

Article

Blind Fault and Thick-Skinned Tectonics: 2025 Mw 6.4 Paratebueno Earthquake in Eastern Cordillera Fold-and-Thrust Belt

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Highlights

What are the main findings?

- Multi-sensor InSAR (Sentinel-1 and ALOS-2) resolves up to 43 cm line-of-sight (LOS) displacement and constrains a NW-dipping blind reverse fault (strike $\approx 213^\circ$, dip $\approx 58^\circ$) with peak slip of ~ 5 m at 8–12 km depth, without surface rupture.
- Static Coulomb failure stress change (ΔCFS) modeling indicates that the 2023 Mw 6.2 Meta-Cundinamarca earthquake increased stress on the 2025 rupture plane.

What is the implication of the main finding?

- Rupture located beneath the 7–10 km sedimentary cover, together with the regional structural framework, indicates basement-involved (thick-skinned) reactivation, most plausibly along a Guaicáramo-related fault within the Eastern Cordillera fold-and-thrust belt.
- The combined 2023–2025 sequence concentrates positive ΔCFS on the southeastern Guaicáramo and adjacent segments, implying elevated near-term seismic hazard and priority targets for monitoring and risk mitigation.



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Abstract

On 8 June 2025, the Mw 6.4 Paratebueno earthquake struck the eastern foothills of the Eastern Andes, Colombia. The event occurred near the Guaicáramo fault, along the eastern margin of the Eastern Cordillera fold-and-thrust belt. To investigate its rupture characteristics and tectonic implications, we utilized ALOS-2 and Sentinel-1 SAR data to derive coseismic deformation fields. Source geometry and slip distribution were inverted with the Okada dislocation model, and static Coulomb failure stress change were calculated to assess the triggering relationship with the 2023 Mw 6.2 Meta-Cundinamarca earthquake. The results reveal maximum line-of-sight displacements of 43 cm, 23 cm and 32 cm, respectively, caused by a northwest-dipping blind reverse fault (strike $\sim 213^\circ$, dip 58°) with ~ 5 m maximum slip concentrated at depths of 8–12 km, without surface rupture. Combining geological and stratigraphic evidence, including regional structures and sedimentary cover thickness, this event implies a transition from a normal fault to reverse fault due to ongoing shortening of fold-and-thrust belt, consistent with a thick-skinned tectonic origin. Coulomb stress modeling suggests the 2023 event promoted the 2025 rupture, and the combined

effect of the two events further increased stress on the southeastern Guaicáramo fault, implying elevated seismic hazard.

Keywords: 2025 Paratebueno earthquake; InSAR; coseismic surface displacement; blind fault; thick-skinned deformation; Coulomb failure stress change; Cordillera fold-and-thrust belt

1. Introduction

At 13:08 UTC (8:08 a.m. local time) on 8 June 2025, an Mw 6.4 earthquake occurred approximately 100 km east of Bogotá, Colombia, at a depth of ~12 km, with its epicenter located at 4.42°N, 73.23°W, about 15 km southeast of Paratebueno (Global Centroid Moment Tensor, GCMT). The event caused localized building damage and casualties, with Santa Cecilia, Japón, Medina and Villanueva among the most affected areas. According to the UNGRD (Unidad Nacional para la Gestión del Riesgo de Desastres), at least 508 people were directly affected, 362 houses were damaged, 174 collapsed, and ~1400 residents were displaced to temporary shelters. Tectonically, Colombia lies within a complex interaction zone between the Nazca, Caribbean, and South American Plates, dominated by oblique convergence (Figure 1) [1]. Far-field stresses are transmitted inland via a network of thrust and strike-slip faults, producing recurrent damaging earthquakes along the Eastern Cordillera fold-and-thrust belt, well beyond the subduction front. Notable examples include the 2008 Quetame earthquake, the 2023 Meta-Cundinamarca earthquake, and the 2025 Paratebueno earthquake (Figure 1), all located within the Eastern Cordillera fold-and-thrust belt, indicating sustained tectonic activity and repeated stress release in the region. For the 2008 Quetame earthquake, Dicelis et al. (2016) utilized only a single ascending (ASC) ALOS image [2], whereas for the 2023 Meta-Cundinamarca earthquake, no InSAR-based studies have yet been published. Against this backdrop, the 2025 Mw 6.4 Paratebueno earthquake provides a critical opportunity to improve observational capability and enhance seismotectonic understanding in this region.

Nevertheless, several key knowledge gaps remain: (1) due to dense vegetation and rugged topography, the rupture area lacks continuous, high-resolution observations of coseismic deformation, limiting constraints on the fault geometry and source mechanism of the 2025 event; (2) the tectonic evolution and deformation patterns of the rupture zone are not fully understood; and (3) the potential triggering relationship between the 2023 Meta-Cundinamarca and 2025 Paratebueno earthquakes, as well as the static stress transfer associated with both events, have not been quantitatively evaluated.

To address these issues, we integrate multi-source synthetic aperture radar (SAR) observations to derive high-resolution coseismic deformation fields. SAR provides all-weather, day-and-night, wide-area coverage and has become a key tool for mapping coseismic deformation and inverting source parameters [3–6]. Specifically, we (1) combine ASC and descending (DES) Sentinel-1 and DES ALOS-2 imagery to obtain the deformation field of the 2025 Paratebueno earthquake; (2) invert the fault geometry using an elastic half-space dislocation model; (3) perform distributed slip inversion to characterize the slip distribution; and (4) calculate static ΔCFS to explore the possible triggering relationship between the 2023 and 2025 earthquakes and assess stress loading or shadowing effects on nearby faults. These analyses provide important constraints for seismic hazard assessment along the Eastern Cordillera fold-and-thrust belt. Table 1 summarizes the source parameter estimates for both events from major institutions, which, despite differences arising from data and methods, consistently indicate a NE-SW striking NW-SE dipping reverse fault

system with right-lateral strike-slip motion, in line with the overall orientation of the Eastern Cordillera fold-and-thrust belt.

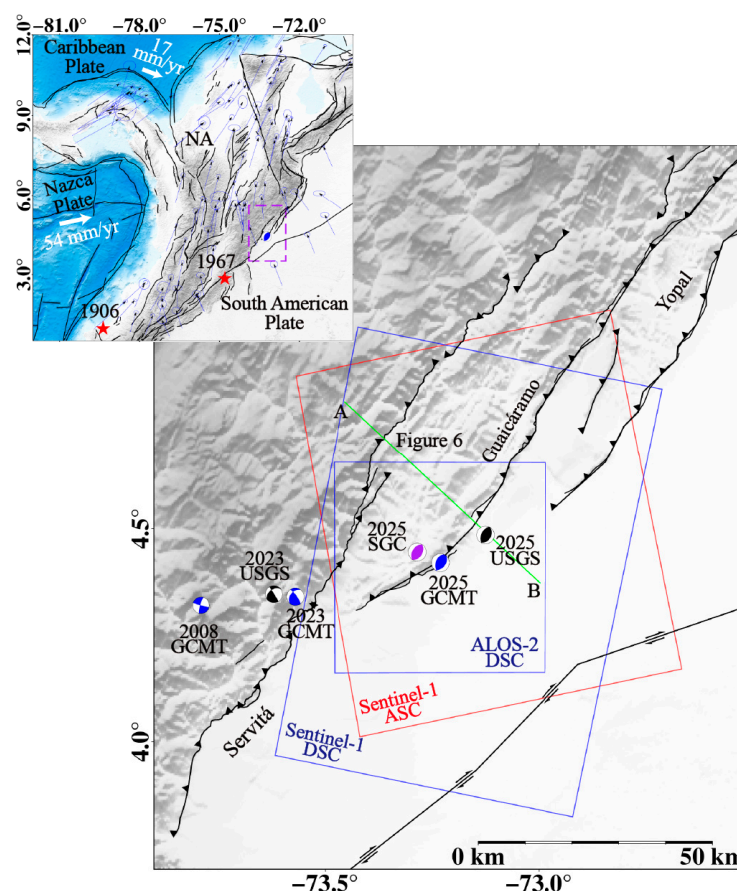


Figure 1. Tectonic setting around the 2023 Meta-Cundinamarca earthquake and the 2025 Paratebueno earthquake (beach balls). The inset figure shows the northern Andes and surrounding regions with the GNSS horizontal velocity field (blue arrows; data source: <http://geodesy.unr.edu/>, accessed on 10 August 2025) in the IGS14 reference frame. Red stars denote earthquakes. NA denotes the North Andean Block. Red and blue rectangles with track numbers represent the coverage of Sentinel-1 and ALOS-2 datasets, respectively. Focal mechanism solutions for the 2023 Meta-Cundinamarca earthquake and the 2025 Paratebueno earthquake are shown, with beach balls from the United States Geological Survey (USGS, black), the Global Centroid Moment Tensor (GCMT, blue), and the Servicio Geológico Colombiano (SGC, purple). Black solid lines represent mapped faults from the Global Active Faults Database (<https://www.globalquakemodel.org/>, accessed on 10 August 2025). The green line AB indicates the location of the cross section shown in Figure 6.

Table 1. Source parameters of the 2023 Meta-Cundinamarca and the 2025 Paratebueno earthquake.

Event	Source	Epicenter			NP1/NP2			Magnitude (M _w)
		Lon (°W)	Lat (°N)	Depth (km)	Strike (°)	Dip (°)	Rake (°)	
2023	USGS ¹	73.62	4.35	10	235	42	176	6.2
					328	87	48	
	GCMT ²	73.57	4.34	20	218	41	159	6.2
					324	77	51	
	GFZ ³	73.56	4.34	16	215	70	131	6.1
					326	45	28	

Table 1. Cont.

Event	Source	Epicenter			NP1/NP2			Magnitude (Mw)
		Lon (°W)	Lat (°N)	Depth (km)	Strike (°)	Dip (°)	Rake (°)	
2025	USGS	73.13	4.48	9	205	52	87	6.3
					30	38	94	
	GCMT	73.23	4.42	12	202	48	79	6.4
					39	43	102	
	SGC ⁴	73.28	4.45	15	213	47	91	6.4
					31	43	89	
	GFZ	73.16	4.48	11	206	62	86	6.4
					33	27	95	
	This study	73.29	4.43	9	213	58	104 ⁵	6.4

¹ USGS: the United States Geological Survey; ² GCMT: the Global Centroid Moment Tensor; ³ GFZ: German Research Centre for Geosciences; ⁴ SGC: the Servicio Geológico Colombiano; ⁵ Average rake of fault slip.

2. Tectonic Setting

Central Colombia lies within a complex transpressional regime shaped by the Nazca, Caribbean, and South American Plates [7,8] (Figure 1). The oceanic Nazca Plate converges eastward beneath South American Plate at approximately 50–60 mm/yr, generating dominant compressional forces in the Andean orogeny. Concurrently, the Caribbean Plate moves eastward relative to South American Plate at around 14–22 mm/yr, introducing oblique convergence and lateral deformation into the northern margin [9,10]. Together, these differential motions orchestrate a transpressional deformation field, driving crustal shortening, right-lateral shear, and the activation of mixed-mode fault systems—including those hosting the 2023 Meta-Cundinamarca and 2025 Paratebueno earthquakes—across the North Andes microplate. The 2025 Paratebueno earthquake was a reverse-faulting event that occurred near the Eastern Frontal Fault System (EFFS) along the eastern foothills of the Colombian Andes [11]. In Colombia, the EFFS defines the frontal structural boundary of the Eastern Cordillera fold-and-thrust belt, accommodating crustal shortening generated during Andean orogenesis through a series of west-dipping thrust faults and oblique-slip faults, with strain predominantly released within the foreland zone. The Eastern Cordillera fold-and-thrust belt comprises several major fault segments, including the Guaicáramo, Yopal, and Servitá faults, which have been active since the Cenozoic, producing significant mountain uplift and frequent moderate-to-strong earthquakes [12,13]. At the regional scale, the tectonic framework of western Colombia is controlled by the eastward subduction of the Nazca Plate beneath the South American Plate along the northern Peru-Chile Trench, which has generated large megathrust earthquakes along the coast, such as the 1906 Ecuador-Colombia M 8.8 earthquake [14].

In contrast, seismicity in central inland Colombia, including the Paratebueno area, is primarily associated with oblique convergence between the North Andean Block and the South American Plate, accompanied by right-lateral shear and crustal shortening [10,15]. Structurally, the Eastern Cordillera fold-and-thrust belt forms an internal boundary between the North Andean Block and the South American Plate, with deformation largely confined to the fault system itself. Since the late Cenozoic, the Eastern Cordillera has undergone significant uplift along this fault system, with strata in its foreland basin (the Llanos Basin) thrust and folded to form a persistently active compressional belt [16]. At depth, the Eastern Cordillera fold-and-thrust belt lies within the collisional suture zone between the

North Andean microplate and the South American Plate, where tectonic stress is highly concentrated, leading to intense crustal deformation and periodic release in the form of moderate-to-strong earthquakes. Historical records indicate that the Eastern Cordillera fold-and-thrust belt is highly seismically active, having hosted several notable events, including the 1967 Neiva earthquake, the 2008 Quetame earthquake, and the 2023 Meta-Cundinamarca earthquake, all of which are closely related to reverse faulting along the eastern margin of the Andes [2,13].

3. Methods

3.1. InSAR Data

To derive the coseismic deformation field of the 2025 Paratebueno earthquake, we collected and processed multi-source synthetic aperture radar (SAR) datasets covering the epicentral region, including C-band (wavelength 5.6 cm) Sentinel-1 ASC and DES tracks Observation with Progressive Scans (TOPS) mode imagery, and L-band (wavelength 23.4 cm) ALOS-2 DES ScanSAR mode imagery (Table 2). Notably, the constellation formed by Sentinel-1A and the recently launched Sentinel-1C restored the six-day repeat cycle capability of the Sentinel-1 mission, enabling acquisition of both ASC and DES postseismic images within one day after the 2025 Paratebueno earthquake. This significantly improved the timeliness and quality of the coseismic interferograms.

Table 2. SAR images used in this paper.

Satellite	Track	Primary	Secondary	Perp. Baseline (m)	Temp. Baseline (Days)
Sentinel-1	Ascending	27 May 2025	8 June 2025	−11	12
	Descending	3 June 2025	9 June 2025	59	6
ALOS-2	Descending	29 May 2025	26 June 2025	416	28

Interferometric processing was conducted using the GAMMA software package (Version 2018) [17] for the Sentinel-1 ASC and DES datasets, following a conventional differential InSAR (DInSAR) approach to generate the corresponding line-of-sight (LOS) coseismic deformation fields. Precise orbit data from the European Space Agency (https://s1qc.asf.alaska.edu/aux_poeorb/, accessed on 20 July 2025) were applied for orbital corrections. For the ALOS-2 data, interferometric processing was carried out using the ISCE software (Version 0.22.1), and ionospheric delays were estimated and removed using the range split-spectrum method [18,19]. For all datasets, topographic phase contributions were simulated and removed using the Copernicus DEM (COP-DEM) with ~30 m spatial resolution (<https://doi.org/10.5270/ESA-c5d3d65>, accessed on 5 August 2025). To enhance the signal-to-noise ratio (SNR), multi-looking factors of 8 (range) $\times$ 2 (azimuth) were applied to Sentinel-1 data and 10 (range) $\times$ 28 (azimuth) to ALOS-2 data. Phase noise was suppressed using the Goldstein adaptive filter [20]. Phase unwrapping for Sentinel-1 interferograms was conducted using the minimum cost flow (MCF) algorithm [21], whereas for ALOS-2 interferograms the SNAPHU algorithm was employed [22], enabling the recovery of LOS surface displacements from the interferometric fringes [23]. To reduce long-wavelength orbital prior to inversion, we removed them by empirically fitting 2D polynomial functions to the interferograms [24,25].

3.2. Model Settings

We inverted the fault geometry and slip distribution of the 2025 Paratebueno earthquake using the elastic half-space dislocation theory [26], constrained by ASC and DES

InSAR-derived coseismic deformation fields (Figure 2). To reduce the spatial correlation and far-field noise in the InSAR data and to improve computational efficiency, the deformation fields were downsampled using a quadtree algorithm [27] prior to inversion. The inversion was performed with the PSOKINV software package (Version 4.5), following a two-step strategy [28,29]:

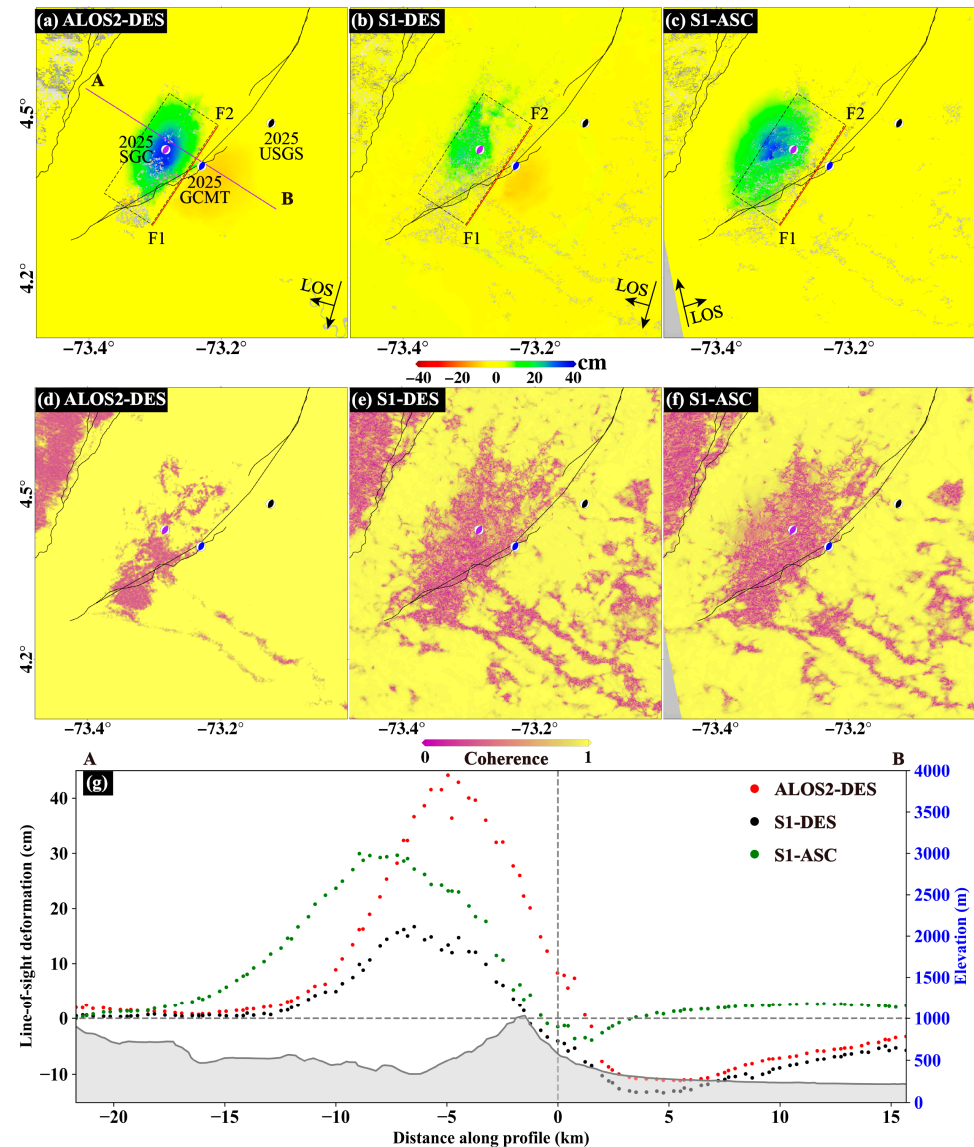


Figure 2. Coseismic deformation fields and average coherence maps of the 2025 Paratebueno earthquake. (a–c) Coseismic deformation fields from ALOS-2 data, DES Sentinel-1 data and ASC Sentinel-1 data; Labels F1 and F2 represent the upper boundaries of the faults. The beach balls represent the focal mechanism solutions of the 2025 Paratebueno earthquake, with solutions provided by the USGS (black), the GCMT (blue), and the SGC (purple). (d–f) Average coherence maps from ALOS-2 data, DES Sentinel-1 data and ASC Sentinel-1 data; (g) surface deformation profile along line AB, with the gray shaded area indicating the topography along the profile. Positive and negative values represent motion toward and away from the satellite, respectively.

1. Assuming a rectangular fault with uniform slip in a homogeneous elastic half-space, we applied a nonlinear search algorithm to estimate the fault geometry. A Poisson's ratio of 0.25 was adopted. Based on focal mechanism solutions from different agencies (Table 1) and the observed InSAR deformation patterns (Figure 2), the search ranges were set to: strike 200–230°, fault length 5–40 km, width 5–30 km, top depth 0–10 km, rake 60–120°, and dip

45–70°. Within this parameter space, a multiple-peak particle swarm optimization (MPSO) algorithm was used to determine the optimal geometry, and Monte Carlo simulations with correlated noise were employed to estimate parameter uncertainties [30–32]. The preferred fault model has a length of 7.89 ± 0.07 km, width of 5.44 ± 0.20 km, strike of $213 \pm 0.08^\circ$, dip of $57.89 \pm 0.10^\circ$, and rake of $103.69 \pm 0.13^\circ$, indicating a reverse-faulting mechanism.

2. Using the fault geometry from the uniform-slip inversion as an initial model, we refined the slip distribution by extending the fault plane to 20 km along strike and 18 km down dip, discretizing it into 360 rectangular patches (1 km $\times$ 1 km each). Strike-slip and dip-slip components for each patch were solved in a homogeneous elastic half-space using linear least squares, with a Laplacian smoothing constraint [27] to suppress spatial oscillations. Recognizing that the optimal geometry for a variable-slip model may differ from that of the uniform-slip model, we jointly optimized the dip angle and smoothing factor. The dip search range was set to 45–70° (1° increment), and the smoothing factor range from 0 to 10 with a step of 0.5.

4. Results

4.1. Coseismic Deformation Fields

Multi-sensor SAR observations resolve the line-of-sight (LOS) coseismic deformation associated with the 2025 Paratebueno earthquake (Figure 2). Panels (a)–(c) show results from the DES ALOS-2 (L-band), DES Sentinel-1 (C-band), and ASC Sentinel-1 (C-band) interferograms, respectively. The deformation fields from the three viewing geometries display relatively simple spatial structures, uniform distribution, and consistent orientation. Differential interferometry results reveal significant uplift northwest of the epicenter, with the uplift center located to the northwest of Paratebueno, forming an elliptical uplift zone, while relative subsidence is observed to the southeast. This uplift–subsidence dipole pattern is a characteristic signature of reverse faulting, corresponding to the hanging wall uplift and footwall subsidence. Considering the tectonic setting of the source region, the event likely ruptured a blind reverse fault within the eastern frontal fault zone. Quantitatively, the ALOS-2 LOS measurements indicate a maximum uplift of ~43 cm (northwest side of the fault) and a maximum subsidence of ~10 cm (southeast side) (Figure 2a). The DES Sentinel-1 data show a maximum uplift of ~23 cm and subsidence of ~12 cm (Figure 2b), whereas the ASC Sentinel-1 data yield a maximum uplift of ~32 cm and subsidence of ~6 cm (Figure 2c). The discrepancy in uplift magnitude between the DES ALOS-2 and DES Sentinel-1 datasets on the northwest side of the fault arises from two factors: (1) the different radar wavelength and viewing geometries of the two satellite systems, and (2) the epicentral area’s location on the eastern flank of the Andes, where dense tropical vegetation and rugged topography reduce coherence in C-band (Sentinel-1) imagery, resulting in local speckle noise, data gaps, and phase unwrapping errors. In contrast, L-band SAR (ALOS-2), with stronger canopy penetration, maintains higher coherence in forested regions, yielding superior deformation mapping quality. To further assess the interferometric quality of the ALOS-2 and Sentinel-1 datasets, we present the corresponding coherence maps (Figure 2d–f). Interferometric coherence ($\gamma \in [0, 1]$) approaches 1 when scatterers remain stable in both position and scattering properties between acquisitions (appearing as yellow areas), whereas changes due to vegetation growth, precipitation, snow cover, or surface disturbance rapidly reduce γ . As shown in Figure 2d–f, the Sentinel-1 (C-band) ascending and descending interferograms exhibit systematically lower coherence than the ALOS-2 (L-band) results. In the near-field deformation zone, widespread decorrelation partly obscures the coseismic signal and increases the uncertainty of Sentinel-1 measurements. By contrast, the L-band ALOS-2 interferograms maintain relatively high coherence, enabling more reliable retrieval of the coseismic deformation field.

Integrating results from the three viewing geometries, the coseismic deformation zone extends approximately $30 \text{ km} \times 20 \text{ km}$. The central deformation boundary trends NE-SW, consistent with the focal mechanism strikes reported by the SGC and USGS, and broadly parallel to the structural grain of the Eastern Cordillera fold-and-thrust belt and the regional subduction-compression tectonic regime. This alignment reflects the influence of Nazca-South American Plate convergence in triggering reverse faulting within the continental interior (www.sgc.gov.co, accessed on 5 August 2025). The InSAR observations thus provide direct surface evidence for the earthquake's source mechanism, indicating that the event was caused by slip on a blind reverse fault, producing significant hanging wall uplift and surface elevation. Panel (g) compares the deformation profiles along the AB (Figure 2a) transect for the three datasets, with the gray-shaded area representing the topography along the profile. The topography rises from southeast (B) to northwest (A). The deformation curves show peak positive LOS displacements (uplift) on the higher-elevation northwest side. The southeast side, corresponding to the lower-elevation footwall, shows smaller-magnitude negative LOS displacements (subsidence). The transition from positive to negative deformation aligns closely with both the projected surface trace of the fault and a topographic break, reinforcing the interpretation that the earthquake rupture occurred on a northwest-dipping reverse fault, with the hanging wall uplifted and the footwall subsided.

4.2. Fault Geometry and Slip Distribution

Using the high-resolution InSAR-derived coseismic deformation fields (Figure 2) as constraints, we inverted the source parameters and slip distribution of the 2025 Paratebueno earthquake. By evaluating the trade-off between model roughness and residual misfit in the logarithmic objective function in Section 3.2 [28], we obtained the optimal dip angle of 58° and the smoothing factor of 2.5 (Figure 3), from which the final faults' slip distribution of the 2025 Paratebueno earthquake was derived (Figure 4).

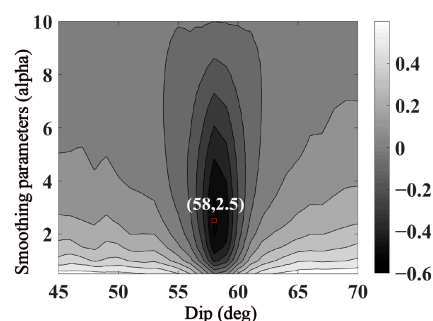


Figure 3. Determination of the optimal dip angle and smoothing factor.

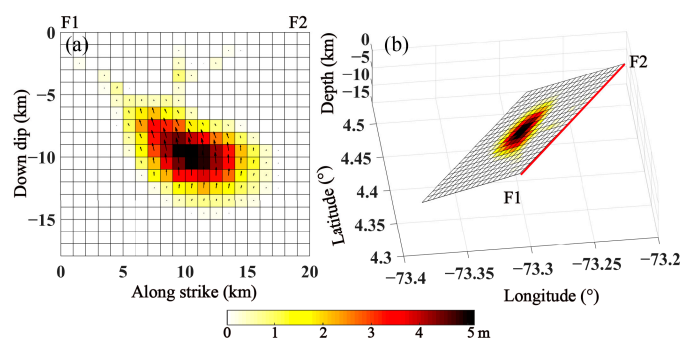


Figure 4. (a) Two-dimensional fault slip distribution of the 2025 Paratebueno earthquake, with black arrows indicating slip directions. (b) Three-dimensional fault slip distribution of the 2025 Paratebueno earthquake, with red lines denoting the fault surface traces used in this study. Labels F1 and F2 represent the upper boundaries of the faults.

The preferred slip distribution of the 2025 Paratebueno earthquake (Figure 4) indicates rupture along a northeast-striking, northwest-dipping reverse fault. The two-dimensional slip model reveals that coseismic slip was primarily concentrated in the central portion of the fault plane, with slip vectors of the shallow subfault patches showing a predominant reverse component and a minor right-lateral strike-slip contribution. This kinematic pattern is consistent with the overall deformation style of the EFFF, where oblique convergence accommodates both crustal shortening and lateral shear. The three-dimensional view further highlighting the northwest-dipping geometry of the fault plane (Figure 4b). Notably, the rupture did not propagate to the surface, corroborating the blind nature of the fault. The slip distribution model reveals that the area with slip exceeding 1 m extends ~9 km along strike and ~7 km down dip, with a maximum slip of ~5 m concentrated at depths of 8–12 km (Figure 4). Such highly localized slip within a small rupture area closely resembles the 2020 Mw 6.4 Petrinja earthquake in Croatia, which ruptured a fault less than 10 km in length but produced peak slip exceeding 5 m [33]. Seismological analyses of the Petrinja event inferred a stress drop of ~24 MPa, significantly higher than the global average for intraplate earthquakes. By analogy, we infer that the 2025 Mw 6.4 Paratebueno earthquake also represents a high stress drop event. This interpretation is physically reasonable because earthquakes rupturing at greater depths, under higher confining pressure and frictional strength, are capable of accumulating and releasing larger amounts of elastic strain energy. Accordingly, the slip pattern and stress drop characteristics of the Paratebueno earthquake suggest that it may represent a high stress-release event within a thick-skinned tectonic regime. Assuming a regional shear modulus of 30 GPa, the seismic moment corresponds to a moment magnitude of Mw 6.4, which is in close agreement with the focal mechanism solutions reported by GCMT and SGC (Table 1), confirming that InSAR data provide robust constraints on earthquake magnitude. Following the event, multiple institutions determined focal mechanism solutions using different seismological approaches (Table 1). While the epicentral locations reported by USGS and GCMT differ somewhat from the InSAR inversion results of this study, the SGC location is broadly consistent with our findings (Table 1; Figure 2), underscoring the critical role of dense near-field seismic networks in accurately resolving earthquake source parameters. Taken together, these results provide key geophysical constraints on the mechanics of blind reverse faulting and refine the seismotectonic framework of the Eastern Cordillera. For context, the 2023 Meta-Cundinamarca earthquake occurred within the eastern fault system as a reverse-faulting event (Table 1). Although no InSAR analyses are available, its focal mechanism indicates a source depth of ~10–20 km (Table 1), and the absence of reported surface rupture is consistent with failure on a blind reverse fault. In contrast, the 2008 Quetame earthquake displayed a right-lateral strike-slip mechanism, with rupture depths of 5–15 km, a rupture length of ~11 km, and an average slip of ~0.3 m, likewise without surface offset [2]. The 2008 event therefore primarily released shear strain parallel to the orogen, whereas the 2023 and 2025 events accommodated compressional shortening approximately perpendicular to the range. This juxtaposition indicates that regional strain in the Eastern Cordillera foreland belt is partitioned between strike-slip and reverse faulting, underscoring a composite deformation pattern characteristic of oblique convergence.

Using the optimal faults' slip distribution, forward simulations were performed for the Sentinel-1 and ALOS-2 InSAR observations. Figure 5 shows the observed coseismic surface deformation fields of the 2025 Paratebueno earthquake (left column), the simulated deformation fields generated from the optimal faults' slip distribution (middle column), and the corresponding residuals (right column). Panels (a1–a3) correspond to ALOS-2, (b1–b3) to DES Sentinel-1, and (c1–c3) to ASC Sentinel-1. The black dashed rectangles denote the surface projection of the modeled fault plane, and the red solid lines represent

the intersection of the fault plane's along-strike extension with the surface. The model simulations reproduce the main features of the InSAR observations for all three viewing geometries, including the characteristic uplift on the northwest side and subsidence on the southeast side of the fault. Quantitatively, we obtained a good agreement with an overall data misfit of ~ 2.5 cm (1.6 cm for ALOS-2 data, 2.5 cm for DES Sentinel-1, and 1.9 cm for ASC Sentinel-1), indicating that the inferred fault geometry and slip distribution provide a reasonable fit to the observed deformation, thus validating the reliability of the inversion results.

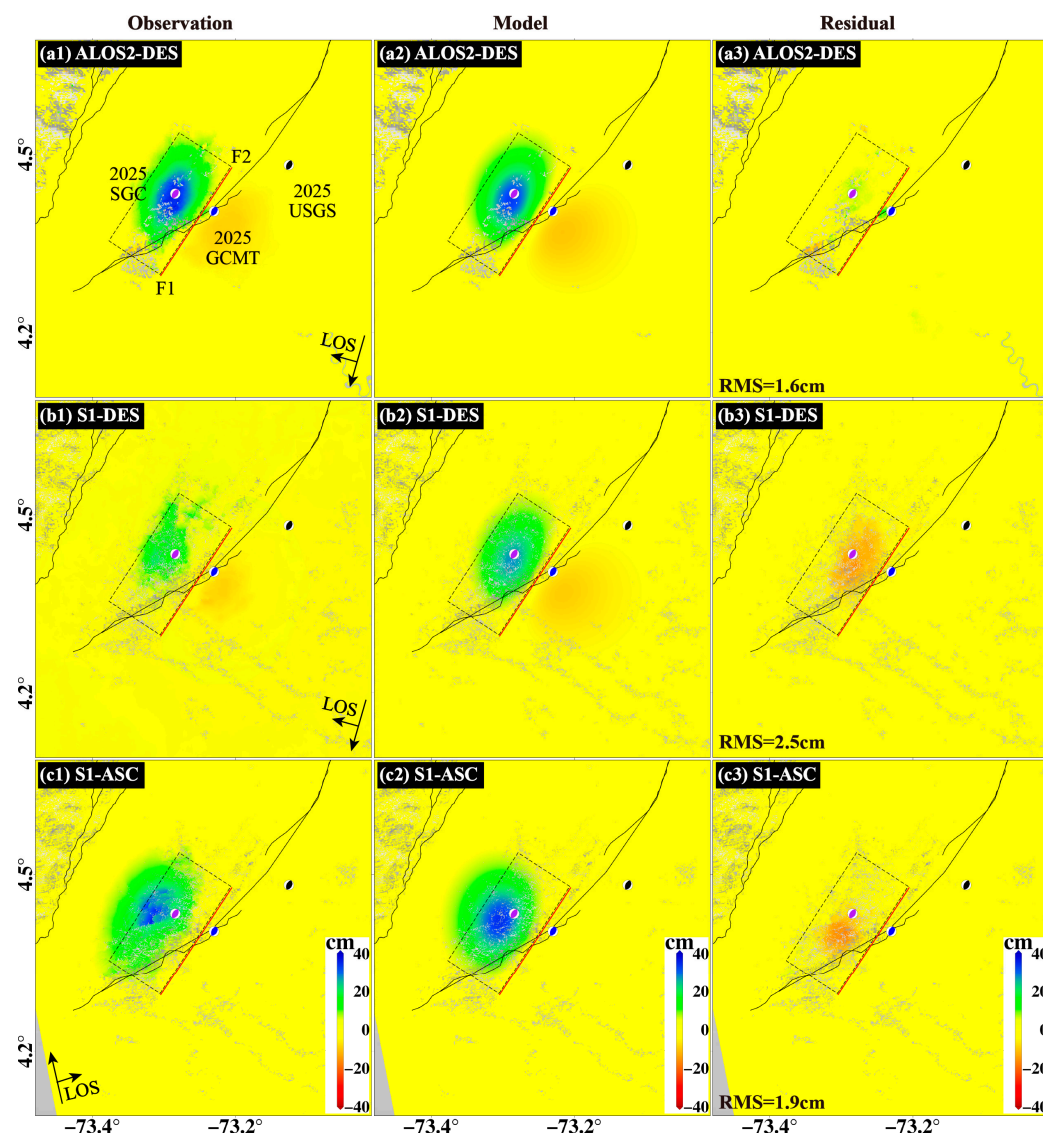


Figure 5. Observed (first column), modeled (second column) and residual (third column) coseismic deformation for 2025 Paratebueno earthquake from both ALOS-2 and Sentinel-1 tracks. Red lines (Labels F1 and F2) represent fault surface traces used in this study. (a1–a3) ALOS-2; (b1–b3) DES Sentinel-1; (c1–c3) ASC Sentinel-1.

Residual patterns reveal that larger misfits are concentrated in the near-field northwest of the fault. These residuals may be attributed to: (1) low interferometric coherence in the epicentral and near-field regions due to rugged topography and dense vegetation, particularly for C-band (Sentinel-1) data in tropical mountainous environments, which can cause fringe discontinuities and phase unwrapping errors; (2) simplifications in the fault geometry used in the inversion, which may not capture the full structural complexity of the fault; and (3) in the joint inversion, the more coherent L-band signals were balanced

against the noisier C-band data, leading to a slight overestimation of the forward-modeled Sentinel-1 deformation north of the fault and consequently to the larger residuals observed in Figure 5(b3,c3). This outcome highlights both the influence of wavelength differences on inversion performance and the complementary advantages of multi-source SAR datasets in regions characterized by rugged topography and dense vegetation. Specifically, the C-band demonstrates higher sensitivity to subtle deformation, whereas the L-band provides more robust constraints under conditions of large deformation gradients and reduced coherence. Collectively, these results emphasize the necessity of integrating multi-source SAR observations to achieve reliable and comprehensive earthquake source modeling.

5. Discussion

5.1. Thick-Skinned Characteristics of the 2025 Paratebueno Earthquake

In orogenic belts, thin-skinned and thick-skinned tectonics represent two fundamentally different deformation styles [34]. Thin-skinned deformation occurs primarily along décollement horizons within the sedimentary cover, where thrusting and folding affect only the upper sedimentary strata, leaving the crystalline basement largely undeformed [35]. In contrast, thick-skinned deformation penetrates into the crystalline basement, with reverse faults rooted in the basement producing basement-involved fault-bend folds, often associated with inversion of pre-existing normal faults [35,36]. In the Eastern Cordillera of the Colombian Andes, both thin- and thick-skinned structural styles are developed [37]. As a key segment of the Andean orogen, the Eastern Cordillera fold-and-thrust belt is controlled by far-field tectonic stresses arising from the complex interactions between the Caribbean, Nazca, and South American Plates [10]. The belt exhibits a double-vergent thrust geometry: east-vergent thrusts from the Central Cordillera on its western margin, and west-vergent thrusts from the Eastern Cordillera on its eastern margin. In the central portion, the Cretaceous-Tertiary sedimentary cover reaches 7–10 km in thickness, while crystalline basement is exposed at the northern and southern terminations [38,39].

A structural cross section across the Eastern Frontal Fault System (EFFS) (Figure 6) delineates a deformation architecture shaped by multiple tectonic episodes from the Cenozoic to the present. Prominent basement-involved thrusts root in the Paleozoic crystalline basement and propagate upward through the Cretaceous-Cenozoic sedimentary cover, linking to the surface trace via a subhorizontal décollement in the central part of the section. The section highlights basement-involved reverse faults within the EFFS generated by inversion of earlier normal faults [37,40,41]. The Servitá fault uplifts the crystalline basement; inversion faults of this type commonly form basement-cored anticlines (e.g., the Farallones anticline; Costantino et al., 2021 [37]). Bermúdez et al. (2024) further demonstrate that the Farallones anticline reflects inversion of the Servitá fault, confirming a basement-involved geometry [41]. The Guaicáramo fault system marks the frontal thrust boundary of the Eastern Cordillera, where the Guaicáramo fault acts as a basement shortcut thrust: it detaches within Lower Cretaceous shales, ramps upward through Upper Cretaceous strata, and daylights at the surface to generate fault-related folds within the Neogene foreland (Medina Basin). The Eastern Cordillera has undergone multiple episodes of extension and compression during its geological evolution. Mesozoic rifting produced a series of NE-trending basement normal faults and sedimentary troughs, which were later inverted during Cenozoic Andean compression, re-activating the normal faults as thrusts and uplifting the basement. Regional structural analysis suggests that the 2025 Paratebueno earthquake occurred on the Guaicáramo fault within the eastern frontal fault system of the Eastern Cordillera. This NE-SW striking, NW-dipping structure originated as a Mesozoic extensional basement fault and was re-activated as a thrust during Cenozoic orogenesis. Its footwall décollement is located near the base of the Lower Cretaceous, linking to the

surface trace via a horizontal décollement in the mid-section of the fault [42]. Seismological evidence also supports the seismic activity of deep basement-involved thrusts in this region; for instance, the 1917 Sumapaz and 1967 Neiva earthquakes originated on deep thrust faults within or along the eastern margin of the Eastern Cordillera [43].

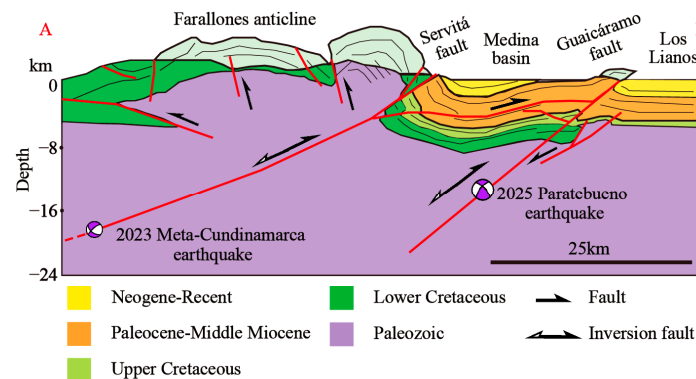


Figure 6. Structural cross section along the Eastern Frontal Fault System (the position of symbol AB is shown in Figure 1. Modified from Costantino et al., 2021 [37]).

Comparison of the hypocentral depth with the thickness of the sedimentary cover provides critical constraints on the tectonic nature of the rupture. Seismological data indicate a focal depth of 9–15 km for the 2025 Paratebuco earthquake (Table 1), with the SGC solution—most consistent with the InSAR-derived epicentral location—placing the depth at 15 km, significantly deeper than the 7–10 km sedimentary cover above the basal décollement in the study area. InSAR deformation fields show a cross-fault uplift–subsidence pattern without clear surface rupture, consistent with a blind fault whose slip is concentrated at depth. The preferred faults’ slip distribution from this study indicates reverse-dominated motion, with rupture extending to ~13 km depth and ~12 km along strike width, spanning from near-surface to mid-crust, cutting through the sedimentary cover and into the basement. In addition, the optimal dip angle of 58° (Table 1) suggests a relatively steep reverse fault, likely formed through the inversion of a normal fault reactivated during the Cenozoic.

Integrating focal depth estimates from multiple agencies, the InSAR-derived faults’ slip distribution, and regional geological and stratigraphic characteristics, we infer that the 2025 Paratebuco earthquake resulted from renewed activity on a thick-skinned pre-existing fault system. The rupture most likely occurred on the Guaicáramo fault or a related basement-involved reverse fault, penetrating the sedimentary cover and extending into the crystalline basement, consistent with the thick-skinned compressional regime along the eastern margin of the Eastern Cordillera. This tectonic setting not only refines our understanding of the seismotectonic characteristics of the eastern frontal fault system but also highlights the potential for deep-seated rupture on other thrust faults within the Colombian foreland fold-and-thrust belt. Such insights are essential for evaluating both the active tectonics and seismic hazards of the region.

5.2. Stress Triggering and Hazard Assessment

Large earthquakes significantly alter the stress state of the source region and surrounding faults, potentially delaying or promoting the failure of nearby active faults. Numerous studies have shown that earthquakes can interact through stress transfer [44,45]. To investigate this process in the 2025 Paratebuco earthquake and assess its impact on the Coulomb stress state of the surrounding region, we performed ΔCFS calculations using the Coulomb 3.3 software package [46,47]. In the calculations, we adopted a Poisson’s ratio of 0.25 and an effective friction coefficient of 0.4 [44,46,48].

The 2025 Paratebueno earthquake occurred only two years after the 2023 Meta-Cundinamarca earthquake, with their epicenters separated by ~50 km. It is therefore important to examine whether the former was influenced by the latter's stress perturbation. Using the GCMT focal mechanism for the 2023 Meta-Cundinamarca earthquake as the source fault and the InSAR-derived fault geometry for the 2025 Paratebueno earthquake as the receiver fault, the results (Figure 7) show that the entire 2025 rupture plane lies within a region of positive Δ CFS induced by the 2023 Meta-Cundinamarca earthquake with the whole fault experiencing stress loading. However, the magnitude of the stress change is relatively small (<0.1 bar, or 10 kPa). This finding suggests that the 2023 earthquake may have facilitated the occurrence of the 2025 event, although the overall effect was limited due to the low absolute stress-change values.

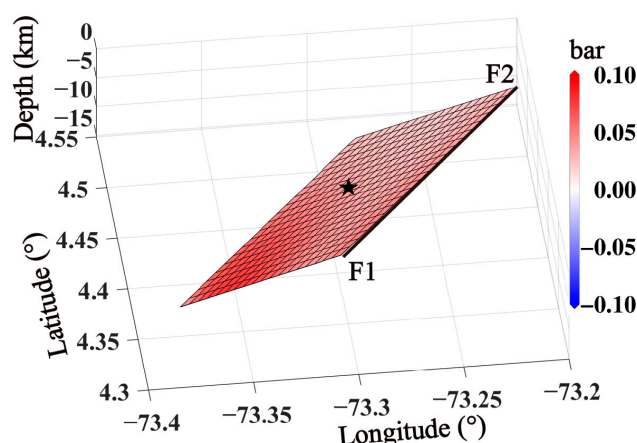


Figure 7. Static Coulomb failure stress changes on the 2025 Paratebueno earthquake fault plane induced by the 2023 Meta-Cundinamarca earthquake. Black star is the epicenter of the 2025 Paratebueno earthquake. Black line (Labels F1 and F2) represents fault surface traces used in this study. Note: Positive (red) suggests the stress accumulation in the area whilst negative (blue) indicates that there is a decrease in the stress along a specific fault.

From a tectonic perspective, the Guaicáramo fault lies within the frontal fold-and-thrust belt along the eastern margin of the Eastern Cordillera, with a strike generally aligned with the maximum compressive stress axis of the 2023 event [7,8]. Such a fault geometry is favorable for stress transfer along the regional plate boundary. Under the stress regime of a double-vergent thrust system, this positive stress loading may have accelerated the failure of the fault segment on a short timescale [10]. This finding indicates that stress transfer and fault interactions are important mechanisms controlling the spatiotemporal distribution of earthquakes in complex orogenic belts. It should be noted that, in addition to static stress transfer, fluid-mediated stress changes can play a critical role in short-term earthquake triggering, with diffusion-related perturbations typically occurring on timescales of hours to months and propagating over distances of several to tens of kilometers [49–51]. However, in this study, the ~2-year temporal gap and ~50 km spatial separation between the 2023 Meta-Cundinamarca and 2025 Paratebueno earthquakes make it unlikely that fluid migration alone could explain a direct triggering relationship.

We also evaluated the static Δ CFS imparted by the 2023 Meta-Cundinamarca earthquake and 2025 Paratebueno earthquake to nearby faults to assess future seismic hazard. Using the GCMT focal mechanism of the 2023 Meta-Cundinamarca earthquake and the InSAR-derived optimal slip distribution of the 2025 event (Figure 4) as source faults, and assuming receiver fault parameters of strike 213° , dip 58° , and rake 103° , the Δ CFS was calculated at a depth of 10 km, which corresponds to the main coseismic slip concentration observed between 8 and 12 km depth. The result (Figure 8) shows that stress was primarily

transferred toward both ends of the rupture and to the southeast. The spatial distribution indicates that positive stress is concentrated at the southwestern and southeastern ends of the rupture (Zones I and II). This pattern reflects significant stress transfer toward the rupture terminations, where ΔCFS commonly exceeds 0.5 bar, with local peaks approaching ~1 bar. Along the southeastern extension, ΔCFS gradually decays and falls below 0.3 bar. In contrast, negative stress is primarily distributed in the northwestern part of the rupture (Zones III and IV), forming a pronounced stress shadow with average values of approximately -0.8 bar, which progressively diminishes outward to a weak shadow zone of -0.1 to 0 bar. These results indicate that Zones I and II warrant heightened attention in future seismic risk assessments. We quantified static stress interactions by computing ΔCFS imparted by the 2023 Meta-Cundinamarca and 2025 Paratebueno earthquakes on adjacent faults—an established, independently informative metric for evaluating stress transfer and potential triggering [44]. While our ΔCFS analysis focuses on elastic static effects, it does not preclude fluid-mediated processes; integrating regional hydrological observations in future work will be important for testing fluid-triggering hypotheses and refining our understanding of earthquake initiation in this tectonically complex region. In summary, seismic hazard assessment is a complex and systematic undertaking. Our analysis of static ΔCFS offers an independent and critical basis for seismic hazard evaluation and provides important insights into potential earthquake risks.

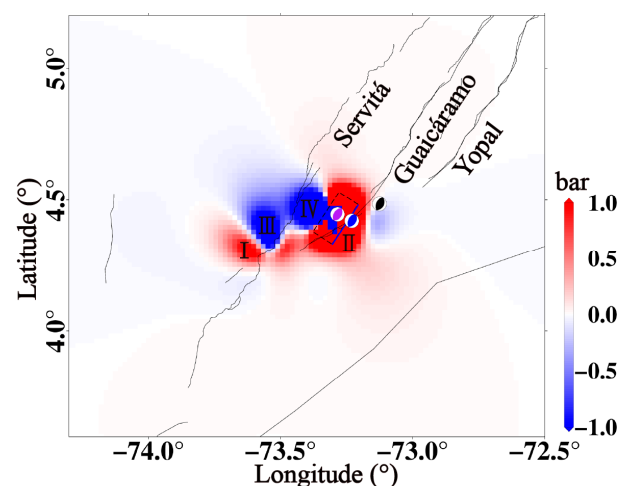


Figure 8. Static Coulomb failure stress changes in surrounding faults and regions caused by 2023 Meta-Cundinamarca earthquake and the 2025 Paratebueno earthquake. Note: Positive (red) suggests the stress accumulation in the area whilst negative (blue) indicates that there is a decrease in the stress along a specific fault. Zones I and II mark the positive ΔCFS lobes, whereas Zones III and IV represent the negative ΔCFS lobes.

6. Conclusions

Using multi-source Sentinel-1 and ALOS-2 InSAR data, we conducted a systematic investigation of the coseismic rupture characteristics and tectonic setting of the 2025 Paratebueno earthquake. The main conclusions are as follows:

1. We obtained high-resolution coseismic deformation fields for the 2025 Mw 6.4 Paratebueno earthquake, revealing a reverse-faulting pattern with pronounced uplift on the northwestern hanging wall and subsidence on the southeastern footwall.
2. Elastic half-space dislocation modeling constrained the causative fault to strike $\sim 213^\circ$ and dip 58° , with a maximum slip of ~ 5 m concentrated at depths of 8–12 km. The resulting seismic moment corresponds to Mw 6.4, consistent with independent seismological solutions, and the absence of surface rupture indicates a blind reverse source with predominantly reverse motion and a minor right-lateral strike-slip component.

3. The focal depth, significantly exceeding the sedimentary cover thickness above the basal décollement, together with the InSAR-derived slip distribution and regional geological context, indicates that the rupture penetrated the crystalline basement, reactivating a Mesozoic extensional fault—most plausibly the southern segment of the Guaicáramo fault—during ongoing Cenozoic compression, thus reflecting a thick-skinned reverse fault rupture propagating up-dip to fold-and-thrust belt.

4. Static Coulomb failure stress change modeling suggests that the 2023 Mw 6.2 Meta-Cundinamarca earthquake imparted the positive ΔCFS to the 2025 rupture plane, plausibly promoting its failure, emphasizing the role of stress transfer and fault interaction in controlling earthquake occurrence in foreland reverse systems. The 2023 event and 2025 event increased ΔCFS along its southeastern extension, particularly on Zones I and II, implying elevated seismic hazard in these areas and the need for enhanced monitoring and regional seismic risk mitigation.

This study indicates the capability and value of integrating multi-source InSAR to overcome coherence limitations in densely vegetated and rugged terrain, enabling accurate characterization of blind reverse ruptures and robust constraint of earthquake source mechanisms in complex orogenic settings. We provide the first geodetic observations and slip-inversion results that directly document basement-involved inversion within the thick-skinned structural regime of the Eastern Cordillera fold-and-thrust belt. These findings advance understanding of ongoing orogenic processes, refine the regional seismotectonic framework, and furnish a physics-based foundation for enhanced seismic-hazard assessment.

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Conflicts of Interest: The authors declare no conflicts of interest.

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