Journal of South American Earth Sciences 155 (2025) 105415

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

A method for estimating the coverage of a seismic network: RESNOM

F. Alejandro Nava[a], Lenin Ávila-Barrientos[a,b,*], Luis Munguía[a], Maria A. Núñez-Leal[a], Francisco Farfán[a]

[a] Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California, División de Ciencias de la Tierra, Departamento de Sismología, Carretera Ensenada – Tijuana No. 3918, Zona Playitas, C. P. 22860, Ensenada, Baja California, Mexico

[b] Dirección Adjunta de Investigación Humanística y Científica, SECIHTI, Av. Insurgentes Sur 1582, Col. Crédito Constructor, Alcaldía Benito Juárez, C. P. 03940, Ciudad de México, Mexico

ARTICLE INFO

Keywords:
Seismological network coverage
Minimum magnitude
RESNOM
Baja California

ABSTRACT

A new, simple, straightforward, and intuitive method for assessing the coverage of a seismic network, by estimating the minimum *measurable* magnitude, i.e., the magnitude corresponding to the smallest identifiable, and quantifiable signal, at any point of the region being monitored, is presented. The method takes advantage of the knowledge implicit in the magnitude determination scheme routinely used by the network, and uses the minimum measurable value of the parameter used at each seismic station to quantify the magnitude, which for different magnitudes may be maximum amplitude, duration, energy, etc. The method is illustrated by application to the RESNOM seismological network that monitors the seismically active region of north-western Baja California, Mexico, and uses synthetic Wood-Anderson seismograms to estimate M_L for small earthquakes. The results, besides identifying regions where more or better seismographic stations are needed, indicate that the observed groupings and gaps in the epicentral distribution are real features of the seismic processes in the region and not artifacts due to coverage.

1. Introduction

The coverage of a seismic network is the network's capability of identifying seismic events, locating them, and estimating their magnitude over the monitored region. Since the smallest earthquakes are the hardest ones to locate and measure, we will estimate the capability by determining M_{min}, the lowest magnitude that can be correctly identified, located, and quantified for each point of the study region. A strict definition of M_{min}, together with a discussion of the implicit assumptions, will be given below. Estimation of the seismic coverage is necessary for the correct interpretation of the observed seismicity for seismotectonics and seismic hazard studies. For instance, it is necessary to know whether the seismicity groupings and gaps observed in the region used as an example (Fig. 1) are real or are an artifact of coverage.

Several methods of evaluating seismic coverage have been proposed. Many methods estimate coverage by means of M_c, the lowest magnitude at which 100% of the earthquakes in a space-time volume is detected (Rydelek and Sacks, 1989; Zúñiga and Wyss, 1995; Mignan and Woessner, 2012). This method has been widely used (e.g., Wiemer and Wyss, 2000; Mignan et al., 2011; Mignan and Woessner, 2012; Puspito et al., 2023) but presents some problems. One is the problem of determining the correct M_c, and many different methods of doing it have been proposed (Woessner and Wiemer, 2005; Amorèse, 2007; Schorlemmer et al., 2010; Mignan and Woessner, 2012; Fischer and Bachura, 2014; Huang et al., 2016; Kijko and Smit, 2017; Herrmann and Marzocchi, 2021; Lombardi, 2021), including Bayesian methods (Mignan et al., 2011; Mignan and Chouliaras, 2014; Feng et al., 2022). Rydelek and Sacks (1989) use the difference in the numbers of events with small magnitudes recorded by day or by night, differences attributed to lower noise levels during the night, to estimate M_c. The detection capability of seismic networks has also been estimated through a probability-based magnitude of completeness (Ringdal, 1974; Schorlemmer and Woessner, 2008; Nanjo et al., 2010; Schorlemmer et al., 2010).

A second problem is that an M_c measurement is representative of a 4D space-time volume, and because a reliable estimation of M_c needs many data, in many cases having enough data requires large observation times and/or large spatial volumes, which translates into poor temporal (b and, hence, M_c change with time), and/or geographical definition (a

* Corresponding author. Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California, División de Ciencias de la Tierra, Departamento de Sismología, Carretera Ensenada – Tijuana No. 3918, Zona Playitas, C. P. 22860, Ensenada, Baja California, Mexico.

E-mail address: lenavila@cicese.mx (L. Ávila-Barrientos).

https://doi.org/10.1016/j.jsames.2025.105415
Received 18 December 2024; Received in revised form 7 February 2025; Accepted 10 February 2025
Available online 11 February 2025

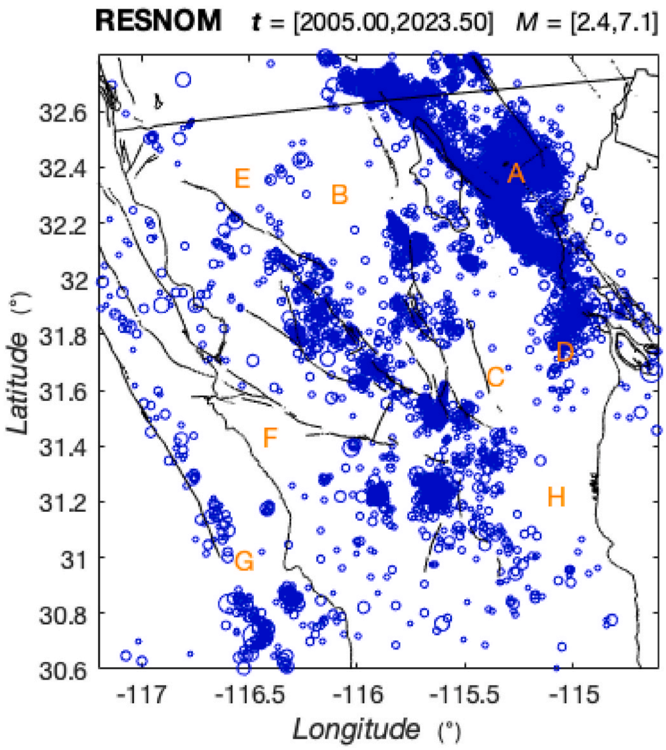

Fig. 1. Seismicity of northern Baja California reported by the RESNOM network. Circles indicate epicenters sized proportionally to their magnitude. Continuous black lines are coastlines, Colorado river, principal faults, and the international Mexico-USA border (Cruz-Castillo, 2002). Letters indicate groupings and gaps that will be referred to in the Discussion section, but roughly speaking indicate, based on results shown below: A and important grouping in spite of $M_{min} \sim 3.06$, B, C, E, and F are gaps in regions of good coverage, D and G are well-defined lineations in spite of poor coverage, and only H could be an apparent gap due to poor coverage.

large area can include more than one seismogenic regions with different characteristics). Some people make estimates based on absurdly few data (as few as four) but their results are, of course, unreliable. Thus, although an M_c measurement may be assigned to point at a given time, it is actually representative of a spatial volume around the point and of the seismic history before the time.

About M_{min}, on an empirical Gutenberg-Richter histogram, there are many data with magnitudes below M_c that have been identified and located by the seismic network and, although the identified events with these magnitudes are only a fraction of the total number, the observed ones may yet provide valuable information about the seismic process. For instance, some small earthquakes with magnitudes below M_c may indicate previously unidentified activity on a given fault or volcano, and this information may be quite important, independently of the fact that not all earthquakes with these small magnitudes are being identified all over a region. Hence, it is important to know how small an event can be identified at any given point of the geographical area under consideration, and the smallest event that can be identified at any given point is our target M_{min}.

Other, rather complicated methods for evaluating coverage at a given point (some of them also estimating M_c) involve using synthetic seismograms (which requires sufficient knowledge about the velocity structure) and determining signal/noise ratios (e.g., D'Alessandro et al., 2011; D'Alessandro and Ruppert, 2012; D'Alessandro and Stickney, 2012).

Gomberg (1991) estimates minimum magnitudes starting, as we do, from the magnitude formula, but proceeds to look for the minimum magnitude that corresponds to the minimum amplitude at the closest station, assumes distance correction is null, and uses an average amplitude. Another method that is somewhat similar to ours and uses the magnitude formula is that of Möllhoff et al. (2019), but theirs is based on seismic noise assessments and different criteria. Schorlemmer and Woessner (2008) also use the network's magnitude estimation formula, but they use it to express distance differences in terms of magnitude differences to select events to be used for probability evaluation.

In what follows we propose a simple method for determining M_{min} for each point of the area covered by a seismic network. The main advantages are its simplicity and a minimum use of assumptions. Only two parameters are used, and they can be tailored to the particular characteristics of a given network or to the preferences of the users.

2. Method

The method we propose is based on the definition of M_{min}, the lowest magnitude that can be correctly identified, located, and quantified ("measured" for short) for each point of a study region monitored by a seismic network. M_{min} is estimated by answering the question 'What is the magnitude that, occurring at a given distance from a particular station, would result in the minimum measurable signal for the station?' The answer is, of course, 'The magnitude that would be assigned to the minimum signal at that distance by the magnitude estimation procedure of the network'.

Our method is applicable to any seismic network that has an established procedure for estimating magnitudes and a store of seismic time series or seismograms (whichever is used for location and magnitude estimation). The method is extremely simple, because it is based on the network's magnitude estimation routine, and thus takes advantage of all the studies on velocity models, attenuation functions, station corrections, azimuthal corrections, etc. that have been made for the magnitude estimations and are routinely implicitly applied.

The method consists of nine steps, of which the first two are critical and require the participation of people with expertise in reading seismograms.

1. For each station, the recorded seismograms are reviewed to determine which is the smallest amplitude for events to be distinguishable from noise well enough for arrival times to be determined, so the event could be eventually located.
2. For the chosen events, measure the parameter used in the magnitude determination for small events and save the smallest value. It is important that the parameter be measured using the same procedure that is routinely used by the network.
3. Select the points in space for which the minimum magnitudes will be estimated. These points can be chosen arbitrarily, but we use a grid, with spacing $\delta Lon \times \delta Lat$, to cover the study region, and estimate the magnitude detection level at each point of the grid.
4. For a postulated source depth, for each grid point the hypocentral distance r (km) and the azimuth ϕ to each station are computed. The distance to each station and the corresponding A_{min} are substituted in the appropriate magnitude formula to obtain the minimum observable magnitude, $M(A_{min}, r)$, which is the smallest magnitude that occurring at that distance from the station would result in the smallest detectable amplitude.
5. The azimuths from the grid point to all stations (if the network is very extended, a maximum distance can be specified) are sorted, and the gaps, γ, which are the absolute differences between adjacent azimuths, are determined. The largest of these gaps is the maximum total gap, Γ_T, which will be smaller or greater than 180° according to whether the grid point is inside or outside the station array. The maximum allowable total gap Γ_{max} is one of the two parameters used in the method; a first conservative choice is $\Gamma_{max} = 180^\circ$ (e.g., Lee and Stewart, 1981) and works fine if the study area is completely within the network, but it is too restrictive when the study area extends outside it. However, if several phase arrivals can be identified, larger maximum gaps can be used according to the network's phase

identification capabilities. If there are enough S-P times, $\Gamma_{max} > 180^\circ$ permits locating events outside the array, such as events occurring offshore but not very far from the array. Earthquakes occurring at grid points with $\Gamma_T > \Gamma_{max}$ cannot be reliably located, so no estimate of M_{min} can be obtained for them.

6. A maximum gap $\Gamma_T < \Gamma_{max}$ is not the only requirement, for an event be locatable it also should be identifiable at a minimum number of stations N_S. This second parameter also depends on the network's phase identification capabilities; a minimum of three stations should be enough to locate an event, but for this illustration we will stipulate $N_S = 4$, to have some redundancy (Schorlemmer and Woessner, 2008; Feng et al., 2022). Hence, after sorting the minimum observable magnitudes, from small to large, the smallest N_S are selected, and from their azimuths γ the maximum gap for the considered stations, Γ, is determined.
7. If $\Gamma < \Gamma_{max}$, the azimuthal coverage is adequate and the earthquake is locatable, hence, the minimum useable magnitude at that grid point, M_{min}, will be the N_S'th smallest $M(A_{min}, r)$. If $\Gamma > \Gamma_{max}$, the azimuthal coverage is not good enough, so the station corresponding to the next $M(A_{min}, r)$ is included, and the process is continued until $\Gamma < \Gamma_{max}$. For that grid point, M_{min} will be the $M(A_{min}, r)$ of the last added station.
8. After computing M_{min} for all grid points, the coverage of the network has been estimated for all the study region for the specified source depth. The resulting values can be visualized as contoured levels or as a surface. Unreliable estimates can be omitted or identified by some symbol over the corresponding grid point.
9. The process is repeated, from 4. on, for the desired range of source depths.

3. Application to RESNOM

We will illustrate the method by applying it to the Northwestern Mexico Seismological network (*Red Sísmica del Noroeste de México*, RESNOM) that covers northern Baja California, Mexico, between longitudes -117.2° and -114.6°, and latitudes 30.6° and 32.8°. RESNOM is a sub-network of the CICESE (*Centro de Investigación Científica y de Educación Superior de Ensenada, B. C.*) Seismic Network. A detailed description and the history of RESNOM can be found in Vidal-Villegas et al. (2018).

Fig. 1 shows the seismicity recorded by RESNOM since 2005, and the spatial distribution raises the question: are the groupings, gaps, and alignments real features of the seismicity, or could they be artifacts of the network's coverage? Another question is whether all regions of high seismic hazard are adequately monitored by the network. We will come back to these questions in the discussion.

4. Local magnitudes at RESNOM

For small events, RESNOM estimates the local magnitude M_L at a given station as

$$M_L = \log_{10} A + 1.1319 \log_{10} r + 0.0017\, r - 2.11 + \mathrm{C}$$

for earthquakes in the Peninsular Ranges of Baja California (PRBC), and

$$M_L = \log_{10} A + 1.0134 \log_{10} r + 0.0025\, r - 1.96 + \mathrm{C}$$

for earthquakes in the Mexicali Valley region (MV), where A is the maximum peak to peak synthetic Wood-Anderson (W-A) amplitude in nm for the given earthquake, r is its hypocentral distance in km (Vidal and Munguía, 1999), and C is a station correction. Use of the synthetic W-A is not uncommon (e.g., Lee and Stewart, 1981; Del Pezzo and Petrosino, 2001).

As mentioned above, for RESNOM the parameter used for magnitude estimation is the amplitude, measured as the maximum peak to peak amplitude in the synthetic W-A seismogram, for other magnitude scales this parameter could be coda-length, energy, etc. We will denote the maximum amplitudes for the smallest useable, events as A_{min}.

5. Minimum amplitudes

The minimum amplitudes are obtained following the routine amplitude measurement procedure: events are identified on a SEISAN display (Havskov and Ottemoller, 1999), and the inbuilt bandpass filters are used to eliminate high-frequency noise and very long period components that obscure the local events, and arrival times are read from the filtered signals of the three components. Next, a time window containing the maximum amplitudes is selected and a synthetic W-A seismogram is built by deconvolving the instrument response and convolving with the theoretical W-A response, and the amplitude is measured directly on the unfiltered synthetic W-A trace. Use of the unfiltered W-A signal sets limitations on the signals that can be used, because very high-frequency signals from very local and very small earthquakes will lie on the outskirts of the W-A response so they are sometimes indistinguishable from noise and so small that a reliable reading cannot be achieved, particularly because the signal is often riding on very long period signals. On the other hand, use of the synthetic W-A removes the problems caused by different instrument responses (Di Grazia et al., 2001). The minimum amplitude A_{min} will be the smallest of all reliable amplitude determinations. Minimum amplitudes are measured using the current procedure in recent recordings to avoid changes in the location capability of the network due to changes in the network operation (Zúñiga and Wyss, 1995). The seismic stations and the corresponding location, elevation, minimum amplitudes, and station corrections for RESNOM are shown in Table 1.

The behavior of the magnitude formulae as a function of distance r is shown in Fig. 2 for the smallest $A_{min} = 0.3$ and the mean value $\overline{A_{min}} = 37.8$; magnitudes change most for the smaller distances.

Fig. 3 shows the study area as a grid with $\delta Lat = \delta Lon = \delta = 0.05^\circ$ where minimum magnitudes will be determined, and the seismic stations used for determining magnitudes (Table 1). Since RESNOM uses different magnitude formulas for the two different provinces mentioned above, it is necessary to distinguish which province each point belongs to, to use the appropriate formula for M_L; grid points in the MV are shown as crosses in Fig. 3.

Fig. 4 shows the result of the minimum magnitude determination, on a grid with $\delta = 0.05^\circ$ spacing and $\Gamma_{max} = 220^\circ$, for a source depth of 9 km (the mean depth of earthquakes in the study region); results are shown as color-coded levels separated by level contours. Minimum magnitudes go from 2.50 to 4.92, have a mean value of 3.20 with 0.468 standard deviation.

The smallest M_{min} do not correspond to regions where stations are more numerous, say around A in Fig. 4, because the near stations are very noisy, whereas the lowest values are found in patches where there are not as many stations, but they are quiet.

The region around the Agua Blanca fault (F) is very important from the seismic hazard point of view (Allen et al., 1960), so our result of $M_{min} = 2.91$ indicates that there should be more stations in the region. Other region that requires better coverage (NW of F) is the offshore continuation of the Agua Blanca and San Miguel faults, the San Diego Trough - Coronado fault system (Anderson et al., 1989; Cruz-Castillo, 2002), that is important for the seismic hazard of the cities of Tijuana (117.046°W, 32.522°N) and San Diego (117.161 W°, 32.715°N).

The histogram in Fig. 5 shows the distribution of M_{min}; the main peak, from 2.5 to ~3.2, corresponds to points within the network in the Peninsular Ranges, NW of station SFX. The second peak from 3.5 to 3.9 corresponds mostly to points in the Mexicali Valley, points to the SE, and the NW costal region, the small peak around 4.6 corresponds mainly to points offshore.

A byproduct of the analysis is a map of N_{Gp}, the minimum number of stations required to obtain gaps $\langle \Gamma_{max}$ (Fig. 6). This map can be useful for

Table 1
RESNOM stations: location, A_{min}, and station correction C. The location of seismographic stations with their names written underneath are shown in Fig. 3.

Name	*Longitude* (°)	*Latitude* (°)	*Elevation* (km)	A_{min} (nm)	*C*
AGSX	−115.1600	32.2658	0.000	32.100	0.00
ALAMX	−115.7080	32.0075	0.033	1.550	−0.05
BAR	−116.6722	32.6801	0.053	2.850	0.00
CBX	−116.6630	32.3131	0.125	1.950	−0.17
CCX	−116.6640	31.8680	0.004	9.500	−0.11
CHX	−115.0520	31.4721	0.004	1.600	0.15
CORX	−117.2480	32.4154	0.007	20.100	0.00
CPX	−115.3040	32.4170	0.019	35.060	−0.42
DOCTX	−114.7450	31.9594	0.000	25.800	0.00
DRE	−115.4468	32.8053	−0.001	117.300	0.00
EML	−115.8270	33.0515	0.016	2.500	0.00
EMS	−115.9852	32.7392	0.001	36.700	36.80
GLA	−114.8270	33.0515	0.061	1.900	2.20
GUVIX	−115.0760	32.3029	0.001	24.700	−0.41
IKP	−116.1095	32.6501	0.091	3.950	0.00
JARAX	−115.5815	32.5378	0.000	30.600	0.00
MBIG	−115.1981	32.4071	0.000	586.250	−0.90
MTG	−116.6472	33.1991	0.109	3.600	0.00
OJONX	−116.1000	31.8573	0.089	0.550	0.00
OLP	−116.9301	32.6077	0.016	15.930	0.00
PBX	−116.7250	31.7415	0.035	2.400	−0.04
PESCX	−114.9640	32.4330	0.000	98.260	0.00
PIX	−113.4600	31.5629	0.008	3.000	0.00
RHX	−115.2840	32.1350	0.002	0.950	0.31
PPBX	−113.6320	31.3350	0.001	6.800	0.00
RITX	−114.9610	32.1659	0.001	65.760	−0.34
RMX	−116.0290	32.6020	0.128	4.950	0.24
SAL	−115.9850	33.2801	0.001	51.300	0.00
SDR	−116.9424	32.7350	0.011	2.860	0.00
SFX	−114.8510	31.0376	0.004	3.050	0.13
SJX	−115.9480	32.0048	0.162	1.530	0.22
SLH	−116.2539	33.1926	0.021	7.100	0.00
SLGB	−114.4040	29.8300	0.002	15.000	0.00
SLRCX	−114.7060	32.4585	0.005	137.950	0.00
SPIG	−115.4660	31.0459	0.279	0.300	0.29
SQX	−115.8760	30.5762	0.011	2.150	−0.16
SV2X	−116.2384	31.3398	0.013	1.750	0.00
SWS	−115.7900	32.9451	0.014	5.200	0.00
TJIG	−116.6762	32.4334	0.032	5.160	0.00
TJX	−117.0540	32.5102	0.021	59.900	0.00
TKX	−116.6070	32.5387	0.054	40.830	−0.06
TL2X	−115.0590	32.4480	0.002	76.150	−0.30
UABX	−115.4500	32.6316	0.004	107.260	−0.44
VTX	−115.7840	31.3914	0.075	1.550	0.18
WES	−115.7310	32.7590	−0.001	30.060	0.00
WMD	−115.5819	33.0382	−0.005	64.600	0.00
YUC2X	−115.0940	32.6054	0.002	63.100	0.00
YUH2	−115.9222	32.6475	0.018	2.300	0.00

judging the reliability of hypocentral locations. Within the network in the Peninsular ranges only four to five stations are required for reliable results, while up to eighteen stations are required in the Mexicali Valley (assuming all stations to be working all the time).

Fig. 7 is the equivalent to Fig. 4 for $D = 1$ km source depth and is shown to illustrate the differences in M_{min} caused by differences in depth. Depth appears in the magnitude formulae only through the hypocentral distance r, so its effect is minimum for stations distant from the source. The general shape of the M_{min} distribution is very much like that for $D = 9$ km, but the values are slightly smaller, ranging from 2.47 to 4.92, with a mean value of 3.18 with 0.47 standard deviation.

6. Discussion and conclusions

We have presented a new and extremely simple method to obtain the minimum locatable magnitude M_{min} for a seismic network at each point of a given region. The method does not require large amounts of data that necessarily imply poor spatial and/or temporal definition, because it is based on the location of the stations and their sensitivity measured through their smallest amplitudes A_{min} that yield minimum magnitude

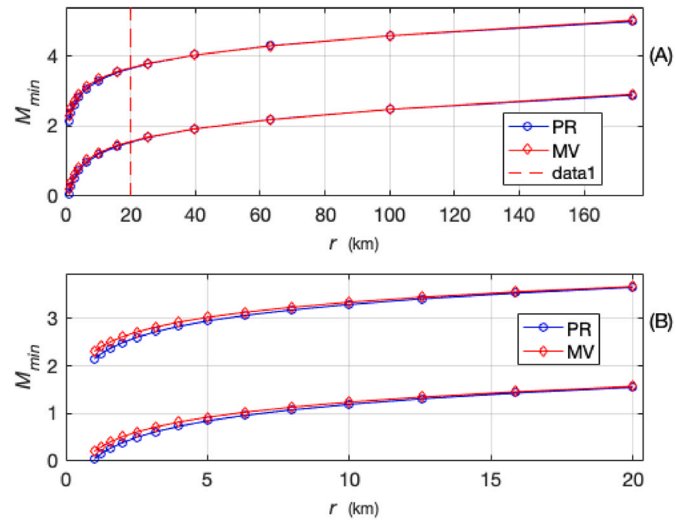

Fig. 2. $M_{min}(A_{min}, r)$ for $A_{min} = 0.3$ and $\overline{A_{min}} = 37.8$ for $r = 1$–175 km (A), and a close-up for small distances (B), showing the difference between Peninsular Ranges (PR) and Mexicali Valley (MB).

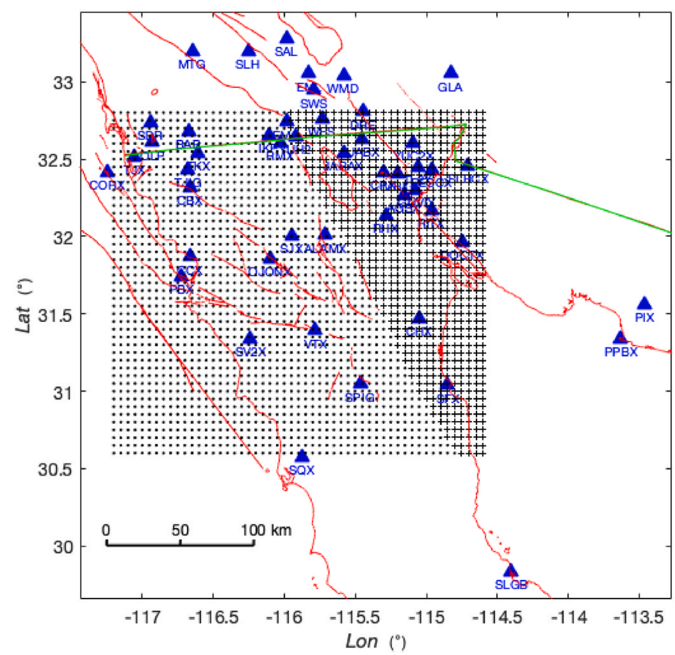

Fig. 3. Study region grid (dots) with $\delta = 0.05°$ spacing, crosses identify points belonging to the Mexicali Valley province. Triangles indicate the location of seismographic stations with their names written underneath. Continuous red lines show the coastlines, the Laguna Salada and Salton Sea lakes, and the principal faults, the international Mexico-USA border is shown in green. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

estimations. Hence, each minimum magnitude estimations refers to a given point in the region. We showed magnitudes for points distributed on grids, but the method can be applied to any distribution of points and to any singular point.

Results are approximate, because A_{min} values and magnitudes themselves are approximate, but the method uses a minimum of assumptions, while other more complicated methods involve so many assumptions and uncertainties that their results cannot be anything more than approximate too. The method is applicable to any method of magnitude estimation (local magnitude, coda, duration, energy, etc.).

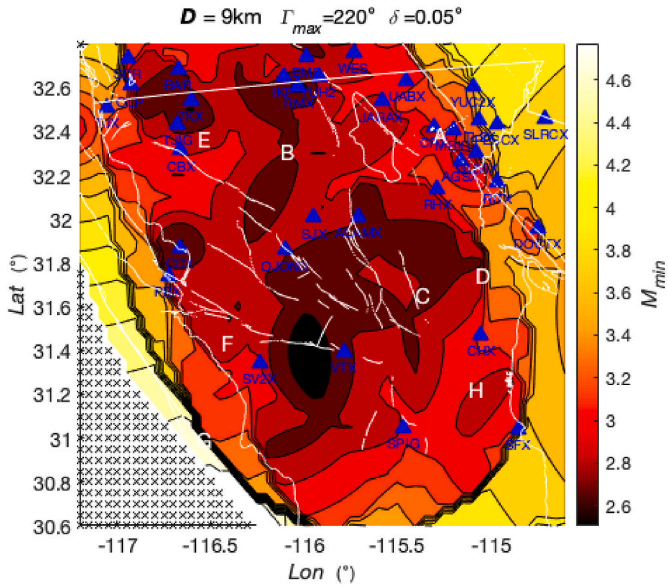

Fig. 4. Color-coded contours of minimum local magnitudes M_{min} at each grid point for source depth $D = 9$ km. X-symbols indicate grid points where locations are not reliable. Blue triangles indicate the location of seismographic stations with their names written underneath. Continuous white lines show the coastlines, the Laguna Salada lake, the principal faults, and the international Mexico-USA border. Letters indicate seismicity features as in Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

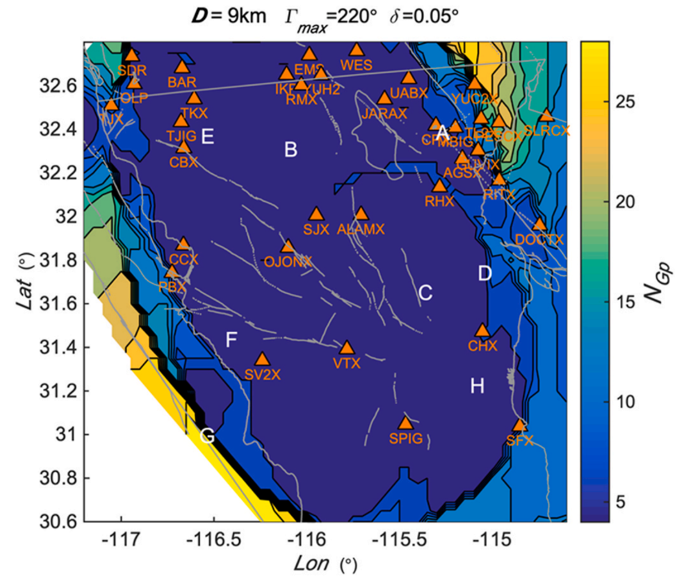

Fig. 6. Color-coded contours of N_{Gp} at each grid point. Red triangles indicate the location of seismographic stations with their names written underneath. Continuous gray lines show the coastlines, the Laguna Salada lake, the principal faults, and the international Mexico-USA border. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

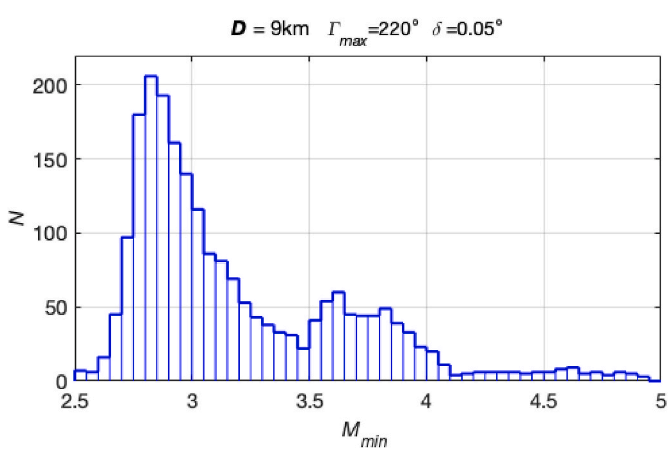

Fig. 5. M_{min} histogram (blue line) of the M_{min} values shown in Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

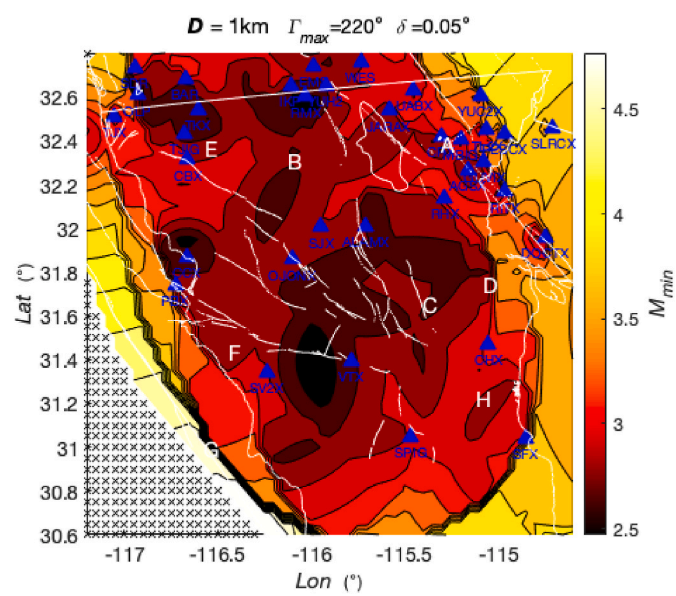

Fig. 7. Color-coded contours of minimum local magnitudes M_{min} at each grid point for source depth $D = 1$ km. X-symbols indicate grid points where locations are not reliable. Blue triangles indicate the location of seismographic stations with their names written underneath. Continuous white lines show the coastlines, the Laguna Salada lake, the principal faults, and the international Mexico-USA border. Letters indicate seismicity features as in Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Tentative coverage estimations would also be useful for planning changes, redistributions or increments of stations, to determine possible optimum locations. The coverage maps can be updated whenever the station distribution is modified. If a station is taken off the network, it can be simply deleted from the station list and steps 3 to 9 of the method applied to get the new coverage. If a new station is added to the network, then strictly speaking it should not be employed until its A_{min} is assessed, but it could be assigned an approximate tentative value depending on the noise characteristics of the site, to obtain approximate coverage estimations. The coverage maps can also be updated whenever the smallest size event changes for some station.

For the particular case of RESNOM, we found, based on the seismicity shown in Fig. 1 and the results shown in Figs. 4 and 7 that the major groupings and gaps are not artifacts of the coverage: the grouping marked A in Fig. 1 is important in spite of M_{min} being greater than ~3.1, gaps B and C are there in spite of good coverage ($M_{min} < 3.0$), and the lineation extending to the NE from D is very well-defined in a region with high M_{min}. E, F, and H are gaps in regions with good coverage ($M_{min} < 3.0$), while the lineation G, corresponding offshore faulting is clear despite poor coverage $M_{min} \sim 4.69$.

On the other hand, the recorded medium and high magnitude seismicity in regions of poor coverage indicates that probably important small magnitude events are being missed, and that the network needs more stations to adequately monitor these regions.

We would also recommend implementing filters on the synthetic W-A seismograms (Uhrhammer et al., 2011) that could make M_L determinations easier and much more reliable and would help to lower M_{min} considerably.

Future work would be to measure minimum amplitudes considering different noise levels, usually higher by day (Rydelek and Sacks, 1989), and higher for bad weather, especially for stations near the coast, to have best- and worst-case coverage estimations.

CRediT authorship contribution statement

F. Alejandro Nava: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Lenin Ávila-Barrientos:** Writing – review & editing, Formal analysis, Data curation. **Luis Munguía:** Writing – review & editing, Formal analysis, Data curation. **Maria A. Núñez-Leal:** Writing – review & editing, Formal analysis, Data curation. **Francisco Farfán:** Writing – review & editing, Formal analysis, Data curation.

Funding

This study had no external funding.

Declaration of competing interest

The authors declare that there are no conflicts of interest or competing interests.

Acknowledgments

Many thanks to the staff of RESNOM, to the networks that share stations with RESNOM: UNAM, SCSN, UABC; to USGS (particularly Alena Leeds and Steve Hartzell) for contributing stations; to CONAHCYT for long-term support. L.Á-B. participation was supported by the *Investigadoras e Investigadores por México* SECIHTI program, project 7095. We are indebted to two anonymous reviewers for useful and constructive criticism.

Data availability

Data will be made available on request.

References

Allen, C., Silver, L., Stehli, F., 1960. Agua Blanca fault—a major transverse structure of northern Baja California, Mexico. Geol. Soc. Am. Bull. 71 (4), 467–482.

Amorèse, D., 2007. Applying a change-point detection method on frequency-magnitude distributions. Bull. Seismol. Soc. Am. 97 (5), 1742–1749. https://doi.org/10.1785/0120060181.

Anderson, J., Rockwell, T., Agnew, D., 1989. Past and possible future earthquakes of significance to the San Diego region. Earthq. Spectra 5 (2), 299–335.

Cruz-Castillo, M., 2002. Catálogo de las fallas regionales activas en el norte de Baja California, México. GEOS 22 (1), 37–42.

D'Alessandro, A., Luzio, D., D'Anna, G., Mangano, G., 2011. Seismic network evaluation through simulation: an application to the Italian national seismic network. Bull. Seismol. Soc. Am. 101 (3), 1213–1232. https://doi.org/10.1785/0120100066.

D'Alessandro, A., Ruppert, N., 2012. Evaluation of location performance and magnitude of completeness of the Alaska Regional Seismic Network by the SNES method. Bull. Seismol. Soc. Am. 102 (5), 2098–2115.

D'Alessandro, A., Stickney, M., 2012. Montana seismic network performance: an evaluation through the SNES method. Bull. Seismol. Soc. Am. 102 (1), 73–87.

Del Pezzo, E., Petrosino, S., 2001. A local magnitude scale for Mt. Vesubius from synthetic Wood-Anderson seismograms. J. Seismol. 5, 207–215.

Di Grazia, G., Langer, H., Ursino, A., Scarfi, L., Gresta, S., 2001. On the estimate of earthquake magnitude at a local seismic network. Ann. Geofisc. 44 (3), 579–591.

Feng, Y., Mignan, A., Sornette, D., Li, J., 2022. Hierarchical Bayesian modeling for improved high- resolution mapping of the completeness magnitude of earthquake catalogs. Seismol Res. Lett. XX, 1–12. https://doi.org/10.1785/0220210368.

Fischer, T., Bachura, M., 2014. Detection capability of seismic network based on noise analysis and magnitude of completeness. J. Seismol. 18, 137–150.

Gomberg, J., 1991. Seismicity and detection/location threshold in the Southern Great Basin seismic network. J. Geophys. Res. 96 (16), 414, 401–16.

Havskov, J., Ottemoller, L., 1999. SEISAN earthquake analysis software. Seismol Res. Lett. 70 (5), 532–534.

Herrmann, M., Marzocchi, W., 2021. Inconsistencies and lurking pitfalls in the magnitude–frequency distribution of high-resolution earthquake catalogs. Seismol Res. Lett. 92 (2A), 909–922.

Huang, Y., Zhou, S., Zhuang, J., 2016. Numerical tests on catalog-based methods to estimate magnitude of completeness. Chin. J. Geophys. 59, 101–110.

Kijko, A., Smit, A., 2017. Estimation of the frequency–magnitude Gutenberg–Richter b -value without making assumptions on levels of completeness. Seismol Res. Lett. 88 (2A), 311–318. https://doi.org/10.1785/0220160177.

Lee, W., Stewart, S., 1981. Principle and applications of microearthquake networks. In: Saltzman, B. (Ed.), Advances in Geophysics, vol. 2. Academic Press, p. 293.

Lombardi, A., 2021. A normalized distance test for co-determining the completeness magnitude and b-value of earthquake catalogs. J. Geophys. Res. 126 (3), e2020JB021242. https://doi.org/10.1029/2020JB021242.

Mignan, A., Werner, M., Wiemer, S., Chen, C., Wu, Y., 2011. Bayesian estimation of the spatially varying completeness magnitude of earthquake catalogs. Bull. Seismol. Soc. Am. 101, 1371–1385.

Mignan, A., Woessner, J., 2012. Estimating the magnitude of completeness for earthquake catalogs. In: Community Online Resource for Statistical Seismicity Analysis, pp. 1–45. https://doi.org/10.5078/corssa-00180805. Available at: http://www.corssa.org.

Mignan, A., Chouliaras, G., 2014. Fifty years of seismic network performance in Greece (1964–2013): spatiotemporal evolution of the completeness magnitude. Seismol Res. Lett. 85 (3), 657–667.

Möllhoff, M., Bean, C., Baptie, B., 2019. SN-CAST: seismic network capability assessment software tool for regional networks-examples from Ireland. J. Seismol. 23, 493–504.

Nanjo, K., Schorlemmer, D., Woessner, J., Wiemer, S., Giardini, D., 2010. Earthquake detection capability of the Swiss seismic network. Geophys. J. Int. 181 (3), 1713–1724.

Puspito, N., Prayitno, B., Nugraha, A., Sahara, D., Kusumawati, D., Zulfakriza, Z., Rosalia, S., Daryono, D., Heryandoko, N., Sudrajat, A., Supendi, P., Adi, S., Karnawati, D., 2023. Evaluation of station performance of the Indonesian seismic network using the primary location parameter. Seismol Res. Lett. XX, 1–16. https://doi.org/10.1785/0220220334.

Ringdal, F., 1974. Estimation of Seismic Detection Thresholds. Technical Report No. 2, Texas Instruments Inc., p. 90

Rydelek, P., Sacks, I., 1989. Testing the completeness of earthquake catalogues and the hypothesis of self-similarity. Nature 337, 251–253. https://doi.org/10.1038/337251a0.

Schorlemmer, D., Woessner, J., 2008. Probability of detecting an earthquake. Bull. Seismol. Soc. Am. 98, 2103–2117. https://doi.org/10.1785/0120070105.

Schorlemmer, D., Mele, F., Marzocchi, W., 2010. A completeness analysis of the national seismic network of Italy. J. Geophys. Res. 115, B04308. https://doi.org/10.1029/2008JB006097.

Uhrhammer, R., Hellweg, M., Hutton, K., Lombard, P., Walters, A., Hauksson, E., Oppenheimer, D., 2011. California Integrated Seismic Network (CISN) local magnitude determination in California and vicinity. Bull. Seismol. Soc. Am. 101 (6), 2685–2693.

Vidal, J., Munguía, L., 1999. The ML scale in northern Baja California, Mexico. Bull. Seismol. Soc. Am. 89 (3), 750–763.

Vidal-Villegas, J., Munguía, L., González-Ortega, J.A., Núñez-Leal, M.A., Ramírez, E., Mendoza, L., Castro, R.R., Wong, V., 2018. The Northwest Mexico Seismic Network: real time seismic monitoring in northern Baja California and northwestern Sonora, Mexico. Seismol Res. Lett. 89 (2A), 324–337. https://doi.org/10.1785/0220170183.

Wiemer, S., Wyss, M., 2000. Minimum magnitude of complete reporting in earthquake catalogs: examples from Alaska, the western United States, and Japan. Bull. Seismol. Soc. Am. 90, 859–869.

Woessner, J., Wiemer, S., 2005. Assessing the quality of earthquake catalogues: estimating the magnitude of completeness and its uncertainty. Bull. Seismol. Soc. Am. 95, 684–698. https://doi.org/10.1785/012040007.

Zúñiga, F.R., Wyss, M., 1995. Inadvertent changes in magnitude reported in earthquake catalogs: their evaluation through b-value estimates. Bull. Seismol. Soc. Am. 85, 1858–1866.