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A general overview of the catalog of recent seismicity compiled by the Mexican Seismological Survey

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RESUMEN

Hemos analizado el catálogo de sismicidad reciente de México del Servicio Sismológico Nacional, el cual está basado en compilaciones automáticas de los reportes de sismicidad. Para ello, empleamos diversas técnicas desarrolladas con el propósito de investigar los índices de sismicidad y sus características. En nuestro análisis encontramos que la tendencia de los reportes en el tiempo sufrió un cambio drástico durante 1988. Antes de esa fecha, los procedimientos de rutina comprendían la localización de un gran número de eventos, pero sin asignarle magnitud a los más pequeños. Esta situación cambió en 1988 ya que se detecta una reducción en el número de eventos pequeños localizados aunado a un aumento significativo en el número de eventos a los que se determinó su magnitud. La magnitud mínima para la cual es completo el catálogo en el período 1988-1998 fue determinada como $M_d = 4.3$. Una comparación de las distribuciones frecuencia-magnitud entre m_b (determinadas por PDE) y M_d (SSN) apoyan la hipótesis que ambas magnitudes son básicamente equivalentes en el rango $M \leq 5.0$. Estos resultados son importantes ya que demuestran lo serio que podrían ser los errores al usar los datos sin consideración de los períodos y cambios en el reporte. Por otro lado, nuestros resultados proporcionan la forma de corregir por inhomogeneidades del catálogo, de manera que los datos puedan ser usados en estudios estadísticos. Con relación a los cambios espacio-temporales más significativos con un posible origen natural se encontraron varios casos que se requiere estudiar individualmente.

PALABRAS CLAVE: Sismicidad, catálogo, México, variaciones naturales, variaciones artificiales.

ABSTRACT

We have analyzed the catalog of recent (1974-1998) seismicity in Mexico, based on the automatically compiled reports of the Servicio Sismológico Nacional (Mexican Seismological Survey). To this end, we employed various tools developed for the analysis of seismic catalogs as well as for detailed studies of seismicity characteristics. Such tools comprise both newly developed techniques and traditional methods which deal with the subject of artificial and natural variations of seismicity. We found that the time characteristics of reporting suffered a drastic change during 1988. Before 1988 routine procedures involved locating a large number of events and assigning magnitude only to the largest. After 1988 a decrease in the location of small events and a significant increase in the number of magnitude determinations were noted. The minimum magnitude of completeness for the period 1988-1998 is $M_d = 4.3$. A comparison of the frequency-magnitude distributions for m_b (PDE) and M_d (SSN) indicates that m_b magnitudes are basically equivalent to M_d for the range $M \leq 5.0$. These results are important in that they show that when using statistics which do not take into consideration the period of reporting, serious biases could be introduced. Conversely, our results provide means to correct for the unhomogeneity of the catalog. In terms of the most significant seismicity variations in both space and time which could be due to natural causes we found several cases that need to be studied individually.

KEY WORDS: Seismicity, catalog, Mexico, natural changes, artificial changes.

INTRODUCTION

Any study which attempts to characterize the seismicity of a particular region, with the goal of analyzing the tectonics and/or hazard, has to make use of a record of information pertaining to the past occurrence of earthquakes in the region of interest as well as its surroundings. Commonly, a researcher makes use of a catalog of seismicity which is a listing of epicenter, depth, size (i.e. magnitude and/or moment), as well as other information related to the damage or other effects of the event.

Often, errors in some of those parameters can be found, generally resulting from problems related to the compilation of data or due to the way parameters were determined in the first place. It is difficult, however, to have a precise account of the history of reporting and the way procedures involved in the calculation of the parameters mentioned were carried out in the past. If one neglects these characteristics, however, important biases may be introduced in the final conclusions of the analysis. For example, variations can be introduced which are related to changes in the routine of reporting seismic events or changes in instrumentation of the networks which provided the raw data. Alternatively, knowing the situation to which certain earthquake data have been subjected to may provide enough information as to be able to merge different data sets in a single catalog and thus increase the amount and quality of data.

The problem of finding artificial variations in the seismic activity record provided by a catalog has been taken up in various studies (e.g. Habermann, 1982; 1991; Habermann and Wyss, 1984; Wyss and Burford, 1985; Wyss, 1991, 1992; Zúñiga, 1989, Zúñiga and Wyss, 1995). Those studies employed a range of tools to test the homogeneity and completeness of a catalog. Some important causes for seismicity variations have been identified of which Zúñiga and Wyss (1995) give a brief summary. Among these we can mention: a) a change of agency operating the network, b) introduction of new software and or hardware for analysis c) removal or addition of seismograph stations, d) changes in magnitude definition, e) differences in station averaging techniques of amplitude data, f) differences in station corrections, g) inclusion or deletion of data from local networks, etc.

In this study, we employ some of the tools that have been developed for the specific purpose of studying seismicity catalogs in an overview analysis of the catalog of recent seismicity of Mexico compiled by the Servicio Sismológico Nacional (Mexican Seismological Survey, hereafter referred to as SSN). This catalog is the result of a systematic digital compilation of earthquake data which started in 1974 but which has been subjected to various stages in its development. Figure 1 is a map showing the spatial coverage of the data as well as other important features. It is worthwhile mentioning that hypocenter location, magnitude, and additional information related to events which have taken place in Mexico has been available by means of a published report since the SSN started operating in 1910. These reports are currently being inspected for their inclusion in a general catalog.

CONSISTENCY OF REPORTING THROUGH TIME

The first stage in analyzing a seismicity catalog deals with the time characteristics of reporting. Thus, we studied the time history of reporting in the SSN catalog, as evidenced by the global seismicity rate (number of events in certain magnitude band per unit time). For this purpose the algorithm GENAS (Habermann, 1983) has proved useful in obtaining a general overview of the reporting history as well as to provide times and range of changes. The algorithm is based on an iterative comparison of the seismicity rates at different magnitude cut-offs.

The method rests on the assumption that only independent events are to be compared. Thus, we declustered the catalog using the algorithm proposed by Reasenberg (1985) with the parameters suggested in that paper together with suitable location errors. In short, the GENAS algorithm allows identification of significant changes in seismicity rate (number of events larger or smaller than a given magnitude with respect to time) by comparing the mean rate before the time (*t*) under study to that of the period which follows *t*. This procedure is repeated for increased values of *t* up to the end of the seismicity record. The algorithm allows the identification of the times which stand out as the beginning of periods were increases and/or decreases of seismicity are detected as well as the magnitude range affected by these changes. Habermann (1983) describes the hypothesis in which the algorithm is based as well as the technique itself. This tool and others used later in this study have been put together in a software package (ZMAP, Wiemer and Zúñiga, 1994) which allows a systematic investigation of a seismic record as well as the seismicity of a region.

Figure 2a shows the result of applying the GENAS algorithm to the complete data set. In the figure, changes in the seismicity rate are highlighted as horizontal lines which correspond to a particular magnitude band and time of occurrence. A shading scale is adjusted to the significance or “Z value” (using the *Z* statistical test, e.g. Zúñiga and Wiemer, 1995), of changes found. In general, *Z* values larger than 2.5 would indicate that a change exists with a confidence better than 99%. Positive values stand for decreases of seismicity while negative values indicate increases. We can see that major changes affecting different magnitude ranges occur at various times. One of the most conspicuous changes shows up after 1984. However, after careful inspection, we observed that most of the events that occurred close to the times of change took place in the northwestern regions of the country. Since events that occur in and nearby the peninsula of Baja California are usually located and reported by the Red Sísmica del Noroeste de México (RESNOM) seismographic network, operated by CICESE in Ensenada, Baja California, and are subjected to operative practices not related to those of SSN, we decided to exclude events north of 24° latitude and repeat the analysis. Figure 2b shows that several of the small changes that were observed no longer occur, indicating that the two data sets can not be merged without additional corrections.

Based on the above findings, in what follows we restrict the analysis to those events that were located by SSN only, i.e., those south of latitude 24°N. A graph of cumulative number of events with time for different magnitude cutoffs is shown in Figure 3. Magnitudes of small events reported by SSN are estimated from coda duration. The curve labeled «All events» in Figure 3 includes those events, after declustering, which lack a magnitude estimate, presumably due to their small size, but nevertheless are listed in the catalog. A major change starting in early 1988 can be clearly observed in Figures 2 and 3. The change affects events at least up to magnitude $M_d = 4.5$, as evidenced in Figure 2 from the extent of the horizontal line which corresponds to that time. The curve for all events in Figure 3, indicates a decrease in seismicity rate after 1987, while the trends of

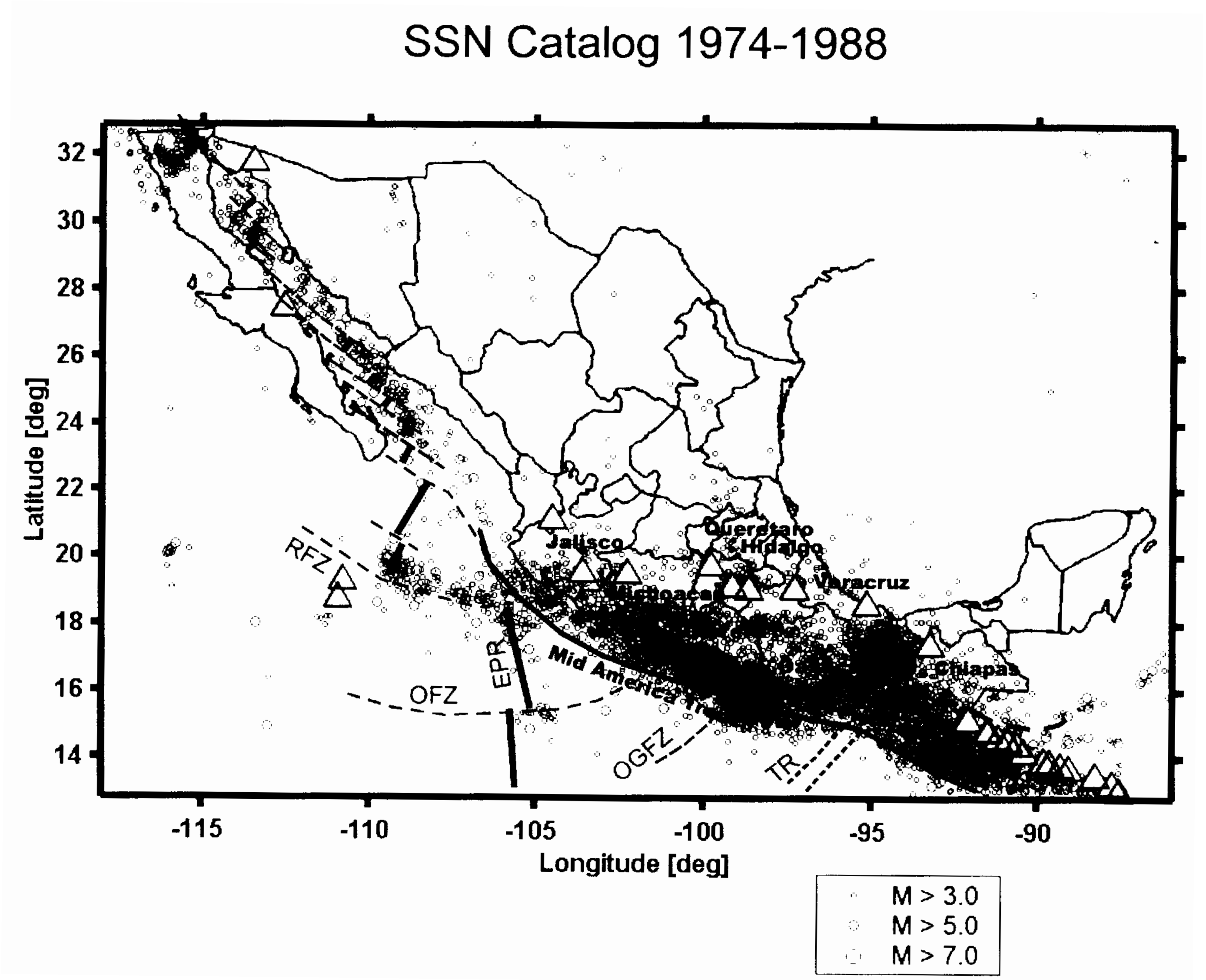

Fig. 1. Spatial coverage of the SSN catalog. Events registered from 1974 to end of 1997 are shown by open circles.. Volcanoes are shown with triangles. Main tectonic features are also shown. RFZ: Rivera Fracture Zone; OFZ: Orozco Fracture Zone; OGFZ: O'Gorman Fracture Zone; EPR: East Pacific Rise; TR: Tehuantepec Ridge.

curves for events larger than M= 3 and M= 4 show the opposite.

We will now discuss the probable implications behind the change which occurred during 1988. Another way of investigating this change is by looking at the frequency histogram of events registered in the catalog per year (Figure 4a). We can see that the annual average gradually increased up to 1982. From 1982 to 1986, the average number of located events per year remained fairly constant reaching a value close to three times the current average. The opposite, however, is observed when we consider events to which a magnitude has been assigned (Figure 4b). In this case the latest yearly average (for the period 1988 to 1997) is nearly and order of magnitude larger than that of the period 1974-1988.

Notice that these results highlight the problem that one could encounter if statistics were to be compiled without any consideration for the period of reporting. Such a situation is commonplace in many catalogs which we and others have had the opportunity to study. For example, using the histogram in Figure 4a, one could be misled to believe that a maximum of activity took place between 1983 and 1986, with a drastic reduction immediately afterwards. However, a more probable scenario is that there were continuous improvements in the detection capability up to 1983. After this time an apparent constancy in detection was reached. Soon after 1986 operative practices changed, increasing the number of magnitude determinations but decreasing the overall number of detected events.

Given the marked difference in the average of events

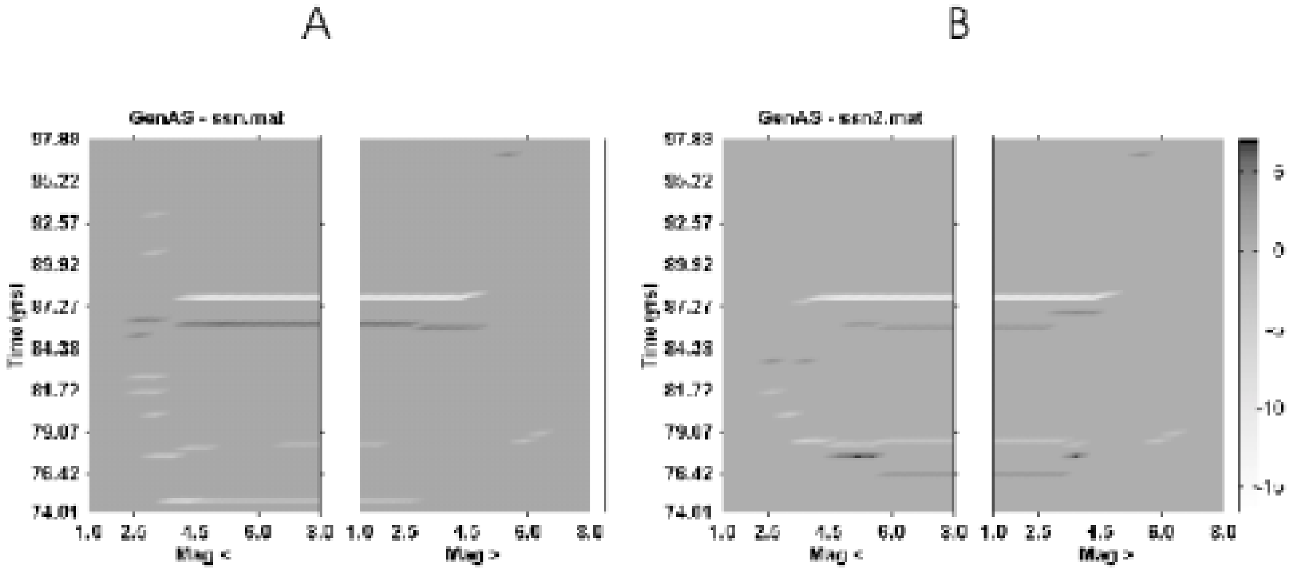

Fig. 2. Magnitude range and statistical significance of seismicity changes vs. time for SSN catalog data resulting after applying algorithm GENAS. Grey shade scale on the right of each frame corresponds to the *Z* value of change displayed on the left. *Z* values larger than 2.57 are significant at the 99% level. Positive (darker shade) Z values stand for seismicity decreases and negative values (light shade) indicate increases. A) Results for magnitudes below and above the respective value, using all events registered with magnitude larger or equal than 1.0. B) Same as before but restricting the analysis to events located below Latitude 24°N.

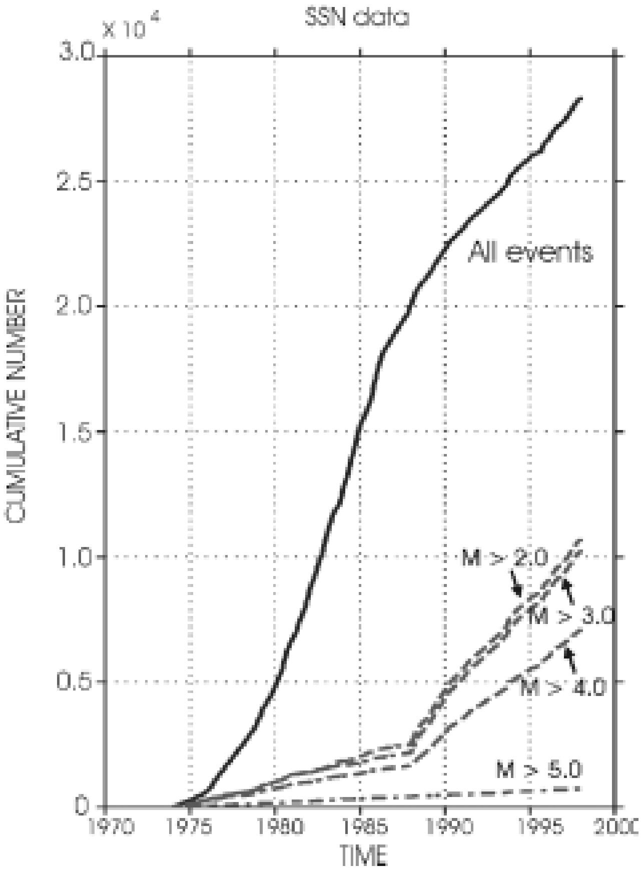

Fig. 3. Cumulative number of events vs. time for different magnitude bands, data restricted to locations south of 24°N Latitude.

registered before and after 1988, it is instructive to estimate an approximate to the minimum magnitude of detection for the period previous to 1988, if we were to assume the average for that period as representative of the threshold of complete detection.

The answer can be sought by means of the frequency-magnitude distribution (also known as Gutenberg-Richter law, hereafter referred to as Frequency-Magnitude or F-M relation)

$$\log N = a - bM$$

for the current period 1988-1997, representative of network capabilities nowadays. In this equation, N is the number of events with a magnitude equal or larger than M, a and b are constants which depend on the physical properties of the region and magnitude determinations. Figure 5 shows the F-M distribution, normalized to a year, for that time interval. If we consider the yearly average of events located for the period where most events were located (1982-1986, Figure 4), we find that it reached approximately 1930 events. Aftershocks of the September 19th and 21st, Mw = 8.1, 7.6, earthquakes were not included in the average, since most of them are removed by the declustering algorithm and since we do not want to add a bias in the seismicity threshold.

Using the a and b values obtained for the F-M distribution shown in Figure 5 (8.2 and 1.3 ±0.02 respectively), we obtain a magnitude of 3.8 which corresponds to 1930 events. Thus, 3.8 might be considered as equivalent to the minimum

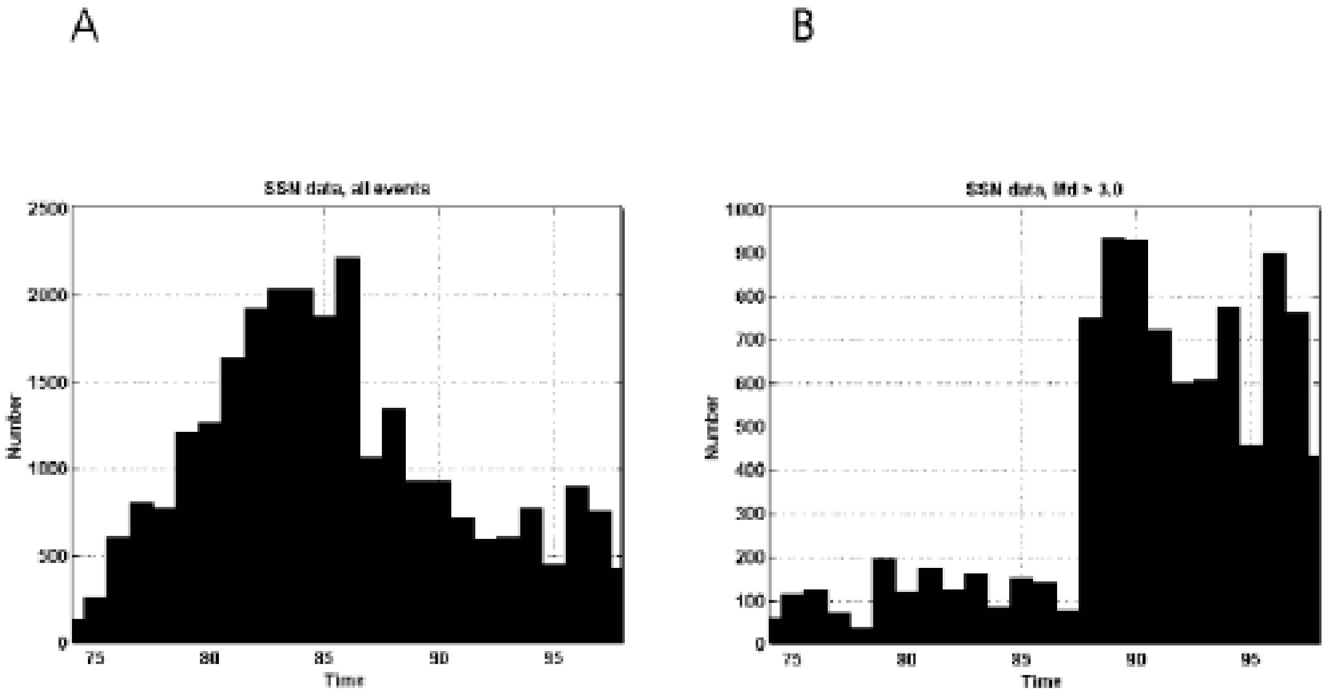

Fig. 4. A) Number of events per year histogram. All events located were considered. B) Number of events with an assigned magnitude per year. Minimum magnitude is 3.0.

magnitude of detection for the period 1982-1986 based on current reported averages, if we assumed that number to lie in the linear part of the FM distribution. Since we can not assure the latter to be true, we can not firmly establish that 3.8 was the actual minimum magnitude above which all events were completely reported for that period. Furthermore, it is most likely that the actual minimum magnitude of detection was higher than that value, even if all events detected had been assigned a magnitude. However, we can state that with current network capabilities a magnitude of 3.8 is a feasible goal.

In trying to find a plausible cause for the observed change we learned that from 1974 to 1987 all located events were compiled in the catalog but magnitudes were assigned only to the largest (C. Jiménez, personal communication). Practice was that most small events registered by enough stations (usually more than four) were located but no magnitude was estimated for them. Thus, the large discrepancy between located and magnitude-assigned events, is due to the large number of events registered before 1988 to which no magnitude was assigned, although a location had been provided. After that time, practically no events have been introduced in the catalog without an assigned magnitude.

Furthermore, the period during which we observe a maximum of reported activity (1983 to 1986) agrees with the time when RESMAC (Red Sísmica de Apertura Continental) network, a seismographic network installed

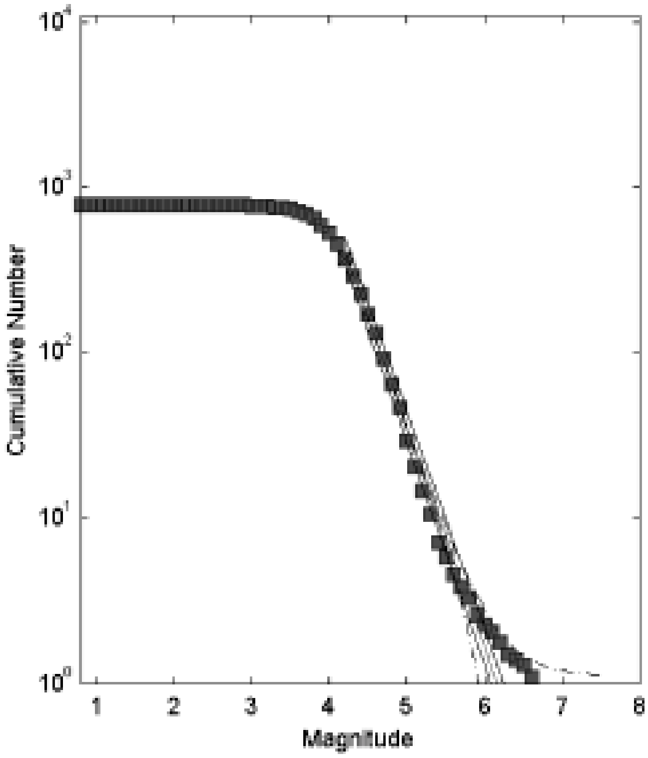

Fig. 5. F-M distribution, normalized to a year, for the time interval 1988-1997. The lines show the standard deviation and the mean, obtained from a least squares fit to the data. The *b*- value of the fit is 1.3 ± 0.05, *a* value is 8.2.

around the country under auspices of the Institute of Applied Mathematics of UNAM, reached its full potential. RESMAC employed automatic phase picking and location procedures. There is, on the other hand, also the possibility that data from the SISMEX network, run by the Engineering Institute, may have also been added without further constraints. Soon after 1986, RESMAC network operation was moved from the Institute of Applied Mathematics to the Institute of Geophysics of UNAM. Subsequently, location procedures were homogenized throughout the combined SSN network, employing visual phase-picking and iterative location procedures in all cases. Thus, it is conceivable that the large number of located events during 1983-1986 come from RESMAC results. Given the previous findings, we can consider the time period 1988-1997 as representative of current averages and thus we can use the record of seismicity for that period as a basis for the following steps in the analysis.

COMPARISON BETWEEN PDE AND SSN MAGNITUDES AND MAGNITUDE OF COMPLETENESS

As mentioned above, current practice is to use duration as a means for estimating magnitude for all events except those which exceed magnitude M = 6.0. For the largest events (M ≥ 6.0), magnitudes are based on amplitude and energy estimations (Pacheco and Singh, 1994). The relation for coda magnitude employed since start of compilation had originally been calibrated against body-wave magnitude reported by the USGS in the Preliminary Determination of Epicenters catalog (PDE). However, since operative procedures have changed and data has increased since that time it is necessary to verify whether the relation still holds for modern data.

Figure 6 shows the normalized F-M distributions of SSN and PDE based on duration magnitude (M_d) and on body-wave magnitude (m_b) respectively. It can be seen that both distributions (Figure 6ab) are not too far apart although a difference exists in particular for magnitudes above 5.0. We employed the technique introduced by Zúñiga and Wyss (1995) to search for a magnitude relation which would produce a best fit for the F-M distribution based on m_b. Several possibilities emerge from this analysis.

If one is to assume that a shift as that given by $m_b = M_d + 0.1$ (Figure 6cd) attains the lowest residuals in the 5.0 < M < 6.0 range, such as relation might be best suited for correction purposes. However, such residuals are close to those obtained

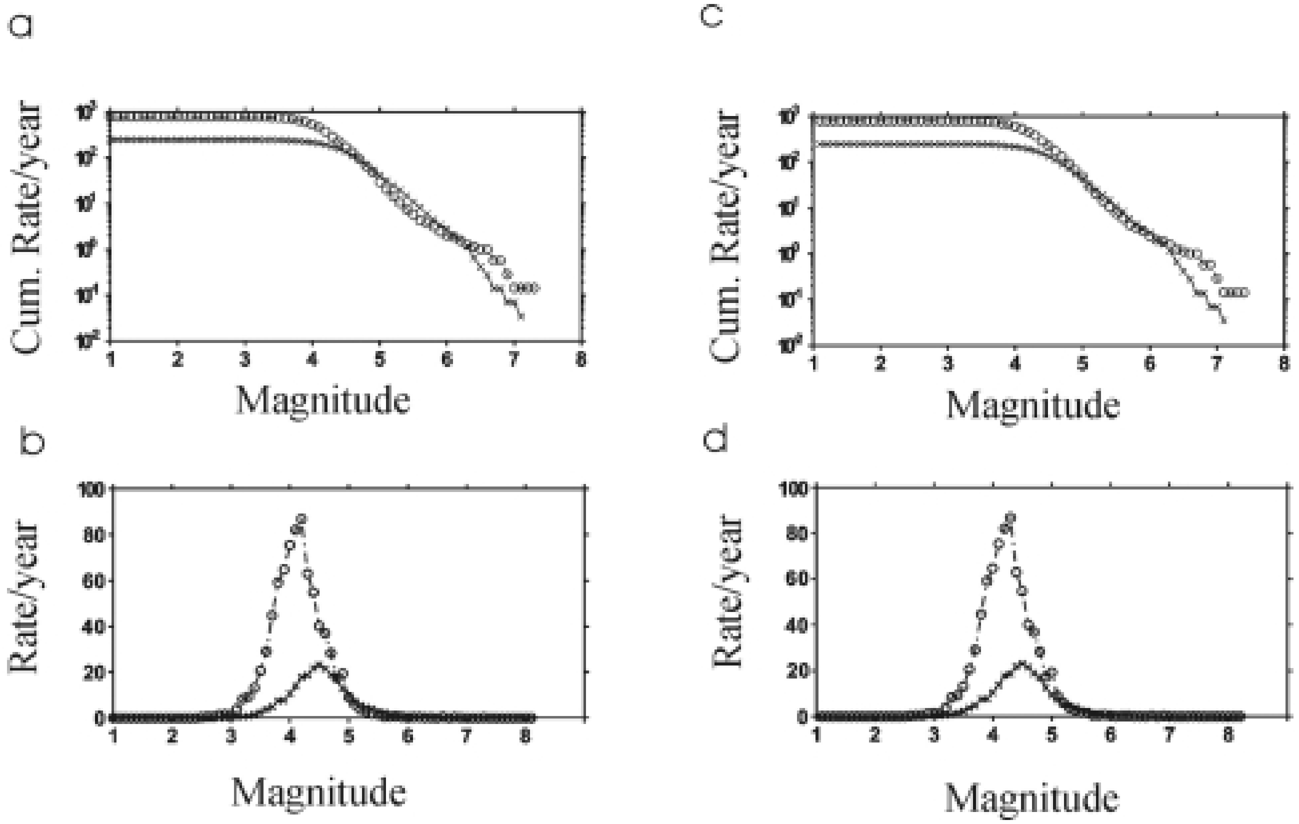

Fig. 6. Normalized frequency-magnitude distributions for SSN (circles) and PDE (crosses) data. Data has been selected for the periods 1988-1995.5 (SSN) and 1965-1995.5 (PDE). a) Cumulative frequency, original data b) Non-cumulative frequency, original data. c) Cumulative frequency, after applying a magnitude shift to SSN data (see text). d) Non-cumulative frequency for same data as in c).

without any shift (Figure 6ab) for the range 4.5 < M < 5.0. Furthermore, we can see that the frequency-magnitude distribution of M_d departs from linearity for events with M > 5.0.

It is our experience that magnitude determinations based on duration at this range show the largest differences from other estimates based on body or surface waves.

Thus, we propose that SSN data at the $M_d < 5.0$ range can be merged with PDE data, after careful revision for possible duplicates.

In order to find the minimum magnitude of completeness of SSN data, we fitted a straight line to the M_d distribution (Figure 5) for the interval 4.0 to 5.0 and found the minimum magnitude at which M_d data departed from the fit (in the least squares sense) for more than one standard deviation. We found that magnitude to be equal to 4.3. The same magnitude was obtained using a recent technique (Wiemer and Wyss, 2000) which makes use of a comparison between the observed distribution and synthetic distributions calculated as a function of a minimum magnitude, M_{min}, where the actual minimum magnitude of completeness is that which gives the lowest residuals between both. It is worthwhile mentioning that using both techniques on the PDE data we get a minimum magnitude of 4.8. Such estimates are useful as an overall means of comparison between catalogs, however, it is necessary to have information on the spatial behavior of the magnitude of completeness to be able to make useful inferences.

SPATIAL CHARACTERISTICS OF THE SSN CATALOG

In order to obtain a general spatial overview of the main seismicity changes in the catalog, we employed the so called *Z score* following the mapping technique described by Wiemer and Wyss, 1994. Briefly, the technique relies on the calculation of the seismicity rate (number of events for unit time) which corresponds to each one of the nodes of a previously assigned spatial grid. The seismicity around the node is defined by considering a fixed number of events located nearest to that node. Next, seismicity rate variations are determined by comparing the average rate calculated for the total span of the catalog against the rate in a predefined time window. Iterating after moving the center of the window in time allows to extract information on the changes experienced by the seismicity which surrounds each node as a function of time. For our study we used 150 nearest events at each node and a window length of 0.5 years.

The results of this analysis are displayed in the form of map (Figure 7), in which different colors correspond to different Z values according to the scale shown. Values larger than 2.5 are significant at the 99% level. Positive Z values stand for seismicity decreases while negative values indicate seismicity increases. This procedure yields an estimate of largest rate changes as a function of space for the complete data set and within the time interval under study (i.e. 1988-1997).

The most outstanding features of this map are:

- An increase in seismicity (dark blue shading in Figure 7) in the central-east Volcanic Belt region (central Mexico) which initiated in early 1996, affecting mostly the states of Mexico, Hidalgo, Puebla and Tlaxcala.
- A seismicity increase which started in 1997 in central Guerrero.
- An increase in seismicity centered at the Ometepec segment of the subduction zone in Oaxaca, which started in 1996.
- A seismicity decrease (dark red in Figure 7) near the central inshore region of Oaxaca which started in 1995.
- Decreases in seismicity rate located offshore the Tehuantepec Isthmus and towards the east, offshore the coast of Chiapas, which iniciated in early 1994.
- A decrease in seismicity which started at the beginning of 1990 in the Gulf of Mexico, near southern Veracruz.

These results are useful in providing preliminary information related to probable important seismicity variations, however, further analysis is needed to shed light on the causes of such variations as well as to differentiate natural from artificial sources of the variations.

As an additional piece of information that provides some means to discriminate artificial variations, we plotted the minimum magnitude of completenes (M_{comp}) as a function of space. The procedure is similar to the one employed for the Z map in that we select a number of events around grid nodes, in the manner previously described. Then, we calculate the b-value distribution to each subcatalog by the maximum likelihood method (Aki, 1965). The results are shown in Figure 8, where we use a coloring scale to outline the regions that comprise similar M_{comp}. Notice that the area with the smallest M_{comp} corresponds to the central regions, where we get values as low as 3.4. It is conceivable that this is due to coverage of seismic stations in and near the Valley of Mexico since in the last few years there has been a marked improvement in quality and quantity of stations installed in this area. The largest values are for offshore regions which agree with a lack of seismic stations coverage. The region of western Jalisco is also highlighted as having a poor coverage.

DISCUSSION AND CONCLUSIONS

We showed that during the period 1982-1986, the network detection capability was good enough to register events with magnitude as low as 3.8. In that period, however, most small events were located without any magnitude

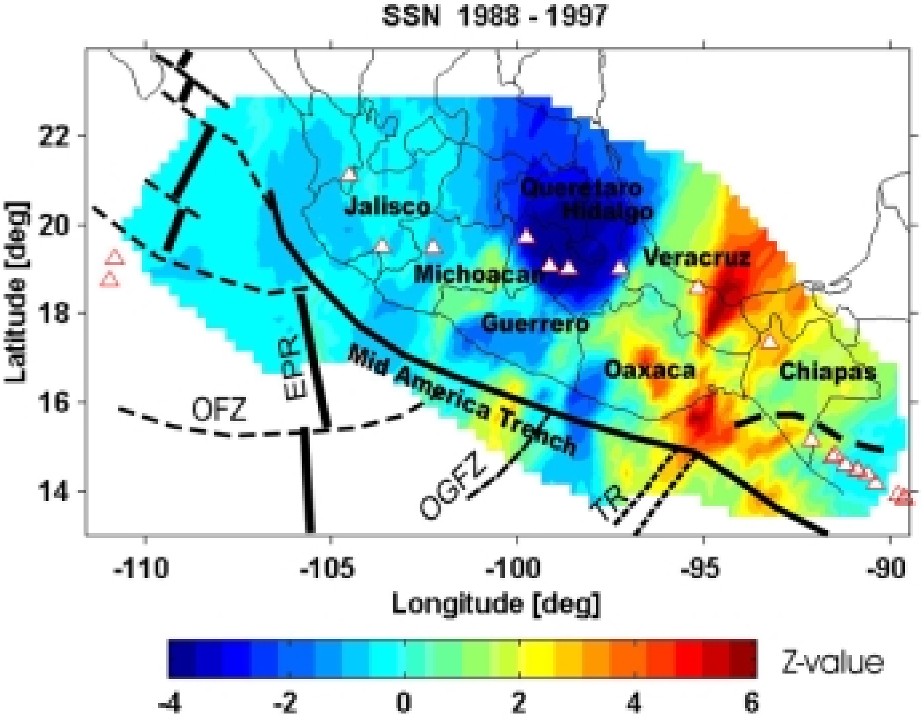

Fig. 7. Maximum seismicity changes, in terms of the *Z* statistic, as a function of space for the period 1988-1997. The area of resolution has been selected according to the sampling resolution. Resolution is given by the maximum radius of a circle which includes the nearest 150 events to each node. Color zones which correspond to radius larger than 300 km are not plotted. Names of regions mentioned in the text are indicated.

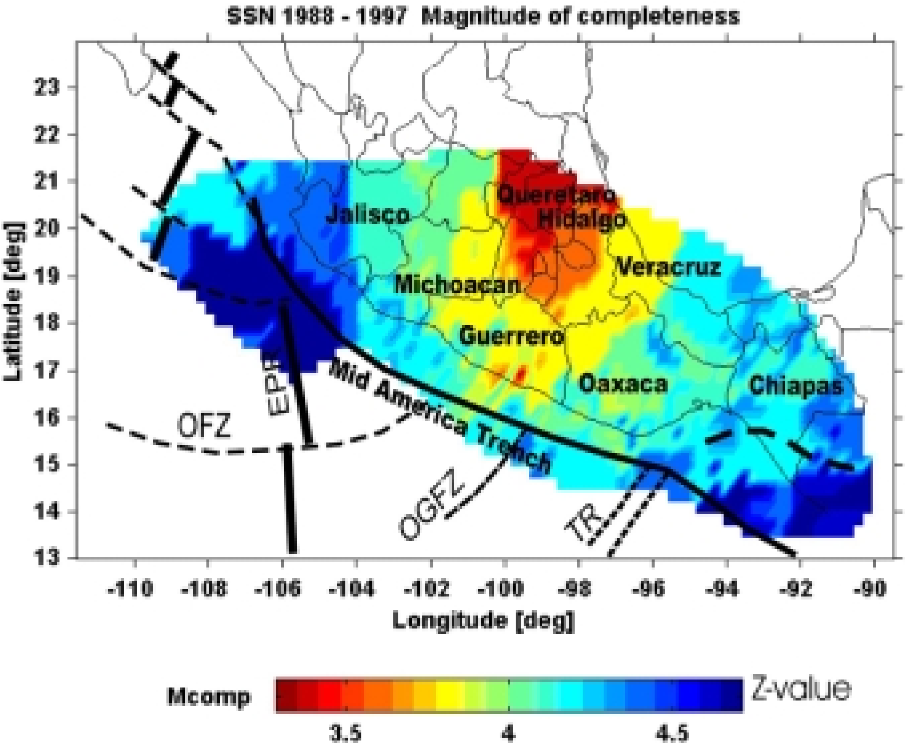

Fig. 8. Map of minimum magnitude of completeness for SSN catalog data in the period 1988 to end of 1997. The procedure employed is similar to that of the map of maximum Z values (Figure 7) and is discussed in the text.

determination. Nowadays the capabilities of the network are greatly improved by the addition of modern broad-band instrumentation as well as standard short period instrumentation. Nevertheless, the large heterogeneity in crustal properties around the country, together with the problems posed by logistics of reading and correcting a large quantity of small events by visual inspection every day makes it difficult to deal with the objective of lowering the magnitude of completeness. The introduction of automatic phase picking, and suitable crustal models dependent on azimuth may help overcome some of these difficulties. Some tests have already been conducted on these basis and their result is encouraging for the design of new tactical approaches.

Concerning the spatial characteristics of the most significant seismicity changes, the increase observed in the central section of the Mexican Volcanic Belt region, is a pattern that correlates with the occurrence of a series of seismic sequences which have been taking place in that region since the start of the anomaly (early 1996). It is worthwhile mentioning that additional stations around the Valley of Mexico have been put in operation in the past few years (starting in 1993), a situation which is reflected in the current small magnitude of completeness for that zone (Figure 8). However it is unlikely that these sequences are a consequence of lowering the detection threshold, since magnitudes were large enough to be registered by most stations in the regional network in most cases. In particular, significant sequences of events near Maravatio, (state of Michoacán); Sanfandila (state of Querétaro); and Tula (state of Hidalgo), all occurred during 1998 with the largest magnitudes reaching 4.3. The case of the Querétaro sequence, even though it consisted of small events ($1 \leq M \leq 3$), stands out since no such sequence had ever been reported to the best of our knowledge. Thus, the observed increase in seismicity may indeed be related to a regional strain episode.

It is interesting to note that no event larger than 6.0 has been located in the central Guerrero (the so-called Guerrero Gap, Suárez *et al*., 1990) portion of the Mexican subduction during the period 1988 to 1997, although at least three events within this magnitude range took place during this period (in 1989, 1993 and 1996) which were located at both extremes of the anomalous region. In the case of western Oaxaca, and event with Ms = 7.5 took place on September 14th 1995 (Courboulex *et al*., 1997) near the Ometepec region, and a large aftershock (Ms = 6.8) occurred on February 25th, 1996. So, the increase observed is likely to be due to the aftershocks of the main event.

On the other hand no particular events have been reported which we can relate to the occurrence of the rate decrease in southern Veracruz and central Oaxaca. Special attention has been paid to the Veracruz region in the last few years, with some stations being installed in the area, thus we can exclude the possibility of a reporting decrease as causes of the anomaly. Nevertheless, since this rate is maintained through the end of the catalog studied, it is important to keep a close watch on both zones.

A similar situation exists for the Tehuantepec region, a zone where no large event has ever been located. It is unknown whether this region is aseismic or presents an uncommonly large recurrence period for the subduction regime. The decrease in seismicity rate, however, appears not to be related to reporting variations since the operation of stations nearby has not changed. The situation to the east off the coast of Chiapas, however, is different since it is possible that there is a relation to the event which took place on September 10, 1993 (Ms = 7.3). We also note that the Colima-Jalisco event of 9 October 1995, Ms = 7.6, Mw = 8.0 (Escobedo *et al*., 1998) had no significant effect on the seismicity record as compared to the background.

With our results, we hope to provide additional insight into the problem of finding suitable strategies which help improve the quality of regional seismic monitoring in Mexico. Our results may also provide some basis for future research related to the earthquake process in the tectonic regions which comprise Mexico.

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