Geodesy and Geodynamics xxx (2017) 1–9

Contents lists available at ScienceDirect

Geodesy and Geodynamics

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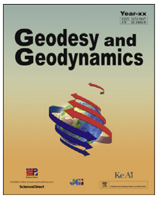

Seismic hazard analysis for central-western Argentina

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ARTICLE INFO

Article history:
Received 13 April 2017
Received in revised form
25 July 2017
Accepted 25 July 2017
Available online xxx

Keywords:
Probabilistic seismic hazard analysis
Seismic-resistant construction standards
Seismic sources
Visual cumulative method

ABSTRACT

In this study, we present a PSHA (Probabilistic Seismic Hazard Analysis) for the city of San Juan, which is located in the central-western region of Argentina (30°S–35.5°S; 66.5°W–71°W). In addition to crustal earthquakes provided by catalogues, recent paleoseismological and neotectonic investigations have permitted to consider events which occurred during the last 400 years.

Four seismogenic sources that could cause damages to the studied site corresponding to Precordillera, Western Sierras Pampeanas, Basement of the Cuyana Basin and Cordillera Principal were identified. Based on the evaluation of the contribution of these sources, maximum moment magnitudes above 7.5 (*Mw*) are expected.

High values of SA (spectral acceleration) (0.2 and 1 s periods) and PGA (peak ground acceleration) were found in the city of San Juan, which suggests that it is located in a zone of high seismic hazard.

Finally, the obtained SA spectra were compared with the seismic-resistant construction standards of Argentina INPRES-CIRSOC 103 [1]. Results suggest that for the city of San Juan and for a return period of 475 years, it covers the seismic requirements of the structures.

1. Introduction

The city of San Juan is located at 31.5°S and 68.5°W (central-western region of Argentina). It has an area of 30 km^2 and a population density of 3759.3 pop/km^2 (National Census 2010). In this area significant seismic activity has been observed within the continental crust (South American Plate) for shallow earthquakes at depths less than 35 km, and within the subducted plate (Nazca Plate) with depths ranging from 100 to 300 km. Comparatively, shallow earthquakes ($\leq$35 km) have been responsible for the greatest natural disasters in the history of Argentina and are associated with the geological structures of Precordillera, western Sierras Pampeanas and the interaction between both in the north of the Mendoza Province (Fig. 1). As an example we can mention the earthquakes that occurred in San Juan in 1894, 1944, 1952 and 1977 and those that occurred in Mendoza in 1861 and 1985. These events caused great destruction and casualties that in some cases were counted by hundreds. For this reason, the region under investigation is recognized as the area exposed to the greatest occurrence of earthquakes, with some of them of great magnitude [2,3] possibly related to the type of crustal structure and the geometry of the Nazca plate that subducts horizontally under South America [4]. In this sense it becomes essential to analyze the seismic hazards in the area.

2. Preparation of the earthquakes catalog

A catalog of seismic parameters was compiled with data from the Centro Regional de Sismología para América Del Sur CERESIS until 1981 [7] and, after that and until July 2016 with data from the National Earthquake Information Centre NEIC [8]. Table 1 summarizes the primary sources of information used in the compilation of the instrumental part of the catalog.

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Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.geog.2017.07.006

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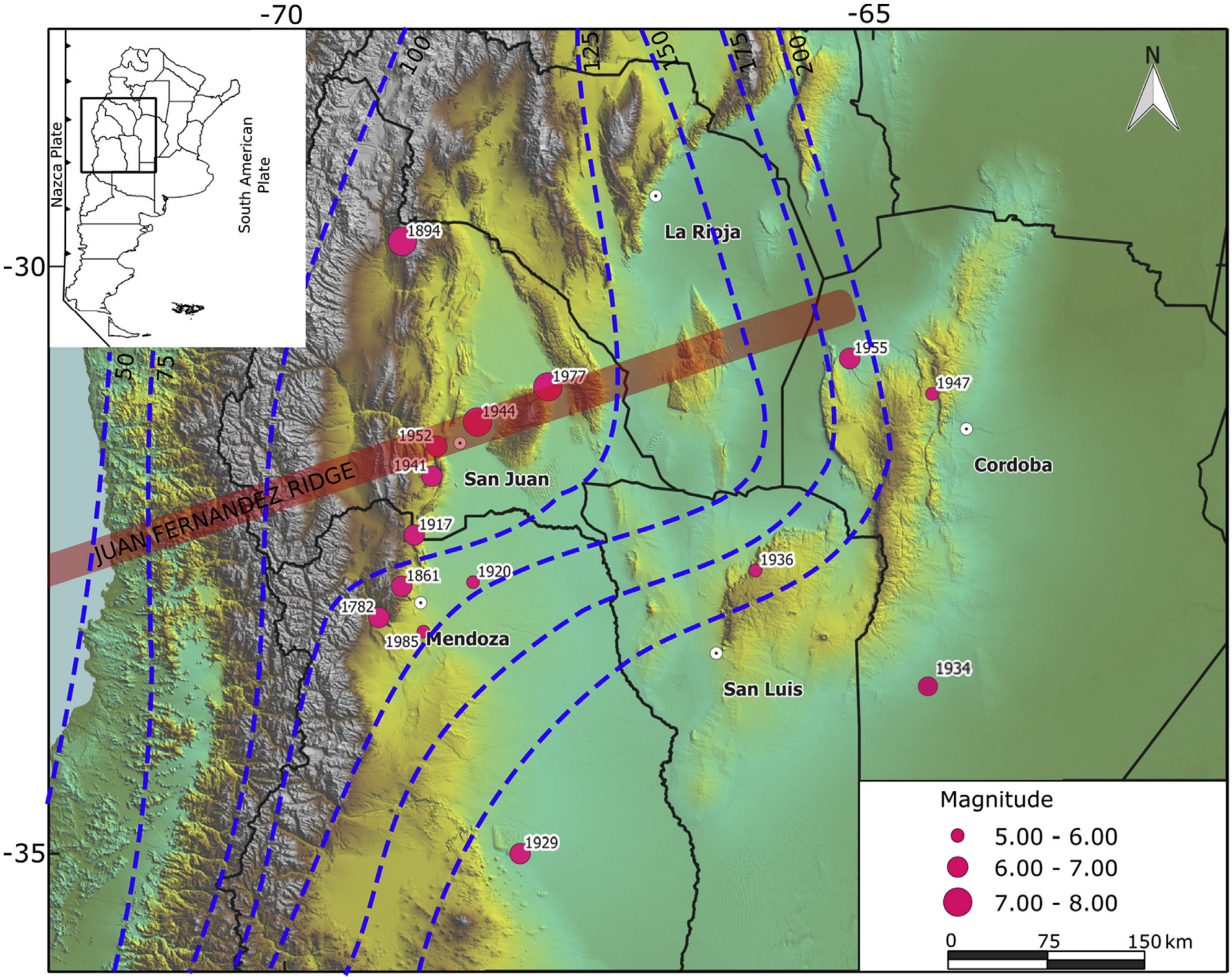

Fig. 1. Epicentral distribution of historical earthquakes in the central-western region of Argentina. The range of magnitudes reported by INPRES (ML) are indicated in the box. Blue dashed lines represent the Crustal and Upper Mantle Structure in the Flat Slab Region of Central Chile and Argentina (Modified from Refs. [5,6]).

Table 1
Main sources of information used in the catalog taken from Ref. [7].

Time interval	Source
1906–1917	G-R
1918–1932	G-R + ISS
1933–1950	G-R + ISS + USCGS
1951–1960	ISC + USCGS + BCI
1961–1963	ISC + USCGS
1964–1973	USCGS + ISC + USGS
1974–1981	ISC + USGS
1982–2016	USGS

G-R: Gutenberg and Richter; ISS: International Seismological Summary; USCGS: United States Coast and Geodetic Survey; BCI: Bureau Central International de Seismologie; ISC: International Seismological Centre; USGS: U. S. Geological Survey - NEIC.

3. Identification of the main seismic sources and seismotectonic regionalization

To evaluate the seismic hazard in a region, it is necessary to subdivide it into a system of geological subregions that are seismically homogeneous and also called seismic sources. This means that the parameters of the Gutenberg and Richter relationship remain fixed to the occurrence of earthquakes and can be attributed to the tectonic characteristics of that subregion. Such subdivision is called seismotectonic regionalization.

3.1. *Regional morphostructural units*

The area under study forms a part of the Andean retroarc as a consequence of the east-west compression generated by the subduction of the Nazca plate under the South American plate. GPS studies indicate a relative movement velocity of 63–79 mm/year [9].

From the analysis of the crustal seismic activity associated with the morphostructural units and neotectonic studies, four seismotectonic subregions or seismic sources have been selected in this work (Fig. 2 and Table 2).

4. Conversion of magnitudes – elimination of aftershocks

Prior to the elimination of the aftershocks, all catalog magnitudes were converted to moment magnitude scale through the multipath process proposed by Scordilis [10]. This procedure uses globally valid empirical relationships that allow the conversion of magnitudes expressed in different scales to moment magnitude

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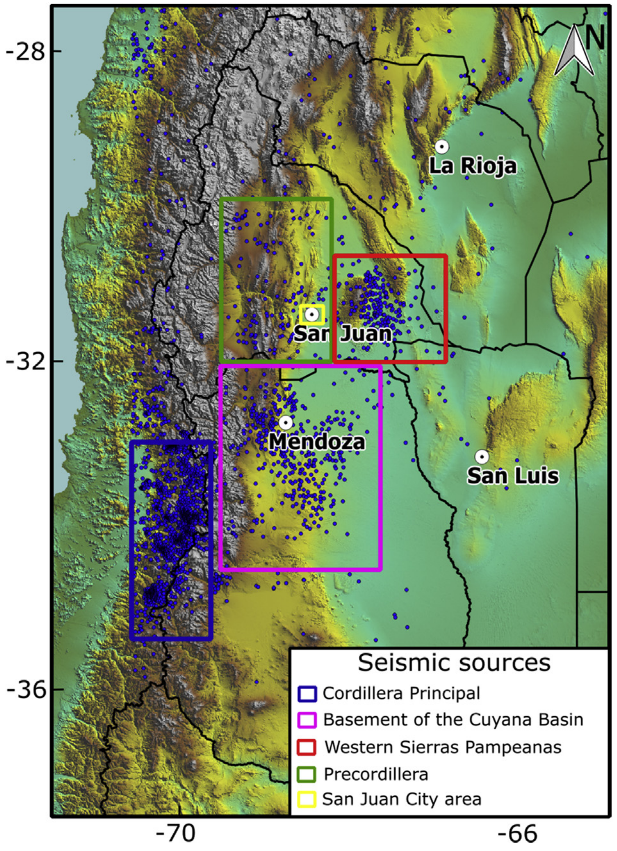

Fig. 2. Seismic sources.

Table 2
Characteristics of the four seismotectonic sources.

Seismogenic Sources	Type
Precordillera	Crustal
Western Sierras Pampeanas	Crustal
Basement of the Cuyana Basin	Crustal
Cordillera Principal	Crustal

Mw. In this way it was possible to obtain a very useful tool in the compilation of homogeneous seismic catalogues.

Aftershocks and foreshocks present in the catalog were identified and eliminated as detailed below.

If M is the magnitude of the main earthquake, an event is identified as a secondary earthquake if the following conditions are met:

1. Its magnitude does not exceed the value M
2. The distance between the epicentre of the main earthquake and the secondary earthquake does not exceed the value $R_a(M)$
3. The difference in time between the main event and the secondary event is less than $T(M)$
4. The difference in focal depth between the main and secondary event does not exceed the value $H(M)$

where $R_a(M)$, $T(M)$, $H(M)$ are empirical functions established for each particular region.

The magnitudes of the main earthquakes were considered for a range $0 < M < 9$ and this interval was subdivided into smaller subintervals $M1<m1<$ …... $<m6<M2$ in order to optimize the process.

Table 3 summarizes the values of the parameters used in the program for the elimination of secondary earthquakes.

The distances between the epicentre of the main earthquake and that of the secondary R_a were calculated for each particular region and for different intervals of magnitude M: $R_a < R_a(i)$. In order to obtain $R_a(i)$, in the case of crustal earthquakes ($h \leq 70$ km), the existing reports of the event of Caucete – San Juan, Argentina, on November 23, 1977 [11] and Mendoza, Argentina, on January 26, 1985 [12] were used. The choice of these two earthquakes was due to the large number of aftershocks reported by networks of seismographs that were installed in both epicentral zones immediately after the main events. With these data, the distances between the epicentres of the main events and the most distant secondary earthquakes were estimated, obtaining $Ra = 80$ km for the 1977 San Juan earthquake and $Ra = 30$ km for the 1985 Mendoza earthquake. These distances were used as limits for the corresponding magnitude range of the main earthquake. For example, for $Ra = 80$ km a range of magnitudes 6.50–9.00 was used; for $Ra = 30$ km a range of magnitudes 5.50–6.49 was used. For the remaining intervals, the value of $Ra(i)$ was obtained according to previous works done in the International Institute of Earthquake Prediction Theory and Mathematical Geophysics of Moscow, Russia [2].

Limits in depth are relative: $H - \mathrm{d}H1 < Ha < H + \mathrm{d}H2$, where H is the depth of the main earthquake focus, and $\mathrm{d}H1$ *and* $\mathrm{d}H2$ are estimated constants. In the present study these parameters were set as −30 km and 30 km respectively. The limits for the time (Ta) between the main earthquake and the secondary earthquake were fixed: $Ta < Ta(i)$, where $Ta(i)$ was defined for each magnitude interval.

5. Integrity of the seismic catalog

Success in seismic hazard estimation and seismotectonic studies is established from the unequivocal knowledge of all earthquakes that took place at a site of interest. However, the available seismic history is the result of a collection of quite heterogeneous data ranging from the last instrumental records to the macro-seismic observations obtained from ancient documentary sources. For this data group, it is essential to characterize the different levels of reliability due to heterogeneity in sampling procedures, data processing and the availability of relevant information.

With respect to the instrumental part of the catalog (events detected by seismographs), procedures of parameterization of earthquakes are influenced by changes in the recording networks, density and distribution of stations and types of instruments. Thus, based on these parameters, it is possible to characterize the different levels of integrity and reliability [13,14].

As for the macro-seismic part, due to the scarcity of information sources and lack of complete documentation, the probability of "lost" earthquakes increases as time goes back, so the catalog is progressively less representative of true seismicity as it extends more in time. It has been observed that this worsening of seismic

Table 3
Limits used in the elimination of secondary earthquakes.

Magnitude (Mw)	Distance (km)	Time (days)	Focal depth (km)
0.00–3.49	10	7	−30, 30
3.50–3.99	10	7	−30, 30
4.00–4.49	10	7	−30, 30
5.00–5.49	20	7	−30, 30
5.50–6.49	30	30	−30, 30
6.50–9.00	80	500	−30, 30

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information depends not only on the existing information of ancient seismicity but also on the socioeconomic evolution of the area [15].

Due to the low population density of the areas affected by earthquakes and the lack of seismological instrumentation during the first decades of the last century, Argentina does not have a continuous seismic record over time. The oldest existing data are fragmented and often partial [16]. It is expected, therefore, that the catalog selected for this study is not complete for all magnitudes, especially for those of low magnitude that are the most difficult to be perceived as well as for major events which occurred before 1700. Therefore, it is advisable to include an analysis of the completeness or integrity of the catalog that has been used in this work.

A technique that has been widely used to evaluate the integrity of the catalogues based on existing seismic data was initially developed by Tinti and Mulargia [17] and is currently called the CUVI (Visual Cumulative Method). It states that the occurrence of earthquakes follows a stationary process, where the average speed of occurrence of the events is constant in time. Catalogues are incomplete due to the lack of corresponding reports mostly of low magnitude earthquakes. For this reason, the evaluation of the catalog integrity was performed for different levels of magnitude and observation time intervals.

The analysis showed that it is possible to consider the catalog to be complete for the range of magnitudes from 6 to 6.5 since 1922. It is important to note that the seismological station of the Universidad Nacional de La Plata was installed at that time [7]. Later, the WWSSN (World Wide Standard Network) was installed around 1963 to produce a control over atomic tests and simultaneously generated an improvement in the ability to detect and locate smaller seismic events. This global seismological network was gradually improved and a progressive increase in global seismicity was observed [18]. With the WWSSN network, it was possible to obtain absolute time data with a precision of one-tenth of a second for larger seismicity, whose magnitude ranges from 5.0 to 5.5 which are consider complete since 1963. The range of magnitude 4.5 can be considered complete since 1993 due to the densification of regional seismic monitoring networks.

In the analysis of major earthquakes, all surface events of magnitude larger than 7.0 have been included. The CUVI method has not been applied to this range since the observation period of the catalog is very small for the analysis of larger magnitudes. The central-western region of Argentina includes six events that correspond to the 1782 and 1861 Mendoza earthquakes and the San Juan earthquakes in 1894, 1944, 1952 and 1977.

Taken into account that the foundation of Mendoza occurred in March 1561, San Juan in June 1562, La Rioja in May 1591, San Luis in August 1594, and that these dates have constituted the first historical information in South America related to the perception of tremors and the occurrence of damages and casualties caused by earthquakes (e.g. Valdivia, Chile 1575), it is not risky to consider that the range of magnitude 7 is complete for the entire central-western region of Argentina since 1600.

The largest earthquakes in the area in the last century have been studied well. For this reason, their quantitative parameters are known in great detail, such as the 1944 San Juan earthquake ($Mw = 7.0$) [19]. The rate of occurrence of major earthquakes is consistent with the results of paleoseismological studies for some areas of San Juan [20–22].

Fig. 3 shows the graphical representation of the seismic catalog in this study based on the analysis of completeness.

6. Calculation of the annual frequency of exceedance

The annual frequency of exceedance is the value that represents the number of earthquakes that exceed a certain magnitude in a certain time period and for a determined area. It is calculated with Eq. (1):

$$\lambda(M) = \lambda_{\min}\frac{e^{-\beta M} - e^{-\beta M_{\max}}}{e^{-\beta M_{\min}} - e^{-\beta M_{\max}}}, \quad M_{\min} \le M \le M_{\max} \tag{1}$$

where:

$\lambda(M)$ = annual frequency of exceedance of magnitude M

M = magnitude

$M_{\min}$ = minimum magnitude for which the catalog is considered complete

$M_{\max}$ = maximum magnitude considered for the source

$\lambda_{\min}$ = annual frequency of exceedance of the minimum magnitude ($\alpha = 2.303.\ a$, $\beta = 2.303.b$). It can be estimated with Eq. (2)

$$\lambda_{\min} = e^{(\alpha - \beta M_{\min})} \tag{2}$$

where a and b are the parameters determined from the Gutenberg and Richter relation.

The annual frequencies of exceedance were calculated for the four seismic sources defined in the seismotectonic regionalization. Table 4 and Fig. 4 show the parameters obtained from the adjustment of the Gutenberg and Richter relation for the four seismotectonic subregions. The annual frequencies of exceedance have been calculated and normalized for a year and for an area of 1000 km^2.

7. Attenuation relationship

In order to evaluate the seismic hazard in a region, it is necessary to know the attenuation relationship between the ground motions with the distance. This equation or law of attenuation is an expression that relates magnitude, distance, and seismic intensity [23]. The greater the distance from the area of rupture to the site where the hazard is evaluated is, the smaller the influence of the size of the earthquake will be. This is due to the fact that as a seismic wave propagates away from its source through the crust, two types of relevant physical phenomena occur. The first is the geometric expansion in which the amplitude of the wave decreases due to distance in close contact with energy preservation. The second is physical attenuation where the materials which constitute the interior of the earth absorb part of the energy of the wave.

At present, there is no relation between the attenuation of accelerations with distance and magnitude for crustal earthquakes in the central-western zone of Argentina. For this reason we have analysed those earthquakes currently available that have been developed from shallow seismic events in tectonically active zones of the world. Several expressions have been proposed to which the data are adjusted, as well as the parameters that characterize the movement, the size and type of source that produced the event. For example, there are certain attenuation laws for crustal earthquakes [24–26] and other laws characterizing the seismicity of subduction zones [27–29]. Seismic attenuation laws which are used to estimate crustal earthquakes take into account the type of fault that produced the event (thrust, normal or strike slip) and which fault block the hazard is being evaluated in (e.g. upper block effect or " Hanging wall "). In this way the expressions reflect the geotectonic characteristics of the region.

In this paper we used the attenuation law proposed by Abrahamson and Silva [24]. These authors obtained empirical response spectral attenuation relations as a function of the distance and magnitude. This relationship takes into account surface

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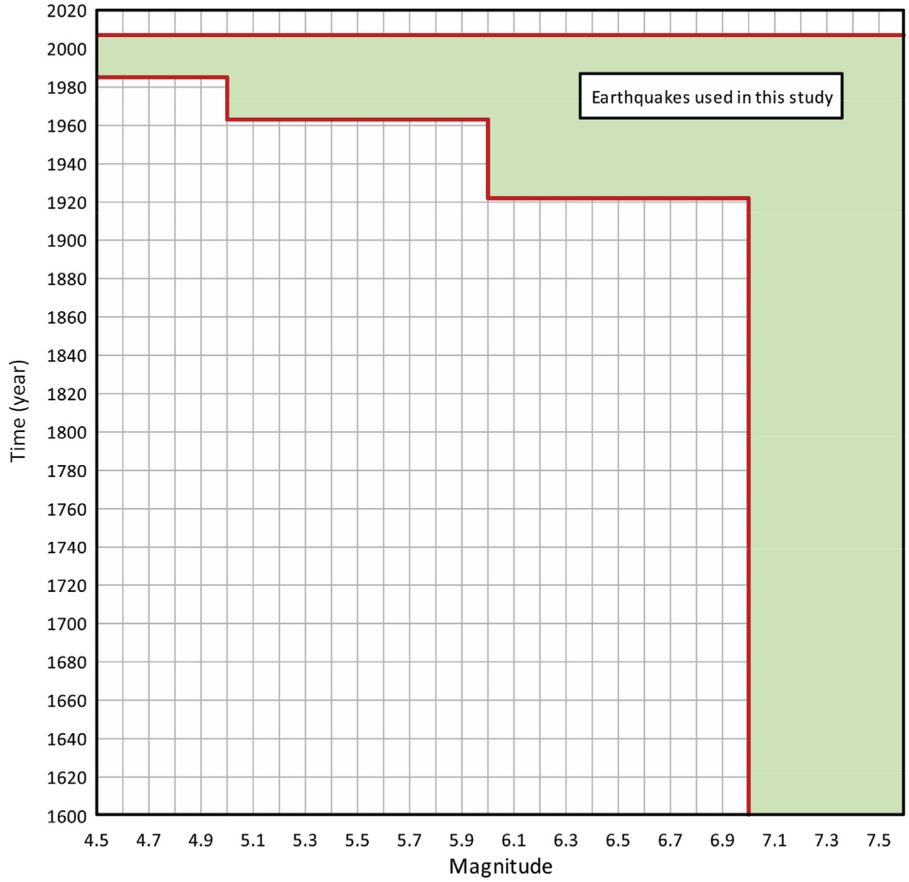

Fig. 3. Minimum value of magnitude (horizontal axis) adopted for different intervals of time (vertical axis), determined according to the study of completeness.

Table 4
Gutenberg and Richter relation parameters obtained for each seismic source identified for this work.

Source	Precordillera	Western Sierras Pampeanas	Basement of the Cuyana Basin	Cordillera principal
$M_{\min}$	4.5	4.5	4.5	4.5
$M_{\max}$	8	7.8	7.8	7.2
a	2.6	4.12	3.20	3.9
b	0.87	1.05	1.01	1.11
$\lambda_{\min}$	0.04839	0.24825	0.04516	0.08031

earthquakes in tectonically active zones of the world based on 655 observational records of horizontal and vertical components corresponding to 58 earthquakes of magnitude greater than 4.4. This regression analysis was developed based on a random effects model, which uses the maximum likelihood method to correlate the records obtained from an earthquake. For example, if an earthquake has a greater stress drop than the average earthquake of that magnitude, it can be expected that soil movement produced by this event at all sites will be greater than average. It is important to emphasize that the sampling of the data must be uniform to be able to observe some tendency produced only by the source or the site.

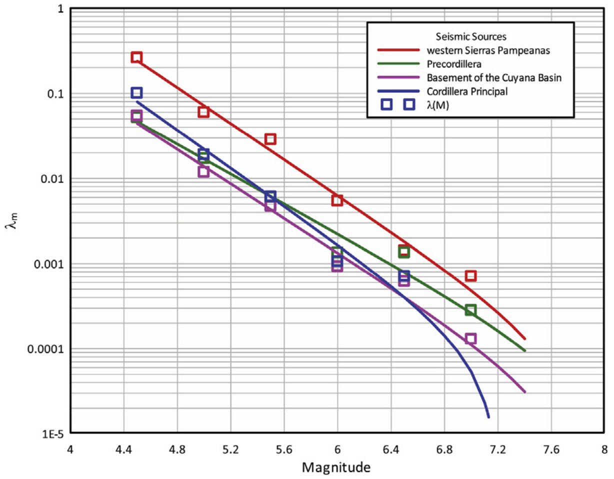

Fig. 4. Results of the adjustment of the Gutenberg and Richter relation for the four seismic sources defined in this work. The obtained parameters are presented in Table 4.

8. Estimation of seismic hazard

The seismic hazard generated by the different seismic sources (seismotectonic subregions) was estimated individually and jointly in order to evaluate each contribution to the total seismic hazard. All estimates were made considering rock soil or firm soil conditions. For the calculation, we used CRISIS software which is currently used in researches in different parts of the world.

This software was developed at the Instituto de Ingeniería of the Universidad Autónoma de México [30] following the methodology of Cornell [31]. This method incorporates the influence of all potential sources of earthquakes, assigns the average activity rate to them, and then evaluates the seismic risk at the site of interest.

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8.1. PGA (peak ground accelerations) and SA (spectral accelerations) values for the city of San Juan–Argentina

The results of the seismic hazard analysis for the City of San Juan, including PGA (peak ground acceleration) and SA (spectral acceleration) values, are shown in Tables 5 and 6 respectively.

The maximum accelerations reach 194 gal for a return period of 72 years, and 350 and 503 gal for return periods of 475 and 4275 years, respectively.

The considered structural periods were 0.2 and 1 s, with 50%, 10%, and 2% chances of exceedance in 50 years (72, 475, and 2475 years return periods), which are calculated based on rock soil and crustal depth of earthquakes. In order to analyse the contribution of each seismic source the results are shown separately.

As seen in Table 5, the seismic sources of Precordillera and Western Sierras Pampeanas with maximum acceleration values of 452 and 420 gal for earthquakes with a return period of 2475 years display the maximum accelerations for the City of San Juan.

In Table 6, an important SA (spectral acceleration) of 1343 gal is observed for the period of 0.2 s in the case of earthquakes with a return period of 2475 years.

The seismic source that contributes least to the total seismic hazard in the case of the City of San Juan is the Cordillera Principal because of the distance (more than 270 km).

8.2. Annual frequency of exceedance of the PGA (peak ground acceleration) and SA (spectral acceleration)

In Figs. 5–7, the annual frequency of exceedance of the PGA (peak ground acceleration) and the SA (spectral acceleration)

Table 5
PGA. (Peak ground acceleration) values for the City of San Juan, in units of gal, with 50%, 10%, and 2% probability of exceedance in 50 years (72, 475, and 2475 year return periods) taking into account earthquakes of crustal depth.

Seismic Source	Probability of exceedance		
	50% in 50 years (72 year return period)	10% in 50 years (475 year return period)	2% in 50 years (2475 year return period)
Total	194	350	503
Western Sierras Pampeanas	146	279	420
Precordillera	145	298	452
Basement of the Cuyana Basin	30	62	111
Cordillera Principal	14	24	35

Table 6
Values of SA (spectral accelerations), in units of gal, for periods of 0.2 and 1.0 s, with 50%, 10%, and 2% probability of exceedance in 50 years (72, 475, and 2475 years return periods), for the City of San Juan, taking into account earthquakes of crustal depth.

Seismic Source	Probability of exceedance					
	50% in 50 years (72 year return period)		10% in 50 years (475 year return period)		2% in 50 years (2475 year return period)	
	Period (sec)		Period (sec)		Period (sec)	
	0.2	1	0.2	1	0.2	1
Total	473	157	895	340	1343	550
Western Sierras Pampeanas	353	117	709	262	1105	445
Precordillera	339	94	742	261	1176	469
Basement of the Cuyana Basin	75	33	161	82	288	155
Cordillera Principal	34	17	63	38	97	63

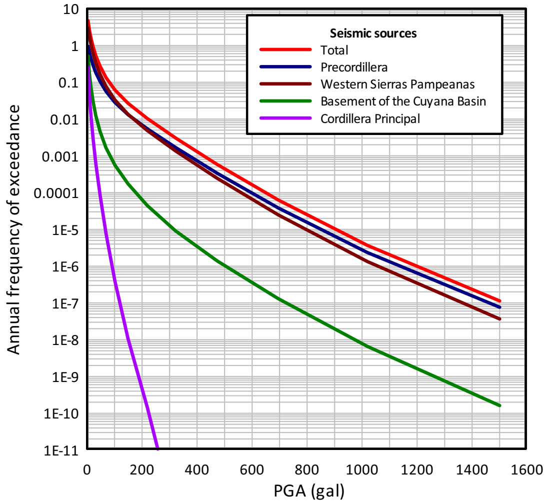

Fig. 5. Annual frequency of exceedance of the peak ground accelerations calculated for the City of San Juan.

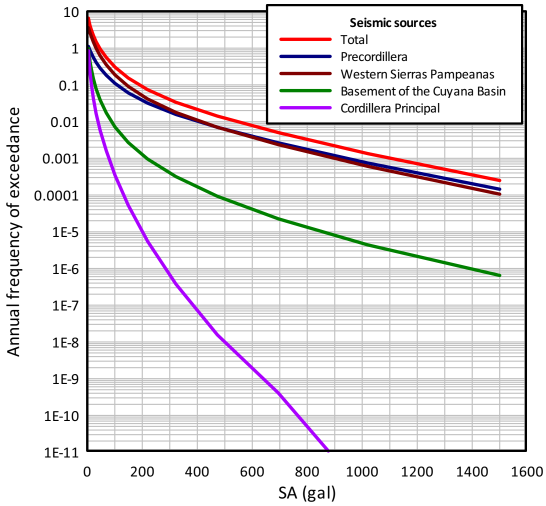

Fig. 6. Annual frequency of exceedance of spectral accelerations for a period of 0.2 s, with a damping of 5%, calculated for the City of San Juan.

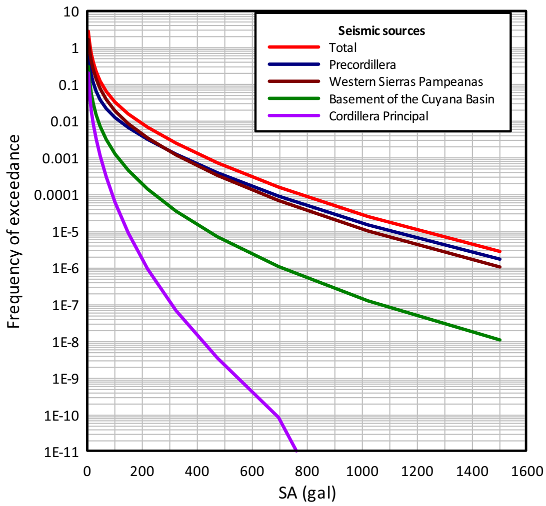

Fig. 7. Annual frequency of exceedance of the spectral accelerations for a period of 1 s, with a damping of 5%, calculated for the City of San Juan.

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values for vibration periods of 0.2 and 1 s with a damping of 5% generated by each of the seismic sources (Precordillera, Western Sierras Pampeanas, Basement of the Cuyana Basin and Cordillera Principal) are presented. Considering all of them together, the total seismic hazard was calculated for the central point of the City of San Juan (31.5° S, 68.5° W).

In the previous three figures it can be observed that the two sources which make most contribute to the seismic hazard for the City of San Juan are Western Sierras Pampeanas and Precordillera. The first region (Western Sierras Pampeanas) contributes more to the maximum accelerations that do not exceed the threshold of 200 gal and lesser to values higher than that. A possible explanation for this fact is that in the area of Sierra de Pie de Palo after the earthquake of Caucete of 1977 ($Mw = 7.5$), a large number of earthquakes of medium magnitude have occurred, resulting in a greater annual frequency of exceedance for the peak ground accelerations that do not exceed 200 gal.

On the other hand, the seismic source of the Basement of the Cuyana Basin produces a major seismic hazard for the City of San Juan. Although it is further away, it constitutes a potential source of danger due to the occurrence of important crustal earthquakes, such as the 1861 Mendoza earthquake ($Mw = 7.0$), which destroyed the city and left the sad balance of 8000 deaths in a population of 13,000 inhabitants [11], and the most recent 1985 Mendoza earthquake ($Mw = 5.9$).

8.3. Acceleration response spectrum

In Fig. 8–10, the annual frequency of exceedance for the spectral acceleration with a damping of 5% and return periods of 72, 475 and 2475 years, generated by each of the seismic sources (Precordillera, Western Sierras Pampeanas, Basement of the Cuyana Basin and Cordillera Principal) and all of them together (total seismic hazard) calculated for the central point of the City of San Juan (31.5° S, 68.5° W), is presented.

It is observed that the greater demand for the structure occurs for a structural period of 0.2 s. Acceleration values reach 500, 900 and 1350 gal, for each return period respectively. On the other hand, when analysing each source separately, it is observed that Precordillera and Western Sierras Pampeanas are the ones that contribute most reaching values of 350, 750 and 1200 gal, according to the case of earthquakes with return periods of 72, 475 and 2475 years respectively.

It is important to note that the spectrum for earthquakes with a return period of 475 years deserve a special analysis, since apart from utilization in the standards of world construction, it is also used in INRES-CIRSOC 103 [1], which regulates seismic-resistant constructions in Argentina. The Argentine standard presents different types of spectrum according to the seismic hazard for the region, zones the country into 5 areas, and classifies the soil into three types: rock, medium and soft. Table 7 shows the seismic zoning according to the degree of seismic hazard and the seismic-resistant construction code [1].

According to the zoning of the argentine regulations, the City of San Juan is located within zone 4 of seismic hazard. In order to compare the results, the spectrum presented in INPRES-CIRSOC 103 corresponding to the analysed area and the type of soil, has been included in the previous figures. For example, in Fig. 9, it can be seen that for San Juan the spectrum of the INPRES-CIRSOC standard perfectly covers the requirements for earthquakes with

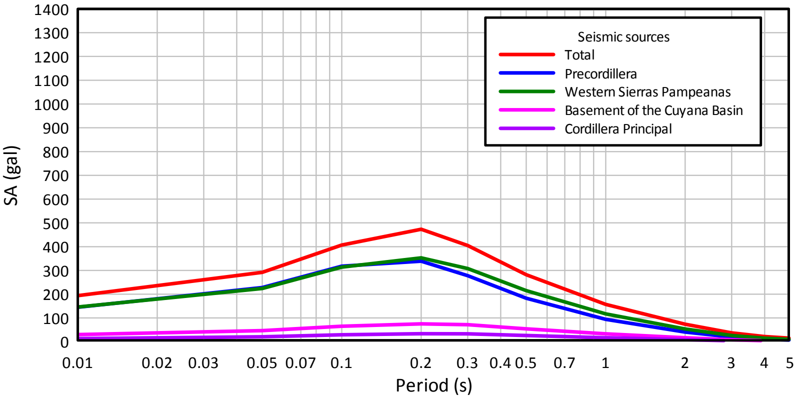

Fig. 8. Acceleration response spectrum for a return period of 72 years for a 5% damping on rock soil type for the City of San Juan.

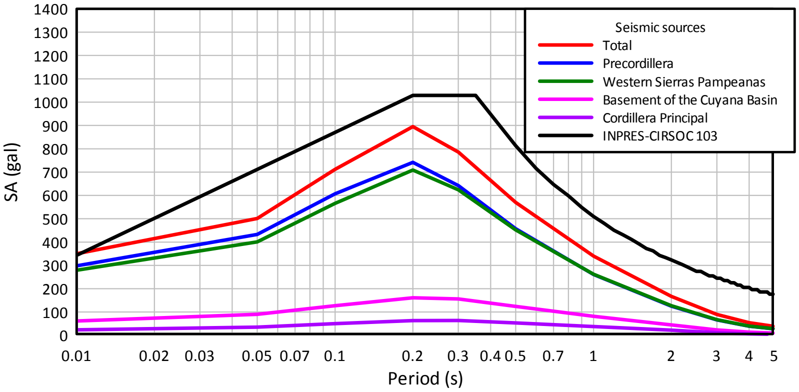

Fig. 9. Acceleration response spectrum for a return period of 475 years for a 5% damping on rock soil type for the City of San Juan.

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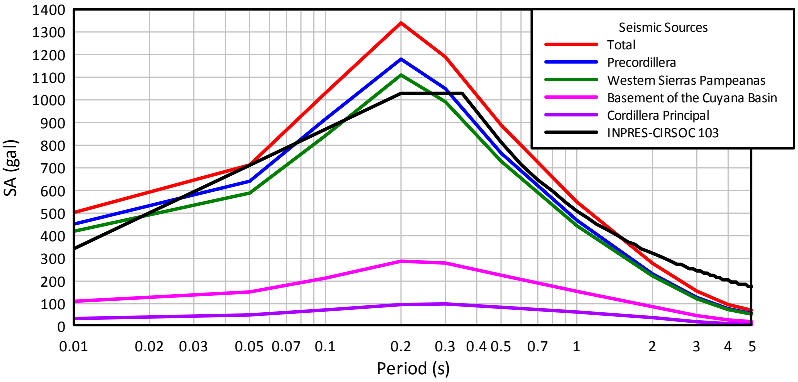

Fig. 10. Acceleration response spectrum for a return period of 2475 years for a 5% damping on rock soil type for the City of San Juan.

return periods of up to 475 years. In order to analyse whether or not this spectrum would also cover the demand for earthquakes with very large return periods (2475 years), the INPRES-CIRSOC spectrum was incorporated into Fig. 10. In this image it can be observed that the seismic sources of Precordillera and Western Sierras Pampeanas surpass the demand. On the other hand, the structure demands for earthquakes that come from the seismic sources of the Basement of the Cuyana Basin and Cordillera Principal are covered.

Table 7
Zoning of Argentina according to the degree of seismic hazard [1].

Zone	Seismic Hazard
0	Very small
1	Small
2	Moderate
3	High
4	Very high

9. Conclusions

In this work the PSHA (Probabilistic Seismic Hazard Analysis) for the Capital City of San Juan Province, Argentina has been made. To achieve this, the seismic activity of the central-western region of Argentina between latitudes 30° S–35° S and longitudes 66.5°W–71°W were taken into account and major earthquakes that occurred in the region were investigated. In this area, seismotectonic conditions favour a greater generation of seismic energy probably due to the Juan Fernández ridge currently subducting under the South American Plate, below of the province of San Juan.

Four seismotectonic subregions (seismic sources) were recognized and delimited geographically according to the genesis of earthquakes of crustal depth ($\leq$35 km). These subregions are identified in this study as Precordillera, Western Sierras Pampeanas, Basement of the Cuyana Basin and Cordillera Principal.

An integrity analysis of the earthquake catalog for crustal seismicity was performed using the CUVI (Visual Cumulative Method) method, which indicates that the magnitudes 4.5 or greater can be considered complete since 1985 and the range of magnitudes equal to or greater than 7 can be considered complete from the year 1600.

The values of the parameter b obtained from the Gutenberg and Richter relation for the subregions vary between 0.87 and 1.11. To have a reference, the value of b in the world oscillates between 0.6 and 1.5, being its most common value near the unit. This value is related to the physical characteristics of each region, and a high value of b implies that small magnitude earthquakes predominate. Therefore the region has little resistance, and a small value of b means that earthquakes of greater magnitude predominate, indicating a greater resistance of the material.

Given the high values of Peak Ground Acceleration and Spectral Acceleration that Precordillera and Western Sierras Pampeanas generate, these regions represent the zones of greater seismic danger in the investigated area. The peak ground acceleration values with 50, 10 and 2% probability of exceedance in 50 years, corresponding to 72, 475 and 2475 years of return period, show values of 194, 350 and 503 gal respectively. The values of spectral acceleration found for the 72, 475 and 2475 years return periods, show that the zone with the greatest seismic hazard is corresponding to the City of San Juan and surrounding departments. The highest SA values estimated for the different return periods vary between 473, 895 and 1343 gal, respectively, and occur for the structural period of 0.2 s.

The areas with the greatest seismic hazard (Precordillera and Western Sierras Pampeanas) correspond to a zone with a thicker, more fractured and faulted crust than Cordillera Principal.

According to the estimated SA spectra for the City of San Juan for a return period of 475 years, the INPRES-CIRSOC 103 [1] covers the seismic structural requirements of the structures.

Acknowledgments

We wish to make a special recognition to Dr. Monica Patricia Alvarado for her important contribution to this publication.

References

[1] INPRES-CIRSOC 103, Normas Argentinas para construcciones Sismorresistentes, 1999.
[2] S.D. Gregori, Riesgo sísmico en la República Argentina, Gerencia de riesgos y seguros (Mapfre España) Año XI – Numero 42 – 2 Trimetre, 1993, pp. 29–31.
[3] INPRES. Listado de sismos históricos de Argentina http://contenidos.inpres.gov.ar/buscar_sismo (Accesed November 2016).
[4] P. Alvarado, S. Beck, G. Zandt, Crustal structure of the south-central Andes Cordillera and backarc region from regional waveform modelling, Geophys J Int 170 (2) (2007) 858–875.
[5] H. Gilbert, S. Beck, G. Zandt, Lithospheric and upper mantle structure of central Chile and Argentina, Geophys J Int 165 (1) (2006) 383–398.
[6] L.S. Wagner, S. Beck, G. Zandt, Upper mantle structure in the south central Chilean subduction zone (30 to 36 S), J Geophys Res Solid Earth 110 (B1) (2005).
[7] CERESIS, Centro Regional de Sismología para América del Sur, Terremotos Destr América del 10 (1985) 1530–1894.
[8] USGS, 2016. https://earthquake.usgs.gov/earthquakes/. (Accessed November 2016).
[9] E. Kendrick, M. Bevis, R. Smalley, B. Brooks, R.B. Vargas, E. Lauría, L.P.S. Fortes, The Nazca–South America Euler vector and its rate of change, J South Am Earth Sci 16 (2) (2003) 125–131.

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[10] E.M. Scordilis, Empirical global relations converting Ms and mb to moment magnitude, J Seismol 10 (2006) 225–236.
[11] INPRES, El terremoto de San Juan del 23 de noviembre de 1977, Preliminary inform, 1977, p. 102.
[12] INPRES, El terremoto de Mendoza, Argentina del 26 de Enero de 1985, General Inform, 1985.
[13] H. Kanamori, K. Abe, Reevaluation of the turn of the century seismicity peak, J Geophys Res 84 (11) (1979) 6131–6139.
[14] O.J. Pérez, C.H. Scholz, Heterogeneities of the instrumental seismicity catalog (1904-1980) for strong shallow earthquakes, Bull Seismol Soc Am 74 (2) (1984) 669–686.
[15] D. Albarello, R. Camassi, A. Rebez, Detection of space and time heterogeneity in the completeness of a seismic catalog by a statistical approach: an application to the Italian area, Bull Seismol Soc Am 91 (6) (2001) 1694–1703.
[16] INPRES, Determinación de los coeficientes sísmicos zonales para la República Argentina, Technical publication, 1978. N° 6.
[17] S. Tinti, F. Mulargia, Completeness analysis of a seismic catalog, Ann Geophys 3 (3) (1985) 407–414.
[18] J. Havskov, G. Aguacil, Instrumentation in earthquake seismology, Springer, 2010, https://doi.org/10.1007/978-1-4020-2969-1.
[19] P. Alvarado, S. Beck, Source characterization of the San Juan (Argentina) crustal earthquakes of 15 January 1944 (M w 7.0) and 11 June 1952 (M w 6.8), Earth Planet Sci Lett 243 (3) (2006) 615–631.
[20] C. Schiffman, Seismotectonics in the eastern Precordillera, San Juan, Argentina: reconciling earthquakes and structural geology in the vicinity of the 1944 earthquake for a new model of crustal scale deformation, M.S. thesis, Oregon State Univ., Corvallis, and EEUU, 2007, p. 95.
[21] T.K. Rockwell, D.E. Ragona, A.J. Meigs, L.A. Owen, C.H. Costa, E.A. Ahumada, Inferring a thrust-related earthquake history from secondary faulting: a long rupture record of La laja fault, San Juan, Argentina, Bull Seismol Soc Am (2013) 269–284.
[22] L. Perucca, M. Rothis, F.H. Bezerra, N. Vargas, J. Lima, Late quaternary evolution of the La Cantera fault system (central Precordillera, Argentina): a morphotectonic and paleoseismic analysis, Tectonophysics 661 (2015) 200–209.
[23] E.H. Field, Probabilistic seismic hazard analysis (PSHA): a primer, 2005. Retrieved May, 17, 2011.
[24] N.A. Abrahamson, W.J. Silva, Empirical response spectral attenuation relations for shallow crustal earthquakes, Seismol Res Lett 68 (1) (1997) 94–127.
[25] N. Abrahamson, W. Silva, Summary of the Abrahamson & Silva NGA ground-motion relations, Earthq spectra 24 (1) (2008) 67–97.
[26] K. Sadigh, C. Chang, J. Egan, F. Makdisi, R. Youngs, Attenuation relationships for shallow crustal earthquakes based on California strong motion data, Seism Res Lett 68 (1997) 180–189.
[27] M. Bufaliza, "Atenuación de intensidades sísmicas con la distancia en sismos mexicanos", Master Tesis, Facultad de Ingeniería, Universidad Nacional Autónoma de México, 1984.
[28] R. Youngs, S. Chiou, W. Silva, J. Humphrey, Strong ground motion attenuation relationships for subduction zone earthquakes, Seism Res Lett 68 (1997) 58–73.
[29] D. García, S.K. Singh, M. Herráiz, M. Ordaz, J.F. Pacheco, Inslab earthquakes of central Mexico: peak ground-motion parameters and response spectra, Bull Seismol Soc Am 95 (6) (2005) 2272–2282.
[30] M. Ordaz, A. Aguilera, J. Arboleda, CRISIS2003. Ver. 3.1.0-Program for computing seismic hazard, Instituto de Ingeniería de la Universidad Nacional Autónoma de México (UNAM), 2003.
[31] C.A. Cornell, Engineering seismic risk analysis, Bull Seism Soc Am 58 (1968) 1583–1606.

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Please cite this article in press as: S.D. Gregori, R. Christiansen, Seismic hazard analysis for central-western Argentina, Geodesy and Geodynamics (2017), https://doi.org/10.1016/j.geog.2017.07.006