SUBDUCTION GEOMETRY BENEATH THE DOMINICAN REPUBLIC AND AFTERSHOCK DISTRIBUTION OF THE 1946 NORTHEASTERN HISPANIOLA EARTHQUAKE BY HYPOCENTER RELOCATION

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ABSTRACT

This research proposes a new model of slab geometry beneath the Dominican Republic (DR), which faces the most significant seismic risk in the region, based on the relocation of earthquakes dating from 1964 to Aug. 2010, using the Modified Joint Hypocenter Determination (MJHD) method. Subduction thrust events represent the higher seismic risk for Hispaniola and the Septentrional (SFZ), Camu, and Enriquillo Plantain Garden (EPGFZ) faults show the seismic risk of strike slip earthquakes, where the SFZ represents the most imminent risk.

We found that the North American and Caribbean slabs converge beneath the central area of DR, between 69.9°W – 69.3°W. In our model we explain that the deeper area (69.1°W – 68.2°W) in southeastern Hispaniola belongs to the Caribbean slab as it evidences continuity of seismicity of Caribbean slab and as the available focal mechanisms of the down–dip extension type, while earthquakes deeper than 110 km belong to the subducting Atlantic slab in the previous model. The Wadati – Benioff zone in the southeastern part of the island of Hispaniola reaches around 180 km in depth.

We also found that the seismogenic slab on northwest of DR reaches until SFZ, while northeast extend beyond this limit. The Camu Fault was responsible for the 2003 Puerto Plata Earthquake (Mw 6.4), with multiples gaps around these two faults.

We also relocated the 1946 Northern Hispaniola Earthquake (Mw 7.9) and almost two years of aftershocks related with this mainshock. The area of the aftershocks distribution for 1946 Northern Hispaniola Earthquake was confirmed as being between 70.4°W – 68.4°W and 18.9°N – 20.0°N.

Keywords: MJHD, Relocation, Caribbean Slab, Hispaniola, Subduction.

1. INTRODUCTION

The island of Hispaniola is located in the North American–Caribbean plate boundary zone (NCPBZ) (Figure 1) and in its northeastern part begins the tectonic transition between the oblique subduction to east-west pure strike-slip motion along the Cayman Trough to the south of Cuba.

Oblique convergence between the Caribbean and North American plates is partitioned between thrusting along the North Hispaniola fault and strike slip faulting under the overriding plate along the left lateral Septentrional and Enriquillo faults systems. In the vicinity of Hispaniola, the North American and Caribbean plates have a 250 km wide zone of deformation (Dolan and Bowman, 2004). By GPS observation, Calais *et al*. (2002) estimated the relative velocity of NCPBZ at 6.3, 21.0,

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8.0 and 9.2 mm/year (red arrows in Figure 1) (NUVEL-1A, blue arrows, 11 mm/year), although the MORVEL model suggests, based on GPS observation, that the Caribbean–North American motion are twice as fast as given by NUVEL-1A (DeMets *et al.*, 2010).

Seismicity is related primarily to subduction around the DR and internal faults that have. In the west part, the seismicity is shallow (less than 55 km), not very active, which is probably caused by the lack of seismometers in the local network that can record small earthquakes. The Septentrional Fault Zone (SFZ) has produced over 8 earthquakes with magnitudes (Mw) between 6.4 and 7.9 in this location in the last 100 years, being the last 2003 Puerto Plata Earthquake (Mw 6.4).

Our purpose is to clarify the seismicity of the Hispaniola (Areas 1 and 2 in Figure 1), using the Modified Joint Hypocenter Determination (MJHD) method, developed by Hurukawa and Imoto (1990, 1992), which is used to relocate all hypocenters in an area simultaneously. We have interest in proposing a new model or confirming the seismotectonic geometry beneath DR, find gap zones of large earthquakes, as the greater frequency of medium and large earthquakes in the last 100 years in the Caribbean zone is concentrated close to the SFZ. We also find the aftershock distribution of the 1946 Northeastern Hispaniola Earthquake (Mw 7.9) as the largest event in this zone in instrumental time.

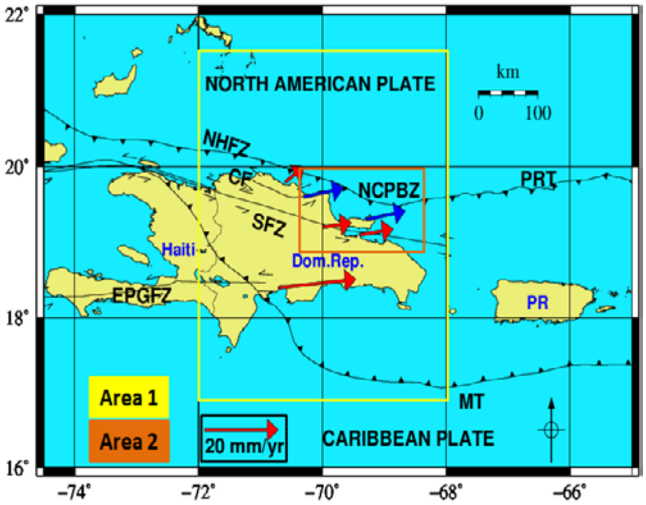

Figure 1. Active tectonic faults around Hispaniola, the squares show the target Areas 1 and 2 in this study. The red and blue arrows (calculated by NUVEL-1A) indicate the relative velocity of DR (Caribbean Plate) relative to North American Plate (fixed). The active faults are: CF, Camu fault, EPGFZ, Enriquillo Plantain Garden Fault Zone, MT, Muertos Trough, NHFZ, North Hispaniola Fault Zone, PRT, Puerto Rico Trench, and SFZ, Septentrional Fault Zone. NCPBZ, represent the North American Caribbean Plate Boundary Zone. Country names in blue. Sources: Bird (2003) for subduction zone, Bakun *et al.* (2012) for strike slip zone, Calais *et al.* (2002) for GPS data.

2. DATA

For this study, earthquakes from the catalogs of the International Seismological Summary (ISS), International Seismological Centre (ISC) and United States Geological Survey (USGS) were relocated, for earthquakes occurring between 1946 and 1948, 1964 and 2008 and 2009 and Aug. 2010, respectively. The hypocenters were located in an area bounded by 17˚N to 21.5˚N and 72˚W to 68˚W, as shown in Figure 1.

1) For observation of temporal change and the geometry structure for the subduction beneath the DR, the period from 1964 until August 2010 was investigated, as this is the total span of the database used (more than 2,000 earthquakes).
2) For aftershock distribution of the 1946 Northeastern Hispaniola earthquake (Mw 7.9) and relative hypocenter location, data from less than two years after the main event was used. The reason is that significant foreshocks for this event were not observed (68 events).

All hypocenters registered in these areas were used without distinction between magnitudes. Phase data of P wave arrival times were used.

3. METHODOLOGY

MJHD method, developed by Hurukawa and Imoto (1990, 1992) was chosen as it provides more stability than other methods such as the Joint Hypocenter Determination (JHD) method, from Douglas (1967) and Freedman (1967) who had generalized the Geiger's method (Geiger, 1912) to calculate the hypocenters of a group of earthquakes and station corrections simultaneously. Station correction parameter removes the effect of lateral heterogeneity on the earth and reflects a travel time difference between the assumed velocity structure and the actual one.

When the media is overly heterogeneous and station coverage is poor, the method explained above is unstable and unreliable because of the significant trade-off between station corrections and focal depths of earthquakes. For this reason Hurukawa and Imoto (1990, 1992) developed the MJHD method for local earthquakes and Hurukawa (1995) for teleseismic earthquakes, which is an improvement of the JHD method using constraints that station correction is independent of both the distance and azimuth from the center of the region in question to the station. Although these constrain sacrifice absolute hypocenter, this makes the JHD method stable.

4. RESULTS AND DISCUSSION

4.1 Subduction Geometry beneath the Dominican Republic

To understand the geometry of Atlantic and Caribbean slabs beneath the DR we take hypocenter distribution in Area 1, from 1964 to Aug. 2010. We were able to relocate 276 earthquakes precisely with the following conditions. Each earthquake was recorded at least by 20 stations and each station registered at least 20 earthquakes. We used phase data with travel time residuals (O-C) $\leq$ 1.5 sec. The stations are shown in Figure 2.

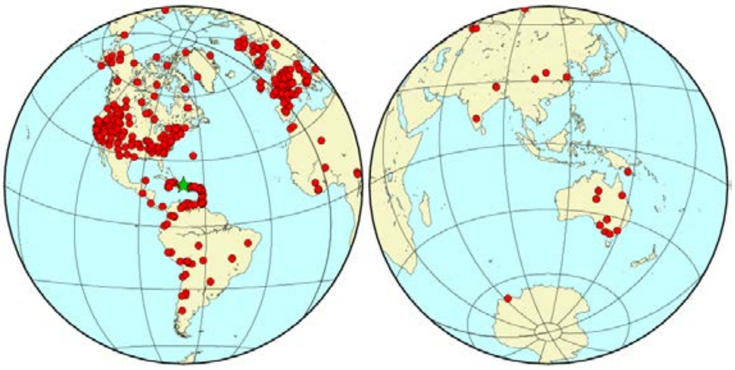

Figure 2. The 422 worldwide stations used for relocation in this study are shown. The green star shows the studied area.

Figure 3 shows the relocated epicenter distribution and cross - sections. Cross–sections A–B and C–D are with orientation of S18˚W to N18˚E and W18˚N to E18˚S, respectively, which are perpendicular and parallel to the subduction structures around DR and the SFZ. During the process of the relocation we observed that all hypocenters fit to a depth less than 180 km, when in the beginning some earthquakes had depths up to 300 km, even if the earthquakes poorly cover the trend to look deep but when the coverage was good and the teleseismic stations were used these offered more stability as fixing simultaneously for all stations that registered these events. So, we can conclude that the Wadati–Benioff zone is around 180 km on southeastern Hispaniola.

The Muertos Trough makes contact with EPGFZ, after that, it becomes the Peralta Belt. Intermediate and deeper events are absent and no high seismicity was registered. On northeastern Hispaniola where the 1946 North Hispaniola earthquake (Mw 7.9) occurred, seismicity is very low probably as the energy release by the event and currently energy can be concentrated for the next large earthquake in the zone.

In the cross section A-B, the right side represents the Atlantic slab and shows two very well delimitated concentrations, the shallow one is related to the Camu fault, which caused the 2003 Puerto Plata Earthquake (Mw 6.4) and extends to a depth of around 30 km. The second concentration is related to the SFZ and extends approximately 60 km, it is clear to see that this fault has a gap of 20 km at the shallow part. The thickness of seismic slab in left side of the cross section A-B is 25 km at the deepest part (Caribbean Plate).

We divide the area into four sub-regions; each sub-region shows the global CMT solutions available in this area (Figure 4).

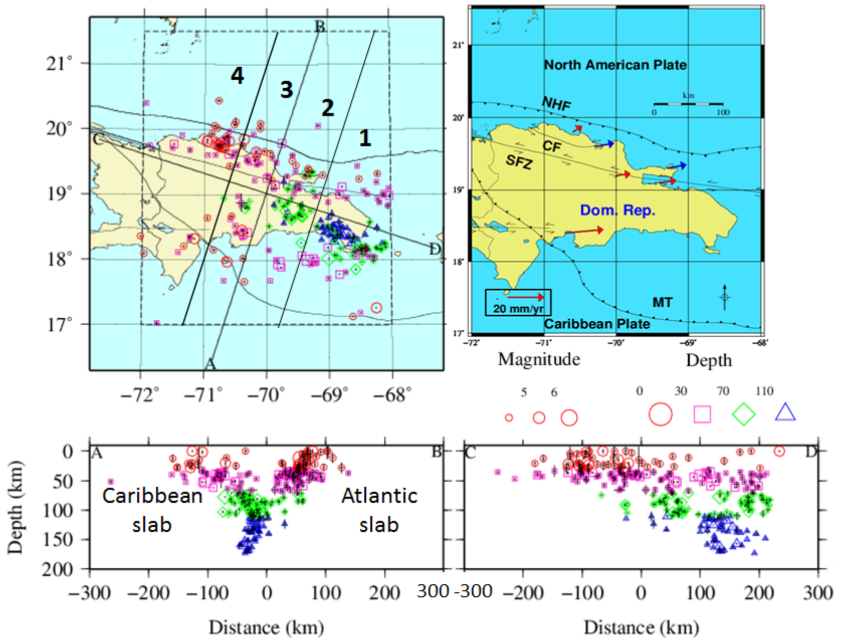

Figure 3. Hypocenter distribution of relocated events, 1964–2010. The dotted line represents the original area of the hypocenter distribution. CF, Camu Fault, NHF, North Hispaniola Fault. 1, 2, 3 and 4 indicate four sub regions, of which cross sections are shown in Figure 4. The size of each symbol is proportional to the magnitude of the earthquake, as shown in the figure legend. Bars represent the standard errors of hypocenter.

Sub-region 1 shows the continuation of the seismogenic slab of the Caribbean SSW to NNE, in the B side between 60 km and 110 km where only two events appears. These events are located in the border of the sub-region, so in the center of the cross section the full gap still continues in this range of depth.

CMT solutions show low angle thrust along the plate boundary shallower than 50 km and down-dip extension deeper than 70 km. This indicates the continuation of the Caribbean slab and the evolution of the gradual change of the slab direction, in this side the seismogenic slab shows a line of events with focal mechanisms opposite to the main slab. We interpreted this result as internal events in the slab due to the bending of the slab in this range of depth.

Sub-region 2 shows the Atlantic slab continuation NNE to SSW, the convergence area is shown in this sub region, the contact area extends from the west around 60 km eastward of about 110 km in depth. Where the Atlantic slab is above the Caribbean slab and it is clear the gap on the left side in the shallow part with a depth of around 30 km; on the right are two lines of events, on the left is the SFZ and the right is a Northeast Hispaniola Slope Fault Zone (NEHSFZ) possibly continuation of the Camu Fault.

In sub-region 3 we can observe the Camu Fault and SFZ well demarcated on the right side, in this side the gap in the shallow zone of the SFZ is notorious, and the left side shows a large gap zone that includes the sub regions 2 and 3. Here, it is clearer how the contact zone of the Atlantic slab in the NCPBZ starts to change from subduction to strike slip westward, both plates are shallow. The CMT solutions show the same behavior as that of sub-region 2 and both slabs start to look shallower. It is obvious the separation between slabs and look clear the Camu Fault and SFZ concentrations.

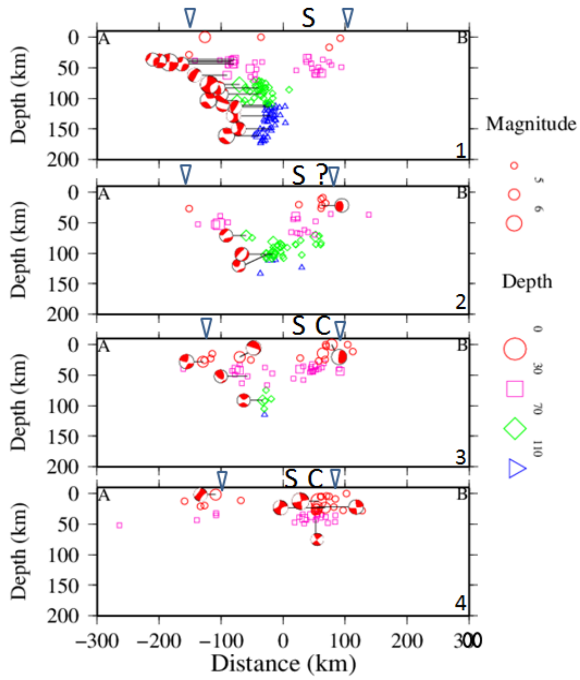

Figure 4. Cross sections defined in Figure 3. A and B represent the Caribbean and Atlantic slabs sides, respectively. Global CMT solutions are also shown. Opposite triangles are the limits of the trench. S, Septentrional Fault; C, Camu Fault. ?, Northeast Hispaniola Slope Fault Zone.

Sub region 4 includes the hypocenter of 2003 Puerto Plata Earthquake (Mw 6.4); this is the last of the series of moderate to great events propagating westward from 1946 to the present. Since these earthquakes do not cross the SFZ, we cannot interpret if the subduction continues more deep than 60 km in this zone. Only shallow events are recorded in this area (less than 50 km).

4.2 New Model of the Caribbean and Atlantic slabs Beneath DR

For a clear comprehension of this geometry, Figure 5 shows the conceptual drawing of seismogenic slabs between both plates relating the 4 sub-regions. Space between slabs represents the gaps observed in this study which are absent of seismicity. The Caribbean slab had a perpendicular extension relative to the contact area, indicating that the eastern part becomes deeper, opposite to the western part that is kept shallow. The important features of this schematic figure are that the SE part of Hispaniola extends around 180 km in depth and belongs to the Caribbean Plate. The converge area between Caribbean and Atlantic slabs is located beneath the central part of DR, between 69.9˚W – 69.3˚W, up to 110 km in depth. Other feature is that in the NW part of DR, the subduction from the Atlantic slab does not cross the SFZ, possibly for the transition between subduction to strike slip of this slab in this area.

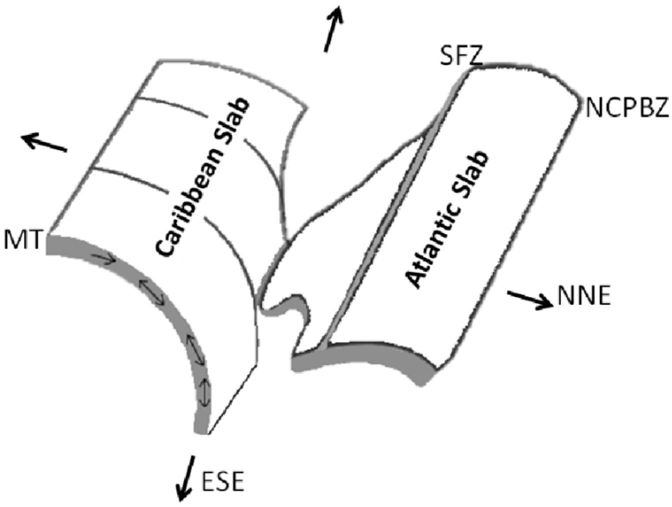

Figure 5. Schematic figure of geometry structure of the subduction zone beneath DR. This construction is made from the seismicity observed during the period under study. Note that the Caribbean slab does not move below the Atlantic slab (North American Plate).

Although the intermediate part of the slab cannot be clear with the interpretation of the bending of the seismogenic slab, as the double seismic layers or continuation from Atlantic slab with a gap in the center part on sub-region 1, the sub-region 2 can clear this point with two focal mechanisms available in the contact area when the T axis, down-dip extension is conclusive.

4.3 1946 Hispaniola Earthquake

Sixty eight events in Area 2 (Figure 1) were taken from ISS; the locations of these events are adjusted for the epicenter area of the three largest events in this period, the main event of Aug. 4, 1946 (Mw 7.9), strong aftershock of Aug. 8, 1946 (Mw 7.3) and April 21, 1948 (Mw 7.0). In this relocation we prefer high accuracy instead of the number of events, so, we used minimum number of stations (MNST), 10, and minimum number of events (MNEQ), 10. Total number of stations used was 50. Travel times residuals (O-C) $\leq$ 2 sec were used for all cases. Then, we relocated 28 events accurately using all available readings.

Most aftershocks are less than 60 km in depth; this is precisely the depth value corresponding to SFZ. The aftershock area of our relocation is almost the same as Russo and Villaseñor (1995).

Because of the long time of the aftershocks period, could be that near events, but not related to the main shock, happened, these events are included in the list and possibly related to the background seismicity.

The deeper area has less than 110 km and matches with the contact area explained by our model. Limit of 110 km is consistent with the contact area of sub-region 2 of this study, where most aftershocks are concentrated.

After the sequence of 1946-1953 on NE Hispaniola, events with M > 6 did not occur, indicating a concentration of stress in this zone and following the Coulomb stress modeling for this sequence by Dolan and Bowman (2004), our model is consistent.

5. CONCLUSIONS

In order to identify the slab geometry beneath DR, we relocated earthquakes during 1964 and Aug. 2010 by using the Modified Joint Hypocenter Determination (MJHD) method. We found that the Wadati – Benioff zone in the southeastern part of Hispaniola reached to around 180 km in depth.

We proposed a new model of subducting slabs beneath DR with three important features. Firstly, we found that the North American and Caribbean slabs converge beneath the central part of DR, where a contact area of around 110 km in depth. Secondly, the deeper area in southeastern Hispaniola belongs to the Caribbean slab and extends around 180 km in depth, although the previous model by Dolan and Wald (1998) regarded that deeper earthquakes occurred inside the North American slab. Our model is consistent with both, seismicity and focal mechanisms data available for this area. Seismic behavior around DR certainly changed after the 1946 Hispaniola Earthquake and indicated the concentrations of stress in this zone.

Thirdly, northwest of DR slab reaches until SFZ, while northeastern of DR extend beyond this limit. The Camu fault was responsible for the 2003 Puerto Plata Earthquake, and therefore, poses a continuing risk to Hispaniola. In shallow areas the SFZ has important gaps that represent the most imminent risk to Hispaniola. Further studies are necessary such as tomographic model in order to confirm our model.

6. RECOMMENDATION

The seismogenic geometry beneath DR is a new model that we were proposing, so, we recommend that further study should be conducted to enrich this result and continue shedding light on the Caribbean tectonics. Examples of these studies are seismic tomography, focal mechanism determination for small earthquakes, etc.

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