The first instrumentally resolved complex seismic faulting near Bogotá

- the 2019 Mesetas Mw 6.0 earthquake sequence

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Key Points:

- For the first time, an M~6 earthquake sequence is in-depth analyzed in a focal zone potentially affecting Bogotá with future M>7.
- The 2019 sequence and reinterpreted geomorphology data reveal recently activated faults.
- Two mainshocks occurred as doublet on nearly parallel faults oblique to the major Algeciras Fault System.

Abstract

The Northern Andes boundary is a first-order tectonic structure in Colombia with historically M>7 earthquakes. However, details about the individual sections of the system remain unknown. We illuminate the seismotectonic of the Algeciras fault by investigating an earthquake sequence that started on December 24, 2019. Using recent seismic networks of the region, we estimate focal mechanisms of the foreshocks and aftershocks, local stress field, kinematic slip models of the largest events, and Coulomb stress changes. Two mainshocks (a doublet of Mw 6.0 and 5.8) occurred within 16 minutes, rupturing just a few kilometers from each other. Discrimination of causative faults among the centroid moment-tensor nodal planes is difficult because the focal zone is a complex tectonic environment. We reinterpret local faults using geologic information, geomorphology and combine this new information with seismology results. The relocated aftershocks show a cluster with an L-shaped pattern concentrated in a ~7 km x 7 km area. Our model defines the Algeciras fault with two structural styles merging to the Guaicáramo Fault System and border the Eastern Cordillera to the east, supporting its regional dextral and transpressional kinematics. The NW part is characterized by a duplex-style of right-lateral strike-slip with inner secondary faults of the same sense or movement, and the SE zone by a domino-style system with inner minor faults of sinistral kinematics. The earthquake doublet is a part of the duplex style, whereas, the south part of the aftershocks is located on the domino-style, of the northern termination of the Algeciras Fault System.

Plain Language Summary

We studied the twin earthquakes (Mw 6.0 and 5.8) of December 24, 2019, and their sequence of aftershocks occurred in the settlement of Mesetas, department of Meta, Colombia. The seismic activity is located 200 km southeast of the capital of the country in the foothills of the Eastern Cordillera in a region of high seismic potential between Algeciras and Guaicáramo fault systems. To investigate the earthquake rupture, we used local and regional seismic waveforms to estimate seismic source properties of main events and its 17 aftershocks (M>4) through several methods, such as the analysis of location, focal mechanism, finite-extent modeling of slip distribution on the assumed fault planes, and Coulomb stress transfer. Furthermore, we performed geologic and tectonic analysis, such as mapping the fault traces based on geomorphology. We conclude that the Algeciras Fault System is marked by a dextral combined pattern (duplex and domino styles) before reaching the Guaicáramo Fault System and to define the eastern boundary of the cordillera. The results may be useful for seismic hazard assessment in the Bogota region.

Introduction

Bogotá, with a population of 8 million and the capital of Colombia in NW South America, is one of the global megacities with high seismic risk (Acevedo et al., 2020; Cardona et al., 2018; Riaño et al., 2021). A likely location of M>7 earthquakes that represent a major future threat for the city is known to exist within 100 km (Algeciras Fault System, detailed below). Nevertheless, more than 50 years passed between the last M7 in this region and an Mw 6 earthquake that occurred there on 24 December 2019. It is the first instrumentally well-observed event and sequence in the region, so we fully analyze details of its source process and seismotectonic context. No other paper has been devoted to the 2019 event except InSAR study of Noriega-Londoño et al. (2021) and an electrical resistivity study (Vargas et al., 2021). The physics of the 2019 earthquake sequence is appealing mainly because it involves two mainshocks (Mw 6 and 5.8) that occurred close to each other in space and time (i.e., a doublet). Multiple-fault systems have been documented in different tectonic configurations worldwide. Questions have been raised regarding the geometry of the faults related to possible geological or rheological barriers. What mechanisms influence the migration of seismicity between fault segments? What is their relationship to the surface structures and whether new faults are created or the old faults are reactivated? Several studies have aimed to answer these questions in several regions, for example, the 2014 Ludian, China earthquake Mw 6.5 (Xie et al., 2015), the 2019 M 6.4 and M 7.1 Ridgecrest, California earthquakes (Huang et al., 2020; Wang & Zhan, 2020), and two nearby Mw 7.6 deep-focus earthquakes of 2015 in the Peru-Brazil border (Zahradník et al., 2017). Closely spaced doublets, with subevents occurring within a few kilometers and seconds of each other, are relatively rare, such as the Mw 7.1 Araucania earthquake of 2011 in the Chilean subduction zone (Hicks & Rietbrock, 2015), the Mw 5.6 mainshock of the Osaka sequence revealing mixed strike-slip and reverse faulting (Hallo et al., 2019), an Mw 6.8 mixed-faulting event at the subduction termination in Greece in 2018 (Sokos et al., 2020), and the Mw 5.7, 2019 salt-mines earthquake in the Sichuan Basin (Liu & Zahradník, 2020). The earthquake doublet analyzed in this paper reveals seismic source complexity near Bogotá, thus potentially contributing to regional hazard assessment.

The recent tectonic evolution of northwestern South America has been shaped by the complex interactions of the Caribbean, Nazca, South American plates, and the Panamá-Chocó block (Figure 1a). The contact zone between these plates, known as the North Andean Block (NAB), is a tectonic unit that originated from the interaction between terranes of different affinities, ages, and stress regimes that accreted to the continental margin of NW South America (Cediel et al., 2003; Escalona & Mann, 2011; Montes et al., 2005; Spikings et al., 2015; Taboada et al., 2000). At present, the NAB escapes to the northeast (Alvarado et al., 2016; Audemard & Audemard, 2002; Audemard & Castilla, 2016; Diederix et al., 2021; Gutscher et al., 2000; Mora-Páez et al., 2019; Nocquet et al., 2014; Trenkamp et al., 2002; Velandia et al., 2005) along several fault systems that define the NAB boundary in Ecuador, Colombia, and Venezuela. Recent GPS measurements have shown that the NAB moves at an azimuth of 60° at a rate of 8.6 mm/yr relative to the South American plate (Mora-Páez et al., 2019).

The northern section of the NAB border in Colombia (north of 4°N), named the Guaicáramo Fault System (GFS), is dominated by compressive stress regimes and thrust faulting (Diederix et al., 2021; Mora & Parra, 2008), while the southern section (south of 4°N), named the Algeciras Fault System (AFS), is dominated by a strike-slip and transpressive regime (Arcila, M. & Muñoz–Martín, 2019; Diederix et al., 2021; Velandia et al., 2005), see Fig. 1. The latter tectonic zone has been classified as a right-lateral wrench complex geometry where geomorphology, major historical earthquakes, and recent seismic events indicate neotectonic activity (Chicangana et al., 2022; Diederix et al., 2021; Noriega-Londoño et al., 2021; Velandia et al., 2005). The most recent paleoseismology study (Diederix et al., 2021) reports that at least seven M>7 events have occurred along the AFS since 8120 ± 145 BC.

The AFS is one of the most seismically active and continuous fault systems in Colombia and has produced the largest historical crustal earthquakes in the country, with magnitudes of M6+ on February 1616, M7+ on 6 March 1644 and 18 October 1743, Mw 7.1 on 12 July 1785, and Mw 6.7 on 31 August 1917. The last Mw 7.0 earthquake on 9 February 1967 destroyed some populated areas and even affected Bogotá, resulting in hundreds of deaths and extensive damage (Cifuentes & Sarabia, 2009; Dimaté et al., 2005). An Mw 5.9 earthquake on May 24, 2008, occurred close to the GFS (Dicelis et al. 2016), see Figure 1.

From a regional point of view, the transition between the AFS and the GFS was proposed as connected systems (Taboada et al., 2000; Velandia et al., 2005), although NE continuity is also considered since neotectonic activity is known to affect Quaternary deposits of the piedmont and the Llanos basin (LlB) (Gómez et al., 2015). To constrain the AFS at the eastern front of the cordillera, we mapped the fault traces based on hillshade images from digital elevation models with 30 and 12.5 m resolution (NASA – Alaska Satellite Facility (https://vertex.daac.asf.alaska.edu). From the identification of geomorphologic structures related to main and secondary faults, we highlighted the northern termination of the AFS (before its junction with the GFS), since it is well known that the whole system consists of several regional traces with important related earthquakes (Figure 1). However, details about the seismicity in terms of kinematics and structure in depth, remain unknown.

On 24 December 2019, an earthquake sequence started with two almost identical major earthquakes (Mw= 6.0 and Mw=5.8) near the Mesetas settlement in the Eastern foothills of Colombia, approximately 200 km southeast of Bogota (Figure 2). The two events occurred within just a few kilometers and 16 minutes apart, forming a doublet. They were preliminarily located by the National Seismic Network at 3.453°N and 74.194°W and 9 km in depth and 3.474°N and 74.242°W and 12 km in depth, respectively. Some damage to weak buildings was reported, most of which included cracks in cladding, cracks in walls, roof tiles falling, and cracks in structural joints between columns and beams. The following seismic sequence of about 412 aftershocks of M>2.0 lasted three months and showed an L-shaped pattern, suggesting a complex faulting (Figure 3a). The seismic sequence was situated less than 100 km northeast of the 1967 Mw 7.0 earthquake in a transference zone between the GFS and the AFS with a complex fault network. Therefore, the 2019 Mesetas sequence is important in magnitude and consequences, and the present study contributes to better characterization of the recent complex tectonic setting of the Northern Andes.

The Mesetas sequence was well recorded by broadband and strong-motion seismic networks, providing a unique opportunity to decipher the rupture processes and draw their geological implications. To this goal, we model the largest events in terms of centroid moment tensors, space-time development of slip on the faults, local stress field, and Coulomb stress transfer. Seismology and geology results are combined to improve understanding of the complex faulting style of the Algeciras Fault. We interpret the mainshocks as related to the activity of the northern termination of the AFS, developed in two structural styles, as we show later. These results reveal unprecedented details about active faulting in this complex yet poorly known region and may also improve seismic hazard assessments of the nearby densely populated areas of Bogota.

Tectonic insight

The study area occupies the eastern boundary of the NAB (Figure 1a), which is referred by some authors as the Eastern Front Fault System (EFFS) in Colombia and Venezuela (Pennington, 1981; Kellogg and Vega, 1995; Taboada et al., 2000; Audemard and Audemard, 2002; Diederix et al., 2020). In Colombia the EEFS is outlined by the Guaicáramo Fault System (GFS), while the Algeciras Fault System (AFS) crosscuts the Eastern Cordillera and the whole Andes since connecting with the Chingual-Cosanga-Pallatanga-Puna fault system (CCPP) up to the Gulf of Guayaquil in Ecuador, defining the eastern tectonic boundary of the NAB (Alvarado et al., 2016; Velandia et al., 2005).

The Eastern Cordillera border is interpreted as the result of transpression generated by right lateral movement of the AFS and the EFFS during the Quaternary (Audemard & Audemard, 2002; Audemard M. & Castilla, 2016; Diederix et al., 2021; Gutscher et al., 2000; Mora-Páez et al., 2019; Nocquet et al., 2014; Trenkamp et al., 2002), promoting the "escape" of the Northern Andes to the NE with respect to the South American Plate. The motion along the AFS is predominantly dextral strike-slip type with dip component (Chicangana et al., 2022: Noriega-Londoño et al., 2021; Velandia et al., 2005), however, from the latitude 4ºN to latitude 7ºN, along the GFS, the movement is predominantly of dip-slip thrusting. The AFS zone is identified by the presence of several pull-apart basins, extensive and rhomboidal shaped and releasing sidestep basins. Furthermore, synthetic and antithetic faults, as Riedel type, and slight folds located obliquely to the main trace of the system are observed (Velandia et al., 2005). The AFS behaves as a right lateral wrench complex structure, with a major vertical component in which sedimentary cover and basement rocks are involved (Velandia et al., 2005).

The continuity of the AFS to the north was interpreted as connecting the GFS along the eastern piedmont of the Eastern Cordillera (Velandia et al., 2005), but also trending NE along the Río Meta Fault (Audemard & Castilla; 2016; Mora et al., 2013). Nevertheless, here, we constrain the northern termination of the AFS as a regional and independent structure with its own style.

Geomorphological mapping

Before proceeding to the study of the Mesetas latest seismicity, we supplement existing geology information by our own analysis. In particular, we developed detail on the AFS mapping based on geomorphology criteria (Figure 2), which let see the principal displacement zone and minor Riedel structures in a similar model of the strike-slip faulting documented by Christie-Blick & Biddle (1985). Within the morpho-structures, we identified pressure and linear ridges proper of restraining bends and contractional oversteps, also some linear depressions that are located along releasing bends of the main fault system to the right (meaning dextral slip). Other geomorphological features can be observed, such as triangular facets, fault scarps, L-shaped spurs, fault saddles, offset and drainage control, all of them as signals of neotectonic activity. Dextral kinematics of the whole system is confirmed by the geometry and orientation of the minor Riedel traces: NEE (R), E (R'), and NNE (P), while the AFS is trending NE (Figure 2). These Riedel faults work on drainage organization and the occurrence of some ridges and depressions.

These geomorphological features show the AFS as a transpressional style, with secondary faults and local restraining bends of the oblique structures, similar to several world examples documented by Mann (2007). The geomorphology and structural style show the thickening of this fault system towards the north, defining its termination along a regional restraining bend with a positive flower structure. The fault geometry of this transpressional termination can be explained by two domains from the main trend of the Algeciras fault (Figure 1 and 2): i) a dextral transpressive duplex, with the Ucrania fault as the northwestern border, where the oblique inner and minor faults are subparallel and resolve with the same dextral strike-slip kinematics, and ii) a recent domino-style system (where La Florida fault constitutes the southeastern frontal trace of the positive flower structure, as a shortcut from the Algeciras main fault, and between them, a linked set of inner secondary faults in opposite kinematics (sinistral), crossing by a longitudinal back-thrust fault verging northwest, all implying internal rotation of the minor blocks. Similar mixed tip damage zones for the terminations of strike-slip faults are explained by Kim et al. (2004), working from small to large scales.

Relocation of the Mesetas sequence

The Mesetas earthquake sequence comprised 412 events of $M > 2$ (Figure 3). The first arrivals of P- and S-waves were manually picked using 64 stations (Figure 4). The locations were first determined with the NonLinLoc code (Lomax et al., 2000) in the velocity model of Pedraza & Pulido (2018); this model agrees with a previous study of receiver functions and ambient noise tomography (Poveda et al.,2018) developed in the zone. The NonLinLoc locations provide quite a diffuse foci distribution (Figure S1). We then relocated the sequence using the HypoDD code (Waldhauser & Ellsworth, 2000) with the same velocity model, and the foci were efficiently clustered (Figure 3). The epicenters indicate an L-shaped pattern (Figure 3a). It formed within a few hours after the mainshock and remained stable for the whole ~160-day duration of the sequence (Figures S2 and S3 with 24 hours and 160 days, respectively). The sequence occurred between depths of 5 and 20 km in a 7 km x 7 km area (Figure 3).

For the two mainshocks, M1 and M2 (Mw 6.0 and 5.8, respectively), a detailed uncertainty analysis of their hypocenter position was performed, as shown in Figure S4. We used the Oct-Tree method implemented in NonLinLoc, which samples the location probability density function (”scatter cloud”). Due to the network geometry and picking errors, the clouds are elongated approximately in the N-S direction. Dimensions of the M1 cloud based on its confidence ellipsoid are 7.7 km for the major axis and 2.2 km for the intermediate axis. Likewise, for M2, we found values of 7.9 and 1.6 km for the major axis and intermediate axis, respectively. The RMS location errors for the M1 and M2 events are 0.34 s and 0.31 s, respectively.

Two mainshock locations are shown in Figure 3a. Their hypocenters are situated at the bottom of the activated region at a depth of 18-20 km (Figure 2b). Within the uncertainty, the epicenter of M2 is shifted ~2 km in the southwestward direction relative to M1. Although the best-fit hypocenter of M2 is ~5 km shallower than M1, their relative depth shift is less well resolved (see Figure S4 which also shows a trade-off between depth and the NS position).

Moment tensor solutions

Centroid moment tensors (CMTs) were carefully determined by full-waveform inversion of 29 near-regional records, 14 broadband, and 15 strong-motion stations (code ISOLA, Zahradník & Sokos, 2018). Records from broadband and strong motion stations were used (see Figure 4), comprising epicentral distances between 31 and 335 km and relatively low frequencies (0.02-0.05 Hz). The selection of stations and frequency bands was based on the data quality, requiring low noise and the absence of instrumental disturbances. MT was obtained by the least-squares method, assuming a single-point source model. Centroid depth was grid searched beneath the epicenter of each event. Green's functions were calculated with the same 1D model as used for the locations (Pedraza & Pulido, 2018; Figure S1). The depth variation of the correlation between real and synthetic seismograms for the mainshocks is shown in Figure 5, and the respective waveform fit is displayed in Figure 6.

Interestingly, the MTs of M1 and M2 are almost identical, featuring a strike-slip mechanism with a reverse component, characterized by strike/dip/rake (s/d/r) angles 210°/73°/158° and 197°/72°/156° for M1 and M2, respectively. We did not have a prior preference for rupture of these or conjugated nodal planes. The centroids are situated at depths of 10-14 km, the double-couple percentage of M1 (<80%, Fig. 4) is lower than that of M2 (>80%). The CMT inversion is stable around the best-fitting depth, and the waveform fit between real and synthetic seismograms is very good, with variance reduction VR~0.87 and ~0.86 for M1 and M2, respectively (Figure 6). For details, see Table S2. CMTs of 14 aftershocks (Mw > 4) exhibit a mix of strike-slip and reverse faulting, and centroid depths ranging between 5 and 17 km (Figure 3).

Inference about faults and their seismic slip

In this section, we present plausible kinematic models of the two mainshocks (Figure 7). The space-time distribution of the slip and slip rate is calculated by linear full-waveform inversion using the LinSlipInv method (LSI, Gallovič et al., 2015), developed and thoroughly tested in recent years (Mai et al., 2016; Pizzi et al., 2017, etc.). Model parameters are samples of the slip-rate time function over a gridded fault and over the whole duration of the source process. The inversion is regularized by smoothing, by ensuring slip-rate positivity, and by seismic moment (estimated in the CMT inversion). Optimal free parameters of the slip inversion were established by extensive testing: (i) subfaults are 1 km x 1 km, (ii) frequency range of 0.05-0.20 Hz for all stations of Fig. 8, (iii) smoothing between 0.01 and 0.05 m, which represents the data error in the method. Some stations or components were effectively removed from the inversion by down-weighting by a factor of 0.001; the station components remained in the modeling to check how they were predicted by the slip model derived from the remaining stations (shown in gray in Figure 8 and Figure S5 with a bad fit between real and simulated seismograms). In this method, the rupture model is inverted without prior constraints on the position of the nucleation point. The inversion of each event requires a predefined fault plane. To constrain the likely fault planes, we critically examine and combine several pieces of information, such as the position of hypocenters, centroids, and aftershocks.

Beyond the L-shaped aftershock distribution seen in the map view of Figure 3a, in 3D, it is not easy to recognize simple geometrical structures, such as possible fault planes, because (as indicated above by the focal mechanisms) the involved faults are not vertical. Another issue is that aftershocks, although relatively well clustered by double-difference relocation, are still dispersed, partly due to location uncertainties and partly due to possible activation of several different short faults. In this study, we construct trial faults of the two mainshocks as planes passing through their hypocenters. Both nodal planes are tested as potential fault planes in the slip inversion, and it is also tested whether these planes fit aftershocks. With the trial fault planes, we performed approximately 100 slip-inversion tests, until finding good stability and quality parameters in the inversion.

Based on the CMT (s/d/r angles) and the aforementioned tests, we suggest two scenarios, A and B (see Figure 6). In both scenarios, mainshock M1 has a fault plane striking at 210° and dipping 70°. The conjugate nodal plane of M1 was denied for its poor waveform fit in the kinematic slip inversion. Regarding M2 (motivated by the L-shaped aftershock pattern), in scenario A, this event is assumed to have ruptured the conjugated plane characterized by a strike of 298° and dip of 60°. In scenario B, the M1 and M2 fault planes are almost parallel, with M2 characterized by a strike of 197° and dip of 70°.

Slip models are shown in Fig. 7a. We note that they are heavily smoothed due to the stabilizing constrain; that is why the models resemble rather a smoothed centroid, which could be improved only if (more) local stations were available. Stable and unstable features of the slip rate and slip distributions can be identified in Figures 7b and 7c, respectively. We set time t=0 at 3 seconds before the origin time of M1 and at 2 s before M2. The stable features are as follows: (i) M1 consists of the main moment release at t=4 s, continuing for the next two seconds (t = 5 and 6 s) with a still significant slip rate. (ii) M2 is simpler due to its smaller magnitude, primarily rupturing at t=2 and 3 s. Less stable features include disturbances, or 'ghosts' (i.e., regions of low slip rate), for example, at t=2 s in M1 and t=5 and 6 s in M2. The ghosts are artifacts common to all slip inversions due to imperfect modeling, such as inaccurate position of the fault or inaccurate velocity model (Gallovič et al., 2015; Gallovič & Zahradník, 2011; Zahradník & Gallovič, 2010). In our case, M2 with a strike of 197° (scenario B) provides a cleaner slip-rate pattern in the initial phase of the process (t=0 and 1 s), and the waveform fit (VR) is higher than that of scenario A. The waveform fit of scenario A is worse, especially for near stations (Figure S5). Scenario B fits seismic data in the 0.02–0.5 Hz range with variance reduction (VRs) of 0.61 for M1 and 0.72 for M2 (see Figure 8). For these reasons, we prefer scenario B, i.e., M1 (strike 210°) together with M2 (strike 197°). Furthermore, we discuss which of the scenarios should be preferred in the Discussion section, considering additional arguments.

We do not broadly discuss the absolute size of the slip patches (10 x 10 km) and the maximum slip (~30-40 cm) for two reasons: they are not critical from the tectonic viewpoint, and they depend on the adopted smoothing. We tested suitable spatial smoothing following Gallovič et al. (2015). The smoothing parameter of 0.01-0.05 m was chosen as a compromise between the simplicity of the slip pattern (minimum 'ghost' features) and the waveform data fit. Nevertheless, our slip model agrees with empirical relations (Somerville et al., 1999) that predict 30 and 16 cm of maximum slip for M1 and M2, respectively. Regarding the space-time development of M1 and M2, we find in Figures 7b-7c that rupture propagated basically upward. In M1 and M2 (scenario B), we also detected an anti-strike component of rupture propagation in the north-north-eastward direction (i.e., at a 20° azimuth).

Discussion

As inferred from the previous analysis, the fault interpretation of M1 mainshock is well constrained, while M2 is unclear. Therefore, we discuss the two scenarios from the viewpoint of aftershock locations, Coulomb, and tectonics interpretation.

Regarding the aftershock distribution relative to the fault planes, there is no significant preference for scenario A or B. This can be seen in Figure S7 and even better if using a 'rotating' 3D plotting tool, included in the Supporting material of this paper. Indeed, the aftershock cloud seen in the map-view as the SE trending arm of the L-shaped pattern (Figure 3a) can be explained by M2 with strike 197° (scenario B), not strongly requiring a strike of ~298°, orthogonal to M1. If M2 ruptured the plane striking at 298° according to scenario A, many aftershocks project onto the main slip region of that event, unlike M1 (Figure 7a). In scenario B, both M1 and M2 events have their major slip regions associated with the paucity of aftershocks, similar to many other earthquakes (e.g., Das & Henry, 2003; van der Elst & Shaw, 2015; Wetzler et al., 2018). Thus, we consider the aftershocks to support scenario B. The interpretation of the seismological data presented above is well constrained and related to the transpressive structure of the AFS, whether to the duplex of the NW domain or the transverse faults of the SE domino (in plane view). As indicated in Figure 7a, the subparallel faults of M1 and M2 (scenario B), both characterized by right-lateral strike-slip motion with a reverse component, fit well into the general framework of the left-stepping restraining bend.

We estimated the stress field using the StressInverse code by Vavryčuk (2014), shown in Figure 3d. It is characterized by the principal stress axes $_1$ azimuth/plunge = 88°/4°, $_2$ = 350°/61°, $_3$ = 180°/29° and a stress-shape ratio of 0.56. This stress field has two optimally oriented faults (OOFs), characterized by s/d/r (°) = 232/63/168 and 305/69/21 (see Figure 7a). In this context, we can speculate that each mainshock ruptured one of these two OOFs. Such examples have been documented in the literature (e.g., Fojtíková & Vavryčuk, 2018; Noisagool et al., 2016; Singh et al., 2017; Vavryčuk, 2011) and would favor scenario A. Nevertheless, scenario B also remains plausible, i.e., stress-favored, with both M1 and M2 rupturing close to one of the OOFs (within 30° in terms of Kagan angle) with the reactivation of a minor transversal fault of the domino domain, according to the SE side of the L-shaped aftershock pattern.

Note that the transpressive regime (with parallel faults such as in scenario B) is supported by the focal mechanisms of aftershocks (see the ternary diagram in Figure 3c) as noted also by Noriega-Londoño et al. (2021). Furthermore, the tectonic escape of the NAB northeastward that takes place along the AFS and GFS, as suggested by several authors (Gutscher et al., 2000; Audemard & Audemard, 2002; Trenkamp et al., 2002; Nocquet et al., 2014; Alvarado et al., 2016; Diederix et al., 2021; Velandia et al., 2005) and confirmed by Mora-Páez et al. (2019), who estimated a velocity of 8.8 mm/yr, also favors scenario B (according to the main fault system). This escape rate in the Eastern Cordillera is greater than the rate of range-normal shortening (4.3 mm/yr; Kellogg et al., 2019).

Owing to the spatial and temporal proximity of the mainshock, it is natural to assume that M2 was triggered by static Coulomb stress transfer from M1. The Coulomb 3.3 software (Toda et al., 2011) was used, methodology implemented in previous studies in Colombia (Mayorga & Sanchez, 2016, Dionicio & Sanchez, 2012). We applied the slip distribution of M1 (Figure 7c) and calculated Coulomb stress transfer to receiver faults everywhere in space with focal mechanisms of M2 in scenarios A and B. The effective coefficient of friction was 0.4. We investigated whether a positive change correlates with the hypocenter position of the M2 mainshock, including its uncertainty documented in Figure S4. Figures 9 and S6 show the Coulomb stresses for the two receiver focal mechanisms. Positive stress zones were compared with the hypocenter of M2, considering its NonLinLoc uncertainty (Figure S4). We found that, in general, stress transfer supports M2 situated near the lower and southwestern edges of the M1 rupture region, but neither scenario A nor scenario B could be strongly preferred due to uncertainty in the M2 depth (Figures 9 and S6). However, if considering the best-fitting NonLinLoc location of M2, scenario B is preferred, since the M2 depth would correlate with significant positive stress concentration (right panel of Figure 9).

The nature of the AFS (before its junction with the GFS) shows dextral transpressional kinematics, through a positive flower structure, which shows combined structural styles: duplex and domino (Figure 10). The Mesetas doublet and its aftershocks occurred in this zone, where these styles are separated by AFS. The aftershocks locations from NLL, HypoDD, and the CMT inversion suggest that M1 and M2 (scenario B), ruptured within AFS close to duplex style, consistent with dextral and transpressive kinematic. The formed L-shaped seismicity is located between both styles, the northern section of L is located on duplex style, and the southern part on domino style, which matches with an inner secondary fault with opposite kinematics (Figure 10c, in red). Our results suggest the activity of this identified fault from the new morphological results and are supported with seismological evidence. This fault has an approximate length of 3.5 km according to geomorphological results. Considering the rupture of M2 (scenario A) within this fault, it would not be possible to produce an earthquake of magnitude 5.8, as is the case of M2, in which our kinematic inversion results suggest a fault with an approximate rupture area of 11 x 9 km, being more plausible scenario B. However, this fault can generate smaller events (<M4.9) such as those observed in the southern part of the L-shaped sequence, this assuming the relations of Wells & Coppersmith (1994) for a transcurrent fault.

Combining several pieces of information as the orientation of the principal stresses (1 azimuth/plunge = 88°/4°, 2 = 350°/61°, 3 = 180°/29° from stress analysis, the optimally oriented faults (OOFs), characterized by s/d/r (°) = 232/63/168 and 305/69/21 and geomorphology information, the Mesetas doublet is schematized by the interaction of two structural styles: duplex and domino, generated by transpressive regional tectonics where AFS is the main system. The

Ucrania and La Florida faults are the northwestern and southeastern borders respectively of a regional restraining bend with a positive flower structure. The local stress field provides an explication of this regional environment in a transpressive way. Furthermore, the optimal orientation of faults (OOFs) is probably that is related to the orientation of the minor Riedels related to duplex and domino styles (Figure 10b). These faults appear en-echelon form, with a separation that can range from millimeters to kilometers (Hanmer & Passchier, 1991). Is the case the new identified fault with a longitude approximate of 3.5 km, that coincide with the southern part of L-shaped seismicity (Figure 10c).

This interpretation is supported by the resulting L-shaped relocation of aftershocks recorded by the regional seismic network (Figure 4 and 10c), where the cluster observed connects the AFS (northern part of L-arm) with an orthogonal fault in the domino-style (southern part of the L-arm). The kinematic inversion results, with M1 rupturing on the plane of at 210° and dipping 70° (from CMT results) and M2 on the plane of 197° and dipping 70° (scenario B) supported by the results of Coulomb stress modelling (Figure 9) suggest that M1 and M2 are located within the Algeciras fault. Therefore, it is likely that the southern part of the L-pattern was triggered on the orthogonal fault system in the domino style, where minor faults with sinistral kinematics are located. The moment tensor and tectonic stress solutions show principal stress $_1$ of azimuth/plunge = 88°/4° (Figure 3d and 10c), this result is roughly in agreement with local transpressive stress regime in this area (Arcila & Muñoz–Martín, 2019). The occurrence of the Mesetas mainshocks on two closely spaced faults is explained in terms of the duplex style along a restraining bend zone and fit into the regional frame of transpressive tectonics (Figure 10a).

Conclusions

The 2019 Mesetas doublet (Mw 6.0 and 5.8, separated by a few kilometers and 16 minutes) and the associated aftershock sequence occurred at shallow depths

(5-20 km) on two nearly parallel right-lateral strike-slip faults with a reverse component (strike ~ 200°, dip ~ 70°, rake ~ 150°). Both were close to one of the optimally oriented faults existing in the local stress field that is characterized by the following azimuths/plunges of principal axes: $_1$ = 88°/4°, $_2$ = 350°/61°, $_3$ = 180°/29°, and stress shape ratio of 0.56. Both mainshocks ruptured basically upward and in the northeast direction relative to their hypocenters, with peak slips of approximately 0.4 and 0.25 m, respectively. The activated rupture planes, oblique to the dominant strike of the major Algeciras Fault System, can be explained in terms of the duplex style along a restraining bend zone and fit into the regional frame of transpressive tectonics. The proposed source characteristics imply that deterministic models for hazard assessment in the megacity of Bogotá should consider active structures possibly deviating from the known major faults and involving complexities (multiple faults). An example of this is a newly identified fault that is absent in the previous compilation of faulting in Colombia (Veloza et al., 2012, Paris et al., 2000). This fault has been identified from the crustal seismicity and with geomorphological expression, and oblique to the Algeciras Fault System (southern part of the L-arm) in the domino style (Figure 10).

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Figure captions

Figure 1. a) Simplified tectonic framework of NW South America with main tectonic structures (Nazca, Caribbean, South America and North Andean Block), Guaicáramo Fault System (GFS) and Algeciras Fault System (AFS) from the Global Active Database (Styron & Pagani, 2020). The vectors show the GPS-derived motion of the Nazca and Caribbean plates relative to the South American plate (Mora-Páez et al., 2019). b) Historical seismicity in SW Colombia, color-coded by earthquake depth, with focal mechanisms from the GCMT catalog and Mw 7.0 on 9 February 1967 from Suárez et al. (1983). Major earthquakes (1785, 1827, 1834, 1967 and 1917) are related to the Algeciras Fault System. Other important faults are also shown (Styron & Pagani, 2020). Blue square represents the location of Figure 2, principal area of this study. c) The red rectangle shows the location of (a).

Figure 2. a) Map with detailed morphostructural features interpreted along of the Algeciras fault system. Blue square represents the zone of Figure 2b. b) Location of earthquake doublet that occurred on December 24, 2019, with detailed fault mapping and focal mechanisms obtained in this study.

Figure 3. The Mesetas doublet (yellow stars) and aftershocks Mw $>$ 2, color-coded by earthquake depth. The event symbols and focal mechanisms are scaled by magnitude. Focal mechanisms are depicted for the aftershocks of Mw $>$ 4. b) Selected vertical sections based on the seismicity L-pattern and strike of M1 and M2, along profiles of Panel a. Shown in the sections are the events situated within a 1.5 km wide band. c) Ternary diagram obtained from focal mechanisms. d) Principal stress axes derived from the studied sequence based on the StressInverse code (Vavryčuk, 2014).

Figure 4. Seismographs used in this study. Stations of the Servicio Geológico Colombiano, were supplemented by two stations of neighboring countries (see also Table S1). Broadband (red triangles), short period (yellow triangles) and strong-motion (blue inverted triangles) stations were used to locate mainshocks M1 and M2 and aftershocks. For kinematic slip inversion, we used only the near-source strong motion network, whereas for CMT inversion, we used a combination of broadband stations (red triangles with green borders) and the strong motion network.

Figure 5. Depth variation of the single point-source deviatoric MT model of the (a) M1 and (b) M2 mainshocks.

Figure 6. The fit of the observed (black) and synthetic (red) displacement waveforms (in meters) for the single point-source deviatoric-MT model of the (a) M1 and (b) M2 mainshocks. Stations are sorted by epicentral distance from 150 to 334 km. Both data and synthetics are bandpass Butterworth filtered between $0.02 - 0.05$ Hz. The components with bad fit (gray) were removed from the inversion. BET and SPBC stations were not used in the M2 inversion due to instrumental disturbances in the records. (c) The stations of the Servicio Geológico Colombiano used in the inversion.

Figure 7. a) Proposed scenarios A and B of the two mainshocks. The M1 fault plane is fixed, while two trial positions of the M2 plane are considered. The top edge of the fault is marked by thick line. Superimposed on M1 are the optimally oriented faults of the region (dashed lines). b) Space-time evolution of the slip rate. Left column - M1, middle and right columns – M2 in scenarios A and B, respectively. The snapshots are marked with time, 0-9 s; t=0 is 3 and 2 seconds before the respective origin time of M1 and M2, respectively. VR marks variance reduction of the waveform inversion. c) Final slip distribution, arranged similarly to Panel b. Note the different scales of the subpanels. The blue stars are hypocenters from the NonLinLoc location (not used as a constraint for the rupture nucleation position) at depths of 12 km and 15 km for M1 and M2, respectively. In each subfault the source time function is displayed.

Figure 8. Comparison between observed (black) and simulated (red) waveforms for a) mainshocks M1 and b) M2 in scenario B. The gray traces represent the components with poor fitting, unused in the inversion. The station codes are on the right. Peak observed displacements are shown to the left. c) Strong motion stations of the Servicio Geológico Colombiano used in the slip inversion.

Figure 9. a) Coulomb stress transfer for scenario B with the M1 generating fault (213°/73°/158°) and M2 receiving fault (197°/70°/150°). The stress is plotted for a depth of 12 km, the segmented lines on the map show the strike of the receiver faults, and the red grid represents M1. The gray points represent the uncertainty of the absolute location of M2 from NonLinLoc, the star is the best-fit location of M2, lines A and B represent profiles, and the green line represents the projection of the fault top edge of M1 on the surface. b) Profile A with a vertical dip (90°) and c) Profile B with a 70° dip as M2. The red line represents a segment of the rupture area of M1, and the dashed blue line is the assumed M1 fault-center depth. Note the stress concentration on B-B' close to the star at a depth of 12 km, supporting scenario B.

Figure 10. a) General view of northern termination of the AFS with the major central fault and the Ucrania and La Florida as the borders of the transpressive system (positive flower structure). b) Schematic illustration to explain the mixed style of the termination of the AFS, and the optimally oriented faults (OOF) from stress analysis. c) Sketch of the northern termination of the AFS as a restraining bend zone, including the duplex and domino styles, and the W-E maximum horizontal stress ($_1$) causing dextral strike-slip of the longitudinal faults with reverse dip component (transpression). The dashed lines on M1 and M2 planes indicates the top of the fault.