Identification of events of seismic quiescence in the Pacific Mexican coast

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SUMMARY:
We have designed an algorithm for identification of patterns of significant seismic quiescence by using the definition of seismic quiescence proposed by Schreider (1990). This algorithm shows the area of quiescence where an earthquake of great magnitude will probably occur. We apply our algorithm to the earthquake catalogue of the Mexican Pacific coast located between 14^o and 21^o of North latitude and 94^o and 106^o West longitude; with depths less or equal to 60 km and magnitude greater or equal to 4.2, which occurred from September, 1965 until September, 2011. We have found significant patterns of seismic quietude before the earthquakes of Oaxaca (November 1978, Mw = 7.8), Petatlán (March 1979, Mw = 7.6), Michoacán (September 1985, Mw = 8.0, and Mw = 7.6) and Colima (October 1995, Mw = 8.0). Moreover, since the 2000 year, we have found well-defined seismic quiescence in the Guerrero seismic-gap, which are correlated with the occurrence of silent earthquakes in 2002 and 2006, recently discovered by GPS technology. Finally, we identified an episode of seismic quiescence in the Guerrero state in 2011, which ends with the occurrence of moderate earthquakes of magnitude greater than 5.0 and it suggests the occurrence of another earthquake, probably silent, in the end of 2011 or at the beginning of 2012.

Keywords: Seismic quiescence, Schreider algorithm, Silent earthquake

1. INTRODUCTION

The seismic quiescence before the occurrence of great earthquakes has been leaning out as a phenomenon statistically significant, reason why it has been considered as one of the more promising intermediate term precursors in the search for earthquake prediction. The precursory seismic quiescence has been detected in practically all the world seismic regions independently of its tectonic structure (Lay, Kanamori and Ruff, 1982; Wyss and Habermann, 1988; Schreider, 1990). Many authors have discussed that the quiescence can be identified by two methods (Ohtake et al., 1977; McNally, 1981; Habermann, 1982; Schreider, 1990). First, the arithmetic method in which we show in a certain region the variations of a seismicity temporary function. This region presents a seismic quiescence if the function or its derivatives are smaller than certain threshold values, in some time interval. Unfortunately, this arithmetic method does not have a formal approach to define the boundaries of the considered area. The second one, the so-called geometric method, is related with the second class gap patterns and with the donut pattern (Mogi, 1979 and 1985). The quiescence is revealed by a visual analysis of the epicenter density of the adjacent regions. Such seismic quiescence is seismic regions with few events, with frontiers limited by epicentres or with natural boundaries.

To try to formalize the concept of precursory seismic quiescence Schreider (1990) synthesized some elements of the two previous methods. In the Schreider algorithm a seismic quiescence is a time interval in which a function that gives an average value of the time separation between consecutive events that fall in a circular region, takes abnormally big values. This function depends on space and time and it assigns a value for the local seismicity level to each point on the seismic region. Displacing the exploration circle on each point of the region is how we can determine the region that presents a significant seismic quiescence.

2. SCHREIDER ALGORITHM

A reliable and complete earthquake catalog is required for the application of the algorithm with the same magnitude scale for all the events. It is chosen a magnitude as minimum threshold. A circle with radius R is chosen with center in some arbitrary point of the seismic region. Then, in the circular exploration region we calculate the function

$$T'(n) = t(n) - t(n-1) , \tag{2.1}$$

where $t(n)$ is the occurrence time of the n-th earthquake inside the circular region, with magnitude M $\geq M_{min}$. The function *T'* is the time between consecutive events that can be assigned to each point of the seismic region; small values of *T'* indicate that earthquakes occur frequently, and big values of *T'* correspond to low seismic activity. A smoothness procedure for the function is applied calculating the convolution function of *T'* in each point with the Laplace function

$$f(n,s) = \frac{1}{s\sqrt{2\pi}} exp\left(-\frac{n^2}{2s^2}\right) , \tag{2.2}$$

where $n = 1, 2, 3, \ldots$ and s is the smoothness parameter. The k-th seismic event is related with the convolution

$$T(k) = \sum_{n=0}^{l} T'(k-n) f(n,s) , \tag{2.3}$$

the limit l is determined when the function $f(n, s)$ is approximately zero. Thus, the function $T(k)$ is determined by three parameters: M_{min}, R and s, which are chosen in an arbitrary way. To identify a period of seismic quiescence it is necessary to know the average value of $T(k)$ calculated in a big time interval, we consider that this value is stable. The average of $T(k)$ is given by

$$\overline{T} = \frac{1}{N} \sum_{k=1}^{N} T(k) , \tag{2.4}$$

where N is the total number of earthquakes with $M \geq M_{min}$ that fall inside the exploration circle. The standard deviation is calculated as

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{k=1}^{N} \left[T(k) - \overline{T} \right]^2} . \tag{2.5}$$

We calculate again the $\overline{T}$ value but now with those values of $T(k)$ within the interval $\overline{T} \pm 2\sigma$; with this procedure we eliminate approximately 5% of the values that are more deviated of the average, in this way we obtain a more stable value of $\overline{T}$. The σ value remains the same. Because of the temporary convolution function $T(k)$ has an approximately Gaussian distribution, Schreider considered that the values of $T(k)$ greater than $\overline{T} \pm 3\sigma$ are abnormally big, and therefore we can say that a point with coordinates (φ, λ) (the center of the exploration circle) presents an abnormal seismic quiescence if $T(k) \geq \overline{T} \pm 3\sigma$. This is the approach that indicates if a point in a seismic region presents a seismic quiescence; to pass to the formal determination of the area that shows a quiescence, we have to sweep the whole seismic region with an exploration circle and to mark those points that present the quiescence.

3. APPLICATION OF SCHREIDER ALGORITHM

3.1 The convolution function

We apply the Schreider algorithm to the seismic region of the Pacific Mexican coast, located between the 14 and 21°N and the 94 and 106°W (figure 1), we consider earthquakes with depths less or equal to 60 Km, and with magnitude $M_S \geq 4.3$. We use exploration circles with radius 300 Km, the magnitude threshold is $M_{min} = 4.3$ and the smoothness parameter $s = 2$. We take $M_{min} = 4.3$ because it is the smallest value for which our catalog is complete and reliable since 1969 (Rudolf et al., 2010). However, our graphs of temporary convolution begin on January 1, 1965 because the first data in the time series are not plotted; they are used to calculate the convolution. In figures 2, 3, 4 and 5 we show the temporary convolution function against time for the four circular exploration regions that are shown in figure 1. In each graph the inferior horizontal line represents the convolution function mean value, while the superior horizontal line represents the average plus three times the standard deviation; the function picks that surpass this line represent a significant seismic quiescence. In the first graph (figure 2) the exploration circle with center in 16.5°N and 97.0°W completely covers the Oaxaca state.

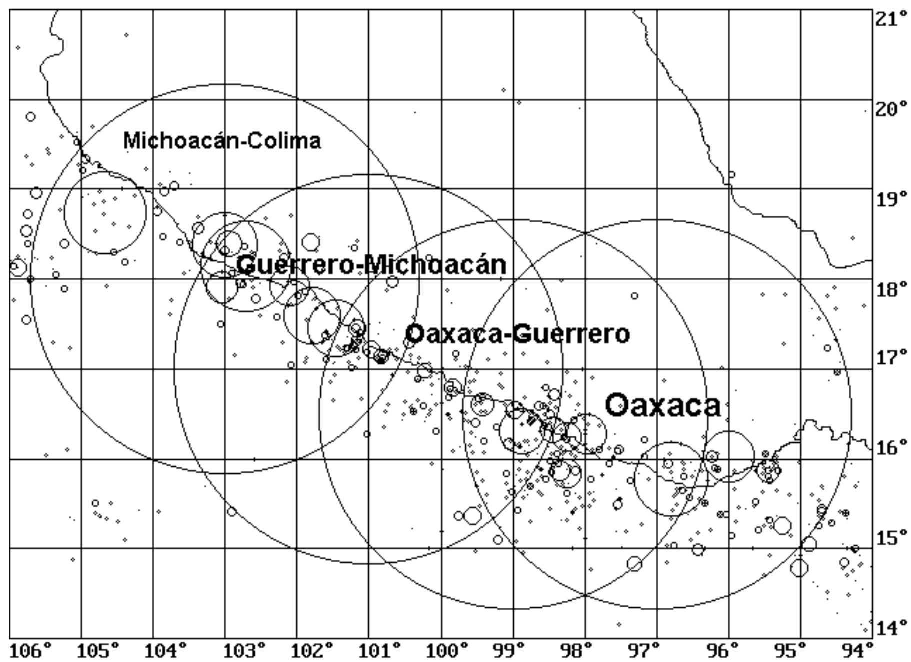

Figure 1. Seismic region of the Pacific Mexican coast, showed circular exploration regions used to calculate the convolution function. Other small circles represent earthquakes occurred between the years 1965 and 2001.

Clearly we can observe an important previous quiescence to the earthquake of November 29, 1978 of magnitude $M_W = 7.8$; the quiescence finishes with a stage of renewal of the activity that lasts almost one year, until the main earthquake occurrence. Although there are other picks that surpass the line $\overline{T} \pm 3\sigma$ they decrease when we increase the parameter s or when we reduce the exploration circle radius, with the exception of the pick that precedes the earthquake of April 25, 1989 of magnitude $M_W = 6.9$, which seems to be significant. Two picks between 1998 and 2002, probably associated with silent earthquakes reported by Lowry (2001) and Kostoglodov (2003). Last pick around 2010 is probably associated with silent earthquakes that were no reported. In figure 3, only the previous quiescence to the earthquake of November 29, 1978 and two picks between 1998 and 2002, probably associated with silent earthquakes survive; a pick that has appeared after 2005 it is probably associated with silent earthquakes reported by Larson (2007); the exploration circle with center in 16.5°N and 99.0°W covers the Oaxaca and Guerrero states. In figure 4 the picks remain and then it begins to appear two picks before the earthquakes of Michoacán (1985) and Colima (1995), this region covers the Guerrero and Michoacán states. Finally, in figure 5, there are two picks of seismic quiescence before the earthquakes of Michoacán (September, 1985; M_W = 8.0, and M_W = 7.6) and Colima (October, 1995; M_W = 7.9) and the pick of previous quiescence to the Oaxaca earthquake decreases and it stops to be significant; in this case the exploration circle with center in 18°N and 103°W covers the states of Michoacán, Colima and part of Jalisco and Guerrero. These last two picks of seismic quiescence remain if we continue displacing the exploration circle toward the Pacific west coast.

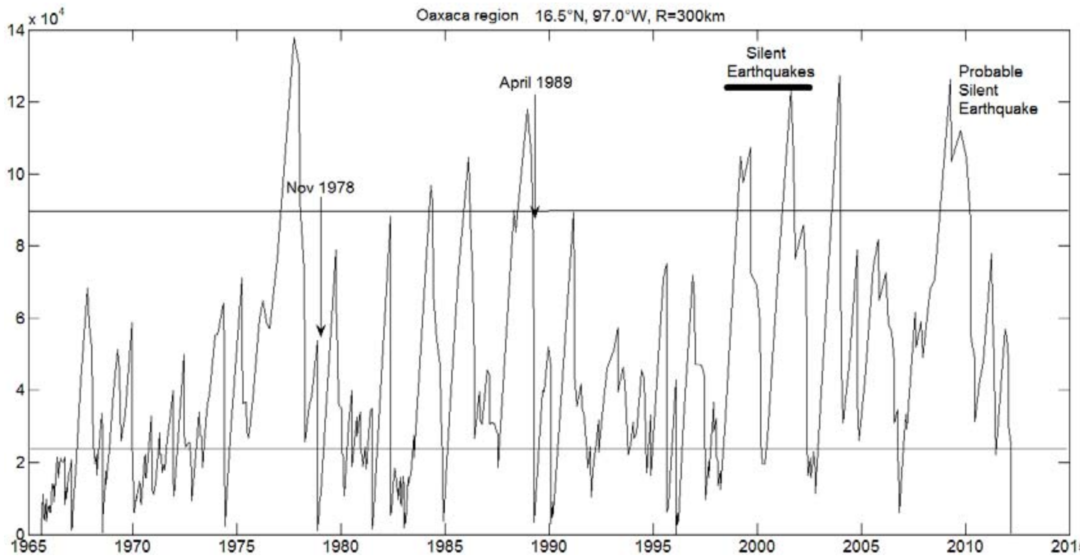

Figure 2. Temporary convolution function of Oaxaca region. Earthquakes with $M_S \geq 4.3$ from January 1965 to April 2012.

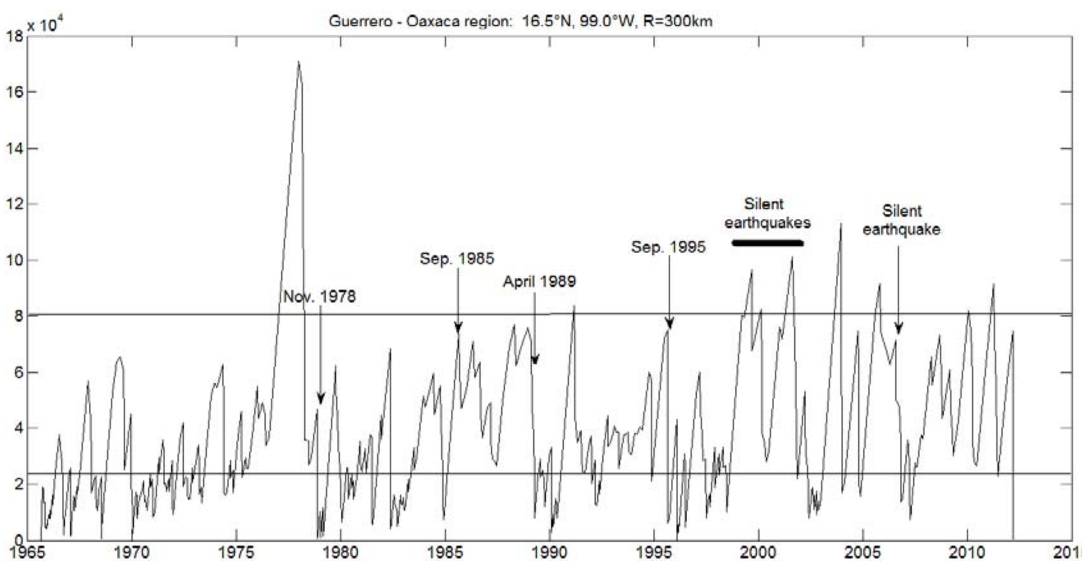

Figure 3. Temporary convolution function of Guerrero - Oaxaca region. Earthquakes with $M_S \geq 4.3$ from January 1965 to April 2012.

These figures illustrate the seismicity behavior in four different regions of the Pacific coast, and we can observe that the quiescence is a local effect associated with the occurrence of a future great earthquake. The four more important picks of seismic quiescence that are observed in these graphs are strong correlated with the five greater earthquakes that have occurred in the last three decades: Oaxaca

(November, 1978; M_W = 7.8), Petatlán (March, 1979; M_W = 7.6), Michoacán (September, 1985; M_W = 8.0, M_W = 7.6) and Colima (October, 1995; M_W = 7.9).

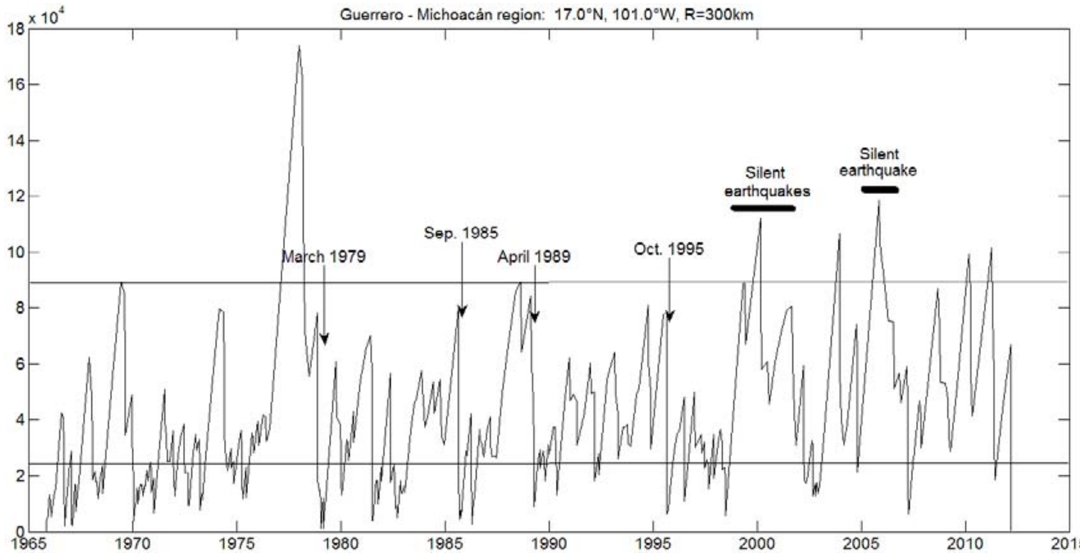

Figure 4. Temporary convolution function of Guerrero-Michoacán region. Earthquakes with $M_S \geq 4.3$ from January 1965 to April 2012.

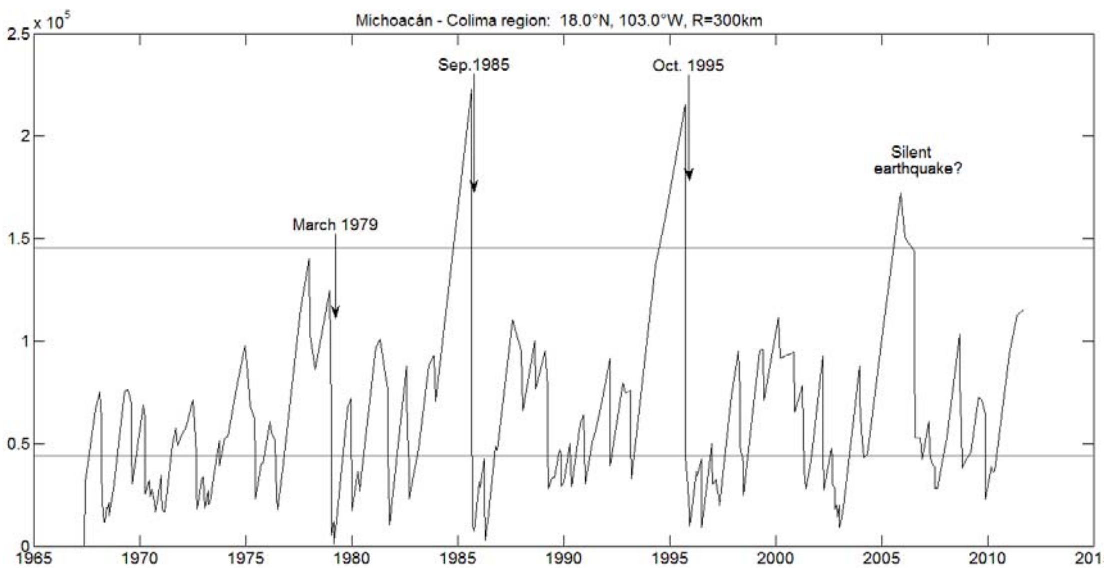

Figure 5. Temporary convolution function of Michoacán-Colima region. Earthquakes with $M_S \geq 4.3$ from January 1965 to April 2012.

3.2 A colors code for the precursory quiescence regions

With the purpose of giving us an idea of the region size of seismic quiescence, we explore the region from 14 to 21°N and 94 to 106°W, sweeping the whole region with exploration circles of radius 300 Km, with 0.2 grades intervals; that is to say, we take a size grid equal to 0.2 grades on the region and the center of each square is the center of an exploration circle. We take a colors code for the convolution values, with the purpose of observing in a more qualitative way the space distribution of the seismicity level, we assign a color to each square according to the temporary convolution function value in that place. We show in table 1 the colors code for each value of the convolution function; the criterion for the assignment of the colors is somewhat arbitrary, it was designed to stand out those significant seismicity variations. The green tones represent the average seismic activity, while the tones from yellow to red mean significant seismic quiescence and the colors blue to violet represent great activity just as the aftershocks or earthquake swarms. The colors are assigned to intervals of the convolution function T, which are expressed in terms of the average E = $\overline{T}$ and the standard deviation $S = \sigma$ of the convolution values. The right column indicates the percentage of function values that fall inside each interval and they give us an idea of the importance of each seismicity abnormal value.

Tabla 1. Colors code for each value of the convolution function

Color	Interval of the convolution function	Percentage of values of T that fall inside each interval
	E + 4S < T	0.60
	E + 3S < T < E + 4S	0.70
	E + 2.5S < T < E + 3S	1.30
	E + 2S < T < E + 2.5S	1.70
	E + S < T < E + 2S	9.60
	E/2 < T < E + S	58.00
	E/4 < T < E/2	15.00
	E/8 < T < E/4	6.60
	E/16 < T < E/8	3.00
	E/32 < T < E/16	1.80
	T < E/32	1.70

In figure 6 we show in red color the region of previous seismic quiescence to the Oaxaca (1978) and Petatlán (1979) earthquakes, which was calculated with earthquakes of magnitude $M_S \geq 4.3$, since January 1, 1965 to August 15, 1977 and with depths smaller than 60 Km, the black circles represent the earthquakes occurred during this period and the white circles represent the Oaxaca and Petatlán earthquakes. This region began to be formed in November, 1976 inside the Oaxaca gap and it was growing and moving toward the west part of the Guerrero state and finally it disappeared in March, 1978, due to an activity increment in both the Oaxaca gap and the region of Petatlán.

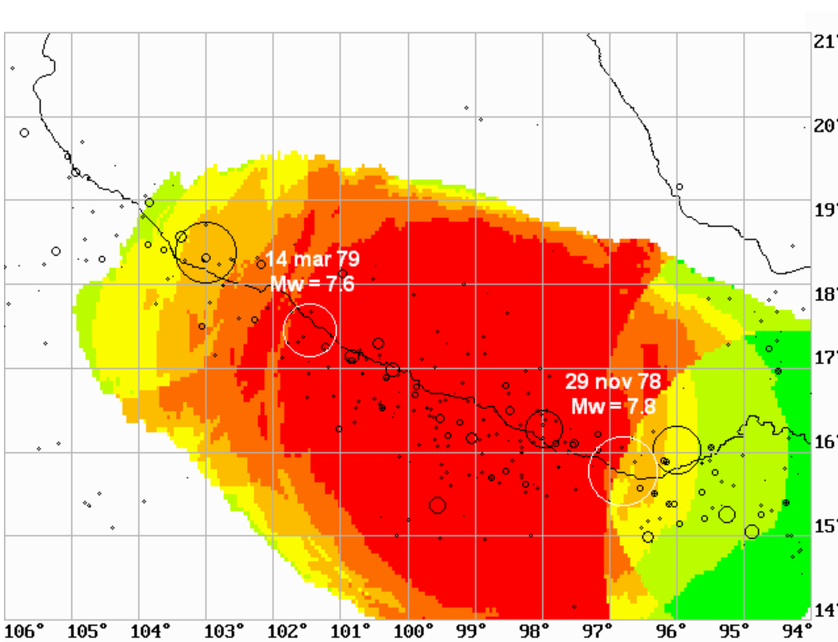

Figure 6. Region of previous seismic quiescence to the Oaxaca 1978, Mw = 7.8 and Petatlán 1979 Mw = 7.6 earthquakes.

In figure 7, we show the region of previous seismic quiescence to the Michoacán earthquakes of September 19 and 20, 1985 which was calculated with earthquakes of magnitude $M_S \geq 4.3$ since the January 1, 1965 to September 18, 1985 and with depths smaller than 60 km, as in the previous figure the two white circles represent these events. The region of quiescence in red color covers the epicentral region of the earthquake of September 19, and the smaller adjacent region, in orange color, covers the epicentral region of the earthquake of September 20. It can be seen a small decrease in the seismic activity in the Guerrero and Oaxaca states. The region of quiescence began in January, 1985 and it finished in the earthquake occurrence day; contrary to the previous case, there was not a foreshock stage or activity renewal before the main event.

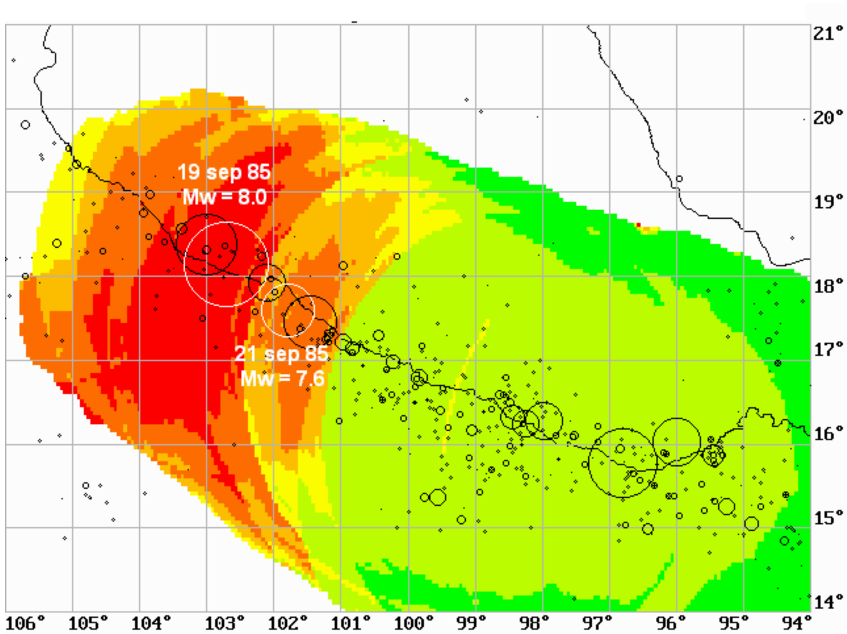

Figure 7. Region of previous seismic quiescence to the Michoacán 1985, Mw = 8.0 and Mw = 7.6 earthquakes.

Finally, in figure 8 we show the region of previous seismic quiescence to the Colima earthquake of October 9, 1995; this was calculated with earthquakes of magnitude $M_S \geq 4.3$ from January 1, 1965 to October 9, 1995 and with depths smaller than 60 km. The region began to be formed in November, 1994 and it concluded the earthquake day; as in the previous case there was not a stage of activity renewal. Contrary to the previous case in this graph the earthquake epicenter is in the boundary of the red region which is small if we compare it with the previous case. However, the epicenter is located inside the orange region which is also very significant. The circular stain of blue color that covers parts of the states of Oaxaca and Guerrero owes to the increasing of activity due to the aftershocks of the September 14, 1995 earthquake of magnitude $Mw = 7.4$.

We carried out several color graphs of the convolution function (level of seismic activity) as that of figures 6, 7 and 8 from January 1, 1975 up to ending, 2001, every 15 days, and we found several regions of quiescence that were not correlated with great earthquakes ($Mw \geq 7.0$), we call them false alarms. We analyze these false alarms, its localization; the date in which it appeared; its duration in months; the quiescence level, which refers to the convolution function values, if these values are bigger than the average plus three or four times the standard deviation. It is also indicated if the quiescence was a precursory sign of a great earthquake or a false alarm, and we do some observations regarding the localization and shape of the quiescence region. During a period of almost 27 years, we observed 19 regions of seismic quiescence of which only 3 were quiescence precursors; approximately 80% of the quiescences were false alarms. This would seem to be discouraging. However, the false alarms are well characterized as we will see later on.

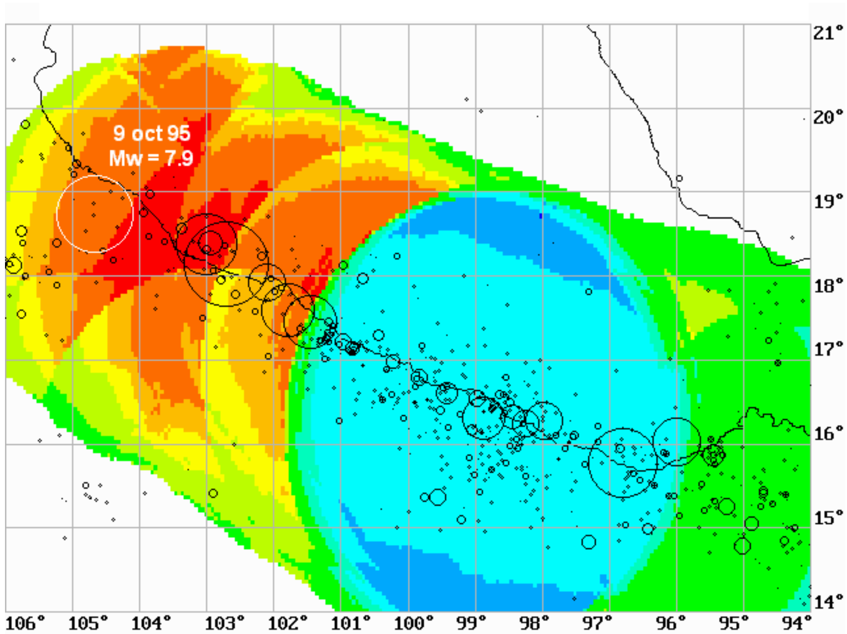

Figure 8. Region of previous seismic quiescence to the Colima 1995, Mw = 7.9 earthquake.

Approximately 65% of the false alarms occur in the Oaxaca state, 20% in Guerrero, 10% in Michoacán and 5% in the region of Jalisco and Colima. The precursory quiescences had durations of more than 7 months, while 80% of the false alarms had durations smaller than 3.5 months, only three false alarms had durations of 6.5, 7.5 and 17.5 months, for its duration they can be compared with the precursory quiescences and they can be confused with them; however they are small in size. The 60% of the false alarms were of quiescence 3σ, while the three precursory quiescences had a quiescence of 4σ.

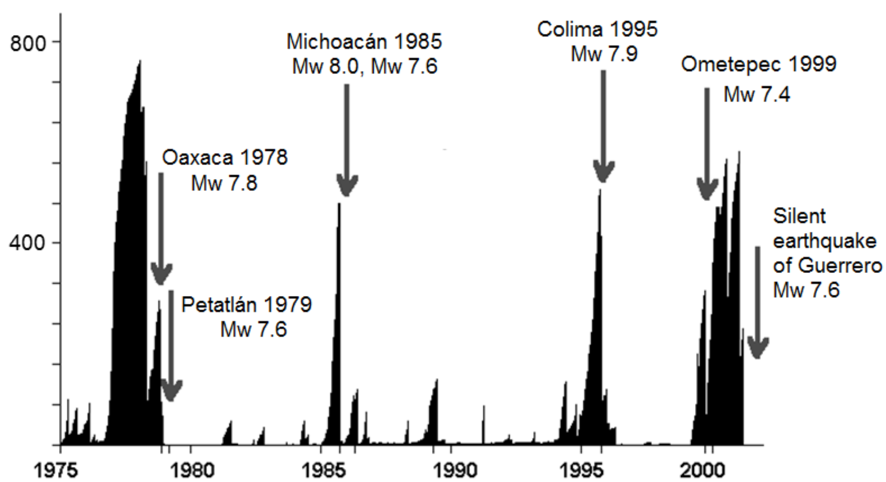

Figure 9. Evolution of the size of the quiescence regions, area of level 2σ and major, in the Pacific Mexican coast. Earthquakes with $M_S \geq 4.6$ from January 1975 to December 2002.

In figure 9 we show in a qualitative way the evolution of the size of the quiescence regions in the seismic region of the Pacific Mexican coast to earthquakes of magnitude $M_S \geq 4.6$, in these graphic we show all the values of the quiescence area of level 2σ and major. The area unit is a square of 0.2°N by 0.2°W. As we can appreciate in figure 9, the three more important picks are correlated with the five more important earthquakes occurred during the period from 1975 to 2002. The previous quiescence to the Oaxaca earthquakes (November, 1978) and Petatlán (March, 1979) is the most significant. The fact that the region of maximum area covered the Oaxaca and Guerrero states can be due to that this was the product of a superposition of two quiescence areas, one in Oaxaca and another in Guerrero. The other two picks that follow in importance and that have approximately half of height of the first correspond to the previous quiescence to the Michoacán earthquakes (September, 1985) and Colima-Jalisco (October, 1995), it can be appreciated in these two cases that there were not foreshocks before the earthquake. Finally, the last pick is similar to the first and corresponds to a quiescence pattern that begins the 2000 year in the Guerrero gap and covers the Guerrero and Oaxaca states, it is similar to those that were presented before the earthquakes of Oaxaca (November, 1978, $M_W = 7\ 8$), Michoacán (September, 1985, $M_W= 8.0$) and Colima (October, 1995, $M_W= 8.0$). The quiescence finished in March, 2001 with two earthquakes in the Guerrero gap of magnitudes 5.3 and 5.4, this quiescence is possibly associated to the silent earthquake reported by Kostoglodov et al. 2003, using a network of permanent GPS stations along the Guerrero seismic gap. This slow slip event began in October 2001 and ended in April 2002.

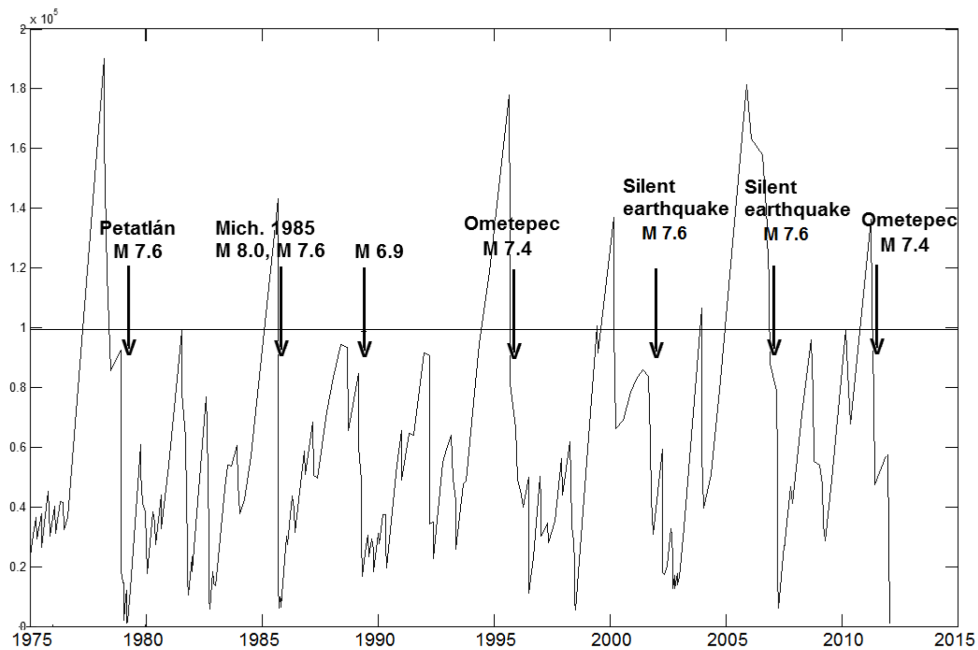

Figure 10. Temporary convolution function in the Guerrero-gap. Earthquakes with $M_S \geq 4.3$ from January 1975 to April 2012; circular region of exploration with R = 250 Km, centered in the Guerrero gap.

Finally, in figure 10 we show the temporary convolution function in the Guerrero-gap since January 1975 to April 2012, considering earthquakes with $M_S \geq 4.3$ in a circular exploration region with radius R= 250 km, centered in the Guerrero gap. In March 20, 2012, an earthquake with $Mw = 7.4$ occurred at Ometepec, Guerrero. We observe picks of seismic quiescence previous to other important events including silent earthquakes recently reported by Lowry (2001), Kostoglodov (2003), Larson (2007) and Payero (2008).

4. DISCUSSION AND CONCLUSIONS

We have used the Schreider algorithm with some improvements, and we have found evidence that five of the more important earthquakes with magnitude Mw ≥ 7.6 occurred during the last 35 years were preceded by an episode of seismic quiescence in the range of magnitudes $M_S \geq 4.3$. In the case of the earthquakes of Oaxaca (November 29, 1978; Mw = 7.8) and Petatlán, Guerrero (March 14, 1979; Mw = 7.6) the stage of quiescence lasted around 3 years and there were foreshocks in both cases. For the Michoacán earthquakes (September 19 and 20, 1985; Mw = 8.0 and Mw = 7.6) the quiescence lasted little more than 2 years and there were not foreshocks. Finally, for the earthquake of Colima (October 9, 1995; Mw = 7.9) the quiescence lasted around 2.5 years and neither there was a clear stage of foreshocks. The precursory quiescences are characterized by duration greater than 7 months, a 3σ region area greater or equal to 200 area units and a 4σ area region greater or equal to 50 area units. On the other hand, 80% of the false alarms are characterized for their duration smaller than 4 months and a 3σ region area smaller than 40 area units. The graphs of the area size of the quiescence region against time show in a very clear way how the five more important events were preceded by much defined patterns of quiescence. As we observe, the size of these regions is not correlated with the earthquake magnitude; because while the 1978 earthquake released approximately half of the energy released by the 1985 earthquake (Mw = 8.0), the duration and size of its precursory quiescence is almost of two times the size that those of the Michoacán earthquakes. This does not surprise us if we consider that the dynamic phenomena of the Earth crust are typically not linear. It is also important than the silent earthquakes recently reported were preceded by an episode of seismic quiescence in the range of magnitudes $M_S \geq 4.3$.

Of special interest for the inhabitants of Mexico City, it is the Guerrero seismic gap that covers the region from Acapulco to Zihuatanejo; it is known that this can generate an earthquake similar to the 1985 earthquake, because since 1911 no one earthquake of magnitude greater than 7.5 has not taken place there. Contiguous to this gap it exists other mature gap that covers from Acapulco to Ometepec, in this region the July 28, 1957 earthquake took place (Mw = 7.7). It is not very probable that both seismic gaps break simultaneously, in which case an earthquake would take place of approximately double energy than the September 19, 1985.

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