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UPDATED EARTHQUAKE CATALOGUE FOR SOUTH AMERICA: TIME WINDOW PRE-1964

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Abstract

On the frame of the project SARA (The South America Risk Assessment), the goal of task 4 (T4 from now on) is to compile an earthquake catalogue for South America, in terms of Mw building on the CERESIS available data, recent national and international studies and analysis conducted during the project. In particular, they include the latest versions of catalogue CERESIS-91 prepared for the Pan American Institute of Geography and History (PAIGH), which was later employed by the same CERESIS in linking the Global Seismic Hazard Assessment Programme (GSHAP); the determination of parameters by recent studies, including those proposed by the ISC-GEM catalogue, and where available, the national catalogues that meet the criteria of transparency required by the project. The activities describe here refer to the pre-1964 time window.

The first phase of the study has been the development of a critical inventory of all public studies related to earthquakes of South America. Studies for the same event have been associated with each other from the comparison of the time, of the epicentre coordinates and the size of the earthquake. For each event, a set of parameters considered reliable has been preliminarily selected.
The main problem of the catalogue is the need to express the values of magnitude in terms of Mw. Currently, few studies on earthquakes provide that value. For many events, values in terms of Ms and mb are available; although for most cases, because of the time of occurrence of these events, the magnitude values were calculated from macroseismic data. For these earthquakes we have used empirical conversion relationships published in literature (Mw / Ms and Mw / mb).
There are also events for which a value of Imax or Io is available, only. For these events, Mw/Io regional relationships have been determined, using the most reliable and recent data terms of Mw and Io.
In a second phase, for some events that have a sufficient number of macroseismic data, the source parameters have been determined using the method of Bakun and Wentworth, regionally calibrated, based on what already has been worked out in Ecuador, Venezuela in literature and Colombia in the present project.

Keywords: earthquakes; catalogue; South America

1. Introduction

South America has a long tradition of intensive historical earthquake investigation [1]. The Regional Centre for Seismology for South America (CERESIS) published a first continental scale earthquake catalogue in 1985, built on the first published set of macroseismic data points in the world [2]. Investigation continued on a national basis, mostly with reference to large earthquakes.

The South America Risk Assessment (SARA) project was a regional programme promoted by the Global Earthquake Model (GEM) initiative which lasted between 2013 and 2015. The project aimed to calculate seismic hazard and seismic risk, and to estimate the compounding social and economic factors that increase the physical damage and decrease the post-event capacities of populations to respond to and recover from damaging earthquake events in South America, by involving local experts from the region. On the frame of seismic hazard component of SARA project, the task 4 project (T4 entry) goal was to compile a new earthquake catalogue for South America, homogeneous as far as possible, in terms of Mw, building upon the methods, implementations and products released by the GEM Global components (ISC-GEM catalogue [3] and Global Earthquake History [4]), and the most updated public material available at CERESIS [5], at the national agencies and in the scientific institutions of the region.

A critical inventory of all public studies related to earthquakes of South America has been compiled, incorporating the CERESIS available data, recent national and international studies and analysis conducted during the project. The main problem of the catalogue is the need to express the values of magnitude in terms of Mw. This task was performed: i) adopting the Mw values already available from ISC-GEM, other catalogues and a few macroseismic studies; ii) converting to Mw the available Ms and mb values, by making use of the Scordilis [6], plus an ad-hoc, Brazilian relationship [7] for Brazil to events with low magnitudes; iii) using the method of Bakun and Wentworth [8] calibrated regionally for some events that have a sufficient number of macroseismic data, based on what already has been worked out in Ecuador, Venezuela and recently in Colombia which was developed in SARA project [9] using macroseismic data from Colombian Geological Survey [10] iv) determining regional Mw(Intensity) linear relations to Argentina, Bolivia, Colombia, Peru and Chile for those earthquakes which do not have magnitude assessment but a value of maximum intensity or epicentral intensity is available [9].
At the end, earthquake parameters have been assessed for 2556 earthquakes in the time-window 1513-1963. The lower threshold is Mw=5(-0.2) for the Andean region: we did not use a lower threshold for Brazil. We have still more than 1700, low size earthquakes, for which the Mw(Intensity) relationships could not be applied, while for more than 200 earthquakes no size assessment is available at all.

2. Data sources

We first considered the following, public items available at a continental scale

- CERESIS [5] that is the catalogue of South America compiled for GSHAP;
- Engdahl and Villaseñor [11], that is the “Centennial Earthquake Catalog”;
- Storchak *et al*. [3, 12, 13], that is, the ISC-GEM instrumental earthquake catalogue.

The first South American catalogue was published in 1985 by CERESIS [2], that has been also considered, to get information on the available macroseismic data points (MDPs).
Next, national current catalogues made available by the partners of this project have been considered. Tab. 1 summarizes the data sources considered and their contribution, while Fig. 1-3 show the distribution of the entries.
In addition, we have consulted a number of earthquake studies (Tab. 1); only part of them were considered by the compilers of the national catalogues. For the large earthquakes ($M \geq 7.0$), the inventory compiled in the frame of the GEM-GEH project [4, 14] has been an important source.

Table 1- Main data sources considered and relevant number of entries

Code	Short Reference (for the complete one see the References)	Number of entries
	Continental scale data sources	
CERES985	CERESIS (1985) [2]	2399
CERES995	CERESIS (1995) [5]	7669
ENGVI002	Engdahl and Villaseñor (2002) [11]	252
ISCGE015	Storchak *et al*. (2013; 2015) [3, 12, 13]	216
National, current parametric catalogues		
OSC013	OSC (2013) [15]	246
BSB012	Catalogo Sismico Brasileiro (2012) [16]	203
SGC014	SGC (2014) [17]	148
ECU014	ECU (2014) [18]	134
FUN014	FUN (2014) [19]	513
INPRE015	INPRES (2015) [20]	48
LEYAL009	Leyton *et al*. (2009) [21]	484
TAVAL001	Tavera *ed*. (2001) [22]	3554
Earthquake studies		
	34 studies published between 1979-2015 [22 to 52]	295

The entries related to the same event have then been clustered. This operation has been performed in two steps: first, automatically, then manually. The last one has allowed to detect and eliminate several duplications, mainly inside CERESIS [5], with respect to border earthquakes. In figures 3b and 3c is presented the earthquake history of Bolivian and Chilean catalogues, to give an idea of the time-distribution of the events.

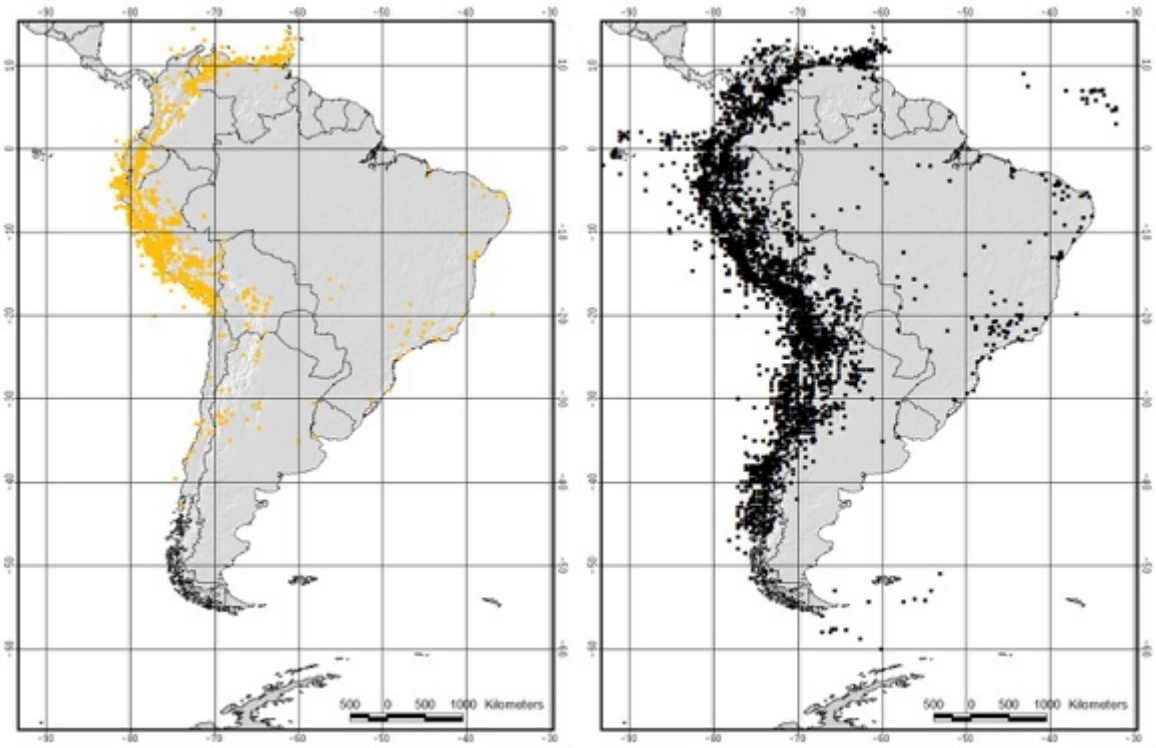

Fig. 1 - Epicentres in the time-window before 1964
a) by CERESIS (1985); b) by CERESIS (1995)

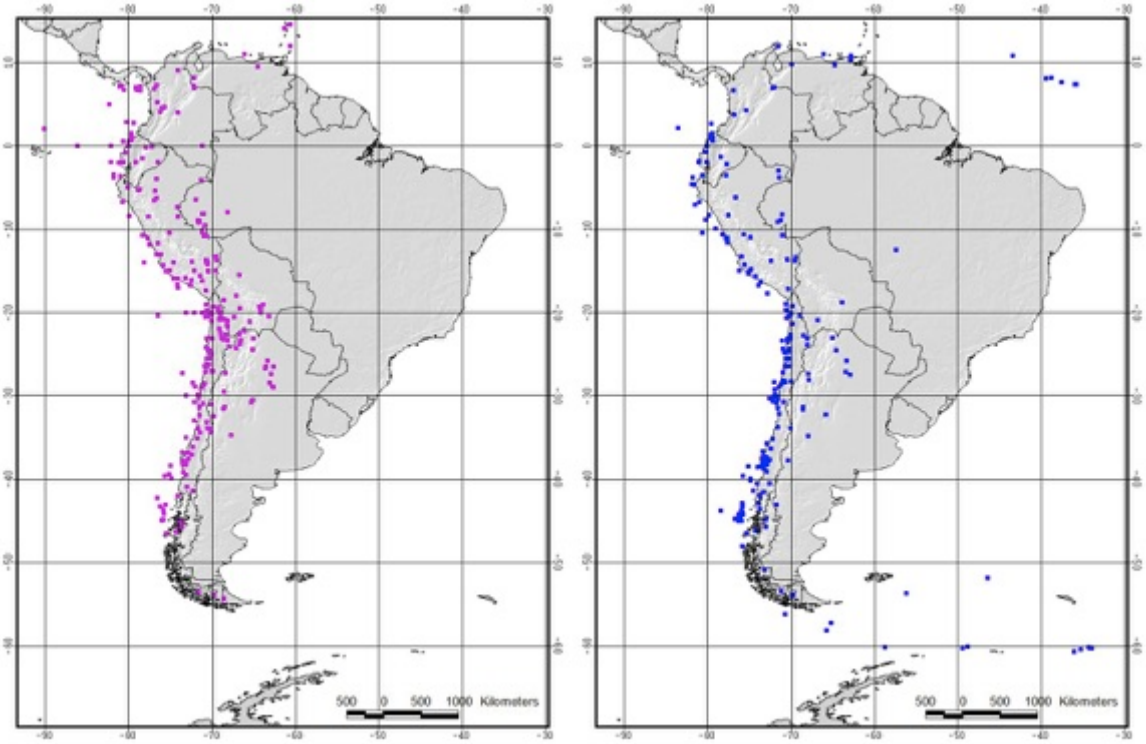

Fig. 2 - Epicentres in the time-window before 1964
a) by Engdahl and Villaseñor (2002) b) Storchak *et al*. (2013; 2015)

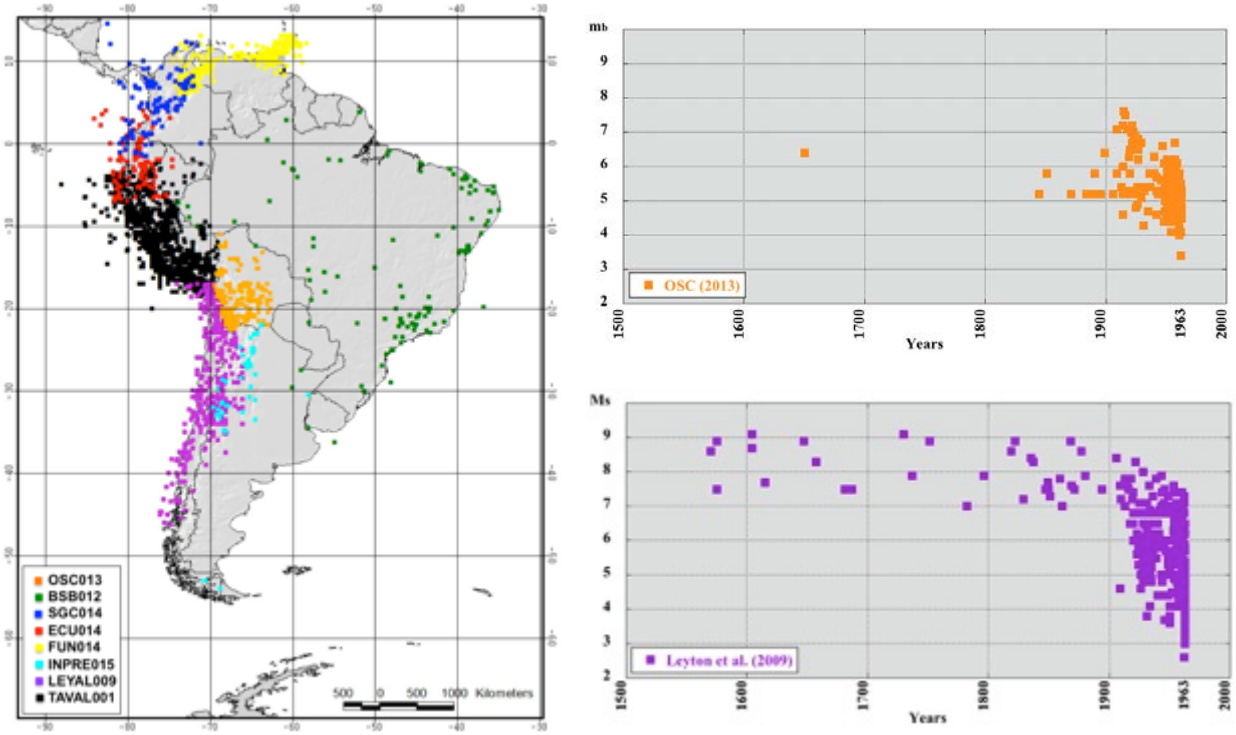

Fig. 3 – a) National catalogues epicentres in the time-window before 1964 b) Earthquake history (before 1964) of Bolivia (OSC, 2013); c) Earthquake history (before 1964) of Chile (Leyton *et al*., 2009)

3. Time, location and depth

One entry for each earthquake has been selected as "preferred" with reference to time, location and depth. Priority was given according to the following order:
• Storchak *et al.* [3, 12, 13]
• Engdahl and Villaseñor [11]
• recent earthquake studies [23 to 53]
• national catalogues [15 to 22]
• CERESIS catalogue [5]
• CERESIS, SISRA Project [2]
However, when entries from national catalogues clearly coincided with the one from CERESIS [5], the last one was selected, as it was the root of them and it gives references.
After compiling this material it is possible to say that, in the time-window before 1964, the CERESIS catalogue [5] contains more entries than the national catalogues which have been submitted to the SARA project (Venezuela, Ecuador, Brazil, Bolivia, Colombia, Chile), or found in websites (Argentina, Peru). It appears that, in many countries, some entries from CERESIS [5] were not included in the national catalogue because of size threshold. On the other hand, some entries unknown to CERESIS [5] have been found in some national catalogues.
Finally, for each earthquake we compiled a row, T4 entry, adopting time, location and depth from the preferred one.

4. Earthquake size

4.1 The earthquake size in the data sources

The data sources considered provide varied type of magnitude (M). CERESIS [5] entries come with a variety of magnitude types and values; for some entries several M values of varied type are given. We decided to adopt one magnitude value according to the following priority scheme:

Mw, Ms, mb, ML, other M.

In addition, CERESIS [5] provides intensity values. The situation in the time-window before 1964, after adopting the magnitude priority scheme, is the following:

Table 2 - Type of size in CERESIS (1995) and relevant numbers

Country	Time-window	N of entries	Mw	Ms	mb	M (other)	Without M
Argentina	1692-1963	554		111	146	3	294
Bolivia	1650-1963	202		47	123	10	22
Brazil	1720-1963	268		24	207	1	36
Chile	1520-1963	1247	4	254	86	4	899
Colombia	1566-1963	783		705	20	2	56
Ecuador	1541-1963	721		70	78	167	406
Peru	1471-1963	3544	8	180	202	16	3138
Venezuela	1530-1963	348		54	32	67	195
Total	**Bef. 1964**	7667	12	1445	894	270	5046

Engdahl and Villaseñor [11], too, provide varied types and values of magnitude, including some of unknown type (UK). Storchak *et al*. [3, 12, 13] provide Mw. The most updated national catalogues provide varied types of magnitude. Bolivia gives Ms and mb; Brazil gives mainly mb; Colombia and Ecuador gives M of varied types; Chile gives Ms; Peru mostly Ms and some Mw; Venezuela gives M (to be interpreted as Ms). As for the earthquake studies, the modern ones gives Mw of macroseismic origin, mainly assessed with the Bakun and Wentworth method [8]. Magnitudes not assessed in terms of Mw, Ms or mb have been converted to Ms or mb

according to [2, 5, 11, 17, 23, 24, 54]. The magnitude of the T4 entries have been compiled selecting the most reliable value available, according to the above mentioned priority scheme: Mw, Ms, mb, (ML), other M.
In addition, if we have two or more Mw values, or two or more Ms, from two entries referred to the same earthquake, we selected one of them according to expert judgement. As a general rule we prefer M values the origin of which is known. At this stage, we had Mw values available for 34% of the entries: we had therefore the task of determining Mw for about 66% entries.

4.2 Converting Ms or mb to Mw

We considered a number of conversion relationships, summarized in Tab. 3, while Fig. 4a and 4b show them graphically. We preferred Scordilis relations [6], which gives values similar to the ones proposed by ISC-GEM [12, 13] in addition, it provides uncertainty. We also considered Contreras Luarte [55] for Chile, but its range of definition is very limited, and Assumpção *et al*. [7] for Brazil. Only this one shows a different behaviour; therefore we adopted it for Brazil, only.

Table 3 - Magnitude conversions considered

Source	Relation	Range	σ
Scordilis [6]	Mw = 0.67(±0.005)Ms+2.07(±0.03)	3.0 ≤Ms ≤6.1	0.17
Scordilis [6]	Mw = 0.99 (±0.02)Ms+0.08(±0.13)	6.2 ≤Ms ≤8.2	0.20
Scordilis [6]	Mw = 0.85 (±0.04)m_b+1.03 (±0.23)	3.5 ≤mb ≤6.2	0.29
ISC-GEM [12]	Mw = 0.67 Ms + 2.13	Ms ≤6.47	
ISC-GEM [12]	Mw = 1.10 Ms- 0.67	Ms > 6.47	
ISC-GEM [12]	Mw = $e^{(-4.66+0.86mb)}$+ 4.56	4.5 ≤mb ≤6.0	
Assumpção *et al*. [7]	Mw = 1.21 mb-0.76	1.6≤mb≤5.5	0.32
Contreras Luarte [55]	Mw = 1.32mb-1.56	5.0≤mb≤5.5	-
Contreras Luarte [55]	Mw = 1.00Ms+0.07	5.6≤Ms≤7.5	-
Lolli *et al*. [58]	Mw = exp(2.133+0.063Ms)-6.205	Ms≤5.5	0.17
Lolli *et al*. [58]	Mw = exp(-0.109+0.229Ms)+2.586	Ms>5.5	0.15
Lolli *et al*. [58]	Mw = exp(0.741+0.210m_b)-0.785	3.6≤mb≤7.2	0.33

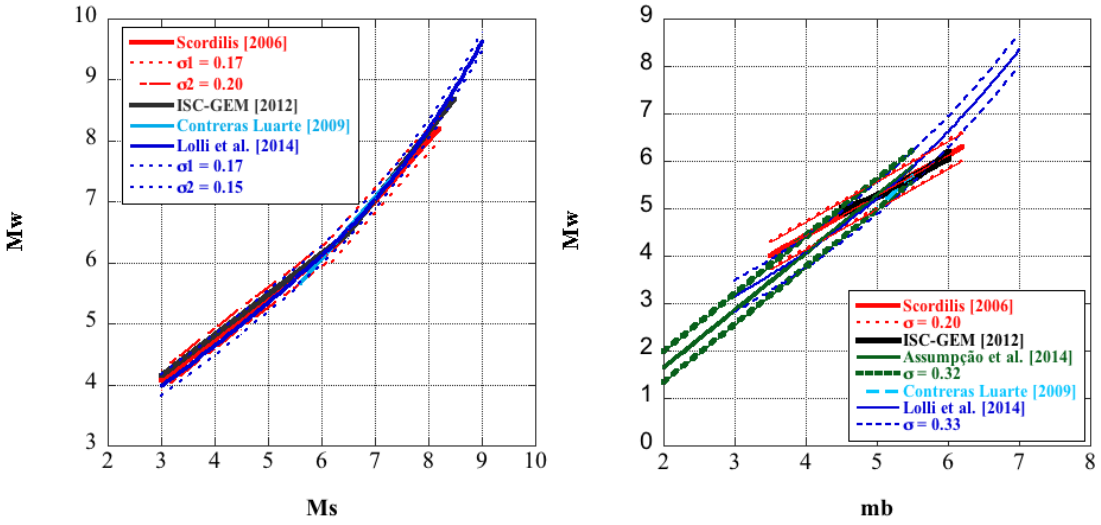

Fig. 4 - Comparison among a) varied Ms to Mw relationship;
b) varied mb to Mw relationships

5. Determining Mw from macroseismic data

At this stage we still had hundreds of entries without Mw, half of them from Peru. For all the entries we had Io given by CERESIS catalogue [5]. The best would be to determine Mw from the macroseismic data points (MDPs), making use of repeatable procedures such as the models proposed Bakun and Wentworth [8] or Gasperini *et al*. [56, 57], as it has already been done for some earthquakes in Venezuela, Colombia and Ecuador [1, 28, 29, 30, 37, 38 41, 45]. However, this requires MDPs, which are not always available, and the determination of the regional coefficients of the models:

- to Colombia through a calibration process; this process was developed by T4 [9] using the method of Bakun and Wentworth [8] calibrated regionally for some events of 20-21st century that have a sufficient number MDPs from Colombian Geological Survey [10] and it was applied to 29 historical earthquakes of Colombian territory;
- to Venezuela and Ecuador, the strategy adopted was to use Mw/I empirical relationships available from literature [29, 41] (Tab. 4)
- to Peru-Chile, Colombia, Bolivia and Argentina from Mw/I linear empirical relationships determined in the present study (Tab.5)

Table 4 - Magnitude as a function of I from intensity attenuation relations selected

Country	Source	Mw/Intensity attenuation relations	M = f(I)
VE	Palme *et al*. [41]	I = -2.2237+1.6684 Mw-0.041214x x is the epicentral distance in km and $x \leq$ 120km	Mw = 1.3328+0.5993 I
EC	Beauval *et al*. [29]	I= -0.85+2.41 Mw-5.39 logΔ_h Δ_h is the hipocentral distance in km $\Delta_h = (x^2+h^2)^{0.5}$ h is the focal depth fixed to10km	Mw = 2.58921+0.41494 I

Table 5 - Relations Mw/I obtained for the areas of Peru-Chile, Colombia, Bolivia, Argentina

Area	Dataset	M = f(I)	N of eq.	Mw range	Intens. range	Time-window	σ
BO	CERES995 Bolivian Catalogue	Mw = 3.9438+0.292 I	18	4.94-6.47	4-8	1650-1928	0.20
PE CL	CERES995 ISCGE015 *IGP015	Mw = 4.513+0.286 I	42	5.42-8.19	5-11	1906-2014	0.47
CO	SGC013 ISCGE015 *RSNC	Mw = 2.761+0.425 I	18	4.30-7.11	4-10	1917-2015	0.35
AR	CERES995 ISCGE015 INPRES015	Mw = 2.901+0.4287 I	24	4.86-7.45	5-9	1903-2002	0.37

*IGP= Instituto Geofísico del Perú [59]; **RSNC:* Red Sismológica Nacional de Colombia [60]

For sake of homogeneity we have assessed the final Mw uncertainty as equal to 0.60 unit, that correspond to the mean of 95% confidence level to one intensity data point following the Bakun and Wentworth method [8, 61].

6. Results and conclusion

We have established the lower Mw threshold at 5 (-0.2) for the areas of the Andean region; for Brazil, no lower threshold has been established. In such a way we got 2556 events, the distribution of which by data sources is presented in Fig. 5a, while the relevant count is given in Tab. 6.

Table 6 - Data sources and relevant number of entries

Short Reference (for the complete one see the References)	**Number of entries**	**Short Reference**	**Number of entries**
CERESIS (1985)	12	Storchak *et al*. (2013; 2015)	214
CERESIS (1995)	1968	National catalogues	241
Engdahl and Villaseñor (2002)	47	Earthquake Studies	74
Total			**2556**

Having now determined Mw for all these earthquakes, for the first time we can see the seismicity plotted in terms of Mw (Fig. 5b). We can also show the earthquake history before 1964 (Fig. 6). In Fig. 7 we also show a comparison between the T4 catalogue and the ISC- GEM [3, 12, 13]. This comparison shows the large improvement that this work introduces in the coverage of historical events in South America.
We have still 1766 events with size below the adopted threshold, for most of which the Mw to other parameters regressions cannot be applied, because they are out of reliability range. In addition, we have 227 without any size.

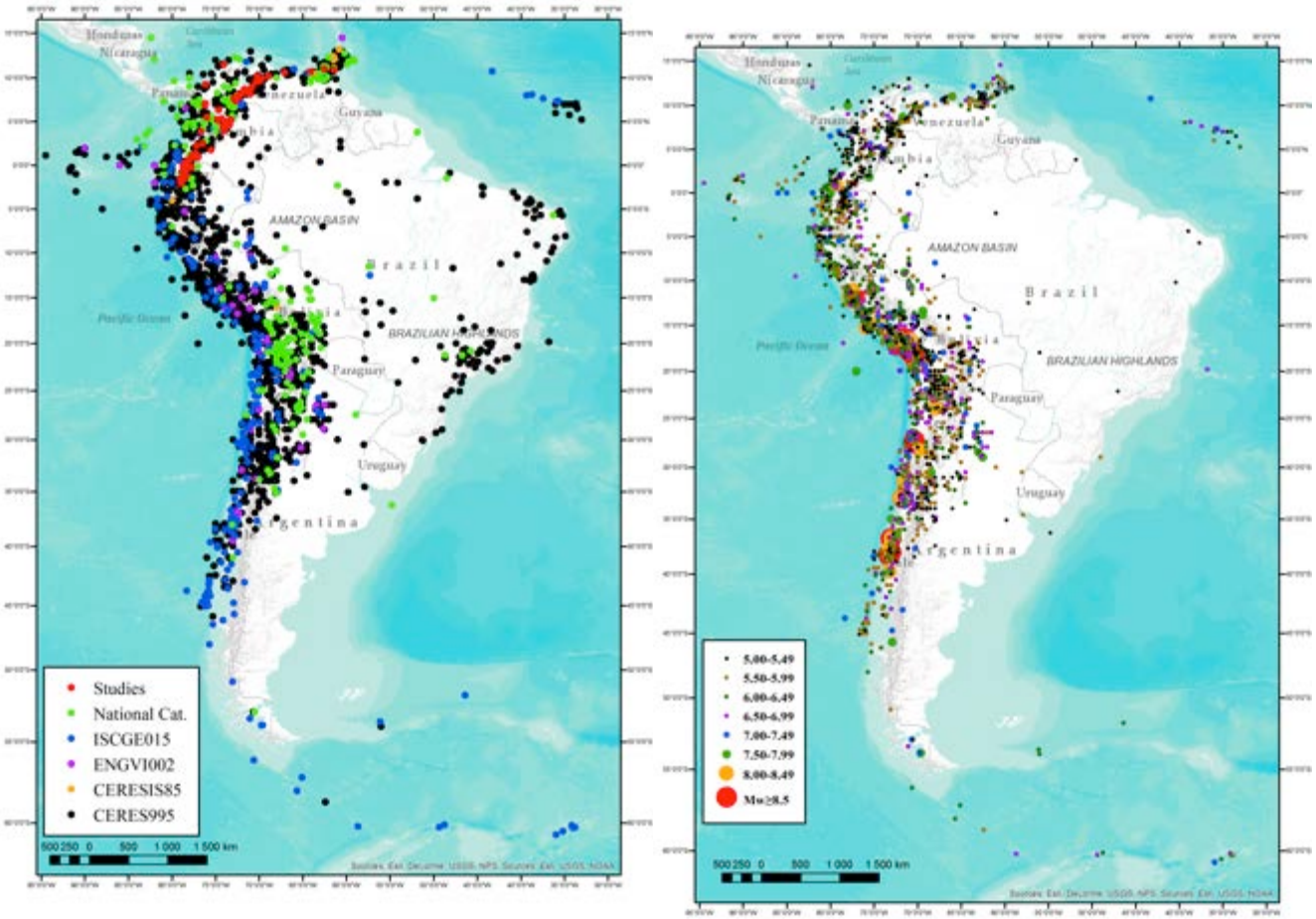

Fig. 5 - Distribution of epicentres in T4 a) by data source ; b) by class of Mw (Mw ≥ 5.0)

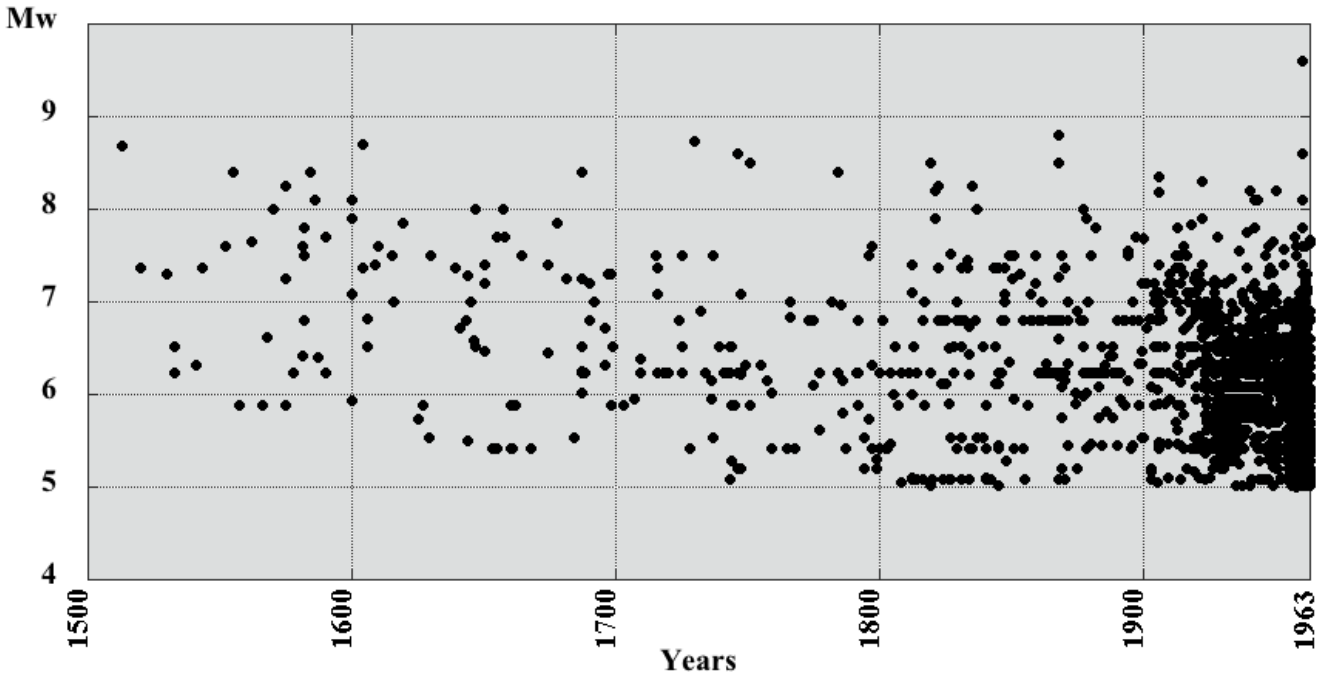

Fig. 6 - Earthquake history before 1964 (Mw ≥ 5.0) of South America

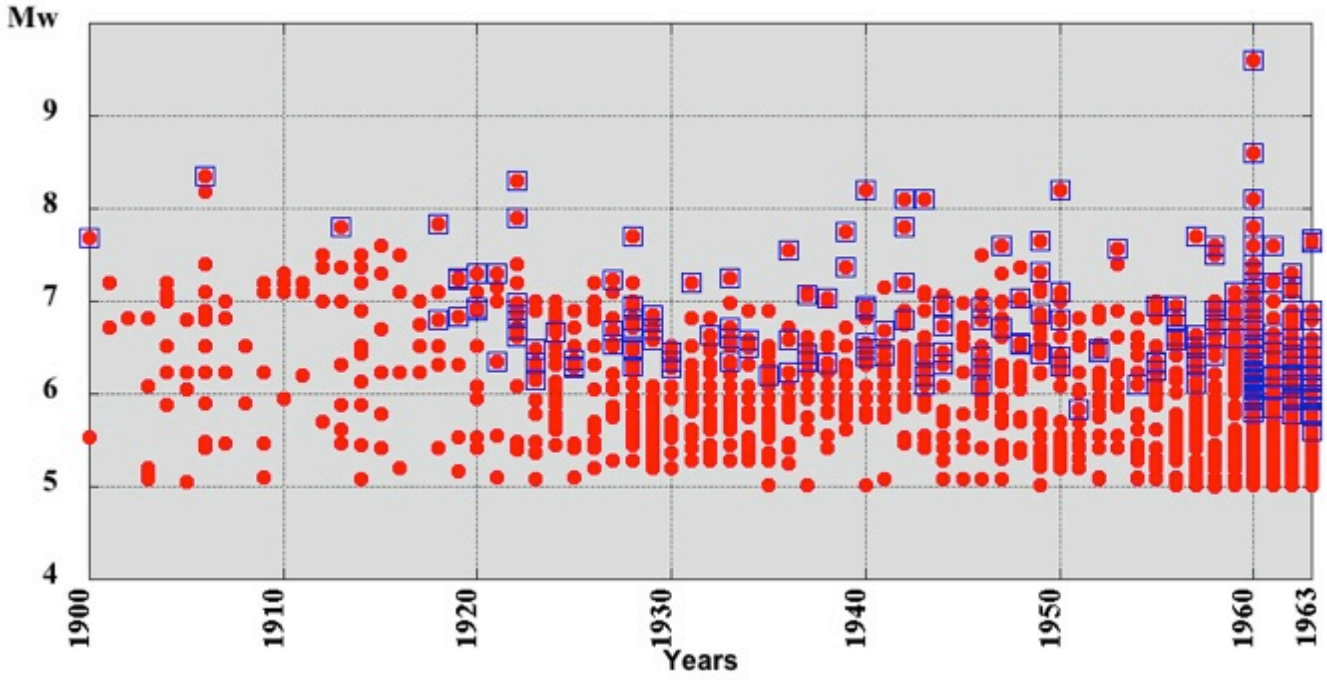

Fig. 7 - Comparison of the T4 (red circles) and ISC-GEM catalogues (1900-1963)

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