

# The RESNOM seismic catalog and its bearing on the seismicity of Northwestern Mexico

F. Ramón Zúñiga<sup>1</sup> and Raúl R. Castro<sup>2</sup>

<sup>1</sup>*Centro de Geociencias, UNAM Campus Juriquilla, Querétaro, México*

<sup>2</sup>*Centro de Investigación Científica y Educación Superior de Ensenada, Ensenada, Baja California, México*

Received: September 18, 2003; accepted: July 6, 2004

## RESUMEN

Se efectuó un análisis del catálogo de la Red Sísmica del Noroeste de México (RESNOM) para proporcionar elementos que pueden ser claves para estudios actuales y futuros que hacen uso de esta importante base de datos. Las características espacio-temporales del catálogo de sismicidad se detallan para dar un panorama global de la historia de reporte. Al investigar las variaciones en los datos reportados se pretende encontrar bases para un mejor entendimiento de la historia sísmica de la región. Se han identificado variaciones con un probable origen artificial y se discuten sus implicaciones para estudios de sismicidad. Así mismo, se ha analizado la historia y los valores actuales de la magnitud mínima de reporte completo ( $M_c$ ), así como su variación en el espacio para poder optimizar las estimaciones de riesgo en la región basadas en los datos de sismicidad. Se identificaron cambios significativos en el reporte que tuvieron lugar durante principios de 1987, mediados de 1992 y principios de 1997. Una inspección de los boletines, para el período de 1987 a 1992, arroja cifras para la tasa de eventos localizados contra eventos registrados de 50% en promedio. Haciendo una comparación entre las tendencias acumulada y no acumulada para los eventos localizados durante el período 1987 a 1992.4 contra las de 1992.4 a 1997.11 encontramos que si se restringe la zona de inspección a la región que concuerda con la máxima resolución de la red, la variación se reduce notablemente. Al efectuar una comparación entre la tendencia durante 1992.4 a 1997.11 contra la de 1997.11 a 2001.5 se demuestra que no es necesaria ninguna corrección, a pesar de que los datos indican que el número de eventos con magnitud de duración  $M_d \leq 3.5$  fue 38% menor durante el período antecedente comparado con los valores actuales. Una comparación entre la distribución obtenida con magnitudes determinadas por RESNOM ( $M_d$ ) contra la que resulta de utilizar magnitudes reportadas por PDE ( $m_b$ ), para eventos en la misma región, indica que se puede obtener una mejor correspondencia entre ambas estimaciones al aumentar las magnitudes de RESNOM por 0.1. Esta misma corrección podría ser aplicada si se desea añadir datos de RESNOM a datos provenientes del catálogo del SSN. La magnitud mínima de reporte completo para la época actual se determinó como 2.1 con una confianza de 90%. La resolución espacial de  $M_c$  indica que algunas áreas con buena cobertura instrumental, particularmente el área cercana a 32°N y 116.5°W alcanzan valores de  $M_c=1.6$ . Al hacer una comparación entre mapas de  $M_c$  para los períodos en los que se determinó que ocurrieron cambios, se demuestra que la resolución de la red en algunas áreas ha mejorado considerablemente, con diferencias en  $M_c$  hasta por 1.0 unidades.

**PALABRAS CLAVE:** Historia sísmica, catálogo sísmico, Baja California, México, variaciones naturales, variaciones artificiales.

## ABSTRACT

The catalog of the Red Sísmica del Noroeste de México (RESNOM) operated by CICESE is investigated. Probable artificial effects are detected. Current values for the minimum magnitude of completeness ( $M_c$ ) and its spatial variations are outlined. Significant changes in reporting were found during early 1987, mid 1992, and early 1997. By inspecting the bulletins for 1987 to 1992 we found that the rate of located to recorded events was close to 50%. Comparing cumulative and non cumulative rates for 1987 - 1992.4 with 1992.4 - 1997.11 there is a difference of about 60% in the trends of located events. The difference is greater in the region of maximum resolution of the network. The change for the period 1992.4 to 1997.11 as compared to 1997.11 to 2001.5 does not warrant a correction; however, the number of events with duration magnitude  $M_d \leq 3.5$  reported during the most recent interval is 38% larger than for the preceding period. Magnitudes calculated by RESNOM ( $M_d$ ) and PDE ( $m_b$ ) match if the magnitudes reported by RESNOM are increased by 0.1. The same correction should be applied when merging data from RESNOM with SSN. The minimum magnitude of completeness for current reporting is 2.4. Some areas with good coverage, in particular around 32°N and 116.5°W, can detect magnitudes as low as 1.6. The resolution of the network in some areas has improved considerably, with  $M_c$  decreasing as much as 1 magnitude unit.

**KEY WORDS:** Seismic history, seismic catalog, Baja California, Mexico, natural variations, artificial variations.

## INTRODUCTION

The seismic record in a region can be compared to the record of a person's heart beat. The latter gives important

information about a person's health. A seismic record provides key data for interpreting the history of the stress state in a region and may give indications when it deviates from a "normal" state. In order to make reliable inferences on the

seismicity it is imperative to know the changes in the seismographic network's history.

A seismic catalog is a collection of data including date, time, location, size, and, whenever possible, detailed source mechanism characteristics and effects. It is a fair assumption to state that the quality of data in the catalog will be dependant on the quality of the seismographs network. A network quality is usually improved over time. However, experience has shown that this assumption is not always wise. For example, Habermann (1982) demonstrated that the overall teleseismic detection capability in North America was significantly diminished after the closure of the VELA array in the late sixties. He also was able to demonstrate other such changes in reporting for most of the western hemisphere that took place in the mid seventies although the causes were not clear.

The goals of this study are to outline the scope of detection and reporting by the RESNOM (Red Sísmica del Noroeste de México) seismographic network from a systematic analysis of the seismic catalog compiled since the start of operation of the network. We wish to provide the researcher with useful information on the scope of the catalog, including time and space variations of detection capabilities. By finding important facts about the thresholds and consistency of the data, we also want to put forward basic information which will be useful towards untangling the tectonic characteristics of the regions covered by the network as well as for better assessments of seismic risk in the area. Additionally, we compare the main aspects of the earthquake catalog with those from the catalog of the Mexican Seismological Survey (Servicio Sismológico Nacional or SSN) which was the focus of another study (Zúñiga *et al.*, 2000). This work is another step towards the compilation of one master data base of seismicity for Mexico, for which SSN and RESNOM are the key providers of information.

### RESNOM DATA THROUGH TIME

The RESNOM seismic network formally started operating in 1978 although systematically cataloguing the seismicity of northern Baja California initiated in 1976 (Frez and Frías Camacho, 1998). Early attempts of recording the seismicity of Northwestern Mexico by means of a seismograph network date as far back as 1969 (Lomnitz *et al.*, 1970; Brune *et al.*, 1976) with the installation of seismographic stations around the Gulf of California. RESNOM has been run since its initial stages by the Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE) with the objective of monitoring the activity of faults which traverse Northern Baja California and Northwestern Sonora. This network was one of the first in the world to operate with digital data transmission (the digital telemetric system

was implemented in 1977). Figure 1 shows the location of current stations, the geographical extent of the data in the catalog, as well as the main tectonic features in the region of interest. It is worthwhile noting here that seismicity north of the international border is outside the coverage of the network, although epicenters located by RESNOM are verified against those located by networks in the U.S. Additional data in this region, as provided by California networks, are also later added to the catalog.

As in other case studies (Zúñiga, 1989; Zúñiga and Wiemer, 1995; Zúñiga *et al.*, 2000) we start our analysis by looking at the temporal behavior of earthquake data. Figure 2a shows a histogram of number of events per year for all events listed in the catalog since start of compilation (end of 1976). It is important to mention that the catalog provides two estimates for magnitude, one based on duration ( $M_d$ ) and, for some events, another more accurate estimate (denominated  $M_{LR}$ ) determined from amplitudes of synthetic Wood-Anderson records (Vidal and Munguía, 1991; 1999). The time period and number of events covered by the latter technique, however, vary substantially and can not conform a complete set for our time analysis. Thus, we base the estimations of time changes on duration magnitudes only, since these estimates cover most of the registered events.

The histogram in Figure 2b, which includes data only for those events which have been assigned a duration magnitude, shows approximately the same general features than the previous graph. In particular, the behavior for the period after 1985 stands out due to the lack of contrast between both populations, which might lead one to conclude that all located events have been assigned a magnitude approximately from that date onwards. The comparison between both histograms also indicates that before 1986 the catalog contains a significant number of events which were not assigned a magnitude much in the manner which was observed for the SSN catalog, although the date in that case being 1988 (Zúñiga *et al.*, 2000).

However, considering the difference between the previous histograms (Figure 2c), the above observation is enhanced and subtle additional differences emerge. It is clear that after 1985 most events were assigned a magnitude, but the period 1986-1994 includes some events (less than 50/yr) which still lack magnitudes. We should point out, notwithstanding, that an estimate for  $M_{LR}$  is provided for some of those events. We can also see that this situation was corrected completely soon after 1995 since the difference is negligible.

We now turn our attention to the trend of located events analyzed by means of the cumulative number against time (seismicity rate). Such a graph provides many important

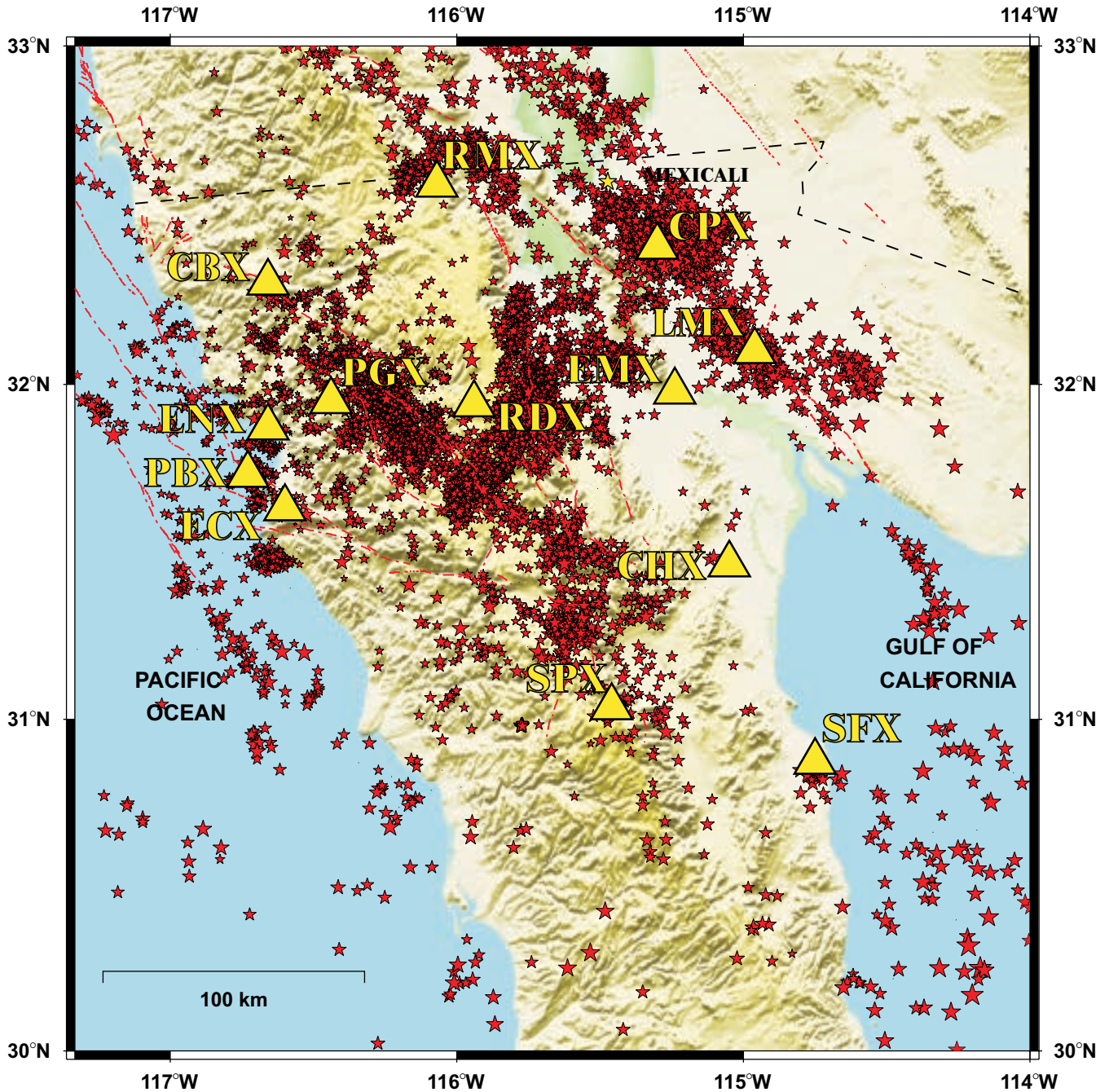


Fig. 1. Epicenter distribution spanning 1976-2001 from RESNOM catalog. Main faults in the area (red lines) and location of current stations (triangles) are also indicated.

pointers pertaining to the level of homogeneity in reporting, and the occurrence of natural or artificial variations. Figure 3 shows the cumulative number of events against time for various magnitude cutoffs. The variation in slope of the curves is an indication that possible changes in the reporting of events at that magnitude level may have taken place. From this we can conclude that there are various reporting changes which

have taken place during the network history, and which have affected most magnitude bands. We can also see that from approximately 1993 onwards, reporting has been quite homogeneous.

In order to obtain a quantitative estimate of changes in reporting with time, we used algorithm GENAS (Habermann,

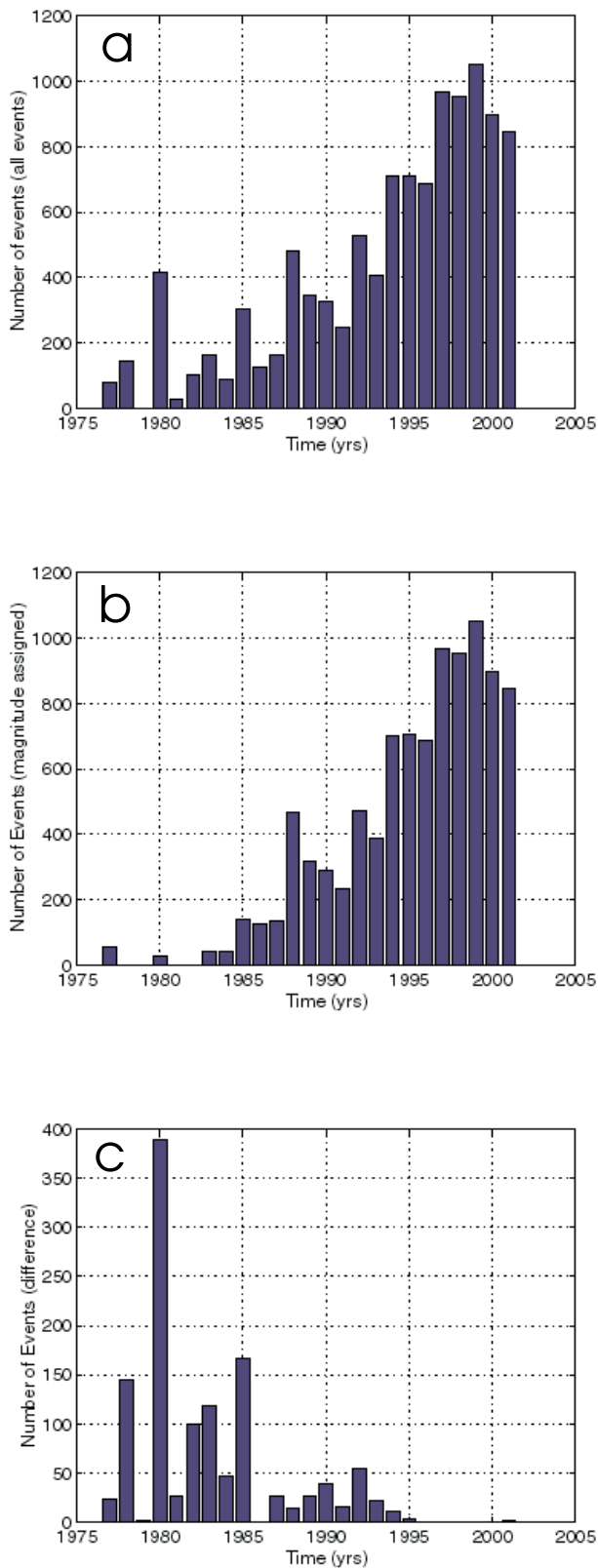


Fig. 2. a) Frequency histogram of number of events per year using all events listed in the catalog (*i.e.* all events located). b) As in a) but considering only those events which have been assigned a duration magnitude. c) Difference between histograms *a* and *b*.

1983). The algorithm rests on the assumption that only independent events are to be compared. Thus, we declustered the catalog using the approach of Reasenberg (1985) with the parameters in that study allowing for location errors. Events removed by the declustering are mostly related to the 1978 Victoria earthquake swarm, the aftershocks of the 1979 Imperial Valley earthquake and those of the 1980 Victoria earthquake, so data for the pre-1980 period is greatly reduced. For post 1980 dates, however, little change was produced by declustering.

GENAS algorithm identifies significant changes in seismicity rate (number of events larger and 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. Every time a significant change is found, the catalog is marked and split into two segments which are iteratively analyzed in the same fashion. The algorithm provides the times which stand out as the beginning of periods where increases and/or decreases of seismicity are detected as well as the magnitude range affected by these changes. This tool and others used later in this study were put together into a software package (*ZMAP*, Wiemer and Zúñiga, 1994; Wiemer, 2001) which allows a thorough investigation of a seismic record and the seismicity of a region.

Figure 4 shows the results of applying algorithm GENAS to the declustered RESNOM data set. The graph indicates the times (we will use decimal time from here on) for which changes are observed (horizontal lines) and the magnitude band (length of the horizontal lines) affected by them. Also indicated in the figure is the significance of the

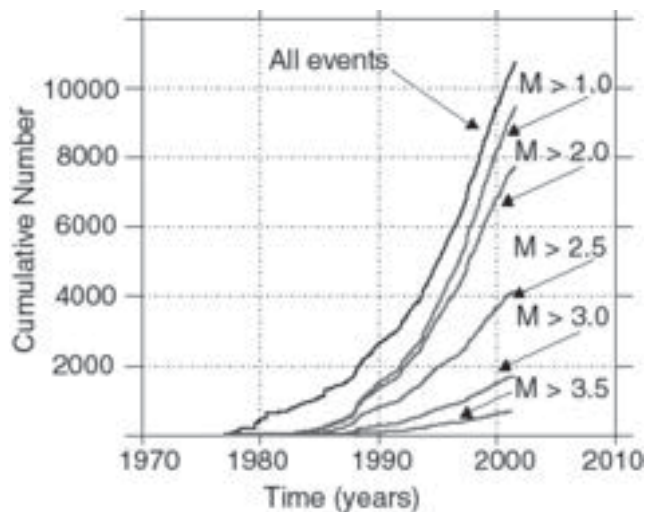


Fig. 3. Cumulative number of events Vs. time for selected magnitude cut-offs.



change using the Z-score (sometimes known as  $t_0^*$  test *e.g.* Hines and Montgomery, 1990) which essentially tests the significance of the difference between two means with unknown variance. According to this test, a Z-value larger than 2.5 would indicate that a difference in seismicity rate is significant with a confidence of 99% or better.

Changes which affect most magnitude bands, and in particular those pertaining to the larger events, can be used as evidence that an operational change has taken place at that time. According to the results of the algorithm as shown in the graph, the most significant changes took place around 1987.2, 1992.4, 1997.11 and 2000, although the latter, being close to the end of the catalog data, might be due to limitations of the algorithm. Since the number of events which have been assigned a magnitude is too limited for pre-1986 dates (see for example the curve for  $M > 1.0$  in Figure 3), we therefore restrict further analysis to data after

1986. We can thus use the reminding dates for additional tests.

The changes reported above could be due to various sources, for example differences in magnitude determinations, number of stations, changes in operative practices, etc.. A review of some of the most common sources of variations can be found in Zúñiga and Wyss (1995). The problem of more accurate magnitude determinations for Baja California events has been tackled by other authors (Munguía and Brune, 1984; Vidal and Munguía, 1991; 1999). Their main objective, however, was set on improving the method of determination of magnitudes, the calculation of station residuals and of differences between magnitudes provided by RESNOM as compared to those of the Southern California network. A systematic analysis of the temporal characteristics of routinely computed magnitudes had not been carried out until now.

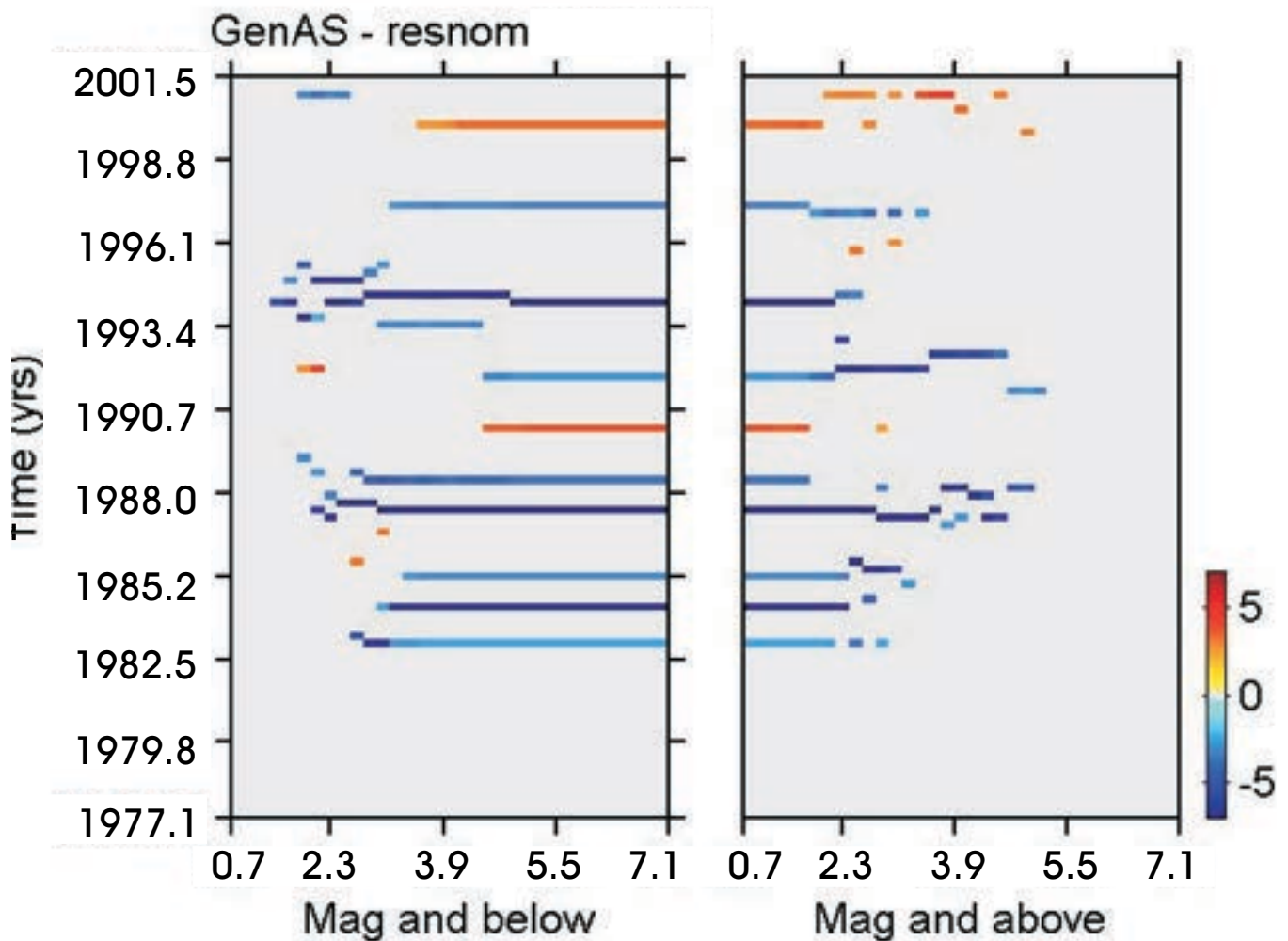


Fig. 4. Results of algorithm GENAS for the declustered RESNOM catalog. The bars indicate that a significant change has taken place and the extent of the line is the magnitude band affected by it. The color of the horizontal lines indicate the Z value according to the scale shown on the lower right. Positive values are decreases in the number of events with time while negative values indicate increases.

### COMPARISON BETWEEN REPORTING AT DIFFERENT TIME PERIODS

We analyzed the seismicity as a function of magnitude for consecutive time intervals bounded by the dates found in the previous stage. Figure 5 shows the cumulative (*i.e.* Gutenberg Richter curves or G-R) and non-cumulative frequency-magnitude (FM) distributions for two time intervals: 1987 - 1992.4 as compared to 1992.4 - 1997.11. Figure 5a shows the original data. The panels at 5b and 5c show the result of applying a rate increase factor and different selection criteria. The direct comparison of both intervals (Figure 5a) shows a marked difference in both the G-R distribution as well as in the non cumulative histogram. It is also clear that the number of located events during the preceding interval is much lower than that of the subsequent interval at all magnitude bands but in particular for  $M_d \leq 3.0$ . If we look again at the histograms in Figures 2a and 2b, we can corroborate that the number of located events per year was much

lower for dates before 1992.4. Notwithstanding, yearly seismicity maps (Frez and Frías Camacho, 1998) do not reflect a clear major change in epicenter distribution. We also notice that there is a conspicuous flat trend in the magnitude band of 2.2 - 2.6 for events recorded during the background interval (best seen in the non-cumulative distribution of Figure 5a) which might be linked to operative practices, although 2.6 could be considered the minimum magnitude of completeness for that period (this is discussed later on). Furthermore, it is our knowledge that there was neither a change in the relation used to compute magnitudes nor in the analysts in charge of reading the phases. We inspected the locations of these events and were unable to identify a region that would include a particular high seismicity increase.

We thus performed an event count on four randomly selected months of each year during the period 1987 to end of 1992, according to the bulletins of RESNOM, and calculated the percentage of located to registered events. The re-

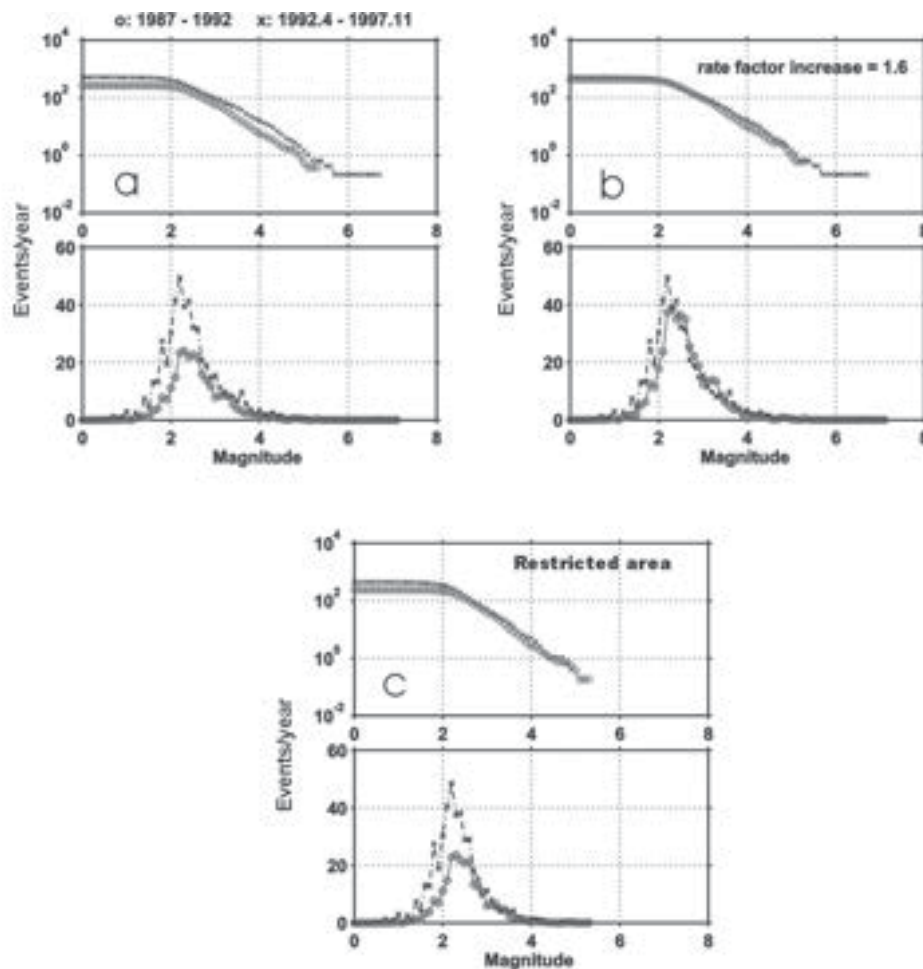


Fig. 5. Cumulative (upper frames) and non-cumulative (lower frames) Frequency-Magnitude distributions of events for the periods 1987-1992.4 (circles) as compared to 1992.4-1997.11 (crosses). a) Original distributions. b) Results of applying a positive magnitude correction of 0.25 units to the data in the first interval. c) Results of applying a linear magnitude correction to the data in the first interval (see text). d) Results of multiplying the number of events per magnitude bin in the first interval by a factor of 1.6.

sults indicate that this percentage varied between 31 and 87, with an average of 53% for the interval (see Table 1). The azimuthal coverage of the network did not allow for the location of all events which were registered. Thus, we decided to test the effect of a rate increase of 60% (shown in Figure 5b). The G-R curves and the non-cumulative F-M distributions match one another well providing support to this being the reason for the observed change. Such an effect might be expected since once new stations were installed the overall locating record should improve.

However, another possibility was that improvement in the capability of the network was reflected on its ability to locate events that fell further away from the area of best resolution. Therefore we performed an additional comparison, this time restricting data to those events which laid within the region of best azimuthal coverage, *i.e.* from Latitude 31° to 33°N, Longitude from 114.8° to 118°W. This region was determined using the minimum magnitude of completeness ( $M_c$ ) as selection criteria and it was in agreement with  $M_c$  maps that we discuss in a following section. The panel in Figure 5c shows the comparison between the two intervals for the restricted region. It is immediately apparent that focusing on the region of best network resolution greatly improves the fit without any preconceived assumptions. Even though there is still a minor deficiency in the number of events with  $M_d < 3.0$ , which we could be related to improvements in instrumentation, we can conclude that the change in located seismicity before early 1992 is mainly affecting events located farther away from the network.

If we now look at the data from 1992.4 to 1997.11 as compared to that from 1997.11 to 2001.5 (Figure 6), given that 1997.11 is the last major change found by algorithm GENAS, we can see little difference in terms of the slope of the G-R curve and general shape of the non cumulative distribution. The main difference is in the number of events for

magnitudes below 3.5 which is 38% lower for the previous interval than current counts. We could attempt to correct for the slight difference in  $b$  value observed by a linear correction in magnitude as discussed in Zúñiga and Wyss (1995) but our experience has shown us that a correction for such a small change in  $b$  value is not warranted. Furthermore, the data do not support an actual  $b$  value change since the slope of the G-R curve is approximately the same in both periods for the magnitude interval 2.5-4.0. Thus, our analysis indicates that in the first months of 1997, the network was sub-

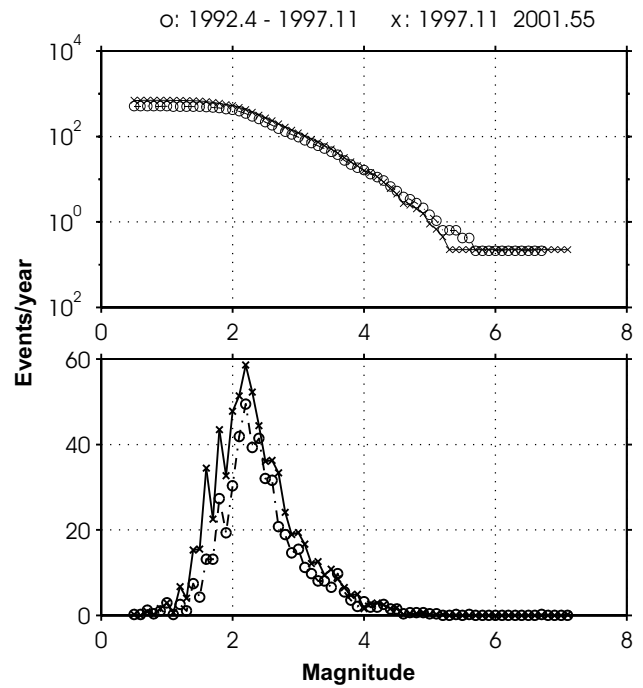


Fig. 6. Cumulative (upper frame) and non-cumulative (lower frame) Frequency-Magnitude distributions of events for the periods 1992.4-1997.11 (circles) as compared to 1997.11 2001.55 (exes).

Table 1

Results of events count for four randomly selected months in the interval 1987 to end of 1992. On the average, over the 6 years, 53.2 % of the events recorded were located. The events registered are those reported in the bulletins

Year	Months sampled	Events registered (R)	Events located (L)	$M_d$ (Located Events)	% L/R	$M_d$ (Events not located)
1987	1,3,7,11	293	91	1.6<M<5.5	31.05	1.5<M<4.7
1988	2,4,8,12	358	175	1.4<M<5.0	48.88	1.1<M<5.5
1989	5,6,9,10	246	120	1.2<M<4.7	48.78	1.1<M<4.7
1990	1,3,5,7	135	72	1.3<M<4.5	53.33	1.2<M<4.5
1991	2,4,6,8	117	91	1.2<M<5.7	77.77	1.5<M<4.6
1992	9,10,11,12	182	159	1.5<M<4.9	87.36	1.8<M<5.9

jected to another change which improved the threshold of detection for events with  $M < 3.5$  without further affecting the magnitude determinations.

### COMPARISON BETWEEN RESNOM, PDE AND SSN MAGNITUDES

As an additional step which can help merge data from other catalogs we compared  $M_d$  data from RESNOM to  $m_b$  from PDE for the same region. The RESNOM data covered the period 1988 – 2002 while that of PDE was obtained from 1973 – 1997. It is worthwhile noting that even though the latter has a higher minimum magnitude threshold this is not an issue when you compare both FM distributions since they are normalized to one year. We employed the technique described in Zúñiga and Wyss (1995) for comparing two  $b$ -value distributions and we found that in order for both magnitudes to yield the same  $b$  value,  $M_d$  data has to be shifted by +0.1. That is, a correction suitable for  $M_d$  data to match PDE values is:

$$m_b(\text{PDE}) = M_d(\text{RESNOM}) + 0.1 .$$

The results of such correction are shown in Figure 7. We can see that even though the two distributions were originally not too far apart, and a corrective factor could be arguable, a better fit is obtained by means of the proposed correction.

We can not perform a direct comparison between events in the SSN catalog with those of RESNOM because SSN does not have good enough resolution in the region covered by RESNOM and the populations differ markedly. However, since SSN magnitudes were found to be basically equivalent to PDE  $m_b$  magnitudes (Zúñiga *et al.*, 2000) for the range  $M_d \leq 5.0$  we can affirm that the same correction could be applied to RESNOM magnitudes in order to merge the data with that of SSN.

### MINIMUM MAGNITUDE OF COMPLETENESS ( $M_c$ )

#### Time variability

The following step in our study was estimating the minimum magnitude for which the catalog can be considered com-

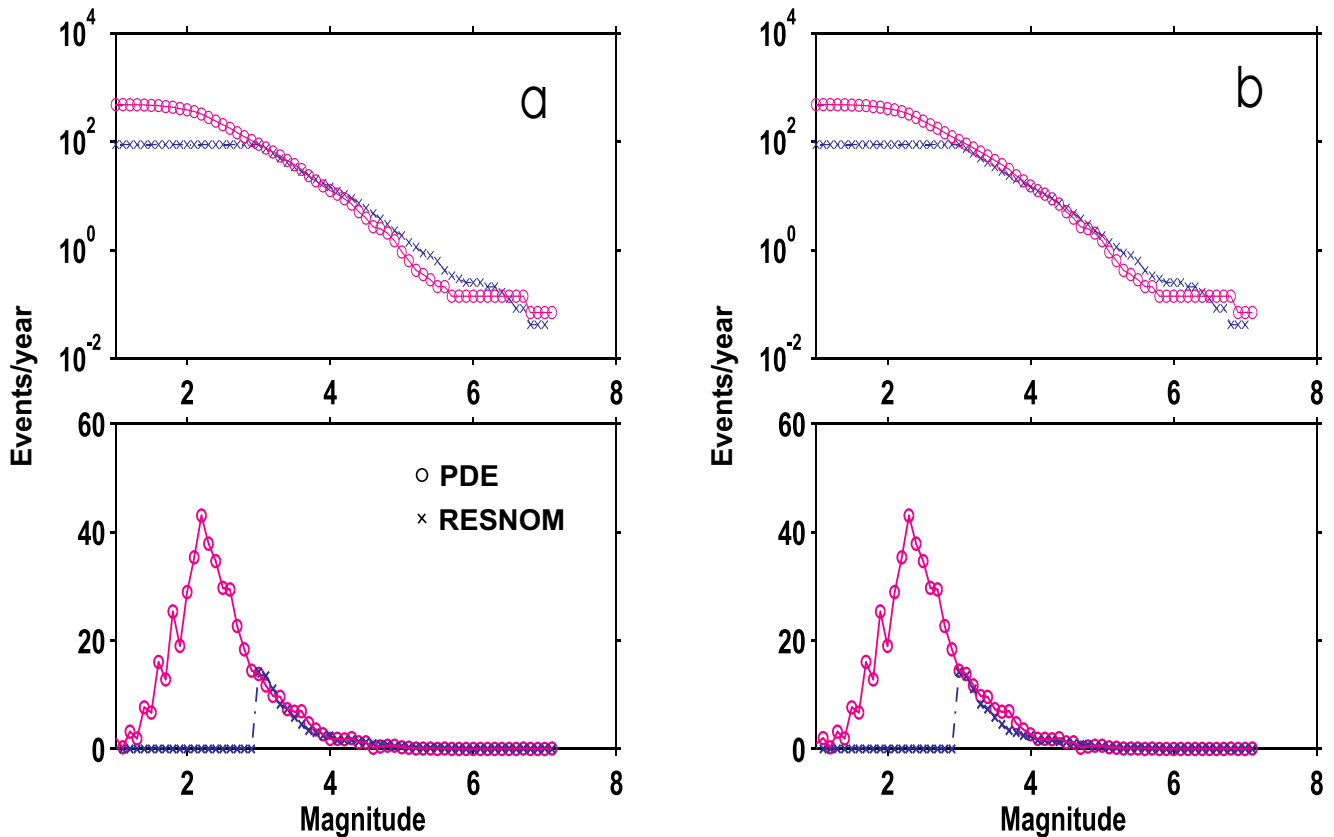


Fig. 7. Comparison between cumulative (upper frames) and non-cumulative (lower frames) frequency-magnitude distributions obtained from RESNOM  $M_d$  magnitudes (circles) against  $m_b$  from PDE (exes) for the same region. The left frames (a) show the original data while the right frames (b) show the comparison after a correction of 0.1 units applied to RESNOM magnitude data.



plete ( $M_c$ ). A very common procedure for determining the threshold or minimum magnitude is to consider the magnitude for which data departs from the linearity of the G-R law with some allowances for uncertainty. Figure 8 is a graph showing the G-R law for the whole catalog, for which the overall  $b$ -value has been found by the maximum likelihood approach (Aki, 1965), giving  $b = 0.73 \pm 0.03$ . Assuming  $M_c$  as the magnitude for which the FM departs from linearity by more than two standard deviations, we thus obtained a preliminary value of  $M_c = 2.2$ .

However, since this type of estimate has been found to give results which may not be too accurate, we employed another technique proposed by Wiemer and Wyss (2000) which makes use of a comparison between the observed FM distribution and synthetic power law distributions calculated as a function of a minimum magnitude. The actual minimum magnitude of completeness is that which gives the lowest residuals between both at acceptable confidence limits. Figure 9 shows the outcome of this procedure. According to these results we can use  $M_c = 2.1$  with a confidence of 90%, although  $M_c = 3.3$  is the best choice for a confidence of 95%.

The value for  $M_c$  obtained before, can be used when it is necessary to use the complete data set, without regard for time and space variations. Nevertheless, it is important to

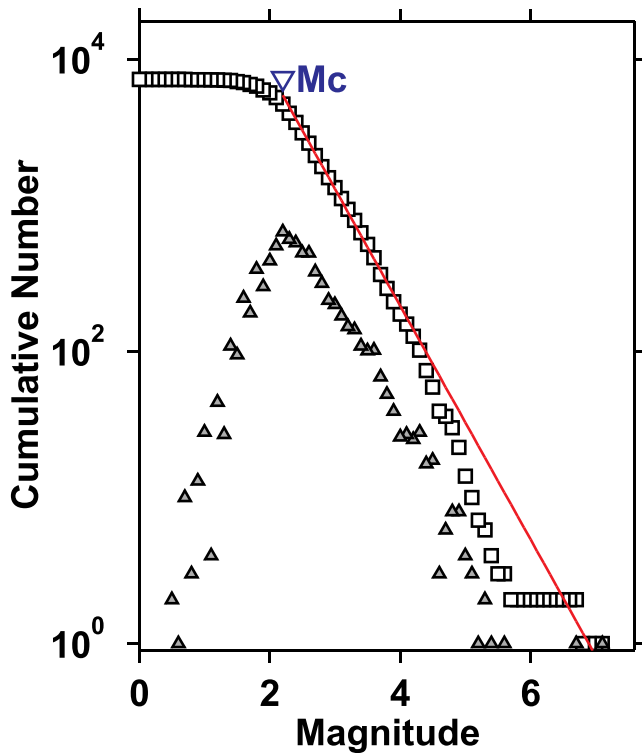


Fig. 8. Cumulative frequency (squares) and non-cumulative frequency (triangles) Vs. Magnitude for the RESNOM data set.  $M_c$  = minimum magnitude of completeness.

know if there are periods when the magnitude threshold has been improved and for how long. It is also necessary to distinguish the regions for which  $M_c$  is low from those for which, due to poor station coverage, the threshold is exceeded.

For purposes of investigating the time dependence on minimum magnitude, we used an iterative calculation of  $M_c$  employing small subsets of the catalog starting at different incremental times. Figure 10 shows the time variation of  $M_c$  for small subsets of 500 events per calculation. We also used different number of events to define the subsets, but the general features remained the same as those in Figure 10. It can be seen that in recent times  $M_c$  has reached values as low as 1.6 but with an erratic behavior which tends to go back to overall values of 2.2 – 2.3. We interpret this observation as evidence that there has been an improvement on the overall registering threshold although routine operation still needs to reach a consistent state in order to keep the minimum magnitude of reporting constant.

#### *Spatial variability of $M_c$*

In the previous step we determined that a reasonable overall estimate of  $M_c$  for the RESNOM catalog is 2.4 and that in recent years,  $M_c$  has been improved to values as low as 1.6. But, what about the spatial extent of these estimates? are they reliable throughout the coverage of the network?

In order to answer these questions we analyzed the spatial variability of  $M_c$  using a gridding technique employed for these and other purposes (*e.g.* Wiemer, 2000).

The technique relies on the calculation of the seismicity associated to each one of the nodes of the grid. The seismicity around the node is defined by considering a fixed number of events located nearest to that node. For our study we used the 150 nearest events. It is clear that a low density of data around some nodes will result in larger sampling regions, but by keeping the number of events constant a comparison between neighboring nodes is more robust.

In our case we selected events around grid nodes separated every 0.07 degrees in the manner previously described. Then, we calculated the  $b$ -value distribution for each node set by the maximum likelihood method (Aki, 1965).

In Figure 11 we show the spatial variation of  $M_c$  for the interval 1977 to 2001.5. As expected, the maximum resolution is found towards the highest density of stations of the network, around 32°N and 116.5°W. Some offshore areas nearby indicate values just as good. The worst resolution is towards the north, although this area includes events which are not located at CICESE but contributed by California networks; and the southeast, where station coverage is poor.

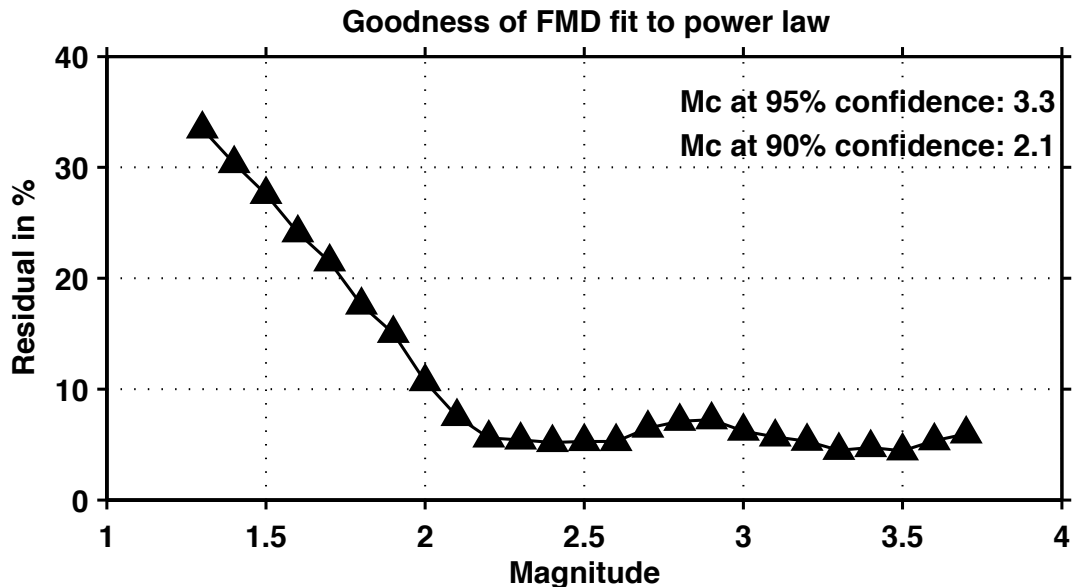


Fig. 9. Goodness of fit of FM to power law with different  $M_c$  cutoffs.

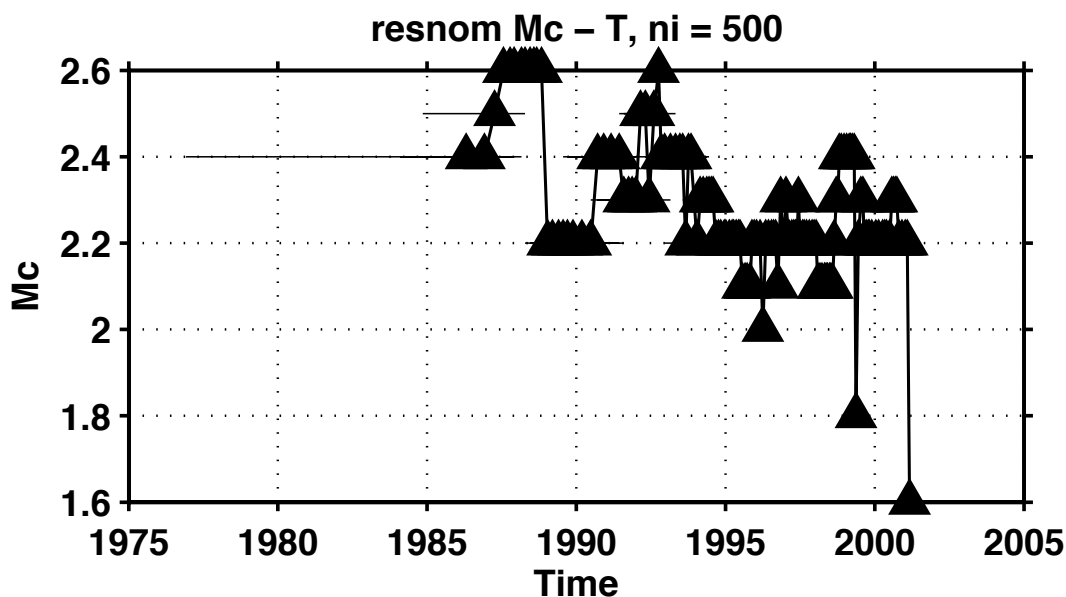


Fig. 10. Minimum magnitude as a function of time for small subsets of the catalog. In this calculation we used 500 events for every time step.

Another way of demonstrating the improvement of the network capabilities through time is by looking at the minimum magnitude for the time intervals identified previously. We consider only recent periods for which reporting has been more steady according to our previous calculations (compare for example with Figure 2). Figure 12 shows the spatial variation of  $M_c$  for the intervals 1987.2 – 1997.11 and 1997.11 to 2001.5 as well as the difference between both.

One thing to notice in Figure 12 is the growth of the area with the best resolution, in particular the region with

values of 1.5 to 2.0 (dark blue). Furthermore, differences in resolution of up to one magnitude unit (Figure 12c) have been reached, confirming results obtained before. It is interesting to note that the area to the east, *i.e.* the NW limit of the state of Sonora, shows a negative difference in  $M_c$  which implies that resolution has worsen in that area at recent times.

#### DISCUSSION AND CONCLUSIONS

Different stages in reporting which affect the consistency and homogeneity of RESNOM data were found in this

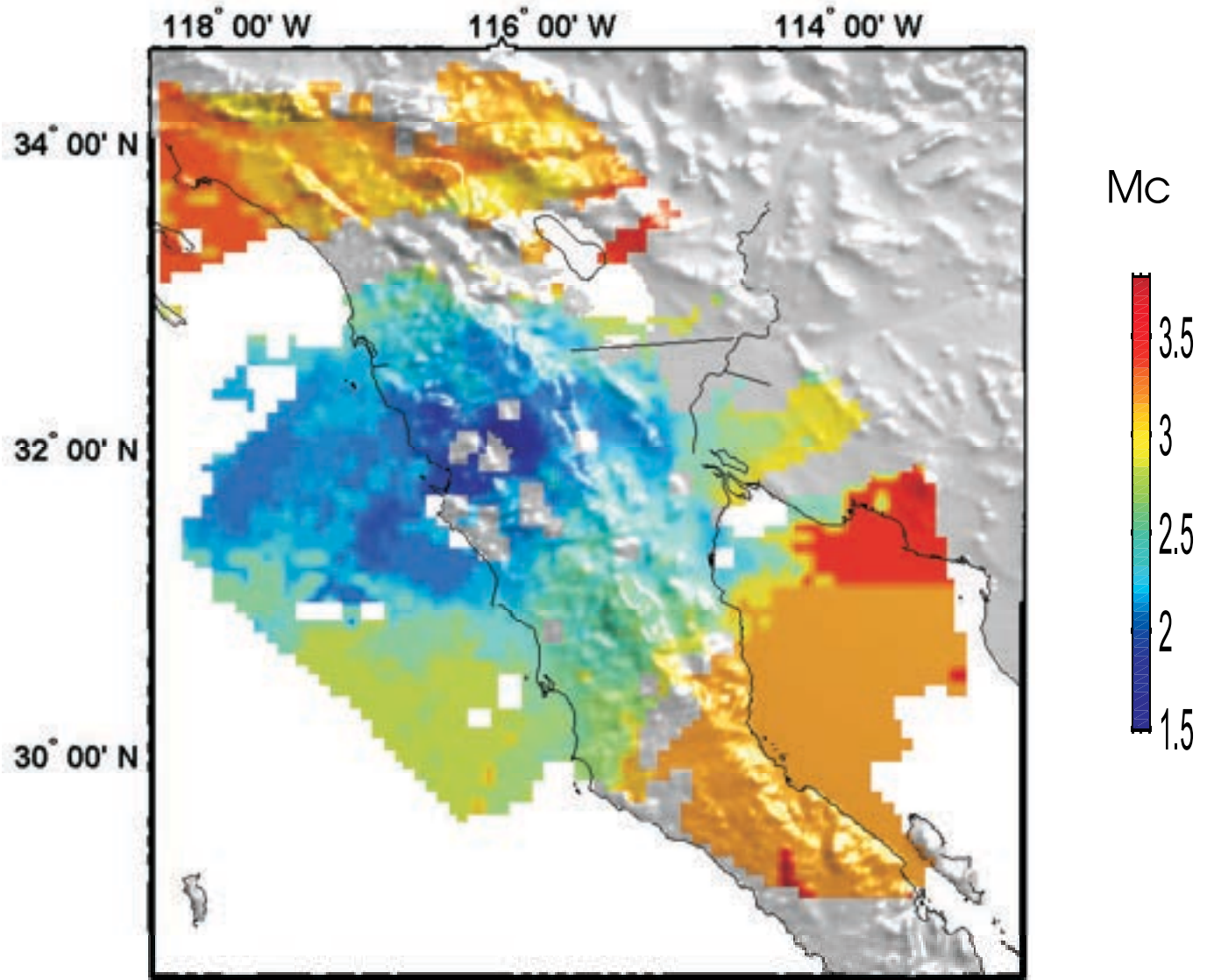


Fig. 11. Spatial variability of  $M_c$  for the declustered catalog. Time interval depicted is 1977 – 2001.5.

study. These stages are common occurrence in seismicity catalogs, since operative practices change through time. Using a systematic analysis we obtained approximate dates for which significant changes in the seismicity record are observed. By analyzing the frequency magnitude distributions of consecutive time intervals we speculate that the difference in the number of events registered from 1987 to 1992.4 as compared to those registered later, may be due to a change in the ability of the network to locate events further away from the area of best resolution. Our analysis also indicates that in the first months of 1997, the network was subjected to additional changes which improved the threshold of detection for events with  $M_d < 3.5$ . This change, however, did not introduce a significant difference in the determination of magnitudes.

By comparing the FM distribution obtained from  $M_d$  magnitudes calculated by RESNOM with that obtained from  $m_b$  magnitudes determined by PDE we found that in order for both magnitudes to yield the same  $b$  value,  $M_d$  data has to be shifted by +0.1. Since previously it had been found that magnitudes determined by SSN are equivalent to those of PDE, the same correction could conceivably be used to homogenize both data sets.

The resolution of the network has also been found to improve steadily in time. We showed that in the most recent period of reporting, *i.e.* after 1997, the network detection capability was good enough to report consistently events with magnitude as low as 1.6. Our results also indicate that such values were attained in the region where station density is

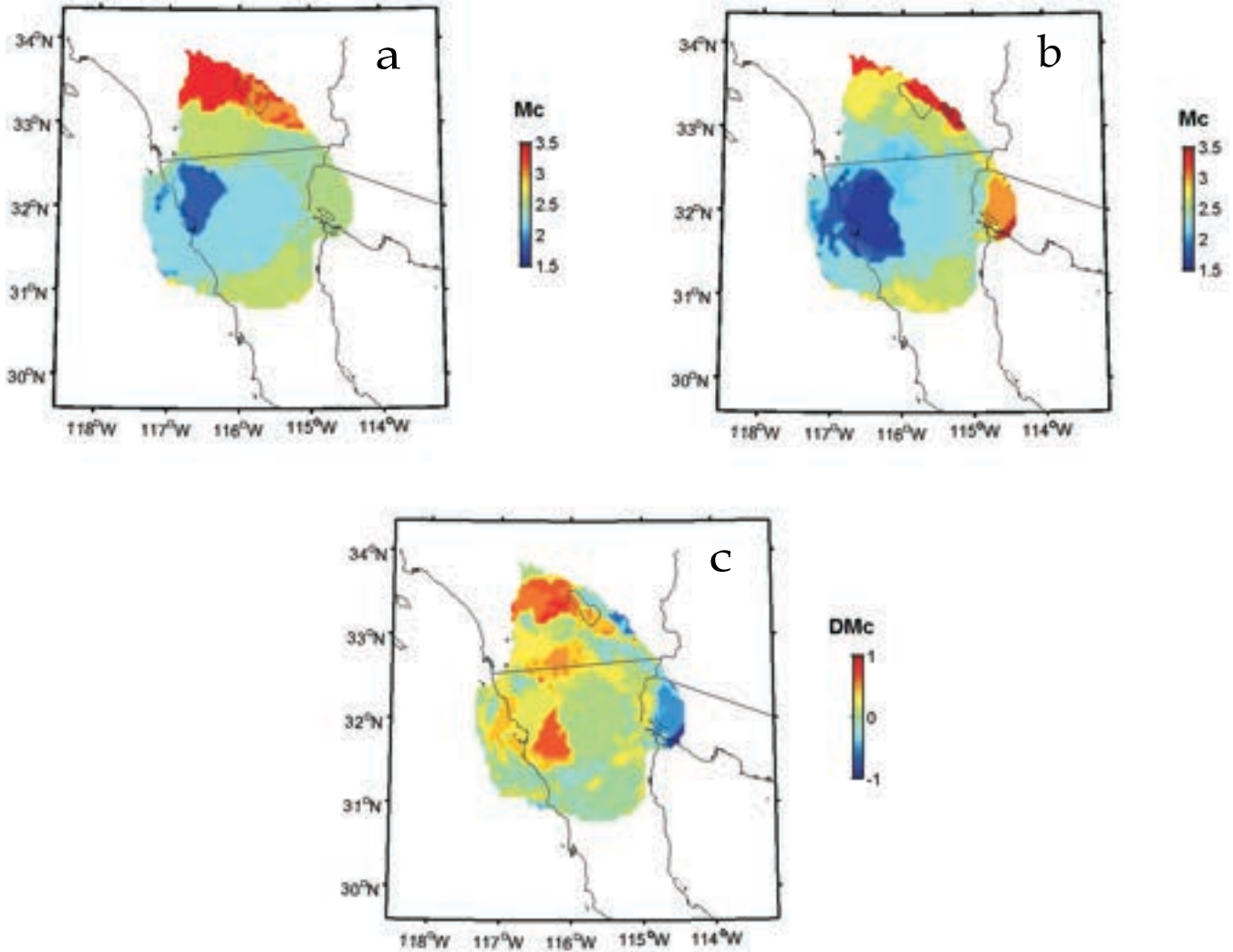


Fig. 12. Spatial variability of  $M_c$  for the two latest time stages defined in previous sections. a) Time interval depicted is 1987.2 – 1997.11. b) Time interval depicted is 1997.11 – 2001.5. c)  $M_c$  difference between both (positive differences are set to show improvement, *i.e.* indicate lower  $M_c$  for the most recent period as compared to before) .

highest (around 32°N and 116.5°W), and that through time this region has grown steadily. Other regions still lack that capability so it may be important to attempt adding stations or change the distribution of current stations in those areas in order to reach the quality of resolution found near the region mentioned above.

Some of the changes outlined appeared to take place at the beginning of the year, which is a time when keeping stations in good operation order is harder due to various operative limitations of RESNOM. In some instances the maintenance budget for RESNOM is already drained out by the end of the year, making it necessary to implement unwanted decisions regarding which stations to serve first. This study may help to overcome this situation by highlighting the importance of keeping all the stations working properly, so that the seismicity record of Northern Mexico is well portrayed

by the data in the catalog. We can not stop stressing the importance that such data bears on seismic risk estimates for that region, which is one of the most active and with higher hazard of Mexico.

#### ACKNOWLEDGEMENTS

We wish to acknowledge the importance of the work carried out by all of the staff of the RESNOM Working Group in tending stations, reading records and compiling data which keeps the network operating, since this is the core of our work and provides the backbone of civil emergency preparedness programs. We also want to thank an anonymous reviewer who pointed out the correspondence between our results and the values reported in the bulletins, and whose comments helped us to improve the presentation of our findings. We thank Luis Inzunza for helping us to inspect the bulletins of

RESNOM. This study was carried out with support from UNAM-DGAPA program thorough project IN-122602.

### BIBLIOGRAPHY

- AKI, K., 1965. Maximum likelihood estimate of  $b$  in the formula  $\log N = a - bM$  and its confidence limits. *Bull. Earth. Res. Inst. Univ. Tokyo*, 43, 237-239.
- BRUNE, J. N., C. LOMNITZ, C. ALLEN, F. MOOSER, F. LEHNER and A. REYES, 1976. A permanent seismograph array around the Gulf of California, *Bull. Seism. Soc. Am.*, 66, 969-978.
- FREZ, J. and V. M. FRÍAS-CAMACHO, 1998. Mapas anuales de sismicidad para la región fronteriza de ambas Californias, *GEOS, Unión Geof. Mex*, 18, 112-130.
- HABERMANN, R. E., 1982. Consistency of teleseismic reporting since 1963. *Bull. Seism. Soc. Am.*, 72, 93-112.
- HABERMANN, R. E., 1983. Teleseismic detection in the Aleutian Island Arc, *J. Geophys. Res.*, 88, 5056-5064.
- HINES, W. W. and D. C. MONTGOMERY, 1990. Probability and Statistics in Engineering and Management Science, 3rd. Ed., John Wiley and Sons Eds..
- LOMNITZ, C., F. MOOSER, C. R. ALLEN, J. N. BRUNE and W. THATCHER, 1970. Seismicity and tectonics of the northern Gulf of California region, Mexico: preliminary results. *Geofís. Int.*, 10, 37-48.
- MUNGUÍA, L. and J. N. BRUNE, 1984. Local magnitude and sediment amplification observations from earthquakes in the northern Baja California-southern California region. *Bull. Seism. Soc. Am.*, 74, 107-119.
- REASENBERG, P. A., 1985. Second-order moment of central California seismicity, 1969-1982. *J. Geophys. Res.*, 90, 5479-5495.
- VIDAL, A. and L. MUNGUÍA, 1991. Local magnitude and source parameters for earthquakes in the Peninsular Ranges of Baja California, México. *Bull. Seism. Soc. Am.*, 81, 2254-2267.
- VIDAL, A. and L. MUNGUÍA, 1999. The ML scale in northern Baja California, México. *Bull. Seism. Soc. Am.*, 89, 750-763.
- WIEMER, S. and F. R. ZÚÑIGA, 1994. ZMAP - a software package to analyze seismicity, EOS, Transactions, Am. Geophys. U., 75, 456.
- WIEMER, S. and M. WYSS, 2000. Minimum Magnitude of Completeness in Earthquake Catalogs: Examples from Alaska, the western US and Japan. *Bull. Seism. Soc. Amer.*, 90, 859-869.
- WIEMER, S., 2001. A software package to analyze seismicity: ZMAP. *Seism. Res. Let.*, 72, 3, 373-382.
- ZÚÑIGA, F. R., 1989. A study of the homogeneity of the NOAA earthquake data file in the Mid-America region by the magnitude signature technique. *Geofís. Int.*, 28, 103-119.
- ZÚÑIGA, F. R. and M. WYSS, 1995. Inadvertent changes in magnitude reported in earthquake catalogs: Influence on  $b$ -value estimates. *Bull. Seism. Soc. Amer.*, 85, 1858-1866.
- ZÚÑIGA, F. R. and S. WIEMER, 1995. Variaciones artificiales de sismicidad y su evaluación. Algunos ejemplos en México. *In: La Sismología en México, 10 Años después del temblor de Michoacán del 19 de septiembre de 1985, Monografía No.2, Unión Geofísica Mexicana, F. Medina, L. Delgado and G. Suárez, eds.*, 100-110.
- ZÚÑIGA, F. R., C. M. VALDÉS and M. REYES, 2000. A general overview of the catalog of recent seismicity compiled by the Mexican Seismological Survey. *Geofís. Int.*, 39, 161-170.

---

F. Ramón Zúñiga<sup>1</sup> and Raúl R. Castro<sup>2</sup>

<sup>1</sup> Centro de Geociencias, UNAM Campus Juriquilla, Querétaro, Querétaro, 76230, México  
Email: ramon@geminis.unicit.unam.mx

<sup>2</sup> Centro de Investigación Científica y Educación Superior de Ensenada, Ensenada, Baja California, 22860, México