

Article

The 24 June 2026 Earthquake Doublet in Northwestern Venezuela: Joint Hypocentral Determination, Fault-Zone Tomography and Four-Track Sentinel-1 Constraints on Rupture Geometry, Slip and Stress Transfer

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Highlights

What are the main findings?

- Joint inversion of 10,000 four-track Sentinel-1 line-of-sight observations constrains dextral moment release on the east–west Morón–western San Sebastián plate-boundary plane. The length scan reaches a misfit plateau of 19.8–19.9 mm at 225 km and longer; the preferred 300 × 30 km model gives $M_0 = 2.51 \times 10^{20}$ N m (Mw 7.53), 84% of accounting for the summed W-phase moment, with peak slip of 2.32 m.
- Synthetic slip-recovery tests on the real observation geometry recover the along-strike slip distribution only at scales of about 30 km and coarser, and a matched two-plane inversion of the identical dataset improves the fit by just 1.7%, so the cumulative interferometric field does not uniquely partition the two subevents.

What are the implications of the main findings?

- Synthetic sources of prescribed moment are recovered at 97–124% under the four-track observation geometry. The geodetic moment is a model-dependent estimate, with source dimensions, regularisation and observation weighting affecting its interpretation; it is not a demonstrated lower bound imposed by coastal coverage.
- Conditional first-event scenarios give positive median static loading at the second hypocentre in twelve of thirteen cases. Direct-wave travel times are shorter than the inter-event delay, permitting delayed dynamic interaction, static loading or their combination. The sequence motivates assessment of closely spaced failures along adjacent coastal segments.



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Abstract

On 24 June 2026, two earthquakes struck northwestern Venezuela 39 s apart, according to the ISC Bulletin. We integrate International Seismological Centre data with four-track Sentinel-1 interferometry to constrain the rupture and tectonic setting. Joint hypocentral determination relocated 225 events, all pre-dating the doublet, and reduced travel-time RMS from 1.79 to 1.11 s; no event of the 2026 sequence was relocated. Tomographic recovery tests support broad interpretation at approximately 30 km and coarser. A joint inversion of 10,000 line-of-sight observations on the east–west nodal plane of the reviewed USGS W-phase solution places dextral moment release along the coastal fault system, increasing eastwards. The length scan reaches a misfit plateau beyond 225 km; the preferred 300 × 30 km model gives $M_0 = 2.51 \times 10^{20}$ N m (Mw 7.53), 84% of the summed

W-phase moment, and peak slip of 2.32 m near 10.55°N, 67.23°W. Synthetic sources of prescribed moment are recovered at 97–124%, so the geodetic moment is reported as a model-dependent estimate. Broad along-strike slip is better resolved than patch-scale amplitude or depth. A warm-started two-plane inversion reduces LOS RMS from 19.79 to 19.46 mm, a 0.33 mm (1.7%) gain, demonstrating source non-uniqueness rather than uniquely separating the subevents. Thirteen conditional first-event stress scenarios give positive median loading at the second hypocentre in twelve cases, with positive medians of +0.31 to +2.35 MPa at effective friction of 0.4. The results are consistent with rapid interaction along the Morón–western San Sebastián plate-boundary system.

Keywords: Sentinel-1; differential SAR interferometry; earthquake doublet; fault-slip inversion; travel-time tomography; Caribbean–South America plate boundary

1. Introduction

The Caribbean Plate is bounded to the north and to the south by major strike-slip fault systems with intense seismic activity. The left-lateral Motagua–Polochic fault system marks the boundary with North America, while the right-lateral San Sebastián–El Pilar fault system marks the boundary with South America (Figure 1). The southern margin accommodates approximately 20 mm/yr of right-lateral motion with respect to South America along a broad, partitioned deformation zone that crosses northern Venezuela [1–3]. Large historical earthquakes (1812, 1900, 1967, 1997) indicate that the main dextral fault systems of this boundary (Boconó, San Sebastián, El Pilar) are capable of M 7+ ruptures [4–7]. The 24 June 2026 doublet (ISC M 7.1 followed, after 39 s, by M 7.5 [8,9]; USGS reviewed M_w 7.2 and M_w 7.5 [10,11]) occurred in a comparatively less instrumented sector of this boundary, at the junction between the inverted Falcón Basin, the Aroa–Yaracuy corridor and the Golfo Triste coastal domain, where the 12 September 2009 M_w 6.4 offshore Falcón earthquake had already revealed active oblique deformation [12–14].

This paper documents the doublet earthquakes in the general seismotectonic context of the southern margin of the Caribbean Plate. Its objectives are: (1) to characterise the regional seismicity and velocity structure from twenty years of parametric data from the International Seismological Centre (ISC) [8,9], through travel-time tomographic analysis; (2) to relocate the best-picked events by joint hypocentral determination; (3) to map the coseismic surface deformation with ascending and descending Sentinel-1 differential interferometry; (4) to jointly invert the four InSAR line-of-sight (LOS) displacement fields for slip on a fault plane constrained by the focal mechanisms and mapped faults, using relocated background seismicity as structural context; and (5) to interpret the results within the geological framework of the southern Caribbean Plate boundary. All results derive from archived pipeline outputs generated from public data sources, and every processing step is documented so that the analysis can be independently reproduced.

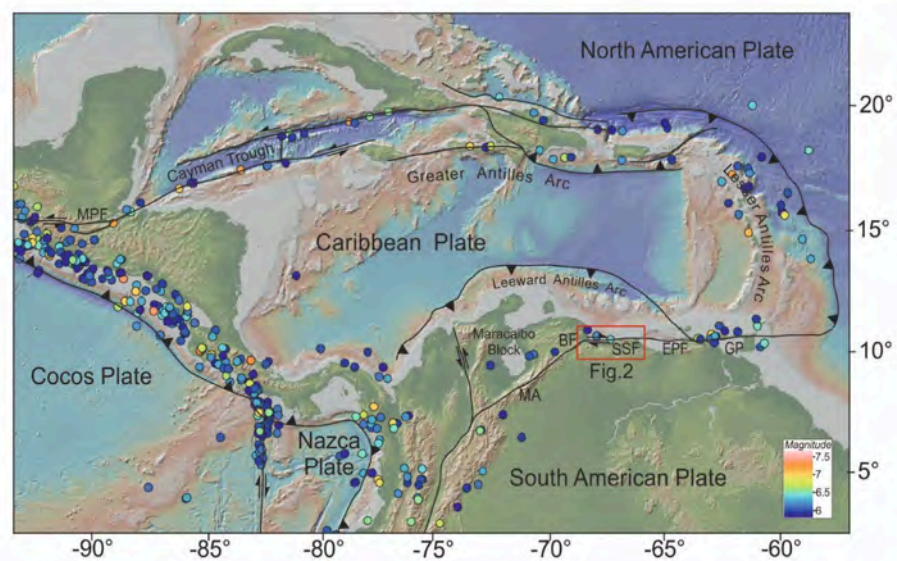


Figure 1. Plate-boundary setting of the southern Caribbean. Plate boundaries (after [15]) are drawn on the GeoMapApp Global Multi-Resolution Topography and Bathymetry synthesis [16]; coloured circles represent earthquakes of $M > 6$ between 1960 and 2026 from the ISC Bulletin [8,9], scaled and coloured by magnitude as shown in the legend. The red box indicates the study area of Figure 2. MPF, Motagua-Polonic fault system; MA, Mérida Andes; BF, Boconó fault system; SSF, San Sebastián fault system; EPF, El Pilar fault system; GP, Gulf of Paria. The arrows represent the planar movement direction of the two part of the fault.

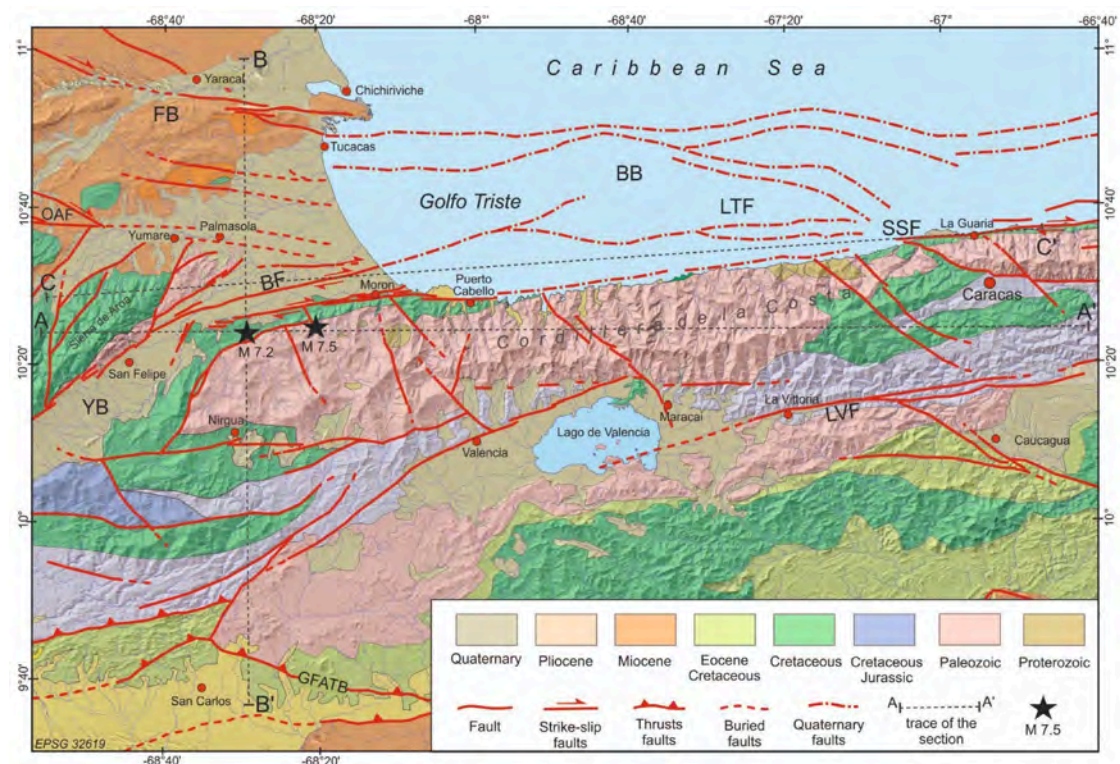


Figure 2. Schematic geological map of northwestern Venezuela showing the principal chronostratigraphic units (modified from [17]). The frame spans the Golfo Triste and the coastal ranges from the Falcón Basin (FB) in the west to the Caracas coast in the east, including the corridor ruptured by the 24 June 2026 doublet. Quaternary fault traces in the Golfo Triste are based on acoustic-reflection profiles [5,18]. BF, Boconó fault system; SSF, San Sebastián fault system; OAF, Oca-Ancón fault system; YB, Quaternary Yaracuy Basin; BB, Bonaire Basin; GFATB, Guárico fold-and-thrust belt.

Geological Setting

Northwestern Venezuela sits within the broad, transpressive boundary zone between the Caribbean Plate and South America (Figure 2). GPS geodesy shows that the Caribbean Plate moves approximately eastward relative to stable South America at 20 ± 2 mm/yr [2,3], with elastic block modelling indicating that most of this dextral shear is accommodated across a roughly 100 km wide zone straddling the Venezuelan coast [1]. Onshore, the plate-boundary strain is concentrated on the right-lateral Boconó–San Sebastián–El Pilar fault system, which traverses Venezuela from the Mérida Andes to the Gulf of Paria (Figure 1) [13,19]. The NE-trending Boconó fault terminates northeastward in the Yaracuy Valley, immediately south of the 2026 epicentral area, where Pleistocene slip rates of several millimetres per year have been measured on offset alluvial fans [20]. Space-geodetic (InSAR) analysis of the Venezuelan plate-boundary faults resolves an alternation of creeping and interseismically locked reaches, with the locked reaches storing elastic strain that is releasable in large earthquakes [21]. From the Yaracuy Valley, slip is transferred to the E–W striking, coast-parallel San Sebastián fault via the Morón fault, the dextral strand that runs along the southern shore of the Golfo Triste and the Puerto Cabello–Morón coast [13,22]. Farther west, the E–W dextral Oca–Ancón fault system bounds northern Falcón, with paleoseismic evidence of Holocene surface-rupturing earthquakes [22,23].

The epicentral region itself exposes two contrasting crustal domains. To the northwest lies the Falcón Basin, an Oligocene to Early Miocene extensional–transtensional basin filled with thick marine clastics and now positively inverted: since the Middle–Late Miocene, the basin has been shortened into the Falcón anticlinorium under a NNW–SSE oriented maximum horizontal stress, consistent with the present transpressive regime [24]. To the southeast, the Sierra de Aroa and the Coastal Cordillera comprise allochthonous metamorphic and igneous terranes (Cordillera de la Costa, Cauagua–El Tinaco, Loma de Hierro and Villa de Cura belts) accreted diachronously, west to east, during the oblique Cenozoic collision of the Caribbean arc with the passive margin of northern South America [25–27]. At depth, seismic tomography images an aseismic, flat-lying slab of Caribbean lithosphere subducted southeastward beneath northwestern South America [28], a geometry refined by finite-frequency imaging that shows shallow, amagmatic underthrusting of the Caribbean Plate beneath the Maracaibo block and western Venezuela [29,30]. Controlled-source transects of the BOLIVAR experiment at 67°W , within the eastern part of the InSAR analysis window, image Caribbean crust underthrusting the margin and a crustal-scale, positive flower-like deformation zone beneath the San Sebastián fault [31]. The interpreted crustal architecture across this plate-boundary domain is discussed with the resolution-calibrated structural interpretation below.

This structural framework has produced a substantial historical and instrumental earthquake record. The 26 March 1812 earthquake sequence, the deadliest in Venezuelan history, is best explained by multiple sub-events distributed along the Boconó–San Sebastián system from the Andes to the central coast [6]. The 29 October 1900 M_w 7.6 earthquake struck offshore north-central Venezuela, with both the San Sebastián and the La Tortuga faults proposed as sources [5]. The 29 July 1967 Caracas earthquake (M_w ~6.6) ruptured E–W striking, right-lateral faults offshore the central coast as a multiple-shock sequence [4], and the 9 July 1997 Cariaco earthquake (M_w 6.9) produced about 30 km of surface rupture on the El Pilar fault in northeastern Venezuela [7,32]. Closest to the 2026 doublet, the 12 September 2009 M_w 6.4 earthquake occurred offshore in the Golfo Triste–Morón area (10.736°N , 67.911°W in the catalogue used here, Supplementary Table S5) and caused structural damage in Tucacas [14], indicating that the Morón–San Sebastián coastal fault system is seismogenic at moderate to large magnitudes.

2. Materials and Methods

All processing was performed with PRISM (Physics-informed Ranking and Integrated Subsurface Modeler), a modular geophysical analysis platform developed at the Università degli Studi di Urbino Carlo Bo (Urbino, Italy) [33]. Implemented in .NET 8 with an OpenGL/IMGUI interface, PRISM harmonises heterogeneous public geoscientific datasets within a common data model and links data ingestion, quality control, three-dimensional visualisation, passive seismic imaging, differential SAR interferometry and elastic source modelling in a single reproducible environment. The seismic component used here is PULSE (Passive sUb-surface LSQR Seismic Engine), which reconstructs V_p and V_s volumes from P- and S-wave arrival times. PULSE supports a selectable one-dimensional velocity seed, station-quality preconditioning, support-aware Laplacian smoothing and damped LSQR inversion with bent-ray tracing. During the outer nonlinear iterations, rays are re-traced through the updated model under combined Tikhonov and Laplacian regularisation. For the Venezuelan application, the starting model, grid, ray set and regularisation are specified with the travel-time tomography below. PRISM also manages the Sentinel-1 acquisition and interferometric chain and passes the geocoded line-of-sight products to the elastic dislocation inversion, both described below. A PRISM tool named ECHO (Earth Coherence and Hazard Observation) is used to perform differential interferometry on four image pairs acquired before and after the doublet. Each stage records its configuration, parameters and quality metrics. The archived run reports are available from the corresponding author; the data sources are summarised in Supplementary Table S4, and the catalogue parameters of the doublet and other events discussed are listed in Supplementary Table S5. Cartographic products were composed with ArcGIS Pro 3.7, CorelDRAW X7 or Python 3/Matplotlib 3.11.2, as appropriate.

2.1. Dataset Assembly

The earthquake catalogue, magnitudes and P and S phase picks were retrieved from the ISC Bulletin via the FDSN event service for the region $0.5\text{--}12.8^\circ\text{N}$, $73.6\text{--}59.7^\circ\text{W}$ over the period 1 January 2006 to 3 July 2026, with a minimum magnitude of 1.5 (45,775 events; the 52 station epochs of the VE network are listed in Supplementary Table S1 and mapped in Figure 3). The Copernicus GLO-30 DEM [34] was mosaicked over the same region for topographic phase removal, geocoding and relief mapping, and the site condition of each station was characterised by a V_{s30} prior used as a shallow starting-model constraint in the tomography.

2.2. Joint Hypocentral Determination (JHD)

Events with at least four picks at stations of network VE were relocated by joint hypocentral determination, with simultaneous estimation of hypocentral perturbations and phase-specific station corrections [35]. The run converged in two iterations and relocated 225 events. Phase-specific station corrections were estimated only where the observation count supports a stable estimate: six corrections at three stations (P and S at BENV, JACV and TURV, each resting on 157–186 observations with a formal uncertainty of about 0.08 s), with values between -0.95 s and $+0.59$ s. The 52 station epochs of Supplementary Table S1 are the full 2006–2026 operating history of network VE, and only these three stations recorded enough of the relocated events to support a correction; corrections resting on a handful of observations, whose formal uncertainty exceeds their own value, are not retained. The RMS travel-time residual decreased from 1.791 s to 1.106 s (Supplementary Table S6); this measures the improvement in fit achieved by the joint relocation and is not a hypocentral uncertainty estimate. Summary statistics for per-event station counts, azimuthal gaps, and residuals are reported in Section 3.1. Per-event outputs are available

from the corresponding author as described in the Data Availability Statement. All 225 re-located events pre-date the doublet: the nine catalogued events of the 2026 sequence carry no phase picks at the stations of network VE in the ISC Bulletin, so none met the four-pick criterion and none entered the relocation. The relocated hypocentres therefore delineate the 2006–2026 background seismicity of the corridor and are not an aftershock distribution.

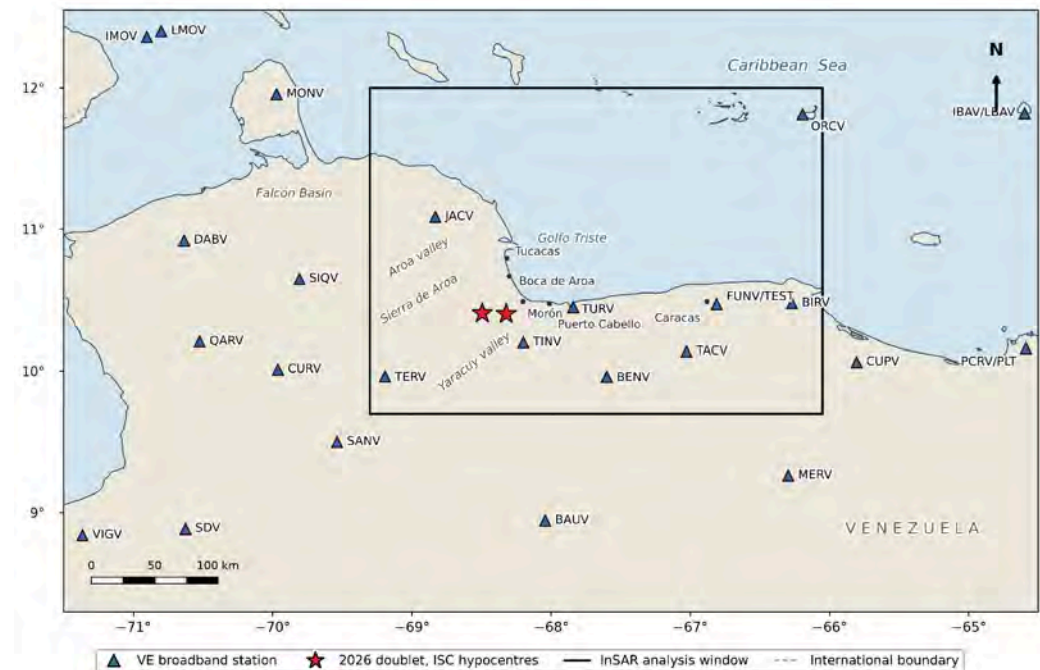


Figure 3. Seismic stations of the Venezuelan national network (network code VE) used for the joint hypocentral determination and the travel-time tomography (WGS84, EPSG:4326). Triangles represent stations, labelled with their code, and co-located sites sharing a marker carry both codes. The frame is cropped to the epicentral region, showing the 27 stations nearest the rupture; the inversion uses all 52 station epochs of the network, and the full inventory, with coordinates, operating epochs, channels and Vs30 site priors, is given in Supplementary Table S1. The red stars indicate the two 2026 mainshocks, and the black rectangle denotes the InSAR analysis window used for the interferometry and the joint inversion (9.70–12.00°N, 69.30–66.05°W). Small dots and italic labels mark the localities and physiographic features named in the text: Tucacas, Boca de Aroa, Morón, Puerto Cabello and Caracas; the Golfo Triste; the Aroa and Yaracuy valleys; the Sierra de Aroa; and the Falcón Basin. The seismicity of the region is shown separately: the instrumental events of $M > 6$ recorded since 1960 are mapped in Figure 1, and the historical earthquakes of 1812, 1900, 1967 and 1997 that define the seismogenic potential of this boundary segment are discussed in the seismotectonic setting above.

2.3. Regional Travel-Time Tomography

P- and S-wave travel-time tomography was computed on the ISC picks with LSQR [36]. The inversion uses the ak135-F starting model [37] on a $48 \times 32 \times 16$ grid covering 8.65–12.45°N, 70.8–65.0°W, to 60 km depth. Of 241,379 traced paths, 191,371 survive the 15.0 s robust residual cutoff: 114,902 P and 76,469 S. Twenty-five nonlinear iterations use damping and Laplacian smoothing of 0.040, with ray retracing through the updated velocity model. Bent-ray Dijkstra tracing [38] provides a path-geometry check. Lateral contrasts and spatially averaged V_p/V_s are interpreted within the support mask defined below; absolute velocities remain conditional on the starting model.

A single inversion volume serves both the regional context and the source, because the grid has to enclose the recording stations, and those stations span the whole region; a second, fault-centred grid would not add resolution; it would only shorten the modelled part of the same ray paths. A ray whose station lies outside the modelled volume is clamped

to the boundary cell, so its predicted time covers only the modelled part of the path, and the unmodelled remainder is absorbed into the velocities; a grid drawn tightly around the rupture encloses only four station sites of network VE and cannot be inverted for absolute travel times. The cells of the regional grid measure 13.2 km in longitude by 13.2 km in latitude by 3.75 km in depth. The volume contains the whole modelled source and 24 of the 52 station epochs of Supplementary Table S1 (21 of the 48 station codes), including every station within 350 km of the doublet; rays recorded at the more distant stations outside the grid are treated by the boundary clamping described above. Every catalogue event with four or more usable network picks is retained, without spatial decimation. The residual is an absolute travel-time residual over a catalogue whose sources are not relocated here, so it carries origin-time and location error as well as velocity error; the structure is interpreted from the variance reduction and the resolution tests, not from the absolute level. The production support threshold is defined explicitly: a cell enters the interpreted volume when its ray hit count is non-zero and it is sampled by both the P and the S phase. Of the 24,576 cells of the grid, 14,901 are retained; each is crossed by at least one P and one S ray, and the most densely sampled cell by 40,634 rays. Real-geometry checkerboards propagated $\pm 8\%$ synthetic perturbations through the recorded event-station geometry on the same grid, damping and smoothing, retaining the 113,974 event-station-phase paths that sample the volume when traced as straight rays, which intersect 14,025 cells, at block sizes of $2 \times 2 \times 2$, $3 \times 3 \times 3$ and $4 \times 4 \times 4$ cells ($26.4 \times 26.4 \times 7.5$, $39.6 \times 39.7 \times 11.2$ and $52.8 \times 52.9 \times 15.0$ km) and with Gaussian pick noise of 0, 0.10 and 0.20 s (Supplementary Figure S2). The synthetic paths are straight where the production inversion bends them, so the test characterises the linearised acquisition geometry and regularisation; it does not establish a lower bound on nonlinear resolution. Its path and cell counts therefore differ from those of the observational inversion (191,371 rays, 14,901 cells), whose rays are bent and retraced and whose cells must be sampled by both phases. A control experiment in which a $\pm 8\%$ west-to-east velocity gradient is imposed identically on V_p and on V_s , so that the true V_p/V_s is uniform, and P and S are then inverted separately with the real unequal ray sets, returns an apparent V_p/V_s of 1.7300 with a 5th–95th percentile range of 1.712–1.749 and an apparent west-minus-east gradient of -0.0001 : the unequal sampling does not by itself manufacture a ratio gradient. Measured over the three thirds of the adopted plane used in Section 3.2, the control returns equal ratios to within 0.0001, which is the artefact floor for a third-to-third contrast; the ± 0.019 5th-to-95th percentile spread of the same control is the separate, larger limit on reading an individual cell. The distinction between ray-intersected cells (checkerboard) and threshold-supported cells (observational volume) is retained explicitly in all maps, and each caption names the population it displays.

2.4. Focal Mechanism

The ISC Bulletin distributes hypocentres, contributed agency magnitudes and arrival picks for the two largest shocks. The 2026 entries used here are unreviewed entries beyond the Bulletin review cut-off; their catalogue magnitudes are distinguished from the USGS W-phase M_w values (Supplementary Table S5). The focal mechanisms adopted for the doublet are the USGS W-phase moment-tensor solutions for event us6000t7zc (M_w 7.2) and event us6000t7zp (M_w 7.5), both dominated by near-vertical strike-slip nodal planes [10,11]. Each moment tensor admits two conjugate nodal planes, either of which gives the same double-couple beachball; the beachball therefore constrains the mechanism but does not by itself identify which nodal plane is the physical fault. For the mainshock, the two USGS nodal planes are the near north–south plane (strike 354.7° , dip 85.7° , rake -16.4°) and the near east–west plane (strike 85.9° , dip 73.7° , rake -175.6°). The latter is selected as the rupture plane on the independent seismological, structural and interferometric evidence

discussed in Section 4.1. Every nodal-plane pair quoted here was verified numerically to represent the same double couple by recomputing the auxiliary plane from the fault-normal and slip vectors. Thus, the apparent difference between the strike-dip rake triplets is a nodal-plane choice, not a different focal mechanism. The slip inversion is performed on this fixed plane, and the seismic moment is computed from the inverted slip as in Equation (1):

$$M_0 = \sum_{i=1}^N \mu_i A_i s_i. \quad (1)$$

Here, A_i and s_i are the area and slip of patch i , and $\mu_i = \rho V_s^2$ is its rigidity. Density is taken from the tomographic cell export where present, with the empirical V_p –density relation of Brocher [39] used otherwise. Rigidity is interpolated from the four nearest sampled cells by inverse-distance weighting in an isotropic kilometre coordinate system. A centroid more than 40 km from every sampled cell would use 33 GPa; none of the 984 centroids requires this fallback. Rigidity spans 26.5–43.7 GPa, with a mean of 35.3 GPa. This proximity criterion does not imply patch-scale tomographic resolution. Uniform rigidities of 30 and 33 GPa give M_w 7.480 and 7.508, compared with 7.533 for the tomographic rigidity; these sensitivities are not formal confidence intervals. Moment in N m is converted using $M_w = (2/3)[\log_{10}(M_0) - 9.1]$ [40]. Beachballs use the double-couple radiation pattern of Aki and Richards [41].

2.5. InSAR Processing

Coseismic surface deformation was mapped by differential SAR interferometry [42]. Sentinel-1 [43] SLC scenes bracketing the doublet were obtained for four independent tracks, two ascending and two descending (Supplementary Table S3; the complete list of SLC products is given in Supplementary Table S2), and processed per track with ECHO through the following differential-interferometry chain. The scenes, the precise orbits and the GLO-30 tiles were retrieved with the ECHO acquisition tools. ECHO also supplies the DEM datum conversion, boxcar coherence estimator, independent per-pixel LOS-vector calculation, quality control and multi-track inversion. The processing steps are:

- Co-registration. Geometric co-registration from the precise orbits and the GLO-30 DEM, giving the range and azimuth offset of every pixel of the reference burst in the secondary geometry, followed by TOPS deramping, resampling and reramping [44,45] and by Enhanced Spectral Diversity azimuth refinement on the burst overlaps [46], with a coherence threshold of 0.7 on the overlap interferograms.
- Interferogram formation. Complex conjugate product of the reference with the conjugated secondary, taken burst by burst; the flat-earth and topographic phase is removed analytically from the precise orbits and the GLO-30 DEM [47] before multilooking, so that the reference ramp cannot alias within the multilook cell. Heights were converted from the orthometric EGM2008 datum of GLO-30 to WGS84 ellipsoidal heights (geoid undulation -32 to -7 m over the area), which is the datum the range-Doppler geometry requires. The bursts and sub-swaths are then merged into a single image and multilooked 16 times in range by 4 in azimuth.
- Coherence. Interferometric coherence was estimated with a 5×5 multilooked-pixel boxcar window using integral images [48] as in Equation (2):

$$\gamma = \frac{\left| \sum_{p \in W} S_{1,p} S_{2,p}^* \right|}{\sqrt{\left(\sum_{p \in W} |S_{1,p}|^2 \right) \left(\sum_{p \in W} |S_{2,p}|^2 \right)}}. \quad (2)$$

- Here, S_1 and S_2 are the co-registered complex SAR images, p indexes pixels in the local boxcar window W , and the overbar denotes complex conjugation. The coefficient γ ranges from 0 (incoherent) to 1 (fully coherent).
- Phase filtering. A Goldstein–Werner adaptive spectral filter with exponent $\alpha = 0.6$ was applied [49], where α controls the strength of spectral weighting.
- Unwrapping. SNAPHU statistical-cost network-flow unwrapping [50] uses minimum-cost-flow initialisation and the deformation (DEFO) cost model, designed for the large phase gradients of a deformation field, on overlapping tiles. Connected components are retained for quality control [51]. Discontinuities and disconnected coherent areas remain potential sources of ambiguity.
- Geocoding and LOS conversion. The unwrapped differential phase is converted as $d\text{LOS} = -\lambda\phi/(4\pi)$, with $\lambda = 5.55$ cm and the processing sign convention defined so that positive LOS displacement is towards the satellite. Products are geocoded in WGS84 (EPSG:4326) on the grid of the multilooked product, with postings of 2.77–4.27'' in longitude and 2.72–4.20'' in latitude (Supplementary Table S7). Each pixel has a ground-to-satellite LOS unit vector calculated from the precise orbit by solving the zero-Doppler condition; incidence angles agree with the processor values to within 0.12°. No atmospheric phase-screen correction is applied. Independently fitted planar ramps absorb a planar long-wavelength component on each track, while spatially correlated residuals can still contain atmospheric signal. Residual DEM error propagates as $\delta d\text{LOS} = B_{\perp} \delta h / (R \sin \theta)$, where $B_{\perp}$ is the perpendicular baseline and R is the slant range. For $R = 850$ km and $\theta = 35^\circ$, a 5 m height error gives approximately 1.0 mm LOS error per 100 m of perpendicular baseline; at a 500 m baseline, it gives about 5.1 mm. This is a baseline-dependent sensitivity, not an incidence-only error estimate.

Radar-geometry stages operate on the full Sentinel-1 bursts intersecting the area of interest; where the area straddles a sub-swath boundary, the covering sub-swaths are de-burst and mosaicked, and the crop to the analysis box happens only at geocoding. All four pairs were processed over the three sub-swaths IW1–IW3, which are joined after multilooking; T25D nevertheless has the smallest coherent area of the four. The four coseismic pairs share a common analysis window of 9.70–12.00°N, 69.30–66.05°W, which contains both epicentres and the entire surface projection of the modelled fault plane (69.25–66.51°W): ascending relative orbits 33 (T33A) and 106 (T106A), and descending relative orbits 98 (T98D) and 25 (T25D), all bracketing the 24 June doublet with pre-event acquisitions on 18 June (T33A and T98D), 23 June (T106A) and 13 June (T25D), and post-event acquisitions on 25 June (T33A and T25D), 24 June (T106A) and 30 June 2026 (T98D). The post-event scenes therefore follow the second mainshock by about 45 min (T106A), 12 h (T25D), 25 h (T33A) and 5.5 days (T98D). The opposing look directions provide complementary east–west and vertical sensitivity over the rupture, and the two tracks per direction give an internal consistency check (Supplementary Table S3; footprints in Figure 4). T33A was processed over this window and T106A, T98D and T25D over 8.00–12.00°N, 71.00–66.00°W, so the geocoded T106A and T98D products extend to 70.74°W and 9.38°N; their coherent pixels outside the window also enter quality control and sampling (Supplementary Table S7).

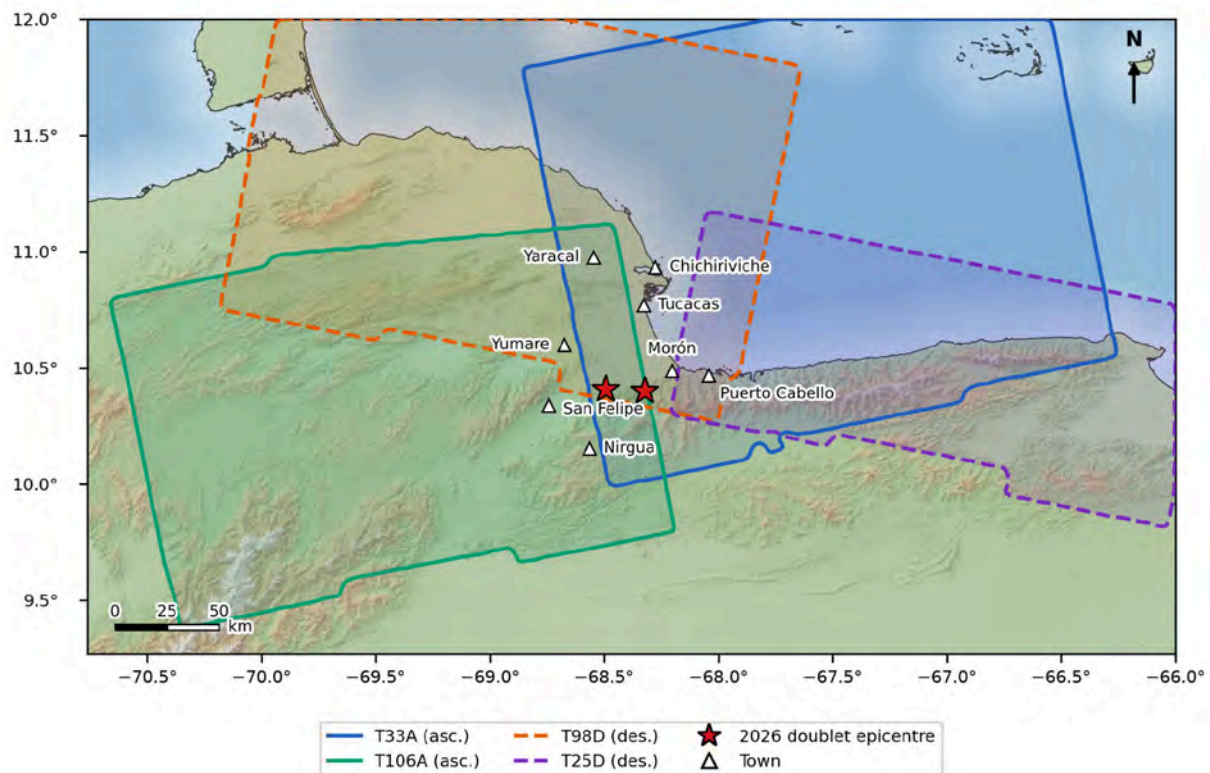


Figure 4. Sentinel-1 coverage of the four coseismic pairs across northwestern Venezuela (WGS84, EPSG:4326). Coloured outlines and light fills show, for each track, the valid unwrapped line-of-sight (LOS) area over land, together with the sea inside the SLC footprint imaged on both dates and the processing box. Ascending tracks T33A and T106A are shown with solid borders, and descending tracks T98D and T25D with dashed borders. Red stars mark the two ISC epicentres, and triangles identify towns from OpenStreetMap contributors via Nominatim. The panel was composed in Python using Matplotlib from the processed Sentinel-1 footprints and Copernicus GLO-30. Acquisition dates are given in Supplementary Table S3, and the complete list of SLC products is in Supplementary Table S2.

2.6. Fault-Slip Inversion

The four geocoded LOS deformation fields were inverted jointly. Pixels with coherence below 0.30 are discarded, and spatial quality control rejects a pixel when it departs by more than five scaled median absolute deviations from the median of the fixed 51×51 -pixel block containing it (Supplementary Figure S3 and Tables S7 and S8). A field-wide median can reject real coseismic lobes: in the unconstrained sensitivity runs, with identical sampling and regularisation, the field-wide test gives a slip correlation of 0.949 with the local test and 20% less moment, whereas no outlier test leaves slip and moment unchanged (Supplementary Table S8). The Table S8 baseline uses variance-driven quadtree sampling; the preferred model uses the equal-budget decimation stated below. Retained pixels are decimated to an equal budget of 2500 observations per track, 10,000 in total, to prevent the track with the largest coherent area from dominating the objective. The inversion uses the per-pixel LOS vectors, with an independent planar nuisance ramp for each track. Equal sampling is a modelling choice and does not make spatially correlated observations independent; its implications are discussed in Section 4.3.

The forward model is the rectangular dislocation in an elastic half-space of Okada [52]. The fixed plane follows the E–W USGS W-phase nodal plane (strike 85.9° , dip 73.7° , rake -175.6°), with the top-edge anchor at 10.502°N , 68.40°W , at 0.5 km depth. At fixed width, orientation, regularisation and ramps, LOS RMS decreases from 23.8 mm at 150 km length to 21.9 mm at 175 km, 20.3 mm at 200 km and a plateau of 19.8–19.9 mm from 225 km

onwards. The same 75 km extension applied westwards gives no improvement. At lengths of 275–350 km, the maximum remains near 67.22–67.24°W, slip tapers to zero at the ends, and Mw is 7.52–7.54. The adopted 300 km length lies in this stable family; the plateau does not uniquely determine rupture length. Widths of 20, 24, 30, 36 and 42 km give RMS values of 21.30, 20.56, 19.79, 19.47 and 19.29 mm, respectively, with Mw 7.36, 7.41, 7.53, 7.58 and 7.63. Wider planes reduce the RMS by at most 0.5 mm (19.29 mm at 42 km) while raising the moment magnitude to 7.63 by placing more moment at depth. The adopted 30 km width keeps about 60% of the moment above 20 km and places the lower edge at approximately 29 km depth, within a plausible seismogenic thickness. The plane has $82 \times 12 = 984$ patches. Halving this mesh to 41×6 changes moment by 0.09 magnitude units and peak slip by 40%; patch-scale peaks are consequently interpreted cautiously. Bounded, smoothed least squares [53] minimises Equation (3).

$$\min_{s \geq 0, a} \left\{ \|Gs + Ra - d\|_2^2 + \beta^2 \|\nabla^2 s\|_2^2 \right\}. \quad (3)$$

Here, d contains 10,000 LOS observations; G maps unit patch slip to LOS displacement through the Okada Green functions [52]; s is non-negative slip in the fixed rake direction; and R and a describe the independent three-parameter planar ramps. The objective is the unweighted squared data misfit plus β^2 times squared Laplacian slip roughness. The trust-region-reflective bounded solver uses $\beta = 0.7$ at the L-curve corner (ECHO $\alpha = 0.5$). A rake search changes total variance reduction by less than 0.2 percentage points across -180° to $+150^\circ$, so the rake is constrained primarily by the seismological mechanism. Track omission and anchor shifts assess source sensitivity.

2.7. Data Availability and Reproducibility

All input data are public: the ISC Bulletin [8], the USGS W-phase moment-tensor solutions [10,11], the Copernicus Sentinel-1 archive and the Copernicus GLO-30 DEM. The archived dataset preserves the catalogue and DEM caches, the SLC archives, and every intermediate and final product, together with the complete run reports and logs in which each processing stage records its configuration, parameters and quality metrics; each step of the workflow can therefore be re-inspected and independently reproduced from the original sources. The full station inventory and the list of SLC products are provided in Supplementary Tables S1 and S2.

2.8. Multi-Plane Source Separability, Resolution and Static Stress Transfer

The four interferograms contain the cumulative displacement of both earthquakes. Source separability was tested with two nested models evaluated on the identical 10,000 LOS observations, identical per-track planar ramps, elastic constants, the $\beta = 0.7$ regularisation selected at the L-curve corner and a 20 m physical slip bound. The 984-patch Morón model was compared with a 1224-patch model adding the N–S candidate plane. The two-plane solver was warm-started from the converged one-plane slip and ramp solution, with zero initial slip on the additional plane; its initial RMS therefore reproduced the one-plane RMS exactly. Resolution was quantified by forward modelling synthetic slip distributions of prescribed moment and shape on the adopted 82×12 mesh through the same four-track Green's functions, look vectors, coherence masks, per-track ramps and Laplacian regularisation as the production inversion, and inverting them with the production settings.

Static Coulomb failure stress was calculated by summing the contribution of every slipping patch as a finite rectangular dislocation in a homogeneous isotropic elastic half-space [52], with four-point quadrature, a shear modulus of 32 GPa and a Poisson ratio of

0.25, differentiating the displacement gradients to strain and stress; there is no point-source approximation at any stage. Rescaling the cumulative two-event slip model to the first-event moment would not establish which patches slipped in the first earthquake, so the calculation is run over an ensemble of thirteen first-event source scenarios of deliberately different provenance: three uniform-slip rectangles centred on the first hypocentre with dimensions bracketing the empirical scaling for Mw 7.2, which use no interferometric information at all; three directivity windows anchored on that hypocentre and propagating eastwards, westwards and bilaterally; four windows cut from the interferometric slip model itself, of which the first is simply the cumulative model rescaled to the first-event moment, retained so that the effect of that assumption can be measured rather than argued away; and three repeats of the first family on the alternative first-event east–west nodal plane. Every scenario is normalised to the USGS W-phase moment of the first event, 7.9×10^{19} N m, which is an observation independent of the interferometry. These are conditional stress scenarios, not an independent demonstration of triggering. Stress was resolved on the E–W receiver (strike 85.94° , dip 73.66° , rake -175.56°) as $\Delta CFS = \Delta \tau + \mu' \Delta \sigma_n$, with tensile normal stress positive and $\mu' = 0.2, 0.4$ and 0.6 [54,55]. Hypocentral uncertainty was sampled on a 3×3 horizontal grid spanning ± 5 km and at depths of 5, 10 and 15 km. The near-field rule excludes entire receiver locations, not individual patch contributions: a receiver is masked if it lies within the exclusion distance of any source rectangle. At two equivalent patch radii, $r = \sqrt{(A/\pi)}$, with A being the patch area, this discards four of the ten scenarios of families A to C entirely and halves the surviving median; the calculation therefore sets the exclusion distance to zero, masking only the analytic singularity, so that no receiver sample and no source moment is omitted; the rules at one and two patch radii are reported as a sensitivity. Median, full range and sign consistency across all 27 spatial samples of each scenario are the stress-transfer observables. The transient stress carried by the wavefield of the first event is estimated separately from the peak-ground-velocity scaling $\Delta \tau_{\text{dyn}} \approx \mu \cdot \text{PGV}/V_S$, with the arrival times computed from the tomographic velocities at the hypocentral depth. This calculation is a sensitivity diagnostic rather than a probabilistic triggering forecast.

3. Results

3.1. Relocated Seismicity

JHD relocation of the 225 best-picked events reduces the residual RMS by 38% (from 1.79 s to 1.11 s, Supplementary Table S6) and confirms a coast-parallel band of seismicity along the coastal corridor, spanning 69.50 – 67.54°W . All 225 events pre-date the doublet; none is an aftershock, and the band represents the 2006–2026 background seismicity of the corridor. Individual relocations use data from 3 to 25 stations (median 9), with azimuthal gaps ranging from 54.1° to 342.5° (median 143° ; greater than 180° for 50 of the 225 events) and final travel-time RMS values of 0.06 to 4.43 s (median 0.70 s). Because each station contributes at most one P and one S pick, no event has more than 50 observations. This geometry constrains epicentral coordinates considerably better than depths, and no conclusion below depends on an individual relocated depth. Station corrections are largest and negative at the coastal stations (BENV: -0.74 s P, -0.65 s S; TURV: -0.95 s P), consistent with shallow structure faster than ak135-F beneath the coastal crystalline basement, and positive at inland station JACV for S waves ($+0.59$ s), consistent with the slower sedimentary cover of the basin fill.

3.2. Velocity Structure

The inversion reduced the RMS travel-time residual from 14.2 s to 6.4 s, a 55% reduction, using the 191,371 rays retained by the robust residual filter of the 241,379 originally traced, and sampled 14,901 of 24,576 cells. Its ray-supported volume has a median V_p/V_s of 1.79 and delineates the coast-parallel high-velocity basement corridor. The same volume provides the direct structural test beneath the 2026 rupture, because it spans the whole adopted plane. Figure 5 shows the W–E section (A–A' section Figure 2) along the strike of the system, Figure 6 the S–N section (B–B' section Figure 2) across it, and Figure 7 the map-view slices at layer centres of 1.9, 5.6, 9.4 and 13.1 km depth.

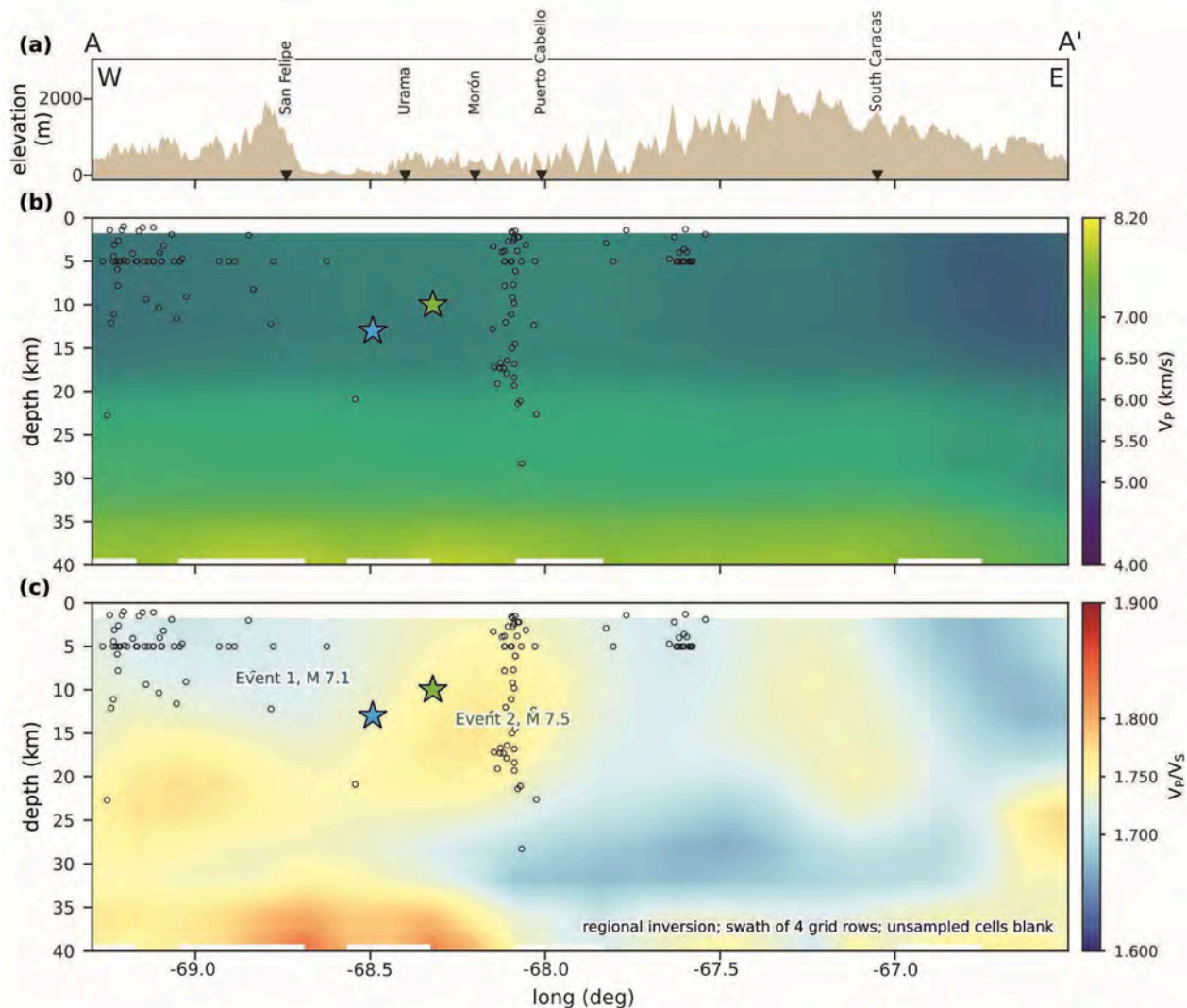


Figure 5. W–E regional velocity section centred at latitude 10.404°N , west on the left and east on the right. (a) Topographic profile, with San Felipe, Urama, Morón, Puerto Cabello and the Caracas coast marked for orientation. (b) V_p . (c) V_p/V_s from the same $48 \times 32 \times 16$ regional inversion. The displayed velocity swath spans four grid rows, as labelled in the image; unresolved cells are blank. Relocated hypocentres are projected from $\pm 0.25^{\circ}$ latitude (about 28 km) about the section. The cyan and green stars mark Event 1 and Event 2 at their ISC positions. The displayed velocity swath and the hypocentre projection width are distinct. Trace A–A' in Figure 2.

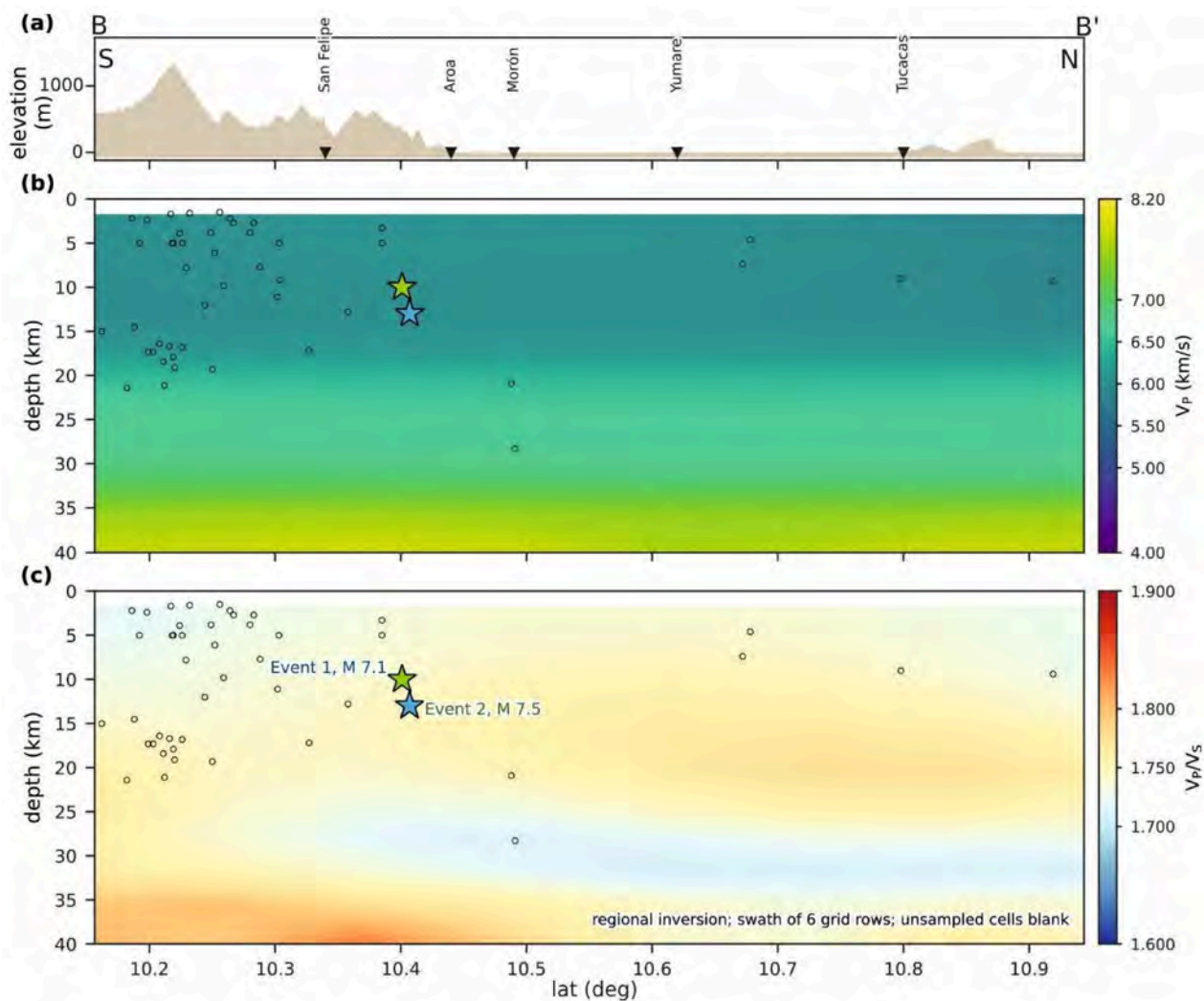


Figure 6. S–N regional velocity section centred at longitude 68.41°W , with south on the left and north on the right, as indicated by the latitude axis. (a) Topographic profile, with San Felipe, Aroa, Morón, Yumare and Tucacas marked. (b) V_p . (c) V_p/V_s from the same $48 \times 32 \times 16$ regional inversion. The velocity swath spans six grid rows, as labelled in the image; unresolved cells are blank. Black dots are relocated background hypocentres projected from $\pm 0.35^{\circ}$ longitude (about 38 km); stars mark the two mainshocks. Elevated V_p/V_s is non-unique and does not independently identify fluids, fractures or a particular lithology. Trace B–B' in Figure 2.

At 4–14 km depth, within a ± 20 km swath about the adopted plane, the median V_p/V_s is 1.720 in the western third of the plane, 1.735 in the central third and 1.721 in the eastern third. The variation is not a west-to-east gradient: the difference between the two ends is 0.001, while the central third stands 0.015 above the western third and 0.014 above the eastern third. These differences are calculated directly from the reported medians. The same thirds measured on the constant-ratio control differ by about 0.0001; this tests broad spatial averages and does not justify interpreting individual cells. Its amplitude is modest, and it is interpreted as a broad central anomaly rather than as a first-order structural boundary between segments. The linearised checkerboard on the catalogue acquisition geometry recovers the imposed velocity structure with $r = 0.82$ for a $39.6 \times 39.7 \times 11.2$ km block without pick noise, $r = 0.81$ at $26.4 \times 26.4 \times 7.5$ km and $r = 0.83$ at $52.8 \times 52.9 \times 15.0$ km, falling to 0.71–0.75 at 0.20 s of pick noise, and recovers 65–67% of the imposed amplitude, indicating substantial amplitude damping in this synthetic experiment; a universal amplitude correction is not applied to the observed V_p/V_s ratio. Within the interpreted 4–14 km band, the number of cells sampled by both phases per

1536-cell slice falls from 1395 at 5.62 km to 1331 at 13.12 km, with a median of 16 rays per sampled cell over the whole volume, and the recording geometry has a median azimuthal gap of 195° , with 45% of the sources recorded over a gap below 180° . This permits cautious first-order interpretation of spatially averaged structure at scales of about 30 km and coarser, and of nothing at the scale of an individual cell. The reported V_p/V_s variation is evaluated as a broad P-versus-S travel-time pattern rather than a cell-scale amplitude. Cells outside the production support threshold remain masked.

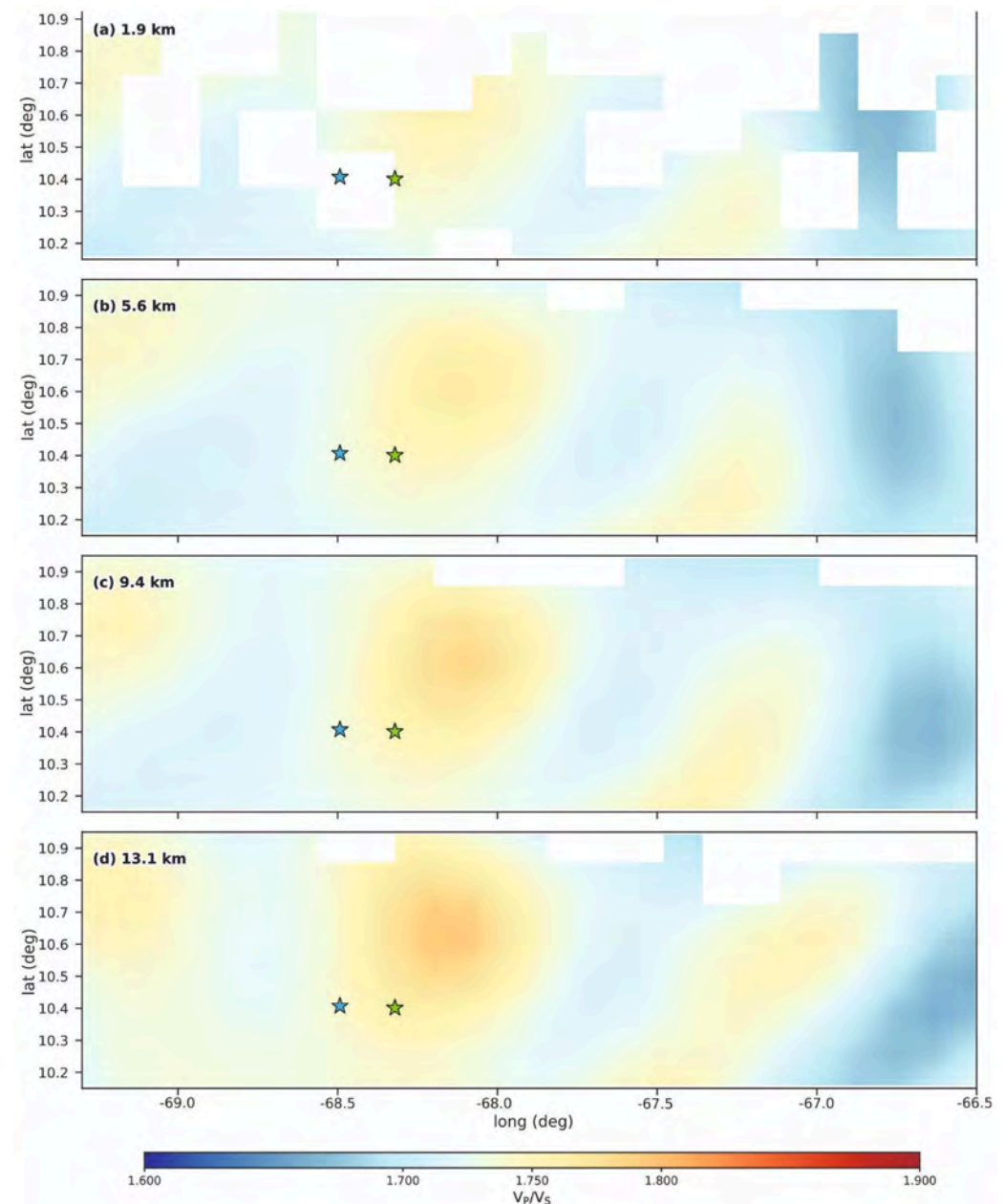


Figure 7. Map-view V_p/V_s slices through the three-dimensional tomography volume, viewed from above, at the centres of the four shallowest layers of the inversion grid: (a) 1.9 km, (b) 5.6 km, (c) 9.4 km and (d) 13.1 km below sea level, over the rupture corridor. Each panel is masked to the ray-covered part of the volume, so the white areas are unresolved rather than anomalous; the shallowest layer is the least completely sampled, which is why panel (a) is patchy. Stars represent the two ISC hypocentres, cyan for Event 1 and green for Event 2.

3.3. Coseismic InSAR

Figures 8 and 9 show the filtered wrapped interferograms and geocoded LOS displacement, and Figure S1 shows coherence for the same four pairs. At coherence ≥ 0.30 the pixel counts are 134,292 (T33A), 2,585,726 (T106A), 297,265 (T98D) and 63,412 (T25D). Coherence varies across land cover and acquisition geometry; comparable median coherence does not imply identical noise. T106A has the greatest coherent area, while T25D has the smallest coherent area. Ascending and descending LOS fields provide complementary sensitivity to the common displacement field; four look geometries do not fully resolve every displacement component or the depth distribution of fault slip.

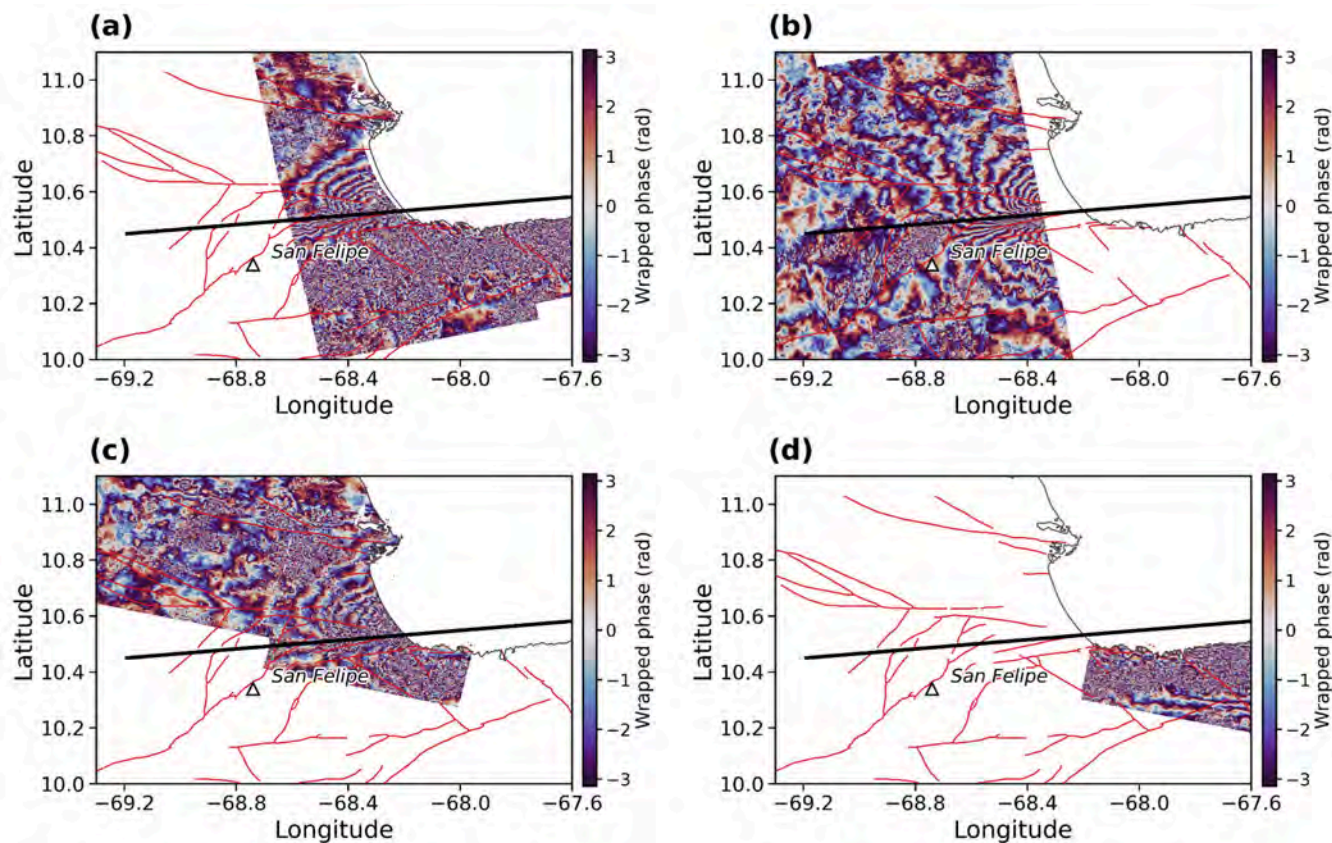


Figure 8. Filtered wrapped coseismic interferograms of the four Sentinel-1 pairs from Supplementary Table S3, coherent pixels only, displayed over the epicentral sector of the analysis window (10.0–11.1°N, 69.3–67.6°W; WGS84, EPSG:4326): (a) T33A ascending, (b) T106A ascending, (c) T98D descending and (d) T25D descending. One full-colour cycle is one fringe, which is half a radar wavelength of range change. Red lines indicate mapped active faults, the black line represents the modelled fault trace, and triangles denote towns: Tocuyo de la Costa, Yaracal, Chichiriviche, Tucacas, Boca de Aroa, Yumare, San Felipe, Nirgua, Urama, Morón and Puerto Cabello. The Interferometric coherence values are shown in Figure S1.

3.4. Fault Geometry, Slip Distribution and Mechanism

Table 1 summarises the joint inversion. The source is the fixed USGS mainshock plane, striking 85.9° and dipping 73.7° south, 300 km long along strike and 30 km wide down dip, anchored on the mapped Morón fault trace; its rake (-175.6°) is right-lateral. Slip increases eastwards along the plane, away from both epicentres: the maximum (2.32 m) lies at 10.55°N , 67.23°W , and the slip falls to zero at both ends of the plane, with more than 1 m of slip over an approximately 90-km-long segment east of 67.6°W . Once the plane is long enough for the misfit to saturate, the along-strike position of this maximum is stable: it lies at 67.24° , 67.23° and 67.22°W in the 275, 300 and 350 km models respectively, so it

is not pinned by the edge of the modelled plane. What the data still do not resolve is the depth of the peak and its patch-scale amplitude. Most of the recovered slip, 67.6%, lies east of 67.6°W , in the eastern part of the analysis window. The corresponding geodetic moment is $2.51 \times 10^{20} \text{ N m}$ (M_w 7.53; 7.52–7.54 across the stable family of plane lengths from 275 to 350 km). The joint model reproduces the four LOS fields (Figure 10) with per-track (demeaned) variance reductions of 85.8% (T33A), 78.5% (T106A), 47.4% (T98D) and 83.2% (T25D). The reviewed USGS origin of the M 7.5 event [11] lies within the eastern modelled high-slip region and is shown for comparison only. A hypocentre and a slip maximum are different source quantities; this comparison does not establish patch-scale positional accuracy. Both mainshocks retain their ISC hypocentres throughout the analysis. Figure 11 compares the two reviewed USGS W-phase mechanisms with the mechanism adopted for the geodetic source. Figure 12 presents the along-strike topographic, tomographic and slip sections, while Figures 13 and 14 show complementary 3-D views of the source, velocity structure and relocated seismicity. The reviewed USGS origin is marked in Figures 12 and 14.

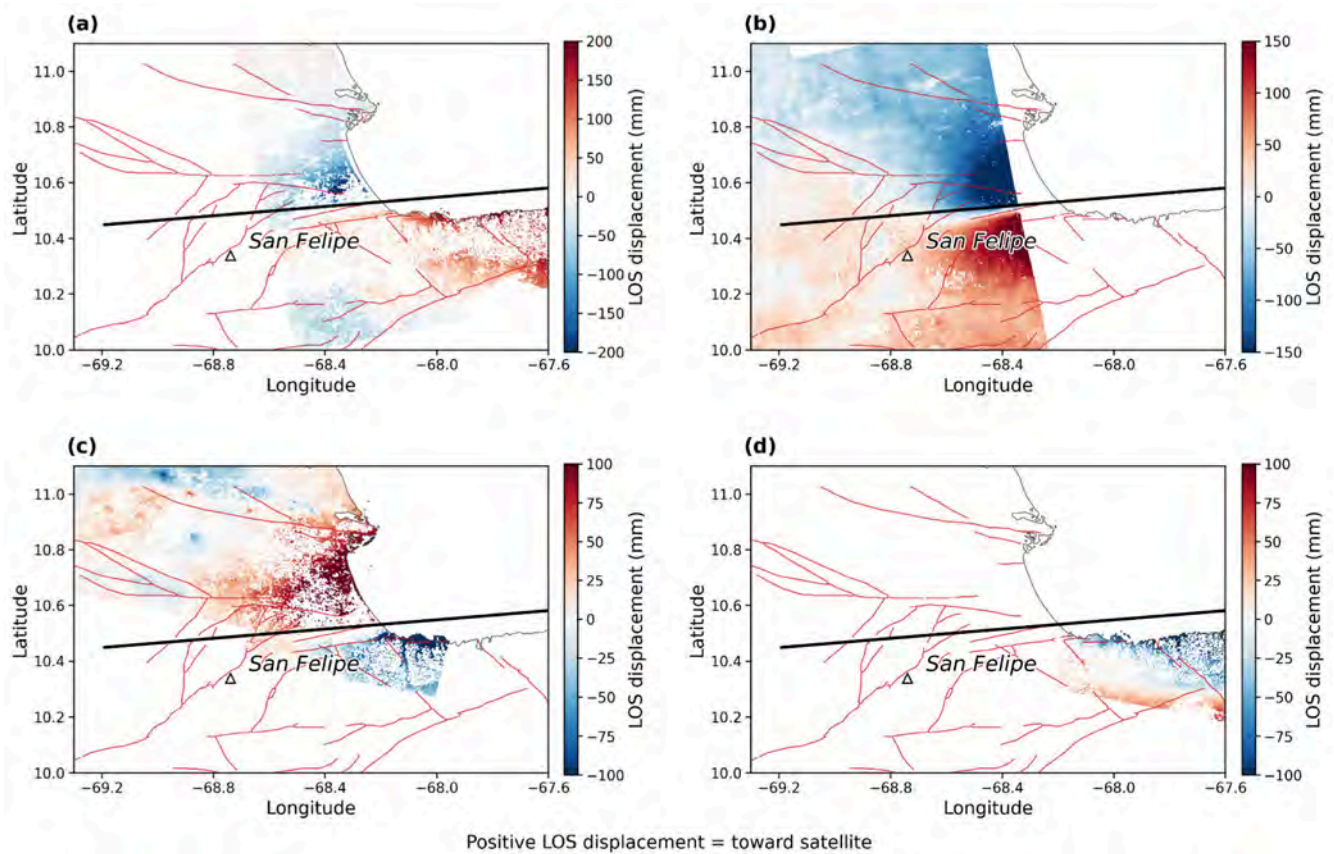


Figure 9. Geocoded line-of-sight displacement of the same four pairs, newest minus oldest and positive towards the satellite, with the per-track median removed and only coherent pixels retained: (a) T33A ascending, (b) T106A ascending, (c) T98D descending and (d) T25D descending. Note the reversal of the east-component sign between the ascending and descending geometries, which is the complementary sensitivity that the joint inversion exploits. Frame and overlays as in Figure 8.

Table 1. Joint four-track InSAR fault-slip inversion: configuration and results.

Parameter	Value
Forward model	Okada [52] rectangular dislocation, elastic half-space
Regularisation	Laplacian roughness [56]; bounded least squares [53]
Solver	Bounded least squares, trust-region reflective
Fault top-edge anchor	10.502°N at 68.40°W (mapped Morón trace), top depth 0.5 km
Strike/dip/rake	85.9°/73.7°/−175.6° (USGS W-phase mainshock nodal plane, fixed)
Fault dimensions	300 km along strike × 30 km down dip; length within the stable misfit-plateau family
Patches	82 × 12 = 984
LOS observations	10,000 (2500 on each of T33A, T106A, T98D, T25D)
Ramp model	Planar, 3 parameters per track (independent)
Smoothing weight	L-curve corner (ECHO $\alpha = 0.5$, equivalent to $\beta = 0.7$)
Maximum/mean slip	2.32 m maximum/1.00 m mean over slipping patches
Seismic moment	2.51×10^{20} N m; patch rigidity from tomography, mean 35.3 GPa, range 26.5–43.7 GPa; no 33 GPa fallback patches
Moment magnitude	7.53 (7.52–7.54 across plane lengths of 275–350 km)
Per-track variance reduction (demeaned)	85.8% (T33A), 78.5% (T106A), 47.4% (T98D), 83.2% (T25D)

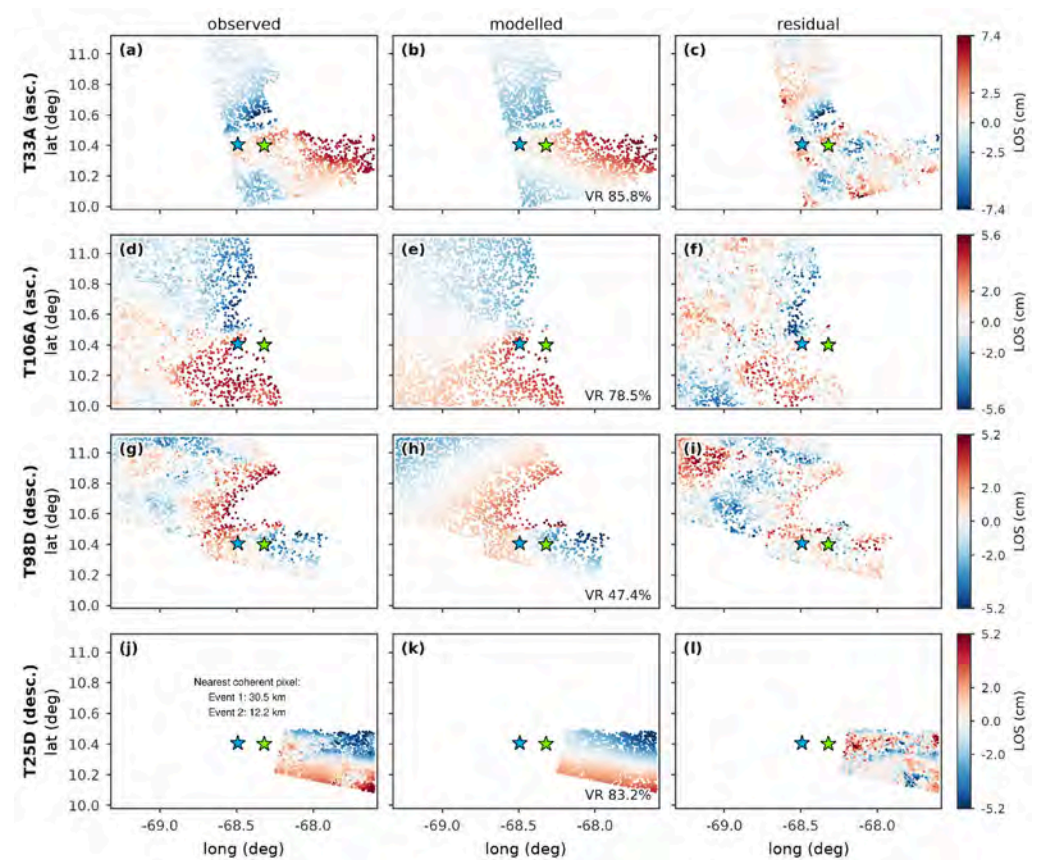


Figure 10. Joint four-track LOS fit, in centimetres, displayed over the epicentral sector of the analysis window (10.0–11.1°N, 69.3–67.6°W). Each row is one track and each column is, from left to right, the observed displacement, the modelled displacement including the fitted planar ramp, and the residual; the colour scale is shared within a row, and cyan and green stars mark Event 1 and Event 2 at the ISC positions in every panel. (a) T33A ascending, observed; (b) T33A modelled, per-track demeaned variance reduction 85.8%; (c) T33A residual, Moran's I at 10 km 0.501. (d) T106A ascending, observed; (e) T106A modelled, variance reduction 78.5%; (f) T106A residual, Moran's 0.672. (g) T98D descending, observed; (h) T98D modelled, variance reduction 47.4%; (i) T98D residual, Moran's 0.587 and a fitted residual correlation length of 14.2 km. (j) T25D descending, observed, annotated with the distance from each ISC epicentre to the nearest coherent pixel (Event 1, 30.5 km; Event 2, 12.2 km); (k) T25D modelled, variance reduction 83.2%; (l) T25D residual, Moran's I 0.239. The independence expectation for Moran's is approximately −0.0004 for 2500 samples. Residual spatial correlation remains and does not by itself identify its physical origin.

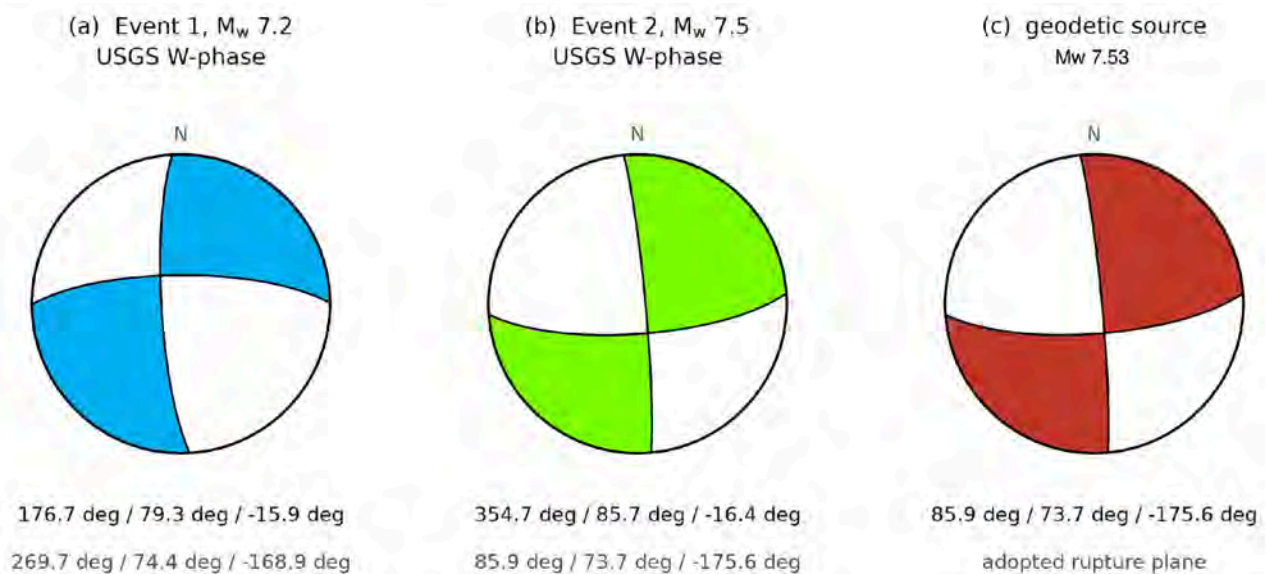


Figure 11. Double-couple focal mechanisms of the doublet and of the geodetic source, in lower-hemisphere equal-area projection with north at the top and compressional quadrants coloured cyan for Event 1, green for Event 2 and red for the geodetic mechanism (Aki and Richards convention [41]). (a) Reviewed USGS W-phase moment tensor of event us6000t7zc, M_w 7.2, nodal planes $176.7^\circ/79.3^\circ/-15.9^\circ$ and $269.7^\circ/74.4^\circ/-168.9^\circ$, the second recomputed as the auxiliary plane of the first. (b) Reviewed USGS W-phase moment tensor of event us6000t7zp, M_w 7.5, nodal planes $354.7^\circ/85.7^\circ/-16.4^\circ$ and $85.9^\circ/73.7^\circ/-175.6^\circ$, the second recomputed as the auxiliary plane of the first and identical to the plane used in Table 1 and in the inversion. (c) Mechanism adopted for the geodetic source, that is, the east–west nodal plane of the mainshock solution, $85.9^\circ/73.7^\circ/-175.6^\circ$, with the geodetic moment of M_w 7.53.

Sensitivity tests give M_w 7.48–7.72 when one track is omitted, M_w 7.28–7.55 over smoothing weights (ECHO α) of 0.5–1.5, and M_w 7.30–7.71 when the top-edge anchor is shifted by $\pm 0.1^\circ$ latitude. The anchor shifts reduce total variance reduction from 96.2% to 94.4% and 92.2%. These are conditional model ranges, not confidence intervals. The peak lies near 22 km depth for the preferred model but moves between approximately 2 and 22 km across the tests. Broad along-strike moment release is consequently more robust than peak amplitude or down-dip position. Rigidity end members change M_w by approximately 0.05 (Section 2.4).

The nine ISC-catalogued events of the sequence up to 3 July 2026 (Supplementary Table S5 lists the largest) are quoted at their catalogue positions and were not relocated in this study, because none of them carries a phase pick at the stations of network VE. At those positions, they migrate eastward along the coast: after the doublet near 68.3 – 68.5°W , aftershocks of m_b 4.5–4.8 occur on 26–29 June at 67.6°W and as far east as 66.7 – 66.8°W , along strike of the San Sebastián segment towards the Caracas coast.

3.5. Multi-Plane, Resolution and Stress-Transfer Tests

The one-plane model gives LOS RMS 19.79 mm, and the warm-started nested two-plane model gives 19.46 mm, a reduction of 0.33 mm (1.7%; Figure 15a,b). The added N–S candidate plane is anchored at the first hypocentre and carries M_w 6.28. Placing the same candidate plane 130 km east gives zero slip on that plane and an unchanged RMS of 19.79 mm. This control tests one alternative location; it does not exclude every possible source geometry. The small fit gain establishes the non-uniqueness of cumulative deformation and does not isolate the moment of either event.

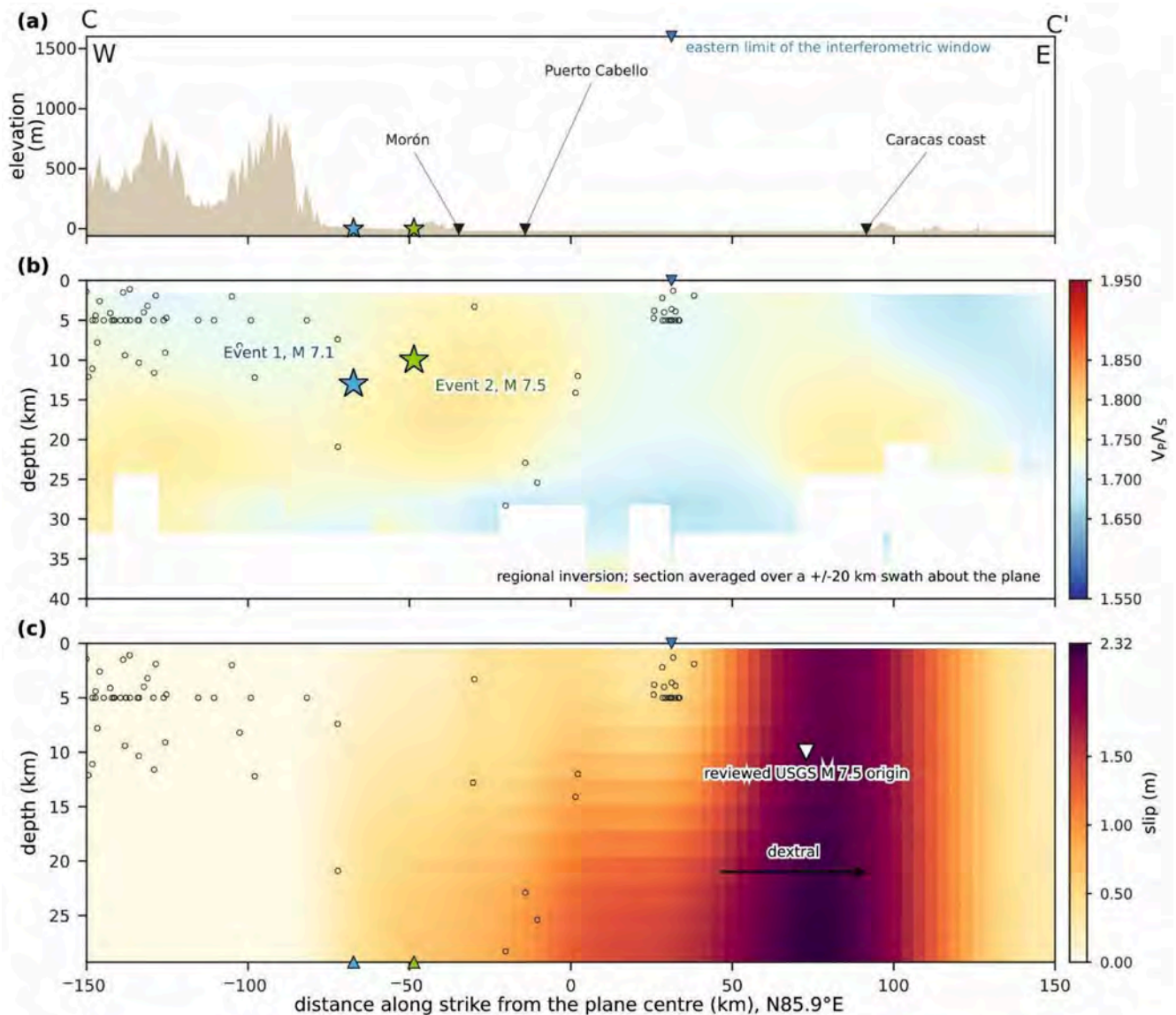


Figure 12. Along-strike W–E profile through the rupture (azimuth 85.9° , parallel to the fault strike, WGS84 geodesic). (a) Topographic profile, with the nearby localities (Yumare, San Felipe, Boca de Aroa, Urama, Morón and Puerto Cabello) and their signed perpendicular offsets from the profile. (b) V_p/V_s tomography with the relocated hypocentres, ray-resolved cells only, and unresolved cells left blank; hypocentres are projected onto the profile from a swath of ± 20 km measured perpendicular to it. (c) Inverted coseismic slip on the fault plane at true dip, with the same hypocentres; the black arrow shows the dextral sense of slip (rake -175.6° , 99.7% strike-slip, 7.7% vertical). Circles are coloured by hypocentral magnitude on the shared scale at the right. The modelled slip increases towards the east and peaks at 67.23°W , and both epicentres lie west of the modelled high-slip region. The relocated hypocentres shown here all pre-date the doublet and are the 2006–2026 background seismicity of the corridor, not aftershocks of this sequence. The reviewed USGS M 7.5 event is displayed on the slip plane [11]. The blue triangle at +30 km marks the eastern edge of the map frame of Figures 8–10, not the eastern limit of the data used in the inversion. Trace C–C' in Figure 2.

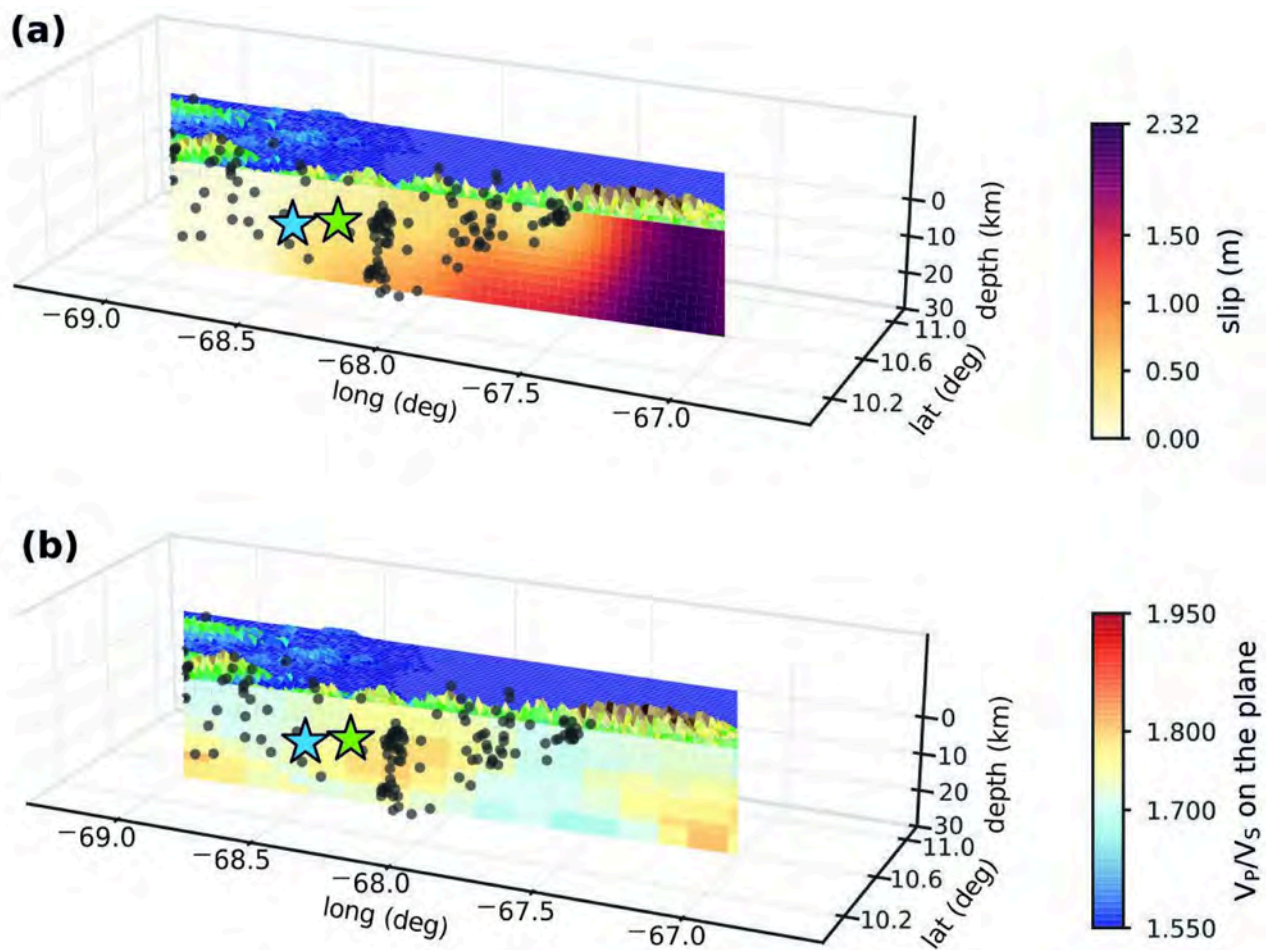


Figure 13. Three-dimensional views of the source, sharing the same camera: (a) the 984-patch fault plane at its true dip of 73.7° , coloured by inverted slip, and (b) the V_p/V_s tomography on the same plane, ray-resolved cells only. Both carry the GLO-30 topography, with a vertical exaggeration of $\times 5$ applied to the terrain only, and the relocated hypocentres; cyan and green stars mark Event 1 and Event 2.

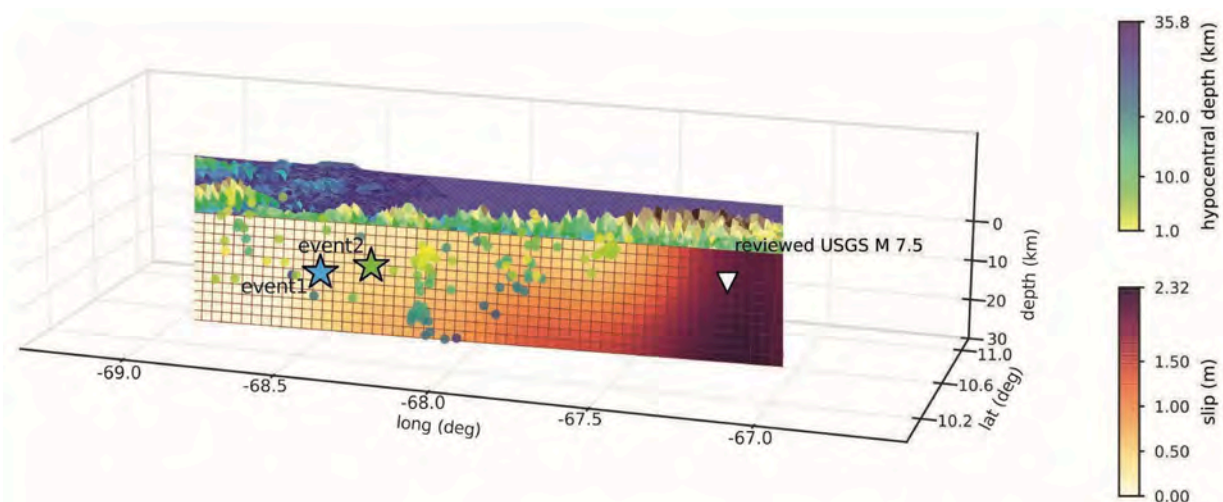


Figure 14. Perspective along-strike view of the modelled fault and regional volume. Background hypocentres, all pre-dating the doublet, are coloured by depth; the plane is coloured by slip. Cyan and green stars mark the two ISC mainshocks, and the white inverted triangle marks the reviewed USGS origin [11], used only for comparison. This is a model display, not independent evidence of the full doublet rupture plane.

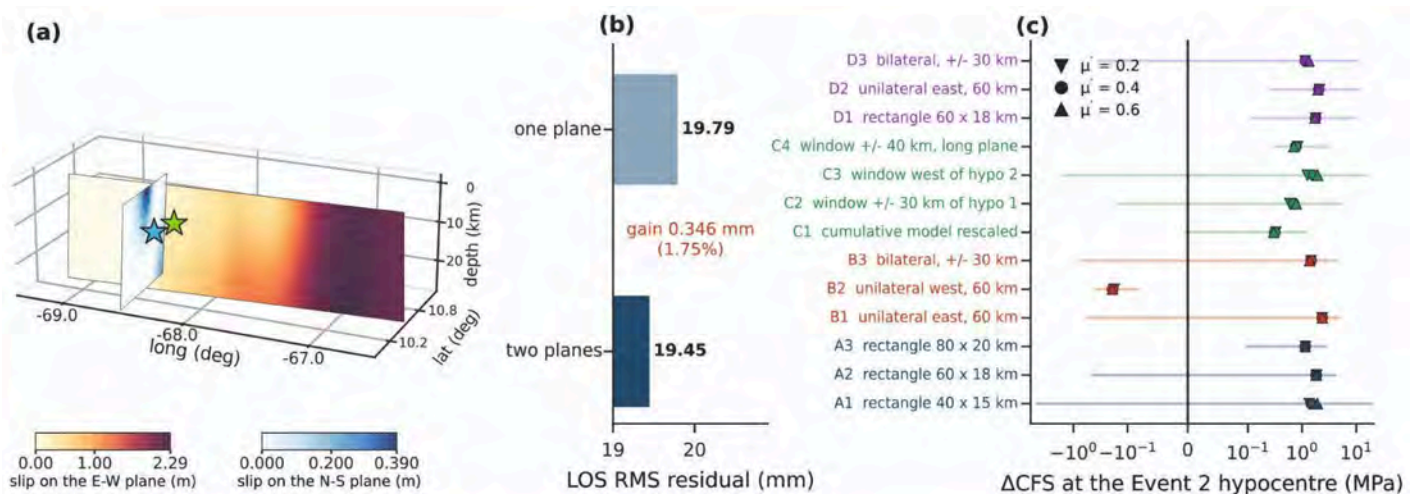


Figure 15. Multi-plane source and conditional stress-transfer tests. (a) Slip on the E–W and N–S candidate planes, with separate colour scales; cyan and green stars mark Event 1 and Event 2. (b) LOS RMS for the nested one- and two-plane fits to the same observations: 19.79 and 19.46 mm, a gain of 0.33 mm (1.7%). (c) Conditional Δ CFS at the Event 2 receiver for thirteen first-event source scenarios. Horizontal bars span the 27 spatial samples (± 5 km horizontally and depths of 5, 10 and 15 km); symbols give medians at $\mu' = 0.2, 0.4$ and 0.6 . Families A and D are finite rectangles, B contains directional rupture windows, and C contains windows from the cumulative slip model. Each source is normalised to 7.9×10^{19} N m. Scenario-specific spatial ranges distinguish receiver-location sensitivity from the assumed source geometry.

Along strike, a single asperity about 35 km across is recovered with a slip correlation of 0.80–0.86 wherever it is placed on the plane, and a pair of asperities about 90 km apart at 0.94. Down dip, the same experiment recovers a depth-dependent distribution at only 0.34, so the along-strike distribution of moment is resolved at these scales while its depth distribution is not. The resolved geodetic result is therefore the along-strike moment distribution at scales of about 30 km and coarser; peak amplitude, patch-scale asperity shape and down-dip position are model dependent. The single Coulomb calculation defined in the methods evaluates thirteen first-event source scenarios on the ± 5 km horizontal and 5–15 km depth grid, with 27 samples each, and no sample discarded. Twelve of the thirteen have a positive median Δ CFS at every friction value over $\mu' = 0.2$ – 0.6 , with medians at $\mu' = 0.4$ ranging from +0.31 MPa for the rescaled cumulative model to +2.35 MPa for a first rupture propagating eastwards towards the second hypocentre, with 70–100% of individual samples positive; the single exception is the scenario in which the first rupture propagates westwards, away from the second hypocentre, which gives -0.19 MPa and no positive sample (Figure 15c). The friction dependence is weak because the receiver is very nearly pure strike-slip.

4. Interpretation and Discussion

4.1. Fault Attribution and Kinematics

The four-track Sentinel-1 inversion places the modelled dislocation on the east–west nodal plane of the USGS W-phase mainshock solution (strike 85.9° , dip 73.7° south, rake -175.6°), anchored on the mapped trace of the Morón fault. The choice between the two conjugate nodal planes is made based on independent evidence: the JHD-relocated 2006–2026 background seismicity band extends approximately east–west for about 215 km and defines the seismogenic corridor; however, because all its events pre-date the doublet, it does not measure the 2026 rupture length, which is instead evaluated with the misfit-versus-length scan. The mapped active faults of this coastal corridor (Morón, Puerto Cabello, western San Sebastián) strike east–west with steep dips in the Quaternary fault compilation

of Audemard, Machette, Cox, Dart and Haller [19], which underlies the GEM active-fault layers. Additionally, the InSAR deformation lobes are elongated east–west; the conjugate north–south plane is incompatible with all three observations. The rupture therefore lies west of the El Pilar fault proper and east of the Boconó junction, on the segment of the plate-boundary system that accommodates the bulk of Caribbean–South American relative motion at this longitude. In this geometry, Boconó is not the principal moment-release segment; it is the western transfer structure that links the Yaracuy valley to the Morón–San Sebastián coastal system [19,22].

The dextral kinematics of the adopted plane is the expected coseismic expression of the southern Caribbean–South America boundary, where the Caribbean plate moves approximately eastward relative to stable South America at about 2 cm/yr [2,3], and the east–west coastal faults carry the boundary-parallel dextral component of the obliquely convergent motion, within the transpressional regime and inverted-basin structural style documented for northern Venezuela [24,57]. The line-of-sight misfit itself is insensitive to the rake, so the geodetic data neither require nor exclude a minor oblique component; the attribution to the Morón–western San Sebastián dextral system rests jointly on the moment tensors, the mapped active-fault traces and the regional strain field. The largest recovered moment release, at 67.23°W (Section 3.4), lies on the western San Sebastián reach, about 135–140 km east of the first epicentre, rather than at the Boconó junction, and about two-thirds of the recovered slip lies east of 67.6°W. In this reading, the Boconó–Morón junction is the western limit of the rupture rather than its moment-release centre.

4.2. Rapid Rupture Interaction Along the Coastal Segment

The two mainshocks are separated by only 39 s and about 19 km along strike, with the second event nucleating east of the first [8–11]. This spacing and timing are consistent with rapid interaction between neighbouring rupture domains, possibly as a cascading sequence with two distinct nucleations; the travel-time comparison in Section 4.5 does not support a single continuously propagating front between the catalogue hypocentres [58]. The resolution-tested geodesy adds a broad spatial constraint: the recovered moment release increases eastwards away from the two hypocentres at scales of approximately 30 km and coarser, so both nucleation points fall on the weakly slipping western part of the modelled plane, about 120–140 km west of the slip maximum. No aftershock of this sequence was relocated here, so the relation between coseismic slip and aftershock distribution [59] cannot be tested with these data; the relocated seismicity shown in the maps is the 2006–2026 background population, and only the nine catalogued sequence events, at their unrelocated catalogue positions, bear on the post-seismic behaviour.

Regional space-geodetic studies document heterogeneous coupling, including creeping and locked reaches, along the broader Caribbean–South America boundary [21], while the historical record demonstrates repeated damaging coastal earthquakes [6,60]. In the nine-event ISC sequence used here, the five-day eastward distribution of m_b 4.5–4.8 aftershocks reaches approximately 66.7°W. This pattern is spatially consistent with along-strike redistribution and identifies the eastern coastal segments as priorities for continued instrumental monitoring.

4.3. Reconciling the Geodetic and Seismological Moments

The preferred geodetic moment is 2.51×10^{20} N m (Mw 7.53), compared with the summed reviewed USGS W-phase moment of 2.99×10^{20} N m (Mw 7.58; 7.9×10^{19} plus 2.2×10^{20} N m). The geodetic estimate is 84% of this reference. Converting the distributed ISC magnitudes M 7.1 and M 7.5 through the moment-magnitude relation gives approximately 2.8×10^{20} N m, but the W-phase sum is the appropriate comparison

because those are measured seismic moments. The geodetic estimate is conditional on fault dimensions, regularisation and data treatment.

An Mw 7.58 synthetic source on the adopted plane is recovered at 97–124% of its moment across nine slip styles, and at 89–136% with 20 mm spatially correlated noise over five realisations; the offshore updip style is recovered at 97% without added noise. These prescribed experiments demonstrate that the observation geometry can recover sources with the summed W-phase moment, but do not establish a universal bound on the earthquake model. The length and width scans, rigidity end members and smoothing sensitivities are reported in Sections 2.4, 2.6 and 3.4. They support Mw 7.53 as a model-dependent estimate, rather than a coverage-imposed lower bound. Residual Moran's I demonstrates that spatial correlation remains (Figure 10); equal track budgets do not remove that dependence, and the unweighted objective does not provide a correlated-noise posterior uncertainty. Budgets proportional to coherent area, diagonal weights by track variance and coherence, and weights declustered over the noise correlation length are compared in Supplementary Table S8. That table also reports a separate conditional sensitivity suite with a soft 2.80×10^{20} N m target derived from the catalogued magnitudes; this is not an ISC-determined moment and the target is not used in the preferred model. Planar ramps do not remove all atmospheric signal. Post-event scenes follow the second mainshock by about 45 min (T106A), 12 h (T25D), 25 h (T33A) and 5.5 days (T98D), so only T98D can contain several days of early post-seismic displacement. With one pair per track, this contribution cannot be isolated from look geometry and other residual terms. No coseismic GNSS offsets, strong-motion records or additional body-wave inversion are incorporated, so they do not provide independent validation of this slip model.

4.4. Resolution-Calibrated Structural Interpretation

Checkerboard recovery supports broad tomographic interpretation only: for the $39.6 \times 39.7 \times 11.2$ km block, the input–recovery correlation falls from 0.82 without pick noise to 0.80 and 0.73 at 0.10 and 0.20 s of noise, and about two-thirds of the imposed amplitude is recovered (Supplementary Figure S2). The central Vp/Vs high of 0.014–0.015 (Section 3.2) exceeds the approximately 0.0001 third-to-third artefact floor of the constant-ratio control, whereas the ± 0.019 cell-scale spread of the same control precludes individual-cell interpretation; no universal amplitude correction is applied to the observed ratio. Elevated Vp/Vs can reflect lithology, fractures or fluids and is not diagnostic of any one cause. Broad source geometry, mapped faults and catalogue seismicity provide the structural context; Figure 16 presents a conceptual geological interpretation.

4.5. Triggering Geometry of the Second Rupture

Cumulative InSAR admits multiple source partitions; adding a second plane improves RMS by 1.7%. The conditional stress ensemble gives a positive median ΔCFS at the second hypocentre for twelve of thirteen first-event scenarios; westward propagation away from the receiver gives a negative median. For the adopted ISC positions, epicentral and hypocentral separations are 18.8 and 19.1 km. With Vp = 6.00 km/s and Vs = 3.44 km/s, direct P, S and Rayleigh travel times are approximately 3.2, 5.5 and 6.0 s, preceding the second nucleation by approximately 26–36 s for the ISC delay of 39 s or the reviewed USGS delay of 32.2 s. Both comparisons use the ISC spatial separation. A front travelling at 0.7–0.9 Vs covers 18.8 km in approximately 6.1–7.8 s. Under these assumptions, immediate nucleation at the direct wavefront or a single uninterrupted rupture front does not explain the delay. For the assumed PGV of 0.2–1.0 m/s, $\mu \cdot PGV/Vs$ with $\mu = 32$ GPa gives approximately 1.9–9.3 MPa, overlapping and extending above the positive static medians of +0.31 to +2.35 MPa. This dynamic amplitude is a conditional estimate, not

a recording. Static loading, delayed dynamic nucleation or both remain admissible; no triggering probability is inferred. Figure 17 displays eastward and westward first-rupture scenarios at the common Event 2 receiver.

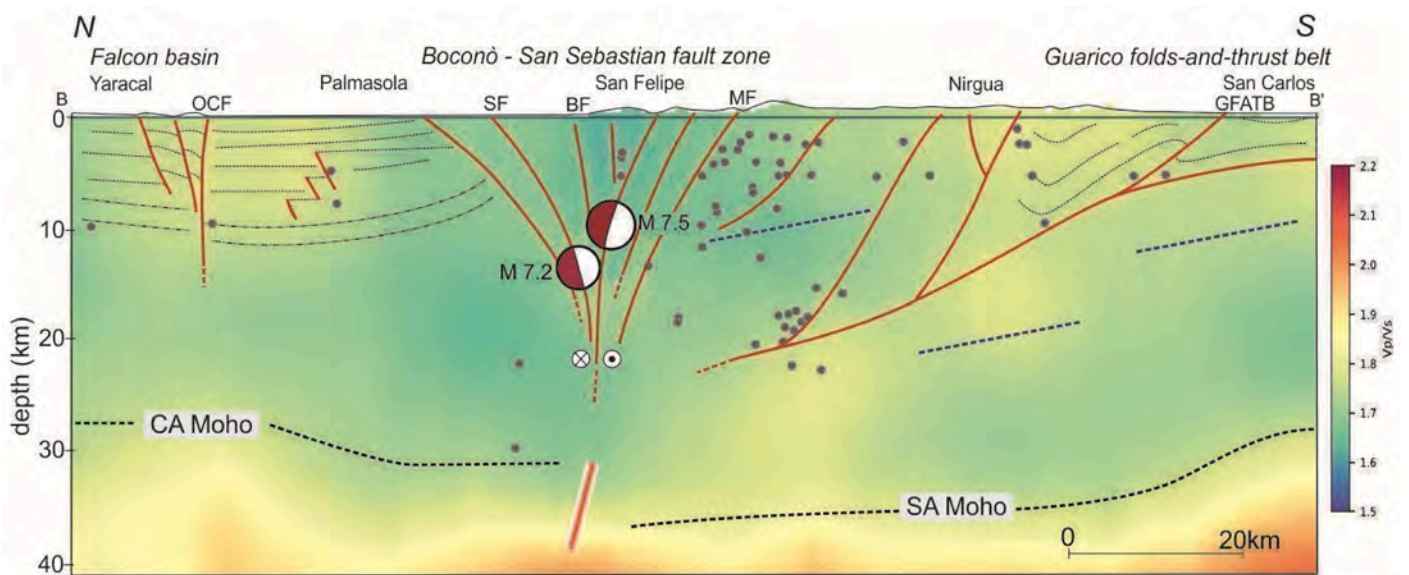


Figure 16. Conceptual N–S crustal section at longitude 68.41°W. The interpreted fault strands (red lines) and stratigraphic markers (blue lines), décollements and Caribbean and South American Moho provide a geological framework for the Falcón Basin, coastal fault system and Guárico fold-and-thrust belt. The Morón–San Sebastián system is represented as a positive flower structure, following the regional interpretation of the BOLIVAR profile [31]. Grey circles show background seismicity; event mechanisms locate the doublet in this structural context. Colours illustrate the conceptual velocity-ratio background. Deep interfaces and fault connections are interpretations, not uniquely resolved tomographic boundaries. Abbreviations: OCF, Oca–Chirinos Fault; SF, San Sebastián Fault; BF, Boconó Fault; MF, Morón Fault; and GFATB, Guárico fold-and-thrust belt. Trace B–B′ in Figure 2.

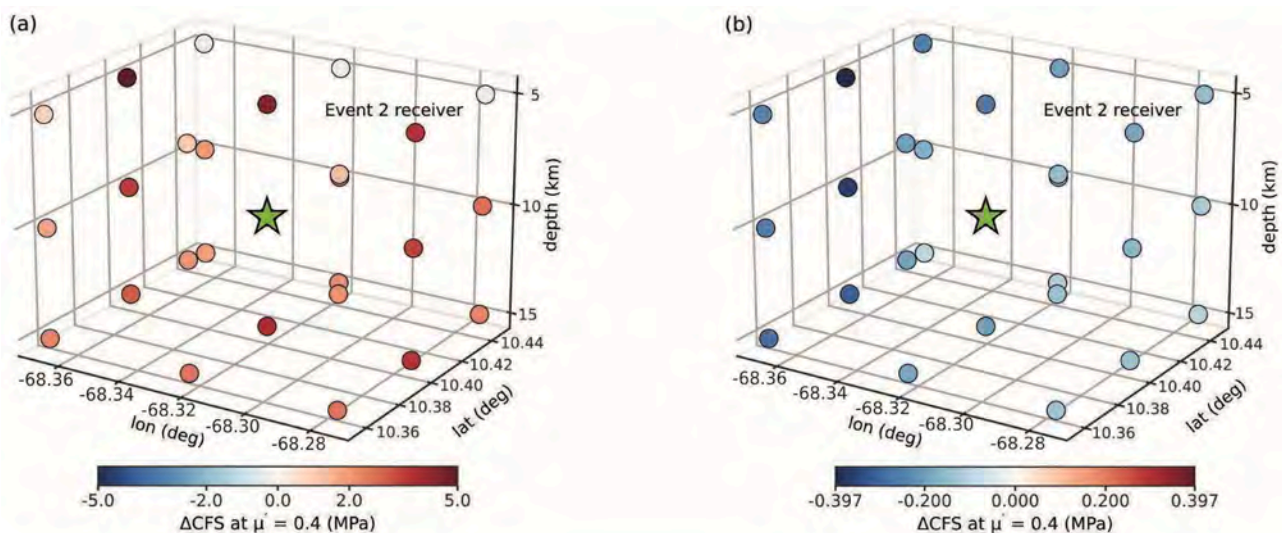


Figure 17. Conditional static stress at the Event 2 receiver for (a) a first rupture propagating eastwards, towards Event 2, and (b) a first rupture propagating westwards, away from Event 2. Circles show the 27 receiver samples, coloured by ΔCFS at $\mu' = 0.4$; the colour scales differ between panels. The green star marks the common receiver at the ISC Event 2 hypocentre (10.401°N, 68.321°W, 10 km depth). Samples span ± 5 km horizontally and depths of 5, 10 and 15 km; no sample is masked. These are conditional source scenarios, not a map of the absolute regional stress tensor.

5. Conclusions

The joint inversion of 10,000 four-track LOS observations gives $M_0 = 2.51 \times 10^{20}$ N m (Mw 7.53), peak slip 2.32 m near 10.55°N, 67.23°W, and demeaned per-track variance reductions of 47.4–85.8%. The adopted 300×30 km plane lies within a length-scan misfit plateau, with Mw 7.52–7.54 across lengths of 275–350 km. Broad dextral moment release increases eastwards along the Morón–western San Sebastián coastal system. Synthetic recovery supports interpretation at approximately 30 km along-strike scale and coarser, while patch amplitudes and depth remain model dependent. A 0.33 mm (1.7%) RMS gain from adding a second plane demonstrates that cumulative InSAR does not uniquely partition the two subevents.

The 225 JHD-relocated events pre-date the doublet and define background structure rather than an aftershock footprint. Tomographic medians identify a broad central Vp/Vs high of 0.014–0.015 relative to the two ends of the plane, without identifying a unique lithological or fluid cause. Twelve of thirteen conditional first-event scenarios give positive median static loading at the second hypocentre. The inter-event delay exceeds direct-wave and simple rupture-front travel times, allowing for static loading, delayed dynamic interaction or their combination. These results motivate assessment of closely spaced failures on neighbouring coastal segments.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/rs18193298/s1>: One Supplementary Material DOCX accompanies this article. It contains Table S1, the VE station-epoch inventory; Table S2, the Sentinel-1 SLC products and acquisition geometry; Table S3, the four coseismic pairs; Table S4, data sources; Table S5, catalogue parameters; Table S6, the JHD summary; Table S7, the coverage of each interferometric track; Table S8, the sensitivity of the joint inversion to quality control, sampling and weighting; Figure S1, four-track interferometric coherence; Figure S2, the tomographic checkerboard recovery test; and Figure S3, the pixels removed by the spatial quality control of the LOS fields. Tables and figures are embedded in that document. Processed data and run outputs are available as stated in the Data Availability Statement.

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