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Deadly Intraslab Mexico Earthquake of 19 September 2017 (M_w 7.1): Ground Motion and Damage Pattern in Mexico City

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ABSTRACT

In the wake of death and destruction left by the 2017 earthquake in Mexico City, it is natural to ask whether the event was unexpected and anomalous. Although such an intraslab earthquake (M_w 7.1; depth = 57 km; epicentral distance = 114 km from the city) was considered likely, the recordings in the city during the last 54 yrs reveal that the ground motion during the 2017 earthquake was anomalously large in the critical frequency range to the city (0.4–1 Hz). The intraslab earthquakes occur closer to Mexico City, at greater depth, and involve higher stress drop than their interplate counterparts. Consequently, the ground motion is relatively enriched at high frequencies as compared with that during interplate earthquakes, which is dominated by lower frequency waves ($f < 0.5$ Hz). This explains the observed difference in the damage pattern during the 2017 and the disastrous interplate earthquake of 1985 (M_w 8.0).

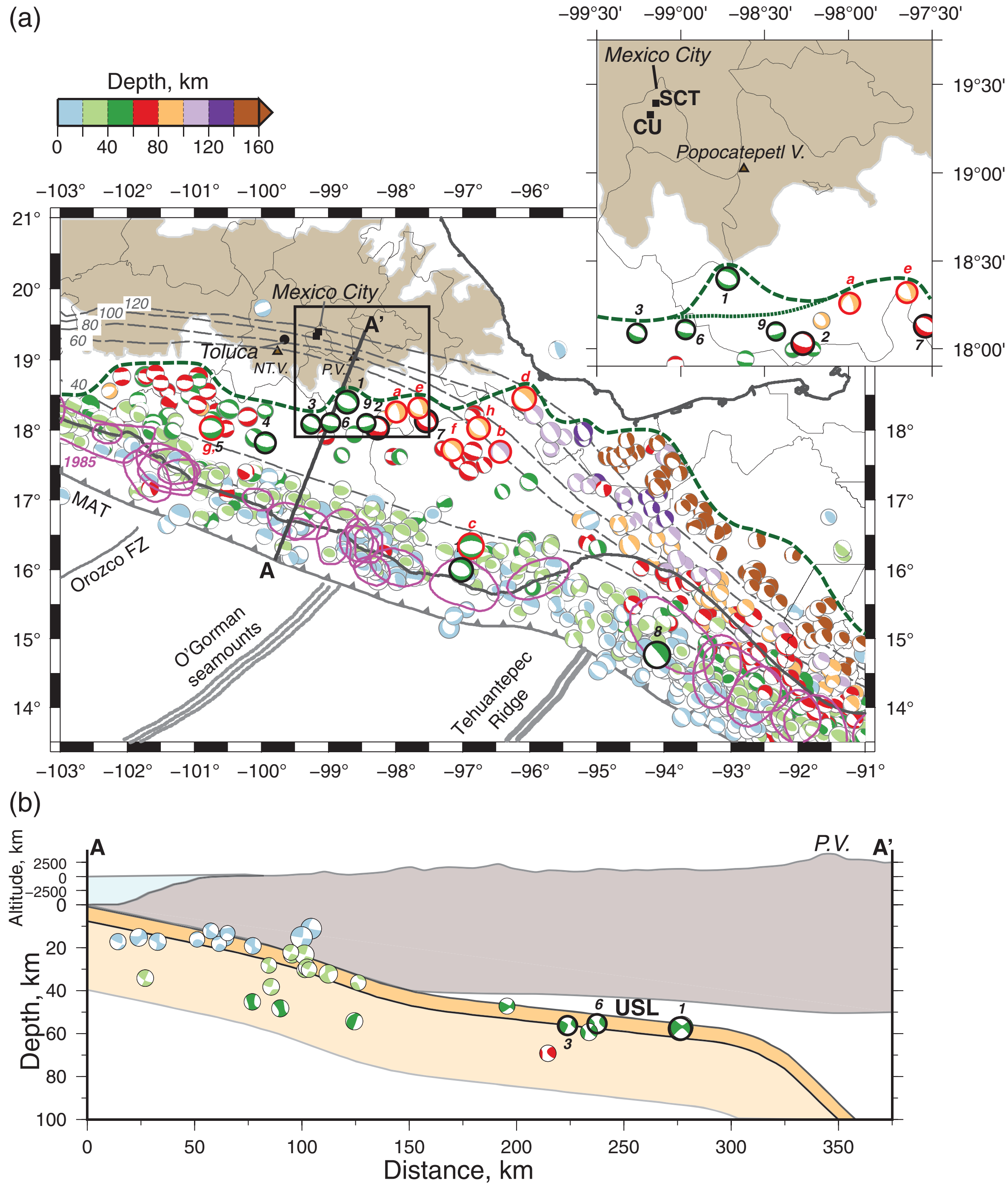
Electronic Supplement: Figures showing spectral ratios, peak ground acceleration (PGA) and peak ground velocity (PGV) as function of distance R, comparison of observed response spectra SA, and predicted median and ±1 s SA from a site-specific ground-motion prediction equation (GMPE) model at CU, plot of accelerograms, Fourier acceleration spectra, and SA at SCT of interplate 1985 M_w 8.0 and intraslab 2017 M_w 7.1 earthquakes, accelerographic stations in Mexico City, which recorded the 2017 M_w 7.1 earthquake, SA of the 2017 earthquake at sites in and near Condesa and Roma colonies, and basis for the estimation of exceedance rate of PGA at CU in Mexico City from intraslab earthquakes, and tables providing a list of 20 (interplate and intraslab) earthquakes with largest recorded PGA at CU in the 1964–2017 period, significant pre-1975 intraslab earthquakes, and a comparison of observed PGA and PGV at CU during the 2017 M_w 7.1 earthquake with predictions from GMPE.

INTRODUCTION

Mexico City is exposed to seismic hazard from interplate earthquakes along the Mexican subduction zone, intraslab earthquakes in the subducting Cocos plate, and crustal earthquakes in the Mexican volcanic belt. The interplate earthquakes rupture Cocos–North American plate interface along the Pacific coast of Mexico at distances of more than 300 km from the city (Fig. 1). The faulting occurs on a low-angle thrust plane at a relatively shallow depth of about 15–25 km. The 19 September 1985 M_w 8.0 Michoacán earthquake, which caused unprecedented damage and probably more than 10,000 deaths in Mexico City, was of this type. The intraslab earthquakes in central Mexico occur in the subducted Cocos plate at a depth of ~40–80 km and involve normal faulting. This type of earthquakes occurs more than 125 km away from Mexico City but still less than the 300 km for earthquakes on the coast (Fig. 1).

On 19 September 2017, exactly 32 yrs after the 19 September 1985 earthquake, the city was once again devastated but now by an M_w 7.1 intraslab event. The 2017 earthquake was located near the border of the states of Morelos and Puebla (18.41° N, −98.71° E; depth $H = 57$ km), to the south-southeast of Mexico City, at a hypocentral distance of about 127 km (Fig. 1). The earthquake occurred at 13:14 hrs (local time), soon after the city had undergone a macroearthquake drill, marking the anniversary of the earthquake of 1985. Many villages and towns in the epicentral region were almost completely destroyed. The earthquake caused great panic in Mexico City and collapse of 44 buildings. About 600 buildings were severely damaged and an additional 15,000 suffered some damage. The earthquake killed 369 persons (228 in Mexico City, 74 in Morelos, and 45 in Puebla). It was the second most destructive earthquake in the history of Mexico City, next only to the 1985 interplate earthquake. The statistics for the 1985 earthquake is incomplete but it is generally believed that more than 10,000 persons were killed and about 190 buildings suffered partial or total collapse.

Intraslab earthquakes have, historically, caused damage to cities and towns in the Mexican altiplano. Some examples are (1) 1931 M_w 7.8 earthquake that devastated the city of Oaxaca (Singh *et al.*, 1985); (2) 1973 M_w 7.0 earthquake that damaged



▲ **Figure 1.** (a) Tectonic and location map. Focal mechanisms and epicenters of earthquakes from Global Centroid Moment Tensor catalog with some exceptions. The locations of 10 intraslab earthquakes, which produced the largest peak ground accelerations (PGAs) at station CU in Mexico City in the last 54 yrs are taken from Table 1. These events are shown in black circles and are marked by numbers (in decreasing order of PGAs from 1 to 10 keyed to Ⓔ Table S1, available in the electronic supplement to this article). Events 1 and 8 are the intraslab Morelos-Puebla earthquake of 19 September 2017 (M_w 7.1) and Chiapas-Oaxaca earthquake of 8 September 2017 (M_w 8.2). Pre-1975 intraslab earthquakes (red circles with letters) are from Ⓔ Table S2. Color of the focal mechanism is keyed to the depth of the event. Shallow-dipping thrust-faulting earthquakes occur near the coast; the events further inland mostly occur in the subducting Cocos plate and are, generally, normal-faulting type. Black dashed lines, depth contours of the Benioff zone as compiled by Ferrari *et al.* (2012). Thick green dashed line defines the observed limit of intraslab seismicity. Aftershock areas of large interplate earthquakes are shown in magenta color. Shaded area, Trans-Mexican volcanic belt; NT.V., Nevado de Toluca volcano; P.V., Popocatepetl volcano. (Inset) Enlarged view of Mexico City area. (b) Section along AA′. The seismicity within ±50 km of AA′ is projected on the section. USL, ultra slow-velocity layer at the top of subducting oceanic crust shown in orange (Pérez-Campos *et al.*, 2008; Song *et al.*, 2009).

cities and towns of the state of Veracruz (Singh and Wyss, 1976); (3) 1980 M_w 7.0 earthquake destructive to the city of Huajuapan de León in the state of Oaxaca (Yamamoto *et al.*, 1984); and (4) 1999 M_w 6.9 earthquake that caused damage to the city of Tehuacán and the states of Puebla and Morelos (Singh *et al.*, 1999; Yamamoto *et al.*, 2002). The recent, great intraslab earthquake of 8 September 2017 (M_w 8.2), which occurred off the coast of Chiapas and Oaxaca, caused widespread destruction to the coastal towns of these states. An $M \sim 7.7$ earthquake in 1858, which may have been intraslab (Singh *et al.*, 1996), was damaging to Mexico City. Since 1858, however, the damage in the city from this type of event has been minor until the 2017 earthquake.

The 2017 earthquake raised questions that are critical to understand the seismic vulnerability of the city and its reconstruction (Cruz-Atienza *et al.*, 2017). Was such an intraslab earthquake (M_w 7.1 at a hypocentral distance R of 127 km) unexpected? Were the recorded ground motions in the city unusually high for such an earthquake? Did the ground motion exceed that contemplated in Mexico City's current building code? Why did the damage pattern during the earthquake differ from that observed during the 1985 earthquake? What is the return period of such ground motions in the city from intraslab earthquakes? Here, we address these issues.

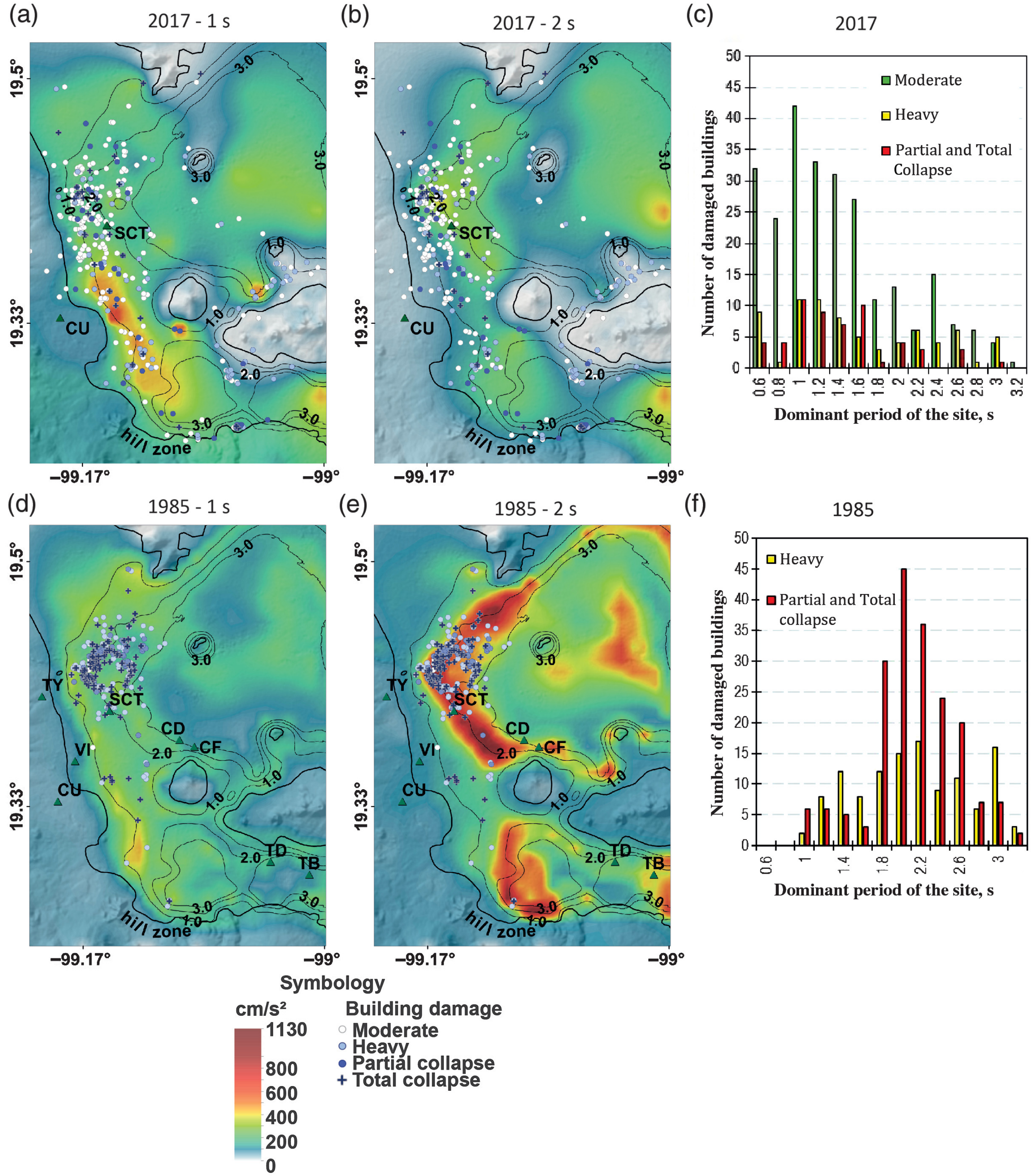
We begin with a brief review of relevant previous studies and emphasize the role that the strong-motion recordings at station CU have played in many of them. Station CU is located at a hill-zone site in Mexico City and has been in continuous operation during the past 54 yrs. We, then, analyze intraslab seismicity of the region to establish that an M_w 7.1 earthquake at R of 127 km was not unexpected. From an analysis of the CU recordings of intraslab earthquakes, we demonstrate that the ground motion during the 2017 earthquake was greater than expected, especially at frequencies, which cause damage to Mexico City. The computed response spectra at 65 sites in Mexico City reveal that the design spectra of the city's 1987 building code was exceeded at only six of them. As intraslab earthquakes occur closer to the city, at greater depth, and involve larger stress drop than their interplate counterparts, we expect the spectra of such events to be more enriched at higher frequencies. This is supported by the spectra at CU and provides an explanation, for the observed difference in the damage pattern during the 2007 and the interplate Michoacán earthquake of 1985. Finally, from the recordings at CU as well as the probabilistic seismic hazard analysis (PSHA), we estimate that an intraslab earthquake with peak ground acceleration (PGA) of about 60 cm/s^2 at CU, such as the 2017 event, corresponds to a return period of the order of at least 150 yrs.

PREVIOUS STUDIES AND CRITICAL ROLE OF RECORDINGS FROM STATION CU

The awareness of the seismic hazard that intraslab earthquakes pose to Mexican altiplano, especially to Mexico City, has motivated detailed studies of many individual events (Singh and Wyss, 1976, 1996, 1999, 2000, 2014, 2015; Hernandez *et al.*, 2001; Iglesias *et al.*, 2002; Santoyo *et al.*, 2005; National Autonomous University of Mexico [UNAM] Seismology Group, 2010; Díaz-Mojica *et al.*, 2014), the estimation of ground motion in the city from postulated intraslab earthquakes (Pacheco and Singh, 1995; Singh *et al.*, 1996; Iglesias *et al.*, 2002), the development of ground-motion prediction equations (GMPEs; García *et al.*, 2005; Jaimes *et al.*, 2015), and studies related with source characteristics of such earthquakes as compared with their interplate counterparts (García *et al.*, 2004; Singh *et al.*, 2014, 2015). Many of these studies benefitted from the recordings at a strong-motion station at CU located on basalt lava flows on the main campus of UNAM in Mexico City (Figs. 1 and 2). The station has been in continuous operation since 1964, recording earthquakes during the last 54 yrs. These recordings are of vital importance in studying and predicting ground motions in the city. Table 1 lists 10 intraslab earthquakes with largest PGA at station CU in the 1964–2017 period. The locations of these events are shown in Figure 1. A list of 20 earthquakes with largest recorded PGA at station CU in the same period consists of 11 interplate and 9 intraslab earthquakes (Ⓔ Table S1, available in the electronic supplement to this article). Analysis of these recordings reveals that the exceedance rate of PGA from the two types of earthquakes at station CU is about the same (Ordaz and Reyes, 1999; Iglesias *et al.*, 2002; Singh *et al.*, 2015). We note that the PGA of 57 cm/s^2 at station CU during the 2017 earthquake is the largest ever, twice that recorded during the 1985 earthquake (29 Gal). These two earthquakes are also the two most damaging events in the history of Mexico City. Even though the PGA at station CU in 1985 was half that recorded in 2017, the damage in the city during the former earthquake was far greater than during the latter event.

The main cause of damage in Mexico City during earthquakes located more than 125 km away is its subsoil that amplifies the ground motion (Anderson *et al.*, 1986; Singh, Mena, *et al.*, 1988; Singh, Lermo, *et al.*, 1988; Ordaz and Singh, 1992). The subsoil is divided in three zones (Fig. 2): the lake-bed zone (consisting of 30–80 m deposit of highly compressible, high-water content clay underlain by resistant sands); the hill zone (comprising a surface layer of lava flows and volcanic tuffs); and the transition zone (composed of alluvial sandy and silty layers with occasional intervals of clay layers). Shear-wave velocities in the upper 30 m of the three zones are 50–100, 750, and 250 m/s, respectively (e.g., Ovando-Shelley, 2011). Seismic waves trapped in the soft layers of the transition and lake-bed zones are greatly amplified at frequencies between 0.2 and 1 Hz. The buildings whose natural periods coincide with the dominant period of the subsoil are highly vulnerable to earthquake ground motion.

In many studies, CU is taken as the reference station. The spectral amplifications of ground motion at other sites in the city have been computed with respect to station CU from earthquake recordings (Ordaz *et al.*, 1988; Singh, Lermo, *et al.*, 1988; Reinoso and Ordaz, 1999). To a first order, the spectral amplification of a site in the lake-bed or the transition zone is independent of the magnitude, epicentral distance, depth, and



▲ **Figure 2.** (a) Map of Mexico City showing its geotechnical subdivision, dominant site period, damage distribution, and level of response spectra SA at 1 s during the 2017 earthquake. Thick black line delineates boundary between hill and transition zones. Contours of iso-dominant site period are shown by thin lines at 1 s interval. The 1 s contour roughly coincides with the boundary between transition and lake-bed zones. Accelerographs at CU and SCT have been in continuous operation since 1964 and 1985, respectively. Color scale represents level of response spectrum SA. (b) Same as (a) but for SA at 2 s. (c) Number of damaged buildings versus dominant period of site during the intraslab 2017 (M_w 7.1). (d–f) Same as (a–c) but for the interplate 1985 (M_w 8.0) earthquakes. Stations that recorded the earthquake are shown by green triangles. The statistics of moderately and heavily damaged buildings during the 1985 earthquake is incomplete; it is shown for heavily damaged buildings but not for moderately damaged ones.

Table 1
Ten Intraslab Earthquakes with Largest Recorded Peak Ground Acceleration (PGA) at CU in the 1964–2017 Period, Listed in Descending Order

Event Number	Date (yyyy/mm/dd)	Latitude (°)	Longitude (°)	H (km)	M_w	R (km)	PGA (cm/s^2)*
1	2017/09/19	18.41	−98.71	57	7.1	127	57.1
2	1980/10/24	18.03	−98.27	65	7.0	184	24.4
3	2013/06/16	18.09	−99.26	56	5.9	148	19.5
4	2011/12/11	17.82	−99.94	57	6.5	194	19.2
5	1964/07/06	18.03	−100.74	55	7.3	221	17.1
6	2000/07/21	18.11	−98.97	50	5.8	145	12.8
7	1999/06/15	18.13	−97.54	60	6.9	225	11.6
8	2017/09/08	14.77	−94.10	42	8.2	739	8.9
9	2009/05/22	18.10	−98.43	46	5.6	160	8.6
10	1999/09/30	16.00	−97.02	47	7.4	433	7.8

Local earthquakes are excluded. Intraslab earthquake of 28 August 1973 (M_w 7.0, $R = 311$ km) is not listed because it was not recorded at CU, probably due to instrumental malfunction. The estimated PGA is 9.3 cm/s^2 (Singh *et al.*, 2015).
*PGA is the quadratic mean of the maximum acceleration on the horizontal components.

azimuth of the source. An example is given in Ⓔ Figure S1, which shows spectral amplification at the lake-bed zone site SCT with respect to station CU during intraslab and interplate earthquakes. Thus, if the Fourier spectrum of ground motion of an earthquake at station CU is known, either from its recording or from prediction based on regression studies (Ordaz *et al.*, 1994), then the spectra can be estimated at all sites in the city whose spectral amplifications are known. An application of random vibration theory (Boore, 2003), along with an estimation of the duration of the intense part of the ground motion, then yields the expected ground-motion parameters in the city. This empirical approach has been validated for the Valley of Mexico by Ordaz *et al.* (1988) and Reinoso and Ordaz (2001). It is very useful in practical applications (Ordaz *et al.*, 2017), circumventing the complex wave-propagation phenomenon of seismic waves in the valley (Cruz-Atienza *et al.*, 2016).

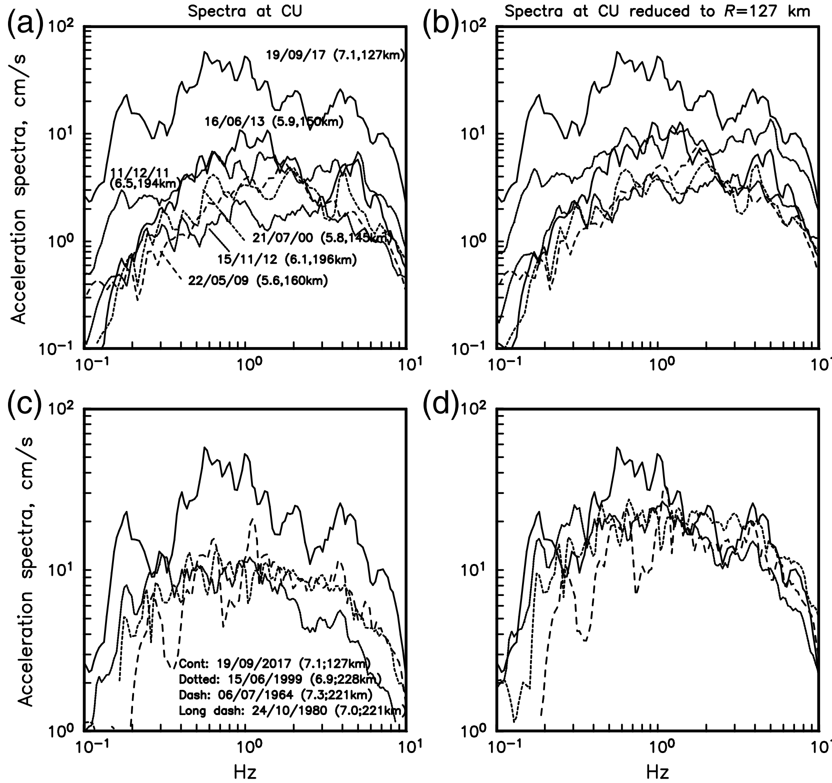
AN UNEXPECTED INTRASLAB EARTHQUAKE NEAR MEXICO CITY?

The geometry of the subducted Cocos plate below central Mexico changes from northwest to southeast. In the region of interest, the subducting Cocos plate flattens and becomes subhorizontal after an initial shallow-angle subduction (Suárez *et al.*, 1990; Singh and Pardo, 1993; Pardo and Suárez, 1995; Pérez-Campos *et al.*, 2008; Pacheco and Singh, 2010; Fig. 1). The unbending of the slab begins ~70 km from the trench and produces both intraslab compressional as well as extensional earthquakes in the of 25–45 km depth range (Pacheco and Singh, 2010). The interface becomes horizontal at distance of ~125 km from the trench at a depth of ~45 km. The intraslab seismicity is sparse between ~115 and 200 km, beyond which it resumes again as the horizontal slab bends and the subduction becomes steep. The epicenter of the 2017 earthquake was located ~270 km from the trench in the direction of the plate convergence at the edge of intraslab seismicity (Fig. 1). The 2017 earthquake was likely a consequence of bending stresses in the slab (Melgar *et al.*, 2018). To the west and the east of the 2017 earthquake, the seismicity ends at closer and greater distance from the trench, respectively (Fig. 1). No intraslab earthquake has been located below the active volcano of Popocatépetl and only recently a magnitude 3.3 earthquake has been detected at depth of 100 km below the Nevado de Toluca volcano (Singh *et al.*, 2017).

As mentioned above, the 2017 earthquake is the closest, reliably located intraslab event to station CU ($R = 127$ km; Fig. 1). However, in recent years M_w 5.6–5.9 events have occurred in the vicinity of the 2017 earthquake at R in the 145–160 km range (Table 1; Fig. 1). Furthermore, in the last 54 yrs there have been M_w 6.9, 7.0, and 7.3 earthquakes at $R = 225$, 184, and 221 km, respectively (Table 1; Fig. 1). Thus, an intraslab earthquake such as the 2017 event (M_w 7.1 at $R = 127$ km) should not be considered an unexpected event. In fact, such an event was considered likely and the recording of event 6 in Table 1 (M_w 5.8, $R = 145$ km) at station CU was used as empirical Green's function to simulate ground motions of a postulated M_w 7.0 earthquake (Iglesias *et al.*, 2002). An M_w 6.5 intraslab earthquake at $R = 80$ km was considered in the elaboration of 1987 version of the city's building code following the 1985 earthquake (Rosenblueth *et al.*, 1989).

GROUND MOTION IN MEXICO CITY

The damage in Mexico City during 2017 was surprisingly large, as was the PGA at station CU, which was the highest recorded in the last 54 yrs (Table 1 and Ⓔ Table S1). For hazard assessment, it is important to know whether the recorded ground motion at CU (and hence, in the metropolitan area of Mexico City) should have been expected or if it was anomalously high.



▲ **Figure 3.** Fourier acceleration spectra (FAS) of intraslab earthquakes at CU (Table 1). (a) 19 September 2017 and five moderate, $5.6 \le M_w \le 6.5$, events; (b) the spectra shown in (a) reduced to a common distance of 127 km. (c) 19 September 2017 and three similar magnitude, $6.9 \le M_w \le 7.3$, events, (d) spectra shown in (c) reduced to a common distance of 127 km. The plotted spectra are the geometric mean of the two horizontal components.

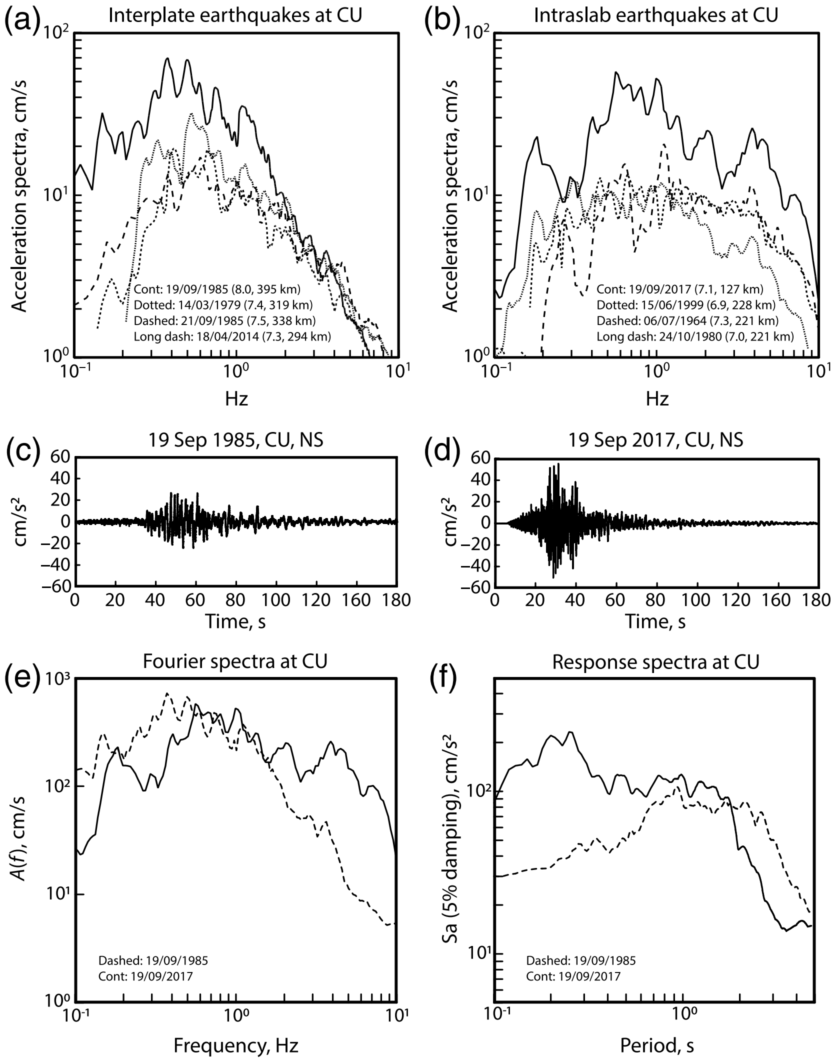
Figure 3a compares the geometric mean of the Fourier acceleration spectra (FAS) of the two horizontal components at CU of the 2017 earthquake with those of five moderate events $5.6 \le M_w \le 6.5$ listed in Table 1. Figure 3b illustrates the spectra of the same events but reduced to a common distance of $R = 127$ km. In the reduction, we used geometric spreading of $1/R$ and quality factor $Q = 251f^{0.58}$, appropriate for intraslab Mexican earthquakes (García *et al.*, 2004). As expected, the spectrum of the 2017 earthquake is well above those of others because its magnitude is greater than the rest. We note that the spectrum of 16 June 2013 M_w 5.9 earthquake is higher at $0.4 \le f \le 2$ Hz as compared with the spectra of the other three $5.6 \le M_w \le 6.1$ events, most probably because the 2013 earthquake had a strong directivity toward station CU (Singh *et al.*, 2014). Figure 3c,d compares observed and reduced spectra of the 2017 earthquake with those of M_w 6.9, 7.0, and 7.3 earthquakes listed in Table 1. Even though the magnitudes are comparable, the reduced spectrum of the 2017 earthquake is higher at $0.4 \le f \le 1$ Hz than those of the other events, suggesting a relatively more energetic source at these frequencies, or, alternatively, a rupture directivity toward CU similar to the 16 June 2013 earthquake. A comparison of observed PGA and peak ground velocity (PGV) as function of R with the expected values from GMPE for intraslab Mexican earthquakes (García *et al.*, 2005) shows that the PGA during 2017 was not unusual but the PGV was higher at $R < 200$ km than the prediction (Ⓔ Fig. S2). A site-specific GMPE has also been derived for station CU for intraslab earthquakes (Jaimes *et al.*, 2015). For the 2017 earthquake, the observed PGV of 8.4 cm/s is much greater than 2.1 cm/s predicted from such site-specific GMPE (Ⓔ Table S3). The observed PGA (56.2 cm/s^2), however, is nearly the same as the predicted value (53.0 cm/s^2). Observed pseudoacceleration response spectrum (SA), 5% damping, was also anomalously high as compared to predicted SA at structural periods $1 \le T \le 1.8$ s ($0.55 \le f \le 1$ Hz; Ⓔ Fig. S3).

Source spectrum retrieved from teleseismic P waves shows a bump around $f = 0.4$ Hz (L. Ye, personal comm., 2018). This points to an energetic 2017 source as the cause of relatively enriched spectral amplitudes observed at station CU. Slip inversion of regional strong-motion and Global Positioning System data (Melgar *et al.*, 2018) suggests that the source directivity may also have played a role in generating anomalous ground motion toward Mexico City.

DAMAGE AND ITS PATTERN

Following the 2017 earthquake, it immediately became clear that the geographical distribution of the damage and its pattern greatly differed from that observed during the interplate 1985 earthquake. Damage during the 2017 earthquake was concentrated along the transition zone (dominant site period ~1 s); small and low-rise buildings were especially vulnerable. In contrast, the damage during the 1985 earthquake occurred mostly in the lake-bed zone (dominant site period ~2 s) and to high-rise buildings. This difference in the damage pattern was anticipated (e.g., Singh *et al.*, 1996, 2015; Iglesias *et al.*, 2002). As we discuss below, the incident wavefield during intraslab and interplate earthquakes provides a physical explanation for the overall damage patterns.

The interplate earthquakes originate at $R > 300$ km from Mexico City at a 15–20 km shallow depth. The damaging intraslab earthquakes in central Mexico, on the other hand, generally occur at $R < 250$ km and at the 40–80 km depth (Table 1). Furthermore, the stress drop of the intraslab events is ~4 times greater than that of the interplate earthquakes (García *et al.*, 2004). Consequently, the FAS of the intraslab earthquakes at station CU are expected to be more enriched at higher frequencies than those of the interplate events (Singh *et al.*, 1996; Furumura and Singh, 2002; Díaz-Mojica *et al.*, 2014). This is confirmed by the FAS of significant, large intraslab, and interplate earthquakes recorded at CU (Fig. 4). The FAS of the interplate earthquakes are peaked between 0.3 and



▲ **Figure 4.** FAS of (a) interplate and (b) intraslab earthquakes recorded at CU that produced large PGA (Table 1 and Ⓔ Table S1). The shape of spectra of the two types of earthquakes differ; those of interplate earthquakes are peaked between 0.3 and 0.8 Hz, whereas those of intraslab earthquakes are relatively flat in the 0.4–2.0 Hz range. The plotted spectra are the geometric mean of the two horizontal components. (c,d) North–south accelerograms of the 1985 M_w 8.0 Michoacán and 2017 M_w 7.1 Morelos-Puebla earthquakes recorded at CU. (e) FAD (the geometric mean of the two horizontal components) at CU of the two earthquakes. (f) Geometric mean of SA, 5% damping, at CU of the two earthquakes.

0.8 Hz, whereas those of the intraslab earthquakes are relatively flat in the 0.4–2.0 Hz range. Because the spectral amplification of seismic waves at sites in the transition and lake-bed zones with respect to CU is roughly invariant, the FAS at CU is reflected in the damage pattern in the city. Severe damage in the city may be expected if the FAS at station CU exceeds 20 cm/s (as was the case during the 1985 and 1979 interplate and the 2017 intraslab earthquakes).

Figure 4c,d show north–south component of acceleration at CU during the 1985 and 2017 earthquakes. A visual examination of the trace of the 2017 earthquake shows that it is, relatively, enriched at high frequencies as compared with the 1985 event. It is clearly seen in Figure 4e,f where the geometric mean of the FAS and SA of the two horizontal components are plotted. The FAS and SA of the 2017 earthquake are greater at $f > 0.6$ Hz ($T < 1.6$ s), especially at $f > 1.6$ Hz ($T < 0.6$ s), but smaller at $f < 0.6$ Hz ($T > 1.6$ s) than during the 1985 earthquake. From Figure 4e,f, we conclude that the sites in the transition and lake-bed zones with dominant period ≤ 1.6 s ($f \geq 0.6$ Hz) had greater FAS and SA in 2017 than in 1985. On the other hand, the FAS and SA must have been greater in 1985 than in 2017 at sites with dominant period > 1.6 s ($f < 0.6$ s). SCT (Figs. 1 and 2), with dominant site period of 2.0 s and the only station in the lake-bed zone that recorded both events, generally supports this inference (Ⓔ Fig. S4). However, the larger SA at $T < 1.6$ s during the 2017 earthquakes at station CU (Fig. 4) is not realized at SCT, in which SA is roughly the same during the two earthquakes (Ⓔ Fig. S4).

It follows from the above considerations that the spatial distribution of the damage and SA at 1 and 2 s during the two earthquakes would differ. To verify this inference, we compiled the statistics of the damaged buildings and their locations, and computed SA for the 2017 earthquake from the accelerograms recorded at 65 sites in the city (Fig. 2a,b and Ⓔ Fig. S5 give locations of the stations). The 1985 earthquake, however, was recorded at only seven sites (five in the lake-bed zone). The SA maps for this earthquake (Fig. 2c,d) were computed from the CU recording, the estimated spectral amplification at sites in the city, and the application of random vibration theory (Boore, 2003), and hence, are approximate. Damage statistics as a function of dominant period of the site during the two earthquakes is given in Figure 2c,f. Figure 2 confirms that the damage during 2017 occurred predominantly in the area bounded by 0.5–1.6 s contours of the dominant site period. Although the damage during the 1985 earthquake also extended to the area between the 1.0 and 1.6 s contours, it was mostly concentrated between the contours of 1.8–3.0 s, with a peak at 2.0 s. As expected, the area that suffered severe damage during the 1985 earthquake coincides with high SA at 2 s (Fig. 2e). Thus, the observed damage patterns during 2017 and 1985 earthquakes follow the general damage patterns expected from the Fourier spectrum of the ground motion during these earthquakes at station CU. Similar patterns will, no doubt, repeat during future destructive intraslab and interplate earthquakes.

The SA values at 1 and 2 s during 2017 are relatively low (less than about 450 cm/s^2) over a large area that includes the Condesa and Roma colonies (19.38°–19.43° N, 99.12°–99.16° W). This area suffered severe damage during both earthquakes. Ⓔ Figure S6 illustrates SA at 10 sites in the area during the 2017 earthquake. For comparison, the figure also includes the SA at SCT during the 1985 and 2017 earthquakes. Clearly, SA of less than 450 cm/s^2 during 2017 was sufficient to cause severe damage in this area. As discussed earlier, the SA at SCT during the two earthquakes was roughly the same at $T < 1.6$ s but was much greater at longer period during 1985. It is quite possible that the trend of SA at other sites in the area was consistent with CU recordings (Fig. 4): greater SA at $T < 1.6$ s in 2017 but larger SA at longer periods in 1985. If so, we expect greater damage during 2017 at sites with dominant period < 1.6 s but higher damage during the 1985 earthquake at sites with period ≥ 1.6 s. This is in excellent agreement with the statistics of number of buildings that suffered partial and total collapse as a function of the dominant period of the site during the two earthquakes (Fig. 2c,f). During the 2017 earthquake, the numbers of partially or totally collapsed buildings with dominant site period < 1.6 s and ≥ 1.6 s were 44 and 12, respectively; the corresponding numbers during the 1985 earthquake were 20 and 170.

EXCEEDANCE RATE OF PGA AT STATION CU FROM INTRASLAB EARTHQUAKES

We use the recordings at CU during the period 1964–2017 to estimate return period of PGA of 50–60 cm/s^2. Figure 5 shows the observed exceedance rate of PGA at CU, computed simply by counting how many times a given PGA value has been exceeded, and dividing it by the observation period of 54 yrs. This empirical exceedance rate is complemented with a statistical maximum-likelihood fit to a truncated Pareto distribution of the following form:

$$\nu(a) = \nu_0 \left(\frac{a_0}{a}\right)^{\alpha}, \qquad a \geq a_0,$$

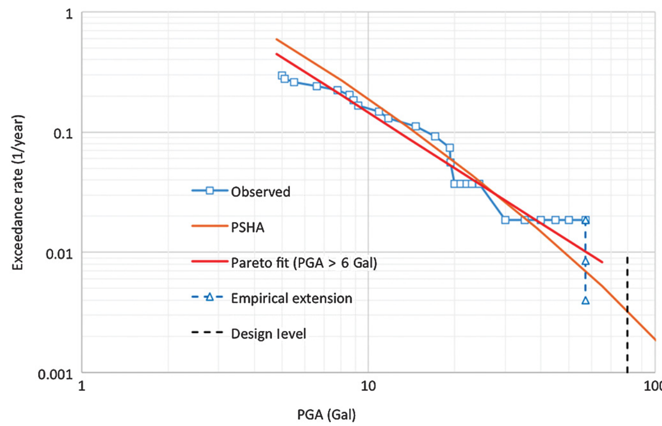
in which a is PGA, a_0 is the acceleration completeness threshold, 6 cm/s^2 in our case (Singh *et al.*, 2015), ν_0 is the exceedance rate for acceleration a_0, and α is a shape parameter. It can be shown that the maximum-likelihood estimators for ν_0 and α, assuming a Poisson occurrence, are (Malik, 1970)

$$\widehat{\nu_0} = \frac{N}{T}$$

$$\hat{\alpha} = \frac{N}{\sum_i \ln(a_i/a_0)},$$

in which N is the number of events with $a > a_0$ in observation period T, and a_i, $i = 1, \ldots, N$ are the observed PGA values in the same period.

In the same Figure 5, we compare these empirical curves with the exceedance rate obtained from PSHA. The PSHA analysis was performed between 2014 and 2017, before the occurrence of the 2017 earthquake, as part of the studies related to the development of the latest Mexico City 2018 building code. The analysis followed the classic Esteva–Cornell approach. Intraslab earthquakes are assumed to occur on the subducted Cocos plate, at varying depths governed by the geometry of the Benioff zone. The subducted plate has been divided into three segments; each one has different magnitude–frequency relation to account for the different observed seismicity. Within each segment, earthquakes are assumed to be uniformly distributed. Earthquakes are modeled as extended sources, using standard area–magnitude relations, with focal mechanisms consistent with those observed. It is worth noting that hazard was computed at station CU using a site-specific GMPE (Jaimes *et al.*, 2015), which was constructed using exclusively recordings at this station obtained during intraslab events. Therefore, there are no other appropriate candidate GMPEs. Calculations were made using code CRISIS v.18.2 (see Data and Resources). It is reassuring to see that the computed hazard matches reasonably well the observed exceedance frequencies, at least for the initial part of the curve.



▲ **Figure 5.** Exceedance rate of PGA at CU in Mexico City from intraslab earthquakes.

The original question remains: what is the return period of the PGA observed during the 2017 event at station CU? According to the empirical curve, we know that the return period must be at least 54 yrs, corresponding to an exceedance rate of 0.0185/yr; this value is the upper triangle in the curve labeled "Empirical extension" in Figure 5. However, it is almost sure that this acceleration level has not been exceeded at least since 1900, although we do not have a complete catalog for this period. If this is true, then the return period of PGA = 57 Gal would be at least 117 yrs, or an exceedance rate of 0.0085/yr; this value is the middle triangle of the "Empirical extension" curve. So we can conclude that the return period of this acceleration is longer than 117 yrs, but perhaps not much longer. PSHA results indicate a return period of about 150 yrs, or an exceedance rate of 0.067/yr. We conclude that an earthquake with PGA of about 60 cm/s^2 corresponds to a return period of the order of at least 150 yrs. For reference, Figure 5 shows also the design level at station CU, PGA = 80 Gal, which was not exceeded during the 2017 event. This acceleration value corresponds to a return period of about 300 yrs, if one accounts only for the intraslab events; if all events are accounted for, this PGA level is associated with a nominal return period of 250 yrs.

CLOSEST DISTANCE OF INTRASLAB EARTHQUAKES TO MEXICO CITY

The green dashed line in Figure 1 delineates observed limit of intraslab seismicity and, if the location error of the events is small, then the line also defines the closest distance of such events to Mexico City. We note that the events identified by numbers marked by letters in the figure (Table 1) were located using local and regional recordings and, hence, are reliable. Epicenters of pre-1975 earthquakes (Ⓔ Table S2) marked by letters are less accurate because they were located from sparse regional recordings. The green dashed line outside the enlarged rectangular box is based on Global Centroid Moment Tensor epicenters. It is likely to be shifted 20–30 km to the north of its true location because the teleseismic locations of Mexican earthquakes are systematically shifted by ~30 km to the northeast (Singh and Lermo, 1985; Hjörleifsdóttir *et al.*, 2016). The error in the location of the observed events is not the only source of uncertainty in defining the green line; relatively short time period covered by earthquake catalogs may also be a factor. This is illustrated by the location of the 2017 earthquake. Before the occurrence of this earthquake, the shortest distance to the green line from Mexico City would have been ~135 km rather than 114 km (Table 1; Fig. 1, inset).

The location error and short time span covered by the catalog, however, are unlikely to be the cause of the misalignment between the green line west of 96° W and the depth contours of the subducted slab; the distance between the trench and the green line between 96° and 102° W increases from west to east in the direction of the plate convergence (N36°E). This may be a consequence of smaller relative convergence rate and younger subducting slab at the trench at 102° W than at 96° W (5.5 cm/yr and 11 Ma versus 6.6 cm/yr and 17 Ma, respectively). The pressure and temperature of the slab may be such that seismic rupture is not possible further north of the green line. From these considerations, the closest epicentral distance of intraslab earthquakes to Mexico City, dictated by the green line in the enlarged rectangular area, is likely to be ~100 km. The magnitude of such an earthquake can easily reach 7.3; after all, two **M** 7.3 earthquakes, in 1937 and 1964 (Ⓔ Table S2; events d and 4 in Fig. 1), occurred near the down-dip limit of the intraslab seismicity (green dashed line in Fig. 1).

CONCLUSIONS

An intraslab M_w 7.1 earthquake at a hypocentral distance of 127 km from Mexico City was not a surprise because M_w 5.6–5.9 earthquakes have occurred in recent years near the 2017 earthquake ($R \sim 145$–160 km). In fact, Mexico City's building code of 1987 incorporated an intraslab earthquake of M_w 6.5 at $R = 80$ km (Rosenblueth *et al.*, 1989). However, the ground motion at station CU, the reference hard site in the hill zone of the city, was anomalously high in the 0.4–1.0 Hz frequency range. The observed PGV at CU and elsewhere was greater than expected from GMPEs. This was also true of the response spectrum, SA, at CU. Anomalously large ground motion at frequencies critical to Mexico City (probably due to a combination of relatively energetic source and source directivity) undoubtedly contributed to the severe damage. However, the strong-motion recordings at 65 sites in Mexico City reveal that the SA exceeded the design spectra of the Mexico City's 1987 building code at only two sites in the lake-bed zone (whose dominant periods are close to 1 s), three sites in the transition zone, and one site in the hill zone. It follows that the large ground motion during the 2017 earthquake was not the only cause of the disaster. The buildings that suffered total or partial collapse were constructed before the 1987 building code became effective and/or involved deficient design and poor construction (Galvis *et al.*, 2017).

From the strong-motion recordings at CU during the last 54 yrs as well as the PSHA, we estimate that an intraslab earthquake with PGA of about 60 cm/s^2 at CU, such as the 2017 event, corresponds to a return period of the order of at least 150 yrs.

Because the frequency content of incident seismic wavefields at station CU from intraslab and interplate earthquakes differ, so do the damage patterns in the city. For this reason, the buildings in the areas of the city with dominant site period of less than 1.6 s suffered severe damage in 2017. On the other hand, severe damage during the 1985 interplate earthquake extended to sites with dominant period between 1.8 and 3.0 s. These damage patterns in the city will, no doubt, repeat during future destructive intraslab and interplate earthquakes.

DATA AND RESOURCES

Strong-motion data used in this study were obtained by the Strong Ground Motion Database System (http://aplicaciones.iingen.unam.mx/AcelerogramasRSM/), the Servicio Sismológico Nacional (SSN; http://www.ssn.unam.mx/doi/networks/mx/), Instituto de Geofísica, Universidad Nacional Autónoma de México (UNAM), and the Centro de Instrumentación y Registro Sísmico (CIRES; http://cires.org.mx/registro_es.php), Mexico City. Figure 1 was made using the Generic Mapping Tools v.4.2.1 (www.soest.hawaii.edu/gmt; Wessel and Smith, 1998). The other information on CRISIS v.18.2 can be found at http://www.r-crisis.com/. All websites were last accessed on February 2018.

ACKNOWLEDGMENTS

The authors thank the personnel of Seismic Instrumentation Group at the Instituto de Ingeniería of the Universidad Nacional Autónoma de México (UNAM), the Servicio Sismológico Nacional (SSN), Instituto de Geofísica, UNAM, and the Centro de Instrumentación y Registro Sísmico (CIRES) for station maintenance, and data acquisition and distribution.

Discussions with Roberto Meli and Jose Luis Camba regarding damage to buildings during the 1985 and 2017 earthquakes are acknowledged. The authors benefitted from comments by Hiroo Kanamori and Lingling Ye. Lingling Ye also shared some of her results prior to publication. The authors thank Faustino Ventura and Luis Manuel Buendía for their help in preparing some of the figures. The research was partly supported by Dirección General de Asuntos del Personal Académico (DGAPA), UNAM-Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT) Project IN101018.

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Published Online 10 October 2018