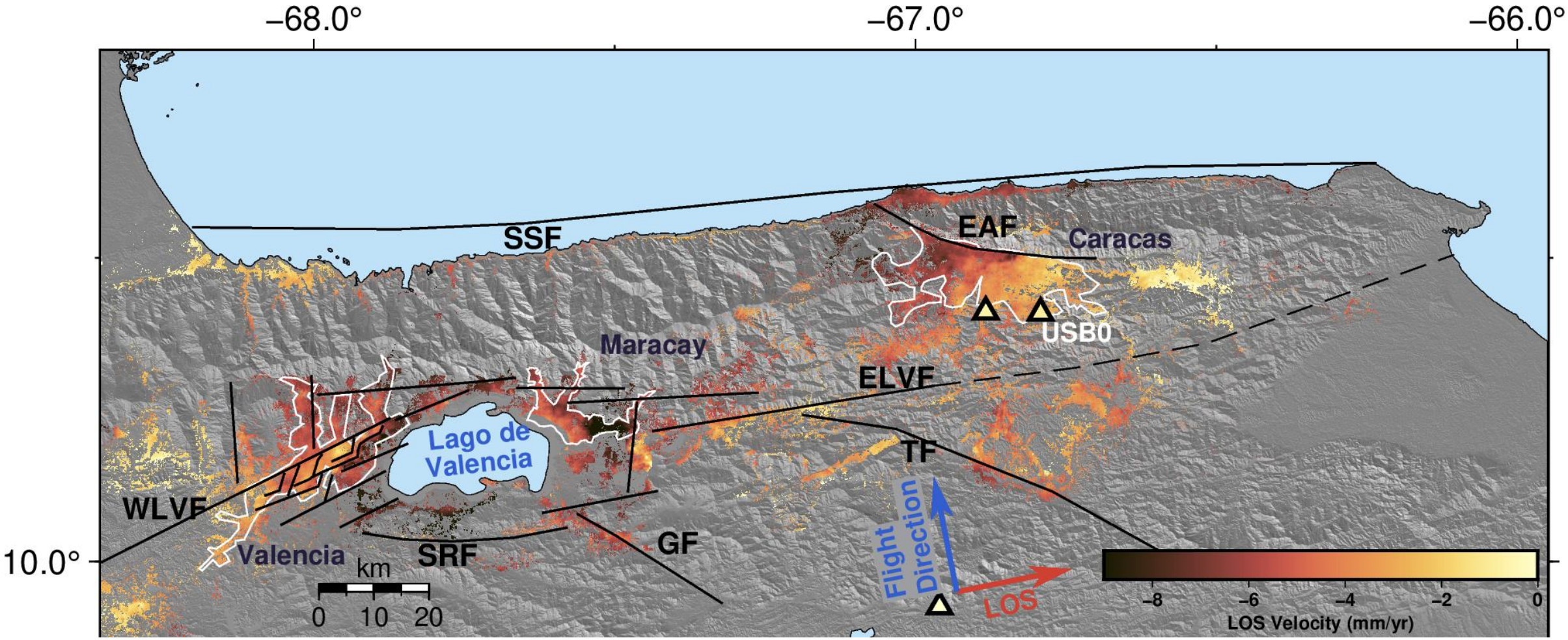
InSAR LOS Velocities



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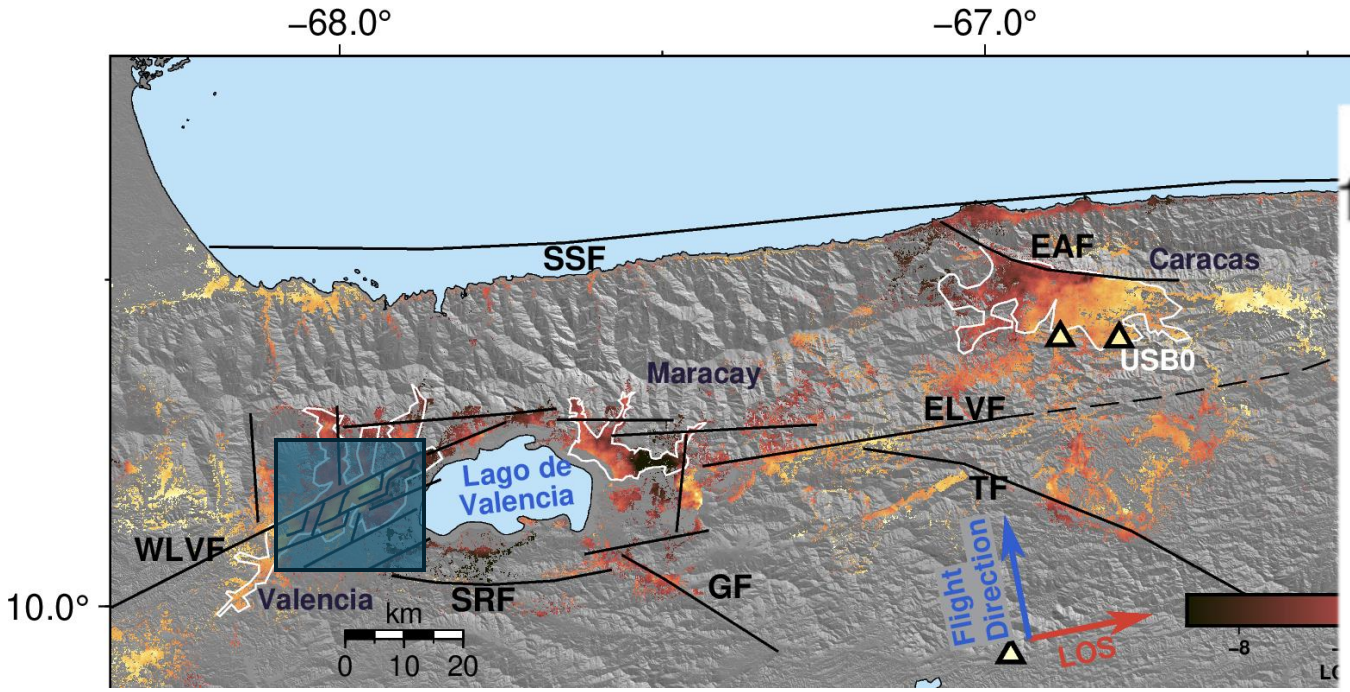
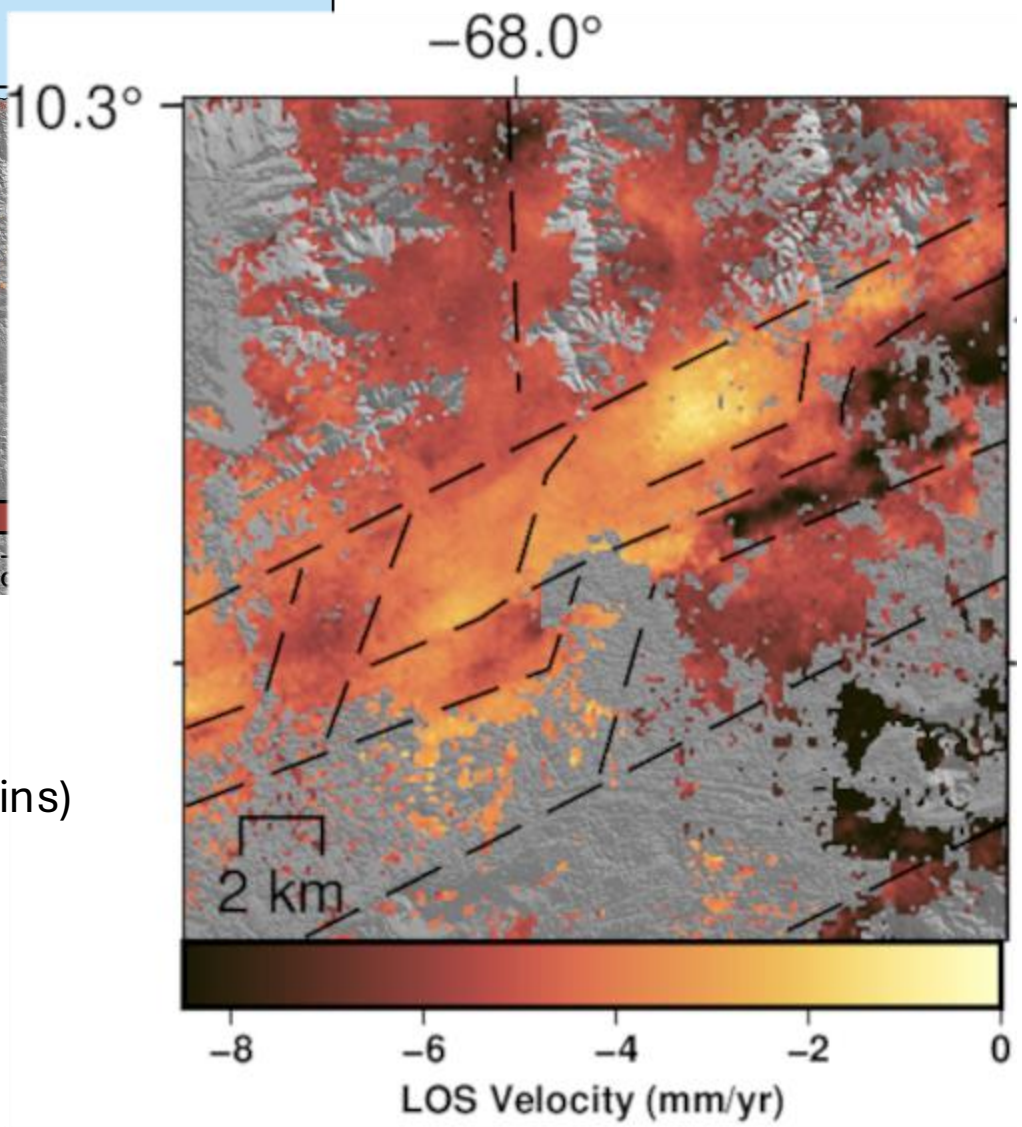
GPS velocities (yellow triangles) are CA-SA reference frame (Kreemer et al., 2014) velocities from Perez et al (2018) projected into LOS.

LOS Velocities referenced to USB0.

Western La Victoria Segments LOS Velocities





Large gradients of velocities suggest en echelon faults that create highly localized regions of compression (push-ups) and extension (sag basins) faulting with differential vertical motion up to 15 mm/yr.

The city of Valencia is the industrial center of Venezuela

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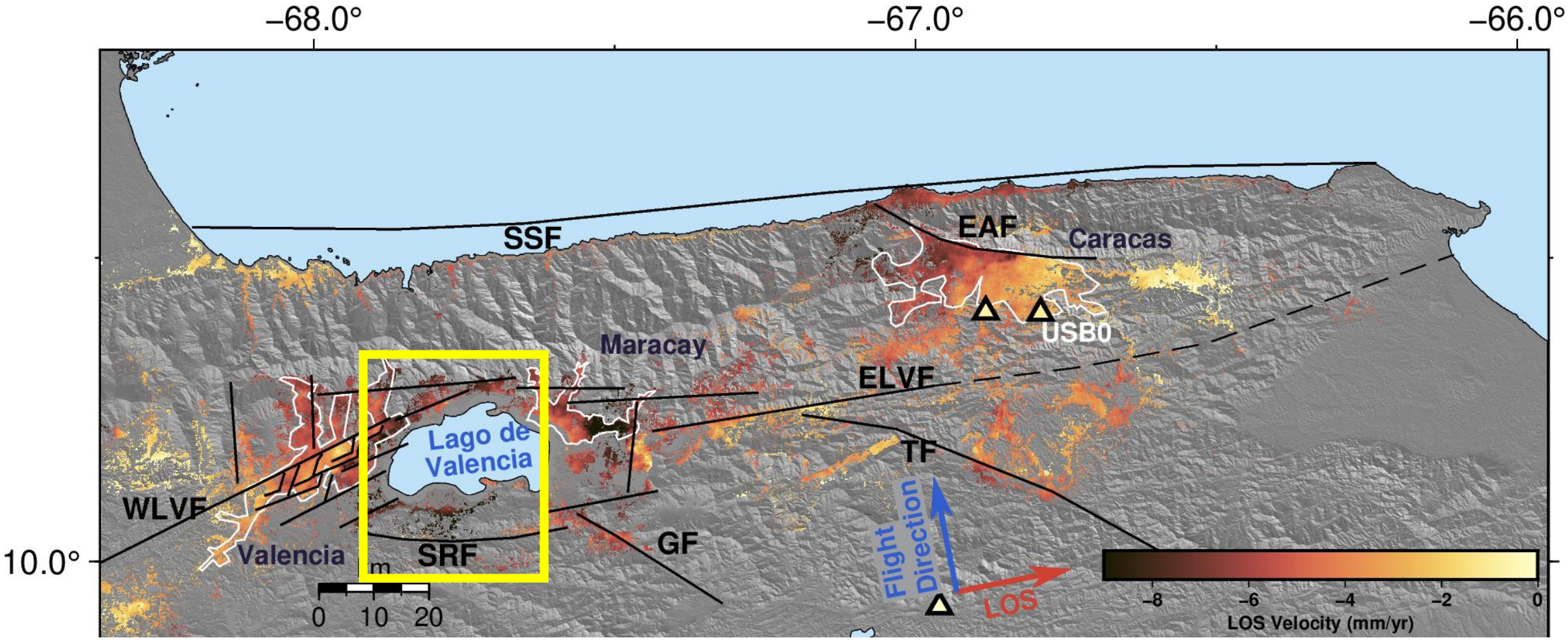
Victoria Basin Pull-Apart LOS Velocities



LOS velocities of -5 mm/yr between the Santa Rosa Fault (**SRF**) and Western La Victoria Fault are interpreted as subsidence.

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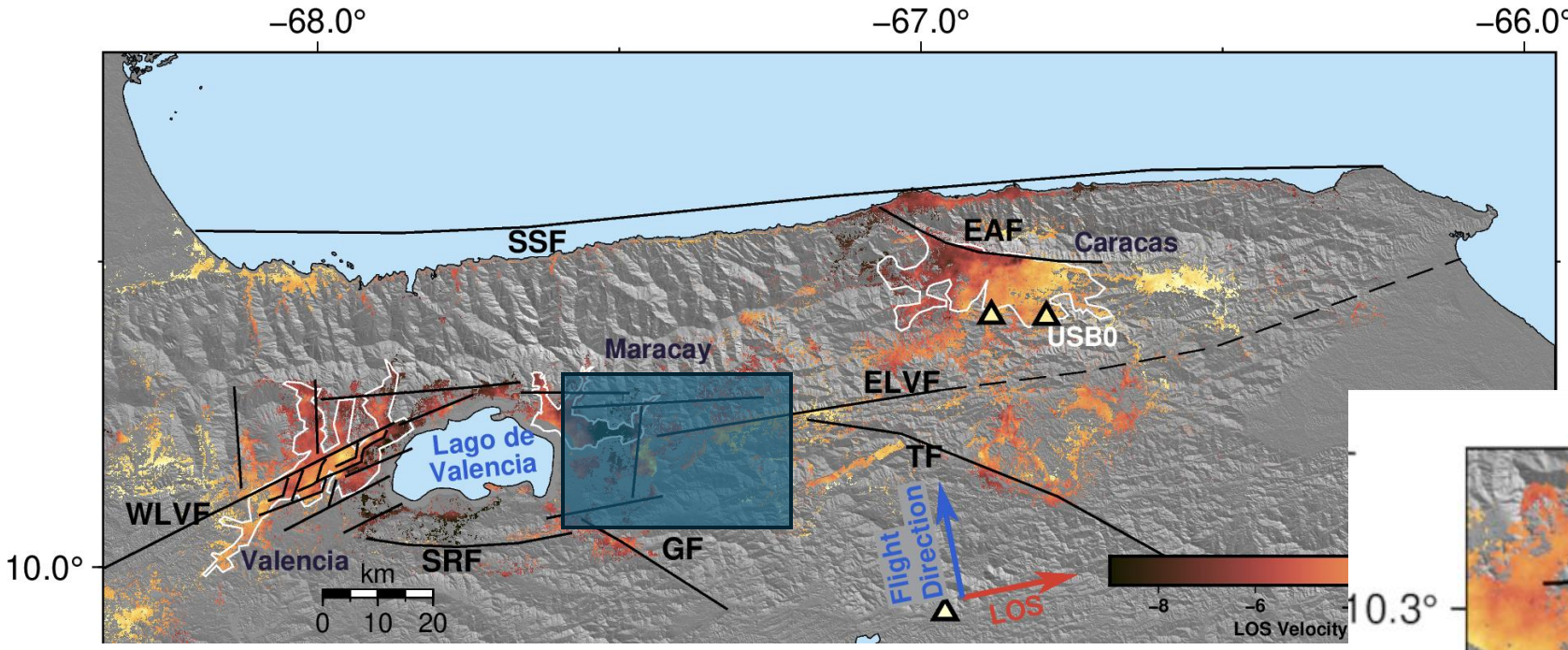
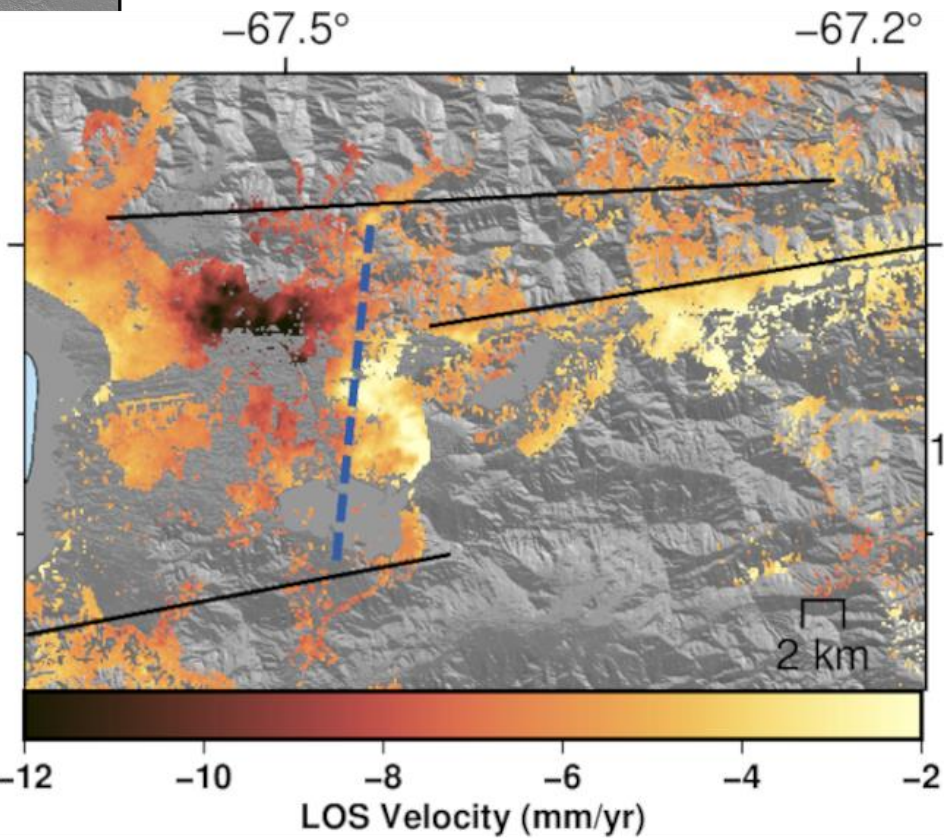
Eastern La Victoria Segments LOS Velocities





- Two large-scale lobes of subsidence and uplift (differential LOS of ~12 mm/yr).
- Possible buried fault (dashed blue line) is from inverted velocities.

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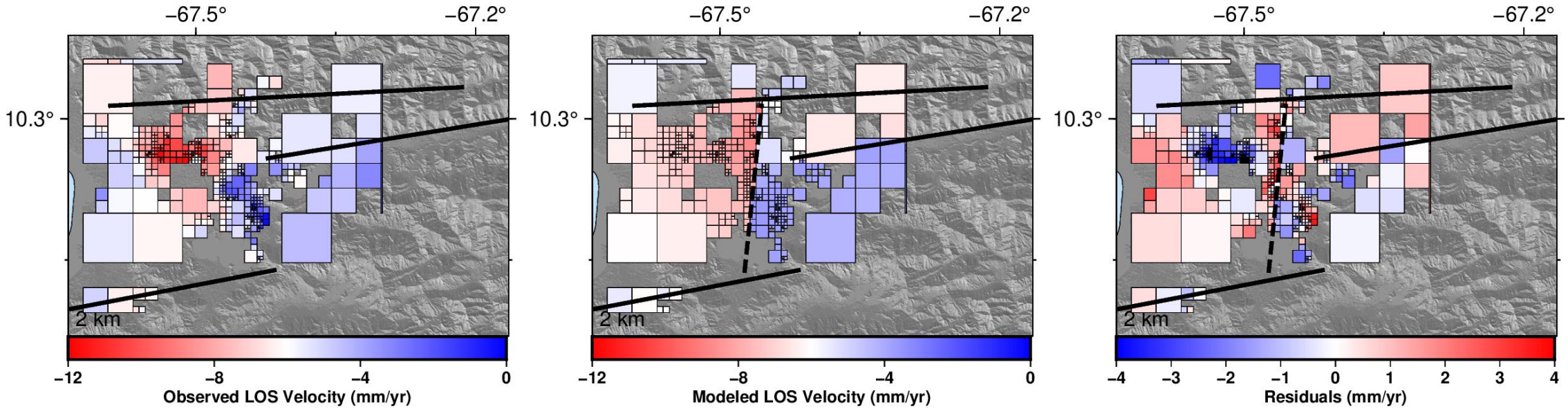
Model Inversion of East La Victoria Segments LOS Velocities



- Inversion for surface displacements due to slip on planar faults (Okada 85).
- Velocity inversion for slip on **only** en-echelon faults **could not** reproduce the two lobes.
- Model required a NNE trending vertical normal fault creeping at 5 mm/yr.
- No surficial expression of fault, possibly due to sedimentation of Lago de Valencia.
- En-echelon faults also creep at 5 mm/yr.

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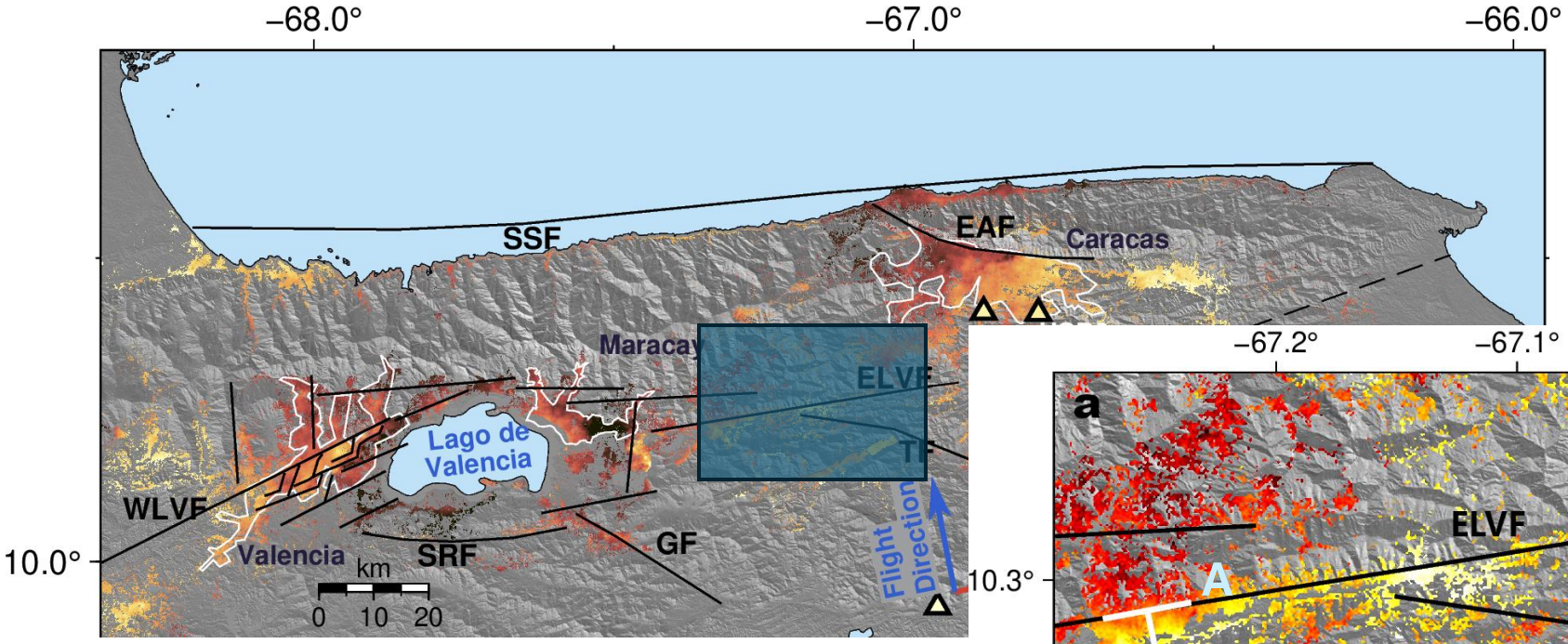
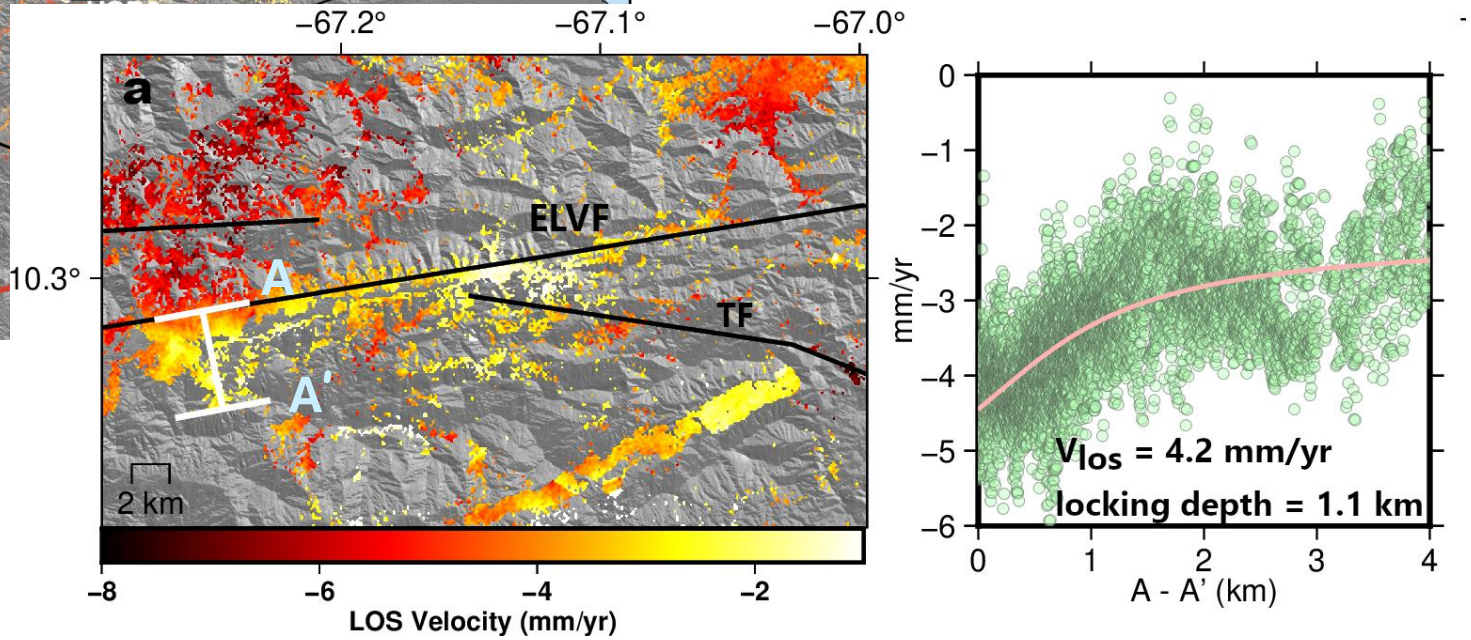
Creeping Eastern La Victoria Segments





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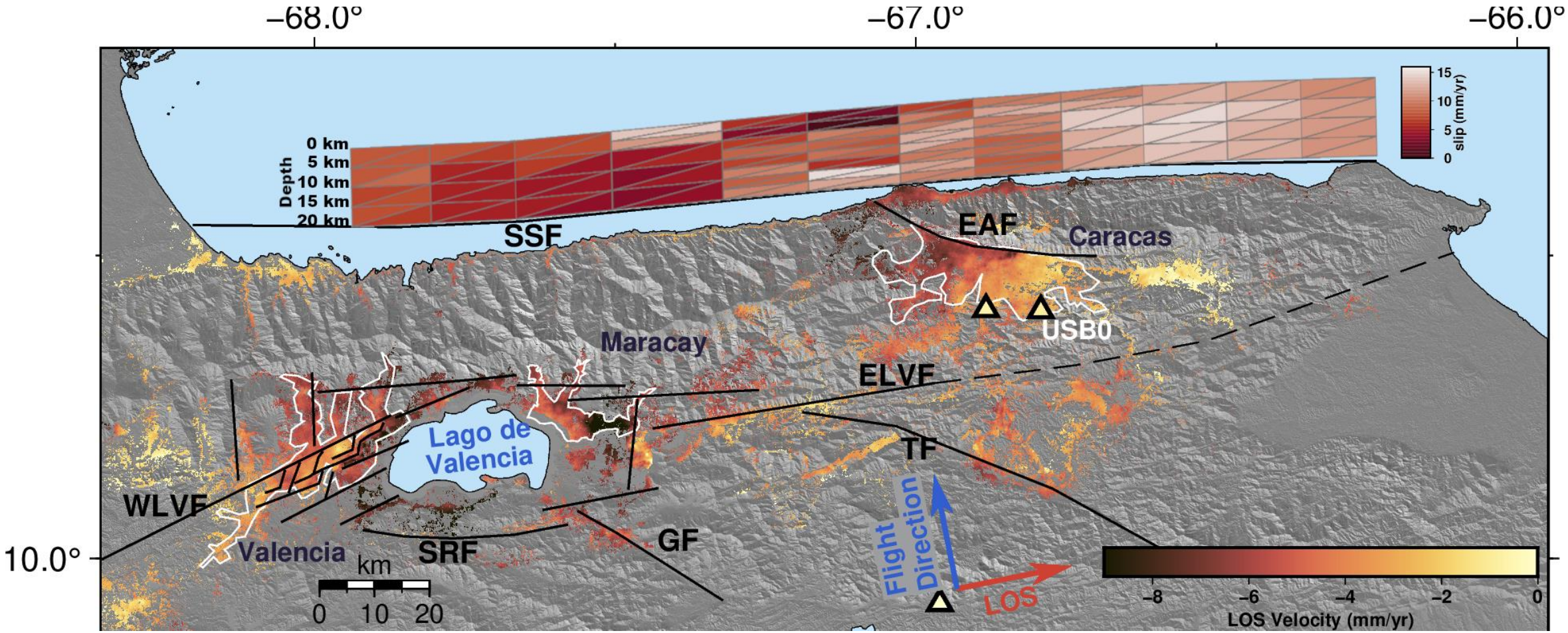
- Inversion results using Elastic Dislocation model show eastern segment of ELVF, up to the intersection with the Tacata Fault (TF), is not locked, and the ELVF accommodates ~5 mm/yr of CA-SA motion.
- Inversion only used velocities south of ELVF to avoid surface displacements of other step faults.

San Sebastian Fault Slip Deficit



- Velocity inversion for discretized fault of triangle dislocation elements.
- The western segment of San Sebastian is locked while the eastern segment creeps.
- Last rupture was 1900 M~7.8. **SSF is capable of rupturing a Mw 7.1 earthquake**.
- Model requires up to 8 mm/yr of reverse motion east of the intersection with El Avila Fault (EAF).

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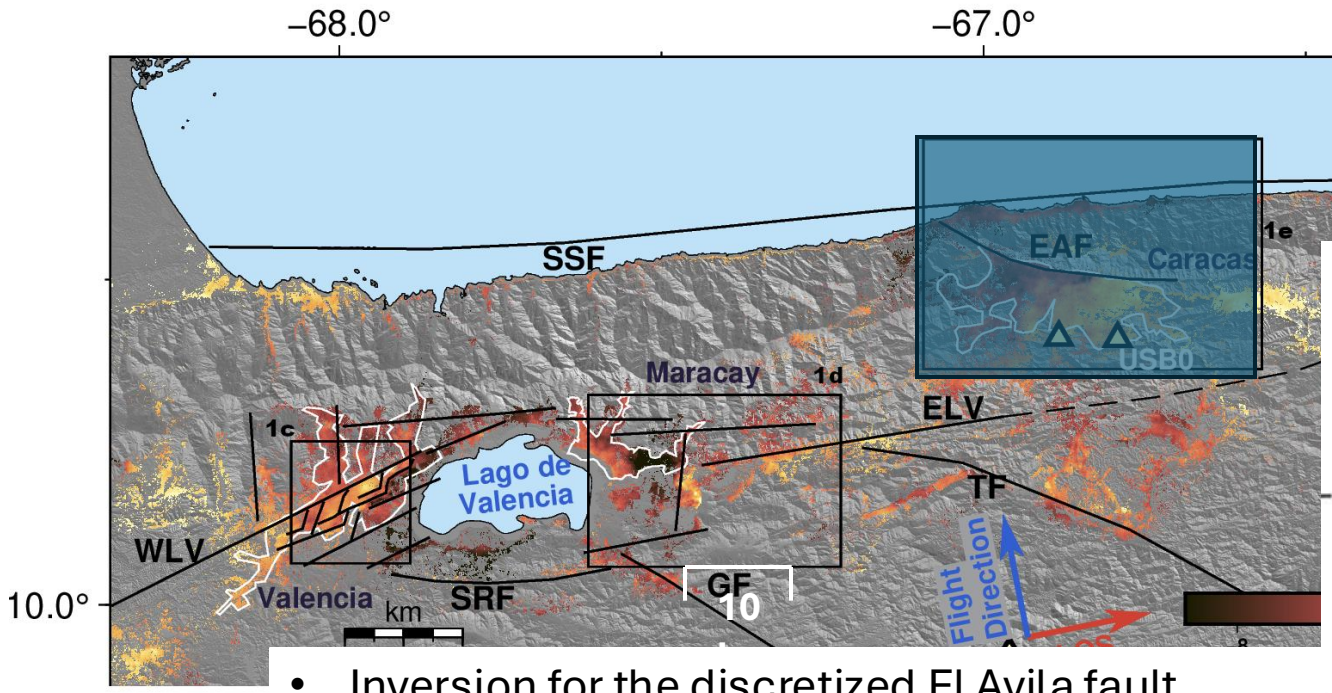
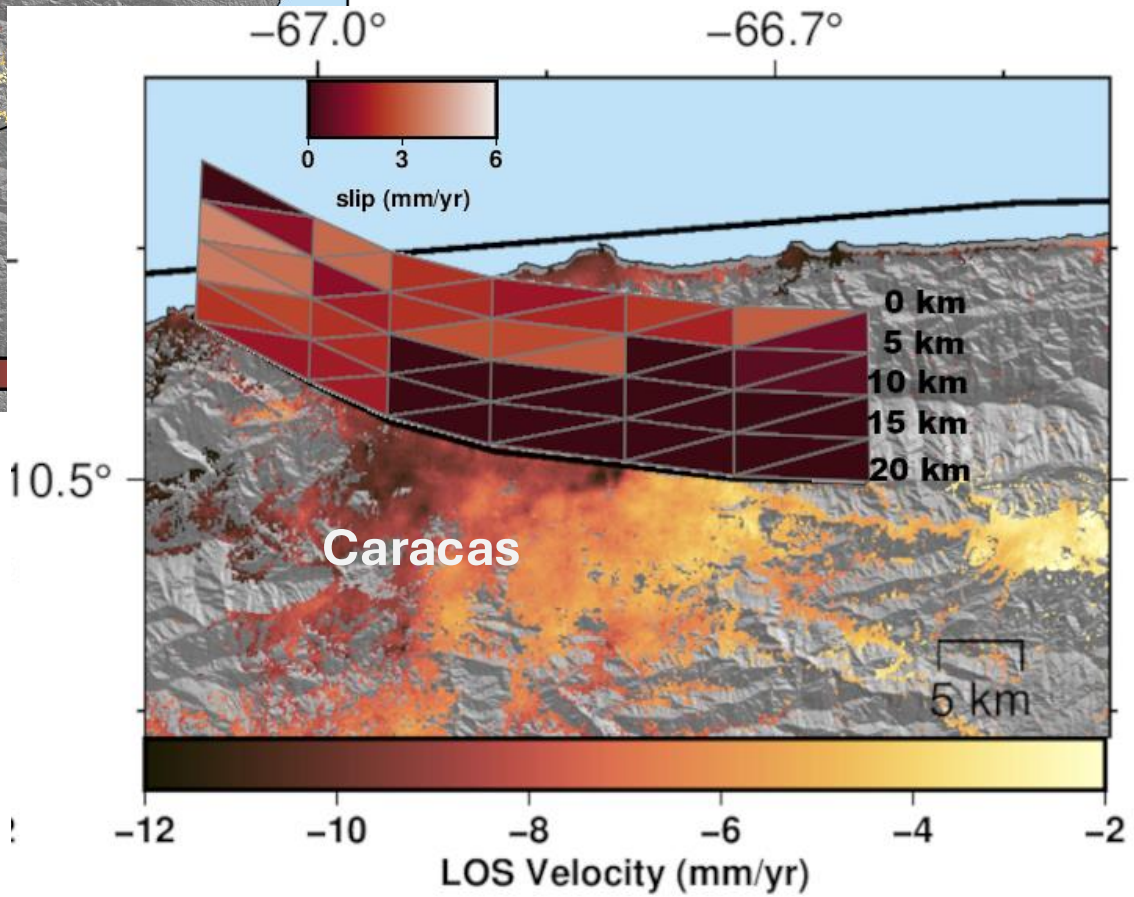
El Avila Fault Slip Deficit





- Inversion for the discretized El Avila fault (**EAF**).
- EAF is partially locked and accommodates ~4 mm/yr of left-lateral and reverse motion equally.
- LVF accommodates no strain here. 1878 M 6-7 earthquake, attributed to the LVF, ruptured the EAF.
- EAF could rupture a Mw 6.6 earthquake.

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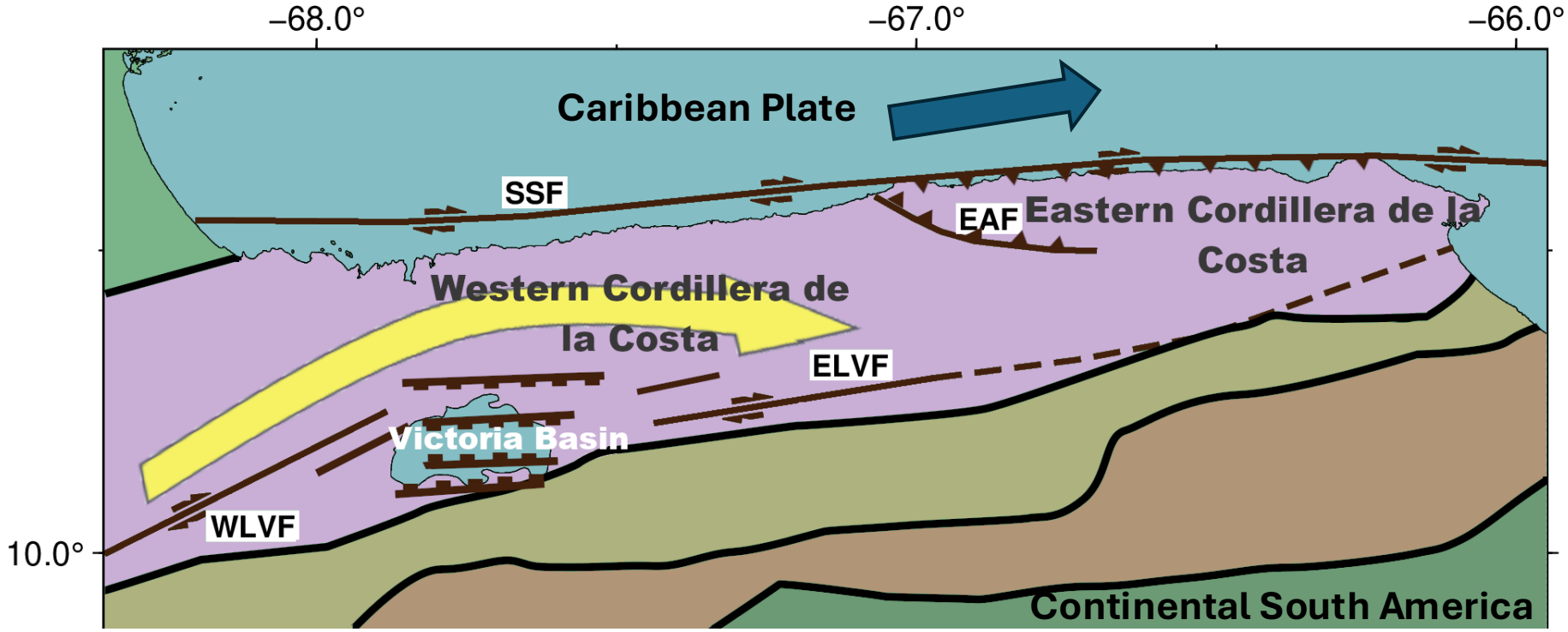
Faults Kinematics



- Victoria pull-apart formed due to a change in La Victoria Fault strike caused by Cordillera de la Costa coupled to CA, and being dragged around previously emplaced terranes.
- Victoria pull-apart is young with no master faults nor lazy “S” shape.
- Pull-apart forms a graben with bottom-top normal faults due to inherited terranes’ contacts.
- Eastern San Sebastian Fault and El Avila fault underthrust the Eastern Cordillera de la Costa, suggesting it is structurally different from other terranes.
- CA-dragged terranes creating pull-aparts may explain the development of the two main basins along this plate boundary

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Summary

- The western segment of the San Sabastian fault (**SSF**) is locked and can produce a Mw 7.1 earthquake.
- The El Avila fault (**EAF**) is partially locked and can produce a Mw 6.7 earthquake.
- ***Both SSF and EAF present a grave seismic hazard for the capital city, Caracas.***
- Victoria Basin pull-apart is a graben and expresses strain as subsidence at ~ 5 mm/yr.
- La Victoria fault creeps with low-magnitude seismicity but causes high gradients of vertical land motion.
- The Eastern Cordillera de la Costa is structurally different from the Western Cordillera de la Costa.

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Summary

Thank you!

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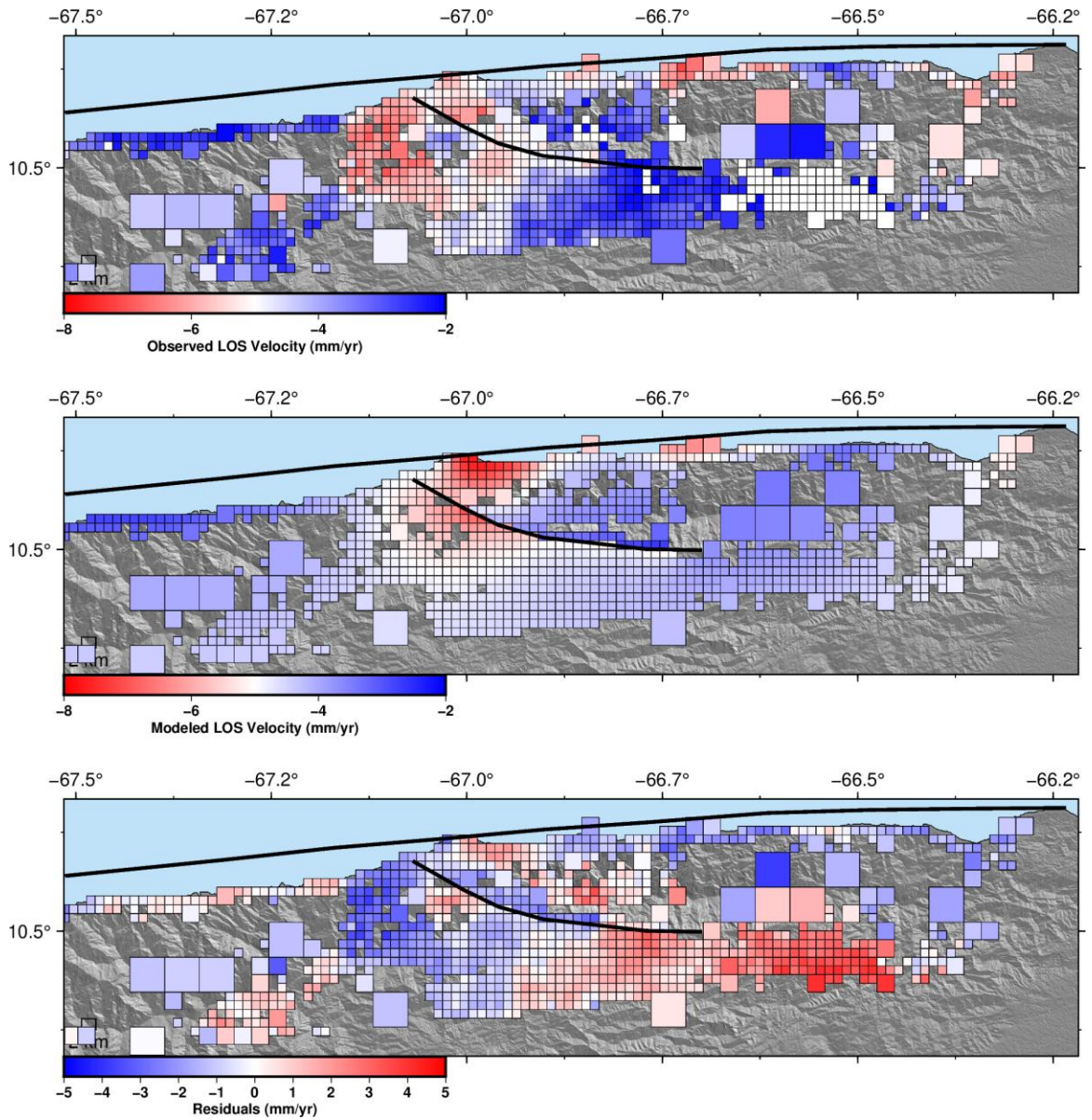
San Sebastian Slip Deficit Model



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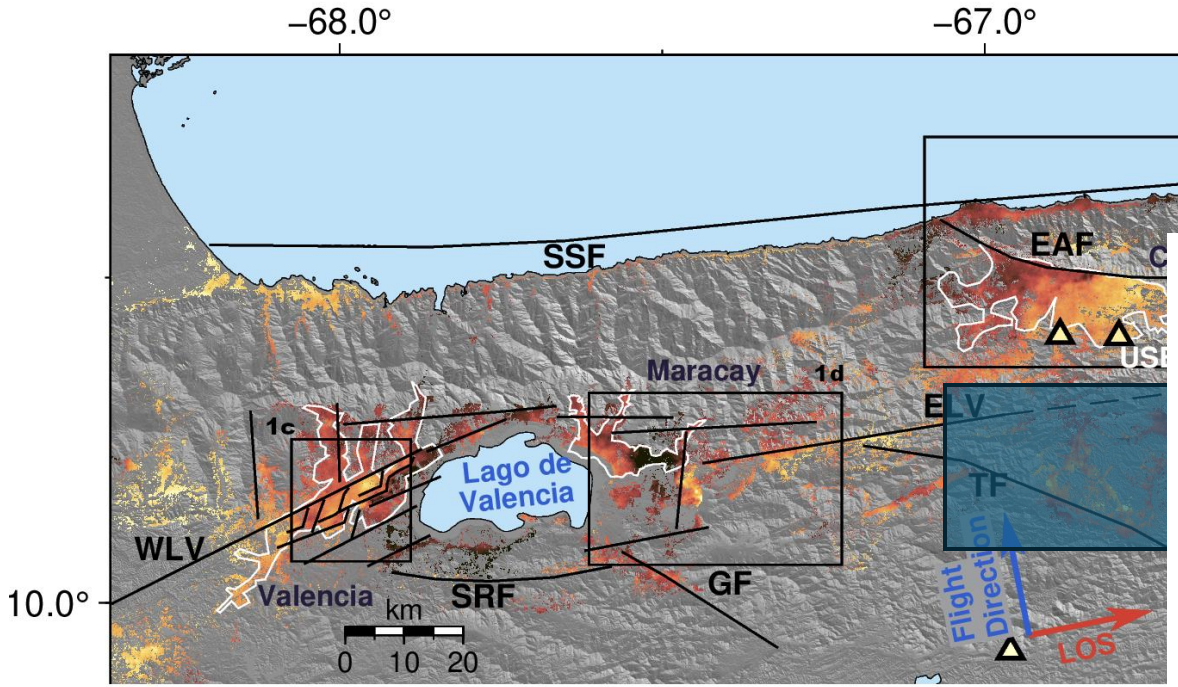
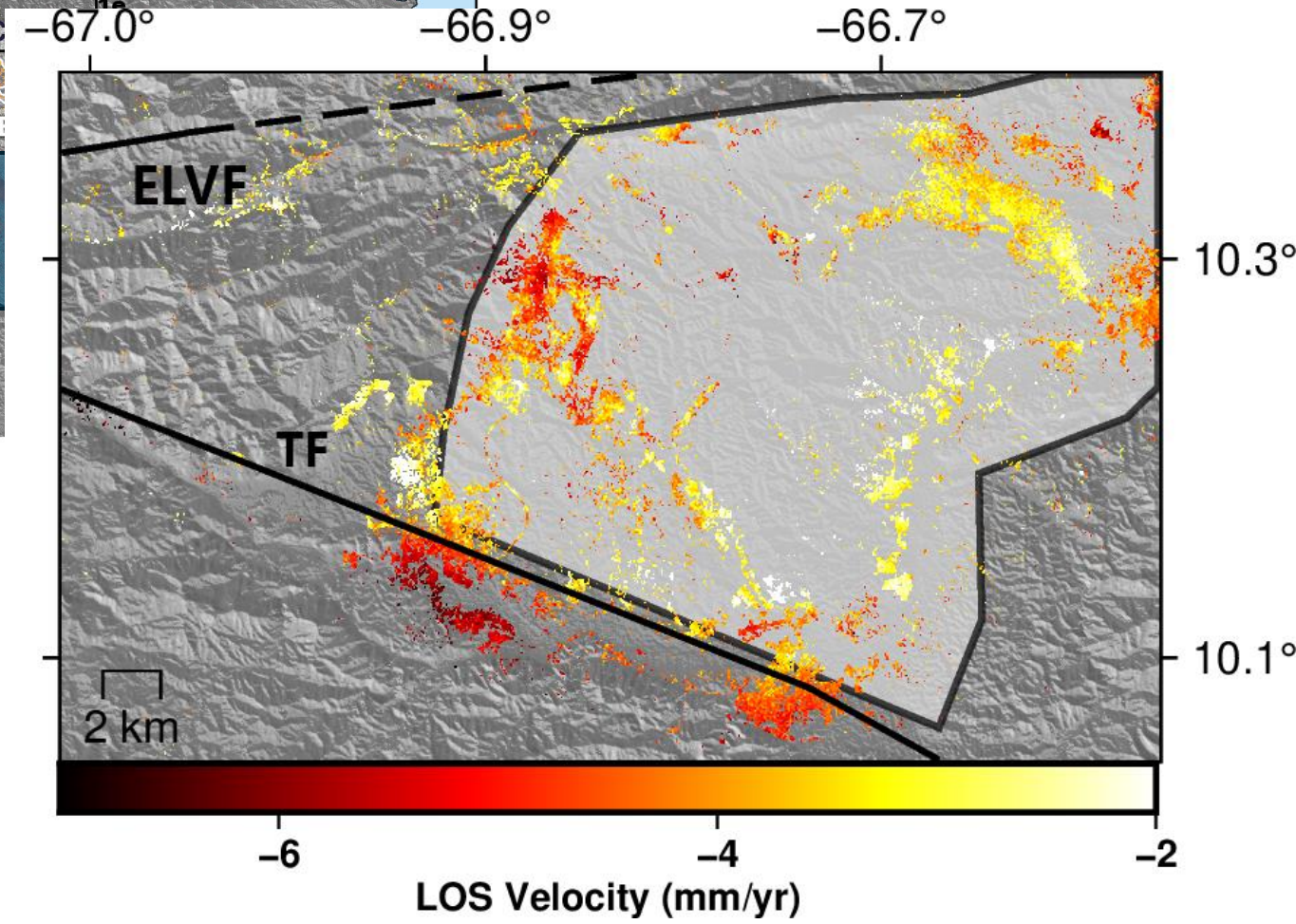
Tacata Fault InSAR LOS Velocities





- LOS velocities show the Tácata Fault is a reverse fault, and the basin to the north is no longer opening.

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