Chapter

GNSS Networks for Geodynamics in the Caribbean, Northwestern South America, and Central America

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Abstract

For several years, under the framework of national and international projects, the number of GNSS geodetic stations has been increasing in countries located in the area comprised by the Caribbean, northwestern South America and Central America. Data from these geodetic stations have made it possible not only to meet the needs for geospatial information in each of the countries, but also to get a better understanding about the geodynamic interaction of the Caribbean, South American, Nazca and Cocos plates, as well as tectonic blocks wedged in between these plates. This article presents a brief description of the tectonic framework, the existing geodetic networks and the results obtained using data from some stations in the study area.

Keywords: GNSS, Plate tectonics, North Andean Block, Caribbean region, South America plate

1. Introduction

Tectonic and volcanic activities are intimately related to the interaction of different lithospheric plates and crustal blocks. In the study region of this paper, the tectonics and volcanic activity are directly related to the interaction of the Caribbean, South America, Nazca and Cocos plates, with the smaller North Andean, Maracaibo, Choco and Panama blocks wedged in between, as has been pointed out by various authors [1–13]. This highly complex tectono-dynamic configuration of intense intraplate deformation is manifested in a high density of faults, most of which are considered active or potentially active over northwestern South America and southeastern Central America. In addition, seismicity is spread over a broad area across the wide plate boundary in northwestern South America, Central America, and southwestern Caribbean. Also, several countries in this region present intense volcanic activity, such as Guatemala, Nicaragua, Costa Rica, Colombia and Ecuador, as well as on many of the islands of the Lesser Antilles.

There is no doubt that space geodesy has contributed significantly to the study of the kinematics of the Earth's crust, allowing to improve the understanding of the tectonics complexity at a global, regional and local level. The analysis and comprehension of the Earth's crust strain in several places of the world, with a variety of different characteristics and tectonic styles, has gradually been supported by the results obtained from the geodetic networks, initially composed of field stations of data gathering under episodic campaigns type, and later by continuously operating reference stations (cGPS). Several authors have pointed out the extensive applications of space geodesy for scientific purposes, e.g. [14–16], among others. In the study area, despite the restrictions due to the limited coverage of the national GNSS/GPS networks, its impact is already being observed in studies of the Earth dynamics. The data from the stations have allowed the generation of high precision products such as geodetic time series, velocity fields and estimation of tectonic plate motion rates, seismic cycle analysis, estimation of the magnitude and spatial variability of the plate coupling, among other aspects. In addition to tectonic studies, its use has been extended to the volcano deformation monitoring in several countries (Colombia, Costa Rica, Ecuador, Nicaragua), subsidence studies; the use of data for ionosphere and troposphere studies as well as its inclusion, still in its initial state, in tsunami warning systems. Progress has also been made in the conception of multiparameter stations, based on the joint installation in the same site of diverse equipment such as geodetic, seismological, strong motion and meteorological instruments, among others. It is also important to note that there is a good data availability, although not from all stations due to particular restrictions, that allows its use for various scientific purposes. However, in some cases, through agreements or by formal request of data to national institutions, these can be obtained.

2. Tectonic setting

Gathering of geologic, tectonic, seismologic and geodetic data through the last decades has led to a better understanding of the Caribbean plate, its margins and adjacent regions, progressively bringing in more complexity to the once drawn "drawer-like" Caribbean plate model [17]. In fact, the Caribbean plate borders are actually "plate boundary zones", PBZ, in the sense of [18], "wide deformation zones" in the sense of [19], particularly transpressional along the southern Caribbean PBZ, or "wide plate margins" in the sense of [10]. These margins amalgamate tectonic blocks of diverse size, composition, origin and geometry (**Figure 1**), somehow surrounding the Caribbean Sea, cored by the Caribbean Large Igneous Province (CLIP) or plateau.

The recognition of such tectonic blocks started first along the southern Caribbean margin and northwestern South America corner, because being poorly defined by a disperse infrequent and moderate-in-magnitude (instrumental) seismicity, as well as by a poor surface/sea-bottom expression of the active tectonic features in comparison with the other Caribbean PBZs (**Figure 2**).

The study of this very complex but subtly expressed southern PBZ was enhanced by the fact that a large portion of the features are on land (**Figure 1**). Conversely, the northern Caribbean plate boundary became a natural laboratory for numerous space geodesy studies due to its apparent structural simplicity, although the first of all GPS studies worldwide, GPS CASA (Central And South America) Project was carried out in the complex southern Caribbean PBZ between 1988 and 1998 [10, 20]. Not as expected, GPS networks have not fully resolved the posed kinematic questions along this northern Caribbean PBZ, since the networks are mostly installed in rather small islands that are within the plate margin themselves that also resulted to be a complex PBZ with several active features lying offshore (**Figure 3**). As a matter of fact, the larger islands, such as Jamaica and Hispaniola, exist as a proof of such PBZ compressional or transpressional processes. A similar situation happens along the eastern border of the Caribbean plate, where the Atlantic plate subducts beneath an arc of active volcanic islands sitting on the

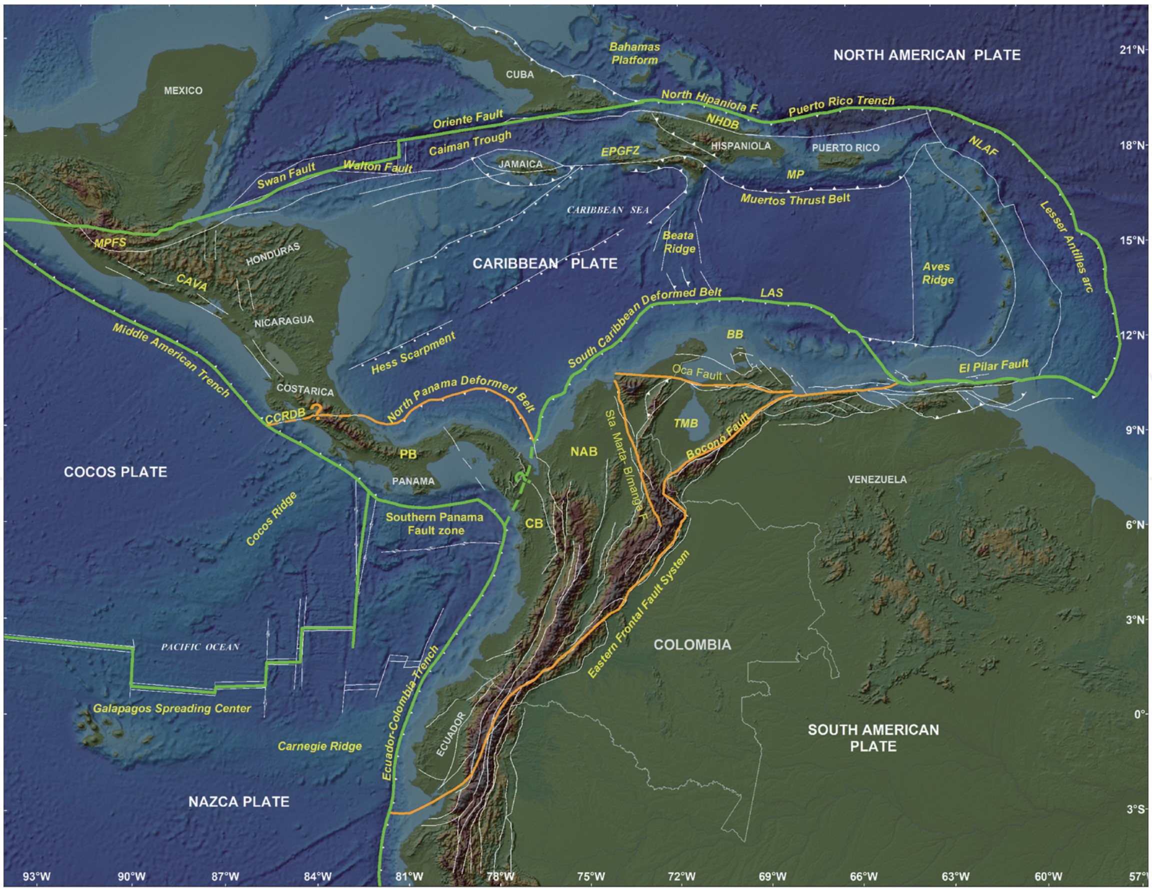

Figure 1.
Tectonic frame. Tectonic blocks: PB (Panama B.), CB (Chocó B.), NAB (North Andean B.), TMB (Triangular Maracaibo B.), BB (Bonaire B.). Other features: CAVA (Central America Volcanic Arc); CCRDB (Central Costa Rica Deformed Belt), EPGFZ (Enriquillo-Plantain Garden Fault Zone), LAS (Leeward Antilles Subduction), MP (Mona Passage), MPFS (Motagua-Polochic Fault System), NHDB (North Hispaniola Deformed Belt), NLAF (Northern Lesser Antilles Forearc). Modified from [13].

Caribbean plate. Stable GPS stations inside the Caribbean, such as on San Andrés and Providencia islands and Serranilla Cay (Colombia), and Aves Island (Venezuela), will provide a reliable answer as to the relative motion between the Caribbean and surrounding plates. In addition, longer time span comparisons between these internal sites to the plate should confirm any internal deformation or fragmentation of the Caribbean plate itself, as proposed by [13].

Besides, strain partitioning at different scales is common to the four Caribbean plate PBZs (**Figure 1**). In Central America, a coastal sliver, bounded by the Central America trench on the southwest and the active Central America volcanic arc (CAVA) on the northeast, escapes to the north-west (NW), taking advantage of the weakening of the continental crust by the CAVA volcanic activity [21–24]. A similar situation is reported in the northern Lesser Antilles arc, where the forearc in this region, limited by the active arc on the west-southwest (WSW) and the Atlantic trench on the north-northeast (ENE), moves northward with respect to the arc [25, 26]. Along the northern Caribbean PBZ, the northernmost sliver of the Hispaniola Island, bounded by North Hispaniola and Septentrional faults on the north and south respectively, displaces west faster than most of the island. In the southern Caribbean PBZ, the Bonaire block as well as the block containing the Caribbean nappes overriden onto South America along northern Venezuela (outcropping in the Coastal and Interior ranges), accommodate shortening while slipping dextrally along the large west–east (W-E) trending Oca-Ancón, San Sebastián and El Pilar fault system (**Figure 1**).

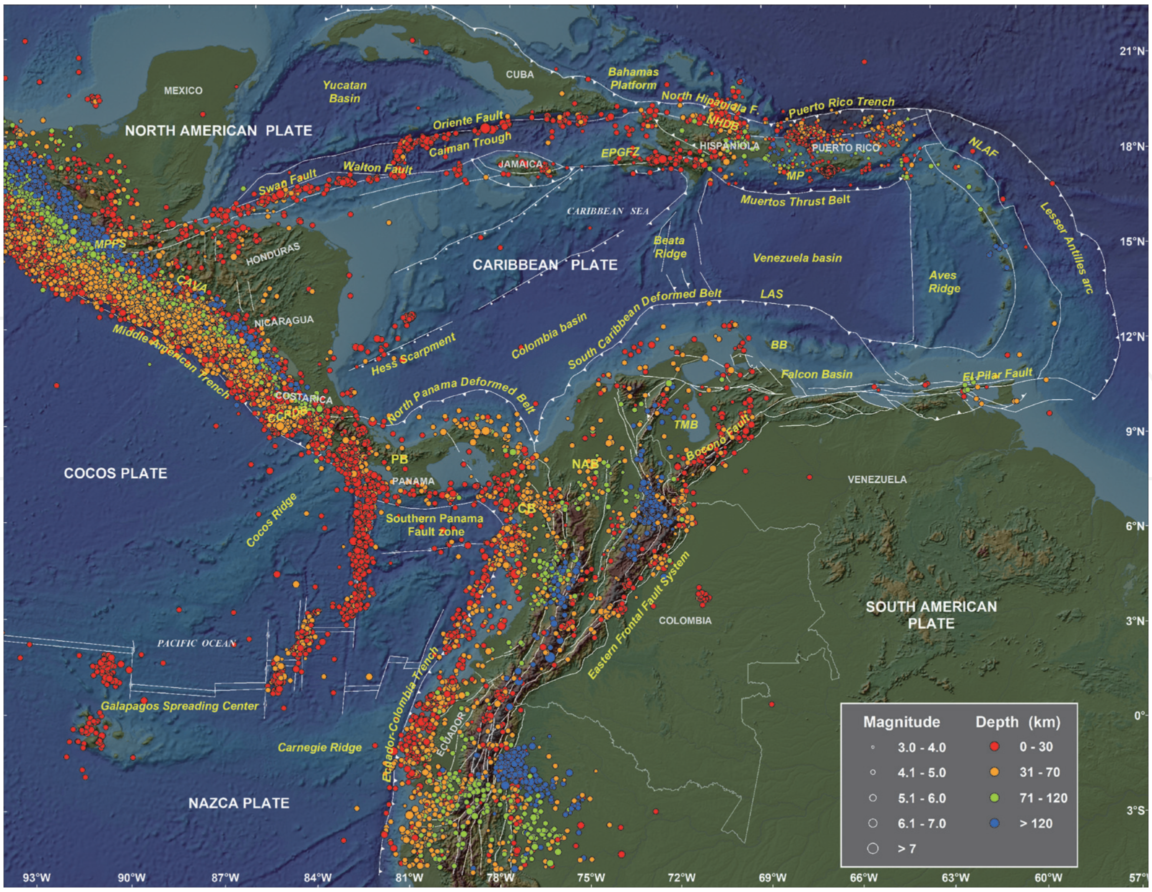

Figure 2.

Seismicity. Earthquake epicenters larger than 3 of magnitude recorded in the study area by the National Earthquake Information Center (NEIC) of the USGS and the National Seismic Network operated by the Geological Survey of Colombia for the period of time 2000–2020.

In addition, block indentation and extrusion, and occasional induced oceanic subduction processes at the opposite side of indenters, are also present and rather common to the Caribbean PBZs. Indentation (collision) by submarine relieves or ridges (e.g. Carnegie and Cocos), as engine of tectonic block escape, has been invoked along the Pacific border of South America against the Nazca plate, as for the Pacific coastal sliver of Central America extending between Costa Rica and Guatemala, respectively. In other cases, such strain partitioning has been attributed to the oblique convergence of the subducting plate beneath the overriding one, such as along the northern sector of the Lesser Antilles arc and northernmost block of Hispaniola Island. So has the Ecuadorian-Colombian trench at the southern tip of the North Andes Block –NAB- [27], in the sense of [3]. However, the best regional example of indentation-extrusion is the collision and latter northward-prograding suturing of the Chocó block (originally a constitutive piece of the Cenozoic Panamá arc) against the north–south trending western coast of South America. Some authors as early as early 90's, e.g. [28–30], propose that such collision and diachronic suturing process induces the NNE-directed tectonic escape of a large portion of northwestern South America, extending from the Guayaquil Gulf-Tumbes basin –GGTB- in SW Ecuador to the Dutch Leeward Antilles (Aruba, Bonaire, Curaçao islands lying north of Venezuela, in the southern Caribbean), and incorporating most of Ecuador territory, the 3 main mountain chains (Western, Central and Eastern) of Colombia and all western mountainous Venezuela. This escape takes place along a major plate boundary named as the Eastern Frontal Fault System –EFFS- by [3]. Much precision has been gathered through the years as to the geometry of that NAB southeastern boundary (e.g., [31–35], among many others). This tectonic escape is probably young in age, starting in the late Miocene

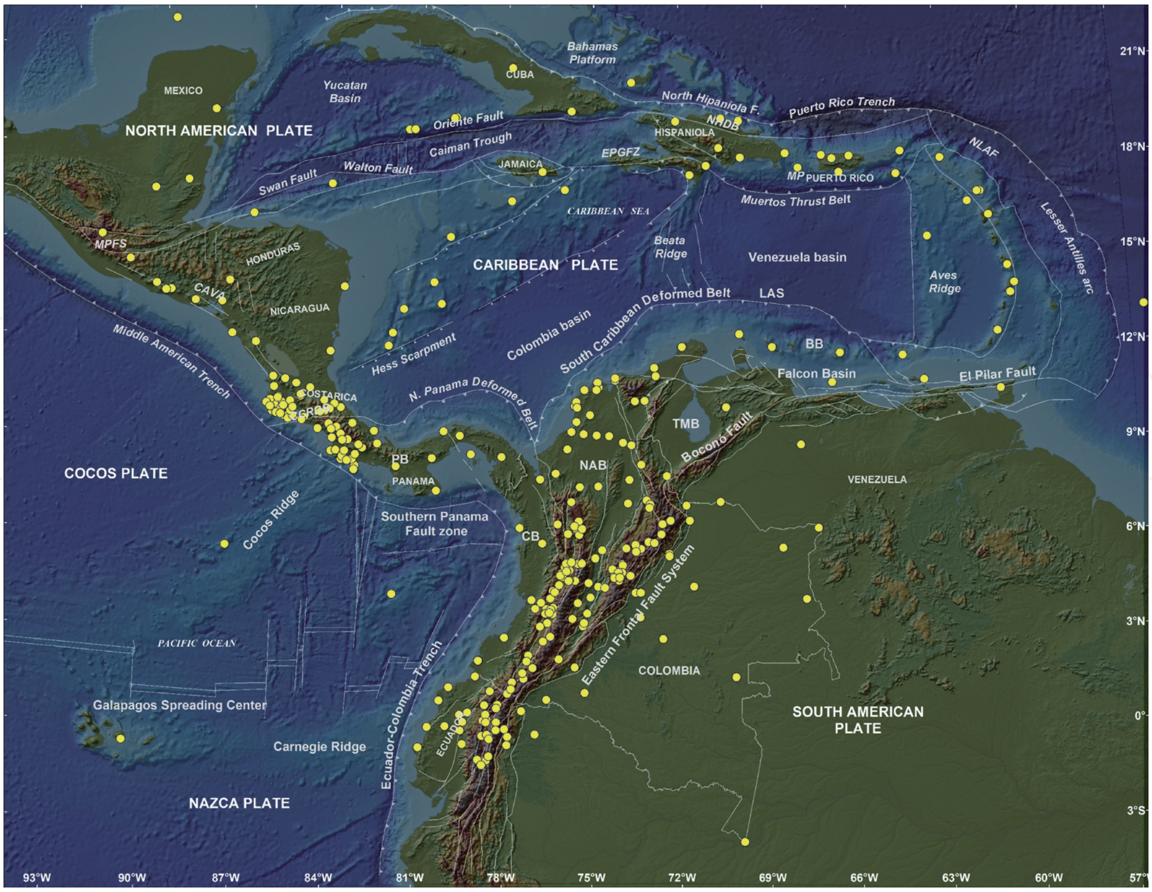

Figure 3.
cGPS stations located on the study zone. ***Table 1*** *lists the cGPS stations by country.*

(e.g., [12, 36]), with a tectonic paroxysm in the Pliocene (last 5–3 Ma, [21]), when most of the Eastern Cordillera of Colombia [37] and Mérida Andes of Venezuela [12] have actually started elevating to their present heights. A significant fraction of the time delay for the effective coupling (suturing) of the Chocó block against South America, besides the obliquity between the confronting plates, may be explained by the low rigidity exhibited by the Panamá arc at the latitudes of Panamá, which is intensely deformed internally by oroclinal bending and NW-SE trending en-echelon left-lateral faulting (e.g. [13, 24, 38]). The effective collision/accretion of the Chocó block drives the extrusion of NAB (in the sense of [3]), which in the sense of [39] already comprises several NE-escaping blocks, such as Chocó, Maracaibo and Bonaire and others; NAB for this author was already an amalgamation of tectonic blocks. The subduction along which Caribbean plateau floor disappeared into the mantle and drove this indentation-extrusion process, is today partly fossilized between the Chocó block and South America, in association with or running near to the Romeral fault system. This collision has surface expression down to latitude 4°N in Colombia, up to an ENE-WSW-trending alignment of surface tectonic features running across the three Colombian chains at the latitude of Santa Fé de Bogotá, such as Garrapatas, Río Verde and Ibagué faults, and the change of structural style of the front of the Llanos foothills of the Eastern Cordillera, where a dominant dextral strike-slip style on the south (e.g. Algeciras fault) shifts to a much more compressional style on the north (e.g. Guaicáramo, Cusiana and Yopal faults. [39]). Also, the latter author underlines that the Eastern Cordillera becomes much wider across, north of this imaginary line. [40] proposes a broken indenter model for the Panamá-Chocó arc, in which the Chocó arc has been recently accreted to the NAB, resulting in a rapid decrease in shortening in the Eastern Cordillera. At depth, such a change of structural style roughly coincides with the Caldas tear, as described by [41]. In fact, it is not a plate tear but the confrontation of two different oceanic slabs [13]. On the north, the oceanic-plateau-affinity Caribbean plate sinks to the ESE, as a flat slab lying under the Triangular Maracaibo block and Mérida Andes and reaching depths of almost 700 km further east. This subducted piece of Caribbean plate was the one carrying the Panamá arc on its trailing edge and its consumption into the mantle conducted to the collision of the Panamá arc against South America. Meanwhile on the south, the Nazca plate which is a typical oceanic plate at these latitude, subducts under western South America. [42] propose that buoyant Caribbean crust has been amagmatically subducting under the North Andes for 75 Ma.

Finally, the Caribbean plate itself can be considered as a single unit, at least at the current resolution level of the GPS results in the order of 2–3 mm/a [43]. However, the Hess escarpment is seismically active towards its southwestern end [13] and is moving left-laterally in that order of magnitude. In addition, this major submarine tectonic feature juxtaposes two very different Caribbean entities at naked eye. And it lies in the southern prolongation of an imaginary northeast-southwest (NE–SW) striking line passing over the southern tip of the Bahamas platform, where transpression north of it is dominant, building up the Island of Hispaniola. This author proposes that such accident may have played a major role in the faster eastward migration of the Southern Caribbean, the one carrying the LIP or oceanic plateau, in the late and middle Miocene. This author further indicates that a modern reactivation could be starting in the recent geologic time, also with dominant sinistral and subordinate normal components, but this time related to the push of the floating Cocos ridge when being subducted.

3. Regional and national geodetic networks

In the study area, it is observed that the number of installed cGPS stations has gradually increased, some of them as part of global networks as well as international networks as a benefic consequence of catastrophic natural events, and others that correspond to different countries to meet the needs of geospatial information and definition of national reference frames in some countries, as well as to carry out studies with various purposes such as tectonic, volcanic, subsidence, among others. cGPS stations established in North America, Central America and the Caribbean are described by [44]. For this paper, a survey of the cGPS stations currently in operation is made, including those of some national networks, which allows establishing that there are about 307 stations with data availability; the location of these stations is displayed in **Figure 3**. Twelve of the stations are part of the International GNSS Service (IGS) global network, installed in 10 countries, three of them in Ecuador.

On January 12, 2010, a magnitude 7.0 earthquake struck Haiti, causing more than 316,000 people dead or missing, 300,000 injured and more than 1.3 million homeless [45]. Due to this disaster, with the purpose of advancing in the knowledge of the geodynamics of the Caribbean plate and strengthening national and regional capacities for the hazards identification and risk mitigation of geophysical and meteorological origin, the National Science Foundation (NSF) of USA sponsored the establishment of the Continuously Operating Caribbean GPS Observational Network (COCONet) project, operated by UNAVCO, conceived as the appropriate strategy to complement existing national geodetic networks [46]. The COCONet network reached a number of 135 stations, incorporating stations owned by several national networks. **Figure 3** shows the location of 54 of these stations corresponding to 22 countries. We have only used these stations in order to have a wide spatial coverage, and because some stations have experienced problems in their operation, limiting the continuous availability of data.

In Colombia, the Geological Survey began in 2007 the development of GeoRED, a research and development project based on space geodesy technology that relied on a multifaceted approach to cataloging and defining the geodynamics of northwestern South America [47]. GeoRED is a Spanish acronym for *Geodesia: Red de Estudios de Deformación*. The general purpose of the GeoRED Project is to improve the technical, scientific and operational capabilities in Colombia for analysis, interpretation and policy formulation regarding phenomena related to crustal deformation in Colombia, using GNSS satellite technology. The GNSS GeoRED project is being executed under the operations framework of the Space Geodesy Research Group-SGRG of the Geohazards Directorate [48]. The current cGPS network has 153 stations installed as December 2020. Among these stations, 117 are GeoRED stations, 5 GNSS stations as part of the COCONet Project, and the Bogotá IGS GNSS station. Under a collaborative partnership with local Colombian institutions, thirteen stations have been installed with the Geographical Institute under a joint initiative named GNSS Colombia; eight with the Sugar Cane Research Institute (CENICAÑA); seven with the Bogota City Water Supply Company; and two stations installed with the Universidad Nacional and the Universidad Distrital, respectively. These stations have been fixed to the ground, following mainly UNAVCO's directions for the installation of permanent stations for the study of crustal deformation. Additionally, the Geological Survey of Colombia –GSC- has deployed another geodetic network composed of 70 permanent stations installed in three volcanic regions for the surveillance of the active volcanoes of the country, where the monitoring is carried out from three volcanological and seismological observatories.

In Ecuador, The Geophysical Institute of the National Polytechnical School of Quito began installing in 2006 a network of GPS stations on the edifices of the most active volcanoes in the country. At the end of 2008, it started to implement a country-wide CGPS network of 70 stations [49]. At present, RENGEO (Spanish acronym for *Red Nacional de Geodesia*) is a geodetic network composed of 85 permanent stations, of which 30 are located in potentially active volcanoes [50]. The GPS receivers acquire data at different data tracking intervals, of 15 seconds and 1 second for volcanoes, and 30 seconds, 1 second and 0.2 seconds for tectonic studies, which are transmitted to the Monitoring Center in Quito through different ways such as radio links, internet, microwaves and satellite system. After the occurrence of the 2016 Pedernales earthquake, in order to improve the capacity of monitoring and generation of early warning information, especially due to tsunami hazards, a geodetic cGPS network in the province of Esmeraldas was implemented in real time. The data from this network are integrated with the seismic data to improve the rapid determination of the magnitudes and better characterize the source of the rupture.

The deployment of the GPS geodetic network in Costa Rica has been the result of actions carried out by institutions such as the OVSICORI, Spanish acronym for *Observatorio Vulcanológico y Sismológico de Costa Rica* (Volcanological and Seismological Observatory of Costa Rica), an institute that belongs to the Universidad Nacional, in coordination with foreign entities and researchers (UNAVCO, universities of South Florida, Central Washington, Georgia Tech, among others), as well as the contribution of National real estate institution. For geodynamic purposes, by the end of 2009, 19 cGPS stations had been established in the Nicoya Peninsula [51]. At present, the geodetic network of Costa Rica is composed of 55 cGPS stations [52].

In Venezuela, [53] points out that there are currently six cGPS stations that are part of COCONet (**Figure 3**), and two stations of the VENCREEP project funded by

COUNTRY	N° of Stations	COUNTRY	N° of Stations	COUNTRY	N° of Stations
Anguilla	1	El Salvador	4	Montserrat (Antilles)	1
Antigua & Barbuda	2	Grenada	1	Netherlands Antilles	1
Aruba	1	Guadeloupe	1	Nicaragua	4
Belize	1	Guatemala	3	Panama	12
British Virgin Is.	1	Haiti	1	Puerto Rico	4
Cayman Is.	4	Honduras	4	Dominican Republic	8
Colombia	141	Jamaica	3	St. Lucia	3
Costa Rica	55	Las Bahamas	1	Trinidad & Tobago	1
Cuba	2	Martinique	1	Venezuela	6
Ecuador	37	Mexico	2	Virgin Islands	1

Table 1.
Number of cGPS stations discriminated by country in the study region and depicted in ***Figure 3****.*

the French National Research Agency. Initial efforts by FUNVISIS since 2003 have focused on the installation of 2 local campaign networks (western and eastern Venezuela) of more than 70 benchmarks. These data is complementary for tectonic studies.

Table 1 indicates the number of stations installed in each country that are part of the study area, which are represented in **Figure 3**. It is possible that there are additional stations in some countries, but we have considered that these stations will improve, in a short-term, the understanding of the geodynamics of the study region.

In terms of instrumentation, **Figure 3** depicts that cGPS station distribution is rather homogenous throughout the Caribbean region and adjacent areas, except for 3 countries (Colombia, Costa Rica and Ecuador). Such homogeneity is a result from the COCONet project implementation, trying to reduce large gaps of data availabilty. Conversely, the concentration of stations in the 3 abovementioned countries responds to national policies, as already mentioned (Nicoya experiment in Costa Rica, post-Pedernales 2016 earthquake instrumentation in Ecuador and GeoRED project in Colombia).

4. Data processing and velocity field

The Geological Survey of Colombia received a grant to host a Regional Data Center headquartered in Bogotá that serves the entire circum–Caribbean community and functions as a mirror for COCONet data and metadata [54]. From the existing stations in the study area and displayed in **Figure 3**, the International Geodesy Lab of GeoRED currently processes 214 stations located on the Caribbean, South America, Nazca and Cocos tectonic plates across many country borders (**Figure 4**).

All GPS data obtained in the own format of each receiver are converted to RINEX format using the TEQC (Translating. Editing. Quality Check) tool developed by UNAVCO [55]. GPS data processing is carried out using the scientific software GIPSY-X/RTGx v 1.3 developed by JPL-CALTECH-NASA [56], and made

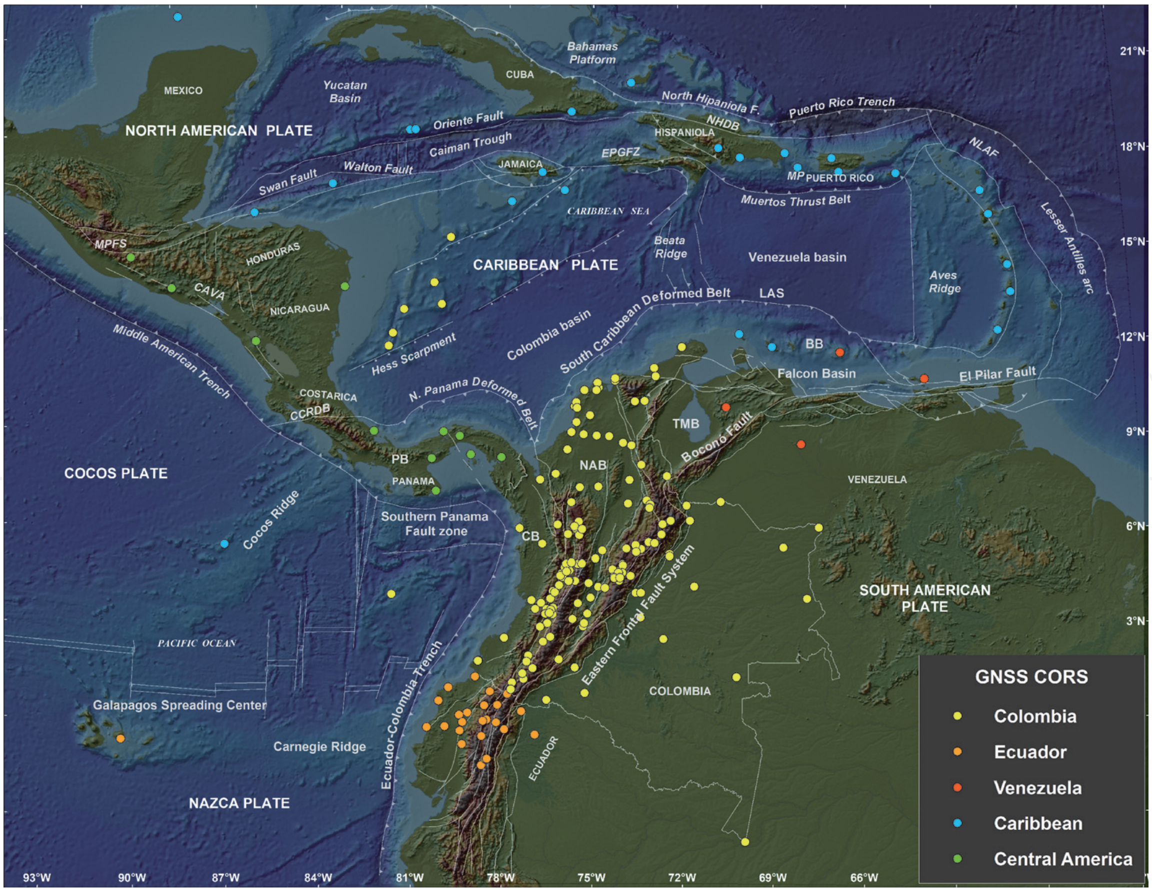

Figure 4.
cGPS stations processed at GeoRED-GSC.

available to GeoRED under a cooperation agreement. Final orbits are used in the processing, which include satellite orbits of the GNSS constellations, satellite clock and Earth orientation parameters that are provided in the appropriate format for Gipsy-X by JPL-NASA as contribution to the International GNSS Service (IGS). For the estimation of the tropospheric delay of the GNSS signals, the numerical model known as the Vienna Mapping Function (VMF1) is used, which is an update of the previous model known as VMF [57]. The ocean loading corrections are obtained from the Onsala Space Observatory, and are applied to eliminate the land and ocean tides. The amplitudes and phases of the main oceanic tidal loading terms are estimated by applying the FES2014b model [58]. The processing includes ionospheric models generated regularly by the IGS.

GIPSY-X/RTGx v 1.3 software uses the Precise Point Positioning (PPP) data processing strategy which is based on obtaining precise reference satellite orbit and clock products using the IGS GNSS global network.

Site coordinates for each day are computed in the non-fiducial frame and transformed to the ITRF2014 frame using a 7-parameter Helmert transformation [59]. The ECEF coordinates have been transformed into topocentric coordinates, which allow daily changes in the coordinates to be expressed in terms of local displacements in the North, East and Up (NEU) components with respect to a position in an initial epoch.

GPS time series have been generated using the HECTOR software v 1.7.2 [60] developed by SEGAL (Space & Earth Geodetic Analysis Laboratory), a center formed by the cooperation between the University of the Interior of Beira (UBI) and the Geophysical Institute Infante D. Luiz (IDL) from Portugal. HECTOR is a specialized software for the study of geodetic time series, which allows estimating the time series trend with temporal noise correlations. It is a dynamic software that only accepts stationary noise with constant noise properties, which allows fast matrix operations, benefiting the reduction in processing time.

For the estimation of geodetic velocities, GeoRED has adopted the recommendation of [61], who consider that the period of time of data required to estimate a trend in geodetic stations should be at least 2.5 years, in order to avoid that the estimated motion rate can be affected by various types of noise, including seasonal noise. Thus, the period of observations used in the processing extends to the time range from 2.5 to 20 years. January 1, 2010 is used as the reference epoch for all velocities estimation rather than the midpoint of each individual time series. For the time series estimation, it was used a combined model of power law plus white noise, and power spectrum predicted and observed plots were generated, to verify that the appropriate noise model has been used.

We present a new horizontal velocity field using data from 105 cGPS stations located in the study region. **Figure 5** shows the velocities with respect to ITRF2014. **Figure 6** shows the velocities with respect to the South American plate (SOAM), **Table 2**, following the procedure described by [40], who determined the velocity field using only 60 cGPS stations. These new velocity vectors allow observing the strain partitioning at different scales at the four PBZs of the Caribbean plate.

The ISCO station, Costa Rica, located on the Cocos plate, subducts beneath Central America, and shows the highest velocity in the study area, 86 mm/yr. wrt SOAM; similar value was obtained by [40] in ITRF2008. The importance of continuous geodetic instrumentation for the seismic cycle monitoring in this zone is indicated by [62] analyzing the occurrence of the Mw 7.6 September 5, 2012, Costa Rica earthquake, recorded in the network installed in the Nicoya Peninsula [51].

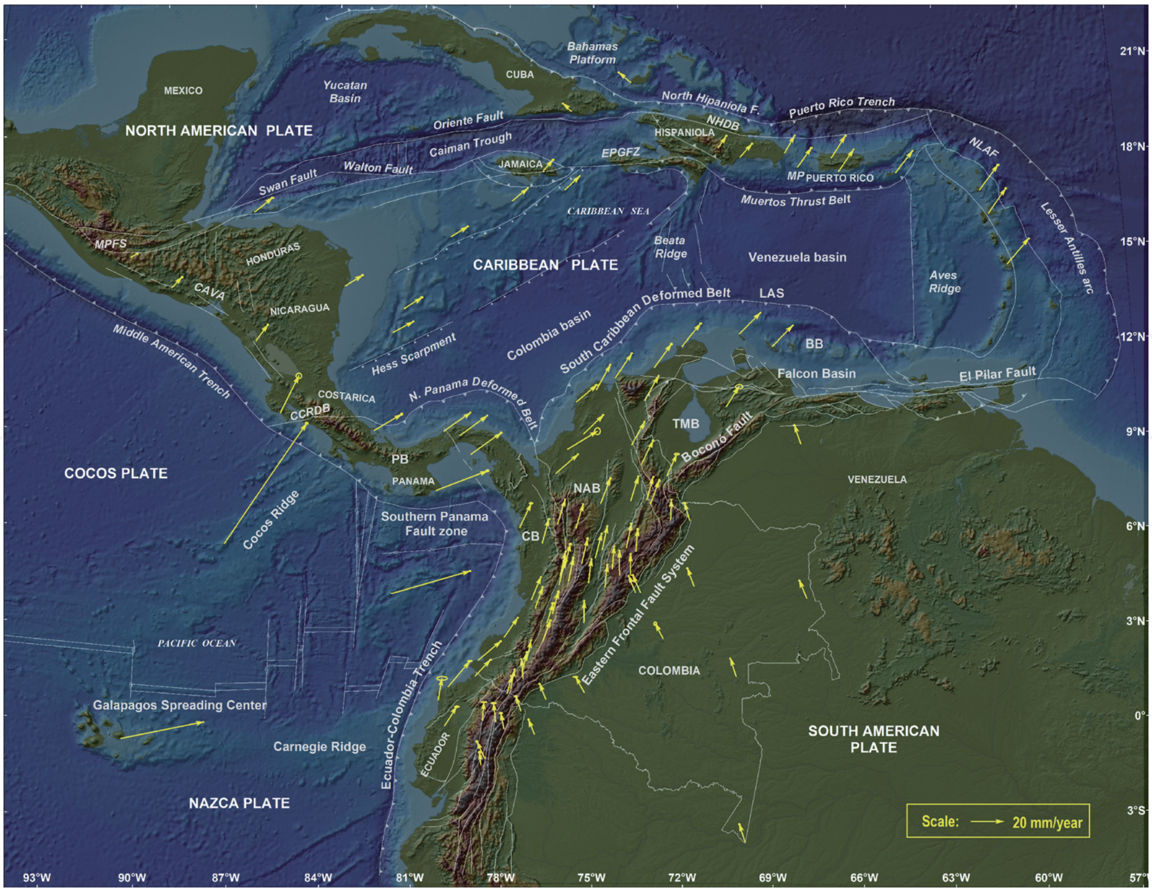

Figure 5.
GPS horizontal velocity field wrt to ITRF 2014.

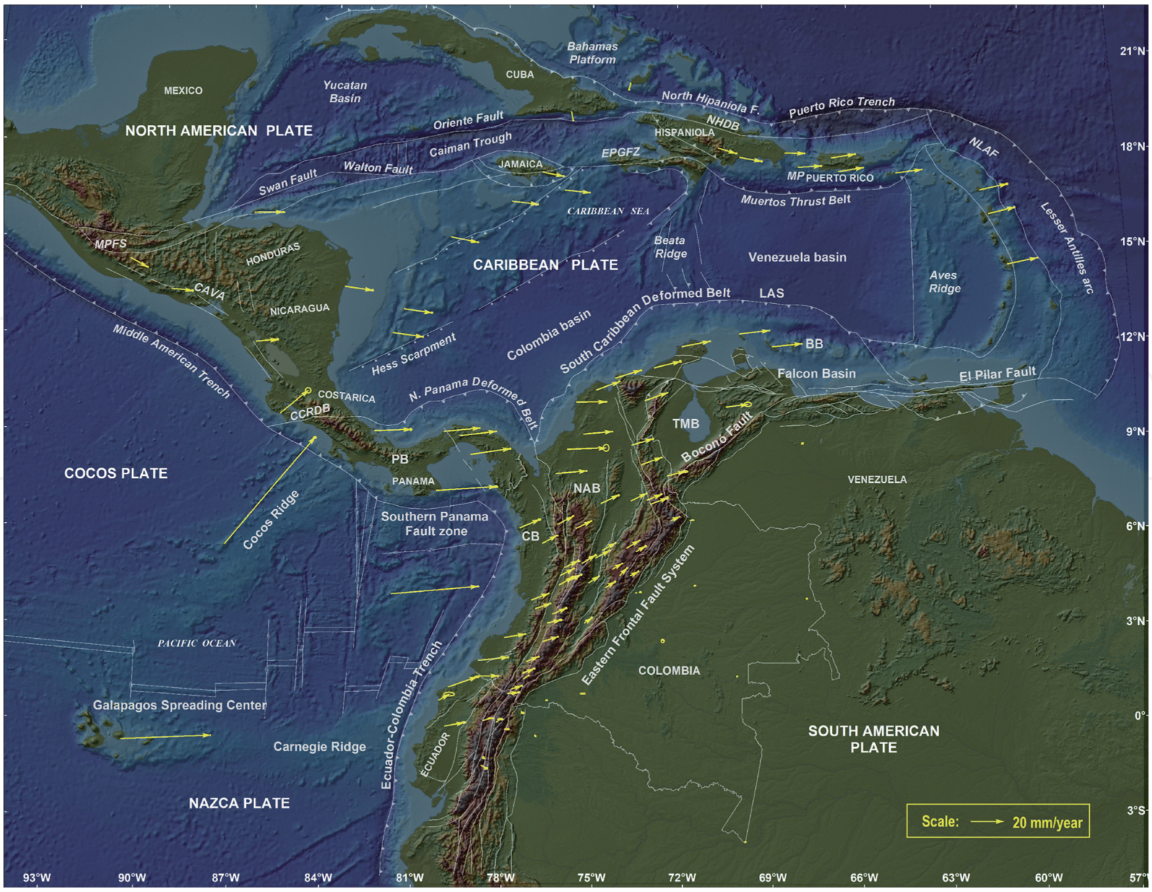

Figure 6.
GPS horizontal velocity field wrt to SOAM, ITRF2014. ***Table 2*** *provides the actual values of all GPS site velocities depicted here.*

The ISCO station, installed in 2011, is the only place that allows estimating the motion of the Cocos plate using GNSS geodetic instruments [63]; these authors estimated the Cocos-Caribbean convergence by comparing the baseline between ISCO and the SANO station, located on the island of San Andrés on the Caribbean plate, obtaining a value of 78 ± 1 mm/yr expressed in ITRF2008. We have made the same comparison, but expressed in ITRF2014, obtaining a value of 76.8 ± 0.5 mm/yr. This result is in agreement with the MORVEL estimate of [43] mentioned by [63] of 76.4 ± 2.5 mm/yr.

Six stations, located on islands in the western sector of the Caribbean plate, show an east-southeast general direction of motion, in a range of 96° to 101° of azimuth, and velocities with respect to SOAM of 18.7 ± 0.3 mm/yr (SAN0), 17.1 ± 0.3 mm/yr (CN35), 16.7 ± 0.5 mm/yr (CAYS), 15.9 ± 0.4 mm/yr (CN11), 15.3 ± 0.3 mm/yr (CN10), and 12.9 ± 0.3 mm/yr (CN12). On the other hand, three stations located on the eastern side of the Caribbean plate on islands of the Lesser Antilles, show velocity values with respect to SOAM about 17.1 ± 0.7 mm/yr (CN01), 16.6 ± 0.5 mm/yr (AMBF) and 18.9 ± 0.4 mm/yr (LMMF), in a general east-northeast direction, with azimuth values in the range of 76° to 78°.

MALO (Malpelo Island) and GLPS (Galapagos Island) stations confirm the rapid motion of the Nazca plate wrt to SOAM. The estimated velocity values in ITRF2014 are not so different from those estimated by [40] in ITRF2008. The ITRF2014 velocities are 53.2 ± 0.5 mm/yr with an azimuth of 87.8° for MALO, and 54.9 ± 0.2 mm/yr and azimuth 87.8° for GLPS.

The GPS stations located on the Colombian coast of the Pacific Ocean show similar values to those obtained by [40], increasing the velocity to the south. However, the ESMR station, located in Ecuadorean coast shows variation in the

ID	LON	LAT	Vel E	Vel N	Sig E	Sig N	ID	LON	LAT	Vel E	Vel N	Sig E	Sig N
ABCH	−73.722	4.638	4.8	2.7	0.3	0.2	INTO	−76.043	4.642	8.1	4.2	0.4	0.2
ABMF	−61.528	16.262	16.1	3.9	0.3	0.3	INVE	−74.232	11.188	15.7	4.9	0.4	0.1
ACHO	−80.173	7.415	36.7	2.4	0.9	0.4	ISCO	−87.056	5.544	55.4	65.1	0.7	0.4
ACP1	−79.950	9.371	22.0	2.0	0.2	0.2	LMMF	−60.996	14.595	18.5	3.9	0.4	0.2
ACP6	−79.408	9.238	22.1	2.6	0.2	0.2	LUMB	−77.328	0.137	1.1	−1.0	0.7	0.3
AJCM	−74.885	5.210	8.7	4.7	0.3	0.2	MALO	−81.606	4.003	53.0	4.5	0.5	0.3
ALPA	−72.918	11.528	15.9	4.0	0.5	0.5	MANA	−86.249	12.149	13.2	1.0	0.4	0.3
ANCH	−76.870	3.535	9.3	3.2	0.3	0.3	MECE	−73.712	7.107	9.7	4.6	0.3	0.2
AOPR	−66.754	18.347	14.4	2.4	0.3	0.2	MIPR	−66.527	17.886	15.0	2.6	0.2	0.1
AUCA	−76.883	−0.641	0.5	−0.9	0.4	0.2	MITU	−70.232	1.261	0.5	0.7	0.2	0.1
BA3E	−75.234	0.742	−1.2	−0.5	1.2	0.2	MOME	−80.047	0.492	6.6	3.8	2.6	0.9
BAAP	−73.554	4.072	0.4	−0.1	0.3	0.1	MOPR	−67.931	18.077	14.3	0.9	0.4	0.2
BAEZ	−77.887	−0.459	2.3	−0.1	0.8	0.3	MORA	−73.683	8.959	13.1	4.0	0.3	0.3
BAME	−74.565	4.236	6.1	3.7	0.3	0.3	OCEL	−71.616	4.271	0.4	0.6	0.4	0.1
BAPA	−74.658	5.466	8.0	4.5	0.2	0.2	OVSC	−77.257	1.210	3.3	2.1	0.3	0.2
BASO	−77.393	6.203	12.0	5.1	0.8	0.4	PAL2	−73.184	7.131	9.0	3.7	0.3	0.3
BIEC	−78.502	−1.447	−1.2	0.8	0.4	0.5	PASI	−76.499	0.513	0.2	−0.3	0.5	0.2
BOBG	−73.358	8.312	12.3	4.4	0.4	0.2	PLTR	−75.332	5.044	8.4	4.8	0.4	0.4
BOGT	−74.081	4.640	4.6	4.8	0.3	0.2	POVA	−76.615	2.449	9.2	2.9	0.4	0.2
BUGT	−76.996	3.826	10.6	4.1	0.3	0.2	PUIN	−67.903	3.851	−0.1	0.1	0.3	0.2
CAYS	−79.846	15.795	16.4	−3.3	0.5	0.2	QSEC	−85.357	9.840	17.0	13.9	1.4	1.3
CCAN	−76.300	3.360	8.3	3.6	0.4	0.4	QUIL	−77.291	1.394	7.3	2.9	0.5	0.3

ID	LON	LAT	Vel E	Vel N	Sig E	Sig N	ID	LON	LAT	Vel E	Vel N	Sig E	Sig N
CCPA	−76.085	4.325	8.5	4.8	1.0	0.5	RDSD	−69.911	18.461	13.4	−2.5	0.4	0.3
CCSQ	−76.474	3.063	8.2	1.9	0.8	0.3	RIOP	−78.651	−1.651	3.2	−2.0	0.5	0.5
CIOH	−75.534	10.391	17.8	0.2	0.8	0.2	ROA0	−86.527	16.318	17.6	0.0	0.7	0.2
CN01	−61.765	17.048	16.7	3.8	0.5	0.4	SALF	−78.155	−0.233	2.7	1.9	1.3	0.2
CN05	−68.359	18.564	12.1	−0.2	0.2	0.2	SAN0	−81.716	12.580	18.5	−2.5	0.2	0.2
CN06	−70.656	18.790	11.0	−3.4	0.4	0.3	SCUB	−75.762	20.012	1.0	−5.4	0.2	0.2
CN10	−75.971	17.415	15.2	−1.5	0.3	0.2	SEL1	−75.529	6.191	9.3	4.6	0.3	0.2
CN11	−77.784	17.021	15.8	−1.9	0.3	0.2	SGCG	−73.064	6.992	10.5	4.0	0.3	0.7
CN12	−76.749	18.004	12.7	−2.5	0.5	0.3	SNLR	−78.847	1.293	14.0	0.2	0.5	0.2
CN14	−73.678	20.975	−1.2	−4.2	0.3	0.3	SSIA	−89.117	13.697	12.7	−1.4	0.4	0.4
CN19	−70.049	12.612	18.4	2.2	0.2	0.2	TEAT	−73.539	5.422	5.9	3.4	0.5	0.3
CN20	−82.256	9.352	22.5	0.8	0.6	0.5	TICU	−69.939	−4.187	0.2	0.0	0.4	0.2
CN28	−79.034	8.625	23.9	3.5	0.4	0.3	TONE	−76.139	6.324	9.6	5.2	0.2	0.2
CN29	−83.375	14.049	16.9	−2.4	0.5	0.4	TUCO	−78.748	1.815	18.4	1.9	0.4	0.2
CN35	−81.363	13.376	16.9	−2.4	0.6	0.3	URR0	−76.210	8.012	18.8	1.7	0.3	0.3
CN36	−75.821	8.820	23.6	0.9	1.4	1.7	UWAS	−72.391	6.451	5.4	2.3	0.3	0.2
CN38	−71.988	12.222	17.1	3.4	0.5	0.2	VBUV	−73.859	5.533	8.0	4.8	0.4	0.2
CN39	−70.524	10.206	13.3	1.7	1.8	1.1	VDPR	−73.248	10.436	14.0	4.9	0.2	0.2
CN40	−68.958	12.180	18.1	1.9	0.2	0.2	VEDE	−75.765	4.460	7.6	3.9	0.4	0.3
CN41	−68.042	8.943	0.9	0.6	0.4	0.3	VMER	−77.153	1.785	7.4	3.0	0.2	0.2
COEC	−77.787	0.716	7.1	0.9	0.6	0.2	VNEI	−75.255	3.062	4.7	3.4	0.3	0.3
CORO	−75.288	9.328	17.5	1.5	0.3	0.2	VORI	−77.672	0.863	6.8	2.2	0.3	0.3

ID	LON	LAT	Vel E	Vel N	Sig E	Sig N	ID	LON	LAT	Vel E	Vel N	Sig E	Sig N
CRO1	−64.584	17.757	16.1	2.1	0.3	0.1	VOTU	−74.710	7.019	11.0	5.2	0.4	0.3
CUC1	−72.513	7.932	11.2	2.9	1.2	0.4	VPIJ	−75.107	4.397	6.4	4.2	0.3	0.1
ESMR	−79.724	0.935	17.6	6.2	1.1	0.3	VPOL	−74.861	10.794	14.0	5.2	0.4	0.2
FLFR	−79.843	−0.357	11.7	2.2	1.2	0.3	VPOM	−73.382	4.068	−0.3	0.4	0.5	0.2
GGPA	−78.594	−0.180	5.1	1.5	1.4	0.2	VQUI	−76.642	5.692	9.0	4.8	0.5	0.2
GLPS	−90.304	−0.743	54.8	2.1	0.2	0.2	VROS	−74.323	4.847	6.0	3.6	0.2	0.2
GUAP	−77.895	2.574	13.0	2.2	0.3	0.2	VSJG	−72.639	2.533	−0.4	−1.1	0.7	0.9
GUAT	−90.520	14.590	10.5	−5.7	0.4	0.2	VTAM	−71.753	6.452	1.6	0.2	0.7	0.2
INRI	−75.897	4.909	8.3	4.0	0.6	0.4							

Table 2.
GPS site velocities (mm/yr) relative to SOAM in ITRF2014.

northern component of velocity, which can be attributed to the effect of the 2016 Pedernales earthquake [64, 65]. It is important to note that the velocity field of [40] is estimated based on data until March 2016, prior to the aforementioned earthquake. The new velocity field contains the offsets associated to the coseismic displacements for the generation of the respective time series and velocity estimation.

At regional scale, wrt to SOAM, we can clearly see how NAB (in the sense of [3]) is detached from SOAM, and is moving at around from few mm/yr to a ten of mm/yr in the ENE-NE direction. In a general manner, slip rates within NAB tend to decrease from west to east, from the pacific border towards inland, and from south to north, implying coupling at the over-ridding plate-slab interface (e.g. [27]). Meanwhile, the Caribbean plate seems to exhibit a more similar (more homogenous) slip rate across the plate, trending E-ESE. The herein obtained values across the Caribbean plate tend to confirm the ≈20 mm/yr of eastward motion of this thickened oceanic plate already known per years now. However, it is very clear now that the Panamá block probably is not part of the Caribbean plate, because exhibiting a higher slip rate to the E-ENE than the rest of the Caribbean plate (e.g. [12, 39, 40]). It appears that such higher slip rate is transferred to NAB located to the east, confirming the indentation-extrusion mechanism responsible for the tectonic escape of NAB, as a consequence of collision and later suturing of the Chocó block against SA (and directly to NAB; e.g. [13, 28–30, 39, 40]).

5. Conclusions

A new horizontal geodetic velocity field wrt SOAM is presented, expressed in ITRF2014. With respect to the previous estimate, the spatial coverage of the study area has been increased, as well as the number of stations and the observation time at each station used in the solution.

The precision of the ISCO motion estimation, located on the Cocos plate, has been improved with respect to previous estimation, using data from 7.6 years of observation.

Although there are no substantial differences in the station velocities processed in this study, located on islands both west and east of the Caribbean plate, except for that shown by one station, it can be concluded that the Caribbean plate probably does not behave uniformly as a unit, as one might conclude from the difference between the directions, about 21°, changing in the general direction from east-southeast to east-northeast.

The study region shows examples of the importance of GNSS geodetic instrumentation for the study of the seismic cycle.

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