Updated Tsunami Catalog for the Jalisco-Colima Coast, Mexico, Using Data from Historical Archives

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ABSTRACT

Modern earthquakes and tsunamis catalogs available online are compilations of earlier catalogs that included some inaccurate information. Here, we present a thorough revision of tsunamigenic earthquakes that, in historical time, have affected the Mexican Pacific coast between Jalisco and Colima. This area is located in a complex tectonic setting where the Rivera–Cocos and North American plates have produced four $\mathbf{M} \geq 8$ earthquakes and two big tsunamis since the nineteenth century. We identified tsunamigenic earthquakes that were not previously documented in modern earthquake and tsunami catalogs available online through a careful reading of original historical archives and documents. Our results indicate the occurrence of 21 events; among those we report 2 earthquakes documented for the first time (1563 and 1816) for the Jalisco-Colima coast, and 8 large or medium intensity tsunamis also first reported (1816, 1818, 1900 [two tsunamis], 1911, 1933 [two tsunamis], and 1941) through documentary evidence. Our results demonstrate the need for a thorough investigation of historical documents and geological evidence of earthquakes and their tsunamis to accurately assess seismic and tsunami hazard.

INTRODUCTION

Global historic earthquake and tsunami catalogs provide the basis for understanding the tsunamigenic potential of a given region and are used to perform probabilistic hazard analysis (Ambraseys and Synolakis, 2010; Pasaric *et al.*, 2012). The quality of a seismic-hazard analysis is determined by the quality of the data input into the analysis. Most of the early catalogs (e.g., Milne, 1911) were only lists of places, dates, and adjectives describing the damage (Udías, 2015), whereas newer ones are parametric because they include the magnitude and location of each epicenter (Gutenberg and Richter, 1954; Duda, 1965; Abe, 1981; Abe and Noguchi, 1983). More recent catalogs are supported by databases and can be accessed online, in which it is possible to display both parametric and descriptive data. Besides the improvement of instrumental monitoring, descriptions of the effects of the earthquakes are very important for seismology research. Historical Seismology, a branch of seismology that combines history and seismic knowledge to assess what Ambraseys (2009) called "long-term seismicity" (Guidoboni and Ebel, 2009), brings the methodology and tools to analyze qualitatively data from historic documents to understand the occurrence and damage produced by earthquakes and tsunamis.

The Mexican Pacific coast runs almost parallel to the Middle American trench, where at least 50 tsunamigenic earthquakes have occurred in historical times (National Centers for Environmental Information [NCEI], 2015).

One of the best-known, and perhaps the first complete, earthquake catalog for Mexico was compiled by Orozco y Berra (1887–1888). This document was the basis of important subsequent catalogs by Figueroa (1963), Soloviev and Go (1975), and Sánchez and Farreras (1993). Recently, García Acosta and Suárez Reynoso (1996) compiled descriptions taken from original sources about historical earthquakes that occurred before 1912 in Mexico. The most recent list of instrumentally observed earthquakes was produced by Kostoglodov and Pacheco (1999). Currently, an updated and validated catalog of earthquakes ($\mathbf{M} > 6.5$), both historical and those measured instrumentally in Mexico, is not yet available.

The tectonic setting where the Jalisco-Colima coast is located is prone to large earthquakes and tsunamis, but only two large tsunamis that occurred in 1932 have been cataloged. This can be explained by the scarcity of historical references given the sparse population, lack of communication from the region, and the occurrence of several wars that have affected the preservation of documents over time. The goal of our study is to revisit data from primary sources cited in previous catalogs and to find new data for earthquakes with tsunamigenic evidence through an exhaustive search throughout archives and libraries.

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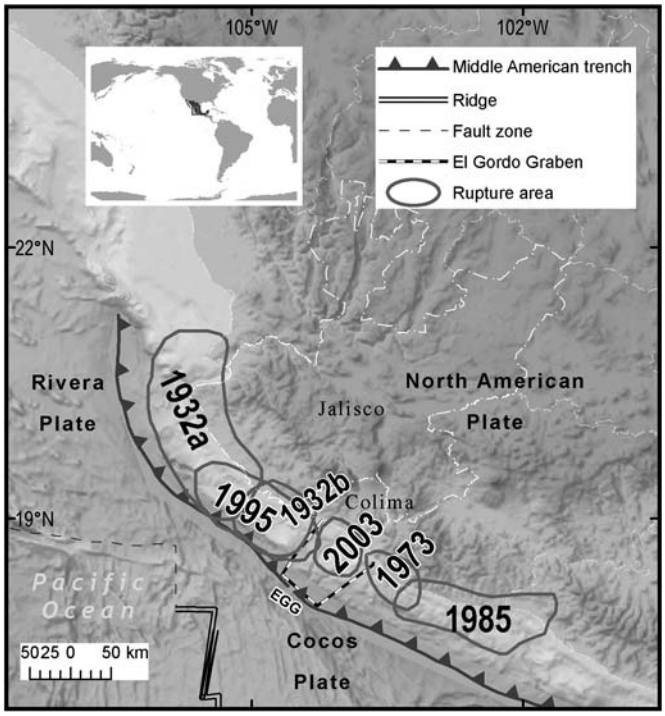


▲ **Figure 1.** Tectonic setting, rupture areas plotted for tsunamigenic earthquakes from 1932 to 2016 (Kostoglodov and Pacheco, 1999). Letters are used to identify epicenters for earthquakes that occurred in the same year: 1932a (3 June 1932), 1932b (18 June 1932).

Here, we present the results of a revision of 23 potential tsunamigenic thrust shallow earthquakes registered historically and/or instrumentally, supported by original documents found in archives and historic newspapers. The data are organized in catalog form accompanied by descriptions and references for every event. We found descriptions for two earthquakes and for some small-to-big tsunamis not included or reported earlier in modern online catalogs, and we confirmed the occurrence of one great tsunami produced by a large earthquake in the last 500 years in the study area.

TECTONIC AND HISTORIC CONTEXT

The section of the Mexican Pacific coast between Jalisco and Colima runs almost parallel to the Middle American trench where the Rivera and Cocos plates underthrust the North American plate. This area is a complex tectonic environment where a triple point results from the convergence of Cocos, Rivera, and North American plates (Singh and Suárez, 1988; Singh and Mortera, 1991; Ruff and Miller, 1994; Bandy *et al.*, 1995; Kostoglodov and Bandy, 1995; Suárez *et al.*, 2013). The convergence velocity increases from northwest (NW, 1.4 cm/yr) to southeast (SE, 6.8 cm/yr) and the geometry of the subducting plate also varies (DeMets and Stein, 1990; Pardo and Suárez, 1995; Kostoglodov and Pacheco, 1999; Bandy *et al.*, 2005; Fig. 1). The Rivera–North American subduction zone is characterized by lower seismicity ($\mathbf{M} \leq 7.5$) and fewer aftershocks than the Cocos–North America subduction zone (Singh *et al.*, 1981; Singh and Suárez, 1988). At least two big earthquakes ($\mathbf{M} \geq 8.0$) are known to have produced tsunamis in 1932 and in 1995. However, the historically sparse population and the low density of seismometers have limited the accuracy of earthquake locations in the area. Tsunamigenic earthquakes in the first half of the twentieth century in Mexico have at least 75 km of uncertainty in epicentral location and 20 km uncertainty in depth (Cruz and Wyss, 1983; Singh and Lermo, 1985). The determinations of epicentral location and depth have been improved since the emergence of global digital seismic networks in the 1980s (Singh *et al.*, 1985; Lee and Benson, 2008).

Historical Seismology research is challenging in the study area because of the damage to county and church archives by humidity, fires, and military conflicts. Also, this area remained almost unpopulated until the first half of the twentieth century. It is known that at least one important earthquake occurred every century: 27 May 1563; 25 and 26 August 1611; and 22 October 1749. However, our results indicate damage related only to the sixteenth-century earthquake, leaving an information gap for the following two centuries.

DATA AND METHODS

We accessed online catalogs to obtain date, location, and magnitude for the reported largest historical earthquakes in the Jalisco-Colima coast (Mexican Pacific coast, Table 1). We also searched for reports of tsunamis to identify tsunamigenic events. The potentially tsunamigenic events were established based on two criteria: (1) epicenter location and/or magnitude of the earthquake, and (2) reference of a tsunami occurrence. A combined reading of the map of epicenters with their magnitudes (when available), along with the descriptions of damage, allowed us to differentiate between those large earthquakes located offshore or close to the coast and those with unreliable epicentral locations.

Because current catalogs are compilations of previous ones, we used the primary sources to find new data for earthquakes with tsunamigenic evidence. The first step was to compile all the descriptions and to locate the original historical sources for every selected earthquake. We reviewed all the repositories available online (databases and/or digital documents) and also those available in libraries and archives. We focused our historical research on data from: (1) *salinas* (saltworks for salt extraction), which were located near the coast and which were an important economic activity during the viceroyalty; (2) pirate surveillance reported by guards settled at some sites along the coastline and who reported any intruder ship, and (3) harbor activity in which authorities and sailors might have reported earthquakes and/or tsunamis. To confirm and/or improve the reliability of our data, we use a cross-checking technique which allowed us to validate date and place of the event and, when available, the authoritative credentials of the informant.

Table 1
Catalogs of Earthquakes and Tsunamis in Mexico

Source	Data	Place and Time	Reference
Significant earthquake database	Earthquake and tsunami catalog (parametric and with descriptions)	World (−2150 to 2015)	National Geophysical Data Center/World Data Service (NGDC/WDS), doi: 10.7289/V5TD9V7K
Global historical tsunami database			NGDC/WDS, doi: 10.7289/V5PN93H7
Historical tsunami database for the world ocean	Earthquake and tsunami catalog (parametric)		Tsunami Laboratory (2015)
Historical earthquake database			Tsunami Laboratory (2015)
Catálogo de los sismos más fuertes de México (M >6.5)	Earthquake catalog (parametric)	México (1900–2003)	Kostoglodov and Pacheco (1999)
Los Sismos en la Historia de México	Earthquake and tsunami catalog (with descriptions of earthquakes effects. Verbatim from original documents and publications)	México (1475–1912)	García Acosta and Suárez Reynoso (1996)
Efemérides Sísmicas	Catalog for earthquakes until 1888 with descriptions and references	México (1460–1887)	Orozco y Berra (1887–1888)
Catalog of tsunamis of the eastern shore of the Pacific Ocean	Descriptions for tsunami and runup occurrence	Pacific basin (1513–1968)	Soloviev and Go (1975)
Seismología. LosTerremotos de Jalisco	Earthquake catalog	Jalisco (1746–1875)	Bárcena (1875)
List of seismic sea waves	Tsunami catalog	World (479–1946)	Heck (1947)
Catálogo de Tsunamis (Maremotos) en la Costa Occidental de México	Tsunami catalog with descriptions and references	Pacific coast of México	Sánchez and Farreras (1993)
Historia Sísmica y Estadística de Temblores de la Costa Occidental de México	Catalog and analysis of earthquakes	México	Figueroa (1963)
Catálogo de Sismos Ocurridos en la República Mexicana	Earthquake catalog (parametric)	México (1900–1970)	Figueroa (1970)
Catalog of shallow earthquakes of Mexico (1900–1981)	Earthquake catalog (parametric)	México (1900–1981)	Singh *et al.* (1984)

THE UPDATED TSUNAMI CATALOG FOR THE JALISCO-COLIMA COAST

In this section, we present the results for an updated catalog for tsunamis in the Jalisco-Colima coast (Table 2,) accompanied by a short description from primary sources. To standardize the data, some conventions were used: the epicentral coordinates are expressed in decimal degrees (latitude, longitude); the date and time are given in UTC; the magnitude is presented in M_s/M_w; all the sources are cited for every event; and sometimes a name for the earthquake and/or the tsunami is included.

The epicenters available for the earthquakes described in this section are plotted in Figure 2, and the rupture areas for the earthquakes from 1932 to 2014 are plotted in Figure 1. The tsunami inundation locations are presented in Figure 3a,b. The descriptions below were translated from their original Spanish version and the equivalent of the ancient Spanish (Castilian) measurement unit is written in parentheses.

1. 27 May 1563
   Probably this is the oldest earthquake reported for the Jalisco-Colima coast and not yet included in online catalogs. Figure 4a shows the report from Puerto de la Navidad, in which "most of the houses fell" (Archivo General de la Nación [AGN], 1563). The destruction of the village is inferred from the description, but unfortunately more detailed information probably no longer exists. The chronicle of Tello (1984) describes the damage in churches at Zapotlán El Grande and Autlán; this earthquake was also felt in Colima (García Acosta and Suárez Reynoso, 1996). No tsunami was reported.
2. 25 March 1806: The Encarnación earthquake
   The earthquake was felt along the Mexican Pacific coast between Nayarit and Oaxaca (García Acosta and Suárez Reynoso, 1996). It lasted 3 min, and according to La Gazeta de México (1806) 2000 people were killed in Zapotlán El Grande. However, the number of dead people seems to be exaggerated, because a letter dated 20 April 1806

Table 2
Catalog of Tsunamigenic Earthquakes and Local Tsunamis in the Jalisco-Colima Coast (México)

	Date			Source						Tsunami				
				Location (°)		Magnitude								
Id	Year	Month	Day	Latitude	Longitude	M_w	M or M_s	Sources: L, Location; M, Magnitude	Type	Quality of Data	Inundation Places	Max Inundation (m)	Max Height Wave (m)	Deposit
1	1563	May	27						Earthquake	Eyewitness written description	Not reported			
2	1806	March	25	18.90	−103.80		7.5	L,M: Singh *et al.* (1984)	Earthquake	Eyewitness written description				
3	1816	November	14						Earthquake/ landslide?	Eyewitness written description	Colima coast, San Pantaleón saltworks	825	25	
4	1818	May	31	19.00	−105.00		8.2	L,M: Zúñiga *et al.* (1997)	Earthquake	Report by governant	Cuyutlán to Coahuayana, Col.		13.9	
5	1845	April	7	16.80	−100.00	8.3		L,M: Zúñiga *et al.* (1997)	Earthquake	Report by governant	Acapulco, Gro. and Jalisco coast	40		
6	1875	February	24	20.00	−105.00		6.5	L,M: Soloviev and Go (1975)	Earthquake	Scientific report	Manzanillo, Col.			
7	1875	March	9	19.40	−104.60		7.4	L,M: Singh *et al.* (1981)	Earthquake	Eyewitness written description				
8	1883	March	12	21.55	−106.50			L: HTDB/WDL	Unknown/ landslide?	Newspaper	Bandera's Bay, Jal.			
9	1900	January	20	20.00	−105.00		8.1	L,M: Singh *et al.* (1984)	Earthquake	Newspaper	Acapulco, Gro. and Manzanillo, Col.	1609		
10	1900	May	16	20.00	−105.00		7.6	L,M: Singh *et al.* (1984)	Earthquake	Newspaper	Zapotillo, Nay. and Peñitas, Jal.			
11	1911	June	7	17.50	−102.50	7.6		L,M: Engdahl and Villaseñor (2002)	Earthquake	Newspaper	Pacific coast			

ISC-GEM, International Seismological Centre-Global Instrumental Earthquake Catalogue.
(Continued next page.)

Table 2 (continued)
Catalog of Tsunamigenic Earthquakes and Local Tsunamis in the Jalisco-Colima Coast (México)

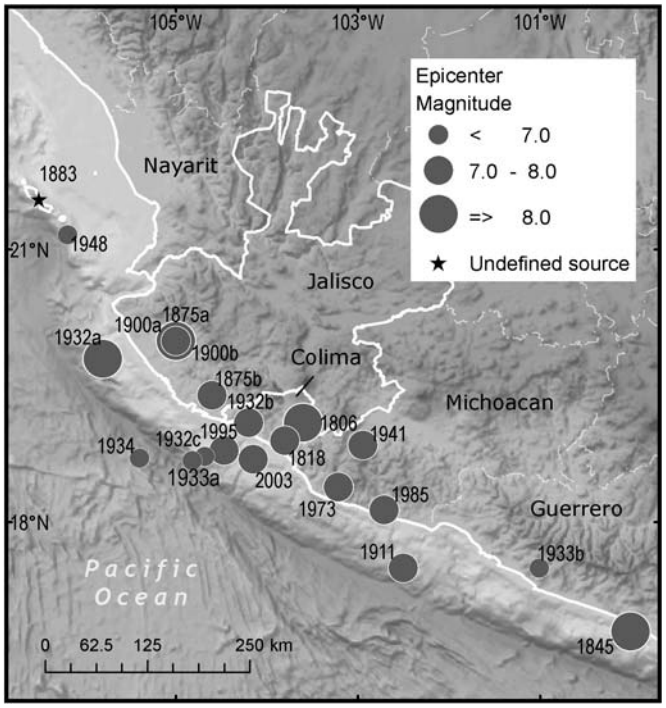
	Date			Source						Tsunami				
				Location (°)		Magnitude								
Id	Year	Month	Day	Latitude	Longitude	M_w	M or M_s	Sources: L, Location; M, Magnitude	Type	Quality of Data	Inundation Places	Max Inundation (m)	Max Height Wave (m)	Deposit
12	1932	June	3	19.80	−105.80	8.1	8.2	L: Cruz and Wyss (1983); M: McNally and Minster (1981)	Earthquake	Eyewitness, newspaper, scientific report, instrumental	Sinaloa-Guerrero coast; United States of America and Hawaii. Maximum in front of Tomatlán coast	8000	10	Yes
13	1932	June	18	19.10	−104.20		7.8	L: Cruz and Wyss (1983); M: McNally and Minster (1981)	Earthquake	Newspaper, scientific report, instrumental	Manzanillo Bay; Hawaii		1	
14	1932	June	22	18.73	−104.68		6.9	L: Kelleher *et al.* (1973); M: Gutenberg and Richter (1954)	Earthquake/ landslide	Newspaper, scientific report	Colima coast; maximum in Cuyutlán -El Tecuanillo coast	2000	12	Yes
15	1933	February	20	18.68	−104.82		4.9	L: Figueroa (1970); M: Singh *et al.* (1985)	Earthquake	Newspaper	Zihuatanejo, Gro., Manzanillo and Armería, Col.		1.13	
16	1933	May	8	17.50	−101.00		6.9	L,M: Kostoglodov and Pacheco (1999)	Earthquake	Newspaper	Boca de Pascuales, Col.			
17	1934	November	30	18.50	−105.50		7	L,M: Wigen (1979)	Earthquake	Scientific report	Not reported			
18	1941	April	15	18.85	−102.94		7.9	L,M: Singh *et al.* (1984)	Earthquake	Scientific report	Jalisco–Colima coast			
19	1948	December	4	21.60	−106.70	6.4		L,M: Jaramillo and Suárez (2011)	Earthquake	Newspaper, scientific report	Marías Islands			
20	1973	January	30	18.39	−103.21	7.65		L,M: Singh and Mortera (1991)	Earthquake	Scientific report; instrumental	Armería River			

ISC-GEM, International Seismological Centre-Global Instrumental Earthquake Catalogue.
(Continued next page.)

Table 2 (continued)
Catalog of Tsunamigenic Earthquakes and Local Tsunamis in the Jalisco-Colima Coast (México)

	Date			Source: Location (°)		Source: Magnitude		Source		Tsunami				
Id	Year	Month	Day	Latitude	Longitude	M_w	M or M_s	Sources: L, Location; M, Magnitude	Type	Quality of Data	Inundation Places	Max Inundation (m)	Max Height Wave (m)	Deposit
21	1985	September	19	18.14	−102.71	8		L,M: UNAM Seismology Group (1986)	Earthquake	Scientific report, instrumental	Manzanillo, Col. - Zihuatanejo, Gro.; Manzanillo, Cuyutlán and Coahuayana river mouth; maximum in Lázaro Cárdenas	500	3	
22	1995	October	9	18.79	−104.47	8		L,M: Courboulex *et al.* (1997)	Earthquake	Scientific report, instrumental	Jalisco–Colima coast; maximum in La Manzanilla and Tenacatita Bay, Jal.	250	10.9	
23	2003	January	22	18.70	−104.15	7.48		L,M: ISC-GEM	Earthquake	Scientific report, instrumental	Manzanillo			

ISC-GEM, International Seismological Centre-Global Instrumental Earthquake Catalogue.



▲ **Figure 2.** Epicenters of historic tsunamigenic earthquakes. Administrative limits are presented. Letters are used to identify epicenters for earthquakes that occurred in the same year: 1875a (24 February 1875), 1875b (9 March 1875), 1900a (20 January 1900), 1900b (16 May 1932), 1932a (3 June 1932), 1932b (18 June 1932), 1932c (22 June 1932), 1933a (20 February 1933), and 1933b (8 May 1933).

(Archivo Histórico del Arzobispado de Guadalajara [AHAG], 1806a) precisely reported that, at the moment of the earthquake occurrence, 1796 people were in the church, in which 254 of them died, 106 were seriously injured and 334 were slightly injured.

Figure 4b shows a fragment of a letter (AHAG, 1806b) in which an anonymous author describes the first shock as having occurred approximately at 17:00 hr (local time) as a "violent shaking." He toured throughout the Colima coast where "in 5 ½ leagues (30.65 km) ...there were abundant cracks in the San Pedro (Armería) river mouth" as evidence of liquefaction, and the river "changed its path." He visited all the saltworks settled along that coastal strip and reported no tsunami occurrence.

3. 14 November 1816: The San Pantaleón earthquake and tsunami

   On 14 November, the priest Gerónimo Arzac (AHAG, 1816a) was heading to Tecomán and mentioned the occurrence of several earthquakes, the strongest of which occurred on 13 November at 18:00 hr, another one on 14 November at 1:00 hr, and a third one at 10:00 hr (local time). These earthquakes caused significant damage in Colima and Tecomán and also damaged some churches and public buildings in Guadalajara (Biblioteca Pública del Estado de Jalisco [BPEJ], 1816), Tecolotlán, Suchitlán, Ayotitlán (AHAG, 1816b), Zapotlán El Grande (Vizcaíno, 1986), and Colima (Río de la Loza, 1863).

   Figure 4c shows a facsimile of the handwritten report by priest José Antonio Enríquez del Castillo (Archivo de la Parroquia de Tecomán [APT], 1817) who was an eyewitness and described a tsunami event on "November 13th of 1816 two o'clock in the morning" when "the sea..." incursion reached 60 *codos* high (25 m); "...the water receded..." causing destruction of the salt beds, that is, harvest infrastructure (an ancient method of salt extraction).

4. 31 May 1818

   According to García Acosta and Suárez Reynoso (1996) this is one of the most destructive earthquakes felt along the Pacific coast between Oaxaca and Colima, where the city of Colima was almost destroyed. Juan Linares (AGN, 1818) wrote "At the saltworks in Cuyutlán the sea rose above sea level about 10 pasos" (13.9 m). "The ground opened in many places throwing sand...," that is, likely liquefaction, and "the salt beds were buried." In Coahuayana only a small tsunami was reported (Fig. 4d).

5. 7 April 1845: The Santa Teresa earthquake

   This was one of the most destructive earthquakes in México City and was felt in half of the Mexican Republic and along the Pacific coast from Guerrero to Jalisco; a tsunami was reported in Acapulco. The local governor of Autlán, Jalisco (AGN, 1845), reported that the earthquake "was felt at the coast accompanied by an ocean roar" and the newspaper El Siglo XIX (1845) mentioned that many people mentioned that "the water seemed to boil...."

6. 24 February 1875

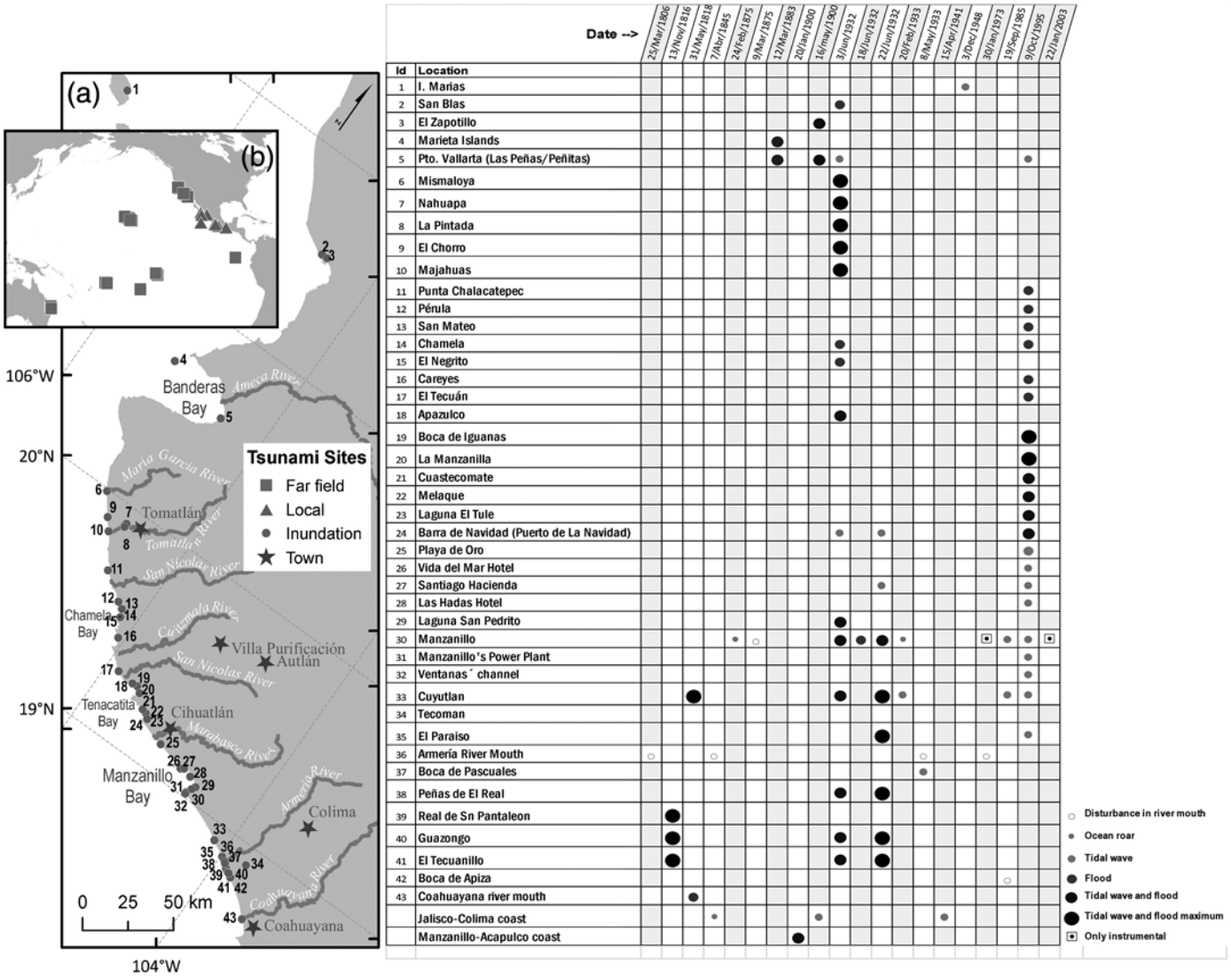
   The Historical Tsunami Database (HTDB)/WLC and National Centers for Environmental Information (NCEI, 2015) catalogs classify this event as a very doubtful tsunami. Soloviev and Go (1975) described the earthquake as a "strong earthquake at Manzanillo and Colima with great movement of water" based on Fuchs (1886). It is likely that Fuchs obtained the information from press releases in which telegrams were published in the *Diario de Jalisco*, 25 February, and were cited as the source. However, the final report from Comision (Comisión Sobre Los Temblores de Febrero de, 1875) stated that "dreadful sea roars" but "no sea wave invasion occurred."

7. 9 March 1875

   A very strong earthquake in Jalisco and Colima was felt from Manzanillo to San Blas "with sea roars and movements of the sea" (La Colonia Española, 1875). At Tecomán, the priest Vicente Pinto (AHAG, 1875) reported that the earthquake occurrence at 9:00 a.m. (local time) damaged the church and houses in the village, and cracks with water pop-ups that could be related to liquefaction at the mouth of the Armería River.

8. 12 March 1883

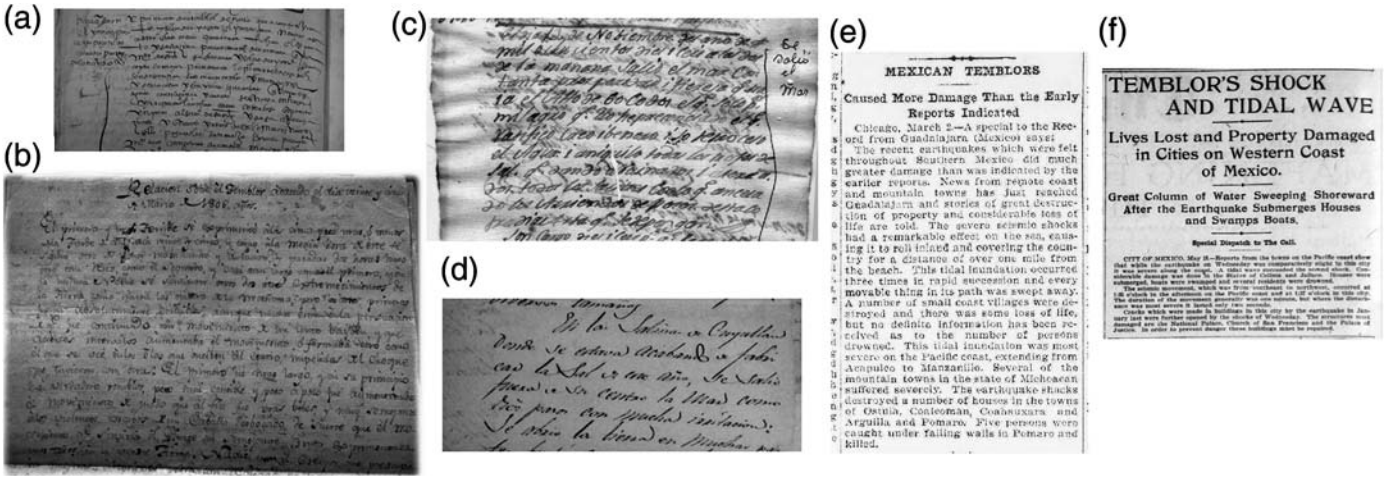
   Orozco y Berra (1887–1888), referenced by Montessus de Ballore (1906), Brand (1958), and Soloviev and Go (1984), described that at "Las Peñas on [March] 12 ... the sea retreated far from the coast, left its usual bed widely



▲ **Figure 3.** (a) Tsunamis triggered by local earthquakes on the Jalisco-Colima coast with summary descriptions. The numbers in the map correspond with the id column in the table. (b) Map of tsunami sites where inundation was reported on the Jalisco-Colima coast (México).

and distantly from the shore, so that the seabed was exposed." Las Peñas is known now as Puerto Vallarta.

9. 20 January 1900
Important villages in Jalisco and Colima states suffered major damage from this earthquake, which happened at 23:45 hr on 19 January (local time). The Cuyutlán lagoon (Colima state) showed noticeable changes (Morales, 1900), train traffic was interrupted when the railway subsided by about 60 cm (El Estado de Colima, 1900; Morales, 1900), and several landslides occurred along the railroad. The earthquake also caused damage in México City and Michoacán (El Sol Diario de la Tarde, 1900; La Libertad, 1900; Silva, 1900; García Acosta and Suárez Reynoso, 1996), and was felt as strong in San Blas (The New York Times, 1900). An isoseismal map by Ezequiel Ordóñez that was published by El Imparcial newspaper (El Imparcial, 1900) presented the most affected area in Jalisco and Colima where he estimated that "it is very likely that the source of the earthquake is located in front of the Colima coast... where it reached very soon the Pacific seashore and spread in the West–East direction." On 2 and 3 March, two North American newspapers published the next news, in which a tsunami was described (Fig. 4e): "A special to the Record from Guadalajara (México) says: The recent earthquakes which were felt throughout Southern México did much greater damage than was indicated by the earlier reports. News from remote coast and mountain towns has just reached Guadalajara and stories of great destruction of property and considerable loss of life are told. The severe seismic shocks had a remarkable effect on the sea, causing it to roll inland and covering the country for a distance of over one mile from the beach. This tidal inundation occurred three times in rapid succession and every movable thing in its path was swept away. A number of small coastal villages were destroyed and there was some loss of life, but no definite information



▲ **Figure 4.** (a) Archivo General de la Nación, Mercedes, 84, ff.129v and 130. Facsimile fragment of Mandamiento, 25 June 1563; (b) Facsimile. Fragment of handwriting report (Anonymous) "Relacion sobre el Temblor acaecido el dia veinte y cinco de marzo 1806 años" Story about the earthquake that occurred 25 March 1806 (AHAG); (c) Facsimile of the report by priest José Antonio Enríquez del Castillo (APT, 1817); (d) Archivo General de la Nación, Indiferente Virreinal, 5765/086. Facsimile fragment of handwriting report by Juan Linares (1818); (e) Mexican temblor news that appeared in the Los Angeles Herald, on 3 March 1932, page 2; (f) Facsimile of "Tidal wave reported in Pacific coast," San Francisco Call 19 May 1900, page 2.

has been received as to the number of persons drowned. This tidal inundation was most severe on the Pacific coast, extending from Acapulco to Manzanillo" (Desert Evening News, 1900; Los Angeles Herald, 1900).

10. 16 May 1900
Gutenberg (1956) considers this earthquake an aftershock of the 20 January event. It was felt strongly in the center and south of Jalisco and Colima states, and it was said that, "...the second shock was followed by a tidal wave many feet in height, enveloping every coast town of Colima and Jalisco. At Peñitas, in Jalisco, and Zapotillo, in Tepic, fishing boats were swamped and several natives were drowned" by the San Francisco Call (1900; Fig. 4f) and Meady County News (1900).

11. 7 June 1911
This earthquake was strongly felt in México City, and the south of the Jalisco state and the whole Colima state were badly damaged. Miranda y Marrón (1912–1914) visited the disaster area in Zapotlán and Colima. In his report, he included an isoseismal map, but without the location of the epicenter, and a letter from Severo Díaz who informed him about the absence of damaged churches in the coastal region. The news appeared in North American press in which the earthquake was described in the following way: "...second earthquake at 5 o'clock yesterday afternoon the severest in the western and southern sections. Meager reports say it was accompanied by tidal wave on the Pacific coast. Communication with several towns has been interrupted, and has caused the report that they have been wiped out" (The Jeffersonian-Gazette, 1911). Major fear was about Port of Manzanillo "Especially is anxiety felt for the seaport..., which is connected by rail with Colima. A large section of this town is near the water's edge and a tidal wave of any great force would practically wipe it off the map" (The Syracuse Herald, 1911).

12. 3 June 1932: The Tomatlán earthquake and tsunami
This earthquake is considered the largest to have occurred along the Mexican subduction zone in the instrumental era. The evidence from seismograms at teleseismic distances suggests a complex rupture process consisting of four subevents that lasted 90 s. This has led to problems in locating the epicenter (Eissler and McNally, 1984; Singh *et al.*, 1984, 1985). The rupture length of the earthquake was estimated to be 220 km long and 80 km wide (Singh *et al.*, 1985). The earthquake also produced a tsunami large enough to strike the coastline between Mazatlán (Sinaloa) and Zihuatanejo (Guerrero) and reached Hilo, Hawaii, and the coast of California. It flooded 8 km inland in the Tomatlán River valley, killed four people in Majahuas and Mismaloya (Valdivia *et al.*, 2012), and was reported in newspapers and scientific publications of the time (see Data and Resources). Sedimentary evidence has been found and reported by Cerny *et al.* (2016) and Ramírez-Herrera *et al.* (2016).

13. 18 June 1932
This was the second main shock of the earthquakes in June 1932 (Singh *et al.*, 1985), which produced a tsunami with a runup reported in Manzanillo, where the sea receded 10 m (El Informador, 1932).

14. 22 June 1932: The Cuyutlán tsunami
This earthquake produced the most destructive tsunami in the history of México, which completely swept away the sector between Cuyutlán and Boca de Apiza, Colima. The seawater flooded 500–3000 m inland with waves of 12 m height (Las Noticias, 1932; Ordoñez, 1933) killing ~50 people (Corona and Ramírez-Herrera, 2012a,b). "The

water incursion lasted about 2 hours..." (El Universal, 1932a) and injured many people. The tsunami disturbed the Cuyutlán lagoon, affecting salt extraction. Most of the houses and hotels were destroyed at Cuyutlán. "...an immense maritime wave ... flooded more than 1 km [inland] from Manzanillo until Tecomán...," Colima (El Universal, 1932b). Eyewitness described it as the "water receded... and a sea wall rather than a wave... was formed offshore, about 300 to 400 m from the beach..." (El Universal, 1932c).

The Tecomán coast was "also hit by the surge damage" (El Universal, 1932d); the tsunami was reported as far south as Guazongo, with damage to Tecuanillo and El Real (El Universal, 1932e). North from Cuyutlán, the tsunami was reported in Barra de Navidad and Santiago Hacienda (El Universal, 1932f). Corona and Ramírez-Herrrera (2012a) estimate the tsunami intensity as VIII in Cuyutlán (in the Papadopoulus and Imamura scale) from historical data analysis that was supported by tsunami modeling. "Two new sea waves have invaded the town: one yesterday night [June, 22] and the other this morning [June, 23] after 9 o'clock with less intensity because waters didn't passed further than the main dune, just reaching the roundabout" (El Universal, 1932g).

15. 20 February 1933
At 11:00 a.m. (local time), an earthquake was felt in the city of Colima, causing panic in Villa de Alvarez, and was felt intensely in Tecomán. A tsunami that invaded the beaches of Zihuatanejo was reported to have swept away fishermen's houses, and in Manzanillo some underground noises were heard "and unusual movements were noticed over the sea water." The earthquake was also felt strongly in Cuyutlán where "a tidal wave washed the trash left by last earthquake" (El Informador, 1933a).
16. 8 May 1933
According to the correspondent reporter for El Informador (1933b) "...another tsunami occurred ... in Boca de Pascuales... producing damage to the seashore hamlet and blocking the Armería river mouth," and affecting the saltworks. Finally, "... sea movement was observed over the Colima, Jalisco and Michoacán coasts...."
17. 30 November 1934
A tsunami of 22 cm height was measured in Tofino, Canada, and referenced by Wigen (1979), who related it to the earthquake that occurred along the Colima coast on the same date; however, it was not possible to find information about a local tsunami occurrence in Mexico.
18. 15 April 1941
This earthquake damaged large areas in Colima state and in the south of the Jalisco state. Brand (1958) affirmed that "this earthquake locally is considered the most destructive of the 20th century; although it was accompanied by one tsunami, the wave was not notable."
19. 4 December 1948
On 3 December, a sequence of earthquakes started. Jaramillo and Suárez (2011) stated that the earthquake of 4 December was the largest in the history of the Tres Marías Islands Escarpment, which is located along the northern segment of the Rivera–North American plate boundary. Besides the destruction of most buildings in the prison, and houses located on Santa María Island, 2 people died and 25 were injured (El Informador, 1948). Moreover, a tsunami struck the islands (Seismological Notes, 1949; Soloviev and Go, 1975).
20. 30 January 1973
This earthquake largely damaged the states of Colima, Jalisco, and Michoacán, and it produced a tsunami recorded by every tide gauge station along the Mexican Pacific. It was most intense in Acapulco and Manzanillo (1.13 m) (Figueroa, 1974; Sánchez and Farreras, 1993). When the tsunami occurred "... the tide level was low... tsunami maximum wave amplitude was 4 ft." In Armería liquefaction was reported. "The sea level rose and loud noises were heard" (Figueroa, 1974). The tsunami was recorded in Hilo (Hawaii) as 240-mm high (Eissler and McNally, 1984).
21. 19 September 1985
This was the most destructive earthquake in the twentieth century in México City. Ciudad Guzmán and Gómez Farías (Jalisco) suffered significant damage as well. The earthquake produced a tsunami recorded by Acapulco's tide gauge (the only analogical record available from a near epicenter station). Pararas-Carayannis (1988) reported damage in Manzanillo to the Zihuatanejo area where sedimentary evidence was reported by Ramírez-Herrera *et al.* (2012); the tsunami reached its maximum peak on the Michoacán coast. On the Colima coast, the tsunami effects were reported as follows: in Manzanillo it was 1.0-m high and the wave moved buoys in the port's entrance to the inner harbor; in Cuyutlán a debris line was observed on the beach as indication of 2.0 m runup; in Boca de Apiza one eyewitness declared that the tsunami reached 1.5 m and flooded the channel of the Coahuayana River inland about 150 m. "There are unconfirmed reports that ships off the coast of México saw waves up to 30 m high and some fishing boats are missing" (Lander *et al.*, 2003).
22. 9 October 1995. La Manzanilla tsunami
This was a tsunamigenic earthquake (Singh *et al.*, 2008) with an epicenter that was seaward of the coast of Colima, with a rupture length that was estimated at 150 km (Courboulex *et al.*, 1997), most of which was offshore. Subsidence along the coast was produced by a downward vertical displacement (Melbourne *et al.*, 1997; Ortiz *et al.*, 2000), and the earthquake generated a tsunami that was reported in 32 places across the Pacific basin: 21 on the Mexican coast (19 by eyewitness and 2 instrumentally), 1 in Ecuador, 2 in Australia, 3 in French Polynesia, 4 in Hawaii, and 1 in Samoa (NCEI, 2015). Along the Mexican Pacific coast, it was reported that a tsunami occurred ~15 min after the earthquake when the sea first receded and was followed by the arrival of two waves. The tsunami

hit the coast between El Paraíso (Colima) and Puerto Vallarta (Jalisco) along a length of about 300 km, and with maximum inundation in Tenacatita Bay (Jalisco) (Borrero *et al.*, 1997).

23. 22 January 2003
The epicenter was located along the Colima coast in El Gordo Graben, near the triple convergence point of the Rivera, Cocos, and North American plates (Gómez-Gónzalez *et al.*, 2010; Andrews *et al.*, 2011). The first tsunami arrival was emergent and was recorded by the tide gauge at Manzanillo 12 min after the earthquake. Eyewitnesses interviewed by phone did not observe any tsunami in Barra de Navidad nor in Melaque, Jalisco. A post-tsunami survey along the coast between La Manzanilla, Jalisco, and San Juan, Michoacán, confirmed no flooding and water heights similar to high tide along this section of the coast (Ortiz *et al.*, 2003).

DISCUSSION AND CONCLUSION

We identified 21 tsunamis through an exhaustive search in archives and libraries, and collected evidence for earthquakes and their tsunamis, some of them not yet cataloged. The updated catalog presented in Table 2 contains parametric information in conjunction with the descriptions presented in the previous section and in maps (Fig. 3). These enabled a complete reading of historic tsunamis in the study area. Location and magnitude data sources were selected from available scientific research papers for every single event.

We identified tsunamigenic earthquakes that were not previously documented in modern earthquake and tsunami catalogs available online through a careful reading of original historical archives and documents. We revealed for the first time the precise date of the 27 May 1563 earthquake, which is the most ancient earthquake reported in the studied area until now. We also provided detailed information on the 1816 earthquake sequence not mentioned in modern online catalogs but frequently described by local chronicles (e.g., Oseguera Velázquez, 1967; Urzúa Orozco, no date). Arzac (AHAG, 1816a) described three of the strongest earthquakes of the 1816 earthquake series: one that occurred at 6 p.m. on 13 November, along with a second one at 1 a.m. and a third one at 10 a.m. on 14 November (i.e., the San Pantaleón earthquake). Of them, the 13 November event was the strongest. Enríquez del Castillo (APT, 1817) described the 13 November earthquake and also included a description of a tsunami occurrence around 1–2 a.m. on 14 November, which is likely related to the second earthquake on 14 November at 1 a.m. The San Pantaleón tsunami of 1816 was presumably produced by a medium-sized earthquake. The 1816 earthquake and tsunami description indicates that the saltworks were flooded with a wave 25 m in height (APT, 1817).

Two years later, in 1818, a tsunami was triggered by a magnitude M 8.2 earthquake. From the descriptions given above, we inferred a wave height of about 13 m in Cuyutlán that decreased southward, and the area affected was restricted to the Colima coast. The 1816 and 1818 events occurred in the middle of the Independence War, and this might explain the relative scarcity of information.

A singular event was on 12 March 1883 in Banderas Bay, Jalisco. It was described as a tsunami but not related to any earthquake report. Thus, we suggest that this tsunami was likely triggered by a submarine landslide because similar submarine landslides have been reported for the Jalisco and Colima areas. Recently in the same Banderas Bay on 8 September 2001, a submarine slump occurred on a steep coastal slope; however, no tsunami was reported (Cupul-Magaña *et al.*, 2004). Also, a submarine landslide has been proposed as the triggering mechanism for the 22 June 1932 tsunami in Cuyutlán, Colima (Corona and Ramírez-Herrera, 2015).

During the remainder of the nineteenth century, other earthquakes produced minor tsunamis in the study area. It was not until the year 1900 when two strong earthquakes generated two tsunamis that only were mentioned in American newspapers (Desert Evening News, 1900; Los Angeles Herald, 1900; Meady County News, 1900; San Francisco Call, 1900).

Undoubtedly, 1932 was a remarkable year: three earthquakes produced tsunamis, and two of them are the largest tsunamis registered over the Jalisco-Colima coast between 1563 and 2015. The 3 June 1932 earthquake is the largest earthquake (M 8.2) instrumentally registered for the Mexican Pacific coast, and it also produced the largest tsunami registered in the Jalisco-Colima coast over the last 500 years. The second 1932 earthquake (M 7.8), on 18 June, only produced a small tsunami, whereas the third earthquake, on 22 June (M_s 6.9), generated a devastating tsunami. However, recent studies suggest that a submarine landslide triggered by the third earthquake (22 June 1932) produced this tsunami (Corona and Ramírez-Herrera, 2012a,b, 2015).

The historical documents for the 7 April 1845, 24 February 1875, 20 February 1933, and 16 May 1933 tsunamis include a common description about "sea movements" and/or "roaring." Recent observations and studies of far-field tsunamis indicate the occurrence of sea currents near the coast in sea harbors (Alan *et al.*, 2012; Admire *et al.*, 2014) that might explain these old historical descriptions. Therefore we consider these as tsunamis.

The historical evidence summarized in this study confirms that the Rivera–Cocos plate subduction has produced at least 21 tsunamis since 1816 and hence is quite prone to tsunamigenic earthquakes, making the Jalisco-Colima coast highly susceptible to tsunami hazard. Tsunami geology studies could broaden the time window and aid in constraining the recurrence period for big earthquakes and tsunamis in this region.

DATA AND RESOURCES

Maps in Figures 1–3 were made using ESRI ArcGis 10.0, and the base map was downloaded from Instituto Nacional de Estadística y Geografía (INEGI; www.inegi.org.mx, last accessed May 2015). We also used data from National Centers for Environmental Information (NCEI; formerly National

Geophysical Data Center, NGDC) at https://www.ncei.noaa.gov/ (last accessed May 2016), the Global Historical Earthquake Archive (GHEA) hosted by Global Earthquake Model (GEM) at https://www.globalquakemodel.org/what/seismic-hazard/historical-catalogue/ (last accessed May 2015), International Seismological Centre (2013). ISC-GEM Global Instrumental Earthquake Catalogue (1900–2009). Retrieved from www.isc.ac.uk./iscgem/ (last accessed May 2015), and Historical Tsunami Database (HTDB) hosted by the Tsunami Laboratory. The data for the Tomatlán earthquake and tsunami are available at https://www.researchgate.net/profile/Maria_Ramirez-Herrera (last accessed May 2015). The acronyms and data sources cited in the text are listed in References section.

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