

The June 24th M7+ Doublet Recovered Bocono and San Sebastian Faults Strain, but Caracas Still Exposed

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Title: The June 24th M7+ Doublet Recovered Bocono and San Sebastian Faults Strain, but Caracas Still Exposed

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Abstract

Forecasting earthquakes is fraught with challenges. We quantify the magnitude and spatial variability of interseismic coupling (locking) on fault systems, which then informs the system's future seismic potential. The June 24, 2026 M_w 7.2 and M_w 7.5 Northern Venezuela earthquake doublet provides an opportunity to test this framework. The earthquakes resulted in up to 6300 deaths and US \$37 billion in direct damage. Quantifying the post-earthquake seismic hazard is essential. If the strain released during the earthquakes reconciles with the pre-2026 accumulated strain, then the faults involved pose no near-term seismic hazard. The earthquake doublet occurred on the Bocono and San Sebastian faults, the main faults accommodating the relative motions between the Maracaibo Block, the South American Plate, and the Caribbean and South American plates (CA-SA), respectively. Here we show, using satellite radar interferometry, that interseismically locked portions of both faults participated in the earthquake doublet, recovering nearly all interseismic strain accumulation. We further document that the El Ávila Fault, which accommodates up to 5 mm/yr of CA-SA motion near Caracas, is partially locked, and the imparted Coulomb Failure Stress following the doublet would delay a future rupture. Nevertheless, the fault remains a significant hazard.

Introduction

The Caribbean-South American transform plate boundary has experienced numerous large and damaging earthquakes in historical and instrumented times. The recent June 24, 2026 M 7.2 and M 7.5 doublet in northern Venezuela, which resulted in up to 6300 deaths and up to US \$37 billion in direct loss, and possibly greater than US \$100 billion in downstream economic losses¹, is a grim example of the maximum magnitude earthquake this plate boundary is capable of producing and the extraordinary seismic risk it poses. The earthquakes occurred at the complex triple junction between the Caribbean (CA) and South American (SA) plates and the Maracaibo Block^{2,3} (MB) (Fig. 1). The first earthquake (M_w 7.2), with an origin time of 22:04:33 UTC⁴, occurred on the Bocono Fault (BF) (Fig. 1), the boundary between the MB and the SA

Plate⁵ (Fig. 1). The MB experiences northeastward tectonic escape due to northward indentation of the North Andean Block and southward subduction of the CA, and at the latitude ($\sim 10.3^\circ\text{N}$) of the ruptured BF segment, the MB-SA relative dextral motion is ~ 7 mm/yr (Fig. 1)⁶. The BF ends at the intersection between the Morrocoy Fault, which is the northern boundary of the MB, and the San Sebastian Fault (SSF), the CA-SA boundary to the east. The CA-SA transform boundary runs from the triple junction to the islands of Trinidad and Tobago, and it has been documented that, at the regional scale, the western segments of the plate boundary are interseismically locked, while most of the eastern segments creep^{6,7}. The second shock (M_w 7.5) occurred 39 seconds after the first shock⁴ and ruptured the mostly offshore SSF⁸. The SSF accommodates 15 mm/yr of the total 21 mm/yr CA-SA relative dextral motion^{7,9} (Fig. 1). The remaining motion is distributed on the sub-parallel La Victoria Fault system (LVF), which accommodates ~ 5 mm/yr⁷, and the El Ávila Fault (EAF), which paleoseismic work suggests accommodates < 1 mm/yr¹⁰. The M_w 7.5 earthquake is not unprecedented, as Caracas, the Venezuelan capital, has been damaged by several historical earthquakes, including M 7.5+ ruptures of the SSF in 1812 and 1900^{11,12}. There is strong evidence that the 1812 earthquake ruptured both the BF and SSF, like the 2026 doublet¹³. Furthermore, in instrumented time, the last damaging earthquake was the 1967 M_w 6.7 Caracas earthquake (Fig. 1), which was a sequence of four earthquakes that occurred on secondary faults off the main strand of the SSF¹⁴. The 250 km-long SSF, if it were to rupture in its entirety, would produce a M_w 7.8 earthquake^{7,11}, and therefore has always presented a grave seismic hazard for north-central Venezuela. The last rupture of the BF was the 1812 earthquake, whereas the SSF last ruptured during the 1900 earthquake. Considering the most recent earthquakes on the faults and the slip rate they accommodate, prior to the 2026 doublet, the slip deficit on locked patches of the BF and SSF should be 1.5 m and 1.89 m, respectively. Knowledge of the pre-2026 interseismic strain accumulation on the SSF and the coseismic slip during the 2026 event is crucial in determining the future danger this fault poses. We explore the pre-2026 interseismic strain accumulation and coseismic slip for the 2026 earthquakes using Sentinel-1 C-band Synthetic Aperture Radar (SAR) data to quantify the earthquake potential of the SSF, BF, and EAF. Data from other space-borne SAR sensors (e.g., NISAR and ALOS2) were not immediately available, lacked the coverage and temporal resolution, or were not robust enough for the analyses we describe below.

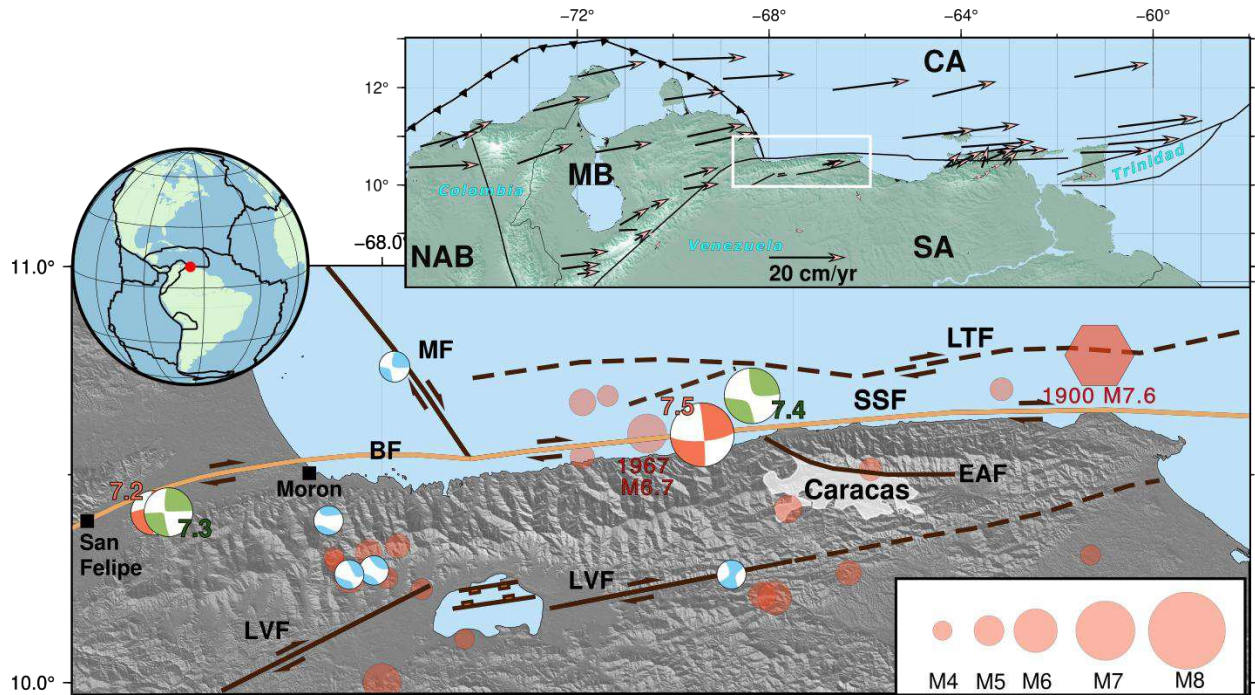


Fig. 1. Major faults (thick brown lines) and M4+ seismicity (red circles; ISC reviewed catalog¹⁵) in North-Central Venezuela. Light brown lines are the faults that took part in the June 24, 2026 earthquakes. Orange focal mechanisms and magnitude labels are for the June 24, 2026 earthquakes retrieved from the National Earthquake Information Center⁴. Green focal mechanisms and magnitude labels are for the June 24, 2026 earthquakes retrieved from GEOFON⁸. Blue focal mechanisms are M4+ seismicity from GCMT¹⁶. Hexagon is location of 1900 M7.6 earthquake from the Centennial Earthquake Catalog¹⁷. MF – Morrocoy Fault. BF – Bocono Fault. LTF – La Tortuga Fault. SSF – San Sebastian Fault. LVF – La Victoria Fault. EAF – El Ávila Fault. Top left inset shows the region of interest and major tectonic units. Top right inset shows the tectonic units around north-central Venezuela and selected Global Navigation Satellite System (GNSS) velocities^{9,18,19} that are in the South American reference frame²⁰. NAB – North Andean Block. MB – Maracaibo Block. CA – Caribbean Plate. SA – South American Plate.

Results

Interseismic Strain Accumulation of the SSF

We use all available Sentinel-1 InSAR data (2016-10-03 to 2021-12-11) to derive a line-of-sight interseismic velocity field for North-Central Venezuela for the observation period (see Methods). We could not perform the same analysis for the BF because of poor coverage of reliable SAR permanent scatters. The velocity field shows variable velocities along the coast, suggesting along-strike changes in locking of the offshore SSF (Fig. 2). The velocity field also presents a large gradient (-7 mm/yr to -3 mm/yr LOS over 6 km) across the city of Caracas, which is associated with variable slip (i.e., creeping or locking) on the EAF (Fig. 3). The velocity field also indicates that at the longitude (67.1°W; start of western EAF) the eastern LVF does not accommodate interseismic strain. Furthermore, east of this longitude, the surface trace of the LVF appears diffuse or non-existent²¹. These observations indicate that, during the period of SAR observations, the EAF is a primary fault on which CA-SA strain is partitioned.

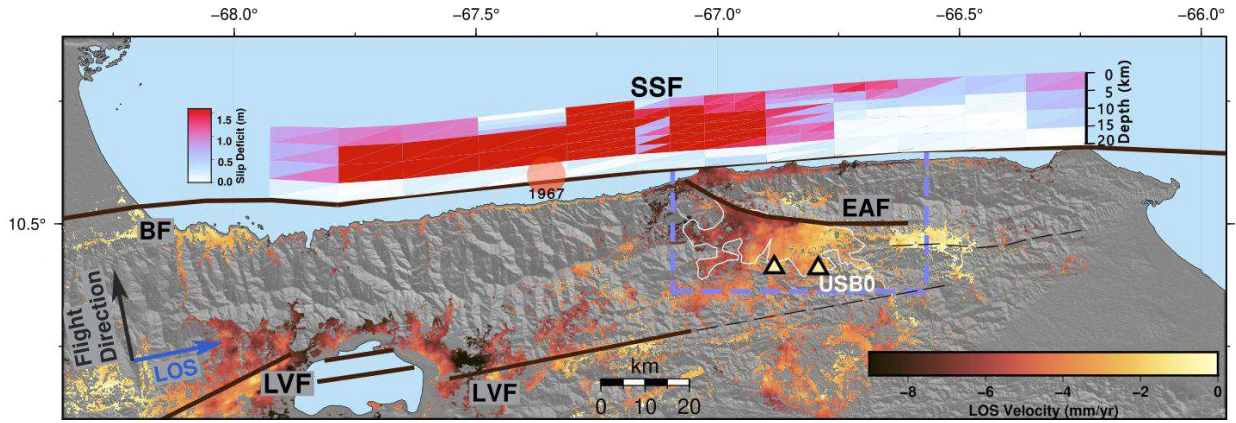


Fig. 2. Interseismic Sentinel-1 LOS velocities (yellow to black) and SSF slip deficit model since the 1900 M7.6 earthquake (discretized fault). Red regions indicate fully locked fault patches, and white indicates fully creeping patches. Triangles around Caracas are GPS stations with velocities (both easting – 4.7 mm/yr and northing – 1.2 mm/yr; see Fig. 1) from²² in SA reference frame²⁰ projected into LOS with same scale as InSAR LOS velocities. InSAR velocities have a minimum LOS detection threshold of 2 mm/yr²³. Faults modified from^{21,24}. Purple dashed box shows the extent of Fig. 3.

During the pre-2026 interseismic period, there is very little seismicity (M4+) associated with the SSF or BF (Fig. 1). However, the LVF is dominated by low-magnitude (M ~4) earthquakes. InSAR-derived interseismic velocities (Fig. 2) were inverted to model the magnitude and spatial variability of the slip deficit rate on a discretized fault of triangular dislocation elements in an elastic half-space for the SSF (see Methods). The model indicates that there are at least 3 segments of the SSF with different interseismic behavior (Fig. 2). The western 120 km of the SSF had two patches locked at seismogenic depths (i.e., 15 km), while the 80 km of the SSF east of longitude 66.8°W was creeping (Fig. 2). Of note, our model also revealed a shallow (<5 km) creeping patch at latitude 67.4°W corresponding to the location of the 1967 M6.7 earthquake (Fig. 2). This earthquake is thought to have been 4 M 4+ subevents, summing to M_w 6.2, that migrated east on an east-west trending fault, north of the SSF¹⁴. At least three of the four earthquakes in the sequence have been attributed to the La Tortuga Fault¹⁴ (LTF - Fig. 1). It is possible that this currently creeping section of the SSF may have taken part in this sequence of earthquakes. If this is the case, the SSF may exhibit the full spectrum of interseismic moment release: (1) a creeping segment; (2) a creeping segment producing low-magnitude earthquakes; and (3) locked segments that rupture in large-magnitude earthquakes. It is also possible that these offshore faults, like the EAF, connect with the SSF and thereby cause segmentation of the interseismic behavior of the SSF. These results, and specifically the magnitude of the interseismic slip deficit, have implications for the maximum magnitude earthquake the fault can generate. Our slip deficit model results suggest that, if the westernmost segments of the SSF were to rupture and assume they were locked since the 1900 earthquake, they would generate a M_w 7.4 earthquake.

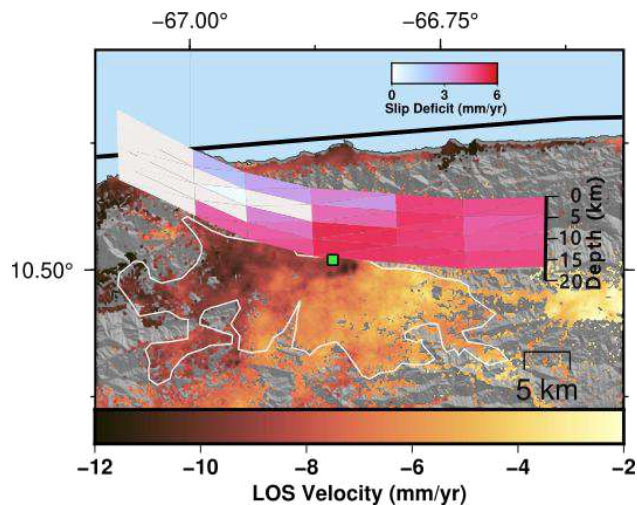


Fig. 3. Interseismic Sentinel-1 LOS velocities around Caracas and El Ávila Fault slip deficit model (discretized fault). Green square shows paleoseismic trench site¹⁰. See Fig. 2 for location.

Sentinel-1-derived LOS interseismic velocities were also inverted for the slip deficit on the EAF (See Methods), and we find that this fault is variably locked along strike (Fig. 3). The western segment was creeping during the period of study, where it joins the SSF. Our interseismic model requires the eastern fault segment to dip to the north at 76° , be locked, and accommodate 5 ± 2 mm/yr of both reverse and dextral motion equally (Fig. 3). The earthquake recurrence interval of the EAF is not well-known. Previous historical seismology work has shown that two moderate-magnitude earthquakes occurred in 1820 and 1842 on the westernmost segments of the fault,^{12,25} while paleoseismic trenching at one site along the fault (green square in Fig. 3) revealed that the last rupture occurred 2700 ya¹⁰ and estimated a geologic slip rate of 0.3 mm/yr¹⁰. The eastern segment of the EAF steps to an unnamed fault to the south and both faults are master faults of a pull-apart that overlap by 17 km²⁶ (Fig. 2). It is possible that the eastern segment of the EAF does not accommodate motion, but this is highly unlikely. Our InSAR-derived velocity gradient along-strike starts ~ 15 km west of the pull-apart (Fig. 2), with no discernible change in velocity across the pull-apart and unnamed fault to indicate that strain is accommodated by these structures. The variability and depth of locking along strike of the EAF can explain the reported discrepancies in the earthquake potential of the fault. The creeping western segment may produce moderate-magnitude earthquakes, while the sub-millimeter geologic slip rate²⁷ in the central segment reflects the deep locking of the EAF, as a deeper earthquake might not rupture to the surface to produce a paleoseismic record. If the locked eastern portion of the fault has not ruptured since before colonial times (~ 400 bp), then it is possible that the easternmost segment of the EAF could produce a M_w 7.2 earthquake. The EAF, which borders Caracas, therefore presents a profound threat to the city.

Coseismic Slip for 24 June 2026 M 7+ Earthquake Doublet

There is a paucity of publicly available aftershock data following the June 24th doublet, which is a limitation in identifying which fault and their segments ruptured. The National

Earthquake Information Center (NEIC)⁴ and GEFON⁸ placed the epicenter of the first shock on the BF but reported magnitudes of M_w 7.2 and M_w 7.3, respectively (Fig. 1). Both agencies also placed the epicenter of the second shock on the SSF but reported magnitudes M_w 7.5 (NEIC) and M_w 7.4 (GEOFON) (Fig. 1). Coseismic interferometric Synthetic Aperture Radar (InSAR) analysis of Sentinel-1 data revealed that both the BF and SSF faults ruptured in the doublet (Fig. 4). Our InSAR surface displacements show a maximum of 330 mm in line of sight to the satellite. The largest coseismic displacements are expected where the SSF runs for 5 kilometers onshore, across the Simón Bolívar International Airport^{11,28} (Fig. 4). However, Sentinel-1 C-band InSAR was decorrelated due to the large displacement gradients.

Our coseismic fault slip model shows that 87% of the BF segment (Fig. 4) from San Felipe to Moron (Fig. 1) ruptured with an average slip of 0.8 ± 0.3 m, a maximum slip of 1.3 m, and had an equivalent moment magnitude of M_w $7.2^{+0.1}_{-0.1}$. The SSF ruptured possibly two distinct fault patches (Fig. 4), with total coseismic slip equivalent to a moment magnitude of M_w $7.4^{+0.1}_{-0.2}$. The main rupturing patch, located on the western 120 km of the SSF, slipped an average of 1.8 ± 0.2 m, with a maximum slip of 1.89 m. The second patch that slipped during the earthquake extends ~55 km east from the EAF-SSF intersection, north of Caracas. This segment of SSF ruptured from the surface to ~10 km depth with an average slip of 0.72 m (Fig. 4).

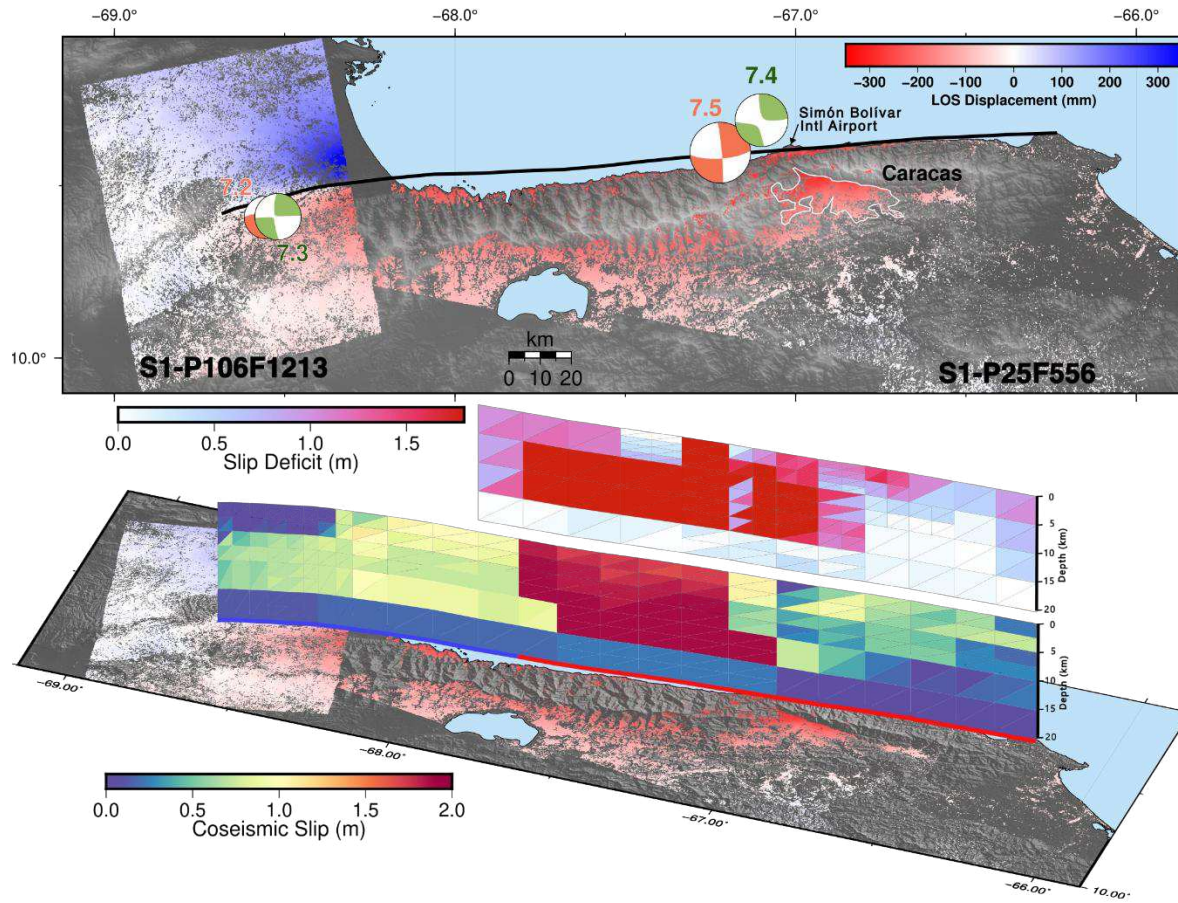


Fig. 4. Top: Coseismic Sentinel-1-derived displacements from ascending Path 106 Frame 1213 (S1-P106F1213) around BF, and descending Path 25 and Frame 556 (S1-P25F556) around SSF. Focal mechanisms same as Fig.1. **Bottom:** Coseismic slip (bottom) and interseismic slip deficit (top; same as Fig. 2) models. Fault surface traces are highlighted for the BF (thick blue line) and SSF (thick red line).

Recovered Strain Accumulation

Our SSF interseismic slip deficit and coseismic slip models indicate that most of the locked patches of the fault participated in the second earthquake (Fig. 4). There was little coseismic slip in the previously identified creeping segment, east of Caracas (Fig. 4), while the locked patches of the western segments had a maximum slip of 1.89 m, which is the full slip deficit, considering the last rupture was in 1900 and the SSF accommodates ~ 15 mm/yr. While we do not have an interseismic slip model for the BF, we do note that most of the fault took part in the earthquake. The last rupture of this segment of the BF was in 1812¹³ and it accommodates 7 mm/yr of relative MB-SA motion⁹, suggesting that the total slip deficit was ~ 1.5 m. We found the maximum coseismic slip to be 1.3 m. The discrepancy could very well lie in the slip rate estimated from geodetic data and block models that treated the MB-SA boundary as one fault⁶. The BF, compared to the linear SSF, is a complicated fault system, and MB-SA motion may be accommodated on other faults near this segment of the BF (see fault map detailed in²¹). The San Felipe-Moron segment of the BF (Fig.1) more than likely fully recovered the slip deficit since

the 1812 rupture. The timing of past ruptures on the SSF and the BF suggests that there is a physical connection, where the SSF ruptures every 100 years and the BF every other 100 years. The two faults may be synchronized in how they release strain²⁹.

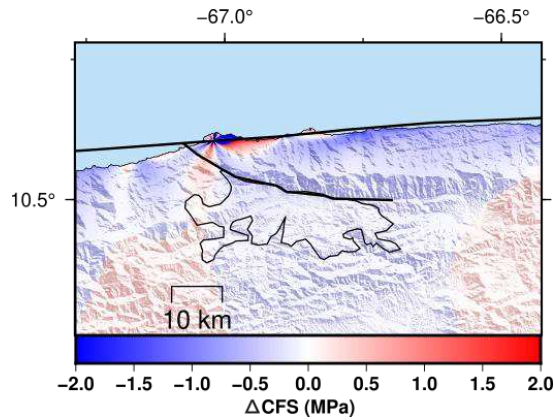


Fig. 5. Coulomb failure stress change imparted from the June 24, 2026 Mw7.5 SSF earthquake onto the EAF with strike = 280°, rake = 135°, and dip = 76°.

The relationship between the SSF and the EAF may be more complex. As stated previously, the EAF earthquake recurrence interval is poorly constrained. The fault is within one characteristic fault length of the earthquake yet was not dynamically triggered. Calculations of the change in Coulomb Failure Stress (ΔCFS) imparted by the SSF rupture for a receiver fault with similar geometry and kinematics to the EAF (strike = 280°, rake = 135°, dip = 76°; see Section S1 for justification of strike) indicate most of the EAF is in a negative region of ΔCFS , which may serve to delay the next earthquake (Fig. 5). If repetitive ruptures through ten SSF earthquake cycles (~1000 years) have pushed back an EAF earthquake, there might be significant strain accumulated to produce an earthquake much larger than a M_w 7.1. This is not an unlikely scenario, as the CA-North American transform plate boundary to the north, in Haiti, produced M7+ earthquakes in 2010 and 2021^{30,31}. Those earthquakes occurred on secondary faults subparallel to the main Enriquillo Plantain Garden Fault and should serve as a lesson in future seismic hazard estimations for Caracas.

The M7+ June 24th, 2026 Northern Venezuela earthquake doublet provided a rare opportunity to compare interseismic strain accumulation and strain release during the earthquakes. We show that the geodetically derived magnitude and spatial variability of interseismic strain accumulation on the SSF were fully recovered during the coseismic slip of the earthquakes. Accordingly, both the SSF and BF do not have residual post-earthquake strain, which substantially reduces the near-term seismic hazard of both fault systems. However, the sub-parallel EAF, part of the CA-SA transform boundary, is a significant seismic hazard, despite the SSF rupture delaying an earthquake on this fault.

Methods

We investigated the interseismic strain at the CA-SA transform plate boundary in northern Venezuela by quantifying the partitioning of strain and the creeping or locking of the SSF (which, at its farthest, runs 5 km offshore), the LVF, and the EAF, by using C-Band Sentinel-1 Synthetic Aperture Radar (SAR) data (path 33 and frame 1213) for the period of 2016-10-03 to 2021-12-11. Interferometric pairs were created based on the method of long temporal, short perpendicular baselines²³, where 625 interferograms were created using the criteria of 800 to 1500 days temporal and <5 m perpendicular baselines (see Fig. S1). This strategy allows for a detection threshold of 2 mm/yr of LOS motion²³. SAR scenes were processed and co-registered with a primary scene using the GMTSAR software³². We used the Permanent Scatter (PS) strategy, where stable PS selection and line-of-sight (LOS) displacement time series estimation were done using the StaMPS code³³. The interseismic LOS velocities from InSAR time series were estimated by fitting a function that took into account seasonal signals and unwrapping error steps (see Supplementary Material Section S2). We neglected displacements due to ocean loading³⁴ because in this region, ocean loading would bias the velocities by only 0.04 mm/yr. The interseismic InSAR velocity field was then referenced to the velocity of the GNSS station USB0 from⁹ (Fig. 2).

The interseismic slip deficit of the SSF and EAF was determined by inverting the subsampled LOS velocities up to 25 km perpendicularly from the SSF for slip on discretized faults of dislocation triangle elements in an elastic half-space³⁵. The inversion was performed using the pestpp-ies code³⁶ which is an iterative ensemble smoother where the ensemble approximates the Jacobian matrix in the Gauss-Levenberg-Marquardt scheme. Pixels farther from the western segment of the SSF (>15 km) were down-weighted during inversion as their velocities may be related to the La Victoria Fault. The inversion method utilized an iterative strategy where the SSF slip was first estimated. Then slip on the EAF and SSF were jointly modeled by fixing the slip of elements on the western segments of the SSF and increasing constraints on elements east of the EAF. See Fig. S3 for interseismic model residuals and RMS. Slip deficit for the SSF was calculated from its last rupture (1900 earthquake - 126 ya), the expected slip rate of 15.5 mm/yr, and the model-derived fault element slip.

Coseismic slip for the M_w 7.2 (Bocono Fault) and M_w 7.5 (San Sebastian Fault) were estimated from displacements from interferometric pairs of Sentinel-1 SAR acquisitions for path 33 and frame 30 (2026-06-18 and 2026-06-25) and path 25 and frame 556 (2026-06-18 and 2026-06-25), respectively. Interferograms were created using the GMTSAR software and were then masked by a 0.15 coherence threshold. To ensure correct unwrapping, isolated sections of the interferograms were manually connected via coherence. Unwrapping was done using the coherence-based minimum spanning tree algorithm implemented in the SNAPHU code³⁷. Coseismic slip was then determined using the same strategy for determining the interseismic slip deficit. Discretized faults of dislocation triangle elements were created for the BF and SSF, and

the subsampled coseismic LOS displacements were inverted for coseismic slip on the faults using the pestpp-ies code. Coseismic model residuals and RMS are detailed in Fig. S4.

Parameter uncertainties for both interseismic and coseismic models were estimated using the pestpp-glm^{38,39} code, which created stochastic model realizations from the parameter posterior covariance matrix derived from the previously determined models' parameter estimates

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