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The historical seismicity of northeastern Sonora and northwestern Chihuahua, Mexico (28–32°N, 106–111°W)

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Abstract

A detailed compilation of the historical seismicity of northeastern Sonora and northwestern Chihuahua (28–32°N, 106–111°W) for the period 1887–1999 from catalogs, archives, and newspaper reports yielded 64 events (excluding aftershocks). The most significant ones are the 3 May 1887 Bavispe, Sonora ($M_W = 7.4 \pm 0.3$), 26 May 1907 Colonia Morelos, Sonora ($I_{max} = \text{VIII}$, $M_I = 5.2 \pm 0.4$), 17 May 1913 Huásabas, Sonora ($I_{max} = \text{VIII}$, $M_I = 5.0 \pm 0.4$), 18 December 1923 Granados–Huásabas, Sonora ($I_{max} = \text{IX}$, $M_I = 5.7 \pm 0.4$) and 28 October 1965 Nicolás Bravo, Chihuahua ($m_b = 5.0$) earthquakes. Most of the compiled seismicity is concentrated in the epicentral region of the 1887 Bavispe earthquake, whose surface rupture is >100 km long. Other seismicity clusters have been located in the Valle de Guaymas graben and in the regions of Fronteras–Nacozari, Granados–Huásabas, and Ciudad Juárez–El Paso. These are most likely tectonic earthquakes related to normal faults of the southern Basin and Range province and the Rio Grande rift. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Seismicity; Southern Basin and Range province; Rio Grande rift; Northwestern Mexico; Northeastern Sonora; Northwestern Chihuahua

1. Introduction

In this paper I present a compilation of the regional seismicity in northeastern Sonora and northwestern Chihuahua, Mexico (Fig. 1; 28–32°N, 106–111°W; $\approx 213{,}300\ \text{km}^2$, including minor parts of Arizona, New Mexico, and western Texas) in the form of seismicity distribution maps (Figs. 2 and 3) and a table containing the source parameters of these earthquakes (64 events, see Table 1). The compilation covers the period 1887–1999. I also make a brief tectonic interpretation of the seismicity distribution. Furthermore, I provide isoseismal maps for four of the pre-instrumental events, which are the 26 May 1907 Colonia Morelos, 7 April 1908 Fronteras, 18 December 1923 Granados–Huásabas, and 10 February 1927 Nacozari earthquakes (Figs. 4–7).

Tectonically and morphologically, most of northern Mexico belongs to the southern Basin and Range province (Stewart, 1998; Henry and Aranda-Gómez, 2000; Suter and Contreras, 2001). The largest historical earthquakes of this province are the 1887 Bavispe, Sonora ($M_W = 7.4$; Natali and Sbar, 1982), 1928 Parral, Chihuahua ($M_W = 6.5$; Doser and Rodríguez, 1993), and 1931 Valentine, Texas ($M_W = 6.4$; Doser, 1987) events (Fig. 1). I carried out this compilation to constrain areas of active faulting. The seismicity compilation and the geological analysis of active faults are important elements in characterizing the seismic hazard of this region, which contains major towns such as Ciudad Juárez, Hermosillo, and Chihuahua (Fig. 2). This seems to be the first detailed seismicity compilation for northeastern Sonora and northwestern Chihuahua. The DNAG (Decade of North American Geology) seismicity map (Engdahl and Rinehart, 1988) contains only nine events for this area, and the seismicity distribution map in Doser and Rodríguez (1993, their Fig. 1) includes 11 events for its eastern part. This low data density can partly be explained by the low population density, poor station coverage, and the large recurrence intervals of most Basin and Range province faults, which are in the range of 10–100 kyr (Menges and Pearthree, 1989; Machette, 1998). The regional seismicity is better documented to the north of our study area in Arizona (DuBois et al., 1982; Pearthree and Bausch, 1999), New Mexico (Sanford et al., 1991; 1997), and Texas (Davis et al., 1989).

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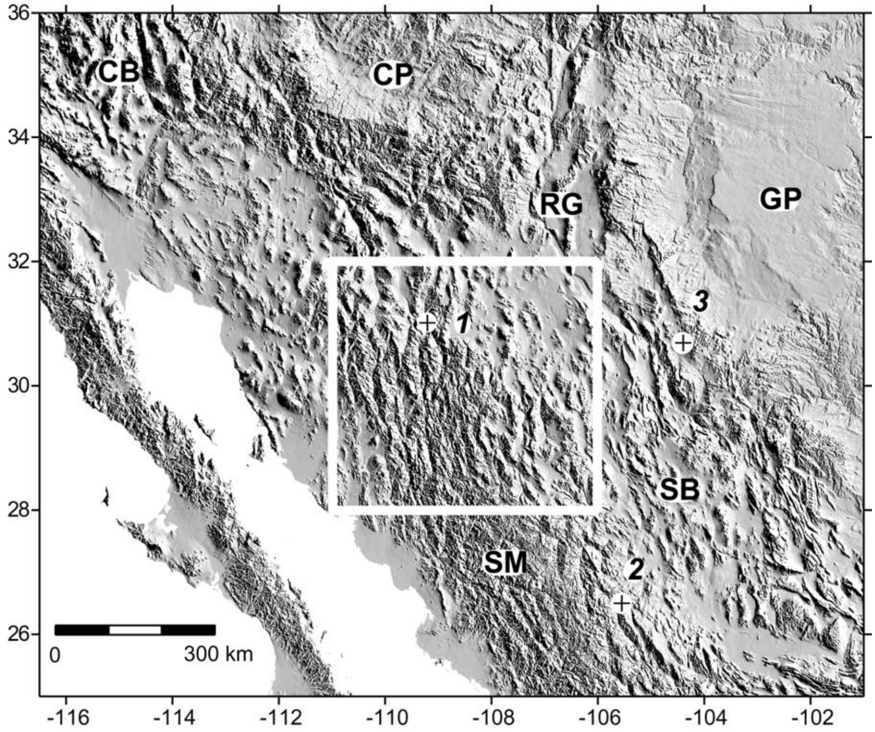

Fig. 1. Digital elevation model (GTOPO30, 30 arc-second resolution) of southwestern North America with morphological-neotectonic provinces (CB — central Basin and Range; CP — Colorado Plateau; RG — Río Grande rift; GP — Great Plains; SB — southern Basin and Range; SM — Sierra Madre Occidental plateau). Crosses indicate the epicenters of the (1) 1887 Sonora ($M_W = 7.4$), (2) 1928 Parral ($M_W = 6.5$), and (3) 1931 Valentine ($M_W = 6.4$) earthquakes. Frame: region for which the seismicity was compiled (Fig. 2).

2. Data sources and compilation techniques

The seismological record for northeastern Sonora and northwestern Chihuahua is mostly dependent on catalogs, since there are no permanent stations. The earthquakes listed in Table 1 have been compiled from various catalogs, publications, newspaper reports, and archives. They form an inhomogeneous data set with varying location quality, which has not been located with a single velocity model.

In descending order of preference, the sources for the earthquakes listed in Table 1 are: (1) Wallace et al. (1988) and Wallace and Pearthree (1989) for the nine events in northeastern Sonora of 1987–1989 relocated by them; (2) the PDE (Preliminary Determinations of Epicenters) catalog of the United States Geological Survey (10 events). The earliest PDE event in this source is from 1977, but earlier PDE events (from 1962 on) are contained in the composite Mexico catalog (National Geophysical Data Center, 1996) (see below); (3) the DNAG (Decade of North American Geology) seismicity archive file (National Geophysical Data Center, 1996) (five events); (4) 13 events were culled from the composite Mexico catalog (National Geophysical Data Center, 1996), which lists 24 records of 20 events for the region of this study; (5) the Tacubaya catalog (National Geophysical Data Center, 1996) (one event); (6) 10 pre-instrumental events from the seismicity catalog for Arizona by DuBois et al. (1982); (7) six events from the SRA catalog (Eastern, Central, and Mountain States of the United States, originally published in Stover et al. (1984), which contains events of this region for the period 1889–1973. Five of the events culled from this catalog cluster in the El Paso, Texas region. For several, mostly pre-instrumental earthquakes, I obtained additional data from the sources referenced in Table 1. I have also searched the Harvard Moment Tensor catalog (National Geophysical Data Center, 1996), the WUS (Western United States) catalog (Mueller et al., 1997), the online catalog of the Arizona Earthquake Information Center, and the catalogs by Orozco y Berra (1887, 1888), Figueroa (1959, 1970), Davis et al. (1989), Molino del Villar (1991) and García Acosta and Suárez Reynoso (1996), which do not contain additional data for this region. Additional events with $M_W \geq 1.3$ in the northeasternmost part of my study area can be found on the epicenter map for New Mexico and bordering areas for the period 1962–1995 by Sanford et al. (1997); however, the source parameters of these earthquakes remain unpublished.

Note that the composite Mexico catalog (National Geophysical Data Center, 1996) contains only events with latitudes <30°N, whereas the northern limit of the study area is at 32°N. On the other hand, the SRA catalog does not cover the region to the south of latitude 31°N. Therefore, the seismicity of the region between latitudes 30 and 31°N (northernmost parts of Sonora and Chihuahua, including the region of the 3 May 1887 surface rupture) is missing in a concatenation of these two seismicity catalogs. Contrary to the SRA and composite Mexico catalogs, the PDE catalog covers the entire study area.

Mueller et al. (1997) assume their WUS catalog to be complete for the western United States (excluding California) and northwestern Mexico for moment magnitudes $M_W > 6$ since 1850, $5 < M_W < 6$ since 1930, and $4 < M_W < 5$ since 1963. This compilation can be assumed to have approximately the same or a somewhat better level of completeness, since it contains more events for this region than the WUS catalog does. The compilation is likely to be less complete for the remote and sparsely populated Sierra Madre Occidental than for the remainder of the study area. The smallest magnitude contained for the region of this study in the PDE catalog is $M_L = 3.5$ for events in 1989 and 1993 (Table 1).

The earthquakes listed in Table 1 do not include aftershocks. Numerous aftershocks of the 3 May 1887, $M_W = 7.4$ Bavispe earthquake took place during 1887 and 1888 (see Orozco y Berra, 1887, 1888; DuBois and Smith, 1980; DuBois et al., 1982). I have listed in Table 1 later shocks in the epicentral region of this major earthquake beginning, somewhat arbitrarily, with the event of 31 April 1889. Numerous aftershocks also occurred following the 17 May 1913, $M_I = 5.0$ Huásabas earthquake and during more than four months following the 18 December 1923, $M_I = 5.7$ Granados–Huásabas earthquake (see below).

3. Distribution of seismicity

3.1. Epicentral region of the 3 May 1887 Bavispe earthquake

Most of the compiled seismicity is concentrated in the region of the 3 May 1887 Bavispe earthquake. The 1887 main shock is the largest historical earthquake of the study area and the largest historical normal fault earthquake of the southern Basin and Range province (dePolo et al., 1991). The known rupture trace length of this earthquake (Fig. 3) adds up to 86.3 km, and the distance between the rupture trace extremities is 101.4 km (Suter and Contreras, 2001). Based on the end-to-end length of the rupture trace and the length versus magnitude regression by Wells and Coppersmith (1994), M_W is estimated as 7.4 ± 0.3. Detailed compilations of the intensity reports for the 1887 main shock are provided in DuBois and Smith (1980) and DuBois et al. (1982); they include the intensity descriptions reported by Aguilera (1888) and the ones compiled by Orozco y Berra (1887, 1888). The second largest shock in this region is the 26 May 1907 Colonia Morelos earthquake ($I_{max} = \text{VIII}$; $M_I = 5.2 \pm 0.4$), for which we present an isoseismal map below (Fig. 4).

Fig. 3 shows in more detail the distribution of seismicity in the epicentral region of the 1887 earthquake. In addition to the epicenters listed in Table 1 and shown in Fig. 2, this figure also includes the microseismicity recorded by Natali and Sbar (1982). Most of the seismicity occurs near the 3 May 1887 surface rupture and is concentrated at its northern end and in the stepovers between the three rupture segments (Fig. 3). This is especially the case for the well-located microearthquakes. These events, which are marked by filled circles on Fig. 3, occurred at <15 km depth and have horizontal location errors <5 km (Natali and Sbar, 1982). They can be interpreted as aftershocks of the 1887 earthquake and explained by an increase of static Coulomb stress at the tips of the individual rupture segments (Hodgkinson et al., 1996). Circumstantial evidence suggests that the horizontal uncertainties of other epicenter locations may also be small: A cluster formed by two low-quality microearthquakes and one PDE event is located exactly in the stepover between the Teras and Otates segments of the 1887 surface rupture (Fig. 3), even though the rupture of this region was not defined at the time when these events were located.

Other earthquakes that may have originated in the epicentral region of the 3 May 1887 event are the ones felt in Tombstone on 5 June 1893 and 6 October 1899 (Table 1; DuBois et al., 1982). However, the Hermosillo newspaper *La Constitución* does not provide felt reports from Sonora for these two earthquakes.

3.2. Fronteras–Nacozari region

A seismicity cluster in the Fronteras–Nacozari region, north–south oriented and 30–40 km long, can clearly be separated from the seismicity on the 1887 rupture (Fig. 3). These earthquakes, which took place in 1987–1989, were relocated by Wallace et al. (1988) and Wallace and Pearthree (1989). For the largest of these events, which occurred on 25 May 1989, Wallace and Pearthree (1989) give a magnitude of 4.2 and estimate the accuracy of its location as ±4 km in the east–west direction and ±5 km in the north–south direction. Three of the microearthquakes (Fig. 3) recorded by Natali and Sbar (1982) and the high-intensity isoseismals of the 7 April 1908 Fronteras earthquake (Fig. 5) also fall close to this cluster. These earthquakes are located 15–30 km to the west of the 1887 surface rupture; they are likely to have initiated on the west-dipping Basin and Range fault that bounds the Fronteras valley on its eastern side (Fronteras fault; Fig. 3). The earthquake cluster has approximately the same length and orientation as the Fronteras fault, which displaces rocks of Quaternary age (Nakata et al., 1982) and is characterized on satellite imagery by a morphologically prominent scarp. However, the earthquake cluster is located *east* of the trace of the west-dipping Fronteras fault (Fig. 3). This may be due to a bias in the location of the teleseismically recorded events as well as the microseismicity, since the azimuthal station coverage does not include stations to the west or south.

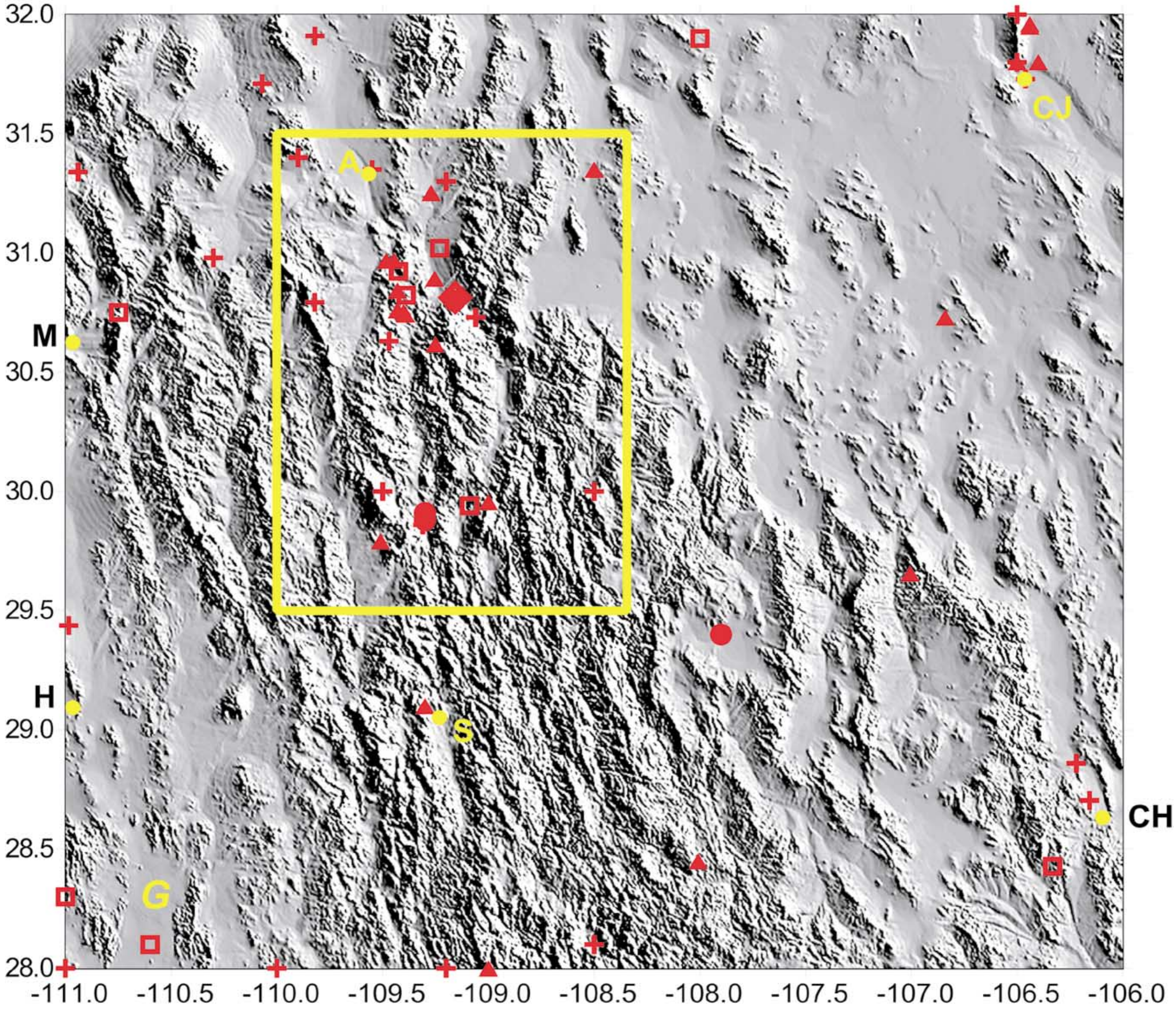

Fig. 2. Seismicity of northeastern Sonora and northwestern Chihuahua (28–32°N, 106–111°W) (location marked in Fig. 1) overlaid on a digital elevation model (GTOPO30, 30 arc-second resolution). The source parameters are provided on Table 1. Earthquake magnitudes: cross — unspecified; triangle — $M < 4$; square — $4 < M < 5$; circle — $5 < M < 6$; diamond — $M = 7.4$. (A — Agua Prieta; CH — Chihuahua; CJ — Ciudad Juárez; G — Valle de Guaymas graben; H — Hermosillo; M — Magdalena; S — Sahuaripa.) Frame: region covered by Fig. 3.

3.3. Granados–Huásabas region

Another seismicity cluster exists 40–50 km south of the documented southern tip of the 1887 rupture along the same fault zone, in the Granados–Huásabas region (Fig. 2). Stress loading on the fault segments near Granados–Huásabas (Fig. 3) by the 1887 rupture may explain this seismicity cluster (Suter and Contreras, 2001). Major events occurred there on 17 May 1913 (Lucero Aja, 1993; $I_{\max} = \text{VIII}$, $M_I = 5.0 \pm 0.4$) and 18 December 1923 (DuBois et al., 1982; $I_{\max} = \text{IX}$, $M_I = 5.7 \pm 0.4$). A more detailed description of the 1923 earthquake, which includes an isoseismal map, is presented in Section 4.3 and Fig. 6. The magnitudes of these two events are based on magnitude-intensity relations discussed below. The earthquake of 10 February 1927 (Table 1; Fig. 7) also may have occurred in this region. More recently, a series of earthquakes with magnitudes $M_L \leq 4.0$ took place in the Granados–Huásabas region in 1993 (Table 1).

The 1913 earthquake remains enigmatic. Despite its large maximum intensity (VIII), it is not well documented from newspaper reports, which suggests that this earthquake was not felt over a wide area, but it also attests to the remoteness of the Granados–Huásabas region. The only sources for this earthquake are unpublished documents in the *Archivo General del Estado de Sonora* (1913, volume 2900; *expediente III, Beneficiencia*; Lucero Aja, 1993) and a report in the newspaper *Douglas Daily International* (19 May 1913). Based on several letters of the Huásabas municipal council

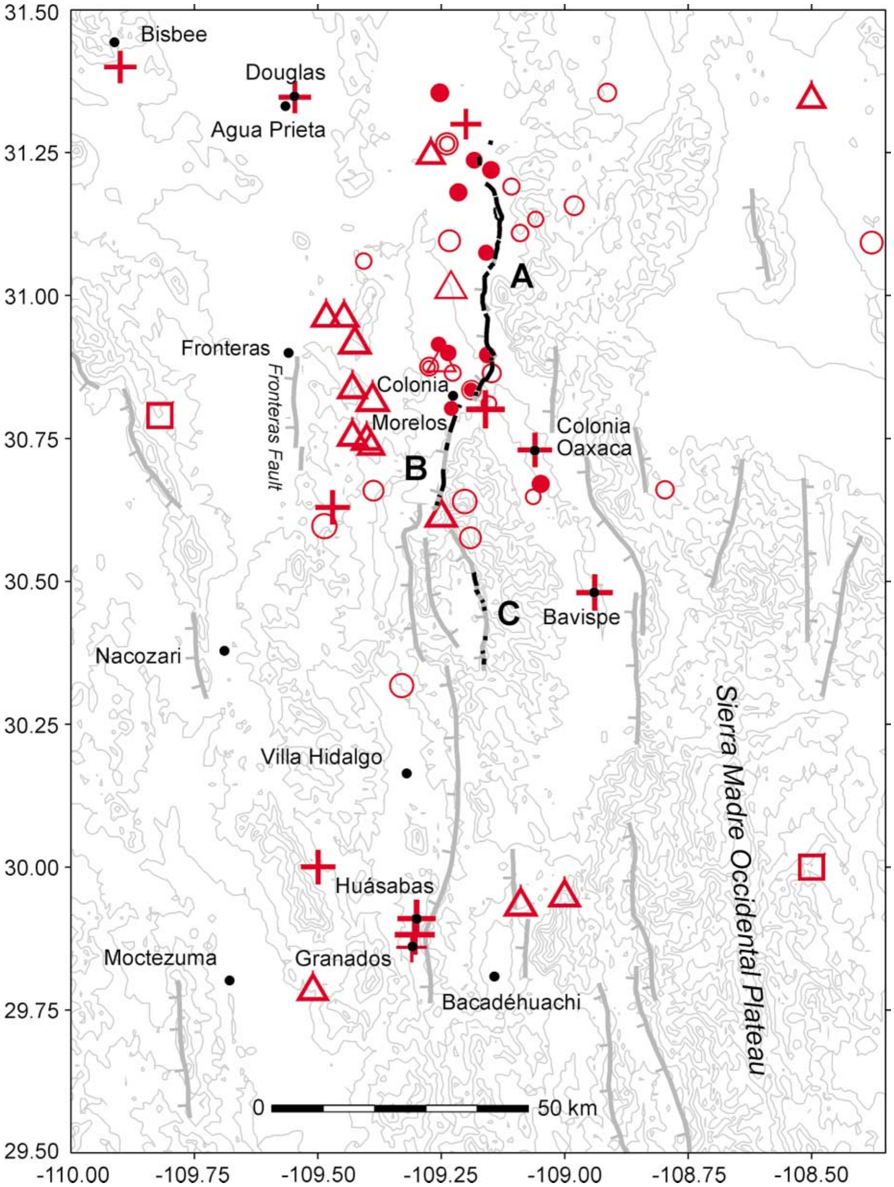

Fig. 3. Seismotectonic map of northeastern Sonora (location marked in Fig. 2) with earthquake epicenters, the 1887 rupture trace (in black; A — Pitáycachi segment; B — Teras segment; C — Otates segment), and the interpreted traces of major Basin and Range faults (in gray; barbs on lower fault block). Epicenter symbols: cross — location based on intensity distribution; triangle — located instrumentally, magnitude specified; square — located instrumentally, magnitude unspecified; circle — microearthquake (closed circle — high quality; open circle — low quality). The symbol sizes are proportional to the magnitude (or maximum intensity) of the events. The topography has a 200-m contour interval. Microseismicity from Natali and Sbar (1982).

to the Sonora state government in Hermosillo, dated between 22 May 1913 and 20 June 1913, a strong shock on 17 May 1913, at 2 a.m. local time, destroyed a third of the buildings in Huásabas and caused major damage to the town hall, schoolhouse, and prison. Based on the newspaper report, the people of Granados were badly frightened by a succession of earthquake shocks that could be felt all along the Granados range of mountains and also affected the region surrounding the Calevria ranges. The shocks, about 40 in all, were severe enough to cause damage in some of the adobe residences, and the people were obliged to leave their homes and camp in the open.

3.4. Valle de Guaymas graben

Three epicenters are located either within or somewhat to the west of the Valle de Guaymas graben, a major north–south-oriented structure of the Gulf of California extensional province, whose northern axial termination seems to be along a transfer fault (Fig. 2). These may be poorly constrained epicenter locations of earthquakes that originated on the master faults of the Valle de Guaymas graben. At a distance of approximately 70–100 km from the Gulf of California plate boundary in the Guaymas Basin (Lonsdale, 1989), these earthquakes are unlikely to have their source at the plate boundary.

Table 1
Source parameters of the compiled earthquakes (in chronological order)[*].

Date	Origin time	Longitude (°W)	Latitude (°N)	Magnitude	Depth (km)	Maximum intensity (MM)
05-03-1887	2:55:36 pm LT[a]	109.157[b,c]	30.813	$M_W = 7.4$[b]	18[a]	XI–XII[d]
04-31-1889	1:30 pm LT[e]	108.94[e]	30.48			VII[f]
05-31-1889	20	106.5[g]	32.0			V[g]
06-05-1893	6:40 am LT	110.07[h]	31.71			V[h]
08-16-1893	9 am LT[i]	109.06[h]	30.73			VI[h]
10-06-1899	11:30 pm LT	110.07[h]	31.71			V[h]
07-16-1906	12:20 pm LT	106.46[j]	31.73			IV[f]
05-26-1907	3:00 am LT	109.16[f]	30.80	$M_I = 5.2$[f]		VIII[h]
10-16-1907	6:30 am LT	110.30	30.98			V[k]
04-07-1908	9:45 pm LT[l]	109.47[f]	30.63[f]	$M_I = 4.8$[f]		VI[f]
05-17-1913	2 pm LT[e]	109.30[e]	29.91	$M_I = 5.0$[f]		VIII[f]
03-30-1916	05:20	110.94[h]	31.34			VI[h]
03-07-1923	05:03	108.0[f]	31.9	$M_{FA} = 4.3$[g]		VI[m]
12-18-1923	5 am LT[f]	109.30[f]	29.88	$M_I = 5.7$[f]		IX[h]
12-19-1923	9 pm LT	109.55[f]	31.35			V[n]
02-10-1927	8:41 pm LT[f]	109.5[f]	30.0			VI[f]
10-02-1931	?	106.5[g]	31.8			III[g]
01-11-1934	07:15	109.82[h]	31.91			V[h]
08-08-1936	01:40	106.5[g]	31.8			III[g]
10-15-1936	18	106.5[g]	31.8			III[g]
03-31-1937	23:45	106.5[g]	31.8			III[g]
09-18-1958	06:03	109.9[h]	31.4			V[h]
02-12-1961	03:51:14	109.2[h]	31.3			IV[h]
06-11-1962	12:54:56.6	109.2[o] (PDE)	28.0	?	33[o]	
09-02-1963	13:20:00.1	109.3[o] (PDE)	29.1	$m_b = 3.7$[o]	33[o]	
03-20-1964	03:05:25.0	108.5[o] (ISC)	28.1	?	?	
05-23-1964	01:57:32.2	110.6[o] (PDE)	28.1	$m_b = 4.7$[o]	33[o]	
09-02-1964	09:05:30.0	108.5[o] (ISC)	30.0	?	?	
10-20-1964	00:53:00.0	106.84[p] (NMI)	30.73	$M_L = 3.3$[p]	?	
02-18-1965	06:33:04.0	109.0[o] (ISC)	28.0	3.9[o]	33[o]	
03-09-1965	13:13:46.5	111.0[o] (ISC)	28.0	?	33[o]	
10-28-1965	20:20:18.3	107.9[o] (PDE)	29.4	$m_b = 5.0$[o]	33[o]	
02-26-1967	13:05:52.0	111.0[o] (ISC)	28.3	4.2[o]	33[o]	
03-21-1969	08:15:20.0	110.0[o] (ISC)	28.0	?	33[o]	
05-12-1969	08:26:18.5	106.44[p] (NMI)	31.95	$M_L = 3.4$[g]	13[g]	V[g]
05-12-1969	08:49:16.3	106.44[p] (NMI)	31.96	$M_L = 3.3$[p]	14[g]	V[g]
12-09-1972	05:58:44.3	106.5[g]	31.8	$M_L = 3.0$[p]	?	IV[g]
12-10-1972	14:37:50	106.4[p]	31.8	$M_L = 3.0$[p]		III[g]
03-13-1973	08:11:19.8	108.008[o] (ISC)	28.449	3.5[o]	?	
03-22-1973	02:45:50	108.50[p]	31.35	$M_L = 2.9$[p]	?	
06-08-1977	13:09:07.40	109.227[q]	31.024	$m_b = 4.6$[q]	5[q]	
09-24-1977	02:34:37.2	110.985[o] (ISC)	29.438	?	33[o]	
12-09-1977	21:48:41.3	106.158[o] (ISC)	28.704	?	33[o]	
03-14-1987	?	109.430[r]	30.843	3.1[r]	?	
08-22-1987	00:17:10.10	109.821[q]	30.793	?	10[q]	
12-19-1987	?	109.483[r]	30.968	3.2[r]	?	
04-10-1988	?	109.447[r]	30.968	3.1[r]	?	
06-11-1988	08:58:35.26[q]	109.425[r]	30.923	$m_b = 4.6$[q]	5[q]	
12-31-1988	?	109.430[r]	30.760	3.2[r]	?	
05-25-1989	07:43:18.6	109.389[s]	30.823	$m_b = 4.6$[s]	5[s]	
05-26-1989	09:08:16.8	109.401[s]	30.753	$M_L = 3.5$[s]	5[s]	
05-26-1989	11:52:11.2	109.392[s]	30.742	2.4[s]		
06-09-1989	17:03:20.7	109.271[s]	31.252	2.8[s]	?	
03-21-1990	8:52 pm LT	106.22[t]	28.86	?	?	
10-31-1990	15:09:52.84	109.254[q]	30.893	$M_D = 3.8$[q]	5[q]	
02-06-1991	10:03:02.72	106.332[q]	28.428	$m_b = 3.9$[q]	5[q]	III–IV[u]
03-10-1992	00:02:55.39	109.251[q]	30.617	$m_b = 3.5$[q]	5[q]	
07-16-1993	20:43:10.59	107.006[q]	29.656	$M_L = 3.8$[q]	5[q]	
09-03-1993	?	109.31[v]	29.86	< 3.5[f,w]	?	?
09-08-1993	12:15 am LT	109.31[v]	29.86	< 3.5[f,w]	?	V[f]
10-05-1993	04:24:16.10	109.089[q]	29.940	$M_L = 4.0$[q]	10[q]	
10-20-1993	05:00:02.41	109.510[q]	29.791	$M_L = 3.5$[q]	5[q]	IV[x]

Table 1 (*continued*)

Date	Origin time	Longitude (°W)	Latitude (°N)	Magnitude	Depth (km)	Maximum intensity (MM)
10-31-1993	05:54:19.39	109.000[q]	29.955	$M_L = 3.7$[q]	5[q]	
10-16-1999	17:15:09.17	110.749[q]	30.751	$M_L = 4.5$[q]	5[q]	VI[f]

[*] *Abbreviations:* (LT — local time; FA — felt area; ISC — International Seismological Centre, Newbury, UK; NMI — New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA; PDE — Preliminary Determinations of Epicenters).

[a] Aguilera (1888).

[b] Suter and Contreras (2001).

[c] Midpoint between the rupture trace extremities.

[d] DuBois and Smith (1980).

[e] Lucero Aja (1993).

[f] This article.

[g] SRA (Eastern, Central, and Mountain States of US) catalog.

[h] DuBois et al. (1982).

[i] DuBois et al. (1982) report a second shock at 5 p.m. of the same day.

[j] Instituto Geológico de México (1909).

[k] Intensity at Cananea based on the newspaper *El Centinela* (Hermosillo, Sonora), 18 October 1907.

[l] Miranda (1909–1910).

[m] Davis et al. (1989).

[n] Intensity at Douglas based on the newspaper *Bisbee Daily Review*, 21 December 1923.

[o] National Geophysical Data Center (1996), composite Mexico catalog.

[p] National Geophysical Data Center (1996), DNAG (Decade of North American Geology) seismicity archive file.

[q] PDE (Preliminary Determinations of Epicenters) catalog.

[r] Wallace et al. (1988).

[s] Wallace and Pearthree (1989).

[t] Carlos García Gutiérrez (*El Heraldo de Chihuahua*, 8 February 1991).

[u] Intensity at Chihuahua City based on the newspaper *El Heraldo de Chihuahua*, 8 February 1991.

[v] Origin time and intensity at Granados based on the newspaper *El Imparcial* (Hermosillo, Sonora), 11 September 1993.

[w] These two events are not listed in the PDE catalog. Their magnitudes were probably <3.5, which is the lower bound for the magnitude of 1993 events of this region listed in the PDE catalog.

[x] Intensity at Granados based on the newspaper *El Imparcial* (Hermosillo, Sonora), 21 October 1993.

The youngest stratigraphic unit of the western graben shoulder (Las Trincheras basalts), which has a K–Ar age of 8.5 ± 1.5 Ma, is cut off and tilted ≤5°W by movement along the western master fault of the Valle de Guaymas graben (Mora-Alvarez, 1992; Mora-Alvarez and McDowell, 2000). The graben must therefore be of late Miocene age or younger. The aquifer of the Valle de Guaymas is characterized by high-temperature anomalies (Prol-Ledesma, 1991), which also suggest that the graben is tectonically active.

3.5. Ciudad Juárez–El paso region

A cluster of historical earthquakes, reported previously by Davis et al. (1989), is located in the region of Ciudad Juárez and El Paso (Fig. 2). It may partly represent a bias toward this region of high-population density, since the cluster mostly contains small events that were only felt at either El Paso or Ciudad Juárez (earthquake of 16 July 1906). However, the seismicity map for New Mexico (Sanford et al., 1997), which contains instrumentally recorded earthquakes of the period 1962–1995 with $M_W \geq 1.3$, also shows this cluster; it extends on that map farther south (at least to lat. 31°N) into the region of the Hueco and Los Muertos basins, which are characterized by faults with Quaternary activity (Seager and Morgan, 1979).

The only one of these events that was felt over a wide area occurred 6 March 1923. According to the reports in the *El Paso Times* (7–8 March 1923), this earthquake was felt as far east as Sierra Blanca (Texas), as far north as Alamogordo (New Mexico), as far west as Lordsburg (New Mexico), as far south as Guzmán (Chihuahua) and was most pronounced at Hachita and Columbus (New Mexico). The SRA catalog and Davis et al. (1989) locate the epicenter at El Paso; whereas, based on the above newspaper reports, it is more likely to be somewhere between Columbus and Hachita (Table 1). Following Davis et al. (1989, their Table 1), the felt area measures approximately 200,000 km^2; however, based on the above newspaper reports, I obtain a value of 55,000 km^2.

3.6. Other seismicity clusters and isolated epicenters

In addition to the seismicity reported above, the epicenter distribution in northeastern Sonora and northwestern Chihuahua (Fig. 2) consists of smaller clusters and isolated events that can be characterized as follows:

1. Isolated epicenters are located in the Basin and Range province of northeastern Sonora near Magdalena and

Sahuaripa (Fig. 2) and WSW of Fronteras, ESE of Moctezuma, and NE of Bacadéhuachi (Fig. 3). These earthquakes may have occurred along the major Basin and Range fault zones located near their epicenters (Figs. 2 and 3).

2. Several isolated epicenters also have been located in northwestern Chihuahua, to the west of Chihuahua City (Fig. 2). The largest of them was of magnitude $m_b = 5.0$ and occurred 28 October 1965 near the village of Nicolás Bravo, in a region that is characterized on the shaded relief map (Fig. 2) by a major NW–SE-oriented lineament that remains to be studied.
3. No earthquakes have been located near Hermosillo, with the exception of an event approximately 50 km north of this town (Fig. 2).

4. Isoseismal maps

Here I present more detailed intensity observations and intensity distribution maps (Figs. 4–7) for four pre-instrumental events, which are the 26 May 1907 Colonia Morelos, 7 April 1908 Fronteras, 18 December 1923 Granados–Huásabas, and 10 February 1927 Nacozari earthquakes. For the construction of the isoseismal maps, I used the techniques outlined in Suter et al. (1996). The intensity values are based on the Modified Mercalli scale (version by Brazee, 1979). The intensity values were gridded (regular grid of approximately 200 × 250 grid lines) with a kriging algorithm (linear variogram model; Isaaks and Srivastava, 1989).

4.1. The 26 May 1907 Colonia Morelos earthquake

The isoseismal map for this earthquake (Fig. 4) is based on intensity observations at 11 locations. The sources for the observations are DuBois et al. (1982) and Instituto Geológico de México (1909). This improves on a previous isoseismal map by DuBois et al. (1982) that did not take into account the data by Instituto Geológico de México (1909). Furthermore, I reevaluated the intensity values assigned by DuBois et al. (1982), who misread the reports for Tucson and Benson given in the *Prescott Weekly Courier* (31 May 1907). The maximum intensity is VIII and was observed at Colonia Morelos (Fig. 4). The kriging algorithm used to grid the intensity values places the area of maximum intensity somewhat southeast of Colonia Morelos (Fig. 4), near the stepover between the Pitáycachi and Teras rupture segments of the 1887 earthquake (A and B on Fig. 3). The 1907 earthquake may therefore have been caused by an increase of static Coulomb stress at the tips of these two 1887 rupture segments (Hodgkinson et al., 1996).

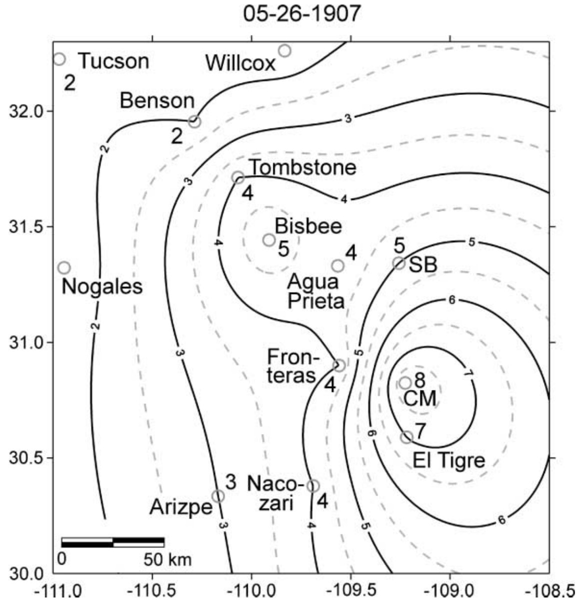

Fig. 4. Intensity map for the 26 May 1907 Colonia Morelos earthquake. CM — Colonia Morelos; SB — San Bernardino Ranch.

The second highest intensity was VII at El Tigre, where 22 aftershocks were felt, whereas no aftershocks were reported from Colonia Morelos. The intensity difference between Colonia Morelos and El Tigre can be explained by the types of subsoil; Colonia Morelos is built on alluvium of the Bavispe River, whereas El Tigre is located on rhyolite (Mishler, 1920). The contour pattern suggests a low intensity attenuation in a northwestern direction (Fig. 4). The earthquake was felt in this direction as far as Tucson, at a distance of 227 km from Colonia Morelos, whereas it was most likely not felt at other places located at a similar distance or closer to the epicenter, such as Hermosillo, Deming, Willcox, and Nogales. No mention of the earthquake could be found in the Hermosillo newspaper *El Centinela*, *The Deming Graphic*, *The Deming Headlight*, and the Willcox newspaper *Arizona Range News*, whereas the event is mentioned in the Nogales newspaper *Oasis*, but without a felt report for this place. No observations are available for the region east of the epicentral region, which corresponds to the sparsely populated Sierra Madre Occidental. Entries from that region would change the contour pattern of Fig. 4.

The areas enclosed by the isoseismals for intensities VI and VII (Fig. 4) are 7750 and 534 km^2, respectively. Based on these values and the maximum intensity (VIII) of this earthquake, I now use regressions between instrumentally determined body-wave magnitudes and the maximum intensities and intensity distributions of shallow normal fault earthquakes in the trans-Mexican volcanic belt in central Mexico (Suter et al., 1996, their Eqs. (2), (4) and (5)) to estimate the magnitude of the 1907 Colonia Morelos earthquake. The upper crust in northeastern Sonora and central Mexico can be assumed to have similar attenuation properties since both regions contain Cenozoic volcanic rocks and rift basins. No published magnitude-intensity relations seem to exist for the southern Basin and Range province; recently published regressions between intensity-related parameters and magnitude (for example, Frankel, 1994; Johnston, 1996) are for ‘stable continental regions’ and are therefore not applicable to the Basin and Range province or the trans-Mexican volcanic belt. The average of five estimates resulting from the application of the central Mexico regressions to the 1907 Colonia Morelos earthquake is $M_I = 5.2$, and the average standard deviation of these regressions is 0.4 magnitude units.

4.2. The 7 April 1908 Fronteras earthquake

The isoseismal map for this earthquake (Fig. 5) is based on intensity observations at eight locations. The sources for the observations are Miranda (1909–1910) and the newspapers *Bisbee Daily Review* and *Douglas American*. Shocks were felt on 7 April 1908, 9:50 and 10:20 p.m., and 8 April 1908, 2:30 a.m. (local times). The first of these three shocks was the strongest. The maximum intensity is VI and was observed at Los Pilares de Nacozari and Fronteras. Given the closure of the innermost isoseismals (Fig. 5), the epicentral region is most likely located between these two places; the epicenter location given in Table 1 is based on the assumption that this event originated in the center of the innermost isoseismal, which is not circular but elongated in a north–south direction. Several earthquakes took place in this same region in 1987–1989 (see Section 3.1., Table 1 and Fig. 3). The earthquake was felt as far as Bisbee, Banámichi, and Moctezuma (Fig. 5), at approximately 100 km from the epicentral region. It most likely was not felt at Tombstone, Nogales, and Willcox; no mention of the earthquake could be found either in the Tombstone newspapers *Tombstone Epitaph* and *Tombstone Prospector* or in the Nogales newspaper *Oasis*, whereas the event is mentioned in the Willcox newspaper *Arizona Range News*, but without a felt report for this place.

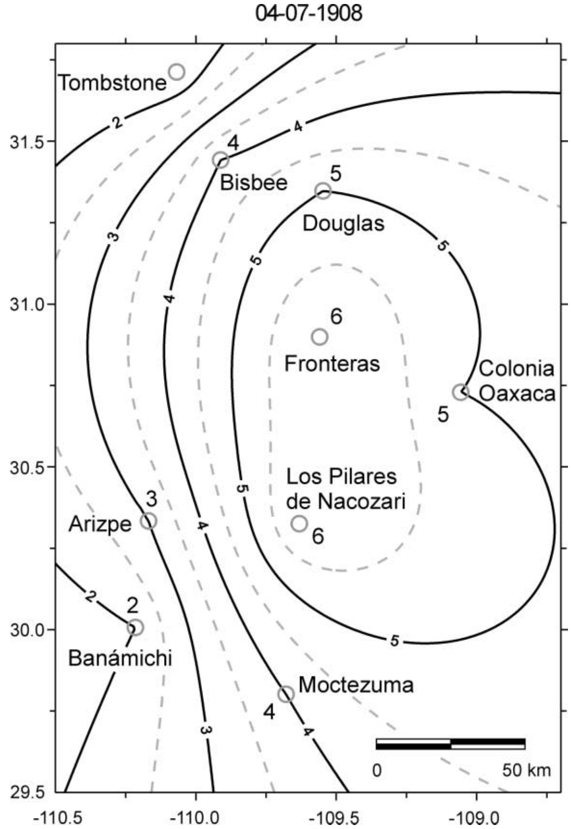

Fig. 5. Intensity map for the 7 April 1908 Fronteras earthquake.

The area enclosed by the isoseismal for intensity V (Fig. 4) is 12,300 km^2. Based on this value and the maximum intensity (VI), the regressions mentioned above can be used to estimate the magnitude of this earthquake. The average of the three possible estimates is $M_I = 4.8$, and the average standard deviation of the applied regressions is 0.5 magnitude units.

4.3. The 18 December 1923 Granados–Huásabas earthquake

The isoseismal map for this earthquake (Fig. 6) is based on intensity observations at only five locations. The source for the observations are unpublished documents in the *Archivo General del Estado de Sonora* (1923, volume 3578, part 1; Lucero Aja, 1993) and the newspapers *The Bisbee Daily Review* (20–27 December 1923), *Douglas Daily Dispatch* (23–27 December 1923), and *El Observador* (Hermosillo, 22 December 1923). A first, relatively short shock on 18 December 1923 at 5 a.m. local time destroyed most adobe constructions in Huásabas and Granados (*Archivo General del Estado de Sonora*, 1923, volume 3578, part 1). A second major shock on 19 December 1923, 6 a.m. local time razed the two villages and was followed by 27 aftershocks on the same day. Some damage was done in Villa Hidalgo, Huépac, and Bacadéhuachi (*Bisbee Daily Review*, 27 December 1923). The two shocks were not recorded instrumentally either at the Tacubaya (Mexico City) or at the Mazatlán (Sinaloa) station of the Mexican

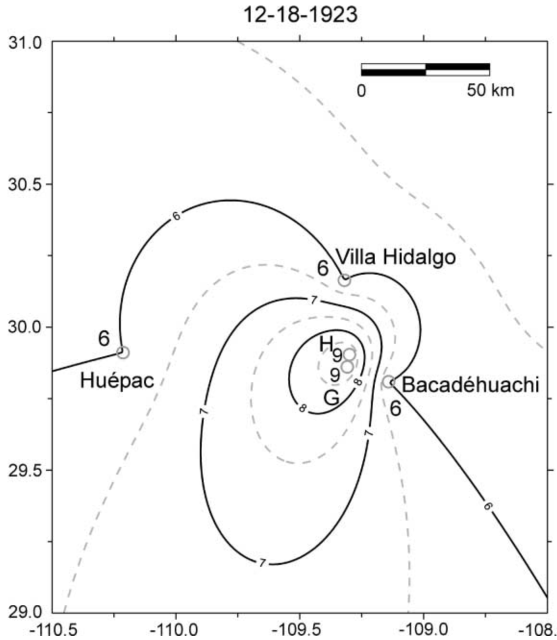

Fig. 6. Intensity map for the 18 December 1923 Granados–Huásabas earthquake. G — Granados; H — Huásabas.

Seismological Network (Instituto Geológico de México, 1926).

DuBois et al. (1982) indicate 20 December 1923, 4 a.m. as origin time for this earthquake, probably because a distinct tremor, accompanied by rumbling noise, was felt by several Douglas, Arizona, residents at that time (19 December 1923, 9 p.m. local time) (*Bisbee Daily Review*, 21 December 1923). However, based on the information in the Sonora state archive referenced above, the two devastating shocks occurred significantly earlier, and no shock is explicitly reported for this time in the archival documents. It is therefore unlikely that the shock felt at Douglas had the same source.

The maximum intensity of this earthquake is IX and was observed at Granados and Huásabas (Fig. 6). The intensity distribution is poorly defined; only the contour for intensity VI is reliably constrained by three relatively well-distributed entry points (Fig. 6). In spite of the large maximum intensity, the felt area of this earthquake is small: Governmental telegrams reporting the disaster from Agua Prieta, Moctezuma, and Nacozari to Hermosillo (*Archivo General del Estado de Sonora*, 1923, volume 3578, part 1) do not mention that the earthquake caused damage or was felt at those locations. The reasons why this earthquake was only locally devastating may be amplification of ground shaking in the alluvium of the Bavispe River underlying Granados and Huásabas and a shallow focal depth. The earthquake may have originated on the Basin and Range fault that forms a pronounced scarp just east of these two towns (Fig. 3).

The area enclosed by the isoseismal for intensity VII of the 1923 Granados–Huásabas earthquake (Fig. 6) is 2670 km^2. As above for the 1907 and 1908 events, this area and the maximum intensity (IX) of this earthquake can be used to estimate its magnitude by applying the regressions defined in Suter et al. (1996). The average of the three possible estimates is $M_I = 5.7$, and the average standard deviation of the applied regressions is 0.4 magnitude units.

This earthquake was followed by a series of aftershocks that lasted at least until April 1924. The aftershocks documented in the *Archivo General del Estado de Sonora* (1924, volume 3713; letters by the mayors of Granados and Huásabas to the Sonoran state government in Hermosillo) took place on 17 January 1924 (four events; the strongest had intensity V); 10 February 1924, 10 p.m. (all times indicated for these aftershocks are local times) (intensity V–VI); 12 February 1924, 8 a.m. (intensity III); 7 March 1924, 3 p.m. (intensity III) and 6 p.m. (intensity IV); and a major shock on 21 April 1924, 9:15 a.m. (intensity VI). In the 20 h following this earthquake, 18 more shocks were felt in Huásabas and 25 in Granados.

4.4. The 10 February 1927 Nacozari earthquake

The isoseismal map for this earthquake (Fig. 7) is based on intensity observations at seven locations. The sources for the observations are the compilation by DuBois et al. (1982), who misread the information for Bisbee provided in the *Bisbee Daily Review* (12 February 1927) and the newspapers *Douglas Daily Dispatch* (12 February 1927) and *Nogales International* (13 February 1927). The maximum intensity was VI at Nacozari, where the brief but pronounced shock at 8:41 p.m. was of sufficient force to break several windowpanes. The earthquake was felt as far as Nogales and Patagonia (Fig. 7), at approximately 150 km from Nacozari.

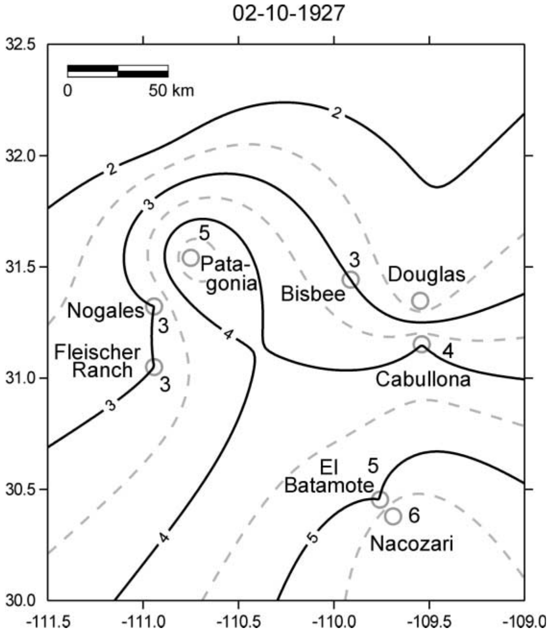

Fig. 7. Intensity map for the 10 February 1927 Nacozari earthquake.

The source of this earthquake was located near Patagonia, Arizona (Fig. 7), by DuBois et al. (1982), but is more likely to be in the Nacozari region. The earthquake was felt very strongly at the Batamote mine near Nacozari (Fig. 7), where the motion was described as trembling, twisting, and wrenching. At Patagonia, on the other hand, the motion was described as gradual swaying (DuBois et al., 1982). These descriptions indicate that the frequency of ground motion was higher at El Batamote than at Patagonia.

Unfortunately, none of the isoseismals is well defined; the observations only indicate a generally northwestward-directed intensity attenuation (Fig. 7). It cannot be excluded that the epicenter was located farther southeast (for example, in the Granados–Huásabas region) and that the maximum intensity was greater than VI. Alternatively, but less in agreement with the intensity distribution, the epicenter may have been located between the high-intensity regions of Patagonia and Nacozari–El Batamote (Fig. 7).

5. Conclusions

A detailed compilation of the historical seismicity of northeastern Sonora and northwestern Chihuahua (28–32°N, 106–111°W) for the period 1887–1999 yielded 64 events (excluding aftershocks), a significant increase with respect to former contributions. Most of the seismicity is concentrated in the epicentral region of the 3 May 1887, $M_W = 7.4$ Bavispe earthquake, which has the longest historical normal fault surface-rupture (>100 km) of the southern Basin and Range province. The second largest earthquake in the epicentral region of the 1887 earthquake is the 26 May 1907 Colonia Morelos event ($I_{max} = \text{VIII}$, $M_I = 5.2$). Other seismicity clusters have been located in the Valle de Guaymas graben and in the Fronteras–Nacozari, Ciudad Juárez–El Paso, and Granados–Huásabas regions. The largest events in the Granados–Huásabas region took place 18 December 1923 ($I_{max} = \text{IX}$, $M_I = 5.7$) and 17 May 1913 ($I_{max} = \text{VIII}$, $M_I = 5.0$).

Isoseismal maps constructed for four pre-instrumental events, the 26 May 1907 Colonia Morelos, 7 April 1908 Fronteras, 18 December 1923 Granados–Huásabas, and 10 February 1927 Nacozari earthquakes, were used to locate these events based on their intensity distributions. The 1907 earthquake originated at the stepover between two major segments of the 1887 surface rupture and is characterized by a low-intensity attenuation in northwestern direction. The intensity distribution of the 1908 earthquake is characterized by a north–south elongation of the innermost isoseismal, which is located in the Nacozari–Fronteras region where several other earthquakes took place in 1987–1989. The 1923 earthquake has a small felt area but was locally devastating, which can be explained by amplification of ground shaking in the alluvium of the Bavispe River underlying Granados and Huásabas and a shallow focal depth. The 1927 earthquake is not located in Arizona as previously reported, but most likely southeast of Nacozari.

Based on their locations with respect to the 1887 surface rupture, the seismicity in the Granados–Huásabas region as well as the 1907 Colonia Morelos event may have been caused by an increase of static Coulomb stress at the tips of 1887 rupture segments.

6. Digital data sources

The PDE and SRA catalogs were consulted online at http://wwwneic.cr.usgs.gov/neis/epic/epic.html, the WUS (Western United States) catalog (Mueller et al., 1997) at http://geohazards.cr.usgs.gov/eq, and the catalog of the Arizona Earthquake Information Center at http://vishnu.glg.nau.edu/aeic/aeic.html. The GTOPO30 digital elevation model (30 arc-second topographic grid) used in Figs. 1 and 2 was downloaded from http://edcdaac.usgs.gov/gtopo30/gtopo30.html. The Open-File Reports of the New Mexico Institute of Mining and Technology (including Sanford et al., 1997) were consulted at http://krach.nmt.edu/. The NGDC Composite Mexican Catalog, the Harvard Moment Tensor Catalog, and the Tacubaya Catalog were consulted on the following compact disc: National Oceanic and Atmospheric Administration (NOAA), National Geophysical Data Center (NGDC), Boulder, Colorado, USA, 1996, Seismicity catalog, vol. 1 — North America, 1492–1996.

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