

# **Interplay of slow-slip faults beneath Mexico City induces intense seismicity over months**

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1 **Abstract**

2

3 In February 2023, a long seismic sequence began in western Mexico City causing widespread panic  
4 and some damage to housing infrastructure. On May 11 and December 14, two Mw3.2 mainshocks  
5 occurred at less than 700 m depth. Unprecedented satellite interferograms captured tectonic  
6 deformations in the two epicentral zones during the days surrounding the earthquakes. Data  
7 analysis revealed extended slip with maximum values around 8 cm on two sub-parallel east-west  
8 trending normal faults 800 m apart: namely the Barranca del Muerto (BM) fault to the south and  
9 the Mixcoac fault to the north. Detailed microseismicity analysis showed that 95% of the slip on  
10 the BM fault was aseismic and initiated at least 6 days before the May 11 earthquake on the main  
11 asperity, located 1 km east of the hypocenter and  $\sim 1.2$  km deep. For the December event on the  
12 Mixcoac fault,  $\sim 70\%$  of the slip was also aseismic but shallower (mostly above 600 m), which can  
13 be partially explained by the induced stresses on that fault due to the May slip on the BM fault. A  
14 quantitative geomorphological analysis allowed to establish the structural connection between both  
15 buried faults and their geomorphic expression to the west, with surface extensions of  $\sim 3.5$  and  $\sim 4.5$   
16 km in the hilly area—where the most intense seismicity concentrates. The spatiotemporal patterns  
17 of fast and slow earthquakes suggest that the seismotectonics west of the city comprises two  
18 mechanically distinct zones: a stable region prone to aseismic deformation to the east where faults  
19 are buried under water-rich sediments, and an unstable region to the west, prone to seismic radiation  
20 where faults are expressed geomorphologically. Thus, the seismic swarms in this area appear to  
21 result from the regional extensional regime, the stresses induced by slow slip on the eastern fault  
22 segments and interaction between these faults.

## 23 1. Introduction

24  
25 It is well known that Mexico City, one of the world's most populated areas, is at great risk from  
26 earthquakes. Largely settled on ancient lake-bed sediments, the city experiences an amplification  
27 of seismic waves and a duration of strong motions that are among the largest known (Chávez-  
28 García & Bard, 1994; Cruz-Atienza et al., 2016; Ordaz & Singh, 1992; Reinoso & Ordaz, 1999;  
29 Singh et al., 1995). Subduction events such as the 1985 earthquake more than 300 km away (Singh  
30 et al., 1988), and intraslab ruptures like the 2017 earthquake 115 km south (Mirwald et al., 2019;  
31 Singh et al., 2018), have killed thousands of people and severely damaged local infrastructure.  
32 Although these two types of events are the most common in Mexico, they are not the only ones  
33 threatening the country's capital. The Valley of Mexico is located in the Trans-Mexican Volcanic  
34 Belt (TMVB) where shallow crustal earthquakes with high intensities have occurred in the past.  
35 Two examples from the last century are the 1912 Acambay earthquake ( $M_w6.9$ ) 80 km northwest  
36 of Mexico City, and the 1920 Xalapa earthquake ( $M\sim 6.4$ ) 200 km to the east that killed at least 647  
37 local people (Córdoba-Montiel et al., 2018; Flores & Camacho, 1922; Lacan et al., 2021; León-  
38 Loya et al., 2023; Urbina & Camacho, 1913). Pre-instrumental historical earthquakes have also  
39 been identified in the TMVB as having a significant hazard to society despite their large return  
40 periods (Bayona et al., 2017; Suárez et al., 2019, 2020).

41  
42 Resulting from a transtensional stress regime, the faults that originate the TMVB crustal  
43 earthquakes have a preferential east-west and north-south orientation (Arce et al., 2019; Ferrari et  
44 al., 2012; Mooser, 1972; Suter et al., 1992). In the Valley of Mexico, which is in the south-central  
45 part of the TMVB (Figure 1), although historically of small magnitude ( $M < 4$ ), these earthquakes  
46 can be intense in the epicentral zone. Most occur in the foothills of the Sierra de las Cruces to the  
47 west of Mexico City (see Quintanar et al., 2024) and manifest as seismic swarm sequences  
48 (Figueroa, 1971; Manzanilla, 1986; L Quintanar et al., 2024; Singh et al., 2020). Among the best  
49 studied are the 1981 swarm with an  $M_L3.3$  mainshock (Havskov, 1982) and the 2019 swarm whose  
50  $M_w3.2$  mainshock produced the highest peak ground acceleration ever recorded on bedrock of the  
51 city (Singh et al., 2020) and panic among the citizens (Figure 1). In fact, this 2019 shock prompted  
52 the capital's authorities to unify the five seismic networks of the Valley of Mexico and its  
53 surroundings to create the Mexico City Seismic Network (MCSN), with more than 170

54 ultrasensitive (broadband) and strong motion seismic stations including borehole sites (Aguirre et  
55 al., 2021).

56  
57 The underlying processes of local seismic swarms have been studied in different tectonic contexts.  
58 Swarm evolution is often thought to be governed by surrounding aseismic processes induced by  
59 fluid diffusion (Eyre et al., 2022). Transient aseismic fault slip in the form of shallow slow slip  
60 events can increase shear stress on the neighboring fault system and has been associated with  
61 seismic swarms along continental fault systems (Gualandi et al., 2017; Y. Jiang et al., 2022; R. B.  
62 Lohman & McGuire, 2007; Sirorattanakul et al., 2022). Besides, there is growing evidence that  
63 slow-slip phenomena are the driving process inducing intense seismicity where underground fluid  
64 diffusion is enhanced by injection wells (Cappa et al., 2019; Ge & Saar, 2022; Guglielmi et al.,  
65 2015; Laroche et al., 2021), and where advanced InSAR imaging has been critical to characterize  
66 the associated surface deformation (Eyre et al., 2022; Pepin et al., 2022; Srijayanthi et al., 2022).  
67 In those cases where seismic swarms are accompanied by slow slip, the seismic moment  
68 accumulated by the seismicity is only a small fraction (<10%) of the geodetically determined  
69 seismic moment released in the fault system (G. Jiang et al., 2015; Y. Jiang et al., 2022; Pepin et  
70 al., 2022; Wicks et al., 2011).

71  
72 The Valley of Mexico basin is subject to massive groundwater extraction to meet ~50% of the  
73 needs of more than 9 million people. This translates into one of the highest ground subsidence rates  
74 in the world (i.e., up to 500 mm/year) (Cabral-Cano et al., 2008; Chaussard et al., 2021; López-  
75 Quiroz et al., 2009; Ortega-Guerrero et al., 1999). Such subtraction of groundwater produces pore  
76 pressure gradients and, therefore, a sustained underground fluid diffusion structurally conditioned  
77 by local fracture systems that may preferentially induce normal faulting (Foulger et al., 2018;  
78 Moein et al., 2023; Segall, 1989).

79  
80 On May 11, 2023, an Mw3.2 local earthquake (700 m depth) occurred in the west part of the city  
81 (Figure 1), producing strong intensities in the epicentral zone (L Quintanar et al., 2024). This  
82 earthquake was the largest of a seismic swarm that began in February about 5 km south of the 2019  
83 crisis, and less than 2 km from the 1981 swarm (Figure 1). Seven months later, on December 14, a  
84 similar Mw3.2 event (500 m depth) occurred 1 km north accompanied by preceding and subsequent

85 earthquakes until at least May 2024. Ground shaking again caused great concern among the  
86 population and some damage to buildings near the epicenter. In the following days, the national  
87 media even reported fracture alignments in nearby streets.

88  
89 Based on unprecedented satellite interferograms and detailed analysis of both microseismicity and  
90 local terrain geomorphology, in this work we explore the origin of local seismicity and show that  
91 two north-facing normal faults below the western part of Mexico City experiencing slow aseismic  
92 slip played an important role throughout the months-long seismic crisis of 2023 and 2024.

93

## 94 **2. Results**

95

### 96 **2.1. Geomorphology of the West Bank of Mexico City**

97

98 Outcrops displaying current or historical geological structures evidencing normal faulting atop the  
99 2023-2024 seismic sequence, which occurred in a relatively flat area, are virtually nonexistent.  
100 Hypocentral locations reported by Quintanar et al. (2024) indicate that seismicity occurs at shallow  
101 depths (<1.5 km). However, the active faults are buried beneath Quaternary sediments  
102 corresponding to the transition from rocky hills to clay-rich lake-bed deposits. Consequently, there  
103 is little to no evidence of event-related scarps formed along these faults visible on the surface (i.e.,  
104 they are blind faults), also because they are beneath a heavily urbanized area where any unaltered  
105 paleo-scarps were likely leveled for construction erasing any direct evidence of displacements  
106 along these faults.

107

108 Less-urbanized hilly areas in the western bank of the city, just a few hundred meters west of the  
109 2023-2024 seismic sequences, have been the focus of various regional studies, as they provide a  
110 more suitable setting for finding evidence of historical faulting (e.g., Vásquez et al., 2021). These  
111 hilly areas show evidence of soil erosion due to the action of running water. Although detailed  
112 geological mapping is limited, SW-NE normal faulting has been reported, supported by the  
113 interpretation of stereographic pairs of aerial photographs (Arce et al., 2015). Focal mechanism  
114 interpretations of comprehensive seismological records roughly align with the orientation of photo-  
115 interpreted fault scarps (Havskov, 1982; Lermo et al., 2016; L Quintanar et al., 2024; Singh et al.,

116 2020). However, orientations provided by these interpretations are somewhat imprecise, and  
117 orientation solutions provided by focal mechanisms prior to the gradual installation of the  
118 broadband seismic network “Red Sísmica del Valle de Mexico” of the Mexican Seismological  
119 Service (SSN) (Luis Quintanar et al., 2018) are limited as well.

120  
121 “Slope” is a term used in two contexts. The first refers to the steepness of any surface, while the  
122 second refers to a specific landform element. Slopes are fundamental landforms characterized by  
123 inclined surfaces that connect higher and lower elevations. We utilize abundant data from a high-  
124 resolution digital elevation model (DEM) to conduct a robust and straightforward analysis of slope  
125 orientation and steepness in the hilly sector west of the earthquake sequence. Given that erosion  
126 rates are lower than the tectonic processes associated with normal faulting in the area, the wealth  
127 of data available from the DEM can capture any statistical tendencies of the preferential directions  
128 of slopes that, as we shall demonstrate later, are produced by normal faulting. Our analysis relies  
129 on a lidar-derived high-resolution (5m pixel-size) digital terrain model (DTM) (Instituto Nacional  
130 de Estadística y Geografía, 2024). We conduct our analysis in three main steps as described below.

131  
132 In the first step, we calculate the orientation and steepness of the landscape slopes in the area using  
133 the Aspect and Slope workflows available in QGIS 3.12.1 (QGIS Project, 2024). Aspect calculates  
134 the relief’s azimuth measured clockwise from true north, indicating the direction towards which  
135 the topography faces, whereas Slope calculates the steepness of the topography measured from a  
136 horizontal plane. With these two calculations, we obtain the orientations and steepness of all pixels  
137 in the area, which range from  $0^\circ$  to  $360^\circ$  and  $0^\circ$  to  $90^\circ$ , respectively. However, to proceed with our  
138 analysis, we need to distinguish landscape slopes from other landforms (e.g., valleys, ridges, spurs,  
139 etc.) and anthropogenic structures captured by the DTM.

140  
141 In the second step, we apply a classification algorithm to identify landforms in our study area,  
142 allowing us to discriminate landscape slopes. We use a texture-based pattern recognition approach,  
143 which exploits the concept of geomorphologic phenotypes, or geomorphons, to classify landforms  
144 (Stepinski & Jasiewicz, 2011). Geomorphons allow a systematic treatment of pixel neighborhoods  
145 to identify terrain features using DEMs, leading to precise and adaptable mapping of landforms  
146 (Jasiewicz & Stepinski, 2013). We use the geomorphons workflow developed by Stepinski and

147 Jasiewicz (2011) and implemented in GRASS (GRASS Development Team, 2022). To retain the  
148 fine details available from the high-resolution DTM, we use a search distance of 3 pixels and an  
149 angle tolerance of 4 degrees. Finally, we produce a mask to identify pixels classified as landscape  
150 slopes. The orientation (aspect) of these pixels (i.e., the orientation of slopes) is shown in Figure 1  
151 with background colors.

152  
153 In the third step of our analysis, we use the mask of landscape slopes on the orientation and  
154 steepness layers to perform a pixel-wise statistical analysis of the orientation and steepness of the  
155 landforms classified as slopes (inset histograms in Figure 1).

156  
157 From the map of terrain orientation (Figure 1), we observe that landscape slopes predominantly  
158 face toward the NW and SE quadrants. This observation aligns with previously reported NE-SW  
159 alignments of photo-interpreted fault traces and focal mechanism analyses (Arce et al., 2019). The  
160 frequency analysis of slope orientation (inset panel a in Figure 1) indicates that slopes are primarily  
161 oriented towards the SE in a subregion west of the 2023 earthquakes and the two normal faults  
162 identified later in this study (dashed rectangle box). The distribution of steepness per class, shown  
163 in color within the petals, reveals that most slopes have an inclination of less than  $20^\circ$  (inset panel  
164 a). However, a focused analysis of slopes with a steepness greater than  $20^\circ$  (inset panel b) shows a  
165 dominant, well-defined modal class oriented towards the N-NW, which is consistent with the dip  
166 directions of the two normal faults (green arrows, inset panel b). As we will justify later when  
167 modeling unprecedented satellite images of the ground deformation, we interpret these landscape  
168 slopes as a surficial manifestation of faults tectonic activity. We infer that the prevalence of slopes  
169 with steepness lower than  $20^\circ$  is due to erosion, while slopes greater than  $20^\circ$  represent more recent,  
170 less-eroded parallel and subparallel fault scarps.

171

## 172 **2.2. Tectonic-Related InSAR Deformations**

173 The systematic search for ground displacements in Mexico City has long been the aim of different  
174 groups, mainly to assess the well-known land subsidence at scales both regional (Cabral-Cano et  
175 al., 2008; Chaussard et al., 2021; López-Quiroz et al., 2009; Osmanoglu et al., 2011) and local  
176 (Solano-Rojas et al., 2020). Our current understanding of this phenomenon on a local scale comes  
177 mainly from the analysis of satellite radar interferometry, which can identify the large ground

178 displacements (up to 500 mm/yr) resulting from subsidence due to aggressive groundwater  
179 extraction (Khorrami et al., 2023). However, as mentioned earlier, the Valley of Mexico lies in the  
180 TMVB (Figure 1), a tectonically active region where shallow, potentially harmful earthquakes  
181 occur (Suárez et al., 2019, 2020). Local seismicity in Mexico City has been studied since 1909  
182 (Figueroa, 1971) with magnitudes of less than 4. As the earthquakes are relatively small, the  
183 associated surface deformations have been likely neglectable or even masked by subsidence, until  
184 now. As a result of a systematic search in Mexico for earthquake-related signals using Sentinel-1  
185 satellite SAR images, in the following we present the first evidence of two tectonic-related signals  
186 found in the very heart of the city, which occurred in May and December 2023 during a long-lasting  
187 seismic crisis.

188 Satellite Interferometric SAR (InSAR) has enabled the observation of ground displacements across  
189 a variety of spatial and temporal scales (Elliott et al., 2016). This technique has allowed observing  
190 surface deformation due to interplate earthquakes producing displacement signals with amplitudes  
191 of tens of centimeters and kilometer-long wavelengths (e.g., (Villafuerte et al., 2022; Wen et al.,  
192 2021). InSAR has also been used to observe signals from smaller magnitude interplate earthquakes,  
193 such as the 1992-2022 Zagros (southern Iran) earthquakes with  $M_w > 4.5$  and depths as shallow as  
194 0.7 km, showing amplitudes of  $\sim 2$  cm using ERS-1 and 2 C-band satellites (Rowena B. Lohman &  
195 Simons, 2005). Reportedly, the long temporal baselines available at that time impeded precise  
196 dating of earthquakes and induced decorrelation, hindering the observation of signals from shallow,  
197 lower-magnitude earthquakes in the region (Lohman & Simons, 2005). No-tectonic events have  
198 shown the potential of short temporal baselines (12 days) available from Sentinel-1 to observe  
199 cumulative displacement signals like such in Jamnagar, India, where a rainfall-related swarm of 76  
200 microearthquakes, over 70% of which were magnitude  $< 3$  with depths  $< 5$  km, produced signals  
201 with amplitudes of  $\sim 2$  cm (Srijayanthi et al., 2022). We therefore profit from the short revisit time  
202 available from the Sentinel-1 mission to conduct an analysis to constrain in time and space any  
203 earthquake-related signals in Mexico City.

204  
205 We first focus on the May 11 and December 14, 2023, earthquakes, selecting pairs of Sentinel-1  
206 SAR scenes to produce interferograms with the shortest possible temporal baselines  
207 (Supplementary Figure S1). To produce the interferograms, we use the InSAR Scientific  
208 Computing Environment (ISCE) (Rosen et al., 2012), applying multilooking to achieve a pixel size



209 of ~30 m and performing a topographic phase correction using a 30 m SRTM DEM (Farr et al.,  
210 2007). For the May 11 event, we use scenes acquired on May 9 and May 21 in ascending orbit, and  
211 on May 6 and 18 in descending orbit. For the December 14 event, we use scenes acquired on  
212 December 8 and 20 in ascending orbit, and on December 11 and 23 in descending orbit (middle  
213 column of Supplementary Figure S1).

214 Although atmospheric noise is present in the May ascending orbit interferogram, we indeed observe  
215 signals typically related to normal faulting in all the interferograms (Figure 2, left column). To  
216 ensure the co-seismic interferograms accurately depict signals constrained in time and are not a  
217 result of regional subsidence, or merely topography-related atmospheric noise, we calculate two  
218 pre-seismic and two post-seismic 12-day interferograms for each event and orbit (first two and last  
219 two columns in Figure S1). We confirm that the signals observed in the co-seismic interferograms  
220 are absent in the pre- and post-seismic interferograms, although atmospheric noise persists in the  
221 May ascending orbit post-seismic interferograms. We additionally observe that the orientation of  
222 the signals we found align quite well with the morphology orientations we determined in the  
223 previous section (compare Figure 1 with Figure 2). We, thus, obtain one interferogram with a clear  
224 co-seismic signal for May, and two for December.

225 We perform an additional examination of the ascending orbit December interferograms to further  
226 constrain the timing of the co-seismic signal (Figure S2). We produce a 24-day interferogram using  
227 scenes acquired from November 12 to December 23. Figure S2 (panels a,c versus b,d) presents the  
228 wrapped and unwrapped phases of this 24-day interferogram alongside the corresponding phases  
229 from the previously obtained 12-day ascending orbit interferogram using scenes from December  
230 11 and 23. We then obtain the difference between the two unwrapped interferograms to produce  
231 Figure S2e. Since both interferograms share the December 23 scene, any residuals would represent  
232 a signal originating between November 12 and December 11. We find, however, a negligible  
233 residual between the two interferograms, indicating no evidence of deformation before December  
234 11, i.e., three days prior to the mainshock of December 14.

235 At this point, we have established that co-seismic signals can be observed in the 12-day  
236 interferograms generated for the Mw3.2 May and December 2023 shallow earthquakes. To ensure  
237 comprehensive coverage of relevant signals for our study, we used the SSN event catalog (“SSN  
238 Catálogo de Sismos UNAM”, 2023) to search for displacements related to similar shallow, small

239 magnitude ( $M_w < 3.5$ ) intraplate earthquakes occurring in the last six years within the city,  
240 including an  $M_w 3.2$  earthquake of July 2019 (Figure 1) (Singh et al., 2020). We present the  
241 resulting 6-day and 12-day co-seismic interferograms corresponding to the reported event in Figure  
242 S3. No additional signals indicating earthquake-related co-seismic deformation were observed.  
243 Several factors may contribute to this observation: atmospheric noise present in several  
244 interferograms, uncertain earthquake magnitudes, underestimated depths, and potentially thicker  
245 clay-rich deposits where the inspected earthquakes occurred compared to the May and December  
246 2023 earthquakes, which were in transition areas with thinner overlaying sedimentary deposits.

247 We thus proceed with the three coseismic interferograms we obtained, where signals are observed.  
248 Due to the abundance of data available from the interferograms, and as an additional measure to  
249 reduce high-frequency noise in the recovered signal, some downsampling is in order. For  
250 downsampling the data, we used the saliency-based quadtree algorithm (SQS) (Gao et al., 2021),  
251 a convenient technique allowing to reduce the data volume while preserving significant  
252 information. Saliency is a property of any image that reflects the relevance of the information to  
253 the human eye, which makes it a powerful mean to identify surface deformations with respect to  
254 its surroundings (Gao et al., 2021). This parameter helps to differentiate between the near-field  
255 (i.e., the deformation zone) and far-field (i.e., the areas unaffected by faulting). While regions with  
256 higher saliency values (indicating more significant deformation) are selected for denser sampling,  
257 the regions with lower saliency values are sampled sparsely or even excluded. We present the  
258 corresponding Saliency values obtained for the three coseismic interferograms in question (Figure  
259 S4), which are used to determine the density of the quadtree data sampling. The right column of  
260 Figure 2 presents the resampled interferograms for the May and December 2024 events, which will  
261 then be used to determine the faults that gave rise to surface displacement signals.

262

### 263 **2.3. Faults Mechanism and Location**

264

265 The study region lies in the foothills of the “Sierra de las Cruces” mountain range. According to  
266 Arce et al. (2019), the fault system that dominates this region has a NE-SW strike direction. The  
267 detailed geomorphological analysis of Section 2.1 indicates that topographic slopes facing north  
268 have dominant trend around  $252 \pm 15^\circ$  (derived from the inset of Figure 1) west of the 2023  
269 earthquakes, which is close to the normal fault mechanism determined by Quintanar et al. (2024)

270 for the Mw3.2 earthquake of May 11, with strike of  $270^\circ$ . However, a visual inspection of the May  
271 interferogram (Figure 2a) suggests that the polarity reversal contour is closer to the topographic  
272 trend found statistically, as it is also visible in the December interferograms (Figure 2b-c).

273  
274 Determining the location and mechanism of the faults responsible for the observed ground  
275 deformation is essential to retrieve the associated slip distributions reliably. For this reason, we  
276 performed a robust and comprehensive analysis of the InSAR data based on a fault model with the  
277 minimum number of parameters possible. The aim is to explain the data from a simple circular  
278 dislocation as well as possible. The problem reduces then to determining the direction of the slip  
279 in space (i.e., strike, dip, and rake angles), the fault center position (i.e., latitude, longitude, and  
280 depth), the circle parameters (the radius and its along-dip fault position), and a factor that scales  
281 the slip. This means a source model with nine parameters. Since the fault cannot extend to the  
282 surface due to limitations of our model, given 100 m long square sub-elements, the fault dimension  
283 is automatically adjusted during the inversion procedure explained below, so that it is truncated as  
284 close to the surface as possible. Figure S5 illustrates the model geometry. The slip distribution on  
285 the circular patch is dictated by a centered ellipsoidal function whose semiaxis is adapted  
286 automatically so that the slip is negligible at the perimeter of the source. To estimate the LOS  
287 displacements at the surface from a given slip model, we used the Okada (1985) formulation for a  
288 homogeneous half-space.

289  
290 The crustal structure below the Valle of Mexico is characterized by a  $\sim 2$  km thick uppermost layer  
291 with shear wave speed around 1.5 km/s that correspond to the southernmost part of the Mexican  
292 Volcanic Belt (Cruz-Atienza et al., 2010). This heterogeneous geologic unit consists of a series of  
293 andesites and volcanic tuffs intermixed with sands, shales, sandstones, lacustrine limestones,  
294 breccias, and conglomerates. Our study area extends over a soil transition composed of alluvial and  
295 clay deposits, so the elastic properties we adopted for the whole study are  $V_P = 2,785$  m/s,  $V_S =$   
296  $1,608$  m/s, and  $\rho = 2,200$  kg/m<sup>3</sup>, which were taken from a local tomography derived from the joint  
297 inversion of receiver functions and surface waves dispersion curves (Aguilar-Velázquez et al.,  
298 2023; 2024).

299

300 To find the fault model optimal parameters, we applied a Simulated Annealing (SA) method  
301 (Corana et al., 1987) that minimizes the mean absolute percentage difference between the observed  
302 and synthetic LOS displacements following the quad-tree data sampling introduced in Section 2.2.  
303 Unlike the May event where only one interferogram is available (Figure 2a), the December event  
304 was modeled from the joint inversion of two LOS components (Figures 2b and 2c).

305  
306 We conducted 54 independent optimizations per event, each with 125 iterations. The algorithm by  
307 Corana et al. (1987) involves multiple explorations per parameter and per iteration, so we set the  
308 algorithm to do 10 explorations. This resulted in a total of 607,500 explored models per event that  
309 were combined for the analysis. Figure 3 illustrates the convergence of the most relevant model  
310 parameters for the May (blue curves) and December (green curves) events, where the solid lines  
311 depict the median values, the colored regions indicate the range from the first to the third quartile,  
312 and the dashed lines correspond to the optimal models.

313  
314 Overall, the inversions of both events converged on two steeply dipping east-west trending normal  
315 faults that are consistent with each other (see Tables 1 and S1) and with the moment tensor  
316 inversions of local earthquakes (L Quintanar et al., 2024; Singh et al., 2020). After careful  
317 consideration including the geological literature, we will refer to these faults hereafter as the  
318 Barranca del Muerto (BM) fault to the south and the Mixcoac fault to the north (Figure 1). The  
319 optimal strikes found of  $256^\circ$  and  $265^\circ$  for the BM and Mixcoac faults (Table 1), respectively, are  
320 also consistent with the  $252 \pm 15^\circ$  trend determined statistically from our independent  
321 geomorphological analysis in Section 2.1 (Figure 1). As expected, the joint inversion of two LOS  
322 components for the December event converged better than for the May event, where the  
323 interquartile ranges for some parameters remained relatively wide (e.g., the rake angle). Since the  
324 May event is less constrained, the misfit function was minimized much faster and the optimal  
325 model parameters are in some cases outside the interquartile ranges. Fault locations on the other  
326 hand converged rapidly in both cases (i.e., after  $\sim 15$  iterations). Figures S6, S7 and S8 show the  
327 optimal fault solutions, reported in Table 1, together with the data misfits for the three  
328 interferograms concerned that we adopted to perform the detailed slip inversions in the next  
329 section.

330

## 331        **2.4. Slip Inversion from InSAR Data**

332  
333 From the exercise above, we constrained the most relevant fault parameters: the fault mechanism  
334 and location. For that purpose, we used an inversion strategy that explains the broad features of the  
335 InSAR data based on simple slip models. In this section, we adopt those optimal fault attributes  
336 (Table S1) to perform a detailed slip inversion of both events using the ELastostatic ADjoint  
337 INversion (ELADIN) method (Tago et al., 2021), a recently developed strategy that honors  
338 physically consistent restrictions (i.e., rake angle and von Karman slip distributions) via a gradient  
339 projection method.

340  
341 The faults were discretized with 100 m length square subfaults and the inversions performed  
342 assuming a von Karman correlation length of 200 m. In both faults, the rake angle could vary about  
343 20% from the optimal value. Since the Okada (1985) model used to generate the Somigliana  
344 Green's functions does not allow the fault to reach the free surface, the tops of the shallowest  
345 subfaults lie around 30 m below the surface. To assess the inverse problem resolution, Figures S9  
346 and S10 show the mobile checkerboard (MOC) tests (Tago et al., 2021) for the BM and Mixcoac  
347 faults, respectively. The tests reported correspond approximately to the minimum-resolvable  
348 asperity size in each case, which is 900 m for the May event, where only one interferogram is  
349 available (Figure 2a), and 600 m for the December event, where two LOS displacement  
350 components were inverted simultaneously (Figure 2b-c). The number of combined synthetic  
351 inversions per MOC test is 14 and 16, respectively. Average restitution indexes (ARI), which are a  
352 slip resolution metric independent of the checkerboard position, correspond to  $0.86 \pm 0.1$  in  
353 average above 1.5 km depth for the May event (Figure S9a), and  $0.83 \pm 0.11$  above 1 km depth  
354 for the December event (Figure S10a). This means that nominal errors in those fault segments are  
355 below  $\sim 16\%$  and  $\sim 17\%$  as compared to the actual fault slip. However, although fit errors are  
356 minimal (panels d), an inspection of individual checkerboard inversions reveals that slip solutions  
357 below  $\sim 800$  m in both cases are affected by smearing effects due to the inverse problem sensitivity,  
358 which makes slip patches to appear slightly deeper than they are (panels b and c). Thus, subsequent  
359 data interpretation at depth should consider this modeling limitation.

360

361 Figure 4 shows the slip inversions for both events assuming the same model parameterization as  
362 for the MOC tests. While no slip penalization was used in the Mixcoac fault, solutions were  
363 penalized below 1.5 km to mitigate deep unresolved slip in the BM fault. The data fit is very  
364 satisfactory, as shown along two profiles on the major asperities together with the standard  
365 deviations within a 400 m profiles vicinity (panels b and e). The standard deviation of the overall  
366 error are 0.171 cm and 0.183 cm for the May and December events, respectively, while the mean  
367 values are close to zero in both cases (panels c and f). Such small data misfits were expected given  
368 the results achieved in the previous section, where the problem geometry was optimized while  
369 fitting the same data (Figures S6-S8).

370  
371 The slip distribution for the May event on the BM fault features a prominent asperity between 0.5  
372 and 1.5 km depth with a maximum slip of 7 cm that extends to the west while getting thinner and  
373 shallower (Figure 4a). Surprisingly, slip to the west surrounds the hypocentral region of the Mw3.2  
374 earthquake of May 11, which can also be appreciated in the three-dimensional representations of  
375 Figure 5b-c. This means that the surface deformation pattern observed between May 6 and May 18  
376 (Figure 2a) is explained by an extended deep asperity about 1 km east of the earthquake (i.e., just  
377 below Revolucion Street, which runs above Line 7 of the Mexico City underground metro) and a  
378 much smaller slip strip reaching the earthquake hypocenter west of the Periferico Main Street,  
379 which may correspond to the coseismic and postseismic slip signature of the event. The moment  
380 magnitude of the slip distribution is  $M_w = 4.1$ , which means that the associated scalar moment is  
381 22 times larger than the mainshock corresponding value. Relocated seismicity between March and  
382 July 2023 reported by Quintanar et al. (2024) (dark blue dots, Figure 4a) and template matching  
383 (TM) detections in May (light blue dots), which will be properly introduced in the next section, are  
384 distributed over and around the fault.

385  
386 Regarding the inversion for the December event on the Mixcoac fault, Figure 4d shows that the  
387 slip concentrated in a much shallower fault region (i.e., above 0.9 km depth) and likely reached the  
388 earth's surface. Indeed, days after the Mw3.2 earthquake of December 14, several public media  
389 reported aligned fractures in the streets around the surface projection of the fault (green line). The  
390 slip pattern is composed by two interconnected asperities with higher overall slip than found for  
391 the May event, with a maximum of 8 cm about 400 m depth in the eastern asperity (i.e., east of the

392 Periferico Main Street) and total moment magnitude  $M_w = 3.9$ , i.e. a scalar moment 11 times larger  
393 than the mainshock corresponding value. Precise enough location of the mainshock to determine  
394 whether it occurred on the fault is a difficult task that we shall discuss in detail on section 2.6. On  
395 the other hand, double-difference relocated earthquakes from December 2023 to May 2024 (blue  
396 dots), first reported here, show that most of the events fall west of the fault (i.e., west of the  
397 Periferico Main Street) with some exceptions near its eastern end. Based on this seismic evidence,  
398 the peculiar two-lobe slip distribution and two stronger arguments given in Section 2.6, we believe  
399 that the western fault asperity may correspond to the coseismic and postseismic signatures of the  
400 December 14 mainshock.

401  
402 A three-dimensional rendering of the slip solutions on both faults is shown in Figure 5 (and  
403 Supplementary Movie S1), where we also included our high-resolution DEM scaled by a factor of  
404 four to appreciate better the geomorphological features, which were statistically characterized in  
405 Section 2.1 and have a local direction of  $342 \pm 15^\circ$  for the steepest slopes (see inset of Figure 1).  
406 A clear structural connection comes out between both normal faults and two north-facing cliffs  
407 emerging to the west from the Periferico Main Street, suggesting that these cliffs, delineated with  
408 dashed gray lines in Figure 1, are the geomorphic westward expression of the buried faults to the  
409 east. This structural connection is particularly important because it rules out other mechanisms that  
410 could produce similar InSAR deformation patterns, such as anthropogenic activity (e.g., water  
411 extraction) and city infrastructure.

412

### 413 **2.5. Seismicity and Slow Slip in the Barranca del Muerto Fault**

414

415 The slip inversions introduced above represent the time integration of the fault slip history between  
416 the two dates where the InSAR scenes were taken. So, nothing can be said about the timeline  
417 involving the mainshocks and the faults slip evolution. For instance, the interferogram used to  
418 model the May event (Figure 2a) and the associated slip (Figure 4a) include everything that  
419 happened on the fault during 12 days between May 6 and May 18. Since the  $M_w 3.2$  earthquake  
420 occurred on May 11, slip could initiate during the 6 days preceding the earthquake. In the past,  
421 local earthquakes in the western part of the city were reported as seismic swarms that may last for  
422 months before a mainshock. This was the case of the 1981 and 2019 earthquakes (Havskov, 1982;

423 Singh et al., 2020). For the 2023 crisis, Quintanar et al. (2024) reported that seismic activity was  
424 initiated in February and continued until the mainshock occurred on May 11, indicating that  
425 fractures' instability and interaction across a fault system occurred during weeks to month-long  
426 periods, certainly driven by some underlying local process.

427  
428 To assess whether aseismic slip was initiated in the BM fault before the mainshock, we used a  
429 template matching (TM) technique (Liu et al., 2020) to detect small local earthquakes with low  
430 signal-to-noise ratio, which is particularly convenient within urban areas. As templates, we used  
431 the waveforms from a double-difference (DD) relocated catalog reported by Quintanar et al. (2024)  
432 shown in Figure 4a (dark blue dots), which contains 22 well-located earthquakes. We applied the  
433 TM technique to estimate the stacked correlation coefficient for each of the templates and the  
434 continuous recording for three local stations (PZIG, ENP8 and BJVM; Figure 1) from May 1  
435 through May 31. The TM performs a continuous search by computing the correlation coefficient  
436 between the templates and the continuous data at each sample step. A detection is declared when  
437 the correlation coefficient exceeds  $n$  times the mean average deviation (MAD) of the correlation  
438 coefficient for each day. By visually inspecting the detections obtained for different MAD threshold  
439 values, we empirically determined that  $MAD \geq 9.2$  provides a robust and reliable catalog with 89  
440 detections in May above the threshold. Figure 6a-b shows a comparison between two templates  
441 and the continuous data for two previously unreported earthquakes with  $MAD = 17.15$  and  $MAD$   
442  $= 9.26$ , respectively. Examples for higher MAD values are shown in Figure S11. The magnitude of  
443 the detections was estimated by comparing the median of the relative amplitude between the peak  
444 values of the template and the detection (Liu et al., 2020). To precisely locate the events, templates  
445 are allowed to move from their position in a cubical regular grid (Supplement Figure S12). By  
446 estimating the delayed times for each grid point based on the local velocity model used for this  
447 study (Section 2.3), correlation coefficients are computed for the whole lattice and the final location  
448 corresponds to the largest correlation coefficient. In this case, we used a grid around the template  
449 location with  $\pm 0.004^\circ$  length in latitude and longitude, and  $\pm 100$  m vertically, with grid  
450 increments of  $\pm 0.002^\circ$  and  $\pm 50$  m, respectively. In summary, we tested 27 possible foci around  
451 each template in addition to the template location. Figure 6c shows the temporary evolution of the  
452 seismic catalog, where orange stems indicate the time and magnitude of the templates, while blue  
453 stems correspond to the TM detections. A similar timeline representation is shown in Figures 6d



454 and 6e in terms of the events depth and MAD values. The magnitude frequency distribution is  
 455 shown in Figure S13 including the DD and TM catalogs, which resulted in the 89-event catalog  
 456 with a magnitude range between 0.2 and 3.2, a magnitude of completeness  $M_c = 1.2$ , and a standard  
 457  $b$ - value of  $1.01 \pm 0.33$  (Figure S13). Figure 6d-e shows the events depth distribution versus time  
 458 color coded by magnitude and MAD value, respectively. High MAD values above 25 correspond  
 459 to the templates (i.e.,  $CC = 1$ ).

460  
 461 Figure 7a-b shows two perspectives of the fault slip together with our TM catalog for May (see  
 462 Supplementary Movie S2). Despite the uncertainties in the foci, which we estimate of the order of  
 463  $\pm 100$  m given the TM grid size, the spatial correlation between the seismicity and the slip  
 464 distribution is remarkable. While earthquakes around the mainshock hypocenter (yellow dot) to the  
 465 west are above  $\sim 800$  m, events to the east concentrate in a deeper region, between 600 and 1,400  
 466 m depth, as does the slip pattern. Based on this spatial correlation while considering the foci and  
 467 slip uncertainties, we will focus only on seismicity rate variations along the fault strike in the  
 468 following. To this purpose, regardless of the events depth, we projected horizontally all hypocenters  
 469 into the fault plane following a strike-perpendicular direction. Figure 7c shows the timing of all  
 470 detections as a function of the along-strike distance from the mainshock hypocenter. Blue dots  
 471 indicate foreshocks and red dots indicate aftershocks. The gray band depicts the time between both  
 472 InSAR scenes used to invert the fault slip. To have a rough estimate of the earthquakes' size and  
 473 their average slip,  $\bar{d}$ , for a circular crack with stress drop  $\Delta\tau$  and radius  $r$  we have  $\bar{d} = \frac{M_0}{\mu\pi r^2}$  and,  
 474 given Eshelby's (1957) solution for this problem,  $r = \sqrt[3]{\frac{7}{16} \cdot \frac{M_0}{\Delta\tau}}$ , where  $M_0$  is the scalar moment  
 475 and  $\mu$  is the shear modulus of our velocity model (Section 2.3). Given the magnitude of each  
 476 detection and assuming a stress drop  $\Delta\tau = 0.5$  MPa, as determined for the mainshock by Quintanar  
 477 et al. (2024), then we have  $d$  and  $r$  for each event, as shown in Figure 7c with horizontal bracket  
 478 bars for the source lengths. To estimate the scalar moments, we assumed that the magnitudes,  
 479 derived by comparing the relative amplitudes of the detections and the templates, are close to the  
 480 expected moment magnitudes. This approach yields a source radius  $r = 396$  m for the Mw3.2  
 481 mainshock with average slip  $\bar{d} = 2.5$  cm. Estimates for all TM detections assuming the same  $\Delta\tau$   
 482 are plotted in Figure 8a and discussed later. Tests for different stress drops did not change the main  
 483 conclusions of the exercise we are about to develop.

484  
485 By taking along-strike bins with 400 m support centered at the hypocenter to group the events (i.e.,  
486 a support significantly larger than the foci uncertainty), Figure 7d shows the events cumulative  
487 count every 24 h, where the black line represents the total number of foreshocks (blue lines) and  
488 the red thick line the total number of aftershocks (red lines). Interestingly, the number of foreshocks  
489 far from the hypocenter (about 1 km) is twice as high as in the hypocentral region. The location of  
490 this seismogenic spot coincides with the slip largest, deep asperity shown in panel a, suggesting a  
491 nucleation process and stress accumulation around the hypocentral area. In case that the aseismic  
492 slip preceded the mainshock, the foreshock distribution indicates that this process may have  
493 occurred deeper and  $\sim 1$  km away. Regarding the aftershocks, three things are clear: (1) they were  
494 abundant during the first 24 hours all the way from the hypocentral region to the eastern deep  
495 segment, (2) after those 24 hours, their occurrence rates decrease sharply and becomes similar to  
496 those before the mainshock, and (3) about four days after the mainshock, events gradually move  
497 away from the rupture area in both opposite directions (arrows in Figure 7c). In Figure 8a we show  
498 the coseismic slip distribution associated with all TM detections predicted by Eshelby's model. The  
499 boxcars represent the source length and average slip of each event, while the blue and red curves  
500 depict the cumulative slip envelopes of the foreshocks and aftershocks, respectively. As expected,  
501 most of the slip comes from the aftershocks sequence. However, if we compare the total coseismic  
502 slip (black curve) with the along-dip cumulative slip inverted from InSAR data (within the 1 cm  
503 slip contour) (Figure 8b), we find that the inverted slip on the fault is much larger, 9.5 times on  
504 average, than the events coseismic slip, and 25.6 times larger in the deep slip patch 1 km east of  
505 the hypocenter. In contrast, cumulative coseismic slip around the hypocenter is only 3 times  
506 smaller, suggesting that the InSAR inverted slip there, is significantly explained by the mainshock  
507 coseismic and postseismic slip. Although the magnitude of the events on the main-slip deep region  
508 is very small (and therefore have a small coseismic slip contribution; panel a), the cumulative count  
509 of foreshocks is the largest (more than twice as large as in the hypocentral region), as depicted by  
510 the red curve, indicating that aseismic slip could happen in this region prior to the mainshock  
511 rupture (i.e., at least during the six days preceding the earthquake).

512  
513 Whether or not slow aseismic slip occurred on the fault days before the Mw3.2 earthquake (i.e.,  
514 whether the InSAR inverted slip partly occurred before the mainshock) may also be assessed by

515 comparing the foreshocks and aftershocks occurrence rates in between the two InSAR scenes (i.e.,  
 516 within the gray band of Figure 7c). Since the aftershocks production is the largest during the first  
 517 24 h following the mainshock (Figure 7d), we estimated the occurrence rates separately for those  
 518 24 h and then for the remaining days before the second InSAR scene. If we define the relative  
 519 earthquake production rate as  $\Gamma = R_a / R_f$ , where  $R_a$  is the aftershocks rate and  $R_f$  is the foreshocks  
 520 rate, then Figure 8c shows that during the first 24 h (i.e.,  $\Gamma_{24h}$ ), aftershocks production was  $\sim 3$  to  
 521  $\sim 30$  times larger than foreshocks across the whole width of the fault (red dotted curve).  
 522 Interestingly, about 1 km away from the hypocenter where the largest slip patch is found,  $\Gamma_{24h}$  is  
 523 minimum, about 3 to 10 times smaller than in the two adjacent segments. After 24 h, a different  
 524 scenario comes out with two major traits (red curve): (1) aftershocks production rate is larger than  
 525 foreshocks (i.e.,  $\Gamma > 1$ ) where the InSAR inverted slip is minimum (i.e., within the white  
 526 background areas), and (2) foreshocks production rate is larger than aftershocks (i.e.,  $\Gamma < 1$ ) in both  
 527 the hypocentral and main slip segments (i.e., twice as large as in the main slip patch). This means  
 528 that during the six days between the first InSAR scene and the mainshock, foreshocks were highly  
 529 active in both slip maxima segments (blue and red background shades) as compared with  
 530 aftershocks during the last five days preceding the second InSAR scene, indicating that slow  
 531 aseismic slip on both fault segments may have occurred, acting as the driving process that  
 532 modulated the foreshock activity.

533

## 534 **2.6. December Event on the Mixcoac Fault**

535

536 As mentioned earlier, it is unclear whether the hypocenter of the Mw3.2 earthquake of December  
 537 14 is located on the Mixcoac fault that explains the InSAR data (yellow dot Figure 5c). Figure 9a  
 538 shows the RMS errors for the P- and/or S-waves arrival times at 48 seismic stations with epicentral  
 539 distance smaller than 10 km (Figure 1 shows those within the study region), estimated for all  
 540 possible foci locations in a 3D volume together with our preferred hypocentral location (gray star).  
 541 Overall errors smaller than 0.2 s enclose the western half of the fault where the western slip asperity  
 542 is located (Figures 4d and 5c) and thus where the mainshock hypocenter is likely found. However,  
 543 as expected, the RMS resolution is poorer in depth. We thus analyzed the characteristics of that  
 544 asperity and confront them with theoretical predictions for an Mw3.2 rupture. The Eshelby's (1957)  
 545 source model introduced in the previous section predicts the slip distribution within a circular crack

546 with radius  $r$  and stress drop  $\Delta\tau$ . By centering the source in the asperity, a grid search for both  
547 parameters to minimize the mean absolute error between the model and the inverted slip yields  
548 optimal values  $r = 320$  m and  $\Delta\tau = 1.05$  MPa for a mean slip  $\bar{d} = 4.3$  cm. Both slip distributions  
549 are shown in Figure 9b, where we also report the resulting magnitude  $M_w = 3.2$  for the optimal  
550 Eshelby's model, which is consistent with the earthquake's magnitude. Nonetheless, considering  
551 that the inverted slip has uncertainties (particularly along-dip as shown by the MOC test, Figure  
552 S10) and includes also the postseismic relaxation of the event, the asperity model should be biased  
553 to some extent. This could explain the relatively high stress drop found, which is twice as large as  
554 determined for the  $M_w 3.2$  earthquake of May 11 (L Quintanar et al., 2024). If we assume an  
555 afterslip of 20%, the Eshelby's model predicts  $\Delta\tau = 0.84$  MPa with  $M_w = 3.17$ , which is probably  
556 closer to the coseismic signature of the earthquake. From these exercises we conclude that the  
557 western slip patch may indeed correspond to the December 14 earthquake rupture.

558  
559 The analysis above suggests that large part of the InSAR-inverted slip (i.e., the slip outside the  
560 mainshock asperity located in the western portion of the fault) was released aseismically. Since  
561 relocated seismicity for December (dark blue dots in Figure 4c) is away from the fault, a similar  
562 TM analysis as for the May event to draw a timeline of the slip history becomes difficult. We do  
563 have, though, two interferograms for December (inverted simultaneously) with initial scenes taken  
564 6 and 3 days before the mainshock, which could in principle be analyzed separately to identify  
565 whether there was activity on the fault in the non-overlapping period. However, as discussed in  
566 detail on Section 2.2, there was no significant deformation between December 8 and December 11,  
567 the initial dates of the two interferograms (Figure S2). Therefore, the slip east of the fault must  
568 have occurred between December 11 and December 23. That is, in the three days prior to the  
569 mainshock or later. A smaller (but significant) earthquake than the  $M_w 3.2$  of December 14 occurred  
570 on December 12 with moment magnitude  $M_w = 3.0$  (Bello et al., personal communication, 2024).  
571 Yet, our double-difference hypocentral relocation is 600 m west of the fault (Figure 4d), so the  
572 possibility that the eastern slip asperity could correspond to the coseismic signature of that  
573 foreshock is unlikely. The most reasonable hypothesis is, therefore, that the slip east of the fault  
574 was slow slip and thus aseismic. There are two possibilities. Either it occurred in the three days  
575 prior to the mainshock, as seems to have occurred before the May mainshock in the BM fault, or  
576 afterwards, as an extended along-strike afterslip.

577

## 578 **2.7. Fault Interaction**

579

580 Whether or not the above hypothesis is true, one wonders how the May slip on the BM fault could  
581 have affected the strain field around the Mixcoac fault, which was activated in December only 800  
582 m to the north (see Figure 5c). Figure 10 shows a 3D rendering of the Coulomb Failure Stress  
583 (CFS) change, estimated with an artifact-free triangular dislocation model (Nikkhoo & Walter,  
584 2015), imparted by the May event on the Mixcoac fault, where we also include the slip contours of  
585 our joint inversion, shown in Figures 4d and 9b. Two main features stand out: (1) the CFS features  
586 a large negative patch below  $\sim 700$  m, with minimum values reaching  $-40$  kPa at  $\sim 1.2$  km depth,  
587 where no slip for the December event is found, and (2) the CFS is positive and maximum, with  
588 values above 10 kPa, in the eastern shallow segment where the main slip asperity is found. This  
589 means that the May event on the BM fault may have inhibited deep slip on the Mixcoac fault and  
590 promoted slip on its shallow part, particularly to the east, which may explain why slip concentrated  
591 near the surface unlike the May event. Although the prestress condition on the Mixcoac fault is  
592 unknown, it is striking how the slip distribution, which most likely includes the coseismic signature  
593 of the December 14 mainshock, seems to surround the deep stress shadow. Thus, the stress  
594 interaction between the two faults indeed supports the evidence discussed in the previous  
595 paragraph, which points to the occurrence of shallow aseismic slow slip about 600 m east of where  
596 the mainshock happened.

597

## 598 **3. Discussion**

599

### 600 **3.1. Origin of Slow Slip Beneath Mexico City**

601

602 Although local seismic swarms are likely to be formed by small ruptures across an extended fault  
603 system, temporal clustering of the events should be driven by local underlying processes, as  
604 happens with the induced seismicity during borehole injection tests. In these cases, there is growing  
605 evidence that fluid diffusion induces changes in the pore pressure that stabilize friction and leads  
606 to aseismic slip instabilities that trigger seismic radiation in the fault system (Cappa et al., 2019;  
607 Guglielmi et al., 2015; Larochelle et al., 2021; Wang & Dunham, 2022). Fault system

608 pressurization can also produce surface deformations measurable with satellite interferometry in  
609 sedimentary basins such as the Delaware, USA, where deformations are due to slip on shallow  
610 normal faults around which most of the seismicity takes place (Pepin et al., 2022). This case seems  
611 to be an analogy of what is happening in the Valley of Mexico basin, where uninterrupted  
612 groundwater extraction produces one of the highest subsidence rates in the world (i.e., up to 500  
613 mm/yr) (Cabral-Cano et al., 2008; Chaussard et al., 2021; López-Quiroz et al., 2009; Ortega-  
614 Guerrero et al., 1999). The buried segments of the BM and Mixcoac faults are in a very densely  
615 populated area where water demand is high and some 14 wells are located within 1 km of the faults  
616 (Júnez-Ferreira et al., 2023). The high foreshocks rate in both the deepest segment of the BM fault  
617 and the shallow hypocentral zone of the Mw3.2 mainshock (Figures 7d and 8c) strongly suggests  
618 that part of the surface deformation in May occurred before the earthquake due to aseismic slip  
619 primarily in the deeper fault area, located ~1 km east the hypocenter. The scalar moment of the slip  
620 events on both faults (Figure 4) are 22 and 11 times larger than those of the associated Mw3.2  
621 mainshocks. On the BM fault, where the largest and deepest slip occurred, only 5% of the inverted  
622 slip can be explained coseismically from our seismic catalog with completeness magnitude 1.2.  
623 This means that 95% of the May slip was aseismic, which is close to the 98% found in the Delaware  
624 basin (Pepin et al., 2022). On the Mixcoac fault, from Figure 9b we can estimate that about 70%  
625 of the seismic moment was released aseismically in December, a percentage consistent with  
626 estimates made in Nevada, USA, and the Apennines, Italy, from geodetic deformations associated  
627 with seismic swarms in the absence of water injection (Gualandi et al., 2017; Y. Jiang et al., 2022).  
628 While this slow slip could be partly attributed to underground fluid diffusion, as has been  
629 demonstrated on natural faults, in the laboratory, and with sophisticated friction models (Cappa et  
630 al., 2019; Guglielmi et al., 2015; Laroche et al., 2021; Wang & Dunham, 2022), unlike controlled  
631 water injection, extraction in Mexico City is sustained over time, making it difficult to attribute the  
632 slip events and associated seismicity to particular time-bound anthropogenic incidents.

633  
634 Earthquakes between December 2023 and May 2024 concentrate west and southwest of the  
635 Mixcoac fault (Figure 4d) as do most of the events reported by the SSN in 2023. That is, mainly in  
636 the hilly area west of the city where the faults are expressed geomorphologically (Figures 1 and 5).  
637 Furthermore, the distribution of seismicity following the May 11 and December 14 mainshocks  
638 moves away from the slip zones with time, as can be seen in Figure 7c (black arrows) on the BM

639 fault and in Figure 4d (compare dark blue dots with light blue dots) around the Mixcoac fault. Also  
640 striking is the absence of seismicity on the Mixcoac fault before and after the mainshock. These  
641 seismicity patterns suggest that the eastern flanks of both faults are prone to slow aseismic slip  
642 unlike their westward extensions, where the faults emerge at surface. The largest slip occurred on  
643 buried fault segments below the flat part of the basin where the soil is composed of water-rich  
644 alluvial deposits and clays. The nature of aseismic slip under similar basin conditions depends on  
645 the hydraulic permeability of the medium, the fault prestress and its constitutive friction  
646 parameters, so that slow slip propagation is mainly driven by changes in pore pressure and the  
647 subsequent drop in fault strength. This mechanism explains the migration of seismicity in the  
648 Cooper basin, New Zealand (Wang & Dunham, 2022), and may explain the outward migration of  
649 microseismicity near the slip zone, especially on the BM fault (Figure 7c).

650

### 651 **3.2. Fault System Mechanical Transition and Intense Seismicity**

652

653 The more general seismicity pattern can be explained by a similar but different mechanism also  
654 suggested by our results. The aseismic slip on fault segments buried beneath sediments with high  
655 water content and the concentration of intense seismicity to the west where the faults have a  
656 geomorphic expression (i.e., where sediments are relatively scarce) suggest that the dynamic  
657 instabilities causing the seismicity are partly due to stress loading to the west induced by aseismic  
658 slip on the buried segments. That is, the fault system west of Mexico City could be divided into  
659 two mechanically differentiated zones with a transition in between (Figure 11). On one hand, a  
660 dominant eastern regime of stable slow slip in the buried segments beneath the sediments, and  
661 another of unstable seismic slip to the west, beneath the hilly zone of the city. Complementary  
662 evidence for this conjecture is the absence of intense seismicity in the vicinity of the Mixcoac fault  
663 during the December event, and the location of the two Mw3.2 mainshocks of May and December  
664 near the western ends of the faults (Figures 4 and 5a), and thus where the stress loading should be  
665 high near the mechanical transition of the fault system from stable to unstable slip (Figure 11). A  
666 similar conclusion was reached after studying hydraulic fracturing-induced seismicity in different  
667 locations around the world, where pore pressure-driven aseismic slip activates unstable slip (i.e.,  
668 intense seismic radiation) along distal nonpressurized fault segments (Eyre et al., 2019, 2022).

669

### 3.3. Seismic Hazard Associated with the BM and Mixcoac Faults

670  
671  
672 To our knowledge, this is the first three-dimensional mapping of seismogenic faults in Mexico City  
673 (see geological compilation by Arce et al., 2019). Their extent invites thinking about the seismic  
674 potential they could pose, a particularly sensitive issue in one of the most populated cities in the  
675 world. Assuming that both faults could produce earthquakes with moment magnitude similar to  
676 those of the inverted slip (i.e.,  $\sim$ Mw4.0) would seem unrealistic, at least in the buried segments of  
677 the faults, where deformation seems to be preferentially accommodated aseismically. In other  
678 words, presuming that the fault extent determines the maximum magnitude of an earthquake means  
679 disregarding what the international community has understood about the dynamic rupture  
680 mechanics of faults in the light of slow slip events. In a recent study, Singh et al. (2020) postulated  
681 a Mw5.0 scenario for Mexico City from a nearby and similar earthquake (Mw3.2) on July 2019  
682 (Figure 1) that produced the largest peak ground acceleration (PGA) ever recorded in the bedrock  
683 of the city, with 213 gal in geometric average of the three components (i.e., 7.4 and 4.4 times larger  
684 than those recorded in bedrock during the devastating earthquakes of 1985 and 2017, respectively;  
685 see Singh et al., 2018). These authors then postulated a hypothetical rupture 3 to 4 km in extent,  
686 which would be consistent with the 3.5 to 4.5 km length of the geomorphologic expressions of the  
687 BM and Mixcoac faults (dashed gray lines in Figure 1). The estimated response spectra for such a  
688 scenario at a site upon lake-bed soft deposits of the basin (i.e., 7.3 km east of the 2019 epicenter)  
689 are smaller (roughly by a factor of 2 up to 5 s period) than those recorded nearby during the  
690 devastating 1985 and 2017 earthquakes. However, these estimates are valid in the far field and for  
691 a point source. In other words, the extended rupture of a  $\sim$ Mw5.0 earthquake west of the city could  
692 imply a different scenario close to the source (i.e., at distances on the order of  $\sim$ 5 km), with  
693 significant damage due to the rupture propagation and its near-field effects that, combined with the  
694 three-dimensional propagation of waves in a basin with exceptionally extreme properties (Chávez-  
695 García & Bard, 1994; Cruz-Atienza et al., 2016; Hernández-Aguirre et al., 2023), could produce  
696 ground motions not yet observed in Mexico City, as unexpectedly occurred during the 1985 and  
697 2017 earthquakes despite the knowledge gathered by experts up to those two dramatic moments in  
698 history.  
699



#### 700 4. Conclusions

701 In this investigation we have studied the 2023-2024 seismic crisis in Mexico City from a broad  
702 perspective. Tectonically driven satellite observations in a densely populated area west of the city  
703 allowed us to identify two east-west trending normal faults as responsible for the deformations.  
704 The first slip event occurred on the BM fault during the days before and after the Mw3.2 mainshock  
705 on May 11, 2023, and whose co-seismic signature is located 1 km west of the main slip patch with  
706 depth  $\sim 1.2$  km. The second event occurred on the Mixcoac fault, 800 m to the north, with shallower  
707 slip likely reaching the surface (i.e., above  $\sim 600$  m mostly) and coincident with another Mw3.2  
708 mainshock on December 14, 2023. A detailed microseismicity analysis revealed that more than  
709 95% of the slip on the BM fault was aseismic and initiated at least 6 days before the May 11  
710 earthquake in the slip patch distant from the hypocenter. For the December event on the Mixcoac  
711 fault, approximately 70% of the slip was aseismic. Stresses induced on the Mixcoac fault by May  
712 slip on the BM fault could explain why the December slip was shallow and concentrated east of  
713 the December 14 hypocenter. A quantitative geomorphological analysis of the surrounding hillsides  
714 indicates that the preferential direction of their north-facing slopes is consistent with the dip  
715 directions of both faults. This, together with the alignment of the faults with two gullies to the west,  
716 allowed establishing the structural connection between the buried faults to the east and their  
717 geomorphic expression to the west with extensions of 3.5 and 4.5 km, which are consistent with  
718 the rupture of a hypothetical Mw5.0 earthquake proposed in recent literature. The seismicity  
719 patterns analyzed and the dominant aseismic slip on the faults suggest that the seismotectonics of  
720 western Mexico City can be divided into two mechanically distinct regions. A stable region prone  
721 to aseismic deformation to the east where faults are buried under sediments with high water content,  
722 and an unstable region to the west, prone to seismic radiation where faults are expressed  
723 geomorphologically. Therefore, the earthquake swarms characterizing the western part of Mexico  
724 City seem to be a consequence of the regional extensional regime, the stresses induced by slow  
725 earthquakes in the eastern segments of the faults and the elastic interaction between these main  
726 faults.

727

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736

737 **CRedit authorship contribution statement**

738 DSR, JT, PMG, and MJAV conceptualized the initial idea for the manuscript development. PMG  
739 processed the satellite SAR data where the geodetic signals that gave origin to this research were  
740 found, under the supervision of DSR, and both contributed to the manuscript's original draft. DSR  
741 performed the geomorphological formal analysis. MJAV performed the simulated annealing  
742 inversions to retrieve the faults' geometry under VMCA and JT's supervision, elaborated some  
743 earthquake location exercises, and contributed to the original draft. VMCA performed the slip  
744 inversions of the signals using ELADIN, elaborated the seismicity formal analysis, and  
745 conceptualized the relationship between seismic and aseismic energy release and their interplay on  
746 the deformations; he also elaborated most of the original draft. LAD performed the template-  
747 matching analysis to detect hidden seismicity and contributed to the original draft. CV calculated  
748 the coulomb stresses on the Mixcoac fault due to the Barranca del Muerto fault activity and  
749 contributed to the original draft. VHE, DBS, and LQ exhaustively worked on obtaining the best  
750 earthquake locations and focal mechanisms (where possible) for the May and December activity  
751 and contributed to the original draft. MP actively discussed and analyzed the results in the working  
752 group meetings. This manuscript results from a collaborative effort showcasing the authors'  
753 commitment to this new and relevant topic for Mexico City. All authors contributed to the final  
754 analysis of this article and reviewed and edited the manuscript.

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758 **References**

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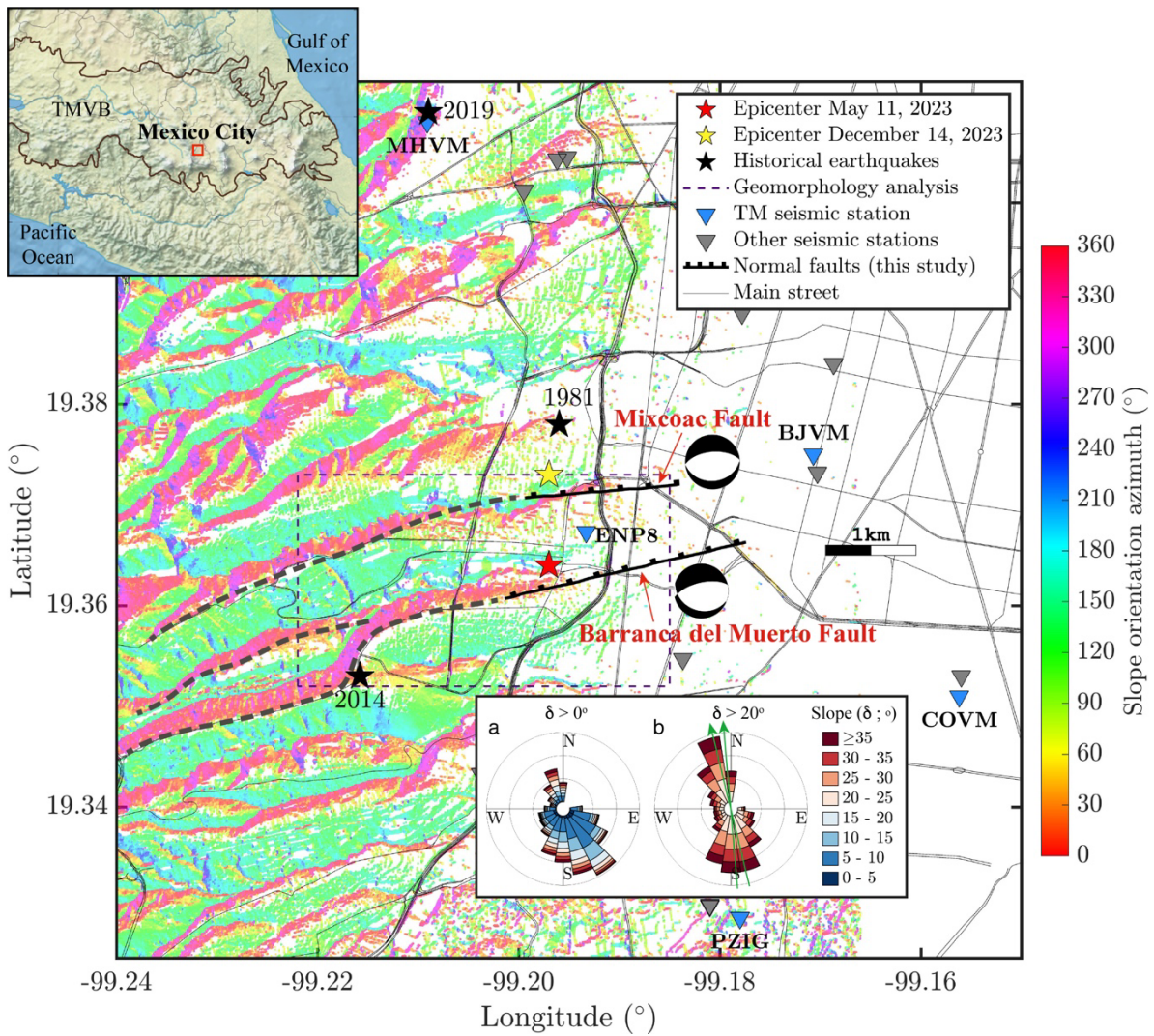


1014 **Table 1** Locations and focal mechanisms of the two 2023 mainshocks and the Barranca del Muerto  
 1015 and Mixcoac faults. The latitude, longitude and depth of the faults correspond to the center of the  
 1016 faults. \*Location and fault mechanism by Quintanar et al., 2024.

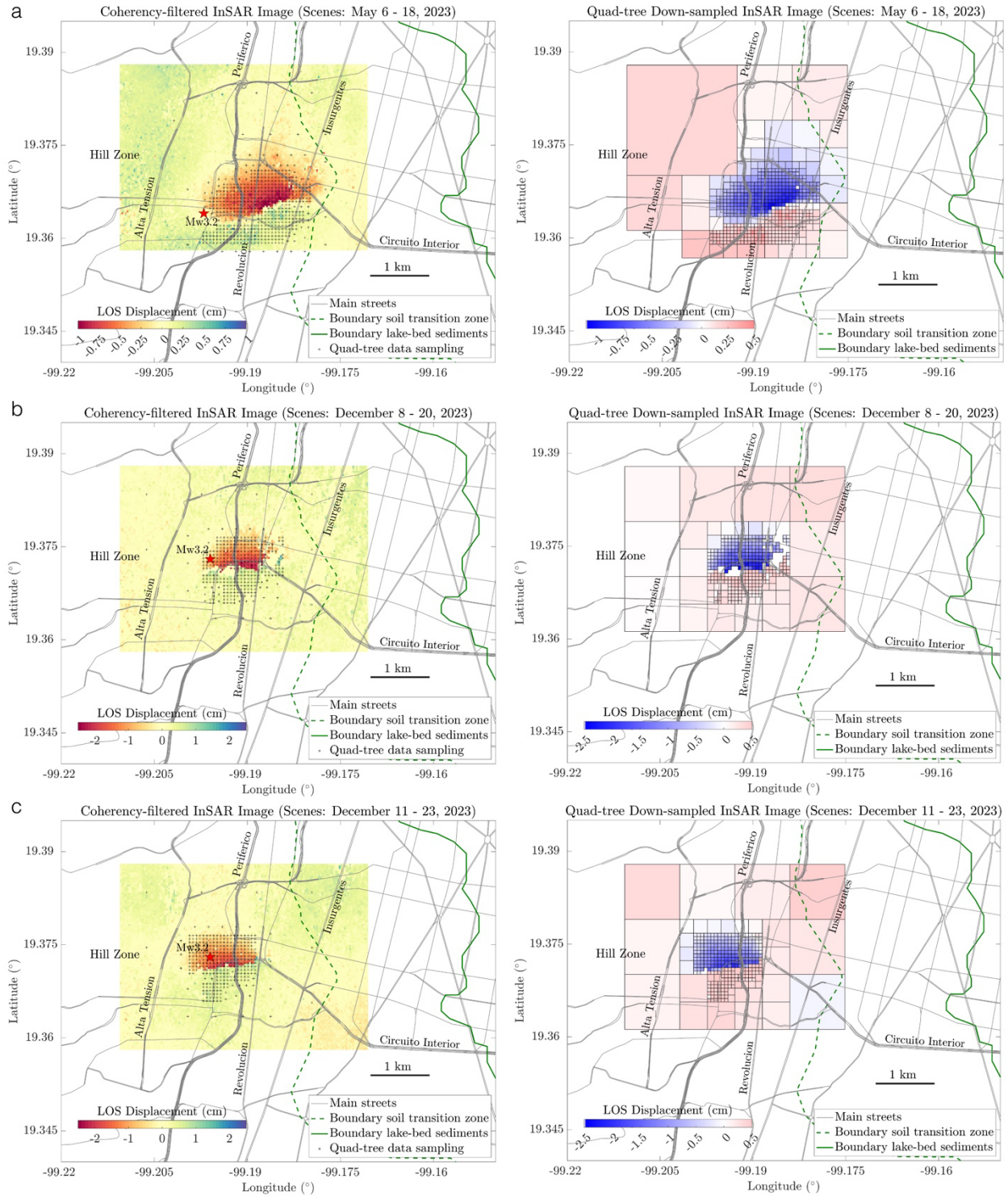
1017

	<b>Latitude (°)</b>	<b>Longitude (°)</b>	<b>Depth (km)</b>	<b>Wide (km)</b>	<b>Length (km)</b>	<b>Strike (°)</b>	<b>Dip (°)</b>	<b>Rake (°)</b>
May 11 earthquake*	-99.197	19.364	0.70	-	-	270	76	-75
December 14 earthquake	-99.197	19.373	0.50	-	-	259	89	-86
Barranca del Muerto fault	19.369	-99.189	1.18	2.6	2.6	256.3	64.8	-105
Mixcoac fault	19.374	-99.192	0.57	1.6	1.6	265.1	59.2	-90.3

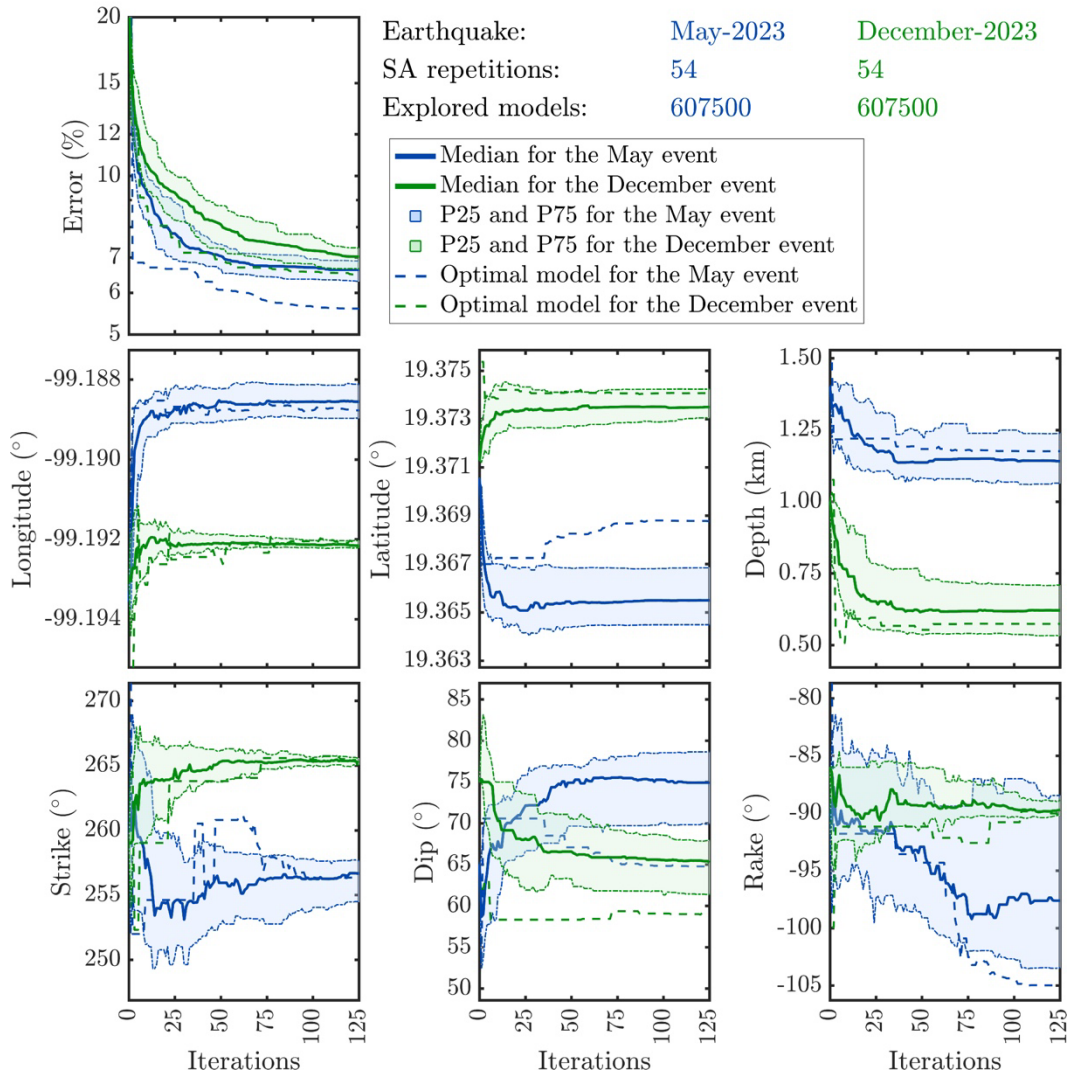
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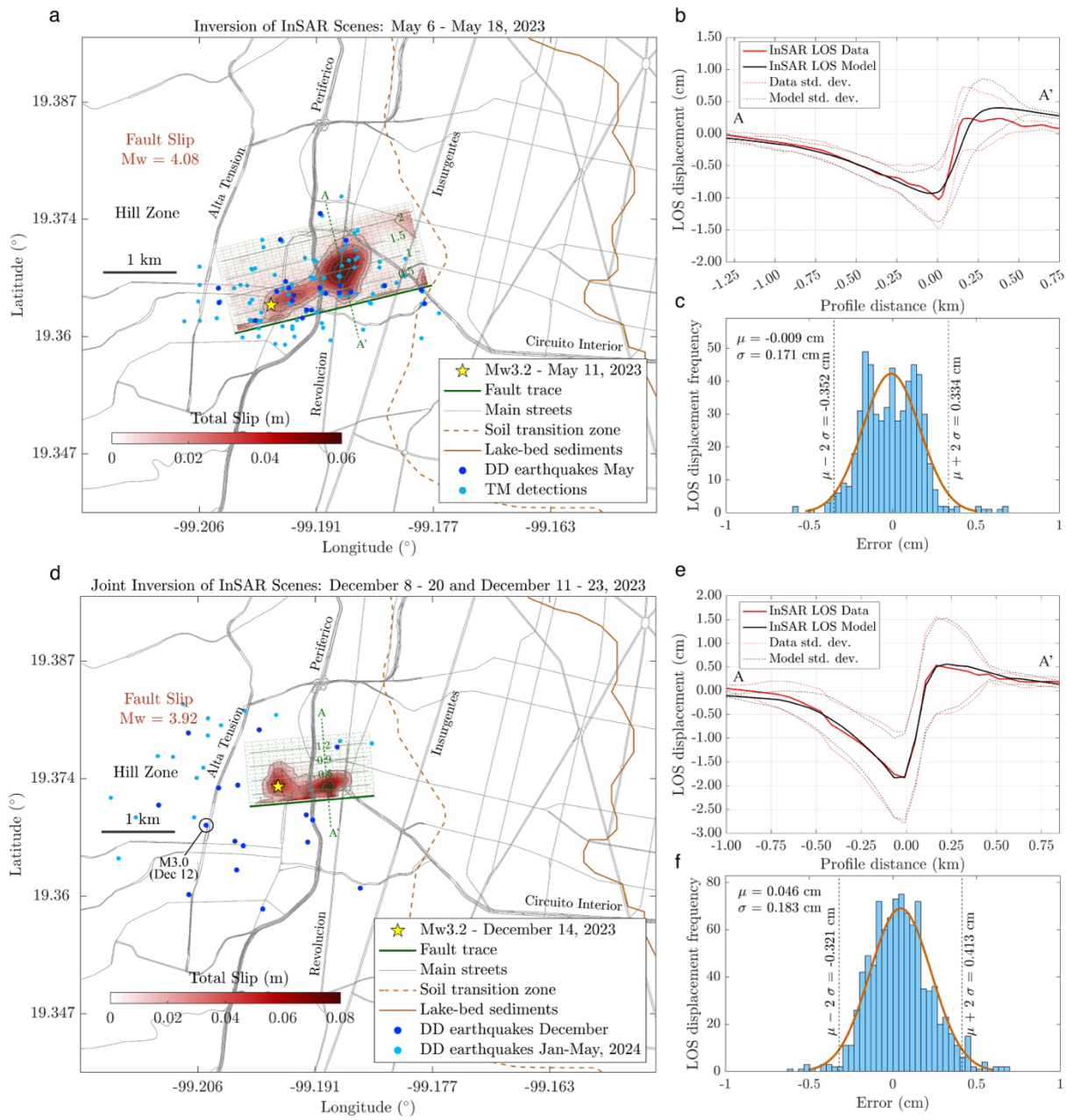
1019  
 1020 **Figure 1.** Seismicity and Topographic Slope Orientation of the Study Area with the Barranca del  
 1021 Muerto (BM) and Mixcoac faults identified in this study. Upper left: Location map showing  
 1022 Mexico City in the south-central part of the Trans-Mexican Volcanic Belt (TMVB), Central  
 1023 Mexico. Main map: Orientation (aspect) of landscape slopes derived from a 5-m Digital Terrain  
 1024 Model (DTM). The map indicates the surface traces of the BM and Mixcoac faults, seismic events,  
 1025 station locations, and main streets. The beach balls show the focal mechanisms determined for both  
 1026 faults from the simulated annealing inversions, and the dashed gray lines indicate the geomorphic  
 1027 extension of the faults to the west. The blue triangles show the seismic stations used to detect  
 1028 template matching (TM) earthquakes and the gray triangles show other stations used to locate the  
 1029 December 14 earthquake. The dashed rectangle delineates the area analyzed for slope orientation  
 1030 shown in the inset. Inset figure: Detailed analysis of the aspect and slope (in degrees) of landscape  
 1031 slopes within the dashed rectangle. (a) shows the aspect and slope of all pixels, while (b) highlights  
 1032 pixels with slopes greater than 20 degrees. Green arrows indicate the preferential orientation of  
 1033 fault planes for the Barranca del Muerto and Mixcoac faults as determined in this study.



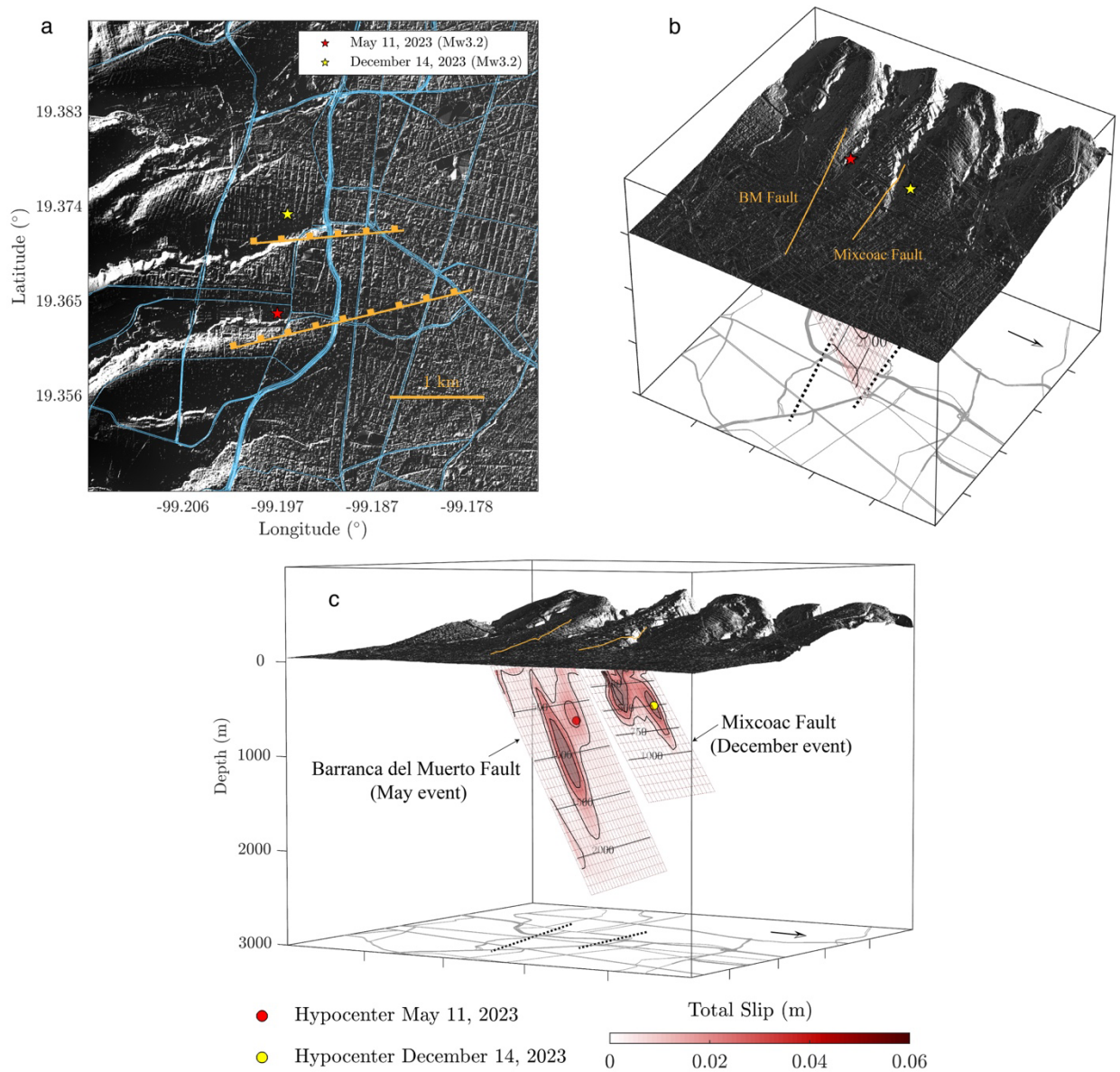
1034  
 1035 **Figure 2.** 12-day Sentinel-1 coseismic interferograms and Saliency-Based Quadtree Sampling  
 1036 (SQS). Dates used for generating each interferogram are specified in the upper part of each pane.  
 1037 (a) Coseismic interferogram and SQS for the May 11, 2023 event. (b) and (c) Coseismic  
 1038 interferograms and corresponding SQS obtained from ascending and descending orbits,  
 1039 respectively, for the December 14, 2023 event.



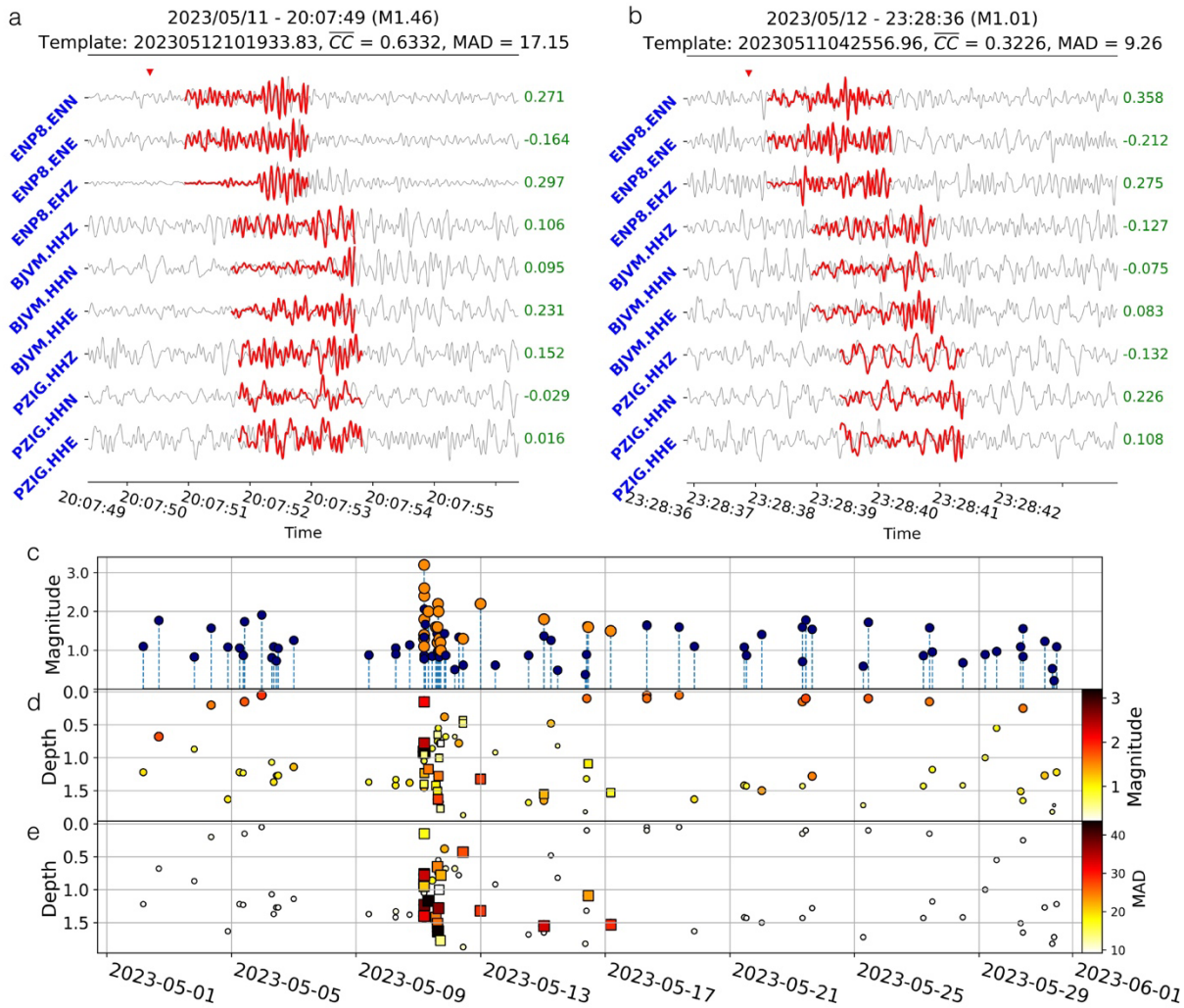
1040  
 1041 **Figure 3** Misfit error evolution and fault parameters convergence during the Simulated Annealing  
 1042 inversions of InSAR data for the May (blue) and December (green) events on the Barranca del  
 1043 Muerto and Mixcoac faults, respectively. See Section 2.3 and Figure S5 for the problem geometry.



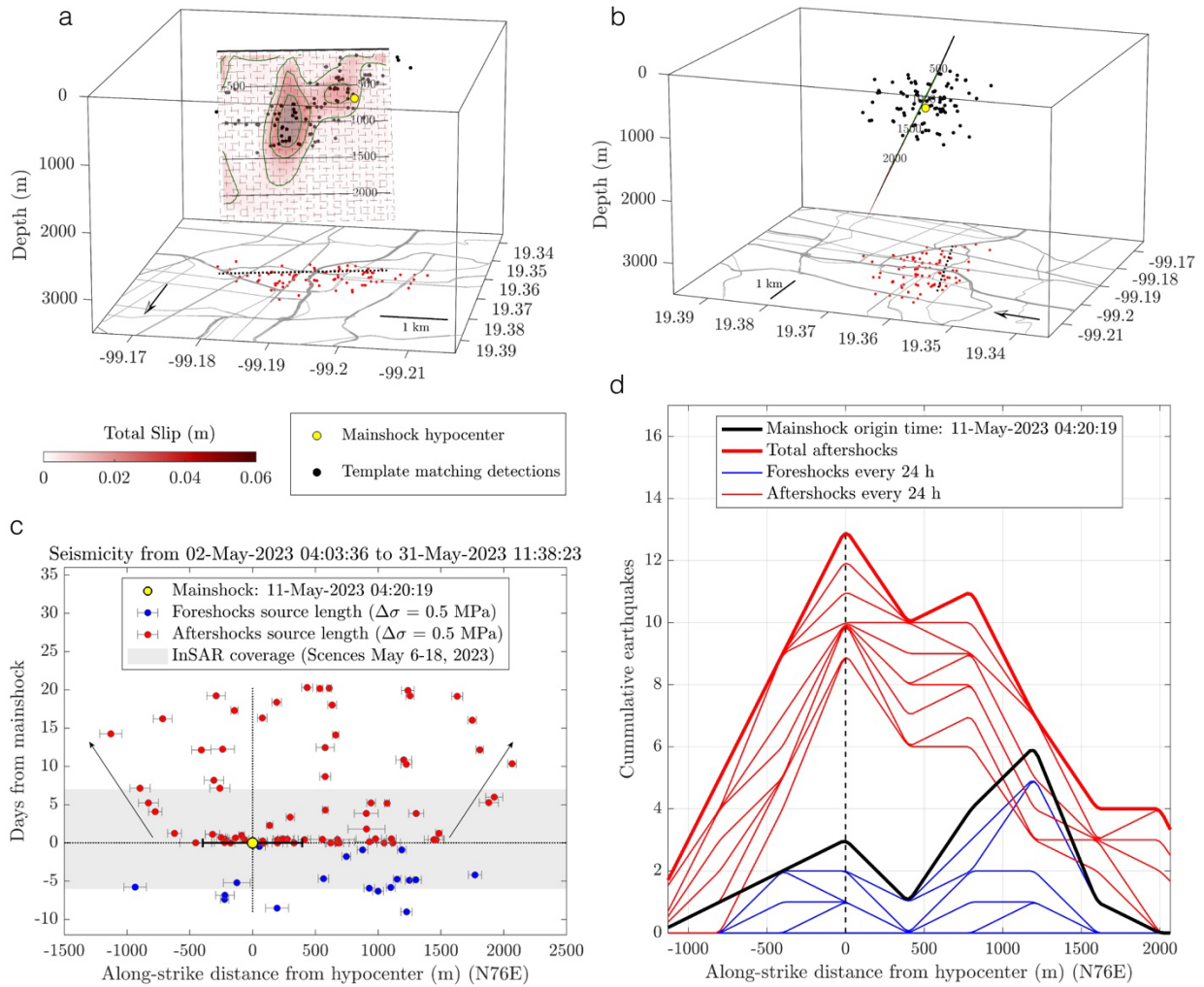
1044  
 1045 **Figure 4** Slip inversions from InSAR data of the May and December events on the Barranca del  
 1046 Muerto (a) and Mixcoac (d) faults by means of the ELADIN method. Comparison of the data and  
 1047 the model predictions within 400 m from the two A-A' profiles are shown in (b) and (e), and the  
 1048 inversions error distributions in (c) and (f).



1049  
 1050 **Figure 5** Three-dimensional rendering of the InSAR inverted slip on the Barranca del Muerto and  
 1051 Mixcoac faults. Notice the structural connection between both blind faults and two north-facing  
 1052 cliffs west from them. The blue curves in (a) show the Mexico City main streets. The topographic  
 1053 relief is exaggerated four times.



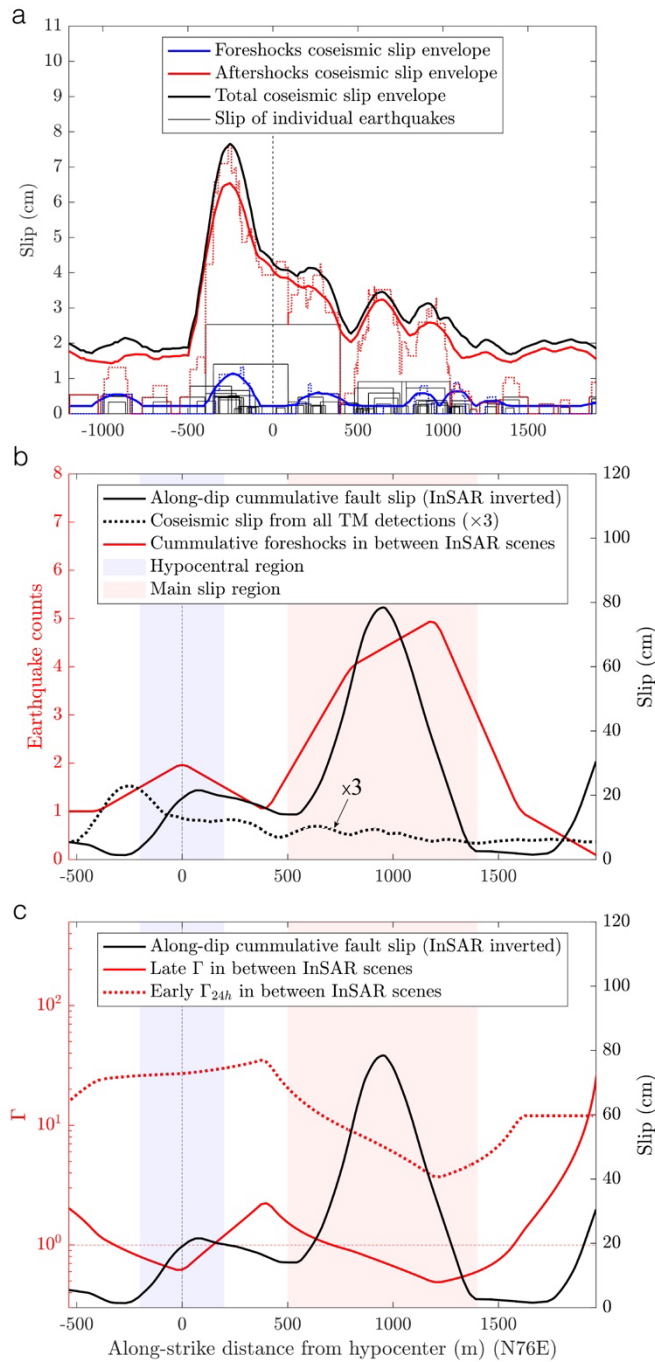
1054  
 1055 **Figure 6** Template matching detections. (a) and (b) shows the comparison between the template  
 1056 (red lines) and the continuous recording (gray lines) for two events detected using the TM with  
 1057 MAD of 17.15 and 9.26, respectively. (c) shows the temporary evolution of the catalog from May  
 1058 1st through 31st, templates are shown in orange and TM detections in blue. (d) and (e) indicates  
 1059 the depth distribution of the detections.



1060

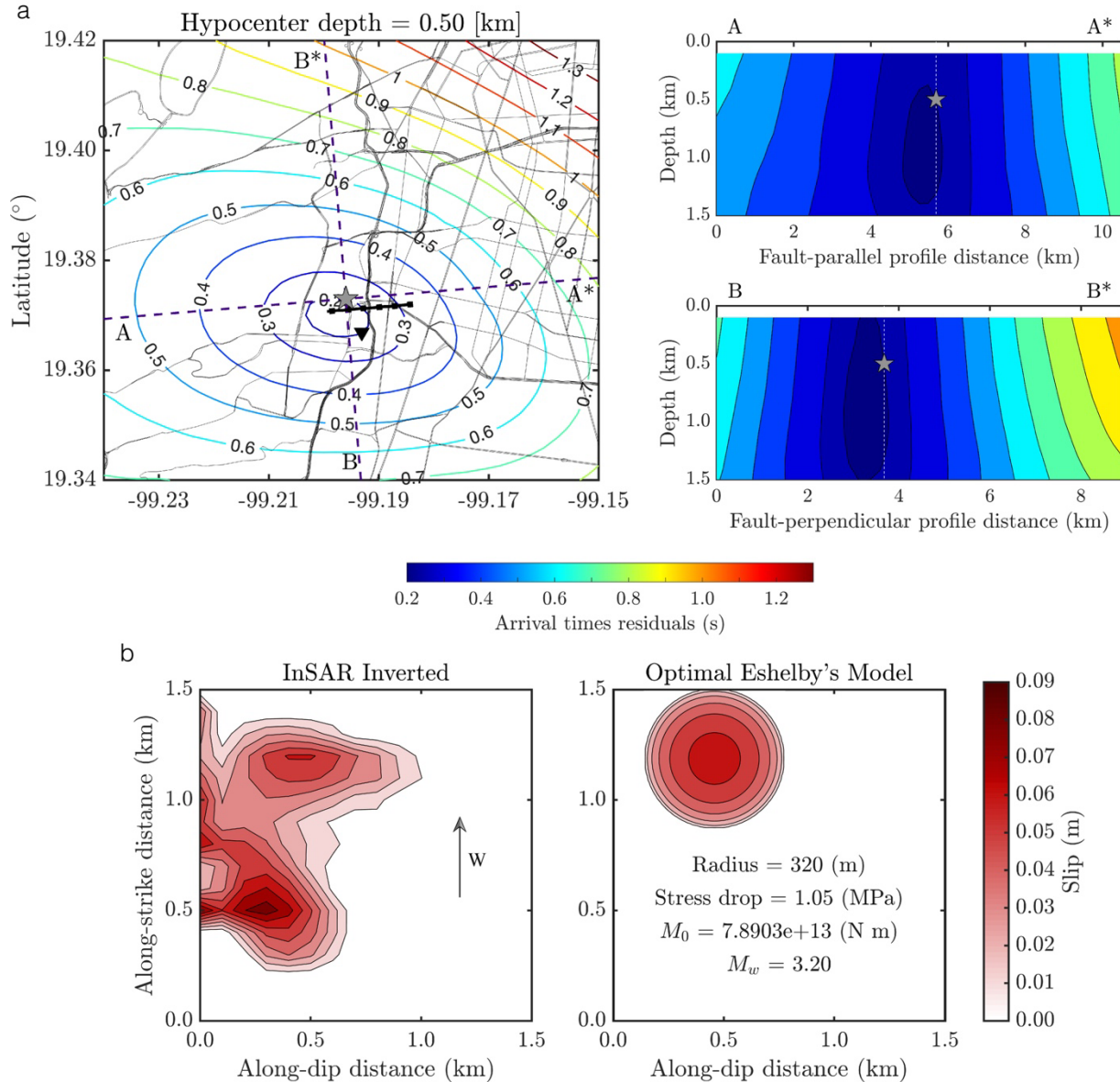
1061 **Figure 7** Analysis of the template matching detections for May 2023. (a-b) Three-dimensional  
 1062 rendering of detected earthquakes around the May slip event on the Barranca del Muerto fault. The  
 1063 bottom gray lines depict the Mexico City main streets and the yellow dot the mainshock of May  
 1064 11, 2023. (c) Fault along-strike projection of the events and their timing with respect to the  
 1065 mainshock of May 11 (yellow dot). Blue dots correspond to foreshocks and red dot to aftershocks.  
 1066 The horizontal brackets show the source length of each event estimated from Eshelby's model for  
 1067 a stress drop of 0.5 MPa. The gray band represents the time interval between the two InSAR scenes  
 1068 used to invert the slip shown in (a). (d) Along-strike cumulative count every 24 hours of foreshocks  
 1069 (blue) and aftershocks (red) as a function of distance from the mainshock hypocenter.



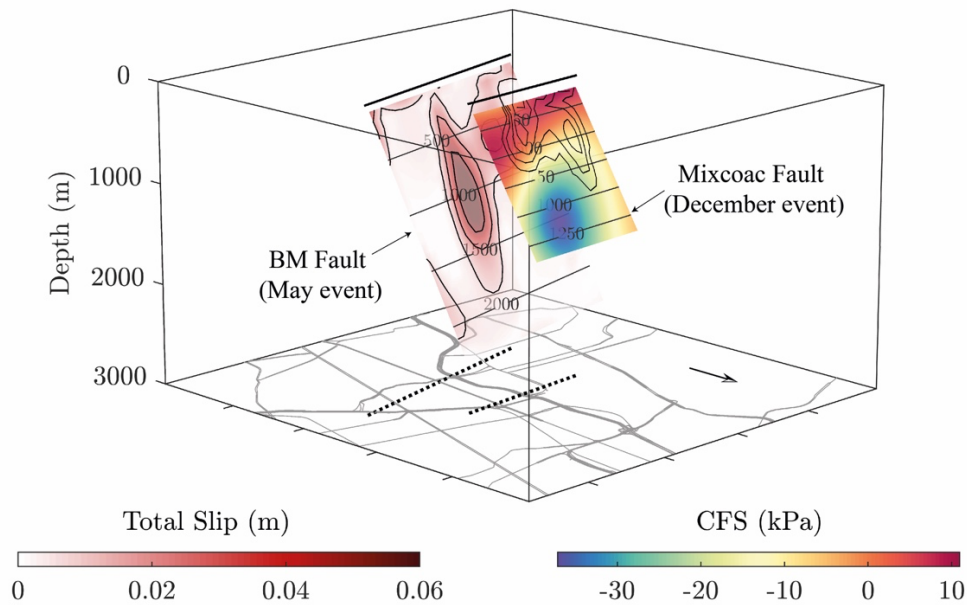


1070  
 1071 **Figure 8** Analysis of the template matching detections for May 2023. (a) Individual average slip  
 1072 for all detections (boxcars) estimated from Eshelby's model assuming a stress drop of 0.5 MPa as  
 1073 a function of the along-strike distance from the mainshock hypocenter. The blue and red curves  
 1074 depict the envelopes of the cumulative slip from foreshocks and aftershocks, respectively, and the  
 1075 black curve the cumulative slip for all the events. (b) Comparison of the cumulative count of  
 1076 foreshocks (red curve), the InSAR-inverted along-dip cumulative slip (black curve) on the BM  
 1077 fault, and the cumulative slip from all foreshocks (dotted curve) show in (a) with the blue curve.  
 1078 (c) Comparison between the InSAR-inverted along-dip cumulative slip (black curve) on the BM

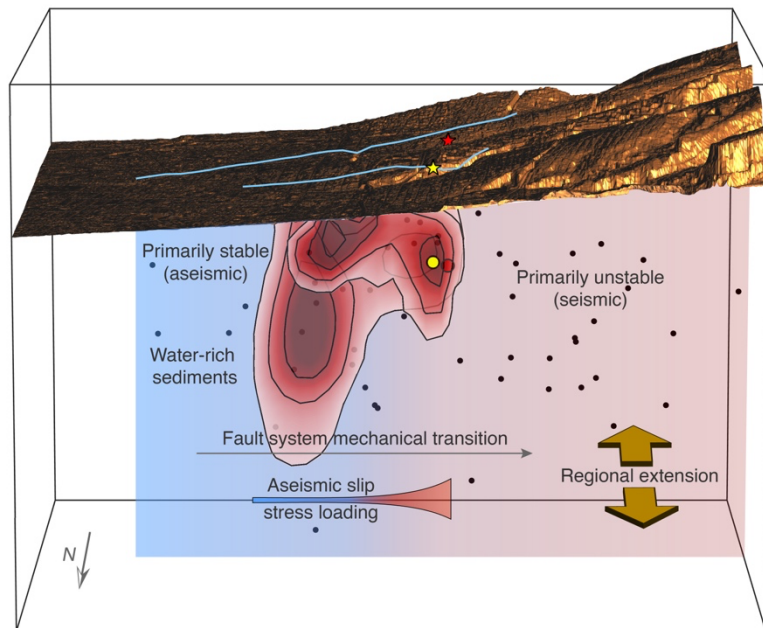
1079 fault and the aftershocks vs. foreshocks production rates during the first 24 h after the mainshock  
 1080 (dotted red curve) and for the remaining five days before the second InSAR scene used to invert  
 1081 the slip event in the BM fault (solid red curve). See text of Section 2.5.  
 1082



1083  
 1084 **Figure 9** (a) RMS errors for the P- and/or S-waves arrival times at 48 seismic stations with  
 1085 epicentral distance smaller than 10 km, estimated for all possible foci locations in a 3D volume  
 1086 together with our preferred hypocentral location for the December 14, 2023, mainshock (gray star).  
 1087 (b) Comparison between the InSAR inverted slip for the December event on the Mixcoac fault  
 1088 (left) and the slip distribution that best explains the western slip asperity (right) given by the  
 1089 Eshelby model. The optimal model parameters are given within the right panel.



1090  
 1091 **Figure 10** Coulomb Failure Stress (CFS) change imparted by the May slip event on the Mixcoac  
 1092 fault. Black contours on the Mixcoac fault correspond to the inverted slip for the December event  
 1093 shown in Figures 4d. Notice how the shallow slip distribution on the Mixcoac fault surrounds the  
 1094 deep stress shadow and concentrates to the east, where CFS is maximum.



1095  
 1096 **Figure 11** Conceptual model summarizing the main findings and ideas. Major aseismic slip  
 1097 asperities to the east of both faults (see Figure 4) produce stress buildup to the west, where the most  
 1098 intense 2023-2024 microearthquakes are concentrated. Slow slip occurs on the flat part of the city  
 1099 beneath water-rich sediments promoting aseismic deformations. The earthquakes shown (black  
 1100 dots) correspond to the double-difference relocations reported in Figures 4a and 4d and arise from

1101 an extended fracture system where the major faults have a geomorphic expression west of the city.  
1102 Note that the two Mw3.2 mainshocks of May 11 (red symbols) and December 14 (yellow symbols)  
1103 are located near the western ends of the slip faults, where a mechanical transition between stable  
1104 and unstable slip appears to occur. The studied seismic swarms may thus be a consequence of the  
1105 regional N-S extensional regime, the stresses induced by slow slip on the eastern fault segments,  
1106 and the elastic interaction between these major faults.