The M_W 6.2 Punta Santa Elena (Coahuila-Zacatecas) earthquake of 28 April 1841, the largest documented pre-instrumental event and its implications on seismic hazard in Northeastern Mexico

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Abstract In this study, we compiled reports from different catalogs and newspapers about the greatest earthquake documented in Northeastern Mexico. From these descriptions, we located the 28 April 1841 earthquake using the Bakun and Wentworth (1997) attenuation model for the Basin and Range region. From 13 observations with an intensity range of III–VII, we calculated a M_w 6.2 and the central intensity SW from Punta Santa Elena, Coahuila (24.65° N, 101.60° W). This earthquake could represent the fourth biggest event in the Mexican Basin and Range province after the events of Bavispe, Sonora, of 1887 (M_w 7.5), Parral, Chihuahua, of 1928 (M_w 6.5), and Valentine, Texas in the Texas-Chihuahua border, of 1931 (M_w 6.4). Finally, this study provides new insights on earthquake potential in the region to be considered for enhanced hazard quantification and shows that the region is seismically active and prone to events up to $M > 6$.

Keywords Macroseismic intensity · Attenuation relations · Mexican Basin and Range province · Historic earthquake

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1 Introduction

Northeastern Mexico (NE) is located in the continental part of the country and is generally considered a tectonically stable region, characterized by low seismicity and a lack of strong ground motion records (Galván-Ramírez and Montalvo-Arrieta 2008). The states of Coahuila, Nuevo León, and Tamaulipas are located in this area and have always been considered the northeastern part of the country. In this region, the permanent seismological observatories are scarce, scattered, and with a relatively short period of recording. This means that the region's earthquake catalog is complete for approximately the last 20 years which implies that the seismic hazard could be underestimated considering this short period of earthquake monitoring. Commonly, the seismic activity of a region can be studied from two perspectives: instrumental recordings and historical documentation. The instrumental perspective has the advantage of being a recording of the ground motion, which leads to event duration and size. However, instrumental recordings in Mexico have been available only for approximately the last 110 years (Suárez and Pérez-Campos 2020). In many cases like NE Mexico, the earthquake cycle has a long periodicity: repetition of an earthquake of a certain size can occur in a time-lapse from decades to centuries (Scholz et al. 1986) beyond the period of the instrumental seismic record. The permanent seismological stations installed in NE Mexico (LNIG, MNIG, GTIG, and MCIG) by Servicio Sismológico Nacional (SSN) have reported more than 500 earthquakes in the region since 2006, with a

magnitude range of $1.9 \leq M_d \leq 4.5$. This short instrumental history excludes earthquake record of considerable magnitude that have occurred in the past. Especially in regions with a lack of knowledge of historical seismicity as NE Mexico, there is still a long way to go to an adequate seismic risk assessment.

García-Acosta and Suárez (1996) formed a descriptive catalog of documented earthquakes in the country from 1 Pedernal (Aztec calendar that corresponds to 1116 years in standard calendar) until December 27, 1912. The catalog consists of descriptions of the earthquakes, listed by location and date, extracted from publications or stories. However, in the 1838–1911 period, only 20 events were identified in different cities and/or villages in NE Mexico. Additionally, Galván-Ramírez and Montalvo-Arrieta (2008) compiled historical seismicity in the same region (they considered the 24–31° N, 97–106° W area) for the 1787–2006 period, using epicentral locations from different national and international earthquake catalogs. Moreover, some other authors have also reported damage in NE Mexico (Leal-Ríos 2001; Casasús 2003).

The distribution of these historical earthquakes is shown in Fig. 1. Most of the events reported by Galván-Ramírez and Montalvo-Arrieta (2008) have small magnitudes ($3.5 \leq M \leq 4.6$, green circles). However, from the 20 events identified in the García-Acosta and Suárez (1996) catalog, the description of one of them stands out because of the losses and great damages in the state of Coahuila (April 28, 1841, hereafter Punta Santa Elena earthquake (PSE)), and a felt radius of a 350 km. Most of the locations where this event was felt and that count with macroseismic descriptions are located in the Mexican Basin and Range province (BR hereafter).

The BR province has always been considered a physiographic entity that is actively deformed, extending from southern Oregon to western Texas, west USA. It consists of a N-S oriented system of elongated ranges and parallel narrow valleys, which are the product of distending tectonics in the Mid-Late Cenozoic (dePolo 1994; Pancha et al. 2006). Several authors suggest that most of the northern part of Mexico represents the southern end of the Basin and Range province, based on tectonics and morphology. It continues until the Mesa Central-Trans-Mexican volcanic belt limit, and previous to the formation of this volcanic arc, it would have extended to the south of Mexico (Jansma and Lang 1997; Henry and Aranda-Gomez 2000; Suter and Contreras 2002).

In this work we search, recover, and analyze available information about earthquake effects occurring in the past, from stories written in newspapers and books. We also used the Bakun and Wentworth (1997) methodology to estimate the central intensity and magnitude of the 1841 earthquake that has been registered in historical documents for NE Mexico. This method can be used to analyze historical earthquakes with few assigned intensities. Knowledge of earthquakes from the past represents a great step in the study of tectonic activity in the long term.

2 Historical seismicity in Northeast Mexico

Galván-Ramírez and Montalvo-Arrieta (2008) presented a catalog of the historical seismicity for the 1847–2006 period in NE Mexico. In that compilation, they found 24 earthquakes. Additionally, they considered reports about human perception that were documented for these historical earthquakes in a 1787–1911 period (the chronicles are described in Table 2 of the Galván-Ramírez and Montalvo-Arrieta 2008 work). Figure 1 shows the location of the cities where these events were reported (red stars).

From this historical catalog, the PSE earthquake of April 28, 1841, is the one with the most information on its effects, which will be presented in Section 4. Also, the compilation made by García-Acosta and Suárez (1996) finds that after the occurrence of the PSE event, reported aftershocks were felt by the population in Saltillo city. The chronicle says: "…May 13, 1841. It was felt an earthquake with underground noise, more earthquakes were felt during the night. Some houses were damaged and suffered several cracks from the earthquake of the night of April 28, 1841. Finally, the chronicle says that since the earthquake of April 28, small earthquakes have been felt until this date…".

The occurrence of the PSE earthquake on April 28, 1841, is not a singular observation, considering that big historical earthquakes have occurred in BR and caused great damage (Fig. 2): M_w 7.5 Bavispe, Sonora, 1887 (Castro et al. 2010; Suter 2015); M_w 6.5 Parral, Chihuahua, 1928 (Doser and Rodriguez 1993); and M_w 6.4, Valentine, Texas, 1931 (Doser 1987). Although the Mexican portion of BR can be divided into various structural domains, which have different geological history and style/state of deformation, these changes represent a continuous series (Aranda-Gómez et al. 2000).

Fig. 1 Historical records for Northeastern Mexico. Red stars represent cities that perceived one or several earthquakes (García-Acosta and Suárez 1996; Leal-Ríos 2001; Casasús 2003). Green circles represent historical seismicity in the study area according to Galván-Ramírez and Montalvo-Arrieta (2008)
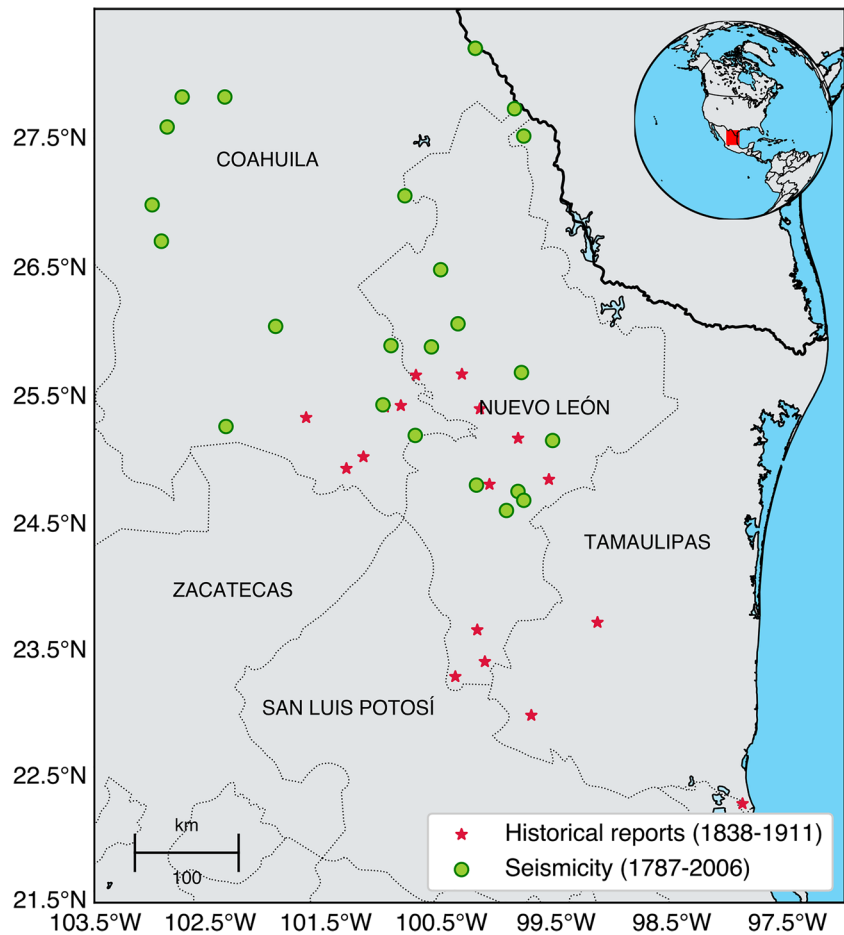
3 Methodology

The Bakun and Wentworth (1997) method determines the best fitting magnitude and central intensity (CI) from modified Mercalli intensity (MMI) values depending on distance, using preset calibrations for the California region from a group of earthquakes with known magnitude and location. This method produces an estimated magnitude (M_I), which is expected to correspond with M_w if M_w values are used as calibration events to determine local attenuation. It requires an attenuation model that represents the study area. These relations are generated from a group of known earthquakes with assigned intensities. Using a preset model with the same geological features is the best option since there is no such database in NE Mexico.

From a group of earthquakes that occurred in the center of Nevada, Bakun (2006) determined an MMI attenuation relationship for earthquakes in the BR

province to estimate magnitudes of historical earthquakes. He obtained the following equation from the resulting magnitudes:

$$MMI_{BR} = (0.44 \pm 2.34) + (1.70 \pm 0.33)M - (0.0048 \pm 0.0014)$$

$$\Delta_h - (2.73 \pm 0.49)log\Delta_h \qquad (1)$$

where M is moment magnitude and Δ_h is hypocentral distance in kilometers.

As seen in Fig. 2, most of the places with intensities are located in BR. It will be assumed then that the seismic source for the PSE earthquake is located in this province and that the intensity attenuation depending on distance has a similar trend as the model previously proposed.

A mesh is defined on the felt region including all the intensities that describe the event. Each node is a potential location for the source, and M_I and its root-mean-square function rms $[M_I]$ value are calculated at each
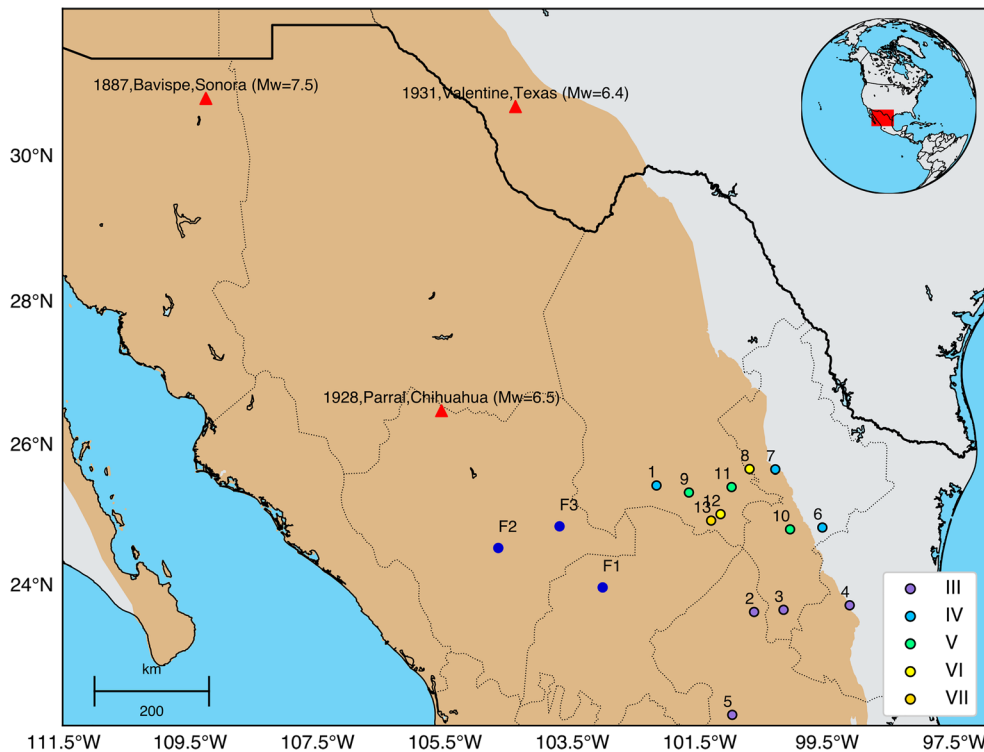
Fig. 2 Numbers are the places where there are reports of the Punta Santa Elena earthquake of 28 April 1841 (see Table 1 for references). 1: Parras, Coahuila (Coah); 2: Matehuala, San Luis Potosí (SLP); 3: Dr. Arroyo, Nuevo León (NL); 4: Ciudad Victoria, Tamaulipas; 5: San Luis Potosí, SLP; 6: Linares, NL; 7: Monterrey, NL; 8: Los Muertos, Coah; 9: Patos, Coah; 10: Galeana, NL; 11: Saltillo, Coah; 12: La Vaquera, Coah; 13: Punta Santa Elena, Coah.; F1: Nieves, Zacatecas; F2: Durango, Durango (Dgo); F3: Cuencame, Dgo. Colors correspond with the MMI obtained in this study. Triangles are the epicentral locations of the Bavispe, Sonora, 1887 (M_W 7.5); Parral, Chihuahua, 1928 (M_W 6.5); and Valentine, Texas, 1931(M_W 6.4) earthquakes. The brown color in the map is the Basin and Range province

one. M_I is simply the mean of all inferred magnitude values from the individual intensities.

$$M_I = \frac{1}{n}\sum_{i=1}^{n} M_i \qquad (2)$$

where

$$M_i = \left[MMI_i - 0.44 + 0.0048\Delta_{h,i} + 2.73 \, log \left(\Delta_{h,i} \right) \right]/1.7 \qquad (3)$$

MMI_i and $\Delta_{h,i}$ represent the assigned MMI and hypocentral distance, respectively, at the observation site i in a mesh of assumed points; n is the number of assigned intensities. In this case, the attenuation model that was used is the one in Eq. 1. rms quantifies the residual between the observed and calculated values:

$$rms[M_I] = [rms(M_I - M_i) - rms_0(M_I - M_i)] \qquad (4)$$

where $rms(M_I - M_i) = \left\{ \sum_i [W_i(M_I - M_i)^2] / \sum_i W_i^2 \right\}^{1/2}$, rms_0 is the minimum $rms_0(M_I - M_i)$ on the test epicenter mesh, and W_i is the distance weighting function:

$$W_i = \left\{ \begin{array}{l} 0.1 + cos\left[\left(\frac{\Delta_i}{150} \right)\left(\frac{\pi}{2} \right) \right], \Delta_i < 150 \, km \\ 0.1, \Delta_i \geq 150 \, km \end{array} \right\}, (5)$$

The $rms[M_I]$ contours delimit the epicentral region for earthquakes with enough assigned intensities (Bakun 2006). The correspondent node to the minimum rms is the CI, the point in which the residual between observed and calculated intensities is the lowest. CI corresponds to the location of major energy release on the fault plane (centroid); therefore, CI does not always match the epicenter (Bakun 2006; Beauval et al. 2010).

4 Punta Santa Elena earthquake (28 April 1841)

In this section, we described the chronicles from historical newspapers collected in the National Digital Newspaper Library of Mexico (Hemeroteca Nacional Digital de México) and books written by local historians. In Table 1 we indicate the sources consulted.

On the night of 28 April 1841, a strong earthquake was felt in the surroundings of Saltillo city (#11 in Fig. 2), causing great damages. Since 1827, Saltillo city is the capital of the Coahuila state. A house collapsed at the Los Muertos hacienda (~50 km NW, intensity VI; #8 in Fig. 2); in La Vaquera community (~55 SW, intensity VI; #12 in Fig. 2), part of the hacienda fell on two children. The greatest damage was reported in Punta Santa Elena (#13 in Fig. 2), located at ~65 km from Saltillo city. A water well sank, and the hacienda was ruined, taking the lives of six persons (García-Acosta and Suárez 1996; intensity VII). This earthquake was also felt in the states of Nuevo León, San Luis Potosí, Tamaulipas, Durango, and Zacatecas, with in a ~350 km radius. According to the documentation compiled by García-Acosta and Suárez (1996), several aftershocks were felt the rest of the night and at least during the following 15 days. Figure 2 shows all the locations where the earthquake was felt.

The MMI values were assigned according to the modified Mercalli intensity scale (Wood and Neumann 1931) to the 13 communities (Table 1) with sufficient information available. These macroseismic intensities were used for the size characterization and location of the PSE earthquake (Table 1). According to methodology, a grid was generated with trial epicenters distributed every 5 km limits on the maximum and minimum coordinates from the data. In Fig. 3, M_I values were interpolated with the rms $[M_I]$ for each assumed epicenter, with an intensity range of III–VII. The locations in the states of Zacatecas (F1) and Durango (F2 and F3; Fig. 2) were not used in the calculation of CI since as there is not enough information to assign an M_I value. The equivalent M_W obtained at the CI is 6.2 and the location resulted SW from PSE (24.65° N, 101.60° W). This location corresponds with the intensity distribution, since the CI is close to the higher MMI values. The 95% and 67% Bakun and Wentworth (1999) confidence parameters were used for the rms $[M_I]$ contours; the 67% probability interval goes from 6 to 6.4 MI and the 95% from 6.2 to 6.7. Figure 3 also shows 2 normal faults located in the 67% interval, and the epicenter appears to be near to the segment of one of them. Figure 3 includes the normal faults identified in the BR province by Stewart (1978) and Henry and Aranda-Gomez (1992, 2000) and described as Plio-Quaternary faults by Padilla y Sánchez et al. (2013). Using the moment magnitude equation from Wells and Coppersmith (1994), we calculated a M_W = 6.2 with the surface rupture length (~11 km) of the closer segment that corresponds to the CI (Fig. 3) which leads us to confirm that this is the preferred location for the event. Nevertheless, more studies will be needed to confirm or reject this proposal.

5 Implications on seismic hazard in NE México

According to the main seismic zones of Mexico, NE Mexico is located in a low hazard zone, classified as zone A. This classification implies that major earthquakes ($M{\geq}6.0$) have not been reported in the last 80 years and that ground accelerations greater than 10% of gravity acceleration are not expected (CFE 1993). Consequently, building codes in the main cities of this portion of Mexico lack seismic considerations. Considering our new results, NE Mexico has the conditions to generate $M \geq 6$ earthquakes. From an instrumental catalog (2006–2009) Montalvo Arrieta et al. (2019) show that $M = 6$ earthquakes have an estimated recurrence period of approximately 200 years in the region. However, considering the results of Bayona-Viveros et al. (2017) for a low seismicity region (Trans-Mexican volcanic belt in central Mexico), if only a short instrumental catalog is taken into account for the estimation of recurrence period of great earthquakes, these periods can be very large. Therefore, if historical earthquakes are included in the catalog, the seismic hazard estimates increase up to 30% in the earthquake-rate model, as the authors found when including historical seismicity in the Trans-Mexican volcanic belt. Reflecting on the results of these authors, a similar effect can be expected for NE Mexico, with the inclusion of the PSE earthquake in the estimation of the recurrence period of major earthquakes in the region.

On the other hand, in Fig. 3, there are several identified extensional faults for late Cenozoic (Stewart 1978; Henry and Aranda-Gomez 1992) with 11-57 km surficial lengths. The values of $6 \leq M_W \leq 7.2$ were obtained using the relations proposed by Wells and Coppersmith (1994) to obtain the magnitude from fault surficial lengths. This range of magnitudes is expected for

Table 1 Locations of the assigned intensities for the PSE earthquake

Label in Fig. 2	Location	Latitude (°N)	Longitude (°W)	Damages	MMI	Reference
13	PSE, Coahuila	24.95	−101.32	A water well sank and another one collapsed Collapsed house Crackings in houses Ruined hacienda Six persons died	VII	García-Acosta and Suárez (1996); HNDM 2020
12	La Vaquera, Coahuila	25.04	−101.17	The hacienda was cracked and a part of it fell and killed two persons	VI	García-Acosta and Suárez (1996); HNDM 2020
11	Saltillo, Coahuila	25.43	−101.00	Poorly built houses were ruined Average built houses full of crackings People claimed it lasted 2–3 s	V	García-Acosta and Suárez (1996); HNDM 2020
10	Galeana, Nuevo León	24.83	−100.08	Damage in the main tower of the church	V	Casasús (2003); Leal-Ríos (2001); Roel (1984)
9	Patos, Coahuila	25.35	−101.67	A lot of people felt it and some even felt the direction of the movement There were 13 aftershocks	V	García-Acosta and Suárez (1996); HNDM 2017
8	Los Muertos, Coahuila	25.68	−100.71	Collapsed house A lot of people felt it	VI	García-Acosta and Suárez (1996); HNDM 2020.
7	Monterrey, Nuevo León	25.67	−100.31	A big earthquake was felt Strong sound as if many carriages were approaching People could guess the direction of the movement	IV	Casasús (2003); Roel (1984); HNDM 2020
6	Linares, Nuevo León	24.85	−99.57	Strong shaking	IV	Casasús (2003); Roel (1984)
1	Parras, Coahuila	25.45	−102.17	Average built houses full of crackings	IV	HNDM 2020
5	San Luis Potosí, San Luis Potosí	22.16	−100.99	Felt earthquake	III	García-Acosta and Suárez (1996); HNDM 2020; Montejano y Aguiñaga (1999)
4	Cd. Victoria, Tamaulipas	23.74	−99.14	Felt earthquake and sounds were similar to explosions	III	García-Acosta and Suárez (1996)
3	Dr. Arroyo, Nuevo León	23.67	−100.18	Felt earthquake	III	García-Acosta and Suárez (1996)
2	Matehuala, San Luis Potosí	23.64	−100.64	Felt earthquake	III	HNDM 2020
F1	Nieves, Zacatecas	23.99	−103.02	Felt by population	F	HNDM 2020
F2	Durango, Durango	24.56	−104.66	Felt by population	F	HNDM 2020
F3	Cuencamé, Durango	24.87	−103.70	Felt by population	F	HNDM 2020

F felt (not considered in the calculation of *IC*), *HNDM* Hemeroteca Nacional Digital de México (newspapers)

Fig. 3 Magnitude and central intensity (*CI*) for the 28 April 1841 earthquake. Circles: intensities. Red triangle: *CI*. Red discontinued lines: M_I contours. Green lines: *rms* contours. The fault traces were obtained from Padilla y Sánchez et al. (2013). 1: Parras, Coahuila (Coah); 2: Matehuala, San Luis Potosí (SLP); 3: Dr. Arroyo, Nuevo León (NL); 4: Ciudad Victoria, Tamaulipas; 5: San Luis Potosí, SLP; 6: Linares, NL; 7: Monterrey, NL; 8: Los Muertos, Coah; 9: Patos, Coah; 10: Galeana, NL; 11: Saltillo, Coah; 12: La Vaquera, Coah; 13: Punta Santa Elena, Coah
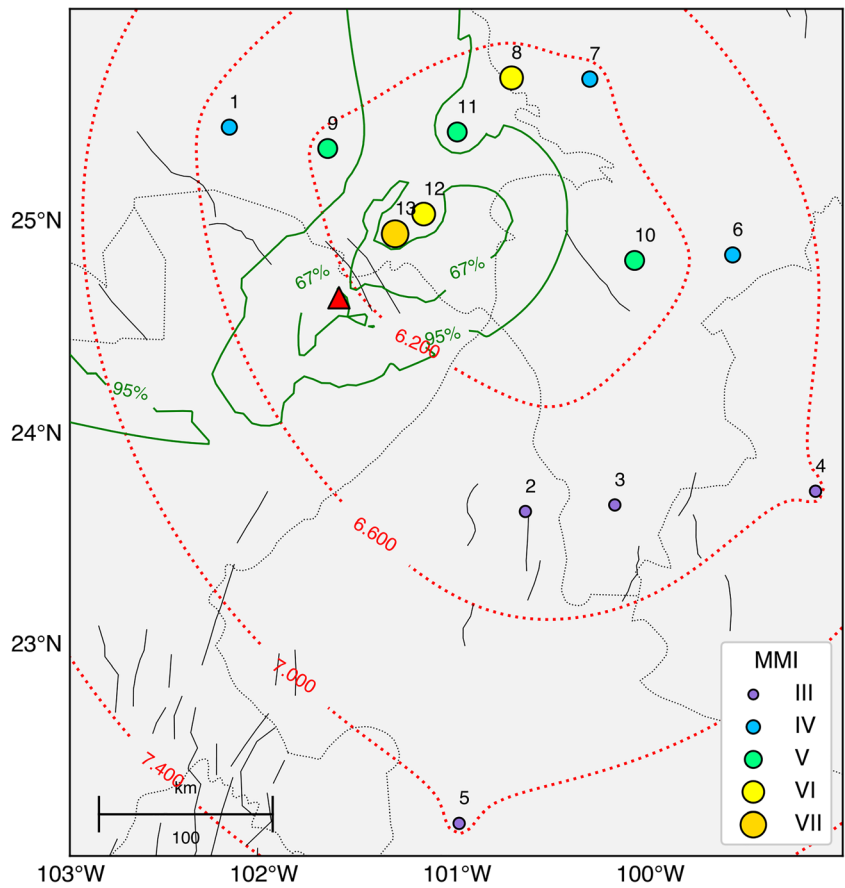
earthquakes in the BR province. Future morphotectonic and paleoseismological studies in this segment will allow to verify if this fault is active and if it could be related with the rupture of the PSE earthquake. The results obtained in this work can be used to improve the quantification of seismic hazard in NE Mexico, a region with more than 11.5 million inhabitants, as they exhibit an earthquake potential that is not fully captured by the instrumental record.

6 Conclusions

From a compilation of 13 historical descriptions of the PSE 28 April 1841 earthquake, we estimated an III-VII MMI range for several sites in NE Mexico. Using the methodology of Bakun and Wentworth (1997), valid for BR province, we obtained a M_W 6.2 for the Punta Santa Elena earthquake, with a central intensity located at 24.65° N and 101.60° W near to the border of the Coahuila and Zacatecas states. The greatest damage

was reported in Punta Santa Elena, located at ~65 km southwest from Saltillo city where a house collapsed and a hacienda was ruined and several houses show cracks, causing eight casualties. This earthquake was also felt in the states of Nuevo León, San Luis Potosí, Tamaulipas, Durango, and Zacatecas, in a ~350 km radius. Additionally, the chronicles mention that at least in a period of 15 days, aftershocks were felt in the Saltillo area causing some types of damage to the houses that were affected during the main earthquake.

The PSE earthquake represents the fourth largest earthquake known in the Mexican BR province after the Bavispe, Sonora, 1887 (M_W 7.5); Parral, Chihuahua, 1928 (M_W 6.5); and Valentine, Texas, 1931 (M_W 6.4) earthquakes, and the first great earthquake reported in NE Mexico. The obtained central intensity lies near a normal fault identified in the region, one segment of this fault with ~11 km length could have generated a M6.2 earthquake. Field research is necessary to confirm if an activation of this fault segment caused the PSE earthquake.

Data Availability The descriptions (in Spanish) of the effects of the Punta Santa Elena earthquake that we used in this study were compiled from newspapers stored in the database of the Hemeroteca Nacional Digital de México (HNDM) Universidad Nacional Autónoma de México (http://www.hndm.unam.mx/index.php/es/) and references pointed in Table 1. The database of mapped faults is available in http://www.datapages.com/gis-map-publishing-program/gis-open-files/geographic/tectonic-map-of-mexico-2013.

Declarations

Competing interests The authors declare no competing interests.

References

Aranda-Gómez JJ, Henry CD, Luhr JF (2000) Evolución tectonomagmática postpaleocénica de la Sierra Madre Occidental y de la porción meridional de la provincia tectónica de Cuencas y Sierras, México. Bol Soc Geol Mex LIII:59–71 (in Spanish)

Bakun WH (2006) MMI attenuation and historical earthquakes in the Basin and Range province of Western North America. Bull Seismol Soc Am 96(6):2206–2220. https://doi.org/10.1785/0120060045

Bakun WH, Wentworth CM (1997) Estimating earthquake location and magnitude from seismic intensity data. Bull Seismol Soc Am 87(6):1502–1521

Bakun WH, Wentworth CM (1999) Erratum to Estimating earthquake location and magnitude from seismic intensity data. Bull Seismol Soc Am 89(2):557

Bayona-Viveros JA, Suárez-Reynoso G, Ordaz-Schroeder MG (2017) A probabilistic seismic hazard assessment of the Trans-Mexican Volcanic Belt, Mexico based on historical and instrumentally recorded seismicity. Geophys Int 56(1):87–101. https://doi.org/10.19155/geofint.2017.056.1.7

Beauval C, Yepes H, Bakun WH, Egred J, Alvarado A, Singaucho JC (2010) Locations and magnitudes of historical earthquakes in the Sierra of Ecuador (1587–1996). Geophys J Int 181:1613–1633. https://doi.org/10.1111/j.1365-246X.2010.04569.x

Casasús FR (2003) Monterrey, 407 trozos de su historia. Creatividad Editorial (in Spanish)

Castro R, Shearer PM, Astiz L, Suter M, Jacques-Ayala C, Vernon F (2010) The long-lasting aftershock series of the 3 May 1887 M_W 7.5 Sonora earthquake in the Mexican Basin and Range province. Bull Seismol Soc Am 100(3):1153–1164. https://doi.org/10.1785/0120090180

CFE - Comisión Federal de Electricidad (CDS-MDOC CFE) (1993) Manual de Diseño de Obras Civiles. Capítulo C.1.3 Diseño por Sismo (in Spanish)

dePolo CM (1994) The maximum background earthquake for the Basin and Range province, western North America. Bull Seismol Soc Am 84(2):466–472

Doser DI (1987) The 16 August 1931 Valentine, Texas, earthquake: evidence for normal faulting in West Texas. Bull Seismol Soc Am 77(6):2005–2017

Doser DI, Rodriguez J (1993) The seismicity of Chihuahua, Mexico, and the 1928 Parral earthquake. Phys Earth Planet Inter 78(1-2):97–104. https://doi.org/10.1016/0031-9201(93)90086-O

Galván-Ramírez I, Montalvo-Arrieta JC (2008) The historical seismicity and prediction of ground motion in northeast Mexico. J S Am Earth Sci 25(1):37–48. https://doi.org/10.1016/j.jsames.2007.07.004

García-Acosta V, Suárez G (1996) Los sismos en la historia de México, tomo I. Universidad Nacional Autónoma de México/Centro de Investigaciones y Estudios Superiores en Antropología Social/Fondo de Cultura Económica, 719 (in Spanish)

Henry CD, Aranda-Gomez JJ (1992) The real southern Basin and Range: mid- to late Cenozoic extension in Mexico. Geology 20(8):701–704. https://doi.org/10.1130/0091-7613(1992)020<0701:TRSBAR>2.3.CO;2

Henry CD, Aranda-Gomez JJ (2000) Plate interactions control middle-late Miocene, proto-Gulf and Basin and Range extension in the southern Basin and Range. Tectonophysics 318(1-4):1–26. https://doi.org/10.1016/S0040-1951(99)00304-2

HNDM (2020) Hemeroteca Nacional Digital de México. Universidad Nacional Autónoma de México. http://www.hndm.unam.mx/index.php/es/

Jansma PE, Lang HR (1997) The Arcelia graben: new evidence for Oligocene Basin and Range extension in southern Mexico. Geology 25:455–458

Leal-Ríos A (2001) Linares, capital de Nuevo León: Series testimonios. Universidad Autónoma de Nuevo León (in Spanish)

Montalvo Arrieta JC, Pérez-Campos X, Ramos-Zuñiga LG, Salinas Jasso JA, Paz Martínez EG, Martínez Jiménez LD (2019) 12 años de monitoreo sísmico en el Noreste de México, retos y realidades. XXII Congreso Nacional de Ingeniería Sísmica (XXII Earthquake Engineering Mexican Conference). 20 al 23 de Noviembre de 2019, Monterrey, Nuevo León. 22 pp (in Spanish)

Montejano y Aguiñaga R (1999) San Luis Potosí la tierra y el hombre. Cuarta Edición. Editorial Universitaria Potosina. San Luis Potosí, México (in Spanish)

Padilla y Sánchez RJ, Domínguez Trejo I, López Azcárraga AG, Mota Nieto J, Fuentes Menes AO, Rosique Naranjo F, Germán Castelán EA, Campos Arriola SE (2013) National

Autonomous University of Mexico Tectonic Map of Mexico GIS Project, AAPG GIS Open Files series

Pancha A, Anderson JG, Kreemer C (2006) Comparison of seismic and geodetic scalar moment rate across Basin and Range province. Bull Seismol Soc Am 96(1):11–32. https://doi.org/10.1785/0120040166

Roel S (1984) Nuevo León apuntes históricos. Tercera Impresión. Ediciones Castillo. Monterrey (in Spanish)

Scholz CH, Avilés CA, Wesnousky SG (1986) Scaling differences between large interplate and intraplate earthquakes. Bull Seismol Soc Am 76(1):65–70

Stewart JA (1978) Basin-range structure in western North America, a review, in Smith, R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 1-13

Suárez G, Pérez-Campos X (2020) 110th Anniversary of the Mexican National Seismological Service. An account of its early contributions. Seismol Res Lett 91(5):2904–2911. https://doi.org/10.1785/0220200157

Suter M (2015) Rupture of the Pitáycachi Fault in the 1887 M_w 7.5 Sonora, Mexico earthquake (southern Basin-and-Range Province): rupture kinematics and epicenter inferred from rupture branching patterns. J Geophys Res Solid Earth 120(1):617–641. https://doi.org/10.1002/2014JB011244

Suter M, Contreras J (2002) Active tectonic of northeastern Sonora, Mexico (Southern Basin and Range province) and the 3 may 1887 M_w 7.4 earthquake. Bull Seismol Soc Am 92(2):581–589. https://doi.org/10.1785/0120000220

Wells DL, Coppersmith KJ (1994) New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bull Seismol Soc Am 84(4):974–1002

Wood HO, Neumann F (1931) Modified Mercalli intensity scale of 1931. Bull Seismol Soc Am 21(4):277–283