aac NEWTON (Inglaterra, 1643-1727): "Lo que conocemos es una gota, lo que no conocemos es un océano."

5-Cuba-Venezuela Earthquakes of 1766: Part II- Modeling the Macroseismic Field and Final Results

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Terremotos de Cuba-Venezuela de 1766: Parte II- Modelado del campo macrosísmico y resultados finales}

Abstract- The macroseismic field, of the two strongest earthquakes of Cuba and Venezuela in 1766, was processed with an elliptical isoseismals model in order to get more reliable estimations of their coordinates and magnitude. Several possible adjustments (varying model or initial parameters) were done for each earthquake. The process included a statistical analysis of the residuals of adjustment to select the better one, in combination with tracing of theoretical isoseismals over felt intensity data. The results reinforced our seismotectonic analysis made in the Part I of this paper set. Also a general discussion of isoseismals' model applied is provided.

Keywords: Caribbean, Cuba, earthquake, historical seismicity, macroseismic field, Venezuela

Introduction

This is a second part of our study. Part I is specially committed to the tectonic and historic seismicity. Also, we comprehend a lively evaluation of two sturdy earthquakes in Cuba and Venezuela. They occurred at the same year, 1766 in two colonies of Spain. The first part includes all information consulted and reviewed, as well as the processing of data on seismicity. It permits to gain exceptional seismotectonic models and to confirm, for the primary time, that Cuba received crucial aid from the Spanish Crown, and none Venezuela. There are 21 tables and 7 figures in Part I some of them are quoted here. We will refer in present paper to some of them.

5.1-Statistical Treatment of the Earthquakes of 1766

Here, we are going to use the seismic information of the two strong earthquakes of 1766 produced in the Caribbean region. They were presented and analyzed in the Part I of this paper. Our proposal is to apply a recognized statistical methods set.

5.1.1-*About treatment of historic earthquakes*

The rough material of historic earthquake is a collection of descriptions about how were felt the earthquakes in different locations. Elementary process that is to be done is an evaluation of intensities using a scale. At first we take into account the intrinsic subjective character of evaluation of intensities, not only for judgment criteria. All effects should be evaluated for assigning an intensity value. Also, we know that in some cases the intensity has a fuzzy character [44].

The need of extracting the maximum information from felt data of earthquakes conducted to the first attempt to model the isoseismals: at the beginning of 20th Century Kövesligethy [52] proposed a model of the kind $I_i = I_0 - f(\Delta, h)$ [where: Δ= epicentral distance; h= the depth of focus]. Later on, with the introduction of the concept of magnitude the term I_0 was substituted by a function of M, and the general formula was transformed into $I = f(M, \Delta, h)$. The most common is called attenuation formula of "Kövesligethian type":

$$I= b\cdot M - k\cdot lg(r) - p\cdot r + d \qquad (1)$$

Where: (**a**) b, k, p, d = coefficients to be evaluated; (**b**) $r= (\Delta^2 + h^2)^{1/2}$, [$\Delta$+constant or a function of (Δ, h)]. The formula describes a field of I in the 2D space and is called “macroseismic field”. But, when the problem is to assess the main parameters of a historic earthquake (coordinates and magnitude) it is necessary to process its observed macroseismic field. There are different methods that process: (**a**) only maximum intensity values; (**b**) several isoseismals; (**c**) rely in the adjustment of a theoretical model of isoseismals. All of them are subjective, but in last time there has been done attempts to introduce statistical procedures to diminish such subjectivism. See Musson and Cecić [56] for the general case and Bakun *et al*. [9] for the use of statistics in macroseismic data processing. The availability of macroseismic data is of several kinds that sometimes appear mixed: (**a**) descriptive documents where all the data of felt earthquakes are presented; (**b**) a summary of data with evaluation of intensities; (**c**) post-processing of data (isoseismal maps, estimation of coordinates and magnitudes).

The drawing of isoseismals in the majority of cases is by eye fitting. Nevertheless, some authors use geostatistical methods to do so [30, 52] or other statistical interpolation procedures (see part I of this paper for an example).

The statistical methods of for assessing main parameters of earthquakes rely on the existence of a dense pattern of felt intensities, as was the case in the preparation of European earthquake catalog [63] and they are based manly in the analysis to close of epicenter macroseismic field. But in the case of Cuba and Northwestern Venezuela, with low density of population in the 18th Century, were it should be drown isoseismals through long sea areas, these methods are difficult to apply. For these cases it seems more reasonable to adjust an isoseismal model that take into account the whole macroseismic field, giving equal weight to close to epicenter and long away from it felt intensities.

The macroseismic field created by formula (1) has circular symmetry and this is not the common behaviour of real isoseismals. There in general are elongated following tectonic features and many scientists prefer to model them as ellipses, using as main characteristics the ratio of major axis to minor axis (A/B) or the area of isoseismals.

With the objective to include it in seismic risk assessment [6] develop a model of elliptical isoseismals characterized by an equation of the type:

$$lg\,[Q_I(M)] = a(I) + b(I)\cdot M + \sigma_Q\xi \qquad (2)$$

Where: (**a**) Q_I (M)= the area of degree I isoseismal; (**b**) $\sigma_Q\xi$= a random variable. Another parameter is the geographic orientation of major axis. This model was tested in several regions of former Soviet Union and Italy.

For the use in deterministic seismic zoning in the former USSR it was developed a model of empirical elliptical isoseismals [11].

Later on, Álvarez [2] develop a model of elliptical isoseismals that was tested in Greater Antilles [4]. Its objective was dual: (**a**) to use in parameter estimation of historic earthquakes; (**b**) to include it in seismic hazard estimation program [3]. The characteristics are: (**a**) a geometric estimation of distance to be used in attenuation formula considering A/B and orientation of major axis; (**b**) a formula of Kovesligethian type for attenuation description, with three forms of evaluating “r” (along minor axis, major axis or average radius of the ellipse); (**c**) possibility of considering a regular variation of ellipticity from inner to outer isoseismals.

The contributions for modeling macroseismic field in elliptical isoseismals continued with time. In China [12, 65] followed a procedure of adjusting a Koveslighetian type formula for major and minor axes of ellipses independently. In New Zealand, Dowrick and Rhoades [31] developed a model with empirical shape of elliptical isoseismals and an attenuation law more complicated that formula (1).

In this paper the model of Álvarez [2] was used (**see ANNEX 1**) for assessing main parameters of the 1766 earthquakes in Cuba and Venezuela.

5.1.2-*Adjusting an Isoseismal Model to Felt Intensities*

As is discussed in **ANNEX 1**, the model of elliptical isoseismal is highly dependent of the attenuation formula that is applied. The formulas have a regional dependency. To select one from literature (or develop it from felt intensities) that fits the intensity data under analysis is not an easy job.

An adjustment of isoseismal model can be done: (**a**) from visual inspection of the fit of calculated isolines to already existing isoseismal map [4]; (**b**) with a map of felt intensities. But visual inspection adds more subjectivism to an already intrinsically subjective material. In this paper we decided to analyze the residuals I_{calc} - I_{obs} for taking a decision. Due to the continuous character of I_{calc}, an ideal fit of the data requires that all the residuals be placed in a range [-0,5 – 0,5]. Then, the adjustment should be best as short as the points separate from this condition. The other aspect to take into account is the behavior of the residuals > 0,5 and < 0,5 with distance that gives information about overall fit of attenuation formula (1).

5.1.3-*Earthquake of 11.06.1766 in Cuba*

In the case of Cuba there we tested two different variants of Kovesligethian formula: (**a**) Fedotov and Shumilina [32] [**FE-1971**] {b= 1,5/ k= 2,63/ p= 0,0087/ d= 2,5} developed for Kamchatka Peninsula, that fits Greater Antilles data with well accuracy [4]; (**b**) Gómez *et al*. [34] [**GO-2003**] {b= 1,4/ k= 3,17/ p= 0,0017/ d= 3,11} by adjusting data of felt intensities in Eastern Cuba.

The earthquake of 11.06.1766, as was discussed before, has two different magnitude estimation: M_S6,8 from Cotilla and Udías [26] and M_W7,5 from Álvarez *et al.* [5]. Then it was decided to test three values of magnitude M_W (6,8/ 7,2/ 7,5). From observed intensity data it was possible to identify a ratio A/B= 1,4. The tests were done for two directions of r_e: A and Δ_m, and both attenuation laws independently, for a total of 12 different adjustments. In each case there were calculated the average and standard dispersion (μ, σ) of residuals and a least square fit of "y= a + b·x" [where: x= distance and y= residual]. The felt intensities data was taken from **table 18B** (Part I) and results presented in **table 20**.

Table 20. **Analysis of residuals I_{calc} - I_{obs} for the mentioned combinations for earthquake in Cuba.**

F	r_e	M_W	μ	σ	a	b	F	r_e	M_W	μ	σ	a	b
FS	A	6,8	-0,95	1,633	0,21	-0,0049	GO	A	6,8	-0,55	0,993	-0,79	0,0010
FS	Δ_m	6,8	-0,46	1,196	0,35	-0,0041	GO	Δ_m	6,8	-0,27	0,903	-0,62	0,0017
FS	A	7,2	-0,34	1,373	0,81	-0,0049	GO	A	7,2	0,01	0,829	-0,23	0,0010
FS	Δ_m	7,2	0,15	1,116	0,96	-0,0041	GO	Δ_m	7,2	0,29	0,907	-0,06	0,0017
FS	A	7,5	0,11	1,335	1,27	-0,0049	GO	A	7,5	0,43	0,935	0,18	0,0010
FS	Δ_m	7,5	0,60	1,260	1,41	-0,0041	GO	Δ_m	7,5	0,71	1,113	0,35	0,0017

Notes: (a) F= formula; (b) (μ, σ) average and standard deviation; (c) (a, b) least squares adjustment of "y= a + b·x" [x= distance and y= residual]; (d) FS = Fedotov and Shumilina [32], GO = Gomez *et al.* [34]; (e) Δ_m – average radius.

The selection of the best fit will corresponds to (μ, σ) closer to (0, 0,5) and (a, b) closer to (0, 0), The best approximations to them are for M_W= 7,2 in the case of FE-1971 formula for r_e= Δ_m and GO-2003 formula for r_e= A. The final selection is done after visual inspections of the corresponding maps (**Figure 8**).

In those maps, it is clear a different behavior of both models. Due to the less value of parameter k in Kovesligethian kind formula for GO-2003, the isoseismal calculated with this model have bigger values at great distances than with FE-1971 model. Any of the model fits well I= VI and behave more of less the same for I≥ VII. For I= III at distances bigger that 400 km the FE-1971 models adjusts better. We use this adjustment. In the **figure 9** are presented the graphics of statistical analysis of the selected solution.

Then, we can estimate that earthquake has more probable parameters [19,9 N -76,1 W/ h= 25 km/ M_W= 7,2]. The isoseismals′ map is described by: A/B=1,4 ; $r_e = \Delta_m$; η = 0, isoseismals ′ orientation = 0° in polar coordinates and FE-1971 coefficients of Kovesligethian formula.

5.1.4-*Earthquake of 21.10.1766 in Venezuela*

In the case of Venezuela there are not any formula of Kovesligethian type tested before. There exist some studies made for Colombia, Bolivia and Ecuador. Nevertheless, they use attenuation formulas not of the type (1) but of the kind I= f (I_0, Δ, h). These are not applicable to use with the isoseismal model. The only one equation of the kind (1) found for South America, correspond to Brazil [59] [QU-2019] {b= 0,995/ k= 1,505/ p= 0,00116/ d= 2,08} for intraplate earthquakes with M≤ 6,2 m_b. We decided test the two ones used with Cuban earthquake: (a) Chen *et al*. [13] [CH-2002] developed for Central America [b= 1,5/ k= 2,7/ p= 0,00106/ d= 1,7] for m_b; (b) QU-2019. As in the previous case, the felt intensities data was took from **table 19** (Part I).

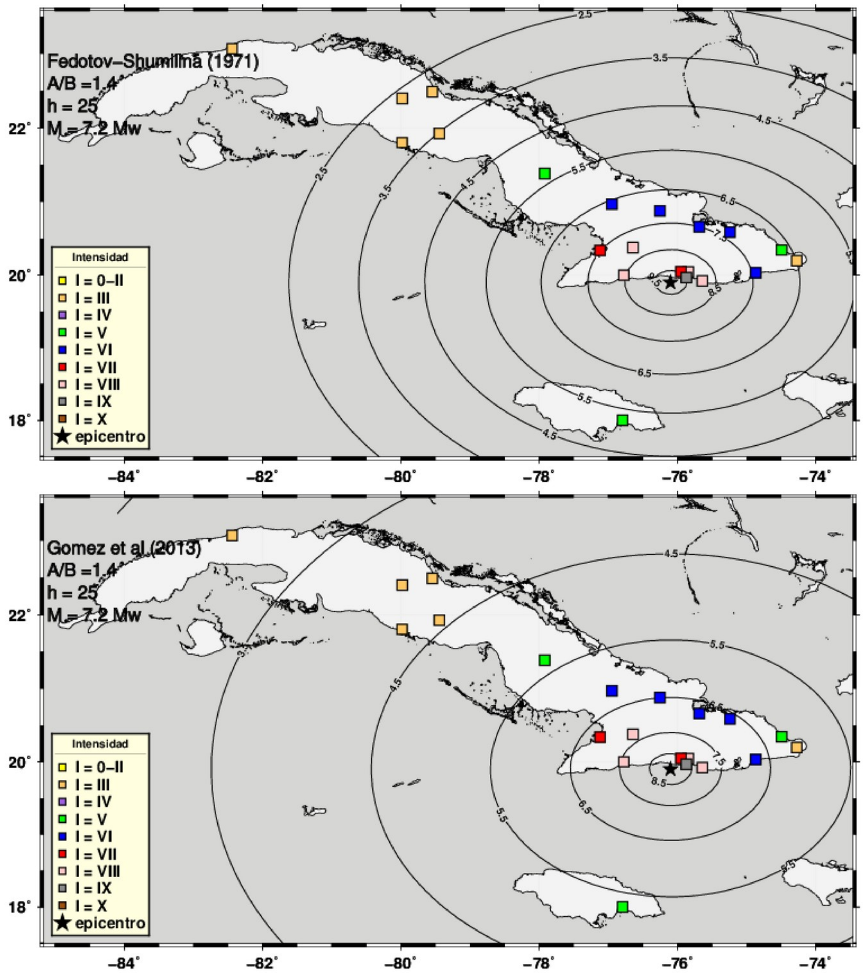

Figure 8. Comparison of the maps with theoretical isoseismals for booth cases.

A preliminary test on the applicability of these formulas determined that the formula of: (**a**) FE-1971 fail in fitting the intensities of points placed far away from epicenter; (**b**) GO-2003 gives worst results than the remainder two; (**c**) CH-2002 and QU-2009 fit the data with acceptable behavior and can be used for the final test. All these formulas were obtained for m_b and we are evaluating an earthquake with possible $M_W \geq 7,5$, where m_b is not defined. Then, we are doing an extrapolation of the formulas. An inspection of real intensity data reflects that isoseismals should have an A/B not very large. A test performed using the CH-2002`s formula for a range of A/B [1,0 1,6] determined that the best fit is with A/B= 1,2. From the data discussed before we will test a magnitude in the 7,5-7,9 interval [three values (7,5/ 7,7/ 7,9) and also three depth values (10/ 20/ 30) km]. Also there will be tested two direction of r_e (A, Δ_m). It gives a total of 36 possible combinations. Results are in **table 21.**

As it can be seen from this table, the best adjustment is obtained by CH-2002 formula with h= 10 km and $r_e = \Delta_m$. The second one is for the same formula and r_e, but for depth 30 km. Then, we estimate that earthquake has probably parameters [10,4 N -61,5 W/ h= 30 km/ M_W= 7,5]. The isoseismal′s map is described by: A/B= 1,2, $r_e = \Delta_m$, $\eta = 0$, isoseismals′ orientation= 0° in polar coordinates and CH-2002 coefficients of Kovesligethian formula. In **figure 10** are the graphics of statistical analysis of the selected solution and in figure 11 the map of the theoretical isoseismal for the selected adjustment.

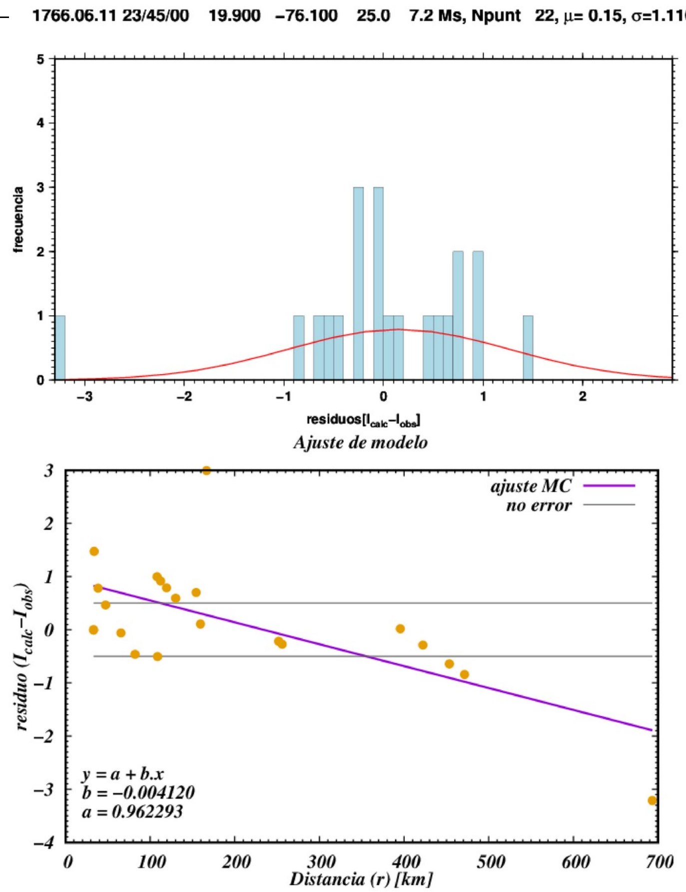

Figure 9. Statistics of residuals for selected adjustment of theoretical model for Cuban earthquake of 11.06.1766. (a) Upper: histogram of residuals, red line represents the normal distribution for values of (μ, σ); (b) lower: dependence of residuals upon distance, gray lines represents the zone in which adjust is correct.

5.2-Discussion

Review of the historical seismicity of the Caribbean, including Cuba and Venezuela, demonstrates the increase in publications since the 20th century where previous data are modified. It indicated that there is a temporal coincidence in terms of the historical seismicity of Cuba (1528) and Venezuela (1530) [5, 54]. They are the initial settlement sites of the Spaniards. They have not volcanic activity but in the vicinity of: (a) Cuba has neither volcanoes: (b) Venezuela has volcanoes (b.1) Colombia (~25/ from [1528] in the Galeras [4.276 m]); (b.2) the Lesser Antilles (~24 strong earthquakes), near Venezuela has three active volcanoes in: (b.2.1) Granada (*Kick-en-Jenny* underwater volcano with 13 eruptions 1939-2001); (b.2.2) San Vicente and Granadinas (*La Soufriere* volcano); (b.2.3) Martinica (*Montagne Pelee*, year 1902 with ~32.200); (b.2.4) Trinidad-Tobago (Devil's Wood Yard mud volcano)). Volcanoes are associated with earthquakes and tsunamis, and can affect Venezuela. These countries are situated in two important zones of seismic activity [**S-A**] where the largest is Venezuela. Nevertheless, Martinica and Trinidad have suffered eight strong earthquakes (1690-1954).

Table 21. Analysis of residuals I_{calc}-I_{obs} for the mentioned combinations.

F	r_e	M_W	h	μ	σ	a	b	r_e	M_W	h	μ	σ	a	b
CH	A	7,5	10	-0,12	1,046	-0,023	0,00018	Δ_m	7,7	20	0,37	1,100	0,36	0
CH	Δ_m	7,5	10	0,04	1,038	0,081	0,00008	A	7,9	20	0,57	1,182	0,62	-0,00011
CH	A	7,7	10	0,24	1,066	0,32	-0,00018	Δ_m	7,9	20	0,72	1,262	0,72	0
CH	Δ_m	7,7	10	0,39	1,110	0,43	-0,00008	A	7,5	30	-0,17	1,052	-0,14	-0,00003
CH	A	7,9	10	0,59	1,165	0,68	-0,00018	Δ_m	7,5	30	-0,01	1,040	-0,05	0,00009
CH	Δ_m	7,9	10	0,75	1,128	0,78	-0,00008	A	7,7	30	0,19	1,055	0,20	0,00003
CH	A	7,5	20	-0,14	1,046	-0,082	-0,00011	Δ_m	7,7	30	0,34	1,094	0,29	0,00009
CH	Δ_m	7,5	20	0,01	1,036	0,014	0	A	7,9	30	0,54	1,171	0,55	0,00003
CH	A	7,7	20	0,21	1,059	0,27	-0,00011	Δ_m	7,9	30	0,69	1,249	0,64	0,00009
QU	A	7,5	10	-0,61	1,266	-1,11	0,00098	Δ_m	7,7	20	-0,28	1,171	-0,85	0,0012
QU	Δ_m	7,5	10	-0,50	1,229	-1,05	0,0012	A	7,9	20	-0,16	1,131	-0,67	0,0010
QU	A	7,7	10	-0,38	1,170	-0,87	0,00098	Δ_m	7,9	20	-0,05	1,138	-0,62	0,0012
QU	Δ_m	7,7	10	-0,27	1,154	-0,81	0,0012	A	7,5	30	-0,64	1,303	-1,18	0,0010
QU	A	7,9	10	-0,14	1,117	-0,64	0,00098	Δ_m	7,5	30	-0,53	1,269	-1,13	0,0013
QU	Δ_m	7,9	10	-0,03	1,123	-0,58	0,0012	A	7,7	30	-0,41	1,205	-0,95	0,0010
QU	A	7,5	20	-0,63	1,283	-1,14	0,0010	Δ_m	7,7	30	-0,30	1,191	-0,90	0,0013
QU	Δ_m	7,5	20	-0,51	1,248	-1,09	0,0012	A	7,9	30	-0,17	1,147	-0,71	0,0010
QU	A	7,7	20	-0,39	1,186	-0,91	0,0010	Δ_m	7,9	30	-0,06	1,155	-0,67	0,0013

Notes: (a) F=formula; (b) (μ, σ) average and standard deviation; (c) (a, b) least squares adjustment of "y = a + b·x", where x=distance and y=residual; (d) CH= Chen *et al*. [13], QU= Quadros *et al.* [59]; (e) Δ_m= average radius.

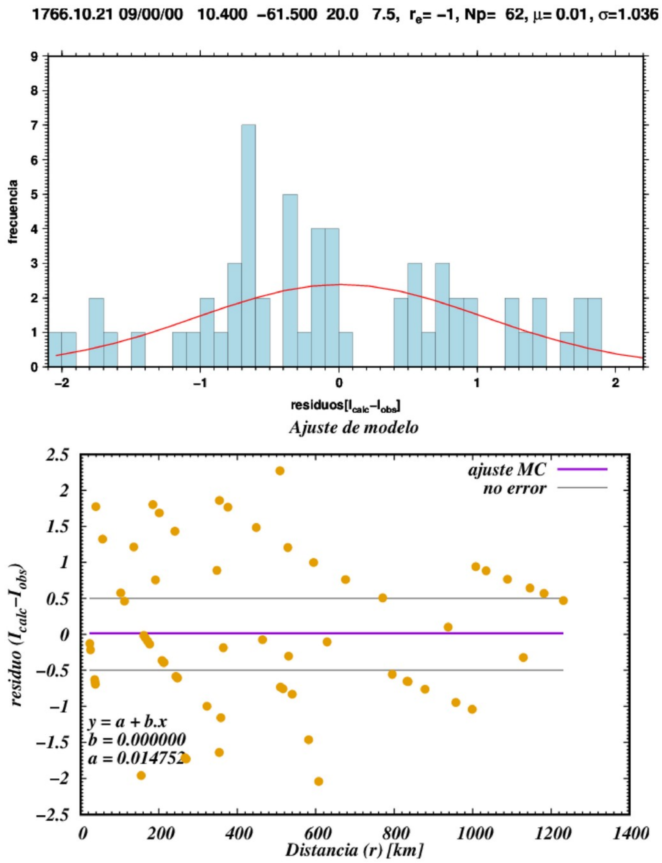

Figure 10. Statistics of residuals for selected adjustment of theoretical model for the 21.10.1766 earthquake in Venezuela. **(a)** Upper: histogram of residuals, red line represents the normal distribution for values of (μ, σ); **(b)** Lower: dependence of residuals upon distance, gray lines represents the zone in which the adjustment is correct**.**

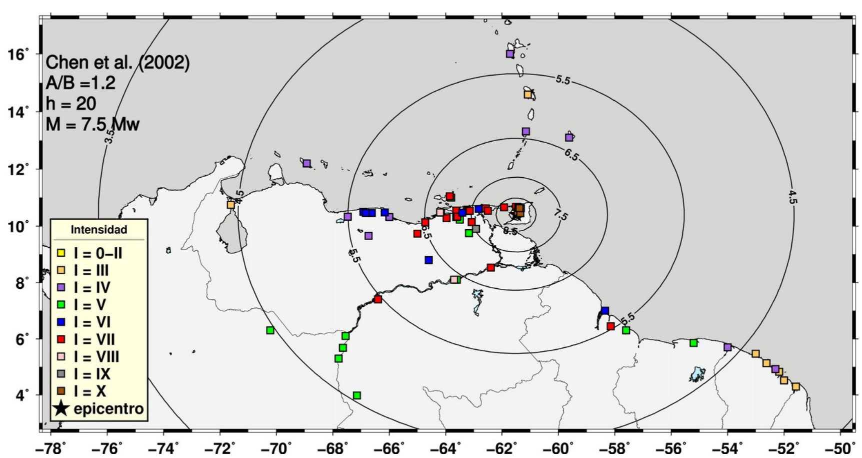

Figure 11. Map with theoretical isoseismals for the adjusted model.

S-A (amount of events and M) of Venezuela is higher than in Cuba (**Tables 15 and 17**). Venezuela has a source of local tsunamis (**Table 16**) and losses (economic, material and human) by earthquakes and tsunamis greater than Cuba. Also, the S-A is larger South American-Caribbean Plate Boundary Zone [**PBZ**] than of North American-Caribbean one. At 1766 two earthquakes occurred in different Caribbean regions: (**a**) Northern (Cuba: 11.06/ M6,8/ 50 [66 days] aftershocks/ 40 deaths/ 10^3 km^2) (**Figure 4**); (**b**) Southern (Venezuela: 21.10/ M8,0/ 14 months of aftershocks/ ? deaths/ $3{,}6.10^6$ km^2) (**Figure 5**); (**c**) epicenters were located for: (**c.1**) Cuba in the Oriente fault (**Figure 4**); (**c.2**) Venezuela in El Pilar fault-subduction zone of Lesser Antilles (El Soldado and Los Bajos faults). They are historically the largest (Cuba [M6,8] and Venezuela [M8,0]) in their respective zones. Other strong events have occurred in such areas. Both countries were colonies of Spain and the events occurred 74 and 78 years, respectively after the Spaniards arrived. There are different recurrence periods (Cuba [1766-1852= 86 years]/ Venezuela [1766-1797= 31 years]) and evidently different S-A.

Information on the historical context of these two earthquakes shows that: (**a**) Cuba and Venezuela had a very different economic situation. Cuba, as an island-port, enjoyed significant control over commercial and monetary traffic, while Venezuela did not; (**b**) the number of governmental and ecclesiastical buildings in Cuba was greater than in Venezuela (**Table 4**); (**c**) the Spaniards authorities of highest rank and category were the ones who described the earthquakes of 1766 and the effects produced. Then there have been not defect of form; (**d**) Cuba received an important economic contribution, from Spain, to repair the damage of the earthquake and Venezuela did not. It has been proven that destroyed and affected fortifications, such as the San Pedro de La Roca Castle (Morro, 1638) and the Lighthouse (1848) were well rebuilt. The 1852 and 1932 earthquakes did not damage them (**Table 17**); (**e**) the situation of Venezuela, regarding the less attention of the Crown, for the earthquakes effects are showed by Altez [1] when comparing what has been lived with: (**e.1**) the tsunami of 1.09.1530 that destroyed the Captain Jacome de Castellon fort in the Cumana River (Venezuela), with hardly any comments; (**e.2**) the 11.09.1541 multiple phenomenon of that devastated Santiago de los Caballeros, Guatemala (earthquake, eruption of the Fuego volcano and collapse of the Agua volcano). “Newspaper” exposed a “creep-able earthquake”. That writing was the first for America; (**f**) there was a noticeable decline in population (~400.000 persons) in Venezuela (1810-1822) (**Tables 5-6**) which is justified with the 1812 earthquake and which affected the Growth index by -2 points. This earthquake is similar to that of 1766. The panic behavior of the population by these two earthquakes was similar. Since the earthquakes in the colonies some anti-seismic measures were considered.

We interpret S-A area in the Caribbean-South American PBZ (**Figures 3 and 6**) at the eastern end of Venezuela, near Trinidad as a knot (NVA knot). The sector has the highest epicenter density (1950-2000), while for Santiago de Cuba (1979-1999) is quite lower. The indicated area coincides with the mentioned fault zones intersection (El Pilar) and subduction area of the Lesser Antilles. Based mainly on [7, 8, 10, 46-48, 57, 61] this type of intersection is seismoactive. The NVA knot has spatial coincidence with the three isoseismals appearing in [33]. The tsunami occurrence with the 1812 earthquake of Venezuela allows to assume that the mechanism must be subduction (combined compressive - right lateral component [like the earthquake of 2018 (USGS)]). Three of the four recorded earthquakes are at the NVA knot (**Table 22**).

Table 22. Earthquakes in Venezuela recorded by the USGS.

Date/ time	M/ depth (km)	Coordinates (N W)	Focal mechanism	Location
1967.07.29/ 00:00:04	6,0/ 25	10,559 67,330		Vargas
1986.06.11/ 13:48:01	6,3/ 18,8	10,597 62,928	97,52 355,75	Sucre
1997.07.9/ 19:24:13	7,0/ 19,9	10,598 63,486	173,76 265,82	Sucre
2018.08.22/ 9:31:45	5,8/ 108	10,659 62,929	83,78 201,27	Yaguaraparo

Our proposal of a seismic knot is not new at all, since in other places there are several antecedents as in: (a) Alpes-Dinarides [38]; (b) Altai-Sayan-Baikal [41]; (c) Armenia [68]; (d) Bering Sea [53]; (e) Carpatos-Balcanes [37]; (f) Cuba: (f.1) Torriente-Jagüey Grande [14-16]; (f.2) San José de las Lajas [16]; (f.3) Cabo Cruz [15, 19]; (g) Himalaya [10, 35, 36]; (h) Greece [42]; (i) Hispaniola [27]; (j) Italy [38, 67]; (k) México [29]; (l) Mongolia [66]; (m) Romania [59]; (n) Russia [7, 8, 49, 50]; (o) Spain: (o.1) to the all territory [18, 40]; (o.2) Béticas [20-22, 28, 62]; (o.3) Galicia [17]; (o.4) Albacete [23]; (o.5) Guadalajara [24]; (o.6) Cantabria [25]; (p) USA: (p.1) New Madrid [64]; (p.2) California [45]. The effectiveness of some of these determinations is presented in table 23.

Figure 1 of Gitis *et al.* [33] shows, in the north-eastern-southern Caribbean band, the results of the GEO automatic system for the M_{max} determination. The highest values are located in the vicinity of Venezuela-Trinidad. For the entire Caribbean region (Figure 1 by Ruiz-Schulcloper *et al.* [62]) the absolute values M_{max} are in the Pacific area. Other areas with small maximus are in Hispaniola, Puerto Rico and Venezuela-Trinidad. The result was obtained by mathematical modeling using pattern recognition techniques. The two mentioned papers indicate that the most active area is on the southern edge, where Venezuela. Figure 1 of [55] shows the NE end of Venezuela as very active. There (Venezuela-Trinidad) in the vicinity of the S-edge of the Lesser Antilles (NVA knot) is a complex arrangement of seismic faults that accommodate deformations and justify the strong earthquakes and tsunamis occurrence. That area is much more active than Cuba.

Table 23. Some effective determinations.

Location	Date	First element		Tectonic environment
		Earthquake	Knot	
Armenia	7.12.1988		X	Plate boundary
USA	1988		X	Plate boundary
Cabo Cruz	26.08.1990		X	Plate boundary
Caucaso	2009		X	Plate boundary
Italy	Series of 2016	X		Plate boundary
Torriente-Jagüey Grande	16.12.1982	X		Plate interior
San José de las Lajas	9.03.1995		X	Plate interior
Galicia	23.05.1997	X		Plate interior
Murcia	11.05.2011		X	Plate interior
Albacete	23.02.2015		X	Plate interior
Guadalajara	Series of 2017		X	Plate interior

We assure that: (a) the two regions affected by the 1766 earthquakes in the Caribbean region were treated very differently by the Crown of Spain. Cuba received a significant economic aid; (b) the seismogenesis of Cuba and Venezuela is quite different; (c) the seismic hazard: (c.1) is real in southeastern Cuba and northeastern Venezuela territories; (c.2) can heavy affect inhabitants of Santiago de Cuba and Cumana; (d) also local tsunamis can be occurred in northeastern Venezuela;

(**e**) the 1766 Santiago de Cuba earthquake was the greatest tragedy to date (40 deaths/ 700 injured) in Cuba; (**f**) the most disastrous seismic events of Venezuela occurred in Caracas (~2.200 deaths); (**g**) Cuba and Venezuela have different percentage values of deaths from earthquakes in relation to the population. Cuba has <0,7 %, and Venezuela, up to 10 %.

Although the interpretation of macroseismic data is intrinsically a subjective matter, we obtained some results in point analysis of felt intensities and adjusting of a theoretic model of isoseismals. In the case of Cuban results, where distribution of felt intensities is somewhat smooth, we adjusted a model that allows to select a M_W7,2 intermediate value between previous estimates by other authors. In the case of Venezuelan earthquake, where the felt intensities pattern was more complex, our results indicate a magnitude M_W7,5 and a depth of 30 km. This depth contradicts the criteria of several researches that considers that this earthquake is of intermediate depth.

The location of Venezuelan epicenter of 1766 earthquake and the two main alignments or axis E-W and NNE-SSW are quite clear in **figure 7A**. In it there is defined the NVA knot.

The results of the adjustment of the isoseismal models show the difficult to fit a Kovesligethian type attenuation law using the macroseismic field. When adjusting isoseismal model for Greater Antillas, Álvarez and Chuy [4] found a good fit of [33] formula with r_e= A for some earthquakes and with r_e= Δ_m for others. With earthquake of 1766 in Cuba, the fit was with r_e= Δ_m also. This means that this formula doesn't fits very well the data. Trying to solve this problem, Gómez *et al*. [34] adjusted a new formula for Eastearn Cuba, but it doesn't fit well the macroseismic field at long distances of epicenter. The case of Venezuela is worst, because nobody tested before a formula of this kind. It seems that the formula of [13] for Central America is applicable, but the test was done with only one earthquake characterized by a very complex macroseismic field. Then the problem of finding adequate formulas of Kovesligethian type for describing the macroseismic field continues open.

The use of an isoseismals' model for assessing earthquake parameters, may look less precise than the use of the statistical criteria developed last time [9] for doing the same. Then, when the initial data produce several researchers to made divergent estimations, as the Venezuelan earthquake of 1766 case, it is possible to consider that, instead to reduce the analysis to closer distances, to use the complete macroseismic field. This should be the better option for assessing magnitude and depth of historic earthquakes. By the other hand, when observed intensities are in islands, separated for extensive sea areas, or a very irregular pattern of intensities, due to the sparse settlement' locations, we must be to analyze the whole observed macroseismic field to extract the maximum information

The model used is highly versatile. It does not depend of a particular attenuation formula, but for a kind of that. It is very common in seismology. Although, we used a Kovesligethian kind, any formula of the kind I= f (M,Δ,h) can be used. Additionally the facility of measuring Δ in three different directions in an ellipse (A, Δ_m, B) gives the possibility of using the same formula for fitting different attenuation behaviors. Finally, there is possible to consider the diminishing of ratio of major to minor axes (A/B) of ellipses as intensity value decreases, in a formula of the kind $A/B|_I = f(I, I_0)$. This situation is frequent in continental earthquakes and we didn't encountered it in Caribbean or Central America earthquakes. In the annex is deduced, for the Kovesligethian kind of formula (with r= hypocenter distance) an expression of the kind $A/B|_I= f(I,r_e,h)$, but it can be deduced for other kind of attenuation formula.

Conclusions

The authors consider that the retrospective study of strong earthquakes is very important for a reliable modeling of the seismic danger. In this sense, the comparative analysis obtained for the case of the 1766 events in two different areas of the Caribbean, Cuba and Venezuela, confirms it.

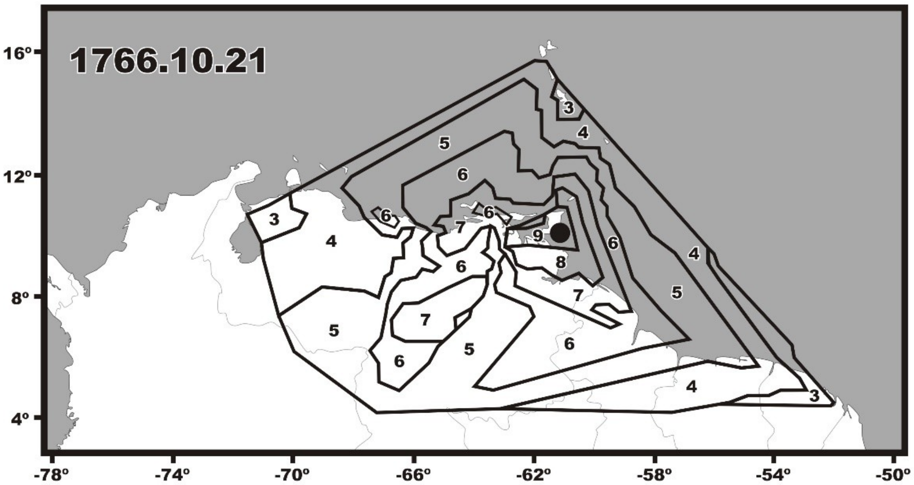

Figure 7A. Generalized isoseismal scheme of 1766 in Venezuela.

Our main results are the following:

(a) The 1766 earthquake is related in: (**a.1**) Cuba to the Oriente fault zone; (**a.**2) Venezuela with the NVA knot in the vicinity of western Venezuela-Trinidad

(b) The adjusted parameters of earthquakes are: (**b.1**) Cuban earthquake [19,9 N -76,1 W/ h= 25 km/ M_W= 7,2]; (**b.2**) Venezuelan earthquake [10,4 N -61,5 W/ h= 30 km/ M_W= 7,5]

(c) The Cuban and Venezuelan felt intensities pattern are quite different, that is reflected in the adjustment. The histogram of the residuals for the case of Venezuelan earthquake shows an appreciable number of earthquakes with values in the ranges (-1, -2) and (1, 2), while for the case of Cuban earthquake, the majority of residuals are in the range (-1, 1)

(d) The relative bigger complexity of macroseismic field of Venezuelan earthquake is explained for the location of his focus in the seismoactive NVA knot

(e) The best fit model for Cuban earthquake was obtained with the Kovesligethian type of attenuation formula made by Fedotov and Shumilina [33] for Kamchatka Peninsula (with distance measured along average radius Δ_m of the ellipses). This reinforce the results of Chuy and Álvarez [4], obtained by a try and error procedure of adjustment of model isoseismals to smoothed hand traced experimental isoseismals of Greater Antilles earthquakes

(f) The best fit model for Venezuelan earthquake was obtained with the model of Chen *et al*. [13] (with distance measured along major axis A of the ellipses). It has to be pointed out that this formula was obtained for m_b that is difficult to consider in a magnitude M_W7.5 earthquake.

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ANNEX 1
The Model of Elliptical Isoseismals

This model requires the existence of an attenuation law of Kovesligethian type [1] that allow to describe the macroseismic field. As was mentioned in the text, the value of "r" in this formula can be calculated in different ways. In the case of an elliptical isoseismal this value is not calculated as a generalized distance hypocenter-point, but a generalized distance hypocenter-ellipse that passes by the point. Present model determines how to calculate this distance, based on the ratio A/B of major to minor axis of the ellipses and, perhaps, a decrease of this ratio from inner to outer isoseismals.

For describing the shape of the ellipses there are used the parametric equations of an ellipse:

$$\Delta = A \cdot \left| \frac{\cos\theta}{\cos\alpha} \right| = B \cdot \left| \frac{sen\theta}{sen\alpha} \right|$$

Where: **(a)** Δ= the distance from the center of the ellipse to a point in its contour; **(b)** α= the polar angle of line joining both point; **(c)** θ= an auxiliary angle calculated as: θ = arctan [A/B·tan(α)] (**Figure A.1**):

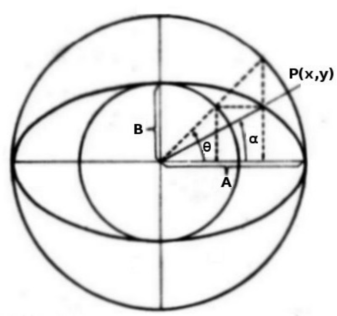

Figure A.1. Scheme of the meaning of the different parameters that describe the shape of isoseismals (modified from Álvarez and Chuy [4].

The attenuation is determined by the Kovesligethian formula evaluated in r= r_e

$$r_e = \left(\Delta_e^2 + h^2\right)^{1/2}$$

Where: (**a**) h= focal depth; (**b**) Δ_e= the distance epicenter-ellipse in a particular direction called "effective radius". The limits are the directions of major axis (Δ_e= max) and minor one (Δ_e= min). In the last case the isoseismals are bigger and more separated

$$\Delta_m = 2/\pi \int \Delta \cdot d\alpha = B \cdot K(m)/2\pi$$

between them. Is convenient to consider and intermediate distance, say the average radius of the ellipse:

Where: (a) m= 1 - $B^2/A^2 \geq 0$; (b) K(m) is an elliptical integral of first kind, which values may be found in special tables. A comparison of isoseismal obtained in the different cases of estimation of r_e is presented in **figure A.2**.

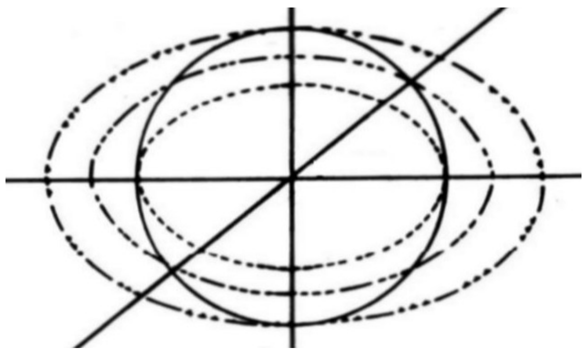

Figure A.2. Comparison of the ellipses obtained by selecting different directions for r_e. (a) Outer ellipse (B); (b) intermediate ellipse (Δ_m); (c) inner ellipse (A). The circle correspond to circular isoseismals. The possibility of selecting this directions increase the applicability of a particular Koveslighethian type formula (modified from Álvarez and Chuy [4].

Sometimes it is observed a behavior in macroseismic field that corresponds to a diminishing of ratio of major to minor axes (A/B) of ellipses as intensity value decreases:

$$A/B\big|_{I=I_i} = A/B\big|_{I=I_0} - \eta \cdot (I_0 - I_i)$$

For a Koveligethian type attenuation formula it is expressed as:

$$A/B\big|_{I=I_i} = A/B\big|_{I=I_0} - \eta \cdot \left[k/\lg(r_{e_i}/h) - p \cdot (r_{e_i} - h)\right]$$

Where: r_{e_i}= the effective radius of the isoseismal with I= I_i.

Then, the model is defined by: (a) parameters of the Koveslligethian kind formula; (b) focal depth; (c) ratio A/B; (d) direction of the effective radius; (e) parameter η of decreasing of A/B as a function of I_0 - I_i. It is added also geographical information on the orientation of major axis for a correct tracing of isoseismals in a map.

"…No hay que apagar la luz del otro para lograr que brille la nuestra…"
(Mahatma GANDHI, India, 1869-1948)