International Journal of the Physical Sciences Vol. 5 (6), pp. 651-670, June 2010
Available online at http://www.academicjournals.org/IJPS
ISSN 1992 - 1950 ©2010 Academic Journals

Full Length Research Paper

Seismic quiescence patterns as possible precursors of great earthquakes in Mexico

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Accepted 20 April, 2010

A catalog of shallow Mexican earthquakes (depth ≤ 60 Km) is presented for a region bounded by $14° - 21°$ north latitude and $94° - 106°$ west longitude, covering the period from January, 1806 to December, 2010, which is incomplete in this period for a wide range of magnitudes, but is complete for different ranges of magnitude in short intervals of time. The catalog is probably complete for $M_w \geq 7.0$ since 1860 and for $M_w \geq 7.7$ since 1846, but for earthquakes of magnitude greater than or equal to 4.3 the catalog is complete since 1969. Using the data of this master catalog, we show that there is evidence that the last earthquakes of magnitude $M_w \geq 7.6$ that occurred in Mexico from 1975 to 2009 were preceded by an unusual seismic quiescence. We use the method of space-time plots and cumulative seismicity plots.

Key words: Seismic quiescence, cumulative seismicity, Mexican earthquakes.

INTRODUCTION

Mexico is one of the countries with higher seismicity. During the 20th century, 8% of all the earthquakes in the world of magnitude greater than or equal to 7.0 have taken place in Mexico. On average, an earthquake of magnitude greater than or equal to 7.0 occurred in Mexico every two and a half years. Great earthquakes in Mexico have their epicenters in the Pacific Coast in which some seismic gaps have been identified; for example, there is a mature gap in the Guerrero State Coast, which potentially can produce an earthquake of magnitude 8.2 (Astiz et al., 1987; Suarez et al., 1990). However, a possible silent earthquake with $M_W = 7.6$ occurred at this gap in 2002 which lasted for approximately 4 months and was detected by continuous GPS receivers located over an area of $\sim 550x250\ km^2$ (Iglesias et al, 2004; Franco et al., 2005). It is necessary to have an idea of the upcoming of such an earthquake, although at the present time a method universally accepted to predict the occurrence of a great magnitude earthquake does not exist. With the purpose of making some prognosis, some researchers study the statistical behavior of certain physical parameters that could be related with the process of accumulation of stress in the Earth crust (Rikitake, 1976; Asada, 1982; Mogi, 1985; Turcotte, 1991; Lomnitz, 1994; Telesca et al. 2003; Ramírez-Rojas et al. 2004). Other researchers study seismic catalogs trying to find seismicity patterns that are manifested before the occurrence of great earthquakes (Kanamori, 1981; Scholz, 1988; Wyss and Habermann, 1988; Keilis-Borok et al., 1990; Keilis Borok and Kossobokov, 1990; Novelo-Casanova and Alvarez-Moctezuma, 1995). Fractal analysis or non-extensive analysis of earthquakes before the occurrence of large events are recent methodologies that have been also applied to study this complex phenomenon (Telesca et al., 2009; Telesca, 2010, Muñoz-

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Diosdado et al., 2005). According to the seismic gap hypothesis, major events are expected along sections of plate boundaries which have a history of great earthquakes and have not ruptured during the last decades (Habermann, 1982). This concept is a first step towards narrowing the spatial limits of an upcoming big earthquake. Many authors (Mogi, 1979; McNally, 1981; Habermann, 1982) have proposed that the study of seismicity rates is an appropriate technique for evaluating how close a seismic gap may be to rupture. With this approach, Ohtake (1977) successfully forecast the $M_W = 7.8$ Oaxaca, 1978 earthquake. Among the studies of changes in seismicity rates is the search of quiescence periods. In particular, this technique has been very successful in identifying some precursors along the Mexican trench. As we said before, it is remarkable the Ohtake's prediction of the Oaxaca earthquake. Other well identified quiescence periods before great Mexican earthquakes are those of Colima 1973, $M_W = 7.7$ (McNally, 1981; Habermann, 1982) and Petatlan, $M_W = 7.6$ (McNally, 1981).

In fact, Wyss and Habermann (1988) defined the quiescence phenomenon formally as follows: “seismic quiescence is a decrease of mean seismicity rate as compared to the background rate in the same crustal volume, judged significant by some clearly defined standard. The rate decrease takes place within part, or all, of the source volume of the subsequent main shock, and it extends up to the time of the main shock or may be separated from it by a relatively short period of increased seismicity rate (as in Ohtake et al. 1977)”. However, the hypothesis of precursory seismic quiescence is not universally accepted and there exist different approaches to measure, map and evaluate possible episodes of seismic quiescence (Wyss et al., 2004). Recently, Huang (2008) reported a seismic quiescence anomaly that appeared during 2006-2007 before the $M_s = 8.0$ Wenchuan earthquake in China. This quiescence was identified by means of the Region-Time-Length (RTL) method (Sobolev and Tyupkin, 1999; Huang et al., 2001).

Some other methods used to identify quiescence patterns before big earthquakes are, for instance, the study of cumulative seismicity along time (McNally, 1981; Habermann, 1982) and the method of space-time plots (Ohtake et al., 1981). In the present article, we use these last two approaches to identify possible quiescence patterns before big earthquakes in Mexico since 1969. These methods have a great dependence in the reliability of seismic catalogs. For this reason, we use the second section of this paper to describe how we elaborated a complete, homogeneous and reliable catalog of Mexican earthquakes. We also discuss about the Gutenberg-Richter law for Mexican earthquakes and the mean recurrence times of big earthquakes in Mexico. We present a discussion on possible quiescence patterns before great earthquakes ($M_S \geq 7.5$) in Mexico.

SEISMIC DATA

Catalog of Mexican earthquakes

The catalog of earthquakes in this article is the summary of several catalogs. Although the National Seismological Service began to operate since 1910, seismic registrations of the first decades of the 20th century are not very reliable due to the small quantity of register stations and the bad operation of them. It is until 1963 when a better registration of the Mexican seismicity was achieved. In the last years several seismologists have revised the old catalogs and they have corrected the localization of the epicenter, the depth of the focus and the magnitude of some important earthquakes.

In what follows we describe the catalogs used for the construction of our master catalog, as well as the covered periods and the scales of magnitude reported in each one.

a) Figueroa (1970) Catalog. This catalog covers the period from January 1900 to June 1970. Most of the events were registered by the National Seismological Service. From 1963 to 1970 this catalog includes events registered by the United States Coast and Geodetic Survey (USCGS) and in a smaller quantity, events registered by the University of Berkeley and the Institute of Engineering of the National Autonomous University of Mexico (UNAM). Figueroa does not indicate what kind of magnitude is reported, but we took Figueroa's magnitude as M_S except for the events registered by the USCGS who reported m_b. A comparison analysis with the catalog of shallow earthquakes ($h \leq 65$ Km) of Singh et al. (1984) indicates that this assumption could be correct for earthquakes with $M_S \leq 5.9$ since 1929 (according to Figueroa, the catalog is reliable since the middle of 1926).

b) National Seismological Service (1970-1987), Institute of Geophysics, UNAM. Catalog of Mexican earthquakes located between the 14° and 21° N, and 94° and 106° W, occurred between January 1970 and December 1987. The magnitudes m_b, M_S and M_c are reported. The magnitude of small events ($M_S \leq 4.0$) was not calculated; the magnitude of the coda M_c was only determined for some events.

c) Singh, Rodriguez, and Espindola (1984) reported a catalog of shallow earthquakes of Mexico from 1900 to 1981. This work includes two catalogs, one for moderate earthquakes $5.9 \leq M_S \leq 6.9$ and the other for big earthquakes $M_S \geq 7.0$, we consider only the moderate earthquake catalog. This catalog covers the period from July 1909 to January 1979. The magnitude M_S is reported for most of the events and m_b for events since 1965. If M_S was determined by more than one institution they took the average. The events of this catalog substitute those of Figueroa and those of the National Seismological Service.

d) Dean and Drake (1978) included in their paper a catalog that covers the period from August 1967 to June 1974, and the magnitude m_b is reported. The events of this catalog supplement the previous catalogs.

e) Tajima and McNally (1983) have a catalog in their work that covers the period from January 1964 to November 1978, and the magnitude m_b is reported. Only events occurred in Oaxaca are included (15° to 18°N, 95° to 98.5° W). Most of the events substitute those of the previous catalogs.

f) Gonzalez-Ruiz and McNally (1988) included a catalog in their work that covers the period from June 1982 to May 1986, and the magnitude m_b is reported. The events of this catalog supplement those of the National Seismological Service Catalog.

g) Nishenko and Singh (1987) included a catalog that covers the period from December 1937 to May 1962, and the magnitude m_b is reported, the magnitude M_S for some moderate and strong earthquakes is also reported. In this catalog the epicenters of some big earthquakes are relocated as those of 1937, 1950, 1957 and 1962. The events of this catalog substitute those of Figueroa's catalog.

h) Singh and Nishenko (1985) reported some events occurred in the Jalisco-Mexico region during the period from June 1932 to December 1933 and the Gutenberg-Richter magnitudes are reported (they were taken as M_S) and also the duration of the coda. These events substitute those of Figueroa.

i) The Pardo's catalog (1993) covers the period from February 1964 to July 1991, and the magnitude m_b is reported for all the events. In this catalog the hypocenter of all the events was relocated, for some of them the seismic moment is reported, and the seismic moment magnitude was calculated for them. Most of the events of this catalog substitute those of the previous catalogs.

j) Bulletins of the National Seismological Service (SSN) (1988-2010), Institute of Geophysics, UNAM. The magnitudes m_b, M_S and M_E (energy magnitude) of earthquakes occurred in Mexico and surroundings are reported. The magnitude of the coda is reported for all the events, the magnitudes m_b and M_S are calculated by the National Earthquake Information Center in the Preliminary Determination of Epicenters (PDE) and the Quick Epicenter Determinations (QED). It seems to be that this is the most reliable and complete information on Mexican earthquakes. The magnitude M_E for some important events is calculated by the SSN.

k) Weekly Preliminary Report of the National Seismological Service (1998-2010), Institute of Geophysics, UNAM. From January 1, 2001 to December 31, 2010. The magnitudes above mentioned are reported for earthquakes occurred in Mexico and its surroundings.

l) Harvard Centroid Moment Tensor Catalog (1977-2010), Harvard University. Since 1976 Harvard University reports the seismic moment magnitude for earthquakes from all over the world, seemingly complete for earthquakes of magnitude $M_W \geq 5.0$. The seismic moment magnitudes of this catalog, for Mexican events, substitute the magnitude M_S of the previous catalogs or they are averaged with the magnitudes M_w, or M_E of other references. This information can be obtained in the Internet page of the Harvard University: http://www.seismology.harvard.edu/.

m) In the Rudolf-Navarro's catalog (1995) earthquakes of magnitude M_S and $M_W \geq 7.0$, occurred since January, 1806, in the area of Mexican subduction and its surroundings are given. The catalog is probably complete for $M_W \geq 7.0$ since 1860 and $M_W \geq 7.7$since 1846. The complete catalog is in the Appendix A, Table IV, which is an important part of our master catalog that was used to obtain the results of this article. The complete catalog can be obtained in the Internet page of the Superior School of Physics and Mathematics of the National Polytechnic Institute: http://www.esfm.ipn.mx.

Although our master catalog is incomplete for a wide range of magnitudes, it is complete for different ranges of magnitude in shorter intervals. The epicenters of the events considered in this work are located between the 14° and 21°N and 94 and 106° W, and the depth of the focus is less than or equal to 60 Km.

Catalog reliability

The catalogs used in the construction of our master catalog do not report the same scale of magnitude, so we had to unify the magnitude data. We considered all events for which both scales of magnitude M_S and m_b, M_S and M_c were determined. A linear correlation was assumed among the different scales of magnitude and for those events whose magnitude M_S is not reported, it was calculated from m_b or M_c. For the goals of this work, the scale of magnitude M_S was chosen, since this is related with the seismic energy. However, in those cases in which M_w or M_E was determined, this substitutes M_S because these scales are more appropriate for moderate and big earthquakes. Thereinafter we will use M_S to denote indistinctly these scales of magnitude.

To obtain the relationship between M_S and m_b we selected 208 earthquakes that occurred between January 1974 and July 1994, and between the latitude 13°-22° N and longitude 90°-109° W ranges, with focus depth less than or equal to 120 Km, and the adjusted linear relationship between M_S and m_b is given by

$$M_S = 1.581 m_b - 3.116, \tag{1}$$

with correlation coefficient $r = 0.8886$ and a typical error of the estimate $\sigma = 0.485$. The relation between M_S and M_c was obtained by using 96 earthquakes occurred from January 1988 to July 1994, and between the latitude 13°-22°N and longitude 90°-109°W ranges, with focus depth less than or equal to 120 Km, and the adjusted linear relationship between M_S and M_c is,

$$M_S = 1.293M_C - 1.793, \tag{2}$$

with a correlation coefficient $r = 0.810$ and a typical error of the estimate $\sigma = 0.486$. In the case that both magnitudes m_b and M_c were reported, M_S was calculated as the average

$$M_S = 0.790m_b + 0.646M_C - 2.454. \tag{3}$$

Once we have calculated the magnitude M_S for all the events of our catalog, the following step was to verify if the catalog is complete for different ranges of magnitude. The approach used to determine if the catalog is complete in an interval of time Δt for a magnitude range $M_S \geq M$ was the following one:

(1). Graphs of cumulative number of earthquakes of magnitude $M_S \geq M$ were obtained, for $4.3 \leq M \leq 8$ in appropriate time intervals. In all the graphs a linear trend was observed during the last decades, which indicates a constant rate of the number of earthquakes per unit time. If we accept that during the last decades the registration of the earthquakes is more reliable, then, it is reasonable to suppose that the catalog is complete in those time intervals in which the graph shows a rate of the earthquake number per unit of time that stays approximately constant until the last few years. These intervals were obtained in a preliminary way for each value of *M*.

(2). Due to the fact that we can register the magnitude of big earthquakes more easily, then it is reasonable to suppose that if the earthquake catalog is complete (in the sense of point 1) in a time interval Δt for a range of magnitudes $M_S \geq M$, then it should be complete for any range of magnitudes $M_S \geq M'$ with $M' \geq M$. The previous condition was applied to the intervals mentioned above and it was not always true, so we have to redefine (to reduce) the intervals, so that the last condition was true. The fact that the catalog is complete (in the sense of point 1) in the range of magnitudes $M_S \geq M$, but incomplete for some range $M_S \geq M'$ with $M' \geq M$, is explained if the magnitude $M_S \geq M'$ was underestimated for some events; that is to say; they were assigned a magnitude $M \leq M_S \leq M'$. We consider that the possibility that such events have not been registered is very low.

(3). Once the time intervals where the catalog is complete were determined (in the sense of points 1 and 2) for different magnitude ranges, the cumulative annual frequencies were calculated, that is to say, the number of earthquakes of magnitude $M_S \geq M$ that occur per year, in the following way: Given the time interval $\Delta T = t - t_0$ on which *N* events of magnitude $M_S \geq M$ have occurred, we denote by t_i the occurrence time of the *i*-th event and by N_i the number of events occurred in the time interval $\Delta t_i = t_i - t_0$. Then the cumulative annual frequency is calculated for earthquakes of magnitude $M_S \geq M$ as the average

$$\dot{N}(M_S \geq M) = \frac{1}{N-k+1} \sum_{i=k}^{N} \frac{N_i}{\Delta T_i}, \tag{4}$$

where we took *k* as the integer part of *N/2*. The typical deviation was calculated for the cumulative annual frequency as

$$\sigma = \sqrt{\frac{1}{N-k'+1} \sum_{i=k'}^{N} \left[\dot{N}(M_S \geq M) - \frac{N_i}{\Delta t_i}\right]^2} \tag{5}$$

where *k'* was taken as the integer part of *N/4*. Finally, to formalize the approach on the catalog completeness, we imposed that the typical deviations were smaller than 20% of the cumulative annual frequency of that interval. This implied the redefinition (or reduction) of some intervals that fulfill the conditions 1 and 2.

The time intervals where it was found that the catalog is complete and reliable for the different ranges of magnitude, according to the approach already mentioned, are shown in Table 1, as well as the cumulative annual frequencies and the typical deviations.

GUTENBERG-RICHTER LAW

Gutenberg-Richter law for Mexican earthquakes

Starting from the data of Table I, we can obtain the empirical relationship of Gutenberg-Richter for accumulated frequencies of earthquakes of magnitude $4.3 \leq M_S \leq 7.0$:

$$log\ \dot{N}(M_S \geq M) - 4.2882 - 0.6857M, \tag{6}$$

where the typical error of the estimate is $\sigma = 0.0275$ and the correlation coefficient $r = 0.998$. In Figure 1 we show the graph of the logarithm of the cumulative frequency against the magnitude and the relationship of the readjusted relation of Gutenberg-Richter for the range

Table 1. Completeness intervals for different ranges of earthquake magnitude, cumulative frequencies and typical deviations.

Magnitude *(M)*	**Catalog completeness intervals**	**Cumulative frequencies** $\dot{N}(M_S \geq M)$	**Standard deviation** $\sigma(\dot{N})$
4.3	January 1, 1969 – December 31, 2009	20.952	0.803
4.4	January 1, 1969 – December 31, 2009	20.222	1.157
4.5	January 1, 1969 – December 31, 2009	16.516	0.735
4.6	January 1, 1969 – December 31, 2009	13.573	0.726
4.7	January 1, 1969 – December 31, 2009	12.792	0.970
4.8	January 1, 1969 – December 31, 2009	10.157	0.659
4.9	January 1, 1969 – December 31, 2009	9.693	0.677
5.0	January 1, 1969 – December 31, 2009	8.075	0.430
5.1	January 1, 1969 – December 31, 2009	6.596	0.278
5.2	January 1, 1969 – December 31, 2009	6.250	0.275
5.3	January 1, 1966 – December 31, 2009	5.498	0.191
5.4	January 1, 1966 – December 31, 2009	4.570	0.227
5.5	January 1, 1966 – December 31, 2009	4.090	0.158
5.6	January 1, 1960 – December 31, 2009	3.490	0.099
5.7	January 1, 1960 – December 31, 2009	2.589	0.107
5.8	January 1, 1960 – December 31, 2009	2.303	0.100
5.9	January 1, 1960 – December 31, 2009	1.882	0.104
6.0	January 1, 1936 – December 31, 2009	1.682	0.0689
6.1	January 1, 1936 – December 31, 2009	1.280	0.0697
6.2	January 1, 1936 – December 31, 2009	1.100	0.0494
6.3	January 1, 1936 – December 31, 2009	0.928	0.0435
6.4	January 1, 1936 – December 31, 2009	0.755	0.0463
6.5	January 1, 1936 – December 31, 2009	0.692	0.0484
6.6	January 1, 1933 – December 31, 2009	0.546	0.0382
6.7	January 1, 1936 – December 31, 2009	0.493	0.0316
6.8	January 1, 1936 – December 31, 2009	0.491	0.0314
6.9	January 1, 1936 – December 31, 2009	0.415	0.0258
7.0	January 1, 1860 – December 31, 2009	0.398	0.0227
7.1	January 1, 1860 – December 31, 2009	0.366	0.0188
7.2	January 1, 1860 – December 31, 2009	0.337	0.0212
7.3	January 1, 1860 – December 31, 2009	0.321	0.0176
7.4	January 1, 1860 – December 31, 2009	0.250	0.0243
7.5	January 1, 1860 – December 31, 2009	0.185	0.0262
7.6	January 1, 1860 – December 31, 2009	0.127	0.0207
7.7	January 1, 1846 – December 31, 2009	0.0752	0.0135
7.8	January 1, 1846 – December 31, 2009	0.0573	0.0129
7.9	January 1, 1846 – December 31, 2009	0.0302	0.0072
8.0	January 1, 1846 – December 31, 2009	0.0129	0.0011

$4.3 \leq M_S \leq 7.0$; the frequencies for $M_S \geq 7.1$ do not fit to this straight line. For great earthquakes, of magnitude $7.5 \leq M_S \leq 8.0$, the adjusted relation of Gutenberg-Richter is

$$log\, \dot{N}(M_S \geq M) = 15.98 \quad 2.22M \mid log\left(1 \quad 10^{2.22(M-8.6)}\right), \tag{7}$$

where the typical error of the estimate is $\sigma = 0.065$ and the correlation coefficient $r = 0.998$. The logarithmic term in this relationship was introduced by the fact that a limit exists for the magnitude of the biggest earthquake that can happen in the area of Mexican subduction, in consequence the cumulative frequencies of earthquakes of magnitudes greater or equal to the limit magnitude

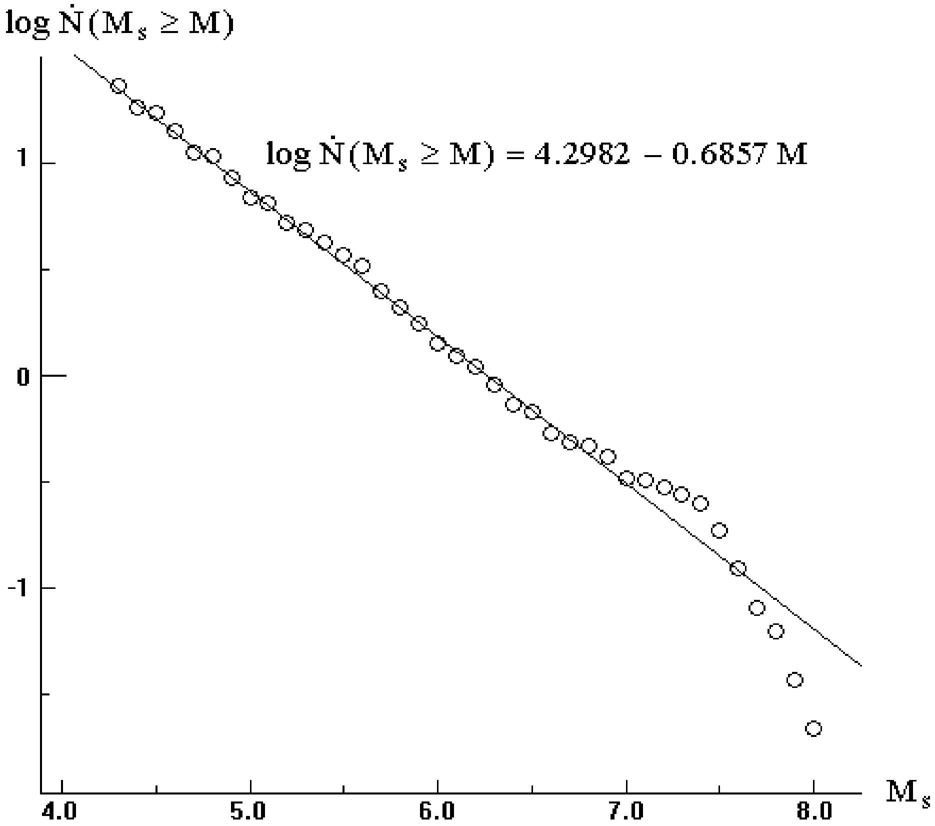

Figure 1. Gutenberg-Richter relation for the cumulative annual frequency of earthquakes of magnitude $4.3 \leq M_S \leq 7.0$ occurred in the Mexican Pacific Coast.

should be zero.

MEAN RECURRENCE TIMES OF GREAT EARTHQUAKES

The great quantity of elastic potential energy, accumulated during the years between the tectonic plates, will necessarily be released with the occurrence of big earthquakes. The empirical relationship between the M_S magnitude and the total energy of the seismic waves was proposed by Gutenberg and Richter (1956) as

$$log_{10}E_S = 1.5M_S + 11.8, \qquad (8)$$

where E_s is the total energy, in ergs, released as seismic waves for an earthquake of magnitude M_S. An earthquake of magnitude $M_S = M_0$ releases an energy E_0; an earthquake of magnitude $M_S + \Delta M$ releases an energy $10^{1.5\Delta M}$ times greater. Therefore, it is necessary that a great number of moderate and small earthquakes occur in a short time interval in order to release the accumulated energy without the occurrence of great earthquakes. However, the statistics show the opposite; only in the 20th century, in Mexico have occurred about 120 earthquakes of magnitude $6.0 \leq M_S \leq 6.5$ and two earthquakes of $M_S \geq 8.0$. Thus, it is interesting to know when the big earthquakes in Mexico will occur. In Table II we show the mean recurrence times of earthquakes of magnitude $M_S \geq M$, for $7.0 \leq M \leq 8.5$, for the real and adjusted data obtained from the Gutenberg-Richter relation. The data from this Table give us an idea of the seismic potential of Mexico; along a man's lifetime in Mexico they will occur from 20 to 30 earthquakes of magnitude greater than 7.0 an one or two of these will be similar to the 1985 earthquake ($M_S = 8.1$).

SPACE-TIME SEISMICITY

Space-time seismicity plots

In this kind of analysis we plot the distance from each epicenter to a fixed point (named pole) against the time

Table 2. Recurrence times of great earthquakes.

Magnitude M	Average recurrence times in years of great magnitude earthquakes $M_S \geq M$	
	Real	**Calculated with the G-R law**
7.0	2.5	2.8
7.5	5.4	4.7
7.6	7.9	7.8
7.7	13.3	13.1
7.8	17.5	22.0
7.9	33.1	37.2
8.0	77.5	63.2
8.1	There are not available data	108.9

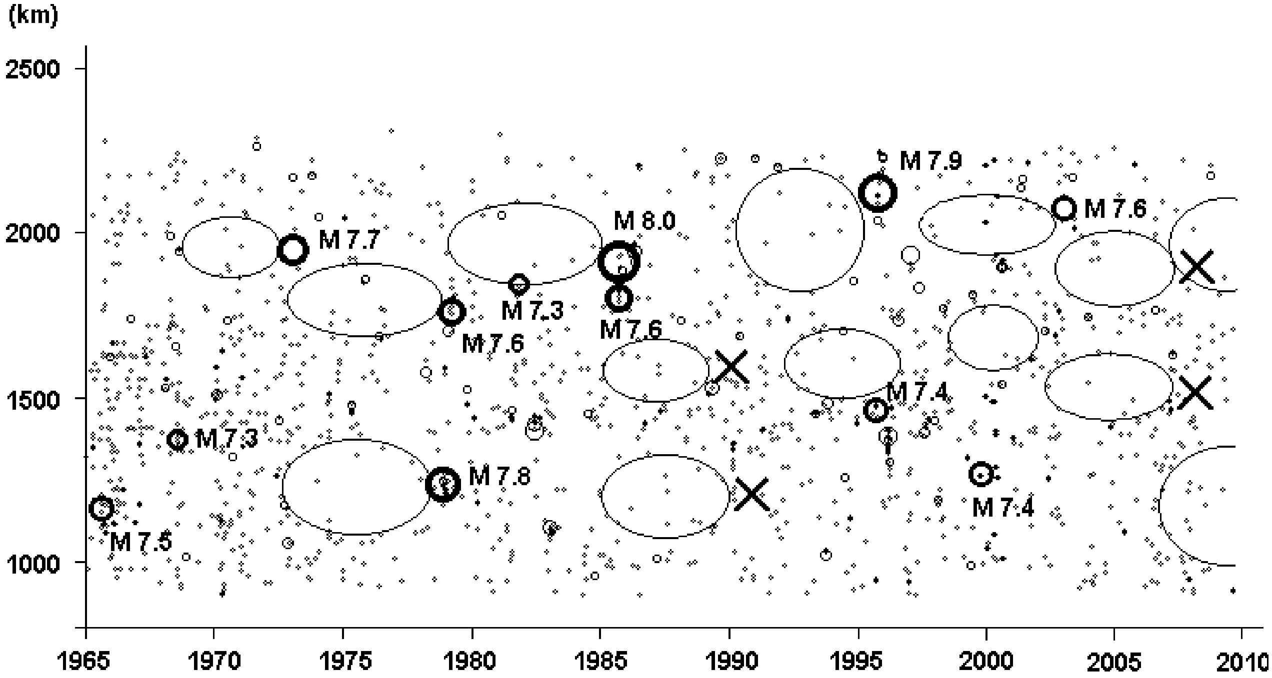

Figure 2. Seismicity space-time plot for the Mexican Pacific Coast for earthquakes with magnitude $M_S \geq 4.3$. In the vertical axis we plot the distance from the epicenter to the pole, in kilometers, and in the horizontal axis the time in years. The ellipses indicate regions of seismic quiescence and the big black points indicate the epicenters of earthquakes greater than or equal to 7.3 occurred since 1965.

(Kanamori, 1981). In Figure 2 we show an example using earthquake magnitude $M_S \geq 4.3$ from 1965 to 2009 in the considered region.

There is not a formal approach for the pole election; this is chosen on the line that passes along the main fault, in our case along the Mexican Pacific Coast and far from the extremes of the trench, for the previous graph we took as the pole the point located at 12° north latitude and 86° west longitude. The small points in Figure 2 represent the earthquake epicenters whose distance to the pole in kilometers is the value of its ordinate; its abscissa is the occurrence time. The big black points represent earthquakes of magnitude $M_w \geq 7.3$ and the ellipses show space-time regions of seismic quiescence, where the epicenter density decreases considerably. As it can be observed, the big earthquakes of magnitude $M_w \geq 7.8$, Oaxaca 1978 ($M_w = 7.8$), Michoacan 1985 ($M_w = 8.0$) and Colima 1995 ($M_w = 7.9$) were clearly preceded by this kind of pattern. It is also considerable

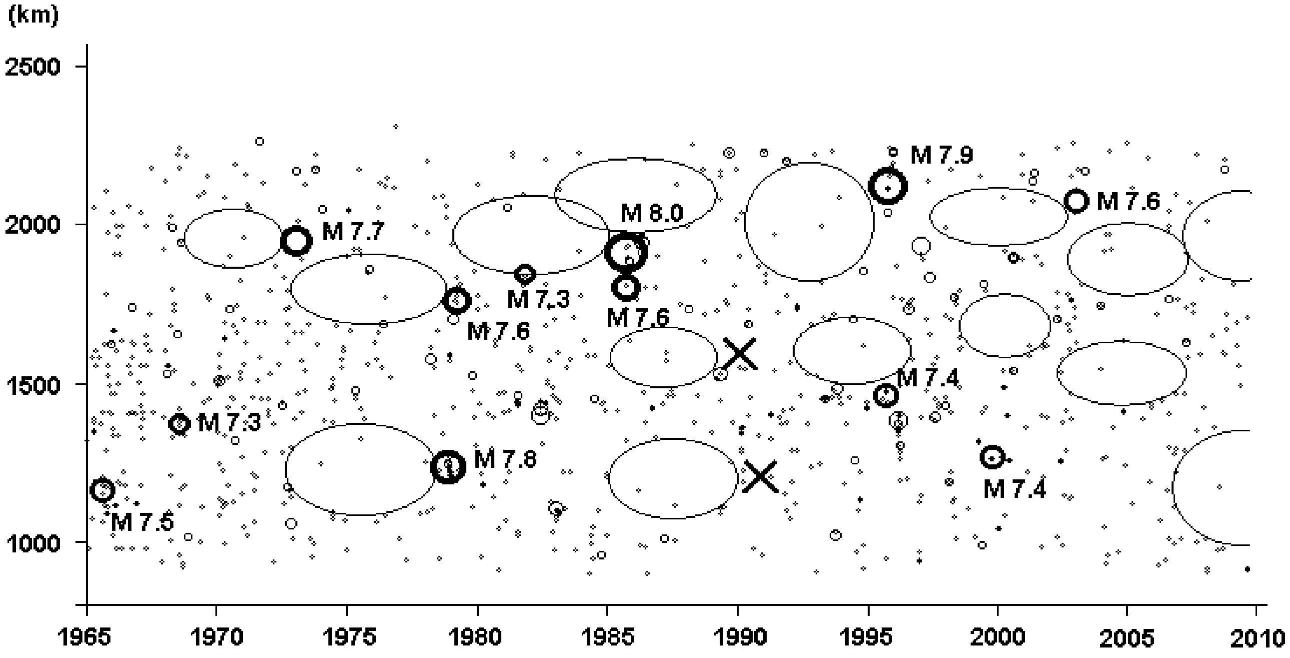

Figure 3. Seismicity space time plot for earthquakes with magnitude $m_b \geq 4.5$ in the Mexican Pacific Coast.

the seismic quiescence previous to the earthquake of Petatlan, Guerrero 1979 $(M_w = 7.6)$ and less significant than the previous quiescence to the earthquake of Colima 1973 $(M_w = 7.7)$. In opposition, we have four regions of quiescence (marked with an X) that are not correlated with great earthquakes. The most important was produced in the epicentral region of the 1978 Oaxaca earthquake, between 1984 and 1990 and it is very similar to the one that was produced before this earthquake; the other quiescence is produced in Guerrero between 1985 and 1989 and it could be associated to the moderate earthquake $(M_w = 6.9)$ occurred in April, 1989. Finally, we have a small quiescence region in Guerrero, which could be correlated with the earthquake of Ometepec, Guerrero on September 14, 1995; but, in opposition to the previous cases this region is not located in the epicentral region of the earthquake, rather it is in a neighboring region to the epicentral one and temporarily this region does not finish before the earthquake but one year later. However, for the case of considerable quiescence ellipses with no earthquake associated, it may not be discarded the possible occurrence of silent earthquakes recently reported in the Mexican Coast by means of GPS technology (Iglesias et al, 2004; Franco et al., 2005) which it was not available for the cases marked with a X.

Although the catalog of earthquakes used in the elaboration of the space-time seismicity graphs is complete and reliable, in accordance with the approach previously described, it is important to mention that the regions of low seismicity change in form, size and localization and they can even disappear when the range of magnitudes or the scale of seismic magnitude is changed. In Figure 3 we show a similar graph to the previous one in which the scale of the surface wave magnitude was replaced by the body wave scale, and the range of magnitude to $m_b \geq 4.5$; while the previous figure had 780 events, this one has 1110 events. In order to compare the two graphs, the low seismicity regions of Figure 2 were plotted in Figure 3. As we can observe, the marked regions with an X that were not correlated with a great earthquake are no longer so significant and those associated to great earthquakes with $M_w \geq 7.7$ are still significant although not as much as in Figure 2.

SEISMICITY TEMPORAL FUNCTIONS

To observe some significant changes in the seismicity behavior, we can use seismicity temporal functions. For example, the earthquake number in each region, the released seismic energy in that region, the relative slip between plates, the deviations of these parameters regarding their average values in the long term, among others.

In Figure 4 we plot the earthquake number against time, for earthquakes with magnitude $M_S \geq 4.5$ occurred from 1969 to March, 2001 in the Mexican Pacific Coast. Each step of unitary height represents an earthquake while the longitude of the horizontal segments represent

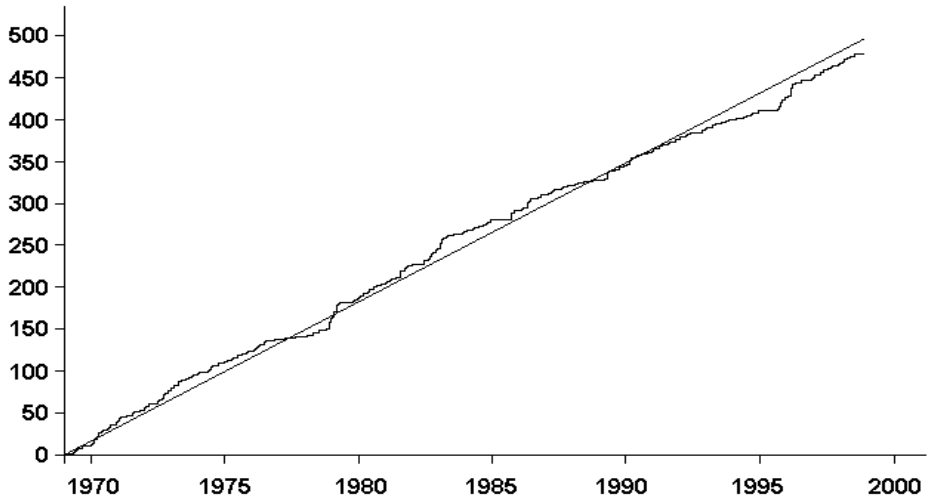

Figure 4. Number of earthquakes against time for earthquakes of magnitude $M_S \geq 4.5$ in the Mexican Pacific Coast.

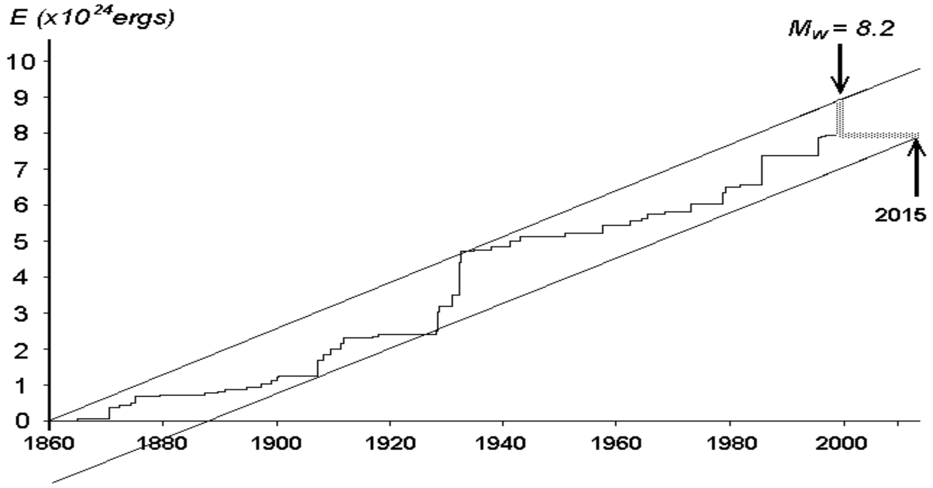

Figure 5. Released seismic energy against time, for earthquakes with $M_S \geq 4.3$ in the Mexican Pacific Coast.

the time between consecutive events. The earthquake number per unit of time has remained approximately constant during the last thirty years. The most important fluctuations that this ratio suffers, increments or decrements with respect to its mean value, represented by the slope of the straight line (see Figure 4), are possibly related with the occurrence of earthquakes of great magnitude.

The seismic potential of a region can be estimated using the graphs of released seismic energy against time. We use Eq. 8 to obtain the released seismic energy. In Figure 5 we show the graph of the released seismic energy for the region under study, considering only shallow earthquakes, with focus depth lower than 60 Km, and magnitude $M_W \geq 7.0$, from January 1, 1860 to March, 2001. Each vertical segment represents the magnitude of the earthquake energy while the horizontal segments represent the time between consecutive events. The parallel straight lines delimiting the graph suggest that for great time intervals, of the order of centuries, the released energy ratio per unit of time re-mains approximately constant, which is in agreement with the Gutenberg-Richter law $\dot{N}(M \geq M_0) = 10^{A+bM_0} = constant,$ for a fixed M_0, and with the empirical relation between magnitude and energy (Eq. 8). Such lines allow us to set lower limits to the total seismic energy that could be released in a certain moment (upper line) and the occur-

Table 3. Earthquakes occurred in the southwest of the Oaxaca state.

Magnitude M	Average recurrence times in years of great magnitude earthquakes $M_S \geq M$	
	Real	Calculated with the G-R law
7.0	2.5	2.8
7.5	5.4	4.7
7.6	7.9	7.8
7.7	13.3	13.1
7.8	17.5	22.0
7.9	33.1	37.2
8.0	77.5	63.2
8.1	There are not available data	108.9

rence date limit of the next earthquake of magnitude greater than 7.0 (lower line). So, according to this graph, if the whole energy could be released in 2001, the magnitude of the biggest earthquake that would take place would have a magnitude M_S of at least 8.2. While the maximum delay in the occurrence of the next earthquake with magnitude greater than or equal to 7.0 would be until the year 2015. However, we cannot discard the possible silent earthquake mentioned in the introduction that could partially release the Guerrero gap energy.

SEISMIC GAPS

Earthquakes of great magnitude occur close others with similar magnitude and fault area. On the other hand, it has been observed that the fault areas of big earthquakes are significantly overlapped with the adjacent ones. For example, the Southwest part of Oaxaca located between 16.1° - 17.0° N and 97.3° - 98.1° W has presented a recurrence of big earthquakes ($M_S \approx 7.5$) since 1854 (Table 3).

The average recurrence time is of 38 ± 4 years. Then, it could be expected that between 2002 and 2010 an earthquake of magnitude $M_S \approx 7.5$ could occur in this region. However, this does not have to happen in this way, because if we go back to the past, it would be expected that there could have been a great earthquake between 1812 and 1820. However, no earthquake with $M_S \approx 7.5$ occurred in that region between 1800 and 1853 (Singh et al., 1981).

In Mexico, there were regions belonging to the Pacific subduction area that had not experienced a great earthquake in approximately 30 years; such is the case of the gaps of Oaxaca (broken in 1978 by an earthquake of magnitude $M_w = 7.8$, Petatlan, Guerrero (broken in 1979 by an earthquake of $M_w = 7.6$), Michoacan (totally broken in 1985 by an earthquake of $M_w = 8.0$ and another of $M_w = 7.6$); the earthquake of Playa Azul $M_w = 7.3$ occurred in 1981 inside this gap that did not break it completely (UNAM, 1986), Ometepec Oaxaca (broken in 1995 by an earthquake of $M_w = 7.4$.) and finally the gap of Colima-Jalisco (broken partially in 1995 by an earthquake of $M_w = 7.9$). In Figure 6, we can observe the existing gaps at the beginning of 1980, together with the earthquakes of magnitude $M_w > 7.0$ occurred from 1940 to 1980. Only two of these five gaps survive at the moment: the gap of Guerrero and the gap of Tehuantepec. The last one has not produced strong earthquakes in the last two centuries, so its potential is ignored; probably the plates slip aseismically (Singh et al., 1981).

The gap of Guerrero, located between Petatlan and Acapulco is considered as a seismic gap of high potential, because since 1911 no earthquake of magnitude greater than 7.0 has taken place in it. Moreover, the San Marcos neighboring region, where it occurred the 1957 earthquake of magnitude $M_w = 7.7$, is considered at the present time as a mature gap. The enlarged gap of Guerrero could produce an earthquake of magnitude 8.1-8.4 (Singh and Mortera, 1991).

However, we remark that the possible silent 2002 earthquake must no be discarded.

PRECURSORY SEISMIC QUIESCENCE

It seems that this is the most observed precursory characteristic of earthquakes (Kanamori, 1981; Asada, 1982; Mogi, 1985, Wyss et al. 2005, Huang, 2008). Now, we will see that the big earthquakes of the last 30 years of the 20th century were preceded by well defined patterns of precursory seismic quiescence.

Oaxaca earthquake (1978)

The most notorious case of a seismic quiescence was the one that preceded the Oaxaca earthquake of Novem-

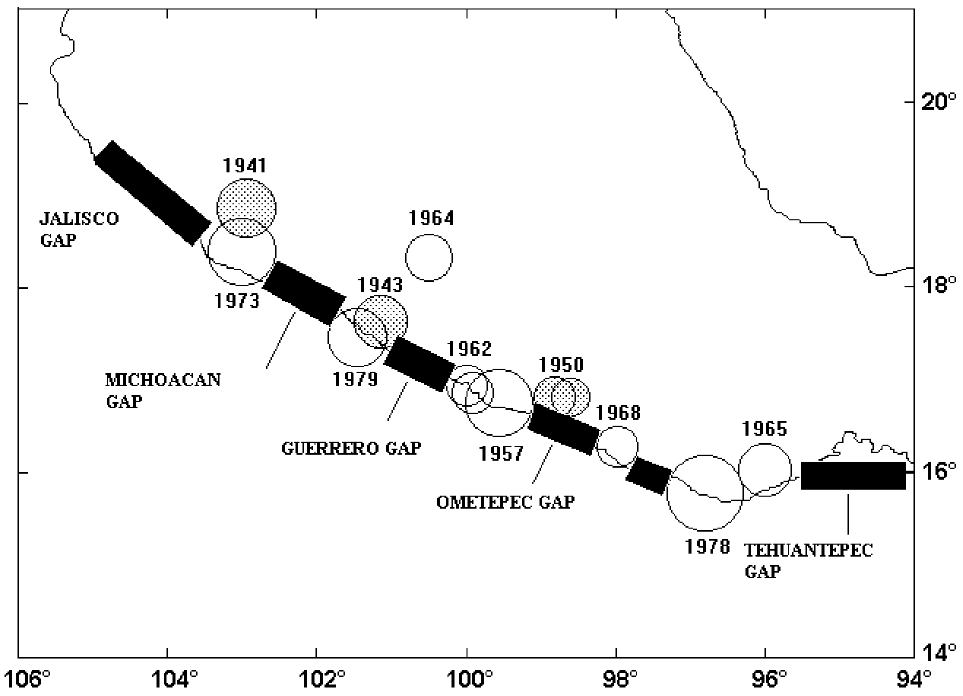

Figure 6. Earthquakes with $M_S \geq 4.3$ in the Mexican Pacific Coast occurred from 1940 to 1980 and seismic gaps in 1980.

ber 29, 1978 ($M_w = 7.8$). A segment of 270 Km of the Mexican subduction zone located between 95.5°-98.0° W almost presented an aseismic behavior (for earthquakes with $m_b \geq 3.0$) which began in June, 1973 and finished in December, 1977. After this stage the seismicity was renewed until the occurrence of the great earthquake. Based on this anomaly, Ohtake et al. published in 1977 the prediction of this earthquake, guessing right in its localization and magnitude (Ohtake et al., 1981). In Figure 7 the graph of the cumulative number of earthquakes is shown against time, for the region of Oaxaca located between 15°-17.5° N and 95.5°-98° W. As it can be observed, before 1974 the earthquakes occurred in a regular way, later the quiescence is observed until December, 1977, when the activity is renewed and finally, the main earthquake occurs; with aftershocks compensating the lack of earthquakes during the quiescence in such a way that the staggered graph approaches the expected value, represented by the straight line whose slope is the mean ratio (in the long term situation) of the number of earthquakes per year. After 1985, we can notice a stage of quiescence that remains until January 1990 when a great activity occurs. Finally, we can observe the stage of precursory quiescence to the earthquake of February 25, 1996 ($M_w - 7.0$). This region includes the fault areas of the earthquakes of 1965 ($M_w = 7.5$) and 1968 ($M_w = 7.3$), which can be considered at the present time as mature seismic gaps.

Michoacan earthquakes (1985)

Figure 8 shows the graph of the number of earthquakes against time for the region of Michoacan located between 16.5°-19.5°N and 101°-103.5°W. This region covers the fault areas of the earthquakes of Colima, $M_w = 7.7$ (January 30, 1973), Petatlan, $M_w = 7.6$ (March 14, 1979) and Michoacan, $M_w = 8.0$, $M_w = 7.6$ (September 19 and 20, 1985). As can be observed, the earthquakes of Petatlan (1979), Michoacan (1985) and the most recent, Michoacan (1997) are clearly preceded by an episode of seismic quiescence.

Colima Jalisco earthquake (1995)

On October 9, 1995, in front of the Colima and Jalisco coasts, the most recent great Mexican earthquake of magnitude $M_w = 8.0$ occurred, comparable to that of 1985 and to the one occurred in Jalisco in 1932, inside the Jalisco gap (Singh et al., 1981). As the previous earthquakes this was also preceded by an episode of seismic quiescence as can be observed in Figure 9. The

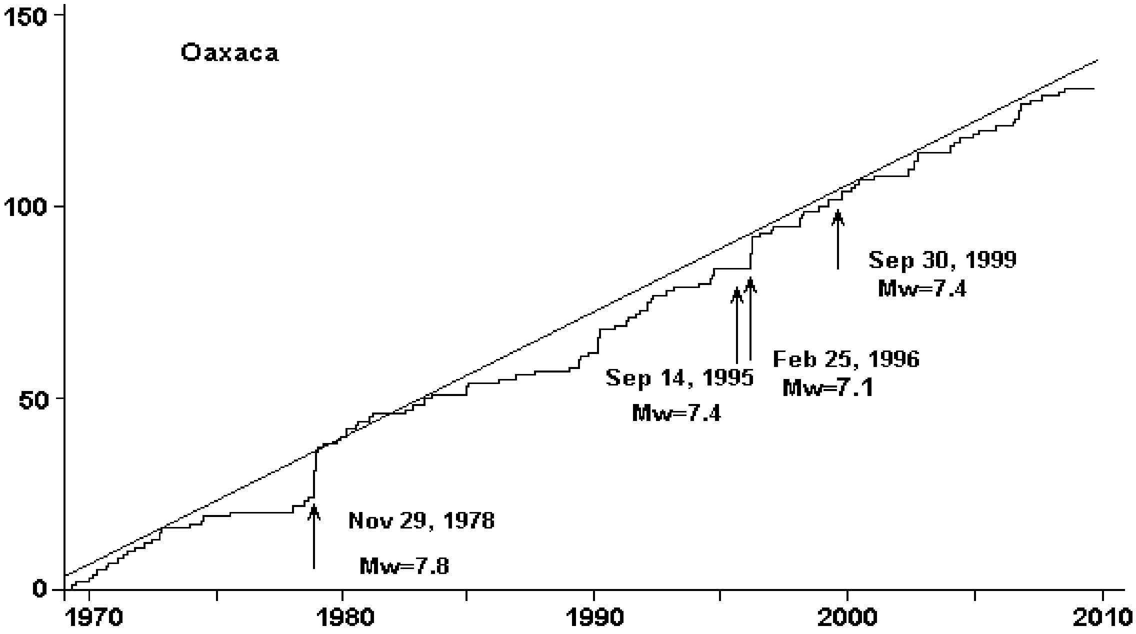

Figure 7. Earthquake number against time ($M_S \geq 4.3$), Oaxaca region. The earthquakes depth is lower than or equal to 60 km, and they are located between the 15.0°-17.5°N and the 95.5°-98.0°W, from January, 1, 1969 to December 31, 2009. The average annual frequency is 3.4 earthquakes per year.

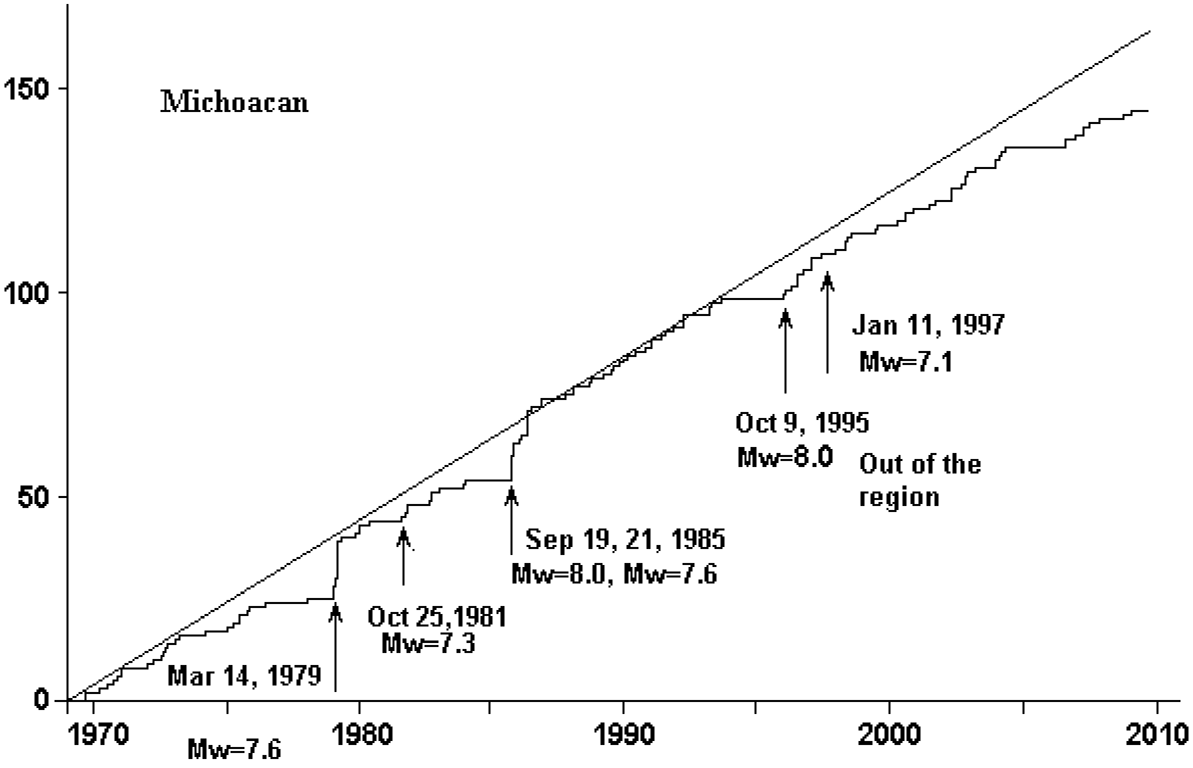

Figure 8. Earthquake number against time ($M_S \geq 4.3$), Michoacan region. The earthquakes depth is lower than or equal to 60 km, and they are located between the 16.5°-19.5°N and the 101.0°-103.5°W, from January, 1, 1969 to December 31, 2001. The average annual frequency is 4.0 earthquakes per year.

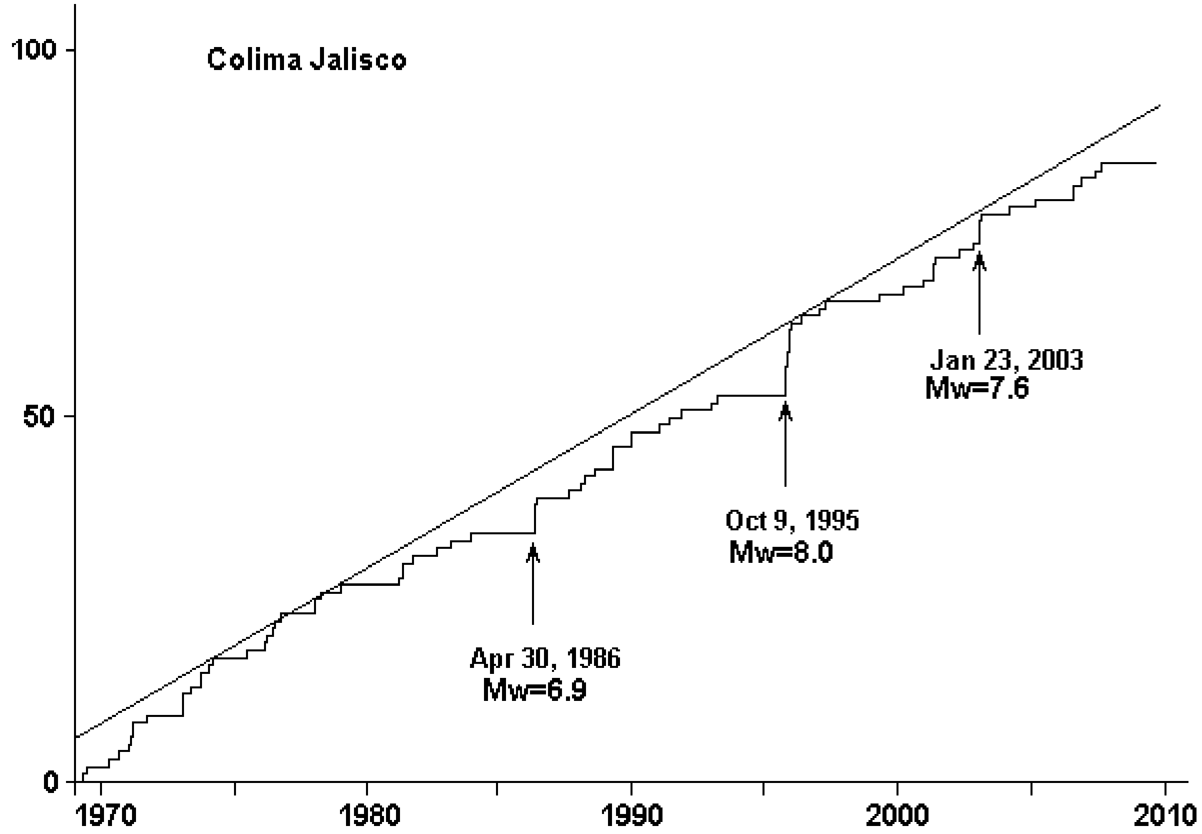

Figure 9. Earthquake number against time ($M_S \geq 4.3$), Colima-Jalisco region. The earthquakes depth is lower than or equal to 60 km, and they are located between the 17.8°-19.8° N and the 103.0°-105.8° W, from January, 1, 1969 to December 31, 2009. The average annual frequency is 2.4 earthquakes per year.

region Colima-Jalisco is located between 17.8°-19.8° N and 103° - 105.8° W. We can observe that the aftershocks compensated the lack of events during the stage of quiescence.

Guerrero seismic gap

At the moment the enlarged gap of Guerrero, located between 16.1°-17.8° N and 99.3°-101.1° W, presents an apparent unusual seismic quiescence, which began at the beginning of 1985, however on April 25, 1989, a moderate earthquake occurred in this region with magnitude $M_w = 6.8$, which produced aftershocks of magnitude $M_S \geq 4.3$, but that did not compensate the previous quiescence (Figure 10). In the beginning of 1994 another stage of quiescence which we could associate to the earthquake of September 14, 1995 ($M_w = 7.4$) occurred in the gap of Ometepec, which is in the vicinity of this region; the quiescence finishes approximately at the beginning of 1996.

The previous graphs show us that all the great Mexican earthquakes with $M_w = 7.5$ occurred since 1978 up to December 2009 were preceded for an episode of seismic quiescence. As of December 2009, the regions of Oaxaca, Michoacan and Colima-Jalisco do not present this pattern in advance. The region of the Guerrero gap is of special interest, since it could produce an earthquake similar to the one of 1985 in a not very distant future.

DISCUSSION

Practically all the seismicity researchers agree that earthquake prediction is not possible at present and this is a highly controversial issue. However, scientists are continuing to look for feasible precursors of earthquakes, and there is a certain agreement in the sense that the occurrence of a large earthquake would change the seismicity before and after the event. There are different approaches to analyze and evaluate possible episodes of seismic quiescence. Although the methods we used in this work have limitations, they can give us valuable

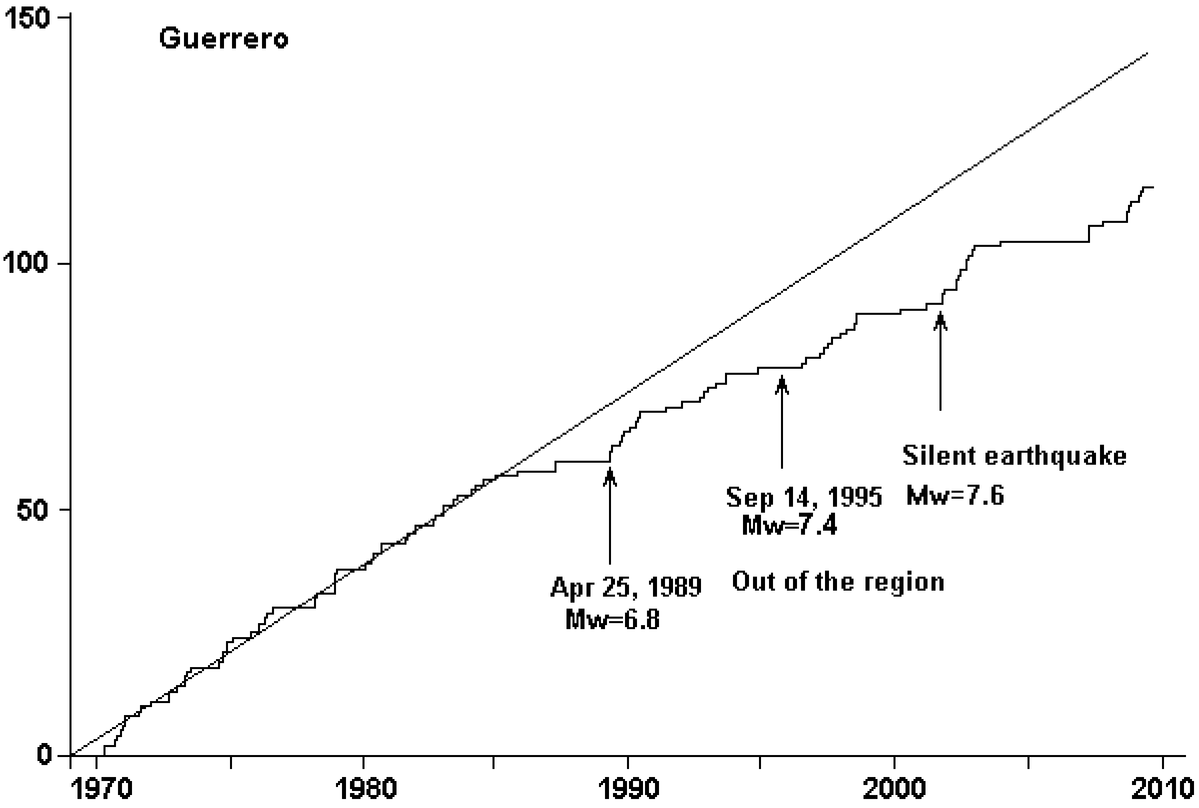

Figure 10. Earthquake number against time ($M_S \geq 4.3$), Guerrero region. The earthquakes depth is lower than or equal to 60 km, and they are located between the 16.1°-17.8°N and the 99.3°-101.1° W, from January, 1, 1969 to December 31, 2009. The average annual frequency is 3.5 earthquakes per year.

information. As we do not have all the data we would like to have, we think that case histories are one of the most important ways to learn about precursory seismic quiescence. As we can see in the seismicity space time plots (Figures 2 and 3) and in the staircase plots of the cumulative seismicity there are false alarms, but this problem occurs because at present, we do not know how to distinguish between precursory and other quiescences (Wyss et al., 2004), there are documented main shocks without precursory quiescences and there are quiescences that are not precursory of a main shock.

The results shown in Figure 10 are controversial, because apparently there are two different behaviors, before and after 1985. The staircase plot is completely separated from the straight line that bounds the first part of the graphic (before 1985), so we can conclude that there is a great quiescence in the Guerrero zone, there is a mature gap in Guerrero so the previous conclusion is possible. But if we plot the cumulative seismicity in this zone from 1990 to 2009 (Figure 11) the situation does not seem to be so problematic. In this figure we show the silent earthquake reported by Iglesias et al. (2004) and Franco et al. (2005), although more research and analysis are needed in order to understand the effect of this kind of earthquakes. In the cumulative seismicity, there is a possibility that silent earthquakes can contribute to the release of energy in this seismogenic zone and probably the expected great earthquake in this gap could be of a lower magnitude. In fact, Franco et al. (2005) have reported not one but three silent earthquakes in this region from 1995 to 2002, with the last one having the greatest magnitude $M_w \sim 7.5 \text{ or } 7.6$. There is other kind of events in this region and we are not very sure how to include them in this kind of analysis.

Conclusions

At present no precursory phenomenon of earthquakes is completely and unambiguously identified. Perhaps the non linear nature of the crust's dynamics implies a high sensitivity over initial conditions avoiding, therefore, a systematic reproduction of the earthquake preparation processes. Nevertheless this difficulty, many researchers

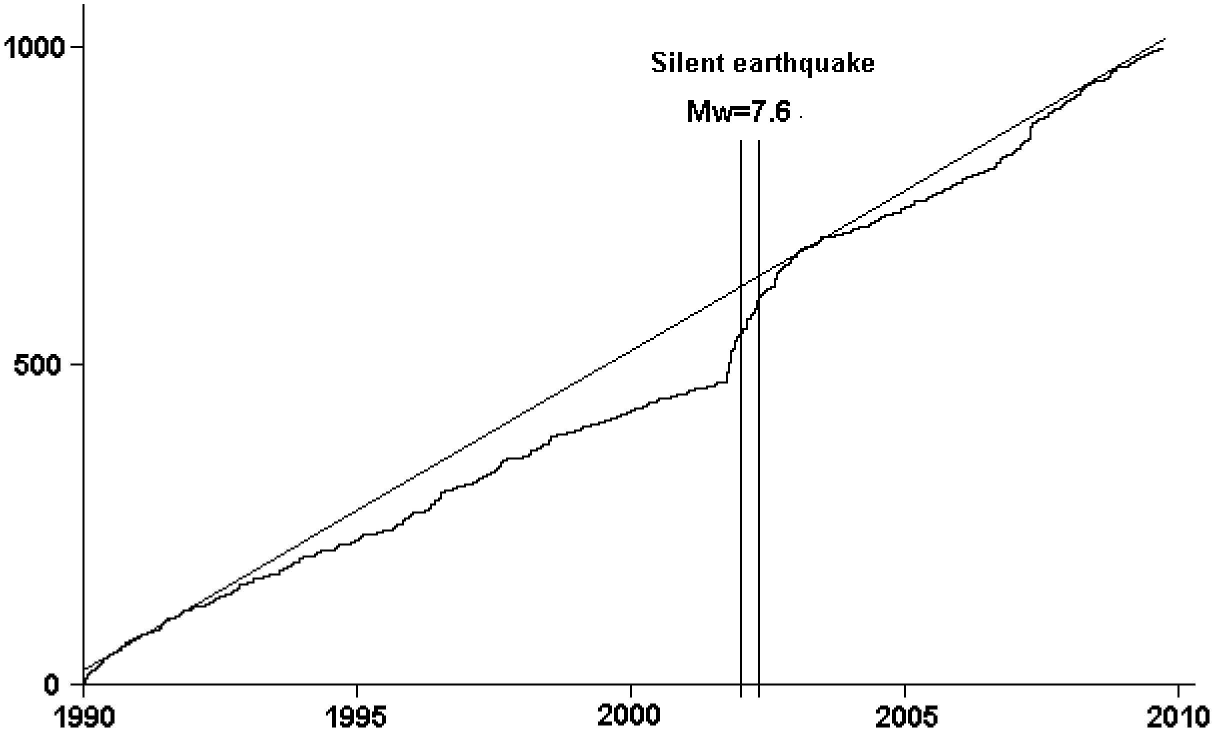

Figure 11. Earthquake number against time ($4 \leq M_C \leq 8.2$), Guerrero region. The earthquakes depth is lower than or equal to 60 km, and they are located between the 16.1°-17.8° N and the 99.3° - 101.1°W, since January, 1, 1990 to December 31, 2009. The average annual frequency is 49.4 earthquakes per year.

look for approximate patterns from the point of view of certain statistical properties of seismic variables. This is the case of the so called quiescence patterns, which have been observed before the occurrence of great earthquakes in several seismic zones around the world.

In this work we have presented spatial and temporal plots as well as cumulative seismic plots of the Mexican Pacific Coast seismicity. The patterns we found show in a qualitative way that there were precursory seismic quiescences for the greatest Mexican earthquakes over the last 40 years. This statement is based on the analysis of such graphs and in a reliable and complete seismic catalog for certain magnitude intervals and time intervals that have been calculated in this work. In particular, the master catalog is complete in the last 40 years for earthquakes with magnitudes $M_w \geq 4.3$.

Certainly, the patterns we have found have their limitations. In the first method in which we obtain temporal and spatial seismicity plots, the analysis that is performed is visual and certainly it does not show uniqueness. Therefore it does not give quantitative information of the importance of the quiescence, the region size is not well defined and the method depends on the threshold magnitude. In the case of the cumulative seismicity plots, the studied region is proposed by the observer in an area that contains the seismic gap and therefore its size is variable; the historical seismicity rate (the average number of earthquakes per year) depends on the reliability and completeness of the available catalogs and it also depends on the threshold magnitude. All these limitations are related with the fact that there does not exist a formal definition of precursory seismic quiescence. In the cumulative seismic plots we have plotted a straight line that cannot be surpassed by the staircase plot of the cumulative seismicity; whose slope is the historical seismicity rate. Our hypothesis is that such a behavior will continue in the long term. To this respect, in our simulation works on the seismic fault dynamics by means of the Olami, Feder and Christensen (OFC) model (1992) (which is a very simple model but has reproduced qualitatively many properties of real seismicity), we have shown that in the very long term there exists a straight line that acts as an "attractor" of the cumulative seismicity (Angulo-Brown and Muñoz-Diosdado, 1999, Muñoz-Diosdado and Angulo Brown, 1999).

However, the seismic precursory quiescence of great earthquakes that are reported in this work seems to be well defined and have been confirmed with more formal algorithms as Schreider's (1990). A very important case is the Guerrero region, which contains the Guerrero gap, which has been recognized as a mature gap. It is because, as we show in Figure 10, the seismicity deficit

Table 4. Catalog of Mexican greatest earthquakes with magnitude M_S or $M_W \geq 7.0$ and depth $h \leq 60$ km.

Event	Year	Month	Day	h	Min	S	Latitude (°N)	Longitude (°W)	Depth (km)	MS	MO $\times 10^{20}$ Nm	Mw
1	1806	03	25				18.9	103.8	<60	7.5	1.79	7.5
2	1818	05	31				19.1	103.6	<60	7.7	3.08	7.7
3	1820	05	04				17.2	99.6	<60	7.6	2.35	7.6
4	1837	11	22				20.0	105.0	<60	7.7	3.08	7.7
5	1845	03	09				16.6	97.0	<60	7.5	1.79	7.5
6	1845	04	07				16.6	99.2	<60	8.1	9.11	8.0
7	1854	05	05				16.3	97.6	<60	7.7	3.08	7.7
8	1858	06	19				19.6	101.6	<60	7.5	1.79	7.5
9	1864	10	03				18.7	97.4	<60	7.3	1.04	7.3
10	1870	05	11				15.8	96.7	<60	7.9	5.30	7.8
11	1872	03	27				15.7	96.6	<60	7.4	1.37	7.4
12	1874	03	16				17.7	99.1	<60	7.3	1.04	7.3
13	1875	02	11				21.0	103.8	<60	7.5	1.79	7.5
14	1875	03	09				19.4	104.6	<60	7.4	1.37	7.4
15	1879	05	17				18.6	98.0	<60	7.0	0.46	7.1
16	1882	07	19				17.7	98.2	>60	7.5	1.79	7.5
17	1887	05	29				17.2	99.8	<60	7.2	0.80	7.3
18	1889	09	06				17.0	99.7	<60	7.0	0.46	7.1
19	1890	12	02				16.7	98.6	<60	7.2	0.80	7.3
20	1894	11	02				16.5	98.0	<60	7.4	1.37	7.4
21	1897	06	05				16.3	95.4	<60	7.4	1.37	7.4
22	1899	01	24	23	43		17.0	98.0	<60	7.5	1.79	7.5
23	1900	01	20	06	33	30	20.0	105.0	<60	7.4	1.37	7.4
24	1900	05	16	20	12		20.0	105.0	<60	6.9	0.35	7.0
25	1907	04	15	06	08	06	16.7	99.2	<60	7.7	7.17	7.9
26	1908	03	26	23	03	30	16.7	99.2	<60	7.6	1.98	7.5
27	1908	03	27	03	45	30	17.0	101.0	<60	7.0	0.74	7.2
28	1909	07	30	10	51	54	16.8	99.9	<60	7.3	2.48	7.6
29	1909	07	31	18	43	10	16.6	99.5	<60	6.9	0.35	7.0
30	1911	06	07	11	02	42	17.5	102.5	<60	7.7	2.83	7.6
31	1911	12	16	19	14	18	16.9	100.7	50	7.6	2.35	7.6
32	1916	11	21	06	25	24	18.0	100.0	<60	6.8	0.27	7.0
33	1917	12	29	22	50	20	15.0	97.0	<60	6.9	0.85	7.3
34	1928	03	22	04	17	03	15.67	96.10	<60	7.5	1.79	7.5
35	1928	06	17	03	19	28	16.33	96.7	<60	7.8	7.05	7.9
36	1928	08	04	18	28	17	16.20	97.52	<60	7.4	1.37	7.4
37	1928	10	09	03	01	08	16.50	96.76	<60	7.6	2.35	7.6
38	1931	01	15	01	50	40	16.1	96.6	40	7.8	4.69	7.8
39	1932	06	03	10	36	52	19.40	104.67	<60	8.2	12.18	8.1
40	1932	06	18	10	12	10	18.95	104.42	<60	7.8	5.8	7.8
41	1934	11	30	02	05	16	19.0	105.3	<60	7.0	0.45	7.1
42	1937	12	23	13	18	02	16.79	98.63	<60	7.5	1.63	7.5
43	1941	04	15	19	09	51	18.85	102.94	<60	7.7	2.94	7.6
44	1943	02	22	09	20	45	17.62	101.15	<60	7.5	1.56	7.5
45	1950	12	14	14	15	52	16.81	98.82	18	7.3	0.89	7.3
46	1957	07	28	08	40	08	16.74	99.55	20	7.5	4.21	7.7
47	1962	05	11	14	11	53	16.93	99.99	20	7.2	0.90	7.3
48	1962	05	19	14	58	15	16.85	99.92	20	6.9	0.80	7.3

Table 4. Contd.

49	1964	07	06	07	22	12	18.31	100.50	55	6.3mb	1.15	7.4
50	1965	08	23	19	46	03	16.02	96.00	16	7.6	1.56	7.5
51	1968	08	02	14	06	42	16.27	97.98	16	7.4	1.00	7.3
52	1973	01	30	21	01	14	18.38	103.00	17	7.5	3.00	7.7
53	1978	11	29	19	52	49	15.77	96.80	18	7.8	4.25	7.8
54	1979	03	14	11	07	11	17.45	101.46	14	7.6	2.25	7.6
55	1981	10	25	03	22	15	17.93	102.10	24	7.3	0.97	7.3
56	1982	06	07	06	52	36	16.25	98.25	20	6.9	0.27	7.0
57	1982	06	07	10	59	39	16.32	98.45	11	7.0	0.25	6.9
58	1985	09	19	13	17	49	18.14	102.71	16	8.1	11.3	8.0
59	1985	09	21	01	37	12	17.6	101.8	20	7.6	2.69	7.6
60	1986	04	30	07	07	23	18.40	102.95	26	7.0	0.23	6.9
61	1995	09	14	14	04	30.5	16.31	98.88	22	7.2	1.15	7.4
62	1995	10	09	15	35	51.0	18.74	104.67	5	7.6	2.7	7.9
63	1996	02	25	03	08	13.9	15.83	98.25	3	6.8	0.3	7.0
64	1997	01	11	20	28	27.3	17.91	103.04	16	6.8	0.45	7.1
65	1999	09	30	11	31	14.0	15.88	97.07	42	7.5	1.2	7.4
66	2000	08	09	06	41	47.0	17.97	102.66	16	6.1	6.4	7.0
67	2003	01	21	20	06	34.0	18.60	104.22	9	6.5	7.5	7.6

in this gap is greater than in others and an earthquake of great proportions could take place in the following years in that region but at the same time we have to understand the effects of silent earthquakes in the seismicity of this region. We need to have more complete and reliable catalogs in wider magnitude ranges and in greater time intervals to be able to give a definitive confirmation of the utility of such methods.

Appendix A. Catalog of Mexican great earthquakes

In this Appendix we show the earthquake catalog of magnitude M_S or M_w greater than or equal to 7.0, occurred between January, 1806 and June, 2009, in the Mexican subduction zone and vicinities. The epicenters of these earthquakes are located between 14°-21° N and 94°-106° W; the focus depth is smaller or equal to 60 km. The catalog includes: origin time, epicenter localization, seismic focus depth (in kilometers), magnitude of superficial waves, seismic moment and the moment seismic magnitude. For all the events, the origin time is universal (Greenwich mean time). The moment seismic magnitude is determined from the relationship $M_w = \frac{2}{3}(log M_0 - 9.0)$ where M_0 is the seismic moment in Nm, obtained from superficial waves. The catalog is probably complete for $M_w \geq 7.0$ since 1860; and for $M_w \geq 7.5$ since 1864. The events occurred in the 19th century were not registered by instruments, with the exception of the last one, their localization and magnitude were estimated, the localization of the epicenters can be affected by an error of $\pm 1°$ and the magnitude for an error of ± 0.3. At the end of the table we give the references where the details of time, localization, depth, magnitude and seismic moment where reported.

Events description

Events 1-21: Time, localization and magnitude reported by Singh et al. (1981), except for the 6-th event. Anderson et al. (1989) assigned a magnitude $M_w = 8.1$ to the 6-th event. According to Singh et al. all the events have depths $h \leq 60$ km, however, Gonzalez-Ruiz and McNally (1988) reported a depth $h \geq 60$ km for the 16-th event. For these events, the seismic moment is calculated with the relationship from Anderson et al. (1989),

$$log M_0 = 1.17 M_S + 18.426.$$

Event 22: Time, localization, depth and magnitude by Abe and Noguchi (1983); the seismic moment by Anderson et al. (1989). Singh et al. (1981) reported for this event latitude 17.1°N, longitude 100.5° W and $M_w = 7.9$.

Event 23: Time, localization, depth and magnitude by Abe and Noguchi (1983); the seismic moment by Anderson et al. (1989). Kanamori and Abe (1979) reported $M_S = 7.9$.

Event 24: Time, Localization, depth and magnitude by Abe and Noguchi (1983); the seismic moment by Anderson et al. (1989).

Event 25: Localization by Figueroa (1970); time, depth and magnitude $M_S = 7.7$ by Abe and Noguchi (1983). Geller and Kanamori (1977) reported $M_S = 8.0$. We take the seismic moment as the average of the values reported by of Anderson et al. (1989) and Singh et al. (1982).

Event 26: Localization by Figueroa (1970); time, depth and magnitude $M_S = 7.6$ and seismic moment by Anderson et al. (1989). Gutenberg and Richter (1954) reported a depth of 80 km.

Event 27: Localization by Figueroa (1970); time, depth and magnitude $M_S = 7.0$ by Abe and Noguchi (1983). Seismic moment by Anderson et al. (1989).

Event 28: Localization by Figueroa (1970); time, depth and magnitude $M_S = 7.3$ by Abe and Noguchi (1983). Geller and Kanamori (1977) reported $M_S = 7.4$. Seismic moment by Anderson et al. (1989).

Event 29: Localization by Figueroa (1970); time, depth and magnitude $M_S = 6.9$ by Abe and Noguchi (1983). Singh et al. (1989) reported $M_S = 6.4$. Seismic moment by Anderson et al. (1989).

Event 30: Time, localization, depth and magnitude by Gutenberg and Richter (1954); $M_S = 7.7$ by Abe and Noguchi (1983). Seismic moment by Anderson et al. (1989).

Event 31: Localization by Figueroa (1970); time, depth and magnitude $M_S = 7.6$ by Abe and Noguchi (1983). Seismic moment by Anderson et al. (1989).

Event 32: Time, localization, depth, magnitude $M_S = 6.8$ and seismic moment by Anderson et al. (1989).

Event 33: Time, localization, depth, magnitude $M_S = 6.9$ and seismic moment by Anderson et al. (1989).

Event 34: Time by Kelleher et al. (1973); localization by Núñez-Cornú and Ponce (1989); depth and magnitude $M_S = 7.5$ by Abe (1981). Seismic moment by Anderson et al. (1989).

Event 35: Time and localization by Kelleher et al. (1973); depth and magnitude $M_S = 7.8$ by Abe (1981). The seismic moment is an average of the values reported by Wang et al. (1982) and Brune an Engen (1969).

Event 36: Time by Kelleher et al. (1973); localization by Núñez-Cornú and Ponce (1989); magnitude $M_S = 7.4$ by Abe (1981). Seismic moment by Anderson et al. (1989).

Event 37: Time by Kelleher et al. (1973); localization by Núñez-Cornú and Ponce (1989); magnitude $M_S = 7.6$ by Abe (1981). Seismic moment by Anderson et al. (1989).

Event 38: Time and localization by Kelleher et al. (1973); depth by Singh et al. (1985); magnitude $M_S = 7.8$ by Abe (1981). The seismic moment is an average of the values reported by Singh et al. (1985), Wang et al. (1982) and Brune and King (1967).

Event 39: Time by of Kelleher et al. (1973); localization by Singh and Mortera (1991); $M_S = 8.2$ by Geller and Kanamori (1977). The seismic moment is an average of the values reported by Wang et al. (1982), Brune and King (1967) and Brune and Engen (1969).

Event 40: Time by Kelleher et al. (1973); localization by Singh and Mortera (1991); $M_S = 7.8$ by Geller and Kanamori (1977). The seismic moment is the average of the values reported by Wang et al. (1982) and Brune and King (1967).

Event 41: Time, localization and depth by Kelleher et al. (1973); magnitude $M_S = 7.0$ by Abe (1981). Seismic moment by Anderson et al. (1989).

Event 42: Time, localization and depth by Nishenko and Singh (1987); $M_S = 7.5$ by Abe (1981). Seismic moment by Anderson et al. (1989).

Event 43: Time, localization and depth by Kelleher et al. (1973); magnitude $M_S = 7.9$ by Abe (1981). Seismic moment by Anderson et al. (1989).

Event 44: Time, localization and depth by Kelleher et al. (1973); magnitude $M_S = 7.5$ by Abe (1981). Seismic moment by Anderson et al. (1989).

Event 45: Time, localization and magnitude $M_S = 7.3$ by Nishenko and Singh (1987); depth $h = 18$ km by Gonzalez-Ruiz and McNally (1988). Seismic moment by Anderson et al. (1989).

Event 46: Time, localization and depth by Nishenko and Singh (1987); $M_S = 7.5$ by Abe (1981). The seismic moment is an average of the values reported by Singh et al (1982) and Anderson et al. (1989).

Event 47: Time, localization, depth and magnitude $M_S = 7.2$ by Nishenko and Singh (1987). Seismic moment by Anderson et al. (1989).

Event 48: Time, localization, depth and magnitude $M_S = 6.9$ by Nishenko and Singh (1987). Seismic moment by Anderson et al. (1989).

Event 49: Time, localization, depth and magnitude $m_b = 6.3$ by Pardo (1993). Seismic moment by Gonzalez-Ruiz (1986).

Event 50: Time, localization and depth by Pardo (1993); magnitude $M_S = 7.6$ by Abe (1981). The seismic moment is an average of the values reported by Chael and Stewart (1982) and Brune and King (1967).

Event 51: Time, localization and depth by Pardo (1993); magnitude $M_S = 7.4$ by EDR (USGS). Seismic moment by Chael and Stewart (1982).

Event 52: Time, localization and depth by Pardo (1993); magnitude $M_S = 7.5$ by EDR (USGS). Seismic moment by Reyes et al. (1979).

Event 53: Time, localization and depth by Pardo (1993); magnitude $M_S = 7.8$ by EDR (USGS). The seismic moment is an average of the values reported by Chael and Stewart (1982) and Dziewonski et al. (1987b).

Event 54: Time, localization and depth by Pardo (1993); magnitude $M_S = 7.6$ by EDR (USGS). The seismic moment is an average of the values reported by Chael and Stewart (1982), Dziewonski et al. (1987c) and Priestley and Masters (1986).

Event 55: Time, localization and depth by Pardo (1993);

magnitude $M_S = 7.3$ by EDR (USGS). The seismic moment is an average of the values reported by Priestley and Masters (1986), LeFevre and McNally (1985), Dziewonski et al. (1988) and Astiz et al. (1987).

Event 56: Time, localization and depth by Pardo (1993); magnitude $M_S = 6.9$ by EDR (USGS). The seismic moment is an average of the values reported by Astiz and Kanamori (1984) and Dziewonski et al. (1983).

Event 57: Time, localization and depth by Pardo (1993); magnitude $M_S = 7.0$ by EDR (USGS). Seismic moment by Astiz and Kanamori (1984).

Event 58: Time and localization by UNAM Seismology Group (1986); depth by Anderson et al. (1989); magnitude $M_S = 8.1$ by EDR (USGS). The seismic moment is an average of the values reported by Priestley and Masters (1986), Eissler et al. (1986), Dziewonski et al. (1986b), Riedesel et al. (1986) and Ekström and Dziewonski (1986).

Event 59: Time and localization by UNAM Seismology Group (1986); depth by Anderson et al. (1989); magnitude $M_S = 7.6$ by EDR (USGS). The seismic moment is an average of the values reported by Priestley and Masters (1986), Eissler et al. (1986), Dziewonski et al. (1986a), Riedesel et al. (1986) and Astiz et al. (1987).

Event 60: Time, localization and depth by Pardo (1993); magnitude $M_S = 7.0$ by EDR (USGS). The seismic moment is an average of the values reported by Pardo (1993) and Dziewonski et al. (1987).

Events 61-67: Time, localization and depth by UNAM, SSN (1988 - 2010); Seismic moment and magnitude M_S, M_w by Harvard CMT Catalog (2010).

ACKNOWLEDGMENTS

We acknowledge EDD, EDI and COFFA -IPN for partial support.

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