PAGEOPH, Vol. 139, No. 2 (1992)

0033-4553/92/020277-16$1.50 + 0.20/0

Statistical Analysis of Seismic Data from North-Western and Western Argentina

A. M. OSELLA,[1,2] N. C. SABBIONE[3] and D. C. CERNADAS[1]

Abstract—Due to the process of subduction of the Nazca Plate, high seismic activity is observed near the Argentine Andean range between 21°S and 36°S. The new version of the Argentine Seismic Catalogue, which includes well-defined events during the period 1964–1989, allows us to perform an analysis of seismic risk.

Earthquakes with epicenters in the provinces included in the north-western and western regions were studied using Gumbel III extreme value distribution. Modal extreme magnitudes and return periods were calculated for both regions and the results were compard with the ones obtained through the entire process techniques (both analytical and graphical).

As a first study, we analyzed each province separately, after which mean values for each region were obtained. Modal values around 5–5.5 have been found and times of recurrence for events with $m_b > 6$ of approximately 25 years were obtained.

Key words: Large earthquake recurrence, western Argentine seismicity, earthquake risk, Argentine seismic catalogue.

1. Introduction

The seismic activity of Argentina is concentrated mostly near the Andean range, due to the process of subduction of the Nazca Oceanic Plate under the South American Continental Plate. This continental plate is more rigid; the Nazca Plate, with higher density rocks, is more plastic and homogenic. It is assumed that the regions of interplate interaction are permanent and, though the Pacific seafloor is moving, producing a compression zone, it is the continental part which controls this kind of contact.

In some cases, in particular near the Andes, the subducting process may produce a distension together with the compression of the continental plate.

The Nazca Plate is thought to be divided by transform faults into blocks with relative movements. There are five recognizable faults: two corresponding to the

---

[1] Dto. de Física, Fac. Cs. Exactas y Naturales, Universidad de Buenos Aires, Ciudad Universitaria, Pab. 1-1428, Buenos Aires, Argentina.

[2] Also at CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas).

[3] Dto. de Sismologia, Fac. Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, 1900, La Plata, Argentina.

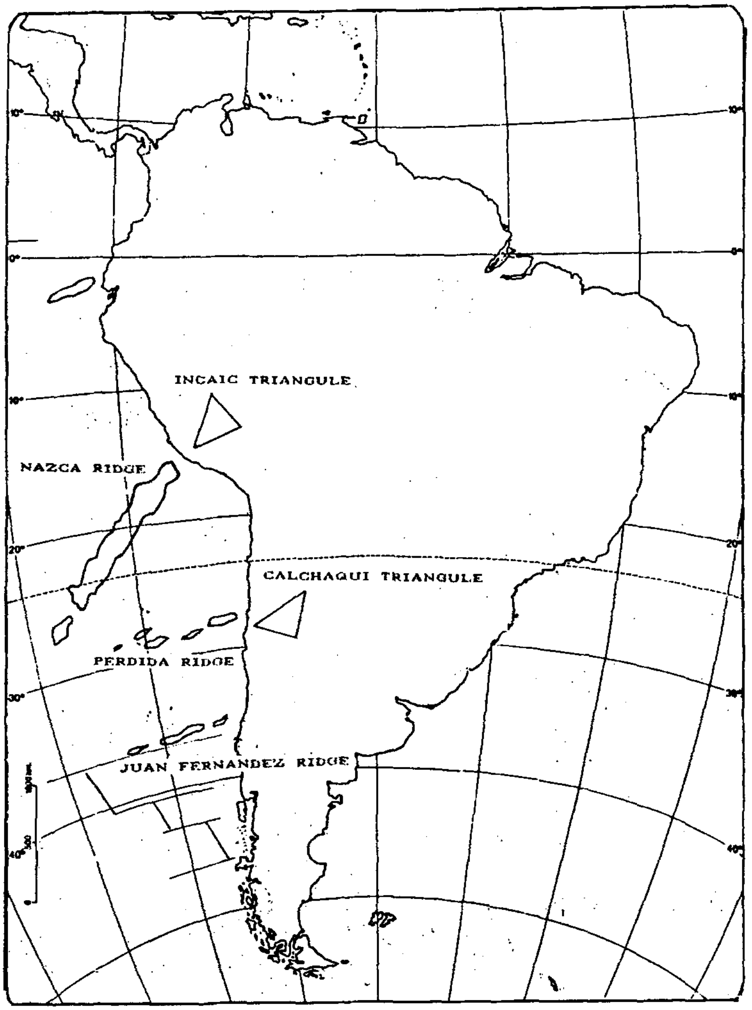


Figure 1
Simplified tectonic features of the South America Andean region (see e.g., BALDIS *et al.*, 1982).

borders of the plate and the remaining three being correlated with Juan Fernandez, Perdida and Nazca ridges (see Fig. 1). It is assumed that this plate has been faulted in a series of blocks which subducted independently.

There are two regions of seismic silence: The Incaic Triangle and the Calchaqui Triangle. In this last one the seismicity is very low at a depth around that corresponding to the subducted plate. In this zone an uplevel of the asthenosphere is detected. The region of high seismicity is extended between 21°S and 36°S, limited to the south with a region of horizontal subduction. The separation is given by a subduction zone with a dip angle greater than the ones obtained to the south, but with low seismicity. This limit is given by Juan Fernandez ridge which is also aseismic.

From seismic analysis, between 21°S and 25°S the earthquake activity is concentrated mostly at a depth of around 60–300 km, between 25°S and 27°S there is no activity, at least at that depth (in this zone foci are generally deeper, though some superficial events were detected). Between 27°S and 36°S there is a band with a relatively high seismicity, suggesting a superposition of faults. In these zones no activity is detected between 300–500 km, except the region between 22°S and 29°S.

From Figure 2 it is clear that seismic activity within Argentina is concentrated mostly near the Andean range. Two regions may be detected to have an important density of earthquakes with $m_b \geq 4$, the north-western zone (NOA), including Jujuy, Salta, Catamarca, La Rioja and Tucuman provinces, and the central one (Cuyo), including San Juan, San Luis and Mendoza provinces (see Fig. 2d), this last

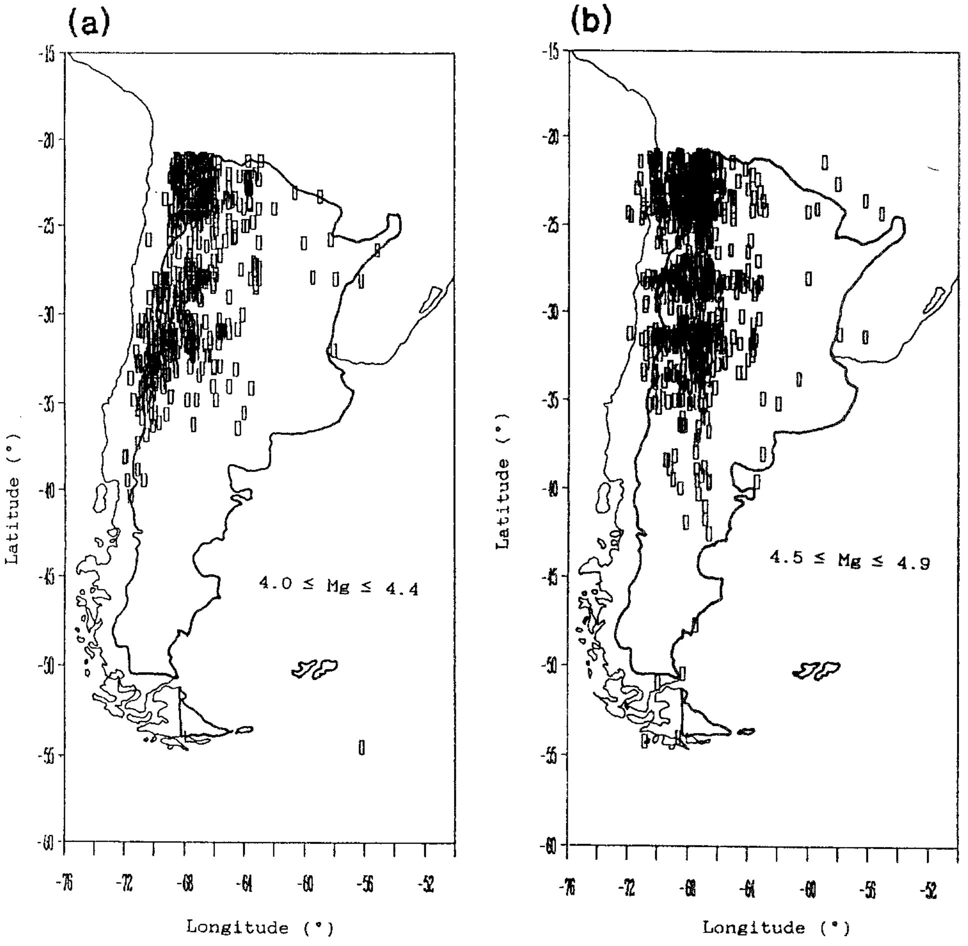


Figure 2(a and b)

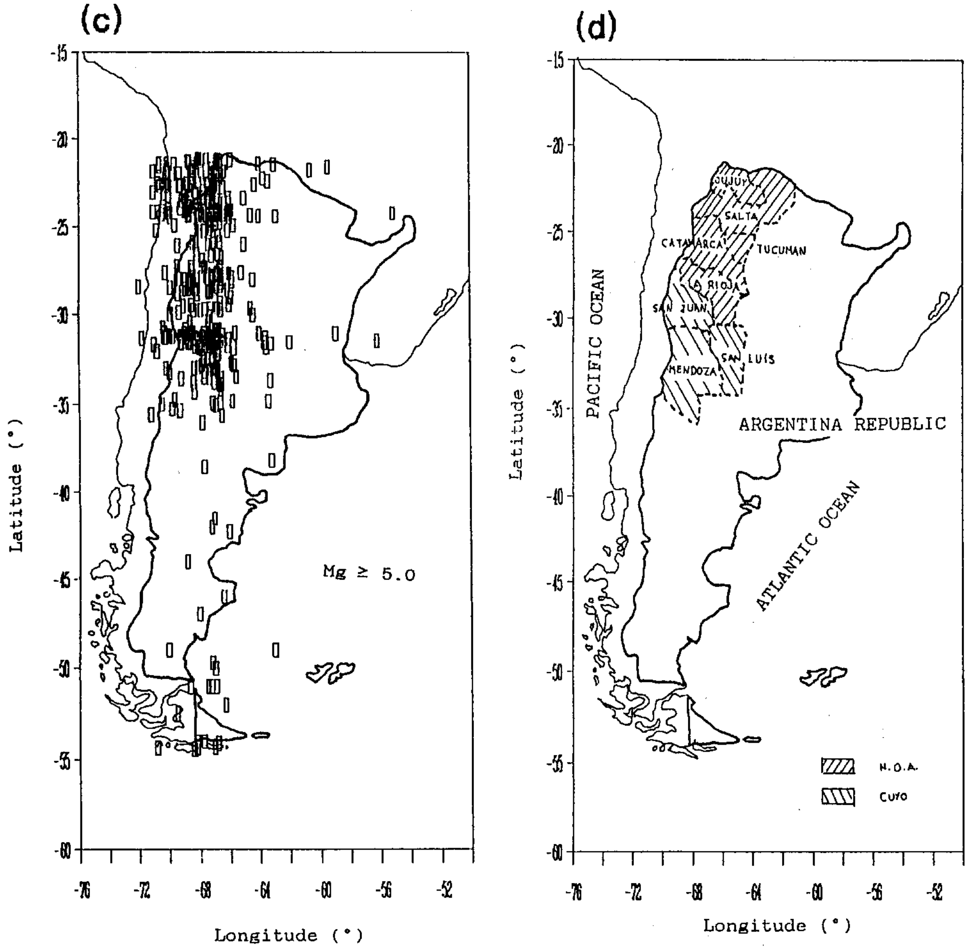


Figure 2(c and d)

Figure 2
Seismicity of Argentina as obtained from the Argentine Seismic Catalogue. Number of earthquakes with $m_b \geq 4$: 2927 for the period 1964–1989. a) Events with $4 \leq m_b < 4.5$; b) $4.5 \leq m_b < 4.9$; c) $m_b \geq 5.0$; d) Studied regions.

zone having sustained at least two earthquakes during the last fifty years which may be defined as catastrophic, both for people and properties.

Improvements of the Argentine seismic catalogue, which includes data from the last 25 years, allow us to perform a study of the seismic risk of these areas.

Assuming the occurrence of earthquakes to be stochastic processes, they may be represented by statistical models. Typically, two different kinds of models have been applied: those which use the entire process (see e.g., MAKROPOULOS and BURTON, 1983) and those in which only larger earthquakes are considered (e.g., KARNIK and HUBNEROVA, 1968; ROCA *et al.*, 1984; BURTON and MAKROPOULOS, 1985).

In the first case, the complete earthquake data set is needed. Using the Gutenberg-Richter relationship, the parameters related to the physical release of strain energy may be estimated. In fact, there is a lack of accuracy in this kind of analysis since catalogues are not complete, especially for lower events. A good description of the process may be achieved through the Gumbel's third asymptotic distribution of extreme values since only the largest earthquakes are necessary, which are the most reliable data, and thus good estimations for the modal extreme magnitudes and return periods may be obtained.

Consequently, in the present paper we study the seismic risk in Argentina employing Gumbel III distribution and we compare the results with those obtained with the whole process technique.

2. Data

We study the regions of high seismicity of Argentina previously described: Region 1, N.O.A., and Region 2, Cuyo. The 1990 version of the Argentine Seismological Catalogue (BANCO ARGENTINO DE SISMOS, 1990) was used for this study. This catalogue has been made by compiling data given by the International Seismological Center of Berkshire, Great Britain, and includes well-defined earthquakes from 1964 to 1989. The precision of epicenter determination is ±10 km. Figure 3 shows the distributions of epicenters of the zone. Earthquakes with $m_b \geq 4$ have been considered, the number of events being 2227 for this period. We used the magnitudes associated with the body waves, m_b, since most earthquakes have a deep focus, in which case m_s, related to the superficial waves, are not representative. Moreover, since the maximum value for m_b is not greater than 6.5, the risk of saturation is very low (KANAMORI, 1977).

Since data from previous years do not have associated magnitudes, they could not be included in the analysis. To increase the number of intervals, we considered a six month period ($T = 0.5$ year) and so statistical analysis is performed over 49 intervals. This period may be used since, in the studied regions, no empty intervals appear due to the high seismicity of the zone. In Figure 4 the distribution of earthquakes in each time interval is shown for N.O.A. (Fig. 4a) and Cuyo (Fig. 4b). In this region two clear maxima may be observed. The first one corresponds to the period which includes the 6.4 San Juan earthquake, and thus the associated foreshocks and aftershocks increase the number of events during that time. The second one corresponds to a period of high activity in Mendoza.

In Figure 5 the distribution is shown as a function of the magnitudes for both zones (Figs. 5a and 5b, respectively).

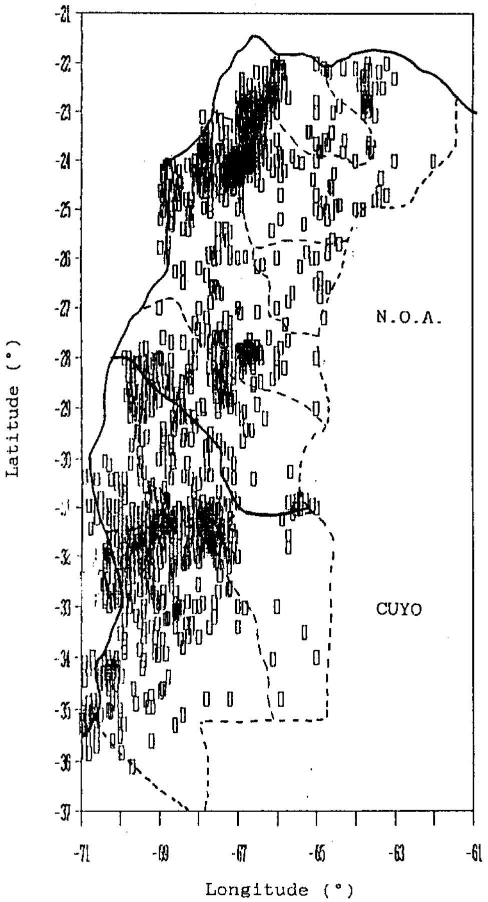


Figure 3
Distribution of earthquake epicenters in the studied region (from Fig. 2). Events with $m_b \geq 4$ have been drawn.

3. *Extreme Value Theory*

Gumbel's extreme value distributions have been widely used in the analysis of earthquake occurrence (e.g., ROCA *et al.*, 1984; BURTON and MAKROPOULOS, 1985; BURTON, 1990). Depending on the characteristics of the data, these distributions may be defined unbounded (type I), bounded from below (type II) and bounded from above (type III). As an upper bound to the earthquake magnitude exists, Gumbel's third asymptotic distribution G^{III} is the most adequate to evaluate seismic risk. This distribution is given by (GUMBEL, 1954)

$$G^{\mathrm{III}}(m) = \exp[-(\omega - m)/(\omega - u)]^k \qquad (1)$$

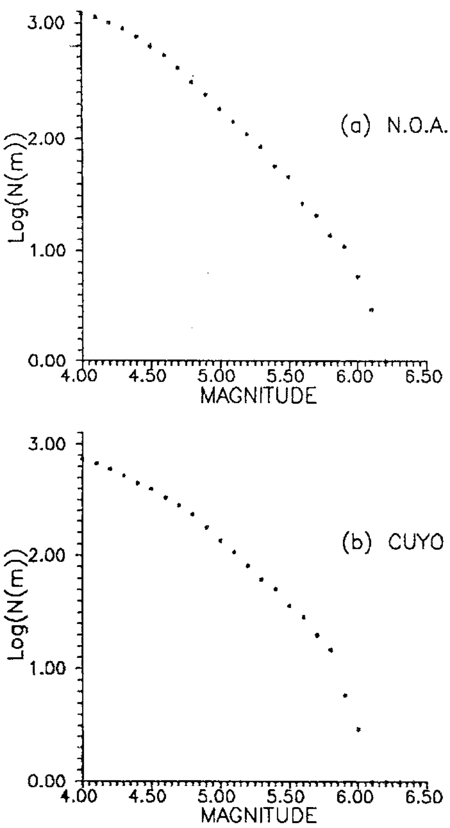


Figure 4

Distribution of earthquakes with $m_b > 4$ in the considered time interval for regions 1 (3a) and 2 (3b).

where $G^{\mathrm{III}}(m)$ is the probability of m being an extreme, ω is the upper bound magnitude, u is the characteristic extreme magnitude value and $k = 1/\lambda$ a parameter related to the curvature of the distribution.

The application of this distribution may be summarized as follows (see, for example, BURTON and MAKROPOULOS, 1985).

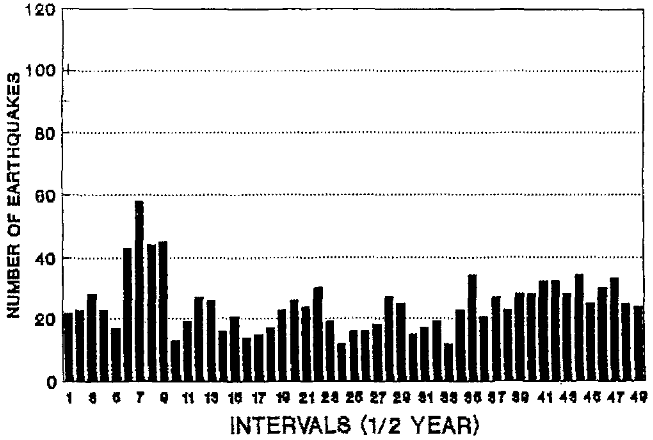
Equation (1) may be rewritten as

$$m = \omega - (\omega - u)[-\ln(G^{\mathrm{III}}(m))]^{\lambda}. \tag{2}$$

For each time interval considered (in this paper 6 months) extreme magnitudes m_i are obtained from the catalogue, divided in n intervals, and are ordered in increasing size

$$m_1 \leq m_2 \leq \cdots \leq m_n. \tag{3}$$

(a) N.O.A.
(1964-1989)



(b) CUYO
(1964-1989)

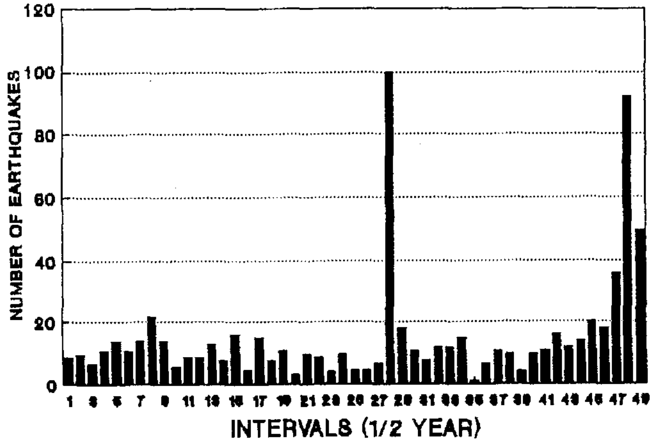


Figure 5

Distribution of earthquakes as a function of m_b for region 1 (5a) and region 2 (5b).

Each magnitude has assigned a "plotting point probability" given by (GRINGORTEN, 1963)

$$G_j = \frac{J - 0.44}{n + 0.12} \tag{4}$$

with $J = 1, \ldots, n$.

A nonlinear square method is used to obtain the values of the parameters ω, u and λ, together with the matrices of covariance and correlation.

With them, the return period, $T(m)$, and the modal extreme magnitude for the next T-intervals of time, $m_1(T)$, in fact the relevant parameters to be estimated, may be calculated from

$$T = \frac{1}{1 - G^{\mathrm{III}}(m)} \tag{5a}$$

$$m_1(t) = \omega - (\omega - u)\left[\frac{1 - \lambda}{T}\right]^{\lambda}. \tag{5b}$$

To check the results we also apply other rules to calculate the plotting point probabilities, in particular, the one proposed by GUMBEL (1954) and then reconsidered by KNOPOFF and KOGAN (1977)

$$G(y_j) = \frac{j}{n + 1} \quad y_1 < y_2 < \cdots < y_n. \tag{6}$$

The agreement between the estimated curves for m_1 using both rules were less than 1%, but the best fitting was obtained with the Gringorten rule.

4. *Whole Process Technique*

The occurrence of earthquakes in a given volume is represented by means of the average number $N(m)$ of earthquakes with magnitudes greater than m in a period T of time. The classic assumption for $N(m)$ is the one proposed by GUTENBERG and RICHTER (1944) given by

$$\log N(m) = a - bm \tag{7}$$

with a and b zone dependent constants.

If this equation is related to the energy-magnitude formula

$$\log E = A + Bm \tag{8}$$

an upper bound for the magnitude may be included (MAKROPOULOS and BURTON, 1983). In this case, considering six months intervals and defining:

M_1 = the most probable semi-annual maximum magnitude;
M_2 = the magnitude corresponding to the mean semi-annual rate of energy release;
M_3 = the upper bound for the earthquake magnitude,

the following relationships are satisfied

$$M_1 = \frac{a}{b} \tag{9a}$$

$$M_2 = \frac{1}{B}\left[bM_1 + (B - b)M_3 + \log\left(\frac{b}{B - b}\right)\right] \tag{9b}$$

$$M_3 = \frac{1}{B - b}\left[BM_2 - bM_1 - \log\left(\frac{b}{B - b}\right)\right] \tag{9c}$$

with M_1, M_2 and M_3 depending on the values of the constants that characterize the region seismotectonically (both a and b values are well-known to be zone dependent).

The constants a and b are obtained from equation (7) by fitting them to the data with the least-squares method. The values of the remaining constants, A and B, are assumed to be (see BÅTH, 1958)

$$A = 4.78 \quad B = 2.57$$

when dealing with magnitudes associated with body waves, m_b.

With this result the waiting time, T_r, which indicates the minimum time required for the accumulation of the maximum energy providing there were no earthquakes meanwhile, may be calculated.

Finally, the set of parameters M_1, M_2 and M_3 may be related to the correpsonding values obtained from the Gumbel III distribution (BURTON and MAKROPOULOS, 1985)

$$M_1 \approx m_1(1) = \omega - (\omega - u)(1 - \lambda)^{\lambda} \tag{10a}$$

$$M_2 \approx X_2 = \omega + \frac{1}{B} \ln \frac{k\Gamma(k)}{(\omega - u)^k B^k} \tag{10b}$$

where X_2 is the magnitude equivalent to the semi-annual total energy release calculated using G^{III} and $\Gamma(k)$ is the Gamma function, and finally

$$M_3 \overset{\sim}{<} \omega. \tag{10c}$$

5. Application

a) Extreme Value Distribution

To apply Gumbel III distribution to data, events with $m_b \geq 4$ have been considered. The values obtained from the set of parameters, ω, u and λ, together

Table 1

Estimated values of ω, u *and* λ *and the magnitude associated with mean energy release,* X_2, *with the corresponding standard deviations,* σ_ω, σ_u, σ_λ *and* σ_{X2}, *respectively*

	ω	σ_ω	u	σ_u	1	σ_1	X_2	σ_{X2}
JUJUY	6.41	0.98	5.00	0.11	0.33	0.28	5.63	0.98
SALTA	6.31	0.94	5.07	0.11	0.34	0.31	5.62	0.91
CATAMARCA	5.96	0.83	4.75	0.11	0.38	0.33	5.32	0.73
LA RIOJA	6.06	1.07	4.87	0.11	0.31	0.34	5.35	1.10
N.O.A.	6.47	1.08	5.39	0.11	0.34	0.38	5.92	1.10
MENDOZA	6.07	0.88	4.88	0.11	0.37	0.34	5.42	0.81
SAN JUAN	6.57	0.93	4.92	0.11	0.34	0.23	5.73	0.91
CUYO	6.50	1.02	5.18	0.11	0.32	0.30	5.74	1.03

with the magnitude associated with energy, X_2, and the corresponding standard deviations, σ_ω, σ_u, σ_λ and σ_{X2} respectively, are listed in Table 1 for the different provinces and also for each region. Data from Tucuman and San Luis were included in the regional analysis but they were not studied separately due to the low seismicity registered there.

With the obtained parameters, the distribution curves may be drawn. Figure 6 shows the results for both regions, N.O.A. (Fig. 6a) and Cuyo (Fig. 6b); Figure 7 for Jujuy (Fig. 7a), Salta (Fig. 7b), Catamarca (Fig. 7c) and La Rioja (Fig. 7d) and Figure 8 for Mendoza (Fig. 8a) and San Juan (Fig. 8b).

Large values of σ_λ have been obtained, as can be observed in Table 1. BURTON and MAKROPOULOS (1985) have stated that regions with small λ and high ω have larger uncertainties in the parameters and showed that the results may be improved by increasing the number of intervals considered.

Values of return periods for the investigated zones and modal extreme values $m_1(T)$ for different numbers of T are displayed in Tables 2 and 3, respectively. These results can be taken as estimates of the seismic activity in the different regions.

b) Whole Process Technique

Table 4 gives the coefficients a and b and the resulting values of M_1, M_2 and M_3 with the corresponding standard deviations for each province and region.

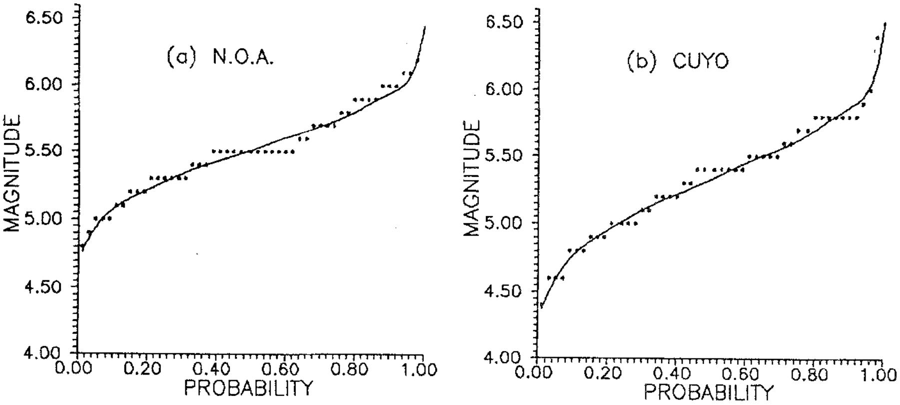


Figure 6
Gumbel III distribution curves for Region 1, N.O.A. (6a) and Region 2, Cuyo (6b).

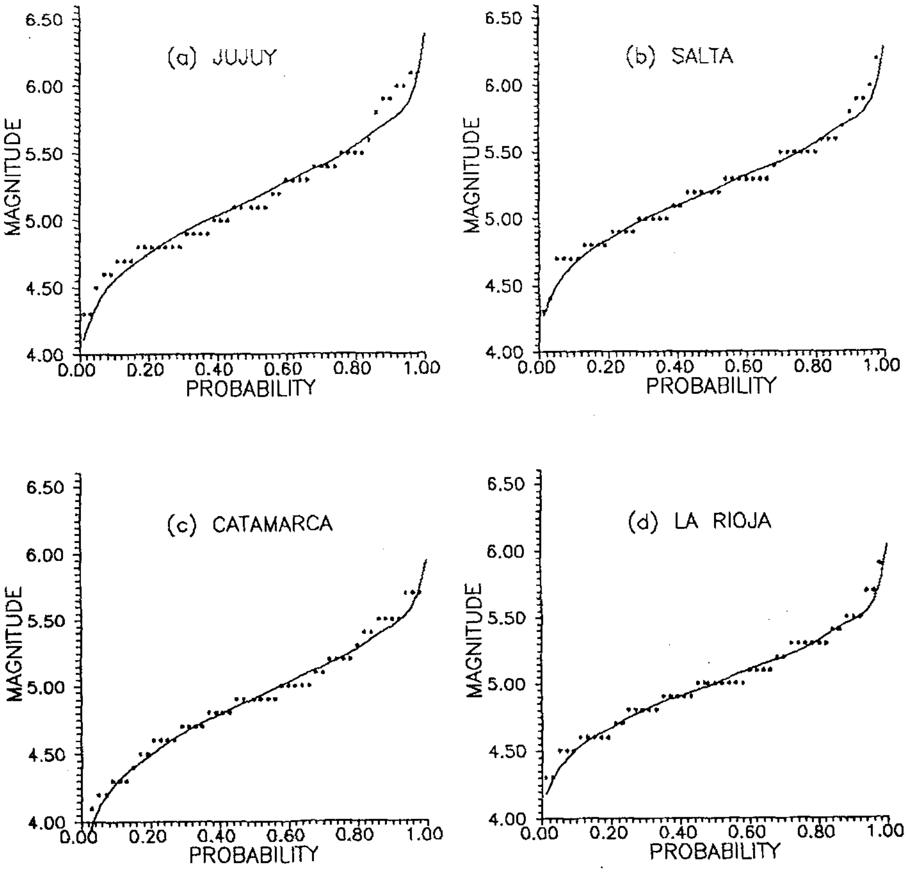


Figure 7
Idem Figure 6 for Jujuy (7a), Salta (7b), Catamarca (7c) and La Rioja (7d) provinces.

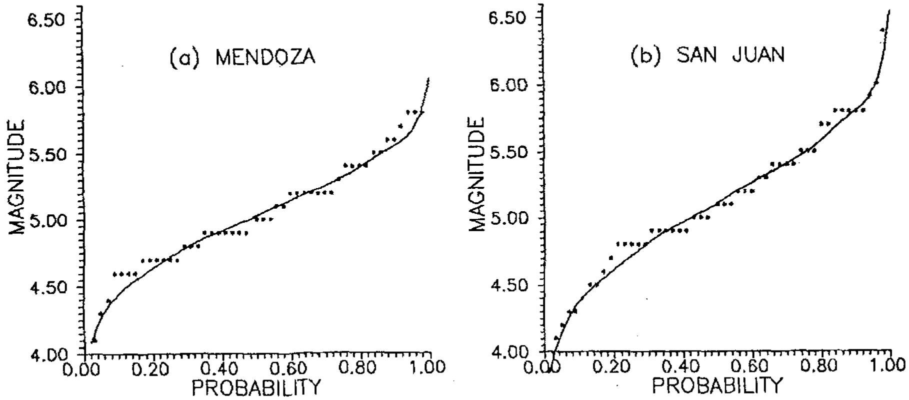


Figure 8
Idem Figure 6 for Mendoza (8a) and San Juan (8b).

Table 2

Return periods (T in 6 months $= .5$ year units)

	$T(m=4)$	σ_T	$T(m=4.5)$	σ_T	$T\ (m=5)$	σ_T	$T(m=5.5)$	σ_T
JUJUY	1.00	0.00	1.09	0.03	1.57	0.37	4.17	31.08
SALTA	1.00	0.00	1.05	0.01	1.44	0.13	3.95	22.82
CATAMARCA	1.03	0.00	1.24	0.05	2.34	1.54	12.29	1300
LA RIOJA	1.00	0.00	1.10	0.04	1.96	0.74	10.87	1174
N.O.A.	1.00	0.00	1.00	0.00	1.07	0.03	1.92	0.53
MENDOZA	1.01	0.00	1.13	0.03	1.88	0.44	7.52	262
SAN JUAN	1.02	0.00	1.16	0.08	1.72	1.01	4.00	31.6
CUYO	1.00	0.00	1.02	0.00	1.29	0.11	2.82	5.89

Table 3

Modal extremes values, $m_1(T)$, for return periods T of 1, 2, 10, 20 and 50, equivalent to 0.5, 1, 5, 10 and 25 years, respectively, with the corresponding standard deviations

	$m_1(T=1)$	$m_1(T=2)$	$m_1(T=10)$	$m_1(T=20)$	$m_1(T=50)$
JUJUY	5.18 ± 0.17	5.43 ± 0.20	5.84 ± 0.42	5.96 ± 0.43	6.08 ± 0.41
SALTA	5.23 ± 0.17	5.46 ± 0.19	5.82 ± 0.41	5.92 ± 0.41	6.03 ± 0.39
CATAMARCA	4.96 ± 0.15	5.19 ± 0.20	5.55 ± 0.37	5.65 ± 0.36	5.74 ± 0.32
LA RIOJA	5.01 ± 0.18	5.22 ± 0.20	5.55 ± 0.46	5.65 ± 0.47	5.76 ± 0.45
N.O.A.	5.52 ± 0.18	5.70 ± 0.20	6.01 ± 0.46	6.10 ± 0.48	6.20 ± 0.46
MENDOZA	5.07 ± 0.16	5.30 ± 0.20	5.65 ± 0.40	5.74 ± 0.39	5.84 ± 0.13
SAN JUAN	5.14 ± 0.16	5.45 ± 0.19	5.92 ± 0.40	6.06 ± 0.41	6.20 ± 0.38
CUYO	5.34 ± 0.18	5.58 ± 0.20	5.96 ± 0.44	6.07 ± 0.45	6.18 ± 0.43

Table 4

Estimated a and b coefficients and the resulting values of M_1, M_2 and M_3, obtained using the whole process technique, and the corresponding standard deviation, σ_a, σ_b, σ_{M1}, σ_{M2} and σ_{M3}, respectively

	a	σ_a	b	σ_b	M_1	σ_{M1}	M_2	σ_{M2}	M_3	σ_{M3}
JUJUY	5.04	0.03	1.020	0.006	4.94	0.04	5.69	0.00	6.31	0.14
SALTA	5.81	0.03	1.167	0.006	4.97	0.03	5.68	0.00	6.33	0.17
CATAMARCA	5.05	0.04	1.088	0.008	4.64	0.05	5.33	0.00	5.93	0.19
LA RIOJA	4.51	0.04	0.956	0.008	4.72	0.06	5.41	0.00	5.96	0.16
TUCUMAN	3.00	0.07	0.812	0.014	3.69	0.10	5.17	0.00	6.04	0.16
N.O.A.	6.67	0.02	1.244	0.004	5.36	0.02	5.83	0.00	6.30	0.15
MENDOZA	4.93	0.04	1.026	0.008	5.81	0.05	5.43	0.00	5.96	0.17
SAN JUAN	5.46	0.03	1.070	0.006	5.10	0.04	5.83	0.00	6.45	0.15
SAN LUIS	3.64	0.06	1.021	0.014	3.57	0.10	5.17	0.00	5.51	0.20
CUYO	6.57	0.01	1.265	0.003	5.19	0.02	5.85	0.00	6.49	0.14

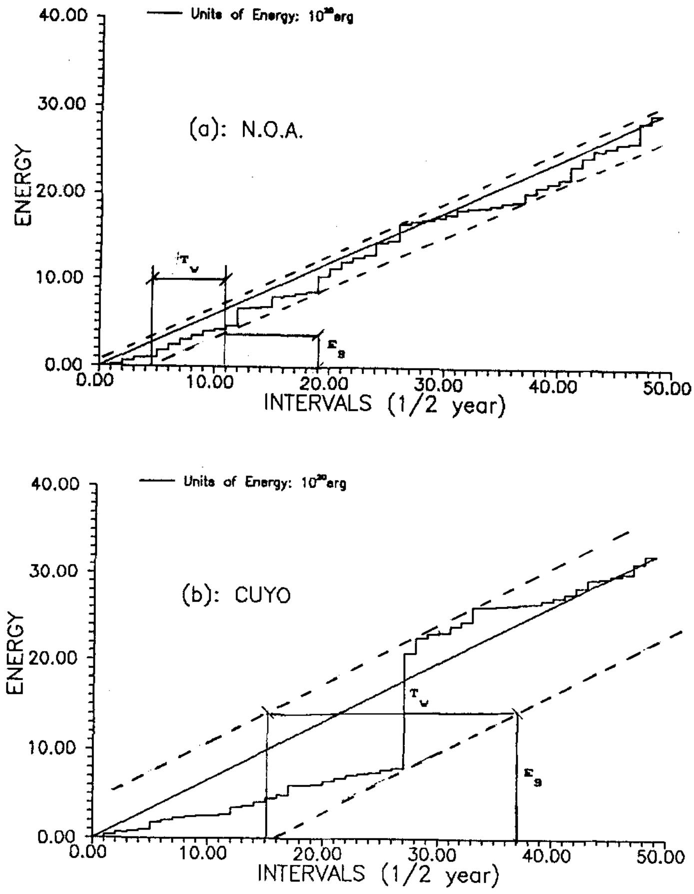


Figure 9
Cumulative energy release as a function of time for Regions 1 (9a) and 2 (9b). The ways for calculating the upper bound magnitude and mean annual energy release are shown (see e.g., MAKROPOULOS and BURTON, 1983).

In Figure 9 the cumulative energy released as a function of time is shown for Regions 1 (Fig. 9a) and 2 (Fig. 9b). The jump observed in Figure 9b is due to the 1977 San Juan earthquake (with $m_b \sim 6.4$). From these graphs, the waiting time, T_w, defined as the minimum time required for the accumulation of the maximum energy if there were no earthquake in the meantime, the mean value of the energy, related to M_2, and the upper bound, related to M_3, are estimated (e.g., MAKROPOULOS and BURTON, 1983) (see Fig. 9). Table 5 shows the resulting values. Good agreement with the values of M_3 previously found (Table 4) may be observed.

Table 5

Estimated values of M_2, M_3 and waiting time, T_w, with the corresponding standard deviations, as obtained from Figure 9

	M_2	σ_{M2}	M_3	σ_{M3}	T_w	σ_{Tw}
JUJUY	5.69	0.00	6.23	0.15	11.0	0.1
SALTA	5.68	0.00	6.20	0.18	7.5	0.1
CATAMARCA	5.33	0.00	5.90	0.20	9.2	0.1
LA RIOJA	5.41	0.00	5.96	0.58	10.1	0.1
N.O.A.	5.83	0.00	6.39	0.24	6.2	0.1
MENDOZA	5.43	0.00	6.03	0.20	10.5	0.1
SAN JUAN	5.83	0.00	6.58	0.19	28.1	0.1
CUYO	5.85	0.00	6.56	0.19	22.2	0.1

6. Discussion of the Results

Comparing the values of M_1, M_2 and M_3 (Table 4) obtained with the entire set of data with the values of $m_1(1)$ (Table 3), X_2 and ω (Table 1) from Gumbel III, respectively, a good agreement is observed. As was expected, in all regions M_3 is less than ω, except at Salta, but there, even so, they are between the error range.

The results show the characteristic of the regional seismicity. The modal values are around 5–5.5 for both regions, and according to the recurrence times (see Table 3), a $m_b > 6.0$ earthquake, quite similar to the 1977 San Juan event, may be expected within the next 10 years in the same province and within 25 years in the remaining ones.

It is clear that more extensive data intervals are needed to improve the confidence of the results for the larger values of m. At least two large earthquakes have occurred in Region 2 within thirty years before the time interval considered in the catalogue, which inclusion could modify the recurrence times in that range. It is our aim to extend the catalogue at least with the largest events, which are the only ones needed for Gumbel III distribution. Moreover, results have shown that a further analysis must include a correlation between tectonic features and the resulting values of the regional parameters (especially through the b values obtained in each case) to determine the different zones in which the statistical analyses may be conveniently performed.

Acknowledgment

This work was partially supported by CONICET.

REFERENCES

BÅTH, M., *The energies of seismic body waves and surface waves.* In *Contributions in Geophysics* (Pergamon, London 1958), Vol. 1, pp. 1–16.

BALDIS, B., FEBRER, J., and VACCA, A. (1982), *Transducción, un fenómeno asociado a procesos de tectónica global.* V. Latinamerican Geological Meeting, Actas *III*, 705–718.

BURTON, P. (1990), *Pathways to Seismic Hazard Evaluation: Extreme and Characteristic Earthquakes in Areas of Low and High Seismicity*, Natural Hazards *3*, 275–291.

BURTON, P., and MAKROPOULUS, K. (1985), *Seismic Risk of Circum-Pacific Earthquakes: II. Extreme Values Using Gumbel's Third Distribution and the Relationship with Strain Energy Release*, Pure and Appl. Geophys. *123*, 849–869.

GRINGORTEN, I. I. (1963), *A Plotting Rule for Extreme Probability Paper*, J. Geophys. Res. *68*, 813–814.

GUMBEL, E. J. (1954), *Statistical Theory of Extreme Values and Some Practical Applications*, Nat. Bur. Standards Appl. Math. Ser. *33*, Washington D.C., 51 pp.

GUTENBERG, B., and RICHTER, C. F. (1944), *Frequencies of Earthquakes in California*, Bull. Seismol. Soc. Am. *34*, 185–188.

KANAMORI, H. (1977), *The Energy Release in Great Earthquakes*, J. Geophys. Res. *82* (20), 2981–2987.

KARNIK, V., and HUBNEROVA, Z. (1968), *The Probability of Occurrence of Largest Earthquakes in the European Area*, Pure and Appl. Geophys. *70*, 61–73.

KNOPOFF, L., and KOGAN, Y. (1977), *Analysis of the Theory of Extremes as Applied to Earthquake Predictions*, J. Geophys. Res. *82*, 5647 –5657.

MAKROPOULOS, K. C., and BURTON, P. (1983), *Seismic Risk of Circum-Pacific Earthquakes: I. Stream Energy Release*, Pure and Appl. Geophys. *121*, 247–267.

ROCA, A., ARROYO, A. L., and SURIÑACH, E. (1984), *Application of the Gumbel III Law to Seismic Data from Southern Spain*, Eng. Geol. *20*, 63–71.

SABBIONE, N., and JASCHEK, E. (1990), *Banco Argentino de Sismos*, FCAG. UNLP.

(Received January 18, 1992, revised/accepted August 25, 1992)