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Seismotectonics of the Nicaraguan Depression from Recent Seismicity

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Abstract

After 9 years without significant earthquakes' occurrence in the Nicaraguan Depression, in the period 2014-2016 have occurred 2 events with magnitude bigger than 6 and several with magnitude bigger than 5 together with a lot of less magnitude events. In this work an analysis of spatial-temporal behaviour of every cluster has been provided, including epicentres' relocation and time history analysis of slip in the focus for earthquake of April 10th, 2014. Additionally there have been determined the moment tensors of bigger earthquakes inside every cluster. The earthquakes held toward the centre of the depression align along NE-SW trending faults and show predominantly left lateral strike-slip movement, while the ones in the inner border align N-S and show a normal mechanism behaviour. Based in obtained results, summing the data of moment tensors of past earthquakes from global databases, and with the consideration of other evidences about geology and tectonics of the study area, it is provided a seismotectonic interpretation of those results as a proposal of a seismotectonic model for Nicaraguan Depression. The proposal includes M_{max} estimations and criteria about the more probable foci of future middle size earthquakes in the Nicaraguan Depression.

Keywords: Big earthquakes; Moment tensors; Clusters of earthquakes; Seismotectonics; Nicaraguan depression

Introduction

Due to different factors, historically, the bigger damage from earthquakes in the main Nicaraguan cities are related to events held at Nicaraguan Depression. First of all, the cities are placed long away of Pacific coast and the biggest earthquakes (M=7.5-8) occur in the subduction zone of Cocos under Caribbean plate. In this part of Pacific ocean the subduction initiates away from coast, with a pronounced angle, and then, near the coast earthquake depths reach 40-50km, highly increasing as moving inside continent [1]. The cities are placed following approximately the volcanic chain line, and it results that subduction seismicity occurs at about 90-100km depth with a relatively less influence that seismicity associated to local surface faulting. This seismicity, with estimated maximum magnitude about 6.5, due to its shallower character and placement near cities produces bigger damage. An example of that is the Managua earthquake of 1972, with magnitude M_s=6.2, that practically destroyed the entire city [2]. The challenge has been, and continues, to identify the places where it can held these events along the volcanic chain, and for example of the lack of knowledge in that sense, the seismic hazard assessment works present all the volcanic chain as single zones with uniform seismicity [3]. In Figure 1a it is shown an epicentre's map of Nicaragua region, for the period 1904-1917 and M ≥ 5, while in Figure 1b there is shown a selection of earthquakes in Nicaraguan Depression for the period 1950-2017 (for which the earthquake locations are better constrained), depth until 30km and magnitude greater than 4.5.

Three main seismotectonic approaches have been used to explain the earthquake occurrence in Nicaraguan Depression. The first, proposed by [4] states from the existence of a transform fault of NE-SW orientation that was responsible of Managua earthquake of 1972, coincident with one of the places were previous studies placed a segmentation of the volcanic chain [5]. A second approach [6], considers that the Managua pull-appart basin [7] is placed between two arc-parallel strike-slip faults bounding the Central American forearc sliver. Finally, another seismotectonic approach, that we consider more coherent, is due to [8]. Following the last authors, the available geodetic measurement results and focal mechanism determinations for this region allow to propose a schema in which the zone between the depression and the Central America forearc sliver moves toward Northwest, and forces a phenomena, called by them bookshelf, in which a series of faults of NE-SW direction are characterized by a left lateral strike-slip movement, forming blocks that rotate as time goes on. They show limits between proposed blocks from Gulf of Fonseca until the south-East of Ometepe island that delimiter 9 of them [8]. In this interpretation the authors do not represent in detail what occurs at the extremes of these transform faults and rotating blocks. In [1] is given an interpretation of this bookshelf model and are drown only 7 blocks for the same region. They added a very simple scheme to explain what occurs at the blocks' extremes, indicating rotation in north-east extremes and undefined situation in south-west ones [1]. Finally, in a paper that discussed the earthquake of April 10th, 2014, [9], gave another interpretation of bookshelf model, reducing the blocks to two big ones at both sides of Tiscapa fault and stating the existence of right lateral strike-slip movement in the segment where it is placed the studied earthquake.

With respect to real data about faults in Nicaraguan Depression, there is a relatively poor information. [8] Draw 3 of them extending from border to border of the depression: Ochomogo fault zone, La Pelona fault zone and La Paz Centro fault zone. But the data about them only cover small sectors close to the centre of the depression, as can be seen in the overall studies of [10,11]. To these information can be added also the transform fault zone that generated the earthquakes that affected Managua in 1931 and 1972 [4]. In this case, later detailed studies of surface faulting give a complex picture of tectonics of Managua grabben [12]. There are also some studies that cover the whole

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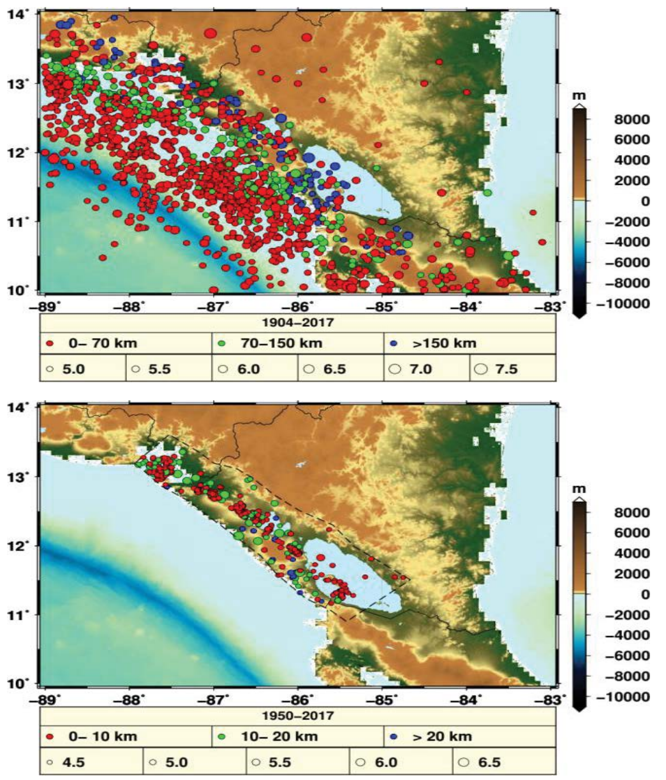

Figure 1: (a) Map of epicentres for the period (1904-2017) with magnitude ≥ 5 for the whole Nicaraguan territory. (b) Selection of earthquakes with magnitude ≥ 4.5 for the period (1950-2017) and depth ≤ 33km for the Nicaraguan Depression. With discontinuous line it is shown the selection area.

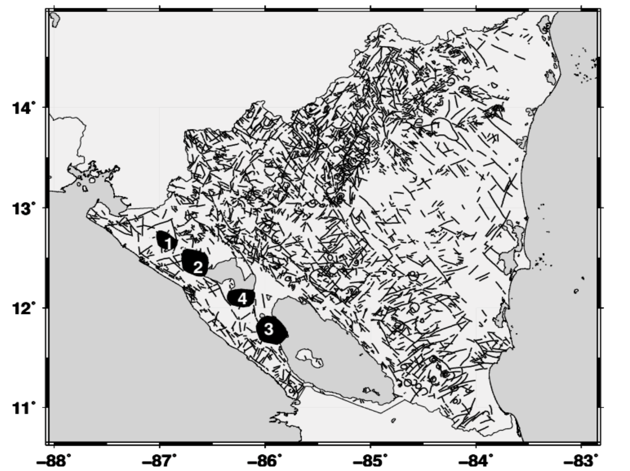

Figure 2: Tectonic knowledge of Nicaraguan territory. With lines are represented the faults that are present in the Geological-Mining map [12] and with black shadowed zones the places in which special geological studies have been done (1 - La Pelona, 2 - La Paz Centro, 3 - Ochomogo [10], 4 - Managua [12]).

Nicaragua [13,14]. It has to be remarked that all existing real tectonic information corresponds to surface faulting, without any detailed data in depth. In Figure 2 there is shown the map of faults that appear in [13], the one that is used currently for seismicity studies at INETER [15], and also are indicated the sectors mentioned in this paragraph in which exist detailed studies of surface faulting.

The lack of tectonic data made necessary to pose a big weight in seismological data, in particular in precise relocation of hypocenter's and focal mechanism - moment tensor results that give the possibility to infer dynamics of lithosphere. An example of that is the main epicentral sector delineated from high accuracy aftershocks' relocation of August 3th, 2005 earthquake, close to southeastern corner of Ometepe Island [16] that practically delineates a fault trace. In [8] are used 13 Harvard CMT solutions indicating strike-slip, interpreted by them as left-lateral, while [9] used only one and interpreted it as right-lateral. In both cases long faults are inferred from focal mechanism data.

In the period 2014-2016 held in Nicaraguan Depression and its internal border several medium sized earthquakes, together with a lot of less magnitude events that are analysed in detail in this work. They, together with information of earthquakes held in the period 1972-2013, are interpreted starting from the above mentioned bookshelf model, but driving into a more complete picture of seismotectonics of Nicaraguan Depression and proposal of a new seismotectonic model.

Materials and Methods

The seismicity of Nicaraguan Depression is characterized by the occurrence of clustered earthquakes [15]. In this work there were studied several earthquake clusters held in 2014-2016 that played an important role in the development of the new seismotectonic model for Nicaraguan Depression:

- 2014 April – July, western half of Managua lake, with main events on April 10th (with epicenter near Momotombito volcano) and April 14th (with epicenter in Chiltepe peninsula)
- 2015 September – October, El Sauce city zone, a swarm with maximum event in September 11th
- 2016 June-December, Puerto Morazán zone, with main event in June 10th
- 2016 September-October, El Hoyo volcano zone, with main events in September 15th and September 28th

There were used the catalogue and waveforms recorded by the INETER seismic network from Nicaragua, as well as from the USGS, SNET network from Salvador, OVSICORI network from Costa Rica, and the National Seismological network from Guatemala. For the earthquake locations and waveform inversions procedures, two velocity models were tested: the Costa Rica model from [17] and the one currently used at INETER, developed from the original established in 1975 [18]. Density values come from the relationship of [19], while the attenuation quality factors Q_p and Q_s are determined by the relationships given by Graves, et al. [20].

The applied methods, not the same in all the cases, were:

Epicentres' relocation, as well by testing different crust models as by using the double difference (DD) and modified joint hypocentres determination (MJHD) methods in order to reveal details of spatial distribution and possible association to a known fault plane

Seismic moment tensor determination of bigger events and its decomposition in order to reveal details about possible fault planes and displacement at the focus and additionally, for helping in the interpretation of results there were used moment tensor determinations prior to 2014, obtained from the data bases of The Global Centroid Moment Tensor Project [21,22] and International Seismological Centre [23].

Daily number of earthquake analysis and adjustment to theoretical distributions for estimation of parameters. Time-history analysis of slip in the focus

The work required the use of several programs written by other authors as well as writing of programs and scripts to be used in different stages of data processing. The more important programs from other authors are:

- ISOLA for the determination of seismic moment tensors [24,25].
- MoPaD [26] and “mtinfo” [27] for the decomposition of seismic moment tensors
- hypoDD for relocation of hypocentres by double-difference method [28,29].
- program package or relocation of hypocentres by Modified Joint Hypocentres Determination [30,31].
- AFT [32] for the adjustment of process main earthquake-aftershocks to theoretical models [33,34].
- program package for waveform inversion and determination of space-time history of slip at the focus [35,36,37].

Additionally there were used general seismological data processing programs as SAC2000 [38] and SEISAN package [39]. For graphics and maps preparation there were used gnuplot [40] and GMT package [41].

Recent Seismicity and Seismotectonics

In case of scarcity of reliable tectonic data, seismotectonic studies are based mainly on earthquake data. It poses a big weight in accuracy of hypocentres’ determination. For the study region, the data of hypocentres determined by international agencies show in general a big dispersion, sometimes of tens of km in epicentres and depth, even in the case of global relocations as EHB [42] and ISC-GEM [43]. By the other hand, local determinations not always are more precise, because of a possible poor azimuthal coverage of stations and the presence of systematic errors due to the use of a particular crust model. Then, for any analysis it is necessary to perform a careful relocation of hypocentres when possible, or to discriminate between different sources based on its reliability. In this paper are studied five earthquake clusters. With respect to earthquake magnitudes, for each earthquake there are in general several determinations from different agencies and of diverse types. There were selected those that were considered more reliable, mainly of M_W type. For each case there are performed: relocation of selected hypocentres, study of time occurrence behaviour, determination of moment tensor of main events and correlation with available tectonic data.

Earthquakes of the western half of Managua Lake in 2014

The seismic activity began on April 10th when held the strongest earthquake (M_W=6.0) in the zone of Momotombito volcano, while on April 14th occurred an earthquake of magnitude M_W=5.1 in Chiltepe peninsula. The errors in the preliminary earthquake locations by the Nicaraguan seismic network didn’t allow isolating both seismic activity sources and initially it was considered the presence of a wide zone of aftershocks. The problem with precision of hypocentres was also with international agencies, where different solutions for the main shock were find along a line of NE-SW direction of about 40 km length (Figure 3a). Even later global relocations (EHB and ISC-GEM catalogues [42,43]) give epicentres 20km apart. With respect to depth, the international agencies give a value of 10-15km while local determinations give a value of 5km or less. This situation is common to all the data of medium size earthquakes in Nicaraguan Depression. An intense work of hypocentres’ relocation was done for the strongest shocks held in April month, using the hypoDD algorithm [28,29] and two different crust models inside SEISAN package [39]. At the end, it appeared that location by hypoDD algorithm and by SEISAN using a crust model determined for Costa Rica [17] were enough coherent. It allowed us to make relocations in some cases with the second procedure. In Figure 3b it is presented the map of relocated epicentres. It is clear from this map, that are two different main earthquake-aftershock processes, where the one initiated on April 10th in the Momotombito volcano area, triggered the other initiated later in Chiltepe peninsula. Also it can be seen, not so clearly, a possible subdivision of main sequence in two, one along a line

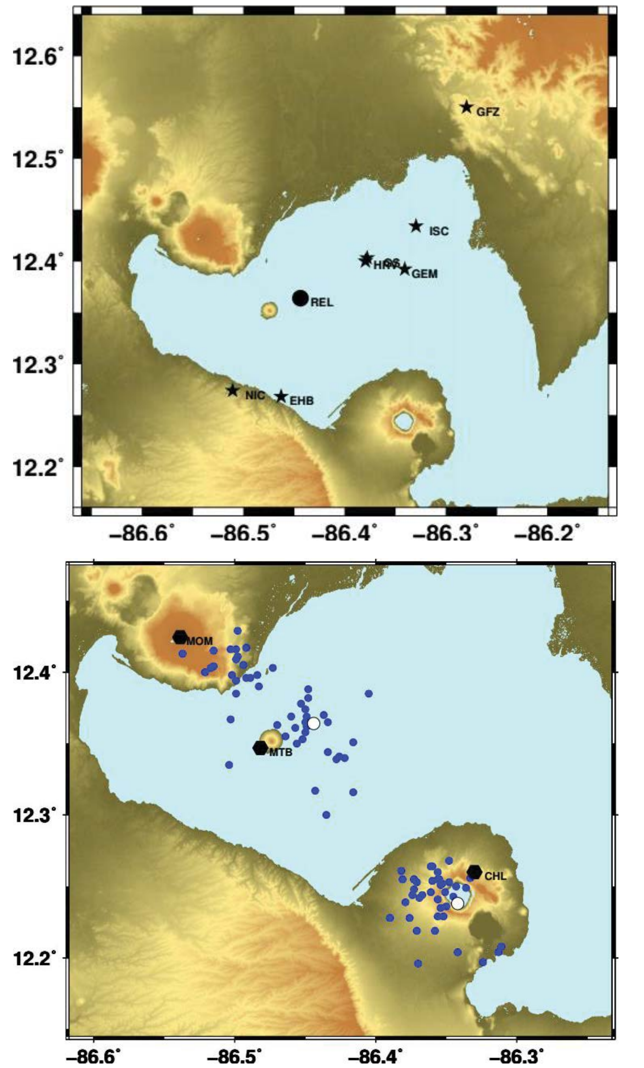

Figure 3: Earthquakes in western half of Xolotlan lake in 2014. (a) Epicentres of main shock of April 10th determined by several agencies: NIC - preliminary determination by Nicaraguan network, HRV - Harvard’s CMT catalogue, GS - US Gelogical Survey, GFN - Geofon Service at GFZ (Germany), ISC - International Seismological Centre, GEM - ISC-GEM project global relocations, EHB - EHB algorithm global relocations at ISC, REL - relocation made in this work. (b) Relocated selected earthquakes with hypoDD algorithm and with SEISAN using crust model for Costa Rica [17]. With white circles are the main earthquakes of the clusters in Momotombito volcano zone (MTB) and Chiltepe peninsula (CHL); MOM - Momotombo volcano.

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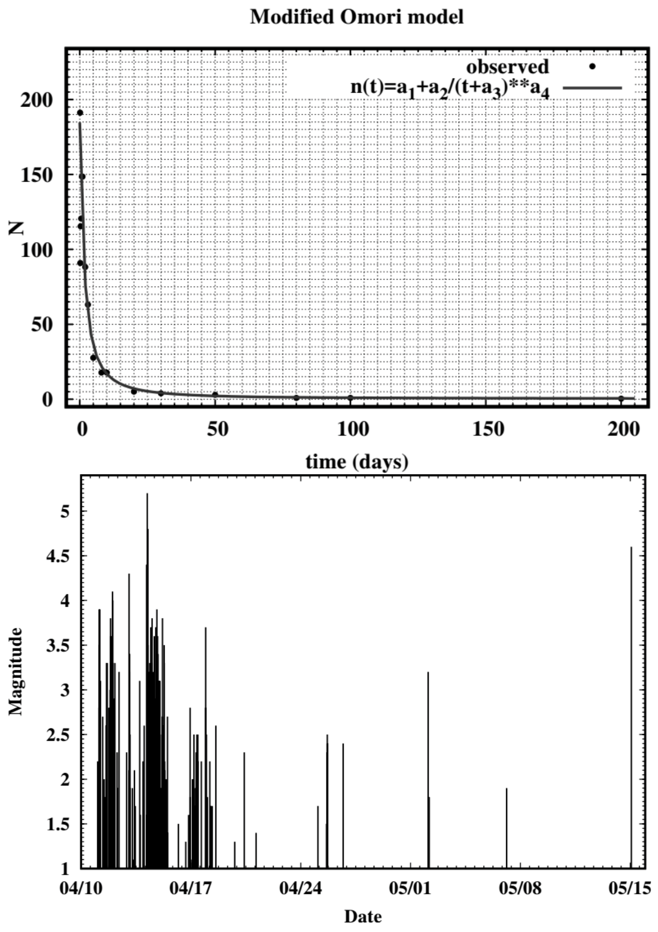

Figure 4: (a) Adjustment of daily number of earthquakes in Momotombito's cluster to the theoretical distribution "Omori modified" (formula 1). Experimental data are presented averaged, while the adjustment was done with the original time series. (b) Time series of magnitudes of earthquakes in Chiltepe's cluster.

passing by Momotombito volcano and another along a line passing by Momotombo volcano. Due to the low precision of earthquake locations, even of relocations, and the close position of possible source zones, we decided to analyse them as only one cluster.

The behaviour of the daily number of earthquakes for April 10th earthquake cluster near Momotombito volcano was adjusted to different theoretical models using program AFT [32]. The model with the best fit was the "modified Omori" with coefficients (a_1=0.262, a_2=0.0212, a_3=1.193, a_4=1.305).

$$n(t)= a_1+a_2/(t+a_3)^{a_4} \qquad (1)$$

In Figure 4a it is shown the graphic of this fit. The aftershocks'

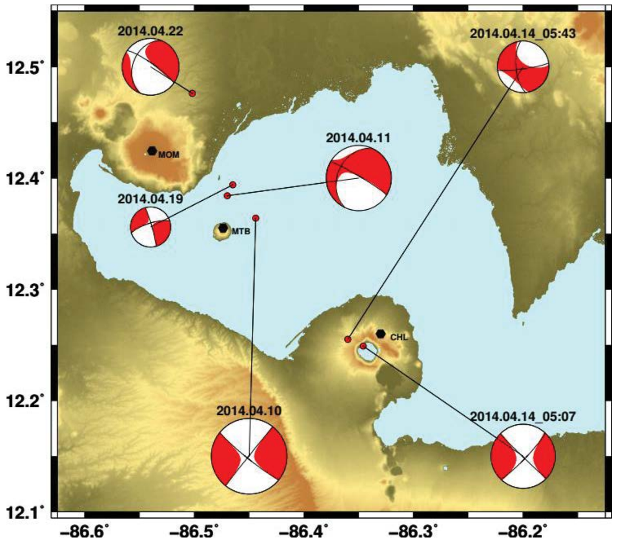

Figure 5: Combined plot of moment tensors and best double couple solutions obtained for some earthquakes of April 2014 series. The parameters are given in Table 1. CHL - Chiltepe Peninsula, MTB - Momotombito volcano, MOM - Momotombo volcano.

Date	OriginTime	Lat.	Long.	h	Mw	Mrr	Mtt	Mpp	Mrp	Mrt	Mtp	Mo	exp	%DC
Momotombito volcano														
2014.04.10	23:27:45.0	12.364	-86.444	5	6.0	-0.099	-1.349	1.448	-0.063	-0.130	-0.312	1.44	18	86.1
2014.04.11	00:01:22.1	12.384	-86.470	0.9	5.2	-1.080	-3.771	4.872	6.611	-2.672	-2.396	8.73	16	78.4
2014.04.19	13:44:28.3	12.394	-86.465	0.5	3.2	-0.789	-4.194	4.984	1.282	-1.966	6.898	8.64	13	91.8
2014.04.22	04:18:38.4	12.476	-86.502	10.8	4.5	-2.141	-2.914	5.155	4.656	-3.641	-3.397	8.14	15	64.1
Chiltepe peninsula														
2014.04.14	05:07:03.0	12.249	-86.346	4.2	5.1	-1.058	-5.787	6.845	-0.526	0.546	-0.276	6.43	16	69.8
2014.04.14	05:43:52.9	12.255	-86.360	5.5	4.1	0.359	-0.590	0.231	-0.829	0.452	1.452	1.81	15	32.3
El Sauce														
2015.09.12	11:22:01.9	12.955	-86.583	15.3	4.4	-3.189	-1.355	4.544	-1.300	1.544	1.246	4.68	15	71.8
2015.09.12	19:35:52.2	12.950	-86.586	6.4	3.6	-0.873	-0.972	1.845	-0.742	2.236	1.162	3.08	14	81.9
2015.09.14	08.13:01.3	12.954	-86.593	15.8	4.6	-8.110	0.824	7.285	-0.713	3.128	1.482	8.50	15	84.4
2015.09.28	06:23:37.5	12.896	-86.573	6.2	3.6	-3.637	0.319	3.318	-0.129	0.703	-0.250	3.57	14	83.9
2015.10.11	23:09:20.5	12.930	-86.570	8.4	4.0	-1.403	0.082	1.320	-0.042	0.258	0.301	1.42	15	97.1
Puerto Morazán														
2016.06.10	03:25:21.0	12.886	-87.056	5.7	5.9	0.095	-7.773	7.678	-4.412	3.651	-3.084	1.01	18	91.1
El Hoyo volcano														
2016.09.15	05:57:24.0	12.462	-86.658	7.4	5.7	-0.770	-2.807	3.577	1.064	0.218	-1.610	3.80	17	82.1
2016.09.28	16:48:55.0	12.456	-86.599	8.5	5.4	-0.993	-0.701	1.694	1.032	0.153	-0.098	1.81	17	79.5

Table 1: Obtained solutions of seismic moment tensors. There are indicated the centroid, the components of tensor (M_{ij}), the % of double couple of forces without momentum of the solution (%DC), date, origin time, magnitude M_w and M_0. The column "exp" indicates the exponent of M_{ij} and M_0 values in scientific notation. The moment tensor is expressed in [Nm]. The coordinates of earthquakes are from relocations done in this work.

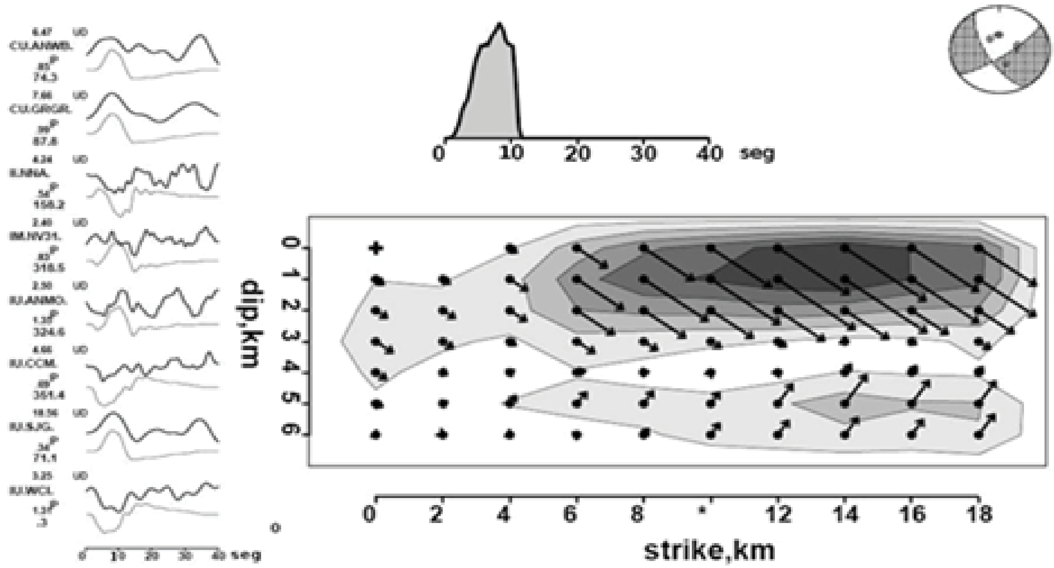

Figure 6: Space-time history of slip at the focus of April 10, M_w=6 earthquakes. In the left are shown the waveforms used for the adjustment. In upper right corner is the best DC solution of the moment tensor determined in present study. In central upper part it is shown the source time function of the rupture process at the focus used. In the bottom it is presented the graphic of the slip on the fault plane.

magnitudes were not big; the main aftershock held 34 minutes after the main shock (M_W=5.2); then, until the end of May, 8 earthquakes had occurred with M_W magnitude estimated between 4.5 and 4.8 (converted from other types, no reliable direct estimations of M_W exist for them). The cluster in Chiltepe peninsula has a different behaviour. It was activated with low magnitude earthquakes since April 11th; then, at April 14th occurred the main shock (M_W=5.1) together with other two of less magnitude, one before and other after. The interpretation of this cluster may be done in two ways: a foreshocks - main event - aftershocks process or a swarm with activity highly concentrated in the first week (Figure 4b).

It was done a detailed study of moment tensors of some events in both zones, 4 for the first one and 2 for the second, using ISOLA program [24,25]. This program works with local and regional data that allows obtaining reliable solutions for earthquakes with low magnitudes. In table 1 there are presented the results of moment tensor determination and in Figure 5 the plots. For the event of April 10th and the first of April 14th it was possible to select the fault plane based in the relationship epicentre-centroid, that in both cases corresponds to a direction NE-SW approximately, and, in spite of that ruptures are not simple, it is predominant the component of left lateral strike-slip movement. For the main shock, the results of field geological reconnaissance [44] clearly show a NE-SW predominance of surface faulting in Momotombito volcano and along the coast of the lake, NE of Momotombo volcano, which reinforce our interpretation, and in the case of Chiltepe Peninsula, the orientations found of surface faulting in four points are also NE-SW at angles between 0° and 30° from North. Additionally, [45] states that from GPS measurements the fault plane direction of main earthquake is the NE-SW, and by the results of a Coulomb static stress transfer analysis it is clear that main event triggered two other sequences, the one at Chiltepe Peninsula, and another in Momotombo volcano. Nevertheless, it should be mentioned that [9] assigned, based on non-relocated epicenter's alignment, the direction NW-SE to main fault and interpreted this earthquake with the pull-apart basin hypothesis of [6]. We consider that it is a misinterpretation, due to the fact that they didn't consider all the available information.

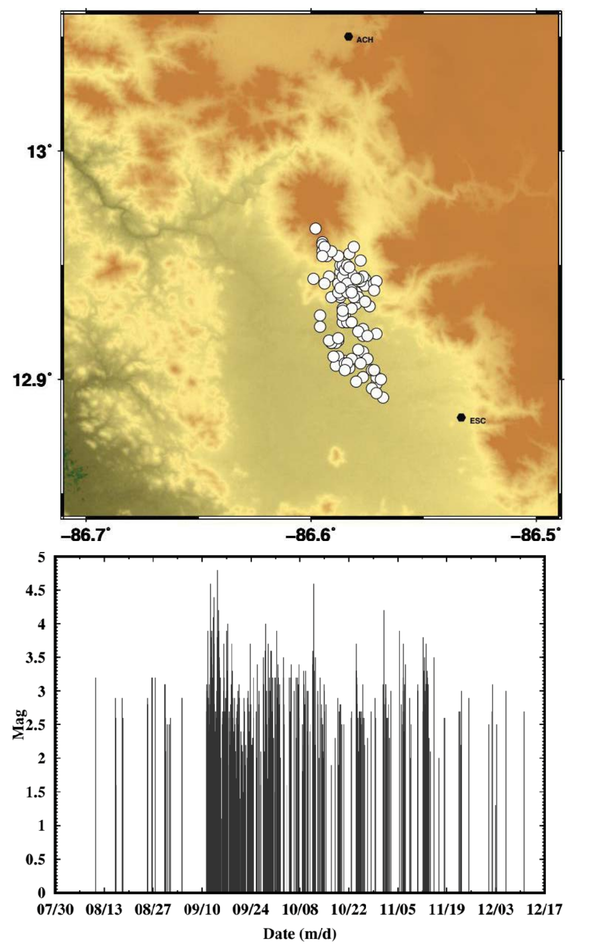

Figure 7: (a) Relocation of events in El Sauce zone held in September-October 2015 by hypo DD algorithm and with SEISAN using the crust model of [17]. ESC - El Sauce, ACH - Achuapa. (b) Time series of magnitudes of events held from the beginning of August until the middle of October 2015.

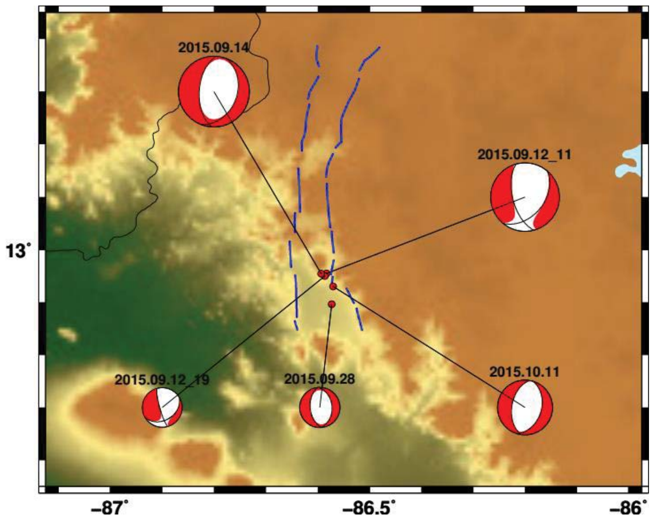

Figure 8: Combined plot of moment tensors and best double couple solutions obtained for some earthquakes of the swarm. The parameters are given in Table 1. Blue solid lines represent the two faults determined by [47-49].

It was also studied the spatial-temporal history of slip at the focus of the main earthquake, considering the NE-SW direction as fault plane, for the main shock of April 10th, using the method of Kikuchi and Kanamori [35,36,37] and the result is shown in Figure 6. From vectors' orientation it can be observed that predominates the transcurrent movement but with a normal component. The biggest rupture is concentrated at the end of the fault plane in the first 3km depth. The process had only duration of 10 seconds. The dimension of the source is 18km length and 6km width. These values are congruent with the ones that may be expected from [46] formulae for strike-slip earthquakes of this magnitude (rupture length – 11.2km and rupture width 9.3km).

Earthquakes in El Sauce zone in 2015

Preceded by a non-significant activity since August 9th, in September 11th began an earthquake series close to El Sauce city, located at the "inner" edge of Nicaraguan Depression, with behaviour typical of an earthquake swarm. In this zone, another series of earthquakes held in 1980, in which, despite the deficient coverage by seismic stations at that time, there were detected 75 earthquakes in the magnitude range M_C=1.5-3.3 [15]. In present case, the swarm extended 3 months approximately. It was performed the relocation of the relatively strongest earthquakes that held during September-October, using both the double difference method (hypoDD) [28] and SEISAN [39] locations with the crust model of Costa Rica [17], already tested in the previous case. The result is shown in Figure 7a. The orientation of epicentres delineates a source zone of approximately N-S direction. The relocated by double difference method shocks are very shallow, being located the majority between 5 and 7km depth. The width of approximately 2km of the band defined by epicentres is between the error limits of its location. The maximum magnitude of earthquakes of the swarm was M_W=4.8, reached at September 14th. The time series of earthquakes is shown in Figure 7b.

In this zone, there have been done 3 geo-structural studies [47-49] that allowed to determine two quasi parallel faults of N-S orientation about 50km length. Later on, [50] suggested that one of these faults could be the source of present earthquake swarm. This N-S orientation was also observed in a series of earthquakes held in May-June/1997 in Dipilto, North Nicaragua [15], a place located about 50km North of the end of both faults.

There were also determined the seismic moment tensors for 5 events of the swarm with ISOLA program [24,25]. They are represented in Figure 8 together with the faults mentioned above. The moment tensor parameters are also in table 1. All of them have an associated fault plane solution of almost pure normal kind with N-S orientation. Due to the particular geometry of nodal planes and earthquake distribution, it was not possible to determine, between the 2 possible planes, the one that corresponds to fault plane. Any of the mentioned above faults could be the fault plane.

Earthquakes of Puerto Morazán zone

On June 10th, 2016, occurred a M_W=6 earthquake in the zone of Puerto Morazán, followed by abundant aftershocks; see a detailed description in [51,52]. It was done a relocation of selected earthquakes (those recorded by 20 or more stations) with the MJHD method [30,31] using the Costa Rica crust model [17]. The orientation of aftershocks zone has a NNE-SSW tendency as it is seen in Figure 9a. No aftershock was recorded with magnitude M > 5 and their number diminished very fast. An adjustment of daily number of earthquakes was done to several theoretical models with AFT program [32] and the best fit was obtained with Otsuka model (Eqn 2, Figure 9b) with coefficients: a_1=0, a_2=37.07, a_3=0.123, a_4=0.841 and a_5=0.007.

$$n(t)= a_1+a_2 \cdot exp\{a_5 \cdot t/(t+a_3)^{a_4}\} \quad (2)$$

With such a little value of a_5, this model is almost equivalent to the modified Omori one. In fact, the difference in the adjustment is very little between the two models.

For the main earthquake it was determined the seismic moment tensor (Figure 10) with ISOLA program [24,25]. In table 1 there are presented the results of moment tensor determination. The kind of mechanism of the associated fault plane solution is left lateral strike-slip with a little normal component. Considering the hypocentral position within the errors, the centroid position, and the orientation of the aftershock zone, it was possible to determine that the fault plane is the one with NE-SW orientation.

Earthquakes of El Hoyo volcano zone

In September 15th, 2016, occurred the main (M_W=5.7) earthquake, that was followed by abundant aftershocks, and the strongest one held on September 28th (M_W=5.4). Details of the series were discussed in [53,54]. It was done a relocation of selected earthquakes (those recorded by 15 or more stations) with the MJHD method [30,31] using the Costa Rica [17] crust model. The results show a wide epicentral area with two foci that can be interpreted as two fault of NE-SW orientation. If we compare this distribution with what is called La Paz Centro fault zone [10] it is clear a close association (Figure 11a) between them. With respect of time behaviour, it seems to occur a reactivation of the process after the M_W=5.4 earthquake. The adjustment of the daily number of earthquakes to theoretical models with AFT program [32] indicates that the best fit corresponds to the modified Omori model for two sequences.

$$n(t)= a_1+a_2/(t+a_3)^{a_4}+H(t-T_2)a_5/(t-T_2+a_6)^{a_7} \quad (3)$$

where H is the Heaviside function [H(t)= 0 for t < 0 and H(t) =1 for t ≥ 0], T_2 is the time of the beginning of the second sequence (13.5 days) and the obtained coefficients are: a_1=9.933·10^{-9}, a_2=3334, a_3=4.383, a_4= 2.381, a_5=6.490·10^6 a_6=4.180 and a_7=8.075. In the Figure 11b it is shown this fit over the histogram of the daily number of earthquakes.

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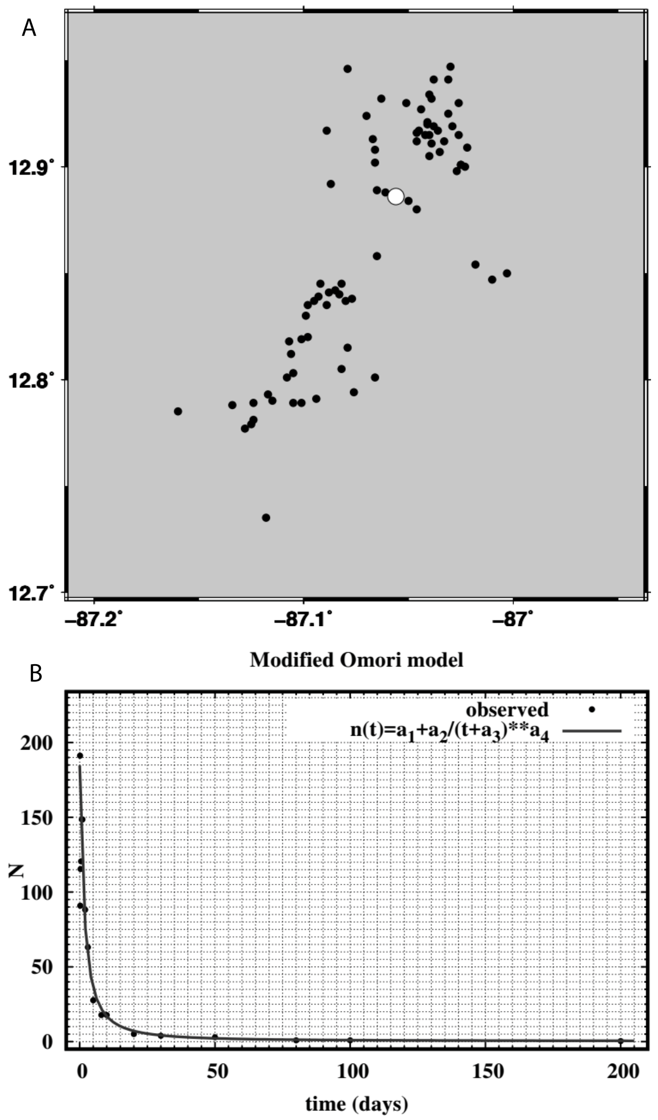

Figure 9: (a) Relocated earthquake epicentres registered by 20 or more stations using the MJHD algorithm with the crust model of [17]. Big white circle corresponds to main shock of June 10th. (b) Adjustment of daily number of earthquakes to modified Omori model. Experimental data are presented averaged, while the adjustment was done with the original time series.

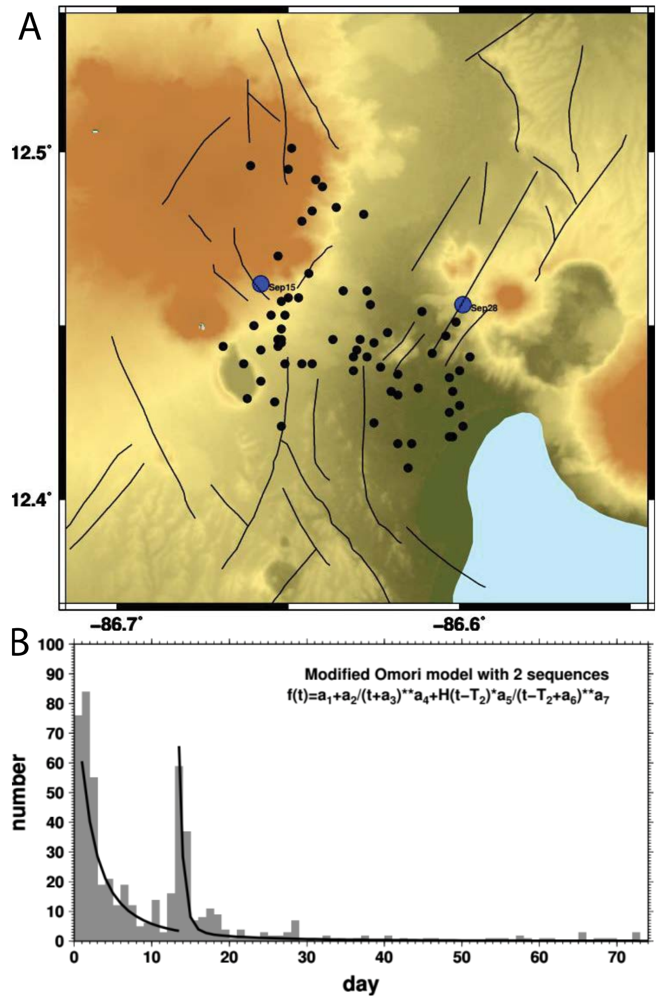

Figure 11: (a) Relocated earthquake epicentres registered by 15 or more stations using the MJHD algorithm with the crust model of [17]. Big blue circles corresponds to main shock of September 15th and aftershock of September 28th. Black lines correspond to the plot of La Paz Centro fault system [10]. (b) Histogram of daily number of earthquakes and the curve corresponding to the fitting of modified Omori model with 2 sequences.

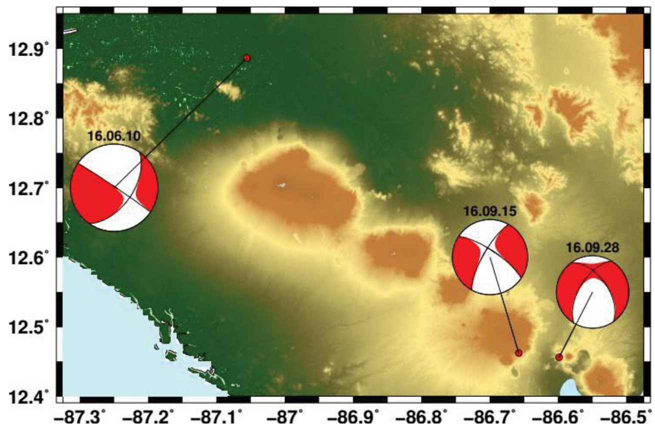

Figure 10: Combined plot of moment tensors and best double couple solutions for the earthquakes of 2016 in Puerto Morazán (the big beach-ball in the left) and El Hoyo. The parameters are given in table 1.

There were obtained seismic moment tensor solutions for this two main earthquakes with ISOLA program [24,25]. The associated fault plane solutions correspond, in the first case to left lateral strike-slip of NE-SW orientation with a little normal component, while in the second to the inverse phenomena: a normal mechanism with a small component of left lateral strike-slip. Considering also the orientation of aftershock zones, in both cases it was identified as fault plane, the one directed in NE-SW direction.

Moment tensors of earthquakes held before 2014

From the Harvard global database of moment tensor solutions [22] there were selected 16 earthquakes in the period from 1982 to 2006 for the study region. It was searched also the ISC database [23] but no additional earthquakes were found, and CMT solutions for the first were preferred. It has to be remarked that exist a difference between coordinates in both sources. The first one give the centroid, obtained in the process of moment tensor determination using a limited number of stations, while the second give the hypocentre determined by using the maximum possible number of stations. As was discussed before, to select a valid location of the earthquakes is difficult, because exist in general several sources of data (ISC, GS, HRV, EHB, ISC-GEM, local Nicaraguan network, etc.). The hypocentral coordinates of the events that give the global agencies are not so precise as the ones of the events studied in this work and should be taken with some caution. In general, for the study region, the more reliable coordinates given by global sources are the EHB ones [42], and for our analysis there were selected, case by case, those considered more reliable. To these moment tensor solutions should be added the fault plane solution of the 1972 Managua earthquake studied in detail by [55]. In Figure 12 there are shown the combined best double couple fault planes together with moment tensors for these earthquakes, and in table 2 there are presented their parameters. It is also shown the fault plane solution of 1972 Managua earthquake. For all the earthquakes it is used the best hypocentre determination, and in table 2 it is indicated the source of it. For earthquake of Dec 23rd, 1972, not included in this table, the source of hypocentre is [55]. All the earthquakes show a predominant left lateral strike-slip movement along a NE-SW fault orientation.

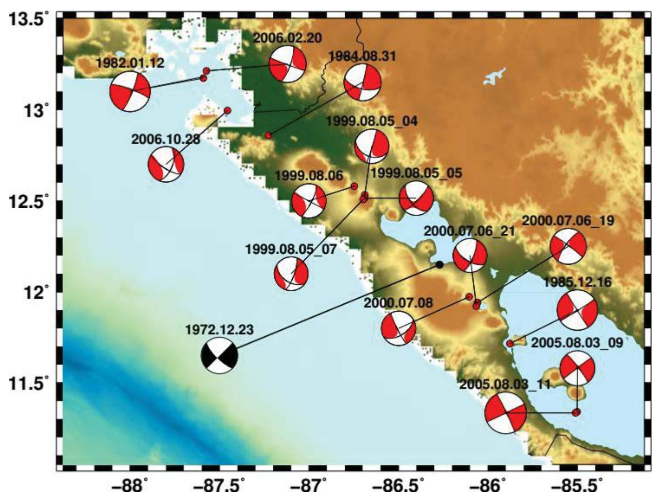

Figure 12: Combined plot of moment tensors and best double couple solutions for the earthquakes held in Nicaraguan Depression from 1982 to 2006 and double couple solution of Managua earthquake of 1972 (filled in black beach ball). All of them have a solution ranging from pure strike-slip (assumed to be left-lateral) to hybrid strike slip – normal. See Table 2 for details.

In central depression there are two interesting zones. The first groups four solutions corresponding to an activity that preceded a Cerro Negro Volcano eruption in 1999 [56]. The coordinates of main earthquakes from global agencies are in general out of epicentral area defined by aftershocks and local network ones were preferred. The magnitudes of local network are of M_L or M_C, sometimes of M_W types, that for $M_W < 6$ are lesser than HRV M_W ones [57]. The earthquake series covers an extensive area along the volcanic chain forming several clusters [15]. The main clusters are placed in Cerro Negro (earthquakes of August 5th) and Rota volcanoes (earthquake of August 6th) and suggest a NE-SW orientation of the associated faults (Figure 13a). The second zone groups 3 solutions of earthquakes corresponding to an activity that affected Masaya - Laguna de Apoyo region in 2000 [15]. For one of the earthquakes no reliable location by local network was obtained and EHB one was selected. In this case the earthquake series forms several clusters placed in Masaya and both sides of Laguna de Apoyo that suggest also a NE-SW orientation of the possible associated faults (Figure 13b).

Discussion

The first thing that is important to consider is that seismicity in Nicaraguan Depression concentrates at its central part. No significant activity is reported in their outer and inner borders. The second is that main earthquakes that occur in this part has a purely tectonic character with an elevate % of double-couple component that indicates the occurrence on faults nearly planar. These earthquakes are followed by aftershock sequences of standard character (Omori or modified Omori model). When magnitude of earthquakes diminished, despite the tectonic character continues, the % of double-couple component, in general diminishes also, which indicates the presence of more complex sources. Other aspect of seismicity is that the occurrence of earthquakes of magnitude greater than 6 may trigger the occurrence of

Date	OriginTime	Lat.	Long.	h	Sour	Mw	Mrr	Mtt	Mpp	Mrp	Mrt	Mtp	M_0	exp	%DC
Northwest															
1982.01.12	05:48:19	13.173	-87.590	4	EHB	6.1	0.085	-1.247	1.162	-0.148	0.366	-1.317	1.83	18	99
1984.08.31	04:42:57	12.858	-87.226	7.2	EHB	5.6	-0.163	-1.225	1.388	-0.427	-1.507	-2.447	3.19	17	96
2006.02.20	06:56:07	13.213	-87.573	0	NIC	5.5	-0.250	-1.490	1.740	-0.551	0.123	-1.930	2.59	17	85
2006.10.28	00:53:44	12.995	-87.456	6.4	NIC	5.3	-0.559	-0.519	1.080	-0.249	0.207	-0.602	1.16	17	27
Centre															
1999.08.05	04:35:53	12.534	-86.688	0	NIC	5.2	-0.749	-2.825	3.574	-1.159	-5.343	-3.255	7.15	17	73
1999.08.05	05:31:51	12.516	-86.690	1.8	NIC	5.1	-1.229	-4.803	6.033	-3.458	-1.475	0.407	6.69	16	85
1999.08.05	07:11:20	12.507	-86.698	3	NIC	5.1	-2.245	-2.639	4.884	-1.296	-2.875	-2.402	5.80	16	82
1999.08.06	18:53:17	12.581	-86.747	3	NIC	5.2	-2.503	-4.887	7.390	-1.077	1.366	-4.394	8.04	16	41
2000.07.06	19:30:17	11.942	-86.058	3.1	NIC	5.4	-0.100	-1.380	1.490	0.330	-0.160	-0.450	1.55	17	91
2000.07.06	21:50:50	11.921	-86.064	16	EHB	5.1	-1.490	-3.040	4.530	-2.190	-1.520	-2.790	5.56	16	98
2000.07.08	00:19:10	11.973	-86.104	5.1	NIC	5.2	-1.260	-4.660	5.920	-1.960	3.560	3.060	7.42	16	81
South															
1985.12.16	02:44:39	11.716	-85.877	31.1	EHB	6.1	-0.158	-1.377	1.535	-0.039	0.043	0.695	1.62	18	81
2005.08.03	09:27:30	11.340	-85.501	1.1	TUC	5.3	0.014	-0.925	0.911	0.089	0.044	0.253	9.57	16	96
2005.08.03	11:03:14	11.334	-85.511	10	TUC	6.3	0.038	-2.360	2.320	0.120	0.079	1.890	3.01	18	97

Table 2: Solutions of seismic moment tensor for earthquakes in Nicaraguan Depression took from Harvard database (GCMT 2017). There are indicated the components of tensor (M_{ij}), the % of double couple of forces without momentum of the solution (%DC), date, origin time, time and hypocentre's source, magnitude M_W and M_0. The column "exp" indicates the exponent of M_{ij} and M_0 values in scientific notation. The moment tensor is expressed in [Nm]. The source of hypocentres (Sour) are: NIC – Nicaraguan nework, EHB [42] and TUC [16].

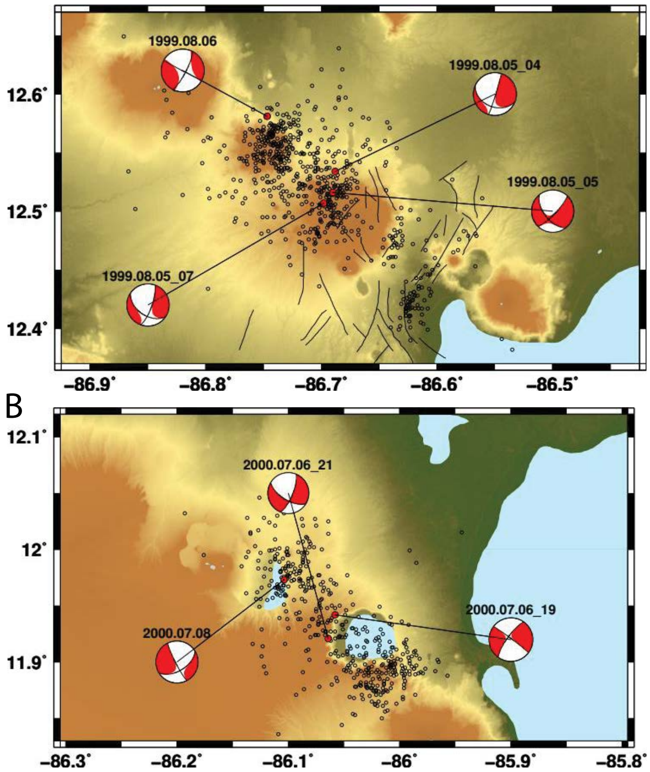

Figure 13: Two earthquake series that reflect complex behaviour. Combined plot of moment tensors and best double couple solutions over non-relocated epicentres' map. In both cases it seems that earthquakes align along at least 3 faults of NE-SW direction, while two of them were characterized by left lateral strike-slip best double couple moment tensor solutions. (a) August 1999. There are shown also the faults of La Paz Centro fault system [10]. The part in which coincide the faults and epicentres at the right-bottom corner is the same as epicentral area of El Hoyo series, discussed above, where two possible NE-SW faults were identified. (b) July 2000. Not reliable tectonic data exist to associate with epicenters.

less magnitude earthquakes on close strike-slip faults. In the analysed by us cases, no volcanic activity was induced. It is interesting to compare the two sequences of aftershocks for $M_W < 6.2$ earthquakes (April 10th, 2014 and June 10th, 2016). The first has many more aftershocks than the second, which is reflected in the differences of coefficient "a_1" of the adjustments that is responsible of the level of aftershocks occurrence, while the other coefficients modulate the shape of the curve. This difference tells about the increased geological complexity of the zone of Momotombito volcano with respect to the NW extreme of Nicaraguan Depression.

Other aspect that requires some comments concern the moment tensor solutions. The moment tensor contents a lot of information and should be decomposed for its correct interpretation. In a first stage there are considered the isotropic part (ISO), that corresponds to explosion/implosion processes, and the deviatoric part that corresponds to tectonic processes. The last one can be divided in different ways, but the more accepted consists of two components: double couple of forces without moment (DC), that corresponds to pure shear in faults, and compensated linear vector dipole (CLVD), that is interpreted as a volume change compensated by the movement of the particle along the plane of bigger stress [58] which corresponds to a movement in non-planar faults. All the plots of moment tensors in this paper contain both real moment tensor (red shadowed zones) and the associated planes of best double couple solutions (black lines).

In our case all the solutions (determined by us or took from global database) have null isotropic component, and then, we are dealing only with shear or planar faults. In the case of our determinations, the bigger %DC corresponds to Puerto Morazán earthquake, that has an epicentre long away of active volcanoes and then his fault plane is not affected by magmatic processes. By the other hand, the lesser values of %DC correspond to earthquakes located under active volcanoes (April 24th, 2014 under Momotombo volcano and the two of the April 14th, 2014 under Apoyeque volcano). In these placements it is highly probably that the faults where displacement occurs are affected by irregularities. In the cases of data took from global database there are also 2 cases with low %DC, that talk about complexity of sources. They are not discussed in this paper; but in the case of August 6th, 1999, its relation with volcanic activity was studied by [56].

Between the different interpretations of seismotectonics of Nicaraguan Depression, the model proposed by [8], based on GPS measurements and best double couple solutions from Harvard moment tensor determinations of earthquakes, is the one that satisfies better the actual earthquake occurrence process. In a late study [59] extensive GPS measurements support the hypothesis about the driven mechanism of the model (continental margin is displaced to the Northwest), were it is presented a model in which movement changes from NW-SW direction at South boundary of Nicaragua to approximately ENE-WSW as moving to El Salvador. In this model, named by them of "bookshelf" kind, the inclined subduction of Cocos plates with respect to shoreline causes the displacement to the Northwest of a coastal bend and a left lateral transcurrent movement inside the depression along faults of NE-SW direction (Figure 14a). In physical terms, the "books" are blocks, and the model starts that these blocks rotate. In the classical bookshelf model [60] they should be present two parallel active strike-slip faults, responsible of bigger earthquakes in the system, where the space between them is filled by blocks separated by strike-slip faults orientated 45° with respect to main faults direction. The movement is complex; blocks rotate, and at their extremes in contact with main faults should be a sequence of short inverse and reverse faults that accommodates the compression and extension resulting from rotation process. Nothing but the strike-slip movement of NW-SW direction during earthquakes has been detected in Nicaraguan Depression; then, for our point of view, the hypothesis of blocks' rotation is not strong.

The moment tensor solutions of events of 2014 and 2016 fit perfectly the hypothesis of strike-slip movement at the borders of blocks, with changing direction from NE-SW to NNE-SSE according to the rotation of the movement of the forearc sliver [59], while the ones corresponding to 2015 events at El Sauce are complete different. These normal faulting solutions indicate that at the border of the proposed by these authors "blocks" no physical rotation of them occurs, but a rotation of compressive stress. While the movement occurs in the central part of border of such "blocks", it is expected that it corresponds to a strike-slip movement, but when it occur in the extremes of the blocks or faults it is created a mass deficit that force a rotation of the stresses, passing the compressive ones to a vertical orientation, while extensive stresses remain their E-W horizontal orientation (Figure 14b). In the outer depression part of the "blocks" or faults, we have not a moment tensor determination of normal kind as the El Sauce ones, but there are hybrid solutions from global moment tensor database with big component of normal faulting together with left lateral strike-slip as in the case of earthquakes held close to Cerro Negro volcano in 1999 (Figure 13a) that obey to the change of orientation of compressive stresses from horizontal to dipping ones. The redirection of stresses may be the cause of the formation of structures of N-S direction from

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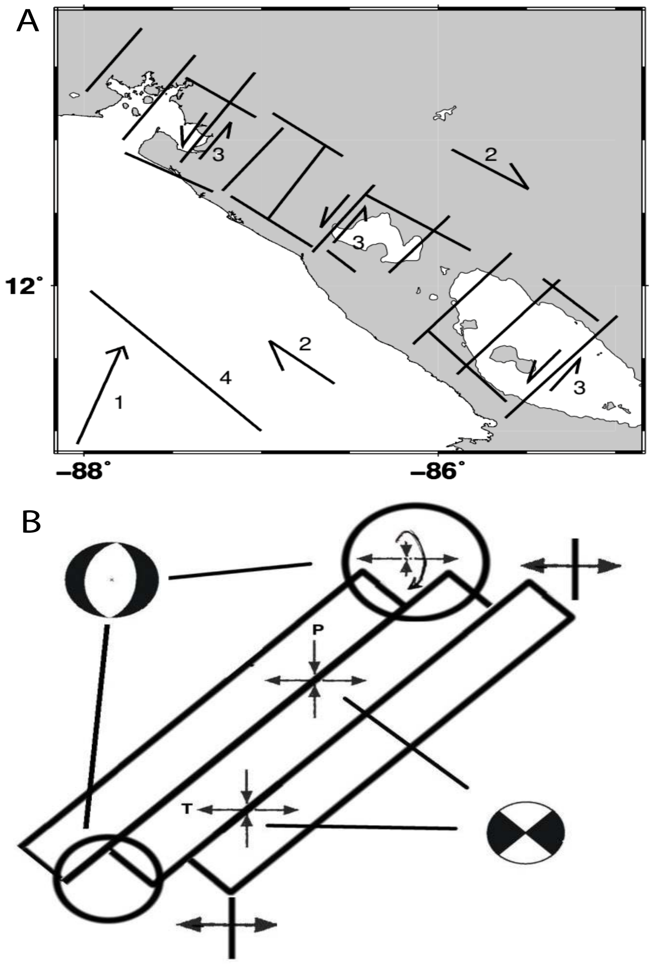

Figure 14: Reinterpretation of "bookshelf" model for Nicaragua. (a) Original representation of the bookshelf model. Inclined subduction (1) under plate boundary (4) causes a North western movement of forearc sliver (2) that forces the formation of a series of NE-SW trending faults with left-lateral strike slip (3) movement that delineate blocks that rotate (modified from [8]). By simplicity the left lateral movement is represented only in three faults. (b) Instead of blocks' rotation, in the extremes of the supposed "blocks" occurs a rotation of the compressive stresses that conduct to the occurrence of earthquakes with associated fault plane solution of normal kind, confirmed in the upper extremes by earthquakes held at El Sauce in 2015.

the borders of Nicaraguan Depression like the case of the asymmetric tectonic depression of El Sauce [47]. By developing this ideas, it can be started that faults of direction NE-SW with movement of the kind left lateral strike-slip are complemented at the borders of depression with faults of N-S direction that have normal character.

There are other evidences that support this hypothesis. For example, the case of a profile of E-W direction in the km 45.6 in the old road from Managua to León, in the outer border of the depression, where it is present a base of sandstones filled with shale diapirs in several positions along it (Figure 15) that could be explained by the existence of extensive stresses of E-W direction [61]. The scheme presented in Figure 14b shows the extreme situations, with two different seismotectonic regimes and a sharp transition, but in practice it doesn't occur, the transit from one to other regime logically should be gradual. In the case of faults should exist a zone where they smoothly rotate, and finally the presence of hybrid (normal - left lateral strike-slip) mechanisms talks about that the compressive stresses also rotate smoothly from horizontal to vertical direction as approaching to the depression borders. That is clearly seen in Managua faulting. It was pointed out with the occurrence of 1972 earthquake [55] the existence of a fault of NE-SW direction and left lateral strike-slip movement inside the lake. Nevertheless, getting out of the lake the main faults have a variable direction, from close to NE-SW in the lake shore to N-S as moving to the South (Figure 16). The research of these faults indicates the occurrence of vertical displacements. For example, in a technical trench that crosses Centroamérica fault about 6km from the shore (diamond labelled "P1" in Figure 16) there are places where vertical movements displaces several Pleistocene deposits (Figure 17a) [62] and in other place belonging to the fault system Zogaib-Escuela, about 6km from the shore also (diamond labelled "P2" in Figure 16) there are clear vertical displacements of early Holocene deposits (Figure 17b). They constitute additional evidence of N-S directed normal faulting at the outer limit of Nicaraguan Depression. In Managua occurred also an earthquake in 1968, but existing information do not include focal mechanism and coordinates are placed about 5 Km South of Managua 1972 earthquake (relocation of [55]), that only guaranties that it held close to outer border of depression.

In original model of [8] several blocks were proposed. It was a big one from La Paz Centro fault zone to Managua. But the activity in 2014-2016 evidenced that inside this block there were two additional faults of NE-SW direction. In the sector from La Paz Centro fault zone to La Pelona fault zone appeared 2 earthquakes with NE-SW fault

Figure 15: Evidences of normal faulting at the inner border of the depression. Photographies took in a profile of E-W direction in km 45.6 of old road to León. It is present a base of sandstones filled with shale diapirs. The fractures are oriented in N-S direction (photographies courtesy of Angelica Munoz).

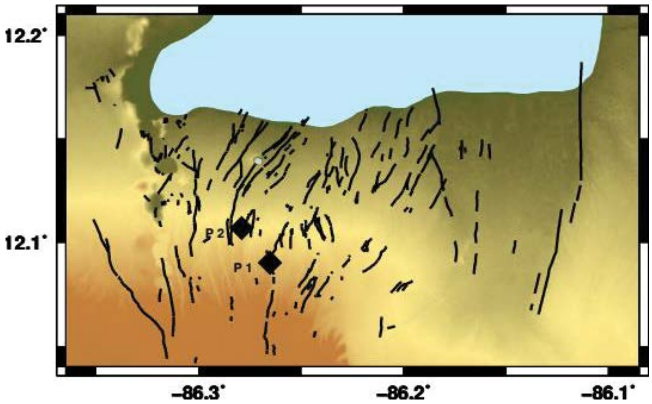

Figure 16: Map of main faults of Managua (modified from [12]), In solid lines there are represented actual faults, in dashed lines the supposed ones. Black diamonds with codes (P1, P2) in the map correspond to places.

Figure 17: Evidences of normal faulting of N-S direction in Managua. (a) Vertical displacements of 0.5 m amplitude in Pleistocene deposits measured in a technical trench that crosses Centroamérica fault (place marked with a star and "P1" in figure 16). (b) Vertical displacement of Holocene deposits in a place located in the fault system Zogaib-Escuela (place marked with a star and "P2" in figure 16) (photographies courtesy of Angélica Muñoz).

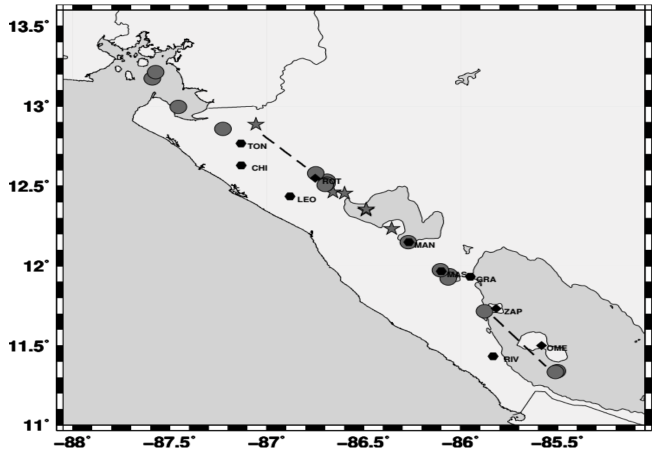

Figure 18: Location of all earthquakes with M ≥ 5 for which exist moment tensor or focal mechanism solutions. From CMT solutions we don't use the centroid but best hypocentral determination. Circles correspond to data from other authors and stars to the cases studied in this work. Discontinuous lines show the two major gaps and consequently where it is expected, with greater probability, the occurrence of earthquakes with $M_W \geq 6$ in the future. In shorter gaps should be expected earthquakes with magnitudes between 5 and 6. With hexagons are represented cities and with diamonds geographical features cited in the paper (CHI - Chinandega, GRA - Granada, LEO -León, MAN - Managua, MAS - Masaya, OME - Ometepe island, RIV - Rivas, ROT - Rota volcano, TON - Tonalá, ZAP - Zapatera island).

plane orientation over the proper fault zone. Finally in the NW, the earthquake of Puerto Morazán marked another fault inside one of their blocks. By the other hand, the series of earthquakes shown in Figure 13a,b suggest clustering of earthquakes along parallel NE-SW directed faults, placing more faults inside the "blocks". If we plot the relocated and better quality hypocentres of M ≥ 5 earthquakes from 1972 until 2016, they form a line with close points and some gaps (Figure 18). In this figure it is seen that activity of 2014-2016 (represented with stars) filled a gap from Managua to Rota Volcano. It is not difficult to imagine that in the future will occur earthquakes in places that are empty yet in (Figure 18). Then the "blocks" of the "bookshelf" model would be subdivided again. The conclusion is that no blocks, but quasi parallel faults exist filling all the Nicaraguan Depression.

Based on the discussed facts we can propose a new seismotectonic model for Nicaraguan Depression. The driven mechanism of the model, as in [8], is the inclined subduction of Cocos plates with respect to Cocos-Caribbean plate boundary that forces the forearc sliver to move approximately in NW direction [59]. This physical process creates a stress distribution with horizontal extensive stress of direction E-W all over the depression, while direction of compressive ones varies from vertical in the extremes of the depression to horizontal of N-S direction in the centre. No blocks are created. Instead of that it is formed a series of quasi-parallel faults that fill all the depression and accommodate the induced movement: normal at the outer depression border (in faults oriented N-S), left-lateral strike-slip in the centre (in faults oriented NE-SW) and again normal at the inner depression border (in faults oriented N-S). The transition between them is smooth, with hybrid (normal–strike-slip) best double couple MT solutions and curved faults (Figure 19).

The expected maximum magnitude of earthquakes can be estimated by several methods, both tectonic and seismological. Due to the lack of information about real faults (extension, width and displacements), we are limited to use only seismological data. The expected maximum magnitude for the different elements of the model was calculated from maximum observed earthquake magnitudes by adding some increment that normally should not exceed 0.5 units. Considering the available information, for strike-slips faults, where maximum observed is in

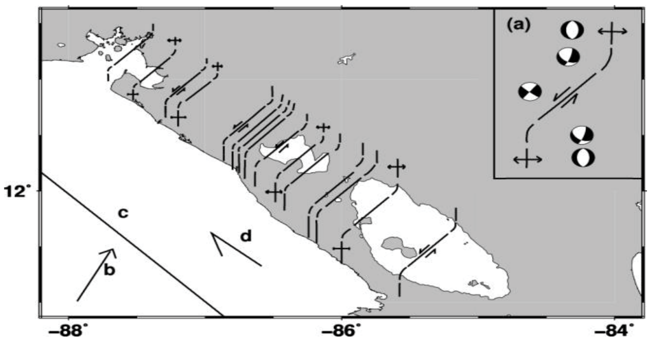

Figure 19: Proposed seismotectonic model. The Nicaraguan Depression is plenty of faults, whose characteristics are explained in (a): left lateral strike-slip NE-SW oriented in the centre, a rotating toward NS intermediate segments with a mix of strike-slip and normal behaviour, and segments of NS orientation with normal faulting at the extremes. There are shown only those faults associated with earthquakes held from 1972 (for better viewing, indications of movement are only shown in a few). The empty sectors in which no middle size earthquakes are reported since 1972, are expected to be the loci of those earthquakes in the next future. There are shown also the elements of the driven mechanism of the model: b - direction of the inclined subduction, c - plate boundary, d - relative movement of the forearc sliver. These elements create a stress distribution with horizontal extensive ones of direction E-W all over the depression, while direction of compressive ones varies from vertical in the extremes to horizontal of N-S direction in the centre. No blocks exist in the depression.

the range 6-6.3, a M_{max}=6.5 seem reasonable. In the case of depression borders we has short data, the El Sauce swarm (maximum M_W=4.8) and Managua earthquake of 1968 (m_b=4.3-4.6) we consider reasonable the estimation of M_{max}=5.5 for the inner border and M_{max}=5.0 for the outer border. These last estimations, perhaps somewhat high, should be revisited as new information will be acquired.

From the distribution of past earthquakes it can be made an estimation of more hazardous zones for the next future inside the Nicaraguan depression. The principle is simple. New medium size earthquakes are more probable to occur in places of the zones marked as gaps in Figure 18. There are two of such zones. The first case corresponds to the sector from Zapatera Island to East Ometepe Island that threats the cities of Rivas in first place and Granada in second place. The second case corresponds to the sector from Rota volcano to Tonalá city, that threats Chinandega and León cities. In this sector held some activity in 1955 [63] that could be associated to La Pelona fault zone [10]. The expected magnitude in both cases could be ≥ 6. With less level of hazard appear two sectors, one from Managua to Masaya cities and other from Granada city to Zapatera Island. They threat the cities of Managua, Masaya and Granada. Finally to the Northwest of Tonalá city there are other 2 sectors that could be activated also. In these sectors considering the recent stress liberation happened in near faults, the expected magnitude could be between 5 and 6. The position of lines in the figure 19 tried to be close to the loci of analysed earthquakes. The empty spaces are the possible location for future earthquakes. It should be remarked that what it is presented here is a scheme; the actual position of real faults should be determined by a detailed seismotectonic study including geophysical surveys. Maximum magnitudes should occur in strike-slip faults and should be always ≤ 6.5. In these faults more common bigger magnitudes would range between 5 and 6.

Conclusions

Based on the analysis of relocation of earthquakes in several clusters held in the period 2014-2016 and of moment tensor – fault plane solutions of medium size earthquakes held in 1972-2016, it is proposed a new seismotectonic model for Nicaraguan Depression. The new model refuses the block structure of Nicaraguan Depression proposed by other authors. Instead of that it considers that the depression is plenty of quasi parallel faults with normal faulting of N-S direction at its borders and left lateral strike-slip of NE-SW direction at its centre. The driven mechanism is the inclined subduction of Cocos plate under Caribbean one that makes the Central America forearc sliver to move toward Northwest. Maximum expected magnitudes would be 6.5 for strike-slip faults, 5.5 for inner border normal normal faults and 5 outer border normal faults. It is considered that in the next future there are two hazardous sectors in the Nicaraguan Depression, one from Zapatera to East Ometepe Island that threats Rivas and Granada cities and other from Rota volcano to Tonalá that threats Chinandega and León cities. Expected magnitude could be ≥ 6. Other less hazardous sectors were also identified with expected magnitude between 5 and 6.

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