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Ground Motion in Mexico City During the Intraslab Earthquake of 19 September 2017 (M_w 7.1) Revisited

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Abstract

The *intraslab* earthquake of 2017 (M_w7.1) was one of the most destructive earthquakes in the history of Mexico City. Several measures of the ground motion reveal that the 2017 event was unusually energetic at CU, the reference hill-zone site in the city, and, hence, in the entire Valley of Mexico, in the critical frequency range of 0.4 to 1 Hz, e.g., Fourier acceleration spectrum (FAS), peak ground velocity (PGV), and pseudoacceleration response spectrum (*Sa*), 5% damping, at structural periods of $1 \leq T \leq 1.8$ s ($0.55 \leq f \leq 1$ Hz). However, the cause of the large ground motion at CU remains unresolved. The issue merits a careful analysis of all available data. On 7 December 2023, an intraslab M_w 5.8 earthquake occurred in proximity to the 2017 event. We analyze the recordings of the 2017 earthquake separately and of the 2017 and 2023 events together in an attempt to isolate the cause of the anomalous high-frequency radiation. In this context, we take recourse of the 2023 recordings as empirical Green's functions (EGFs). Synthesized *Sa* for a M_w7.1 earthquake, using 2023 (M_w 5.8) recordings as EGFs and assuming the same stress drop, $\Delta\sigma$, of 3 MPa for both events, are significantly lower than those observed, irrespective of the azimuth. We find that the source was unusually energetic at all azimuths, and the role of rupture directivity in enhancing the ground motion was relatively small. The possibility that the enhanced ground motion in the city in 2017 was due to a particular direction of the incident wavefield on the 3-D structure of the Valley of Mexico may be ruled out since the recordings of the 2023 event, which was nearly collocated with the 2017 earthquake, show nothing anomalous. The simulated *Sa* using recordings of the 2023 event as EGFs suggest that a postulated intraslab M_w 7.1 earthquake, with source characteristics similar to the 2023 event, at a distance of ~ 130 km from CU, should cause little or no damage in the city. In other words, if the source of the 2017 earthquake had been a scaled-up version of the 2023 event then, quite likely, Mexico City would have been spared the damage and deaths that it suffered.

Key words: Energetic seismic source, Anomalous Ground Motion, Damage in Mexico City

Resumen

El sismo *intraslab* de 2017 (M_w7.1) ha sido uno de los temblores más destructivos en la historia de la Ciudad de México. Diversas medidas del movimiento del terreno revelan que el evento de 2017 fue inusualmente energético en CU, el sitio de referencia en la zona de lomas de la ciudad y, por ende, en todo el Valle de México en el intervalo de frecuencias entre 0.4 a 1 Hz. Esto se puede observar, por ejemplo, en el espectro de Fourier de las aceleraciones (FAS), la velocidad máxima del suelo (PGV) y el espectro de respuesta de pseudoaceleración (*Sa*), con un 5% de amortiguamiento, para periodos estructurales de $1 \leq T \leq 1.8$ s ($0.55 \leq f \leq 1$ Hz).

Sin embargo, la causa de las grandes aceleraciones en CU sigue sin resolverse. La cuestión merece un análisis cuidadoso de todos los datos disponibles.

El 7 de diciembre de 2023, ocurrió un sismo *intraslab* de magnitud M_w 5.8 en la proximidad al evento de 2017. Analizamos por separado, los registros del sismo de 2017 y por otro lado, de manera conjunta, los registros del sismo de 2023 y del 2017 con el fin de aislar la causa de la radiación anómala de energía sísmica en altas frecuencias. En este contexto, utilizamos los registros del sismo de 2023 como funciones empíricas de Green (EGFs). Los valores sintetizados de *Sa* para un sismo de M_w 7.1, usando los registros de 2023 (M_w 5.8) como EGFs y asumiendo la misma caída de esfuerzos, $\Delta\sigma$, de 3 MPa para ambos eventos, son significativamente menores que los observados, independientemente del azimut. Encontramos que la fuente fue inusualmente energética en todos los azimuts, y que el efecto de la directividad de la ruptura en el comportamiento de las grandes aceleraciones fue relativamente pequeño.

La posibilidad de que el comportamiento anómalo de las aceleraciones en la ciudad en 2017 se debiera a una dirección particular del campo de ondas incidente en la estructura 3D del Valle de México puede descartarse, ya que los registros de aceleración del sismo de 2023, que ocurrió casi en la misma ubicación que el sismo de 2017, no muestran nada anómalo. La *Sa* simulada utilizando los registros del evento de 2023 como EGFs sugiere que un hipotético sismo intraslab de M_w 7.1, con características de fuente similares al evento de 2023, a una distancia de aproximadamente 130 km de CU, debería causar poco o ningún daño en la ciudad. En otras palabras, si la fuente del sismo de 2017 hubiera sido una versión ampliada del evento de 2023, es muy probable que la Ciudad de México se hubiera librado de los daños y pérdidas humanas que sufrió.

Palabras clave: Fuente sísmica energética, Aceleraciones anómalas, Daño en la Ciudad de México

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1. Introduction

The intraslab earthquake of 19 September 2017 (M_w 7.1) was one of the most destructive earthquakes in the history of Mexico City, second only to the Michoacán interplate earthquake of 1985 (M_w 8.0). Excluding local events, the earthquake of 2017 produced the highest acceleration at CU, the main campus of UNAM in Mexico City, where an accelerograph has been in continuous operation since 1964. The earthquake was also the closest intraslab event, moderate or large, to Mexico City since instrumental recording began in the early 20th century (Figure 1). The event raised many questions, among them: Were the short distance and large magnitude of the earthquake the main causes of the destruction in the city? Was the source unusually energetic in the critical frequency range that causes damage in Mexico City? Did the rupture involve a directivity towards Mexico City, thus enhancing the ground motion? Was the damage a consequence of an exceptionally unfavorable location of the source with respect to the 3-D structure of the Valley of Mexico? These issues need to be resolved to better understand the seismic hazard in the metropolitan area of the Valley of Mexico, home to about 18% of the nation's population.

From geotechnical considerations, the substratum of Mexico City is divided into three zones: (1) Hill zone, which consists of a surface layer of lava flows and volcanic tuffs; (2) lake-bed zone, which is characterized by 30 to 80 m deposit of highly-compressible, high-water content clay underlain by resistant sands; and (3) the transition zone, between the hill and lake-bed zones, with subsoil consisting of alluvial sandy and silty layers with occasional intervals of clay layers. Average shear-wave velocity in the top 30 m of the three zones are 750 m/s, 50 – 100 m/s, and 250 m/s, respectively (e.g., Ovando Shelley, 2011). Damage to the city from coastal, subduction thrust earthquakes (located more than 300 km away) and inland, normal-faulting, intraslab earthquakes in the subducting Cocos plate (with hypocenters more than 120 km away) results from large amplification of seismic waves at frequencies between 0.3 to 1 Hz trapped in the transition and lake-bed zones (Anderson *et al.*, 1986; Singh *et al.*, 1988a, 1988b; Ordaz and Singh, 1992). Buildings whose natural periods coincide with the critical dominant period of the subsoil, 1 to 3 s, are highly vulnerable to earthquake ground motion. Henceforth, we will often call the 0.3 – 1 Hz band the critical frequency range.

In many studies, CU, located on basalts in the hill zone, is taken as the reference station (Figure 1). The spectral amplifications of ground motion at other sites in the city have been computed with respect to CU from earthquake recordings (Ordaz *et al.*, 1988; Singh *et al.*, 1988b; Reinoso and Ordaz, 1999). To a first order, the amplification at sites in the lake-bed and transition zones is independent of the source's magnitude, epicentral distance, depth, and azimuth. Thus, if the Fourier spectrum of ground motion of an earthquake at CU is known either from its recording or from prediction based on regression studies (Ordaz *et al.*, 1994; Arroyo *et al.*, 2024), then it can be estimated at all sites in the city whose spectral amplification is known. An application of random vibration theory (Boore, 2003), along with an estimation of the duration of the intense part of the ground motion, yields the estimated ground motion parameters. This empirical approach has been validated for the Valley of Mexico by Ordaz *et al.* (1988) and Reinoso and Ordaz (2001). The technique is very useful in practical applications (Ordaz *et al.*, 2017). In fact, it has recently been applied in a comprehensive Fourier-based probabilistic seismic hazard analysis of Mexico City (Ordaz *et al.*, 2024).

From an analysis of the recordings of intraslab earthquakes at CU, Singh *et al.* (2018) reported that the FAS of the 2017 event was anomalously energetic at CU in the critical frequency range (Figure 2). A comparison of observed peak ground acceleration and velocity (PGA and PGV) with the expected values from ground motion prediction equations (GMPE) for intraslab Mexican earthquakes (García *et al.*, 2005) shows that while PGAs during 2017 were mostly within ± one standard deviation of the predicted curve, the PGVs were significantly higher, especially at distances less than 200 km (Figure 3). A site-specific GMPE has also been derived for CU for intraslab earthquakes by Jaimes *et al.* (2015). For the 2017 earthquake, the observed PGV of 8.4 cm/s was four times greater than the 2.1 cm/s predicted from the site-specific GMPE (Singh *et al.*, 2018). The observed PGA (56.2 cm/s^2), on the other hand, was nearly the same as the predicted value (53.0 cm/s^2). The observed pseudo acceleration response spectrum, *Sa*, 5% damping, at CU was also anomalously high as compared to predicted *Sa* at structural periods of $1 \leq T \leq 1.8$ s ($0.55 \leq f \leq 1$ Hz).

Large ground motion in the critical frequency range at CU (and, hence, in the Valley of Mexico) during the 2017 event is beyond doubt. The PGV versus distance plot in Figure 3, which shows that the motions were high at most stations at distances < 200 km irrespective of azimuth, lends support to an unusually energetic source in the critical frequency range as the cause of the damage to the city, rather than to a rupture directivity towards the Valley of Mexico. PGA and PGV contours of the 2017 earthquake are also more consistent with a bilateral rather than a unilateral rupture towards the city (Arroyo *et al.*, 2020).

The issue of unusually energetic source versus source directivity as the cause of the damage during the earthquake, however, merits a careful analysis. On 7 December 2023, an intraslab M_w 5.8 earthquake occurred in the proximity of the 2017 event (Figure 1, Table 2). We take advantage of this opportunity to analyze the recordings of the 2017 and 2023 events in an attempt to isolate the cause of the anomalous

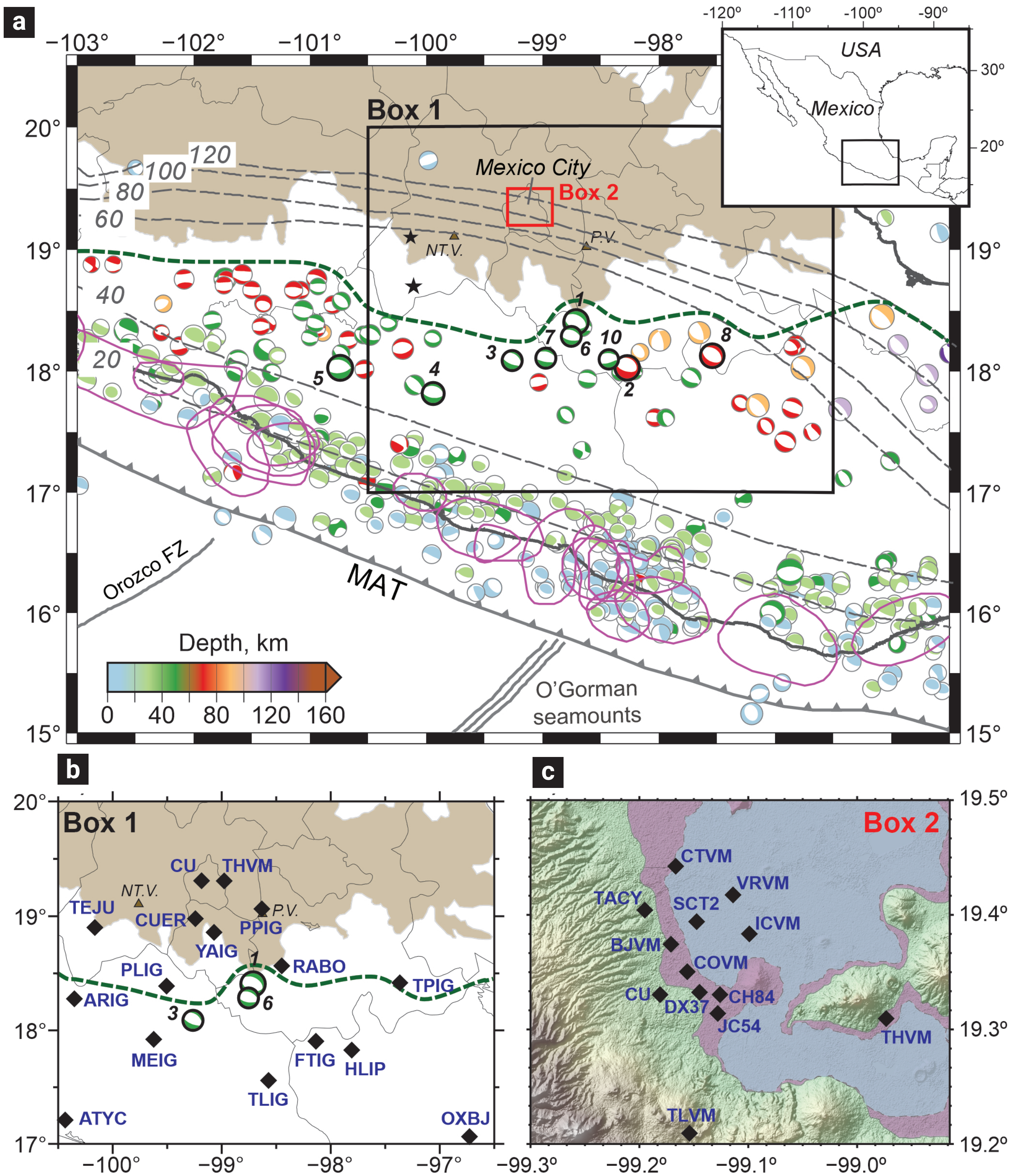

Figure 1. (a) Tectonic and location map. Epicenters of 10 intraslab earthquakes, which produced the largest peak ground accelerations (PGAs) at station CU in Mexico City in the last 60 years, are identified by number (in decreasing order of PGAs from 1 to 10 keyed to Table 1. Events 1 and 6 are the earthquakes of 19 September 2017 (M_w 7.1) and 7 December 2023 (M_w 5.8). Recordings of 7 December 2023 (event 6) and 16 June 2013 (event 3) have been used as empirical Green's function for simulating a postulated M_w 7.1 earthquake. Black dashed lines are depth contours of the Benioff zone (compiled by Ferrari *et al.*, 2012). Thick green dashed line is the observed limit of intraslab seismicity; it excludes two small intraslab earthquakes M_w 3.3 and M 4.1 shown by stars which were studied by Singh *et al.* (2020). Magenta contours show large interplate earthquake rupture areas. Shaded area: Trans-Mexican volcanic belt; NT.V.: Nevado de Toluca volcano; P.V.: Popocatepetl volcano. (b) Enlarged view of the area shown in Box 1 of (a). The epicenters and focal mechanisms of the 2017, 2023, and 2013 earthquakes (events 1, 6, and 3) are shown. Stations whose recordings are analyzed in this study are marked along with their code names. Green dashed line: observed limit of intraslab seismicity. (c) Enlarged view of the Valley of Mexico outlined in Box 2 of (a). Stations whose records are analyzed in the study are identified. Areas in green, magenta, and light blue colors are hill, transition, and lake-bed zones, respectively. CU is the reference station.

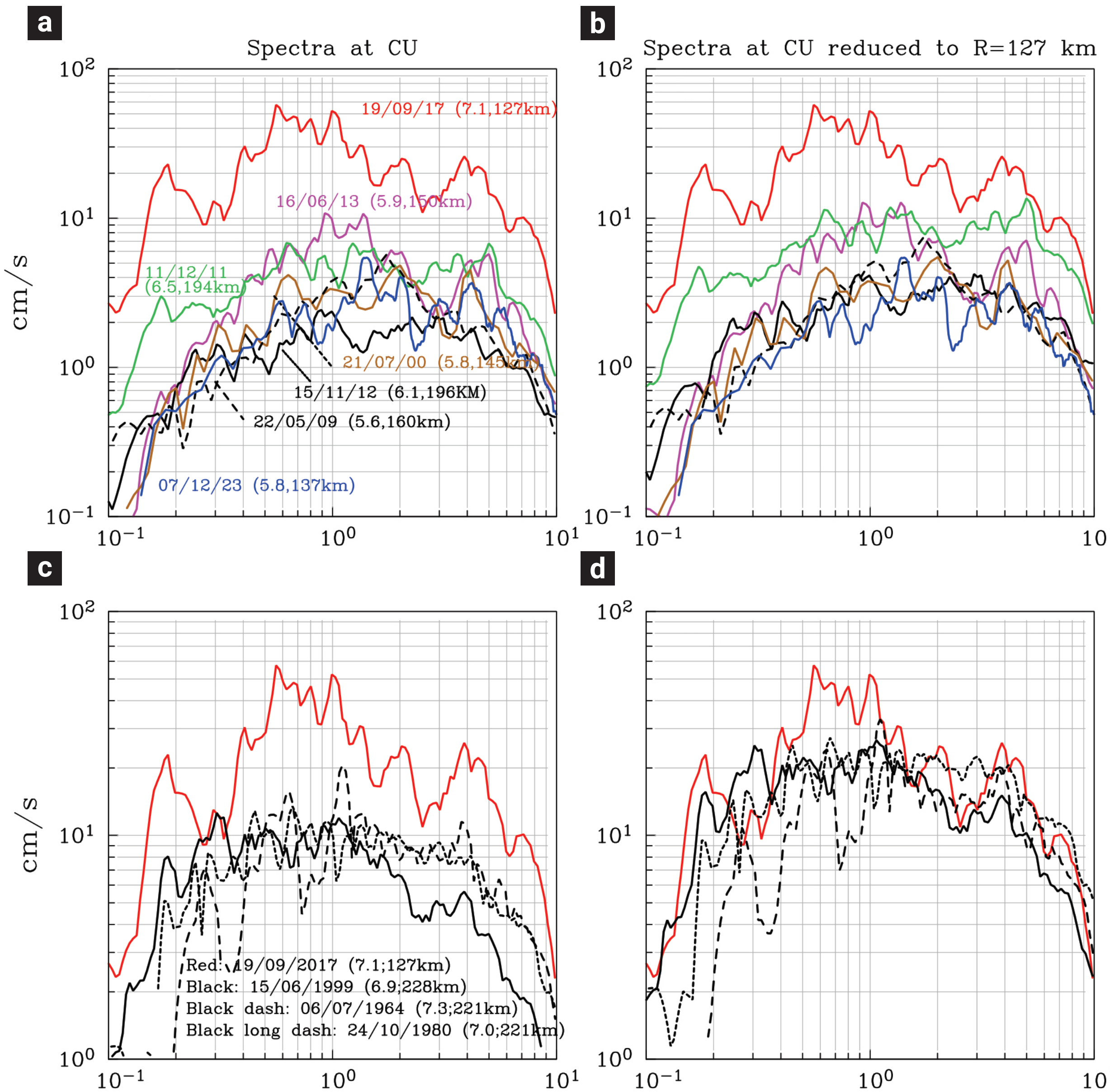

Figure 2. Fourier acceleration spectra (FAS) at CU of intraslab earthquakes close to Mexico City. (a) FAS of six moderate earthquakes (5.6 ≤ M_w ≤ 6.5; 137 ≤ R ≤ 196 km) and the 2017 event (M_w 7.1; R = 127 km). (b) FAS of the six moderate events reduced to R = 127 km and the 2017 earthquake. (c) FAS of three large events (6.9 ≤ M_w ≤ 7.3; 221 ≤ R ≤ 228 km) and the 2017 earthquake. (d) FAS of the three large events reduced to R = 127 km and the 2017 earthquake. FAS is the geometric mean of the two horizontal components. Note that the FAS of the 2017 earthquake is anomalously high, between 0.4 and 1.2 Hz. Modified from Singh *et al.* (2018).

high-frequency radiation in the critical frequency range at CU. In this context, we take recourse of the 2023 recordings as empirical Green's function (EGF). We also use the recordings of the intraslab earthquake of 16 June 2013 (M_w 5.9) located 148 km south of Mexico City (Figure 1, Table 2). A strong directivity towards Mexico City during the 2013 event has been reported by Singh *et al.* (2014).

2. Fourier Acceleration Spectra (FAS) of Intraslab Earthquakes at CU

FAS of intraslab earthquakes recorded at CU have been studied in several papers (e.g., Pacheco and Singh, 1995; Iglesias *et al.*, 2002; Singh *et al.*, 2014, 2015, 2018; Jaimes *et al.*, 2015). Here, we briefly present the evidence that shows anomalously

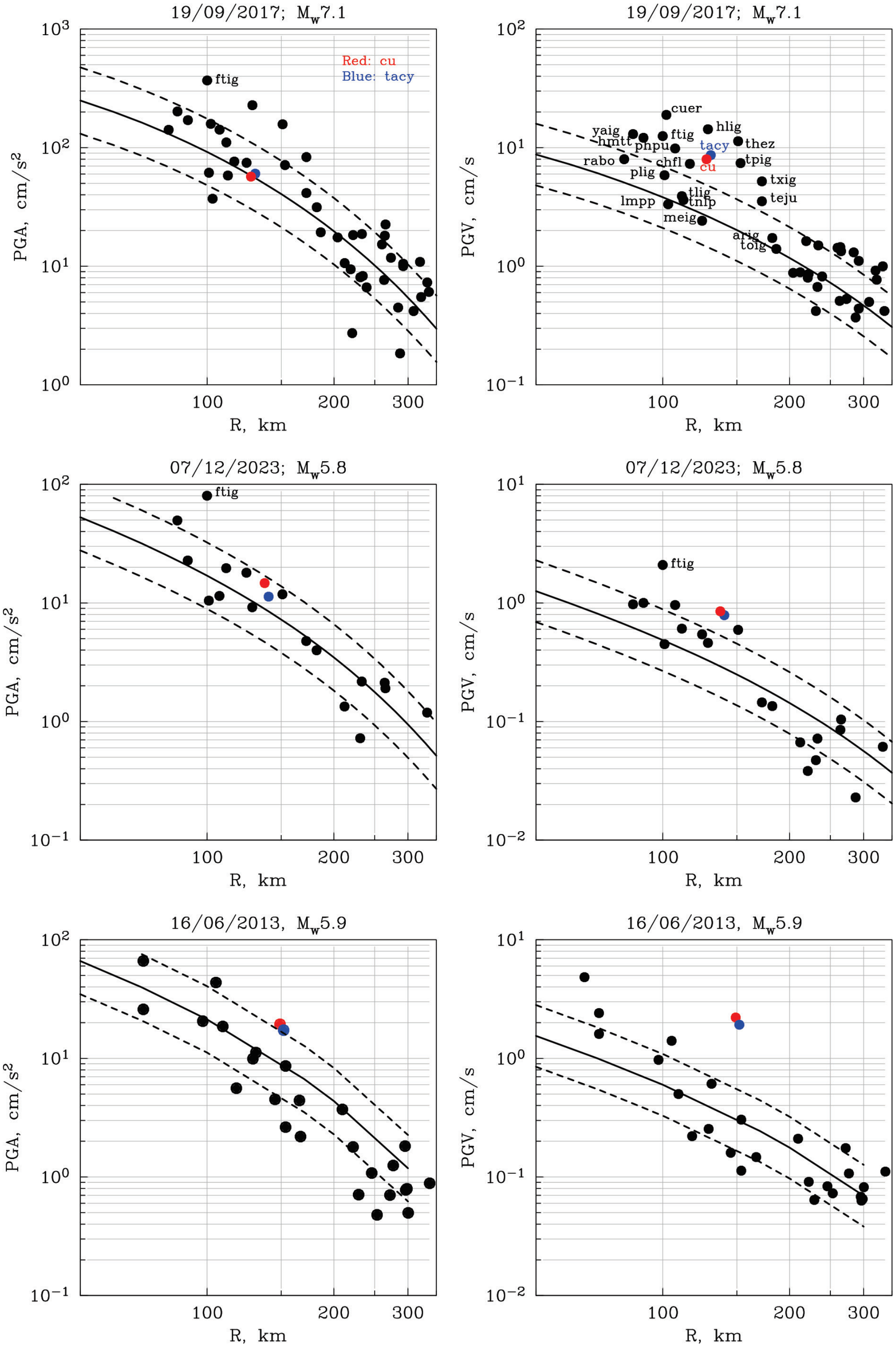

Figure 3. PGA and PGV as a function of distance, R, of intraslab earthquakes of 19 September 2017, M_w 7.1 (top row), 07 December 2023, M_w 5.8 (middle row), and 16 June 2013, M_w 5.9 (bottom row). In the PGV plot of the 2017 event, all stations with $R \leq 200$ km are identified; in other frames, only a few stations are marked. Continuous and dashed curves: predicted and $\pm$ one standard deviation values from GMPE for intraslab Mexican earthquakes (García *et al.*, 2005). Note that while PGAs during 2017 were mostly within $\pm$ one standard deviation of the predicted curve, PGV values were significantly higher, especially at distances less than 200 km. High PGV values at CU and TACY during the 2013 earthquake have been attributed to directivity.

Table 1. Ten intraslab earthquakes with the largest recorded peak ground acceleration (PGA) at CU in the period 1964-2023, listed in descending order. Local earthquakes are excluded. Modified from Singh *et al.* (2018).

Event No.	Date	Lat. °N	Long. °E	H km	M_w	R km	PGA* cm/s^2
1	19/09/2017	18.41	-98.71	51	7.1	127	57.1
2	24/10/1980	18.03	-98.27	65	7.0	184	24.4
3	16/06/2013	18.09	-99.26	56	5.9	148	19.5
4	11/12/2011	17.82	-99.94	57	6.5	194	19.2
5	06/07/1964	18.03	-100.74	55	7.3	221	17.1
6	07/12/2023	18.29	-98.75	49	5.8	133	14.7
7	21/07/2000	18.11	-98.97	50	5.8	145	12.8
8	15/06/1999	18.13	-97.54	60	6.9	225	11.6
9	08/09/2017	14.77	-94.10	42	8.2	739	8.9
10	22/05/2009	18.10	-98.43	46	5.6	160	8.6

* PGA is the quadratic mean of the maximum acceleration on the horizontal components.

Table 2. Source parameters of the intraslab earthquakes of 2017, 2023, and 2013. Recordings of the 2023 and 2013 events have been used as empirical Green's functions (EGFs) to simulate the ground motion of a target M_w 7.1 earthquake.

Date	Lat.* ºN	Long.* ºW	Depth# km	Moment# N-m	M_w#	Focal mechanism# φº	δº	λº
19 Sep 2017	18.41	98.71	51	6.51×10^{19}	7.1	300	44	-83
07 Dec 2023	18.29	98.75	49	5.61×10^{17}	5.8	298	39	-74
16 Jun 2013	18.11	99.23	50	7.80×10^{17}	5.9	311	33	-73

*Reported by National Seismological Service (SSN)
#Global Centroid Moment Tensor Catalog

large high-frequency radiation during the 2017 earthquake; the details are given elsewhere (Singh *et al.*, 2018). Table 1 lists ten intraslab events that produced the largest PGA at CU since 1964. At the top of the list is the 2017 earthquake; the nearby 2023 event occupies the sixth position. In Figure 2a, the FAS of six moderate intraslab earthquakes ($5.6 \leq M_w \leq 6.5$; $137 \leq R \leq 196$ km) are compared with the FAS of the 2017 event (M_w 7.1; $R = 127$ km). The FAS of three large earthquakes ($6.9 \leq M_w \leq 7.3$; $221 \leq R \leq 228$ km), along with that of the 2017 event, are shown in Figure 2c. The 2017 earthquake not only produced the highest PGA at CU but also the largest FAS.

FAS in Figures 2a and 2c correspond to events located at different R. To assess whether the FAS of the 2017 event was anomalous, FAS of all events were reduced to a distance R of 127 km. In the reduction, we used geometric spreading of $1/R$ and quality factor $Q = 251f^{0.58}$. These parameters are appropriate for intraslab Mexican earthquakes (García *et al.*, 2004). Figures 2b and 2d illustrate the reduced FAS corresponding to the observed FAS shown in Figures 2a and 2c, respectively. The FAS of the 2017 earthquake in Figure 2b is well above those of others, an expected result since its magnitude is greater than the rest. We note that the reduced FAS of 16 June 2013 (M_w 5.9) earthquake is greater in the $0.4 \leq f \leq 2$ Hz range compared with those of the other four $5.6 \leq M_w \leq 6.1$ events. This is due to strong directivity toward CU during the 2013 earthquake (Singh *et al.*, 2014). In Figure 2d, the observed spectrum of the 2017 earthquake is compared with the reduced spectra of M_w 6.9, 7.0, and 7.3 earthquakes listed in Table 1. Although the magnitudes are comparable, the reduced spectrum of the 2017 earthquake is significantly greater in the critical frequency range than those of the other events. This may be due to a relatively more energetic source at these frequencies or due to a rupture directivity towards CU, similar to that observed during the 16 June 2013 earthquake.

3. Directivity

We examine whether there was a pronounced rupture directivity towards CU (hence towards the Valley of Mexico) during the 2017 earthquake from (a) available finite-fault rupture models, (b) visual examination of the recordings, (c) variation with azimuth of spectral ratio of the 2017 to 2023 recordings at the same station, and (d) observed and simulated FAS at CU of the 2017 earthquake. We also use the 2023 recordings as EGF to simulate response spectra, *Sa*, of an M_w 7.1 earthquake and compare them with observed *Sa* during the 2017 earthquake.

3.1 Finite-fault Rupture Models

The slip on the fault during the 2017 earthquake has been mapped from the inversion of teleseismic data by the U.S. Geological Survey (**https://earthquake.usgs.gov/earthquakes/eventpage/us2000ar20/finite-fault**, last accessed on 19 March 2005) and L. Ye (personal communication, 2017). Melgar *et al.* (2018) present a slip model based on the inversion of local and regional strong motion and GPS data. The finite-fault slip model of the U.S. Geological Survey suggests a subtle SE-directed rupture. In the slip model of L. Ye a large slip occurs near the hypocenter; the rupture then propagates downdip and, finally, bilaterally along the strike. In the model of Melgar *et al.* (2018), most of the slip occurs downdip of the hypocenter. There are two main asperities, one immediately SE of the hypocenter (peak slip ~ 0.7 m) and another one to the NW (peak slip ~1.3 m). In the slip models of Melgar *et al.* (2018), a NW directivity towards the Valley of Mexico may be discerned. Dynamic modeling of the regional recordings also suggests a NW directivity (Mirwald *et al.*, 2019). Although the directivity seen in different slip models is subtle and not consistent, we give greater weight to NW directivity seen in the models of Melgar *et al.* (2018) and Mirwald *et al.* (2019) as they are based on inversion of local and/or regional data.

Moment rate functions (MRFs) for the 2017 earthquake, retrieved from finite-fault, are compiled in Figure 4a. There is a fairly large difference in the MRFs. The MRF of Melgar *et al.* (2018) shows two large pulses separated by ~ 7 s. Figure 4b illustrates the moment rate spectrum (MRS) corresponding to each MRF. The figure also includes MRS estimated in this study following the methodology of Boatwright and Choy (1986), with an attenuation correction for subduction earthquakes discussed by Pérez-Campos and Beroza (2001) and Pérez-Campos *et al.* (2003). In all cases, the observed MRS is deficient at $f < 0.3$ Hz with respect to the ω^2 source. Above 0.4 Hz, the spectra greatly differ. With respect to the Brune ω^2 source, $\Delta\sigma = 3$ MPa, MRS of L. Ye shows a bump between ~ 0.5 and 1.5 Hz. This bump is not seen in other spectra, including that of Melgar *et al.* (2018). No definitive conclusion can be drawn from Figure 4b about the anomalous nature of the source.

3.2 Visual Examination of the Recordings

Two pulses with a time difference of ~ 5 s are clearly visible in regional displacement traces at stations TPIG, HLIG, and FTIG, and to some extent also at TLIG and RABO (Figure 5). At station PLIG, the separation between the two pulses is smaller (~ 2.5 s); at station TEJU, they appear to merge into one. The traces are more complicated at stations CUER and CU (quite likely due to site effect), making it difficult to identify the pulses. In teleseismic *P* waves of the 2017 earthquake, two pulses, about 4.6 s apart, are clearly visible (Figure 6). We note that the character of the waveforms in the azimuthal range of 101º – 160º differs; the pulses seem stretched out, possibly due to rupture propagating away from these stations. However, a consistent azimuthal dependence in the time difference between the two

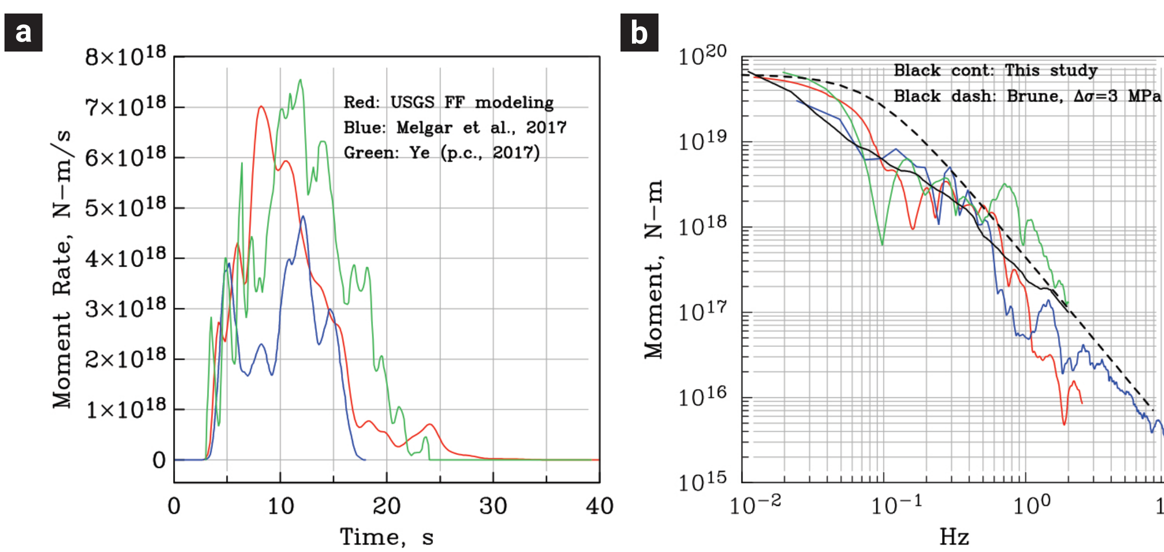

Figure 4. (a) Reported MRFs of the 2017 earthquake. (b) MRS obtained in this study and those corresponding to MRFs shown in (a). For reference, theoretical MRS for a Brune ω^2 source with stress drop $\Delta\sigma = 3$ MPa is shown by the dashed black curve.

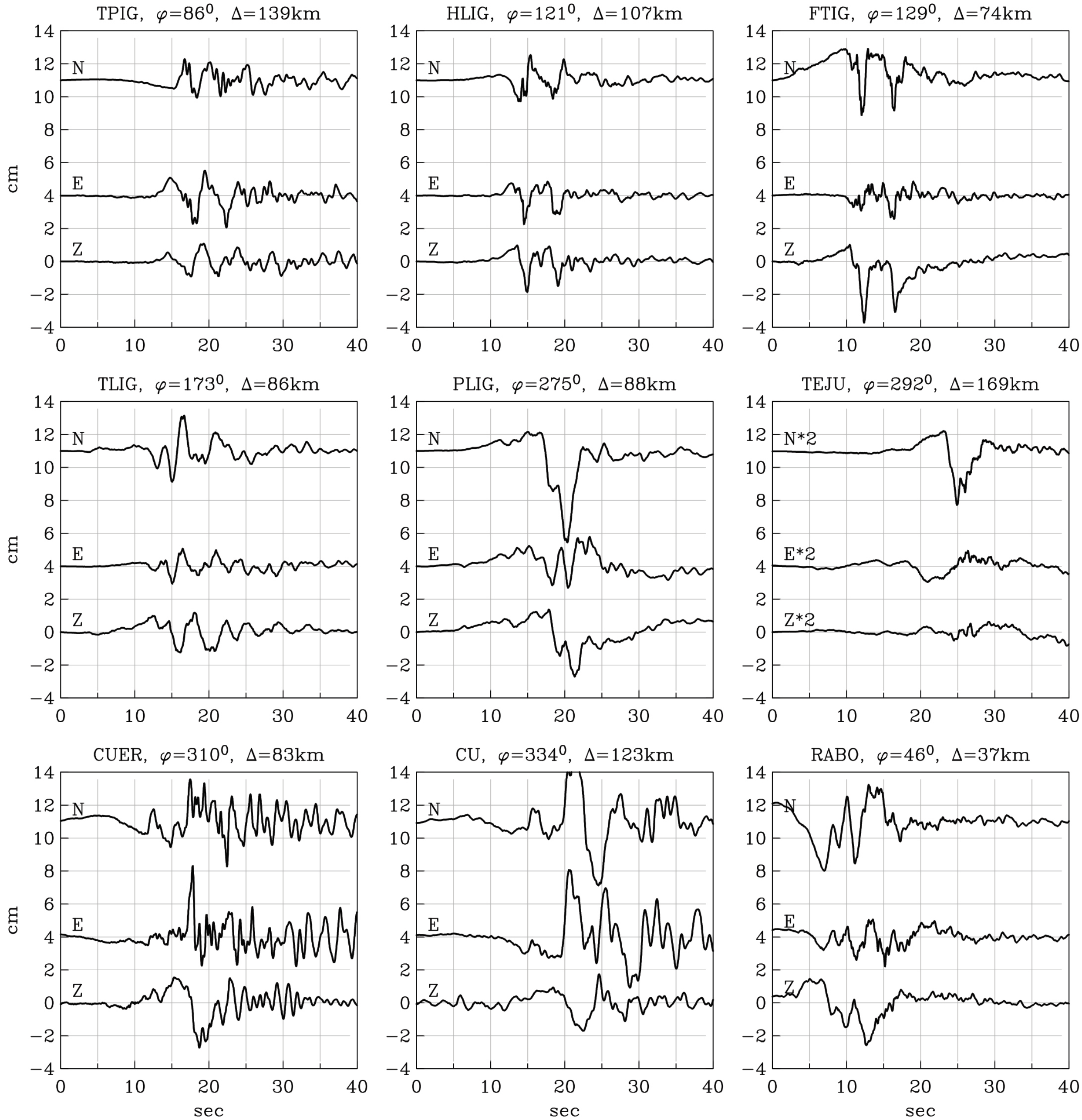

Figure 5. Displacement seismograms at regional strong motion stations. Velocities, obtained by integration of accelerograms, were high-pass filtered at 0.05 Hz and then integrated to get the displacement traces. Two pulses, ~ 5 s apart, can be seen at stations TPIG, HLIG, and FTIG. The pulses appear to merge at stations PLIG and TEJU.

pulses, expected from directivity, is not clearly visible. These observations suggest that a rupture directivity along the fault's strike, $\varphi = 300º$, towards the Valley of Mexico (φ ~ 335º) is likely though not pronounced.

3.3 Azimuthal Variation of Spectral Ratio

The 2017 and 2023 events had the same focal mechanism and were nearly collocated (Figure 1b, Table 2). If we assume that the directivity was absent during the smaller 2023 event, then a variation with the azimuth of the spectral ratio of the 2017 to 2023 recordings at the same station should reveal directivity during the 2017 earthquake. Figures 7a to 7d show the ratios in four azimuthal windows. The ratios are the geometrical mean of the spectral ratios of the three components of ground motion. Superimposed on the figures are theoretical curves for the Brune ω^2 source with constant stress drop $\Delta\sigma = 3$ MPa (continuous blue curves) and increasing $\Delta\sigma$ ($\Delta\sigma \propto M_0^{1/4}$) (Chael, 1987) (dashed blue curves). At very low frequencies, theoretical and observed ratios should be equal to the moment ratio, i.e., 116 (Table 2).

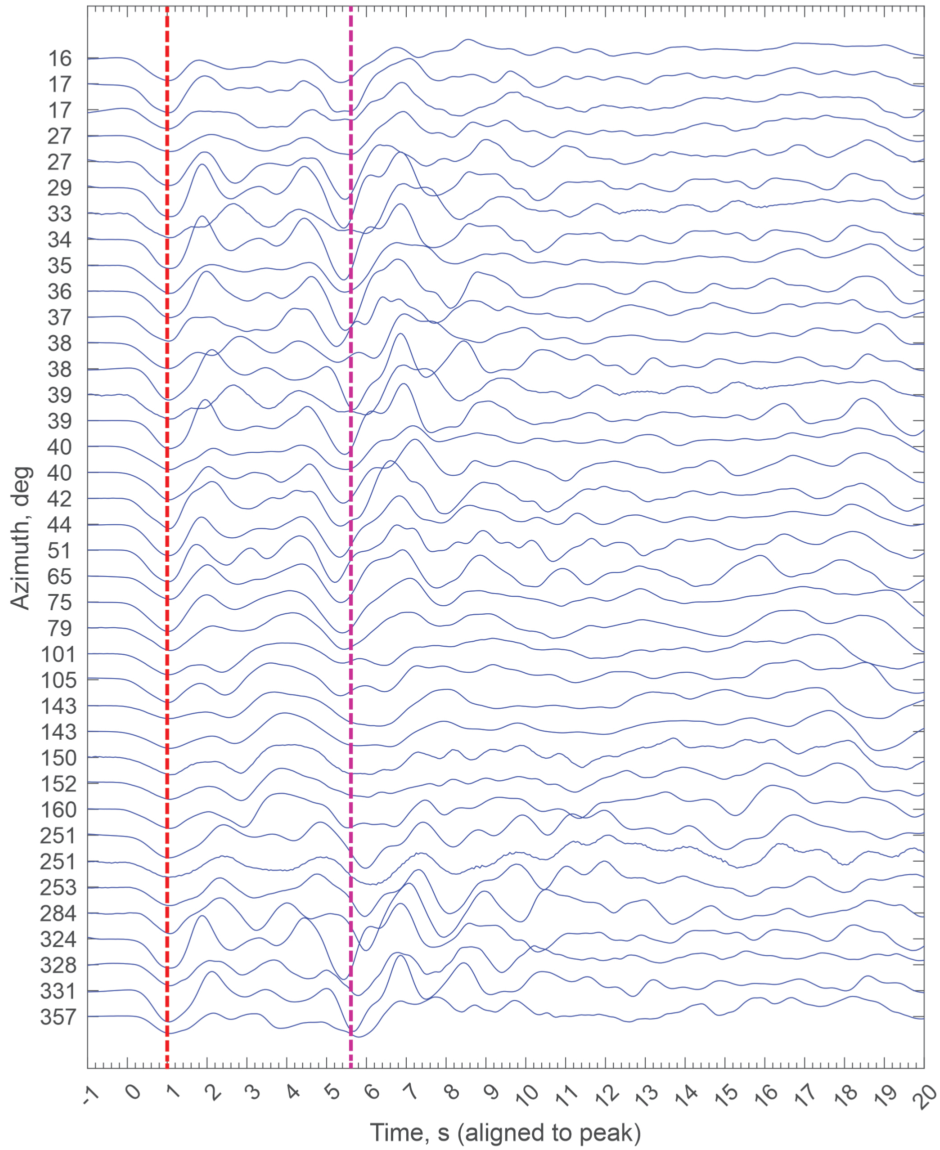

Figure 6. Teleseismic *P* waves of the 2017 earthquake, ordered with the azimuth of the station. Traces have been aligned at the first trough (at time 1 s, red dashed line), as it is difficult to pick the beginning of the P wave. A second trough occurs ~ 4.6 s later (magenta dashed line), which is related to the rupture of a second asperity.

Because of the poor signal-to-noise ratio of the recordings of the smaller 2023 event at low frequencies, the observed spectral ratios are not reliable below about 0.1 or 0.2 Hz, and they do not reach 116. At high frequencies ($f > 2$ Hz), the theoretical spectral ratio for a Brune model (Brune, 1970) with constant $\Delta\sigma$ equals moment ratio to the power 1/3, i.e., $116^{1/3} = 4.9$. Observed ratios are greater than 10 in all azimuthal windows, except in the range of 334º – 350º, in which they are ~ 7. At high frequencies, the ratios are better fit with an increasing $\Delta\sigma$ model, except in the azimuthal range of 334º – 350º, in which it overestimates them. At high frequencies ($f > 2$ Hz), the plots in Figures 7b, 7c, and 7d require 2 – 3 times greater stress drop during the 2017 earthquake as compared to the 2023 event. This, however, does not explain why the ratios at high frequencies in Figure 7a ($334º \leq \varphi \leq 350º$) are lower than those in the other frames. This is contrary to the expectation of a rupture propagating toward the Valley of Mexico. It may be due to fewer stations in other azimuthal windows or rupture directivity during the 2023 event.

Observed ratios are deficient at $f < 0.3$ Hz with respect to ω^2 source, similar to the MRSs in Figure 4b. The ratios in Figures 7a, 7b, and 7d show a bump in the range of 0.3 to 1 Hz. We recall that it is in this frequency range that the FAS of the 2017 earthquake at CU was anomalously large (Figure 2). The bump, however, is not clear in Figure 7b, perhaps because of the small number of stations. In short, at high frequencies ($f > 2$ Hz), the spectral ratios suggest a 2 to 3 times higher stress drop during

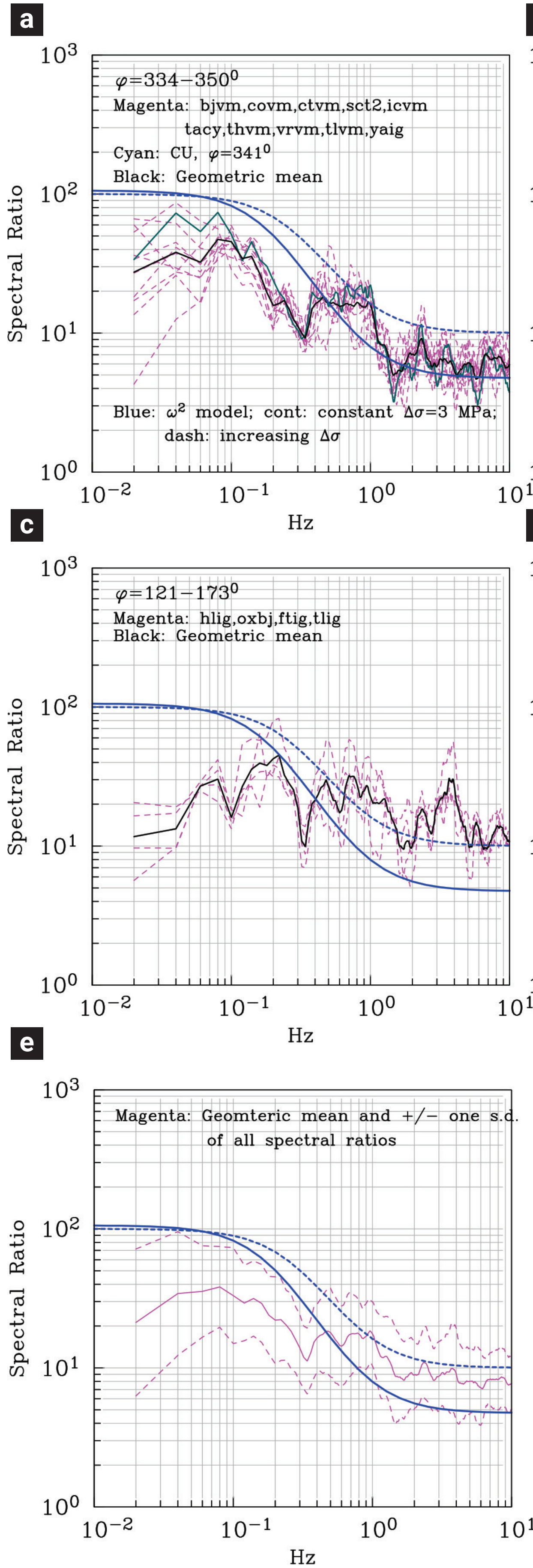

Figure 7. Spectral ratios of 2017 to 2023 recordings in the azimuthal windows: (a) 334º ≤ φ ≤ 344º, (b) 34º ≤ φ ≤ 86º, (c) 121º ≤ φ ≤ 173º, (d) 230º ≤ φ ≤ 275º. Spectral ratios and their geometric mean and ± one standard deviation curves are shown. Each frame lists stations used in computing the spectral ratios. (e) Geometric mean of all spectral ratios and ± one standard deviation. Superimposed on the frames are theoretical curves for the Brune ω^2 source with constant $\Delta\sigma$ = 3 MPa (continuous blue curves) and increasing $\Delta\sigma$ ($\Delta\sigma \propto M_0^{1/4}$).

the 2017 earthquake as compared to the 2023 event. An ω^2 source with different $\Delta\sigma$ for the EGF and target events, however, cannot fit the ratios in a larger frequency band.

3.4 Observed and Simulated FAS at CU of the 2017 Earthquake

We tested whether a greater stress drop during the 2017 event relative to the 2023 event is reflected in the synthesized ground motion of a postulated M_w 7.1 earthquake using the 2023 event as EGF. For the synthesis, we used a random summation technique developed by Ordaz *et al.* (1995). The summation of EGF obeys the ω^2-source scaling law at all frequencies. The method requires the specification of the seismic moment and $\Delta\sigma$ of the EGF and the target events. If only peak ground motion parameters are desired, then the computation of the time histories is bypassed; the Fourier spectrum, along with an estimation of duration (T_R) of the intense part of the ground motion and application of results from random vibration theory (*RVT*), suffices. The duration T_R in seconds is given by $T_R = f_c - 1 + 0.05R$, where f_c is the corner frequency, and R is the hypocentral distance in km (Herrmann, 1985). We considered three cases of stress drop pairs ($\Delta\sigma$ EGF, $\Delta\sigma$ target), of (3 MPa, 3 MPa), (3 MPa, 6 MPa), and (3 MPa, 10 MPa). Tests show that the results are less sensitive to $\Delta\sigma$, but more sensitive to the $\Delta\sigma$ ratio. Figure 8a illustrates observed FAS at CU during the 2017 and 2023 earthquakes and synthesized FAS of a target M_w7.1 corresponding to the three cases of the $\Delta\sigma$ pair. Synthesized FAS with (3 MPa, 3 MPa) and (3 MPa, 6 MPa) envelop well the observed 2017 FAS, except in the critical frequency range of $0.4 \leq f \leq 1.2$ Hz, in which the observed FAS is significantly higher. Even with the $\Delta\sigma$ pair of (3 MPa, 10 MPa), the synthesized FAS still does not reach the level of the observed FAS while, simultaneously, overestimates it outside the critical frequency range. Clearly, it is not possible to approximate well the FAS of the 2017 event at CU by increasing the stress drop of the target event in the simulation using 2023

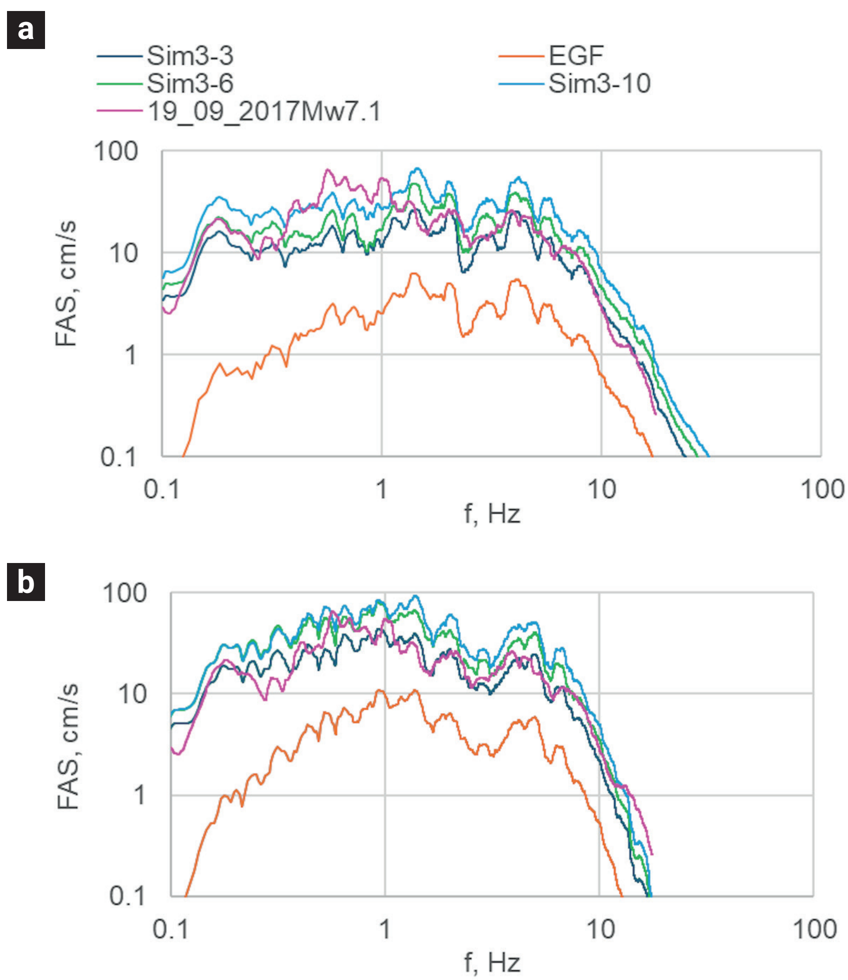

Figure 8. Comparison of observed FAS at CU during the 2017 (M_w 7.1) earthquake with the simulated FAS using the recording of (a) the 2023 (M_w 5.8) event as EGF, (b) the 2013 (M_w 5.9) event as EGF. In both cases $\Delta\sigma$ is 3 MPa for the EGF and 3, 6, and 10 MPa for the target M_w 7.1 earthquake.

recordings as EGFs. The result points to an unusually energetic 2017 source in the critical frequency band of $0.4 \leq f \leq 1.2$ Hz.

Could the anomalous nature of the 2017 recording at CU be due to rupture directivity towards Mexico City? As discussed earlier, this possibility cannot be ruled out. To explore this further, we compare the observed 2017 FAS with the simulated FAS using the 16 June 2013, M_w 5.9, recording as the EGF. The 2013 event was located 148 km from CU (event 3 in Table 1, Figure 1). A rupture directivity towards Mexico City is well documented for this event (Singh *et al.*, 2014); the high PGA and PGV at CU and in Mexico City during the earthquake (Figure 3) were attributed to the directivity. Figure 8b shows that the observed 2017 FAS is reasonably well matched by the synthetic FAS with $\Delta\sigma$ pair of (3 MPa, 3 MPa), except in the critical frequency range, in which it is somewhat higher. Synthetic FAS with $\Delta\sigma$ pair of (3 MPa, 6 MPa) and (3 MPa, 10 MPa) significantly overestimate the observed 2017 FAS.

The results in Figure 8 may be reconciled with a 2017 source (a) with anomalously large energy in the critical frequency range but without significant directivity effect, or (b) with a significant directivity and only slightly higher energy in the critical frequency range. In the latter case, we expect significant azimuthal variation of the ground motion, as was the case during the 2013 event.

3.5 Observed and Simulated Response Spectra of the 2017 Earthquake

We simulate *Sa* of a postulated M_w 7.1 earthquake using recordings of the 2023 earthquake as EGFs and compare them with the observed *Sa* during the 2017 earthquake. The results of the synthesized and observed *Sa* at 15 selected stations are shown in Figure 9. In all cases, synthesized *Sa* curves are lower than those observed for the stress drop pair of (3 MPa, 3 MPa), suggesting a higher stress drop during the 2017 earthquake. This is especially true for lake-bed sites in the Valley of Mexico (e.g., at station SCT2, DX37, CH84, JC54). An important conclusion of the synthesis is that if the source of the 2017 earthquake had been a scaled-up version of the 2023 EGF event, then Mexico City, quite likely, would have been spared the damage and deaths it suffered.

Sa curves for a postulated M_w 7.1 earthquake were again simulated assuming $\Delta\sigma$ pairs of (3 MPa, 6 MPa) and (3 MPa, 10 MPa). The synthesized curves, with $\Delta\sigma = 10$ MPa for the target event, are now nearly equal to or greater than the observed ones (Figure 9), except in the Valley of Mexico. Observed *Sa* at stations in the Valley of Mexico (CU, TACY, SCT2, DX37, CH84, JC54; Figure 9) are greater than the simulated *Sa*, with $\Delta\sigma = 10$ MPa, between 1 and 2 s. At lake-bed sites, the observed *Sa*, as compared to the simulated *Sa*, is not only much greater, but also, the period at which the peak occurs does not coincide with that observed in the simulated *Sa*. The reasons are: (1) the nature of the 2017 source, reflected in the FAS of the 2017 earthquake at CU, which has anomalously large amplitude in the range $0.4 \leq f \leq 1$ Hz (Figure 2), and (2) the transfer function of the soft sites with respect to the reference hard site of CU differs from site to site. The product of the FAS at CU and the transfer function dictates the *Sa* curve at the site. The transfer functions of lake-bed sites in the Valley of Mexico with respect to CU are nearly invariant (e.g., Singh *et al.*, 1988a, 1988b; Reinoso and Ordaz, 1999). Since the transfer function is invariant, the difference between the observed and simulated *Sa* curves in Figure 9 must be attributed to the source difference of the 2017 and 2023 events. The results of this section emphasize that the principal cause of the severe damage to the city was the unusual character of the source in the $0.4 \leq f \leq 1$ Hz range. This source characteristic is not captured by simply increasing the stress drop of the target event in the simulation using 2023 recordings as EGFs.

4. Discussion and Conclusions

Several measures of the ground motion reveal that the intraslab earthquake of 2017 (M_w 7.1) was unusually energetic at CU (hence, in the Valley of Mexico) in the frequency range of 0.4 – 1 Hz. FAS at CU was anomalously high in this frequency range. With respect to site-specific GMPE for intraslab Mexican earthquakes at CU (Jaimes *et al.*, 2015), the observed PGA was normal, but PGV was much greater. Observed *Sa*, 5% damping, at CU was also anomalously high as compared to the predicted *Sa* at structural periods of $1 \leq T \leq 1.8$ s ($0.55 \leq f \leq 1$ Hz).

In this paper, we have focused on the cause of the anomalous ground motion at CU. Was it due to rupture directivity towards the Valley of Mexico or due to special source characteristics? To this end, we analyzed recordings of the 2017 earthquake separately and those of the 2017 and 2023 events together. These earthquakes were nearly collocated and had the same focal mechanism, which permits us to use the recordings of the 2023 event (M_w 5.8) as empirical Green's function. In drawing conclusions, we also relied on previous studies. The results may be summarized as follows:

Finite-fault mapping of slip, reported in different studies, leads to contradictory conclusions on directivity. The slip models, based on the inversion of local and/or regional data, are likely to be more accurate. These slip models suggest a NW rupture directivity towards the Valley of Mexico. NW directivity is also supported by visual inspection of waveforms at regional distances. The recordings show that the source consisted of two pulses. The time difference between the pulses is ~ 5s in the

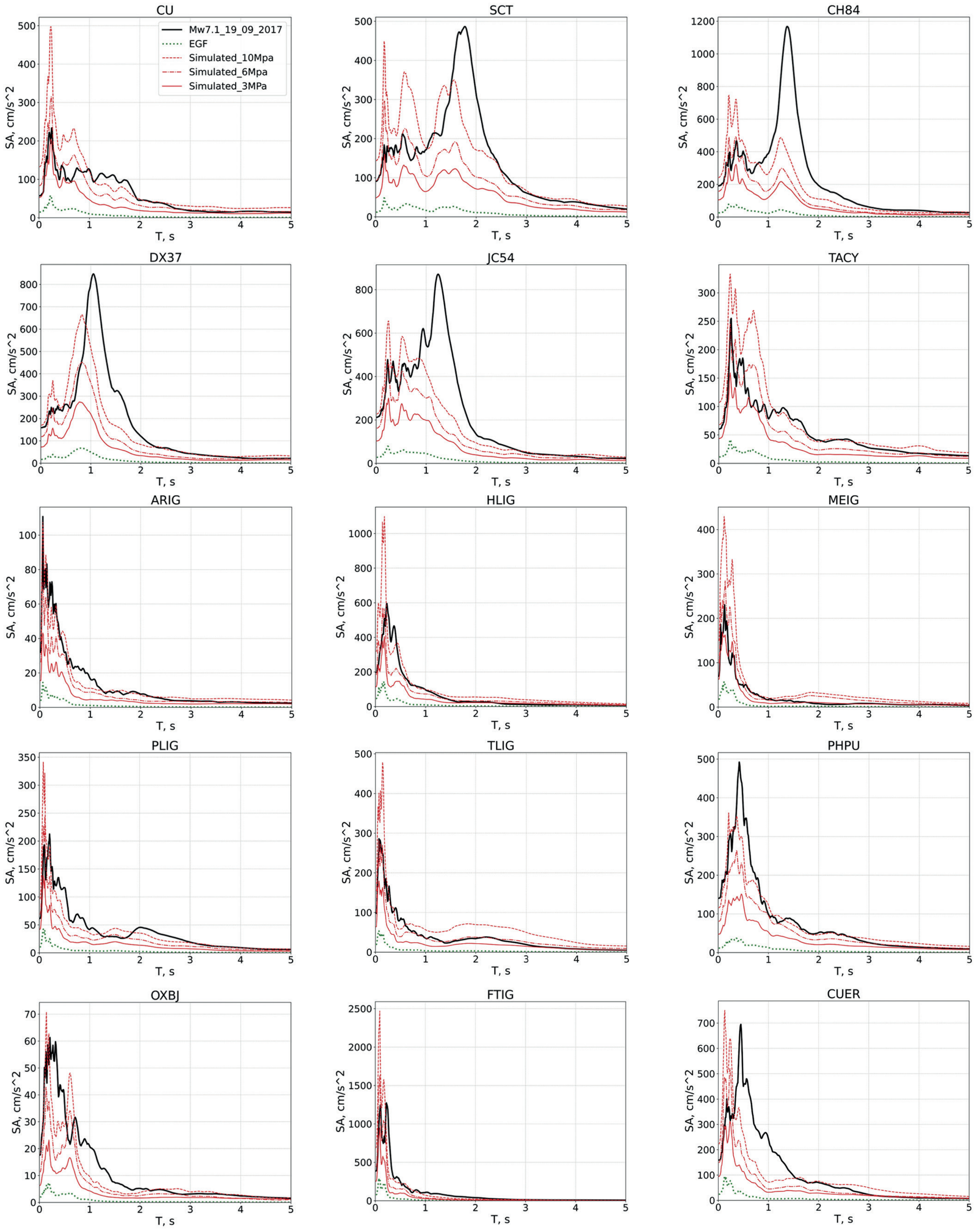

Figure 9. Comparison of observed *Sa* of the 2017 earthquake and simulated *Sa* of a target M_w 7.1 earthquake. The simulation uses recordings of the 2023 earthquake as EGF with $\Delta\sigma = 3$ MPa for the EGF and 3, 6, and 10 MPa for the target M_w 7.1 earthquake.

regional seismograms at stations to the SE of the epicenter. This difference seems less at a couple of stations to the NW, where the pulses can be identified, suggesting directivity towards the Valley of Mexico. While the two pulses are clearly seen in teleseismic *P* waves, the azimuthal variation of the time difference, expected from directivity, is not clear. However, the character of seismograms in the azimuthal range of 101º – 160º differs from others; the pulses seem stretched out, possibly because of the rupture propagating away from these stations.

Within the framework of the Brune ω^2 source, the spectral ratios of 2017 to 2023 earthquakes at high frequencies ($f > 2$ Hz) at regional stations support a 2 to 3 times higher stress drop during the former event compared to the latter one. However, the spectral ratios as a function of azimuth do not reveal a clear directivity. The ratios do show a bump between 0.4 and 1 Hz at most stations, similar to the observed FAS at CU, supporting an unusually energetic source in the 0.4 – 1 Hz frequency band at all azimuths. This also explains higher than predicted PGV values at all azimuths within 200 km (Figure 3).

Synthesized *Sa* values for a M_w 7.1 earthquake, using 2023 (M_w 5.8) recordings as EGFs and assuming the same stress drop, $\Delta\sigma = 3$ MPa, for both events, are significantly lower than those observed, irrespective of the azimuth, which further supports the unusual nature of the 2017 source. It follows that if the source of the 2017 earthquake had been a scaled-up version of the 2023 event, then quite likely, Mexico City would have been spared the damage and deaths that it suffered.

It has been speculated that the damage and its pattern in Mexico City in 2017 may have been due to an unfavorable location of the earthquake with respect to the geometry of the Valley of Mexico. The idea is inspired by the roughly NNW-SSE alignment of the damage in the city and the location of the earthquake, which lies on the extension of this alignment (Figure 1). If so, a source located in the vicinity of the 2017 event, such as the earthquake of 2023, should also have produced more intense ground motion in the Valley of Mexico compared to a same magnitude earthquake located at the same distance but at a different azimuth. However, the FAS of the 2023 event at CU is comparable to or even lower than other events of similar magnitude and distance (Figure 2). Furthermore, the synthesized *Sa* of a target M_w 7.1 event using recordings of the 2023 event as EGFs falls short of the observed *Sa* in 2017, especially at lake-bed sites (e.g., stations SCT2, DX37, CH84, JC54; Figure 9). These observations do not favor the speculation. We note that the NNW-SSE alignment of the damage coincides with the boundary between the transition and lake-bed zones. The dominant frequency of these sites lies between 0.6 and 1 Hz. It is in this frequency range that the 2017 event was unusually energetic, which explains the alignment of the observed damage.

In conclusion, the damage to Mexico City during the 2017 earthquake was due to an anomalously energetic ground motion in the Valley of Mexico in the frequency band of 0.4 to 1 Hz. The role of rupture directivity in enhancing the ground motion appears relatively small; the source was unusually energetic at all azimuths. The simulated response spectra using recordings of the 2023 event as EGFs show that a postulated intraslab M_w 7.1 earthquake, with source characteristics similar to the 2023 event, at a distance of ~ 130 km from CU, should cause little or no damage in the city.

The results in the manuscript also highlight the importance of continuously updating GMPEs and increasing the density of seismic instrumentation. Continuous updating of GMPEs allows the capture of the increment in the ground motion variability related to such anomalous events while an increase in the seismic data also allows the improvement of GMPE models. Such improvements in GMPE models would lead to better seismic hazard assessment.

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