Chapter 14

Contributions of Space Geodesy for Geodynamic Studies in Colombia: 1988 to 2017

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Abstract Space geodetic measurements have transformed our understanding of regional tectonics in the North Andes and southwest Caribbean. The Central and South America GPS project, begun in 1988, provided the first direct measurement of subduction at a convergent plate boundary, and it led to the establishment of a global civilian GPS tracking network. Colombia was the center of the 1988 field campaign, and the leadership of Servicio Geológico Colombiano with logistics, training, and personnel was key to the success of the Central and South America project. Early GPS results showed evidence for northward movement of the North Andes, convergence at the South Caribbean deformed belt, rapid Panamá–North Andes collision, and interseismic "locking" at the Colombia–Ecuador trench. Beginning in 2007, space geodetic measurements took a great step forward with GeoRED project, a continuously operating Global Navigation Satellite System network that now has 108 sites providing the first accurate comprehensive model of North Andean Block motion. Recent GeoRED findings include that the North Andean Block is moving to the northeast at a rate of 8.6 mm/y, the Eastern Cordillera is being compressed at a rate of 4.3 mm/y, the Panamá Arc is colliding eastward with the North Andean Block at approximately 15–18 mm/y, and the Panamá–Chocó collision may have been responsible for much of the uplift of the Eastern Cordillera. The new continuous Global Navigation Satellite Systems measurements help quantify tectonic deformation in northwestern South America and the southwest Caribbean, including earthquake hazards at the Colombia trench, the Caribbean margin, the East Andean Fault System in the Eastern Cordillera, and the Panamá collision zone in northwestern Colombia; as well as the deformation of Colombian volcanoes.

Keywords: *space geodesy, North Andean Block, crustal deformation, Global Positioning System.*

Resumen Las mediciones geodésicas espaciales han transformado nuestro entendimiento sobre la tectónica regional en los Andes del norte y el suroeste del Caribe. El proyecto Central and South America GPS comenzó en 1988, suministrando la primera medición directa de la subducción en un límite de placa convergente, y llevó al establecimiento de una red de rastreo global civil. Colombia fue el centro de la campaña de campo de 1988 y el liderazgo de Ingeominas (ahora Servicio Geológico Colombiano) con la logística, entrenamiento y personal fue la clave para el éxito del proyecto Central and South America GPS. Los primeros resultados de GPS mostraron evidencia de movimiento de los Andes del norte hacia el norte, convergencia del cinturón deformado del sur del Caribe, rápida colisión Panamá–Andes del norte, y

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"bloqueo" intersísmico en la trinchera Colombia–Ecuador. A comienzos del 2007, las mediciones geodésicas espaciales dieron un gran paso con el proyecto GeoRED, una red de operación continua del Sistema Global de Navegación por Satélite que ahora tiene 108 sitios y ofrece el primer modelo preciso de movimiento del bloque norte de los Andes. Hallazgos recientes de GeoRED indican que el bloque norte de los Andes se está moviendo hacia el noreste a una tasa de 8,6 mm/año, la cordillera Oriental está siendo comprimida a una tasa de 4,3 mm/año, el Arco de Panamá está colisionando hacia el este con el bloque norte de los Andes a 15–18 mm/año aproximadamente y la colisión Panamá–Chocó puede haber sido responsable en gran parte del levantamiento de la cordillera Oriental. Las nuevas mediciones continuas del Sistema Global de Navegación por Satélite ayudan a cuantificar la deformación tectónica en el noroeste de Suramérica y el suroeste del Caribe, incluyendo la amenaza sísmica en la trinchera de Colombia, el margen Caribe, el sistema de fallas andino oriental en la cordillera Oriental y la zona de colisión de Panamá en el noroeste de Colombia, así como la deformación de los volcanes colombianos.

Palabras clave: *geodesia espacial, bloque norte de los Andes, deformación cortical, Sistema de Posicionamiento Global.*

1. Introduction

Prior to the establishment of the Global Positioning System (GPS), measurements of crustal deformation in Colombia and the rest of the world were limited to time–consuming land surveys and covered only small areas. Rigid plate velocities were estimated at million–year time scales from seafloor magnetic anomalies and occasionally from geodetic measurements across continental transform boundaries (Agnew et al., 1989). It is possible to obtain velocity values from the study of kinematics of active faults with clear morphological expression (Audemard, 1997; Audemard & Giraldo, 1997; Audemard et al., 1999, 2005; Pousse–Beltrán et al., 2017). Precise geodetic measurements with GPS made it possible, for the first time, to make economical widespread measurements of non–rigid plate motions and near real time crustal deformation rates across broad plate boundary zones (Stein & Sella, 2002). Satellite geodetic measurements have transformed our understanding of regional tectonics in the North Andes and southwest Caribbean. The CASA (Central and South America) GPS project, begun in 1988, provided the first direct measurement of subduction at a convergent plate boundary and the first use of a global civilian GPS tracking network (Kellogg & Dixon, 1990). Problems such as the seismic cycles, large–scale plate motions, and intraplate deformation at convergent margins can be addressed with GPS information collected, compared, and analyzed over time. The introduction of GPS technology in Colombia for scientific purposes, especially in the field of geodynamics, has been led by the Servicio Geológico Colombiano (SGC). The first three decades of that history can be divided into two major periods: first, the original CASA GPS project, and second, the Global Navigation Satellite System (GNSS) GeoRED project, a continuously operating network with 108 sites providing the first accurate comprehensive model of North Andean Block motion (Mora–Páez et al., 2019). The new velocity field has important implications for estimating earthquake hazards in Colombia, especially near the large population centers of Bogotá, Medellín, and Pasto.

1.1. Tectonic Framework

Colombia is located in an area of tectonic convergence between the Nazca, South America, and Caribbean Plates. Two additional blocks or microplates, the Panamá Block and the North Andes Block, both of which are subject to internal deformation, have been proposed in order to explain the complex tectonics of the area (Figure 1; Pennington, 1981; Kellogg et al., 1985, 1995; Audemard, 2014; Kobayashi et al., 2014). The tectonic setting of South America is unique: in no other part of the world does a major oceanic plate subduct beneath a large continental plate along a trench almost 8000 kilometers long (Assumpcao, 1992). Active seismicity is spread out over a wide area from the Panamá fracture zone south of Panamá to the East Andean and Boconó Fault Systems at the eastern edge of the Andes (Pennington, 1981). The earthquakes are caused by on–going arc–continent collision, northeastward movement of the North Andes, mountain building, and the subduction of the Nazca and Caribbean oceanic plates beneath Colombia (e.g., Trenkamp et al., 2002; Audemard, 2014).

1.2. The CASA GPS Project

The CASA project dates back to early 1988, when scientists from more than 25 organizations and 13 different countries cooperated in what was then the largest GPS project in the world, using 43 receivers to obtain daily information from 59 stations (Figure 1; Kellogg & Dixon, 1990). The CASA UNO experiment in 1988

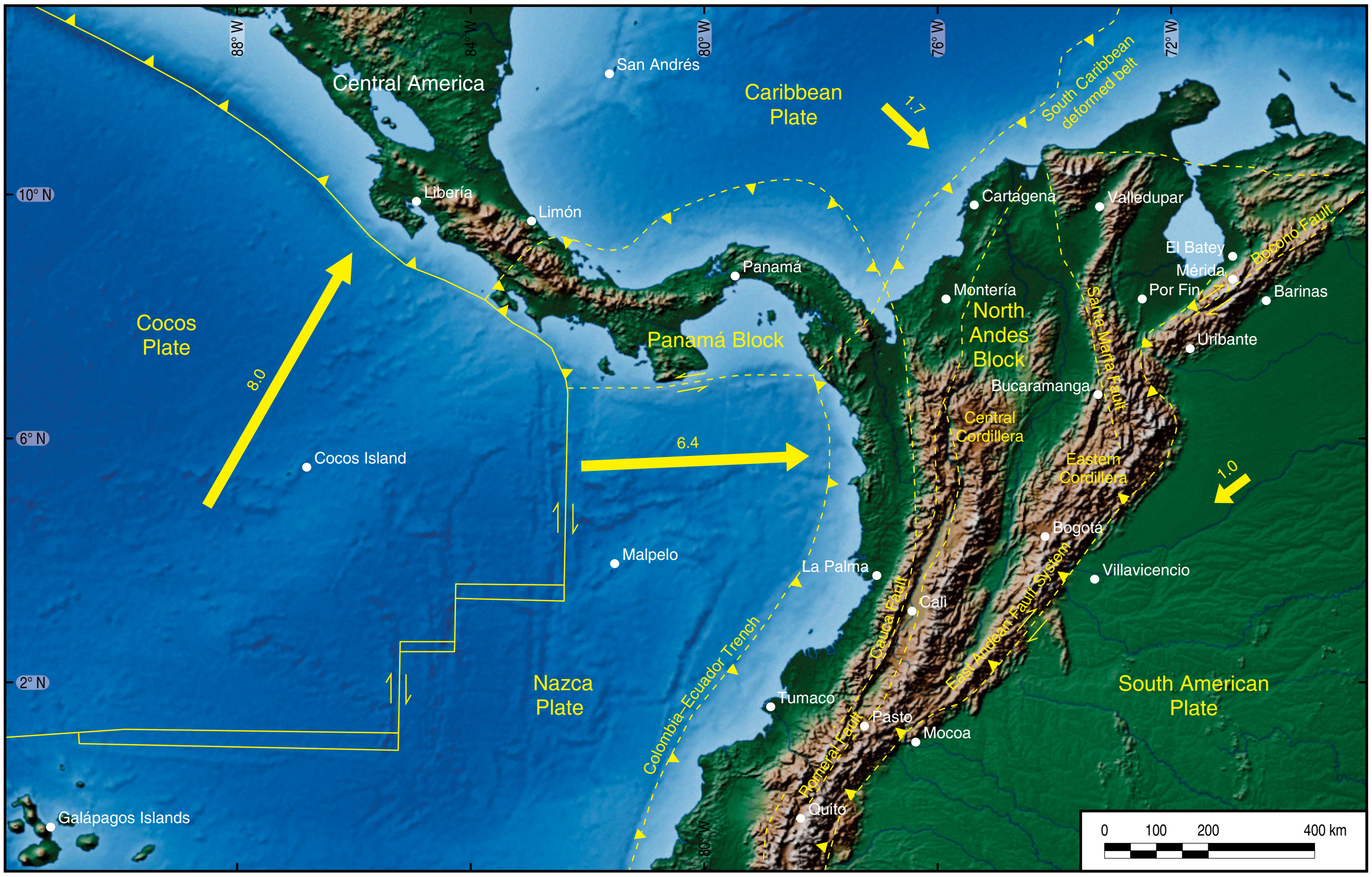

Figure 1. 1988 CASA UNO site locations (white circles) of the first GPS network in the North Andes and Central America (Kellogg et al., 1990). Plate motions (bold arrows) relative to North Andean Block (Cocos Plate motion relative to Caribbean) showing average slip rates (cm/y) during the last 5 to 10 my after Minster & Jordan (1978). Modified from Kellogg & Dixon (1990). The rates are estimates as of the late 1980s, prior to the GPS measurements. Compare to later figures that show the observed GPS velocities.

was supported by the first civil global tracking network (Neilan et al., 1989), an important step in the development of a global network of permanent GPS stations (Figure 2; Freymueller & Kellogg, 1990). CASA was sponsored by NASA and NSF from USA together with institutions from each of the participant countries. Colombia was the center of the North Andean field campaign, and the enthusiastic participation of Ingeominas (now Servicio Geológico Colombiano) with logistics, training, and personnel was key to the success of CASA (Figure 3).

The 1988 measurements were followed by 1990 CASA campaigns in Ecuador, Panamá, and Costa Rica, as well as 1991 and 1994 CASA campaigns in Costa Rica, Panamá, Colombia, Ecuador, and Venezuela helped further expand the 1988 global reference frame (Figure 2). Additional campaigns in Colombia were carried out in 1996 and 1998. An important date for the development of a GPS network in Colombia was 4 November 1994. Under a cooperation agreement between the National Aeronautics and Space Administration (NASA) of USA and Ingeominas, the first permanent GPS station in Colombia was installed as part of the global Fiducial Laboratories for an International Natural Science Network or FLINN. Since then, the operation and maintenance of the permanent station have been the responsibility of the Servicio Geológico Colombiano.

The CASA project was planned with the following initial scientific objectives for the first decade, 1988–1998 (Kellogg & Dixon, 1990):

- Obtain baseline measurements between several Pacific islands located on the Nazca and Cocos Plates, and sites in Colombia, Ecuador, Costa Rica, and Panamá, that, when compared with future observations, will monitor subduction rates across the trenches and spreading rates across the Galápagos Rise.
- Establish a GPS network across the South Caribbean deformed belt that will demonstrate whether the Caribbean crust is subducting amagmatically beneath the northern Andes.
- Acquire baseline measurements across the Romeral, Santa Marta, and Boconó–East Andean Fault Systems that would eventually determine strain distribution across the North Andean continental margin.
- Obtain elevation measurements that would determine whether the northern Andes are still rising, as suggested by uplifted terraces of Pliocene – Quaternary age.

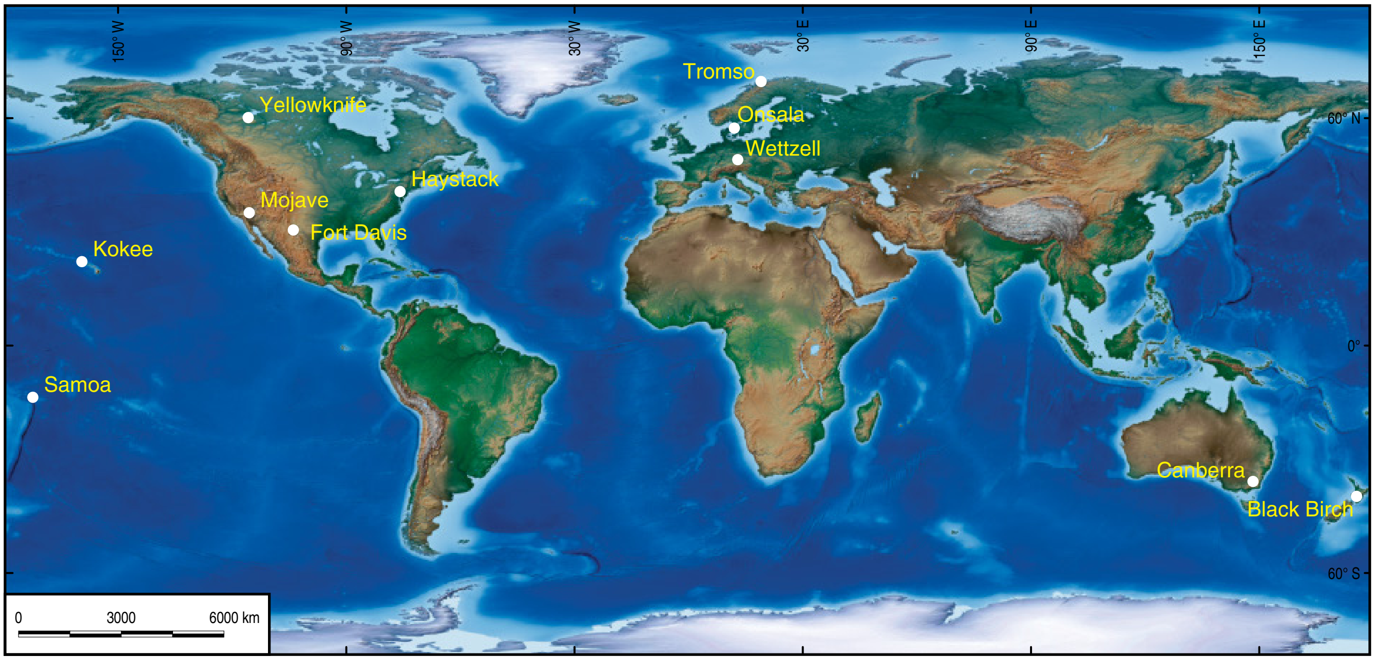

Figure 2. Extended fiducial network for 1988 CASA project (Neilan et al., 1989). World's first civilian global tracking network; (Freymueller & Kellogg, 1990; Kellogg & Dixon, 1990). Modified from Kellogg & Dixon (1990).

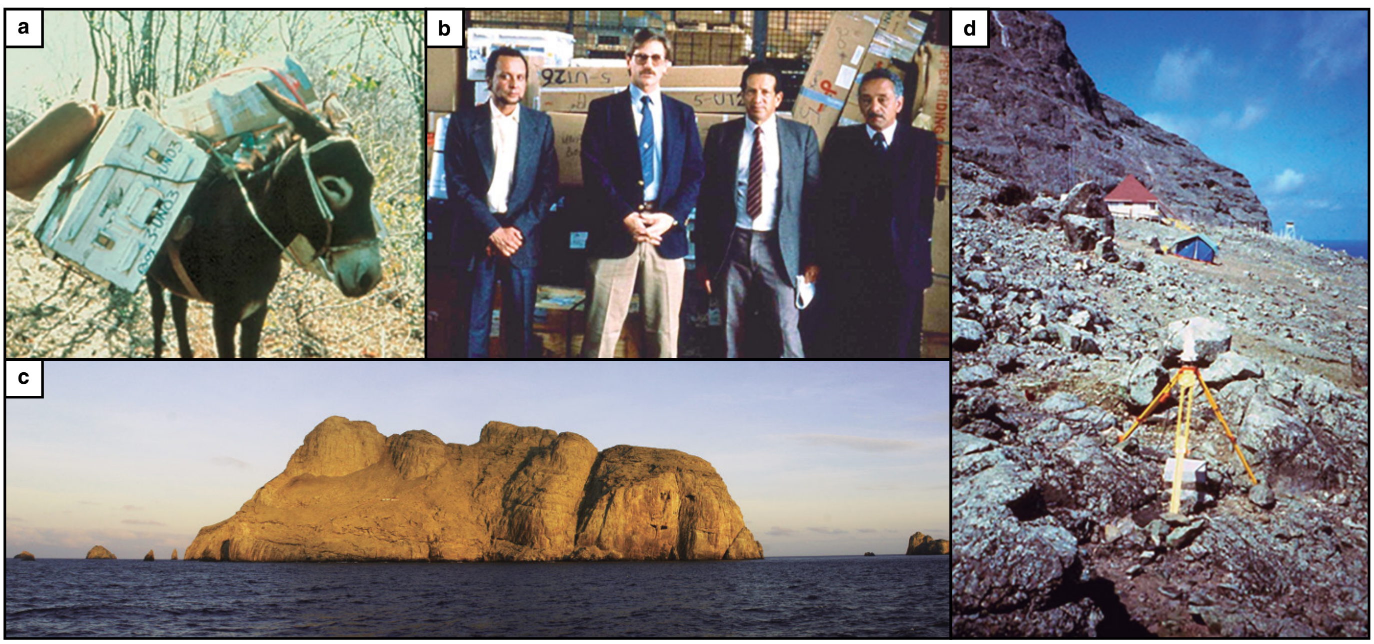

Figure 3. (a) CASA 1988 burro with GPS receivers near Valledupar. **(b)** 1988 James STOWELL and Clemente ROPAIN at Servicio Geológico Colombiano, Bogotá**. (c)** 1988 Malpelo Island, courtesy of Jair RAMÍREZ. **(d)** 1988 1st GPS measurements on Malpelo Island.

- Co–locate GPS and Doppler stations to improve the transformation between the WGS72 and WGS84 reference systems in this region.

The first investigations made in the CASA project were focused on understanding the different sources of GPS errors, especially those caused by the wet troposphere (Dixon & Wolf, 1990) and the need for a global tracking network to correct the orbit errors. Initial investigations in the CASA project focused on the accuracy of the data analysis as well as geological interpretation and modeling. For example, GPS measurements along the Middle America trench demonstrated a seismic cycle of cumulative strain near the trench produced by the convergence of the Cocos and Caribbean Plates (Dixon, 1993).

The comparison of results with previous measurements (Dixon et al., 1991), suggested that the relative motion of the Caribbean Plate with respect to North America in the east component was faster than the rate estimated by the global model NUVEL–1A. By that time, the relative motion of most of the major tectonic plates had been predicted from global geological models, with a precision of a few mm/year, or a few degrees in azimuth (DeMets et al., 1990, 1994). Those models were tested with GPS measurements of relative plate motion in the northwest corner of South America. Using GPS results from the first three CASA GPS campaigns (1988–1991), Freymueller et al. (1993) showed evidence for northward movement of the North Andes and convergence at the South Caribbean deformed belt, in addition to measurements of the motions of the major plates.

In the 1994 CASA campaign, most of the stations occupied in the 1988, 1990, and 1991 campaigns were reoccupied, and a process of site densification was begun in Colombia. Mora–Páez (1995) and Kellogg et al. (1995) used the 1988–1994 CASA GPS results to propose a rigid Panamá Block and rapid Panamá–North Andes convergence. Based on earthquake focal mechanisms, offset glacial moraines, and Quaternary thrust faults, Mora–Páez (1995) proposed that the oblique Nazca–South America convergence at the Colombian–Ecuadorian margin was partitioned into components of right–lateral slip parallel to the margin and crustal shortening perpendicular to the margin.

In 1996, all of the CASA GPS stations and most of the densification stations that were built and occupied for the first time in 1994, were reoccupied. During the 1998 GPS campaign, Ingeominas devoted its efforts to the northern part of Colombia focusing on northwestern Colombia, the boundary with Panamá, and the eastern border with Venezuela. Trenkamp et al. (2002) presented CASA campaign data from 1991 to 1998 that showed wide plate boundary deformation and escape tectonics from the subducting Carnegie Ridge along approximately 1400 km of the North Andes, locking of the subducting Nazca Plate and strain accumulation in the Ecuador–Colombia forearc, collision of the Panamá arc with Colombia, and Caribbean–North Andes convergence. White et al. (2003) modeled GPS deformation in the Ecuador–Colombia subduction zone to show that elastic strain accumulation at the trench in southern Colombia was continuing to build up, but was masked by viscoelastic relaxation in the viscous upper mantle following the 1979 trench earthquake.

In 1998, under the Ingeominas institutional framework of the project "Survey of Geodynamics Information of the Colombian territory", a systematic process began as an extension of the CASA project, to densify the passive network. Coverage was expanded, including volcanic areas such as Nevado del Ruiz and Galeras. The primary purpose of this activity was to more accurately measure the stress field in Colombian crust using GPS techniques.

On 25 January 1999, two shallow earthquakes affected the coffee growing region in Colombia, with profound implications at national, regional, and local levels. The earthquakes caused 1185 deaths and approximately 8500 injuries (Programa de las Naciones Unidas para el Desarrollo & Comisión Económica para América Latina y el Caribe, 1999). It was the first opportunity to apply GPS technology to obtain measurements of coseismic displacement in Colombia. A field campaign was carried out to re–occupy sites located near the epicentral areas of the earthquakes, previously occupied in 1998, and measure horizontal and vertical co–seismic displacements.

In the same year, 1999, Ingeominas acquired its first GPS receiver, a Trimble 4000 SSI receiver with choke–ring antenna. From 2001 through 2006, GPS field campaigns were conducted using the receivers owned by Ingeominas and two Trimble 4000 SSI GPS receivers with choke–ring antennas provided by the Andean Geophysical Laboratory at the Department of Geological Sciences of the University of South Carolina, USA.

In 2003, a subset of 36 sites previously occupied by Ingeominas was chosen for a geological and geophysical project to understand the stresses and neotectonic deformation within the Cauca Valley and the city of Cali, the largest urban center in southwestern Colombia. Trenkamp et al. (2004) analyzed GPS data collected between 1994 and 2003, and concluded that the strain rates determined in the study area for two Delaunay triangles near Cali, while not high compared to subduction zone rates (10^{-5}–10^{-6}) (Bilham & Zerbini, 1989), they are consistent with the seismicity observed in this region of the North Andean Block.

1.3. GNSS GeoRED Project

In 2006, the Instituto Colombiano de Geología y Minería (Ingeominas) submitted to the Departamento Nacional de Planeación a proposal named "Implementation of the GPS Satellite Geodesy National Network for geodynamic purposes" (Mora–Páez, 2006). Mora–Páez (2006) proposed to use GPS geodesy for geodynamic studies of the northwestern corner of South America to accurately estimate seismic hazards and integrate and analyze the data collected by other instrumental networks. This project, approved in 2006, began activities in January of 2007. The general purpose of the GeoRED project has been 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".

GeoRED is a research and development project based on space geodesy technology that takes a multifaceted approach to cataloging and defining the geodynamics of northwestern South America. It has become an essential tool for measuring interplate and intraplate continental deformation, and to accurately predict hazards within a wide plate margin deformation zone associated with the earthquake cycle. Our current endeavors are focused on the acquisition of high quality GPS/GNSS data to be shared by intergovernmental institutions and university research centers within Colombia as well as collaborative international research efforts including reciprocal data sharing between the neighboring countries of Panamá, Venezuela, Brasil, Perú, and Ecuador.

GeoRED is also designed to meet the following specific objectives (Mora–Páez, 2006):

- Implement a National GNSS Permanent Network for geodynamics with data transmission to an information–gathering center.
- Create GNSS mobile teams for campaign style data acquisition (active fault studies, post–seismic assistance, volcanic crisis assistance, mass movement monitoring, mud volcano studies, and land subsidence due to water extraction).
- Generate information about horizontal and vertical displacements for studies of crustal deformation.
- Establish a high precision geodetic reference frame for multipurpose activities within the Servicio Geológico Colombiano.
- Provide information within SGC as well as to other government institutions toward the execution of research and development projects using GNSS data.

For geohazard decision making in Colombia, especially related to seismic and volcanic hazards, it is of great importance to enhance the technical and scientific capability to capture, process, analyze, and display crustal deformation in near real time. To increase our knowledge of geodynamic phenomena, especially seismic and volcanic, and help to reduce the risks associated with these disasters, instrumental networks are needed: seismographs, accelerometers, and GPS receivers for geodynamic studies, among others, with good spatial coverage, long term functioning, high data quality, and timely information retrieval. These integrated information networks will allow us to better formulate local, departmental, regional and national development and disaster management plans.

In 2011, the Colombian government released executive order 4131 as part of a reorganization of the country's mining and energy sectors. Ingeominas' name was changed to the Servicio Geológico Colombiano. The survey currently falls under the administration of the Ministerio de Minas y Energía and it is affiliated with the Sistema Nacional de Ciencia, Tecnología e Innovación (National System of Science, Technology, and Innovation), which was created in 2009 by law n° 1286.

1.4. GeoRED Network

Currently, the GeoRED Network is composed of two sub–networks: one composed of permanent GNSS CORS (Continuously Operating Reference Station), and the second one, consisting of campaign style field stations.

The CORS network now has 108 stations: 92 GeoRED GNSS stations; 4 GNSS stations that are part of the COCONet (Continuously Operating Caribbean GPS Observational Network) project run by UNAVCO (University NAVSTAR Consortium); the Bogotá IGS GNSS station (BOGT); the San Andrés Island station (SAN0), and 10 stations installed under a collaborative partnership with local Colombian institutions, such as Cenicaña (Centro de Investigación de la Caña de Azúcar), Universidad Nacional de Colombia, Área Metropolitana del Valle de Aburrá, and the Empresa de Acueducto de Bogotá (Figure 4). Eight of the CORS stations were collocated with seismic stations that are part of the Red Sismológica Nacional de Colombia run also by the Servicio Geológico Colombiano and eleven stations were installed with meteorological sensors (Mora–Páez et al., 2018). Some of these stations have been used to perform geodetic ties with tide gauges installed in Colombia by the Dirección General Marítima (Dimar).

The CASA project (1988–1998) established a network of field stations in Colombia, built mainly for geodynamic studies (Kellogg & Dixon, 1990; Kellogg et al., 1995; Trenkamp et. al., 2002) that was densified by SGC until 2006. The Space Geodesy Research Group of the Servicio Geológico Colombiano through the GNSS GeoRED project has continued expanding that network since 2007. Currently, the field station network is composed of 382 stations (Figure 5). Of those, 49 stations built under a collaborative project with the Unidad Administrativa Especial de Catastro Distrital, are dedicated to study land subsidence in the area of the city; 55 are used to measure landslide displacements; and 11 are for mud–diapirism analysis. The other 267 stations are used for tectonic studies and are occupied every one or two years with campaign–style measurements. The main tectonic goals are to deploy geodetic arrays along active geological faults zones, such as the Algeciras, Bucaramanga, and Ibagué Faults among others, and to measure the kinematics of the Colombian extension of the Boconó Fault zone of Venezuela.

2. Materials and Methods

2.1. GPS Data Processing

At present (Mora–Páez et al., 2018), GPS data are processed with GIPSY–OASIS II software, version 6.3 developed by the Jet Propulsion Laboratory (JPL), California Institute of Technology (Zumberge et al., 1997; Bertiger et al., 2010). The station velocities are computed using HECTOR (Bos et al., 2013), a software package developed at SEGAL (Space & Earth Geodetic Analysis Laboratory at the University of Beira Interior, Portugal) which is capable of taking into account temporal correlations in the data to estimate the associated uncertainties. HECTOR is based on the maximum likelihood estimation (MLE) that is the method of predic-

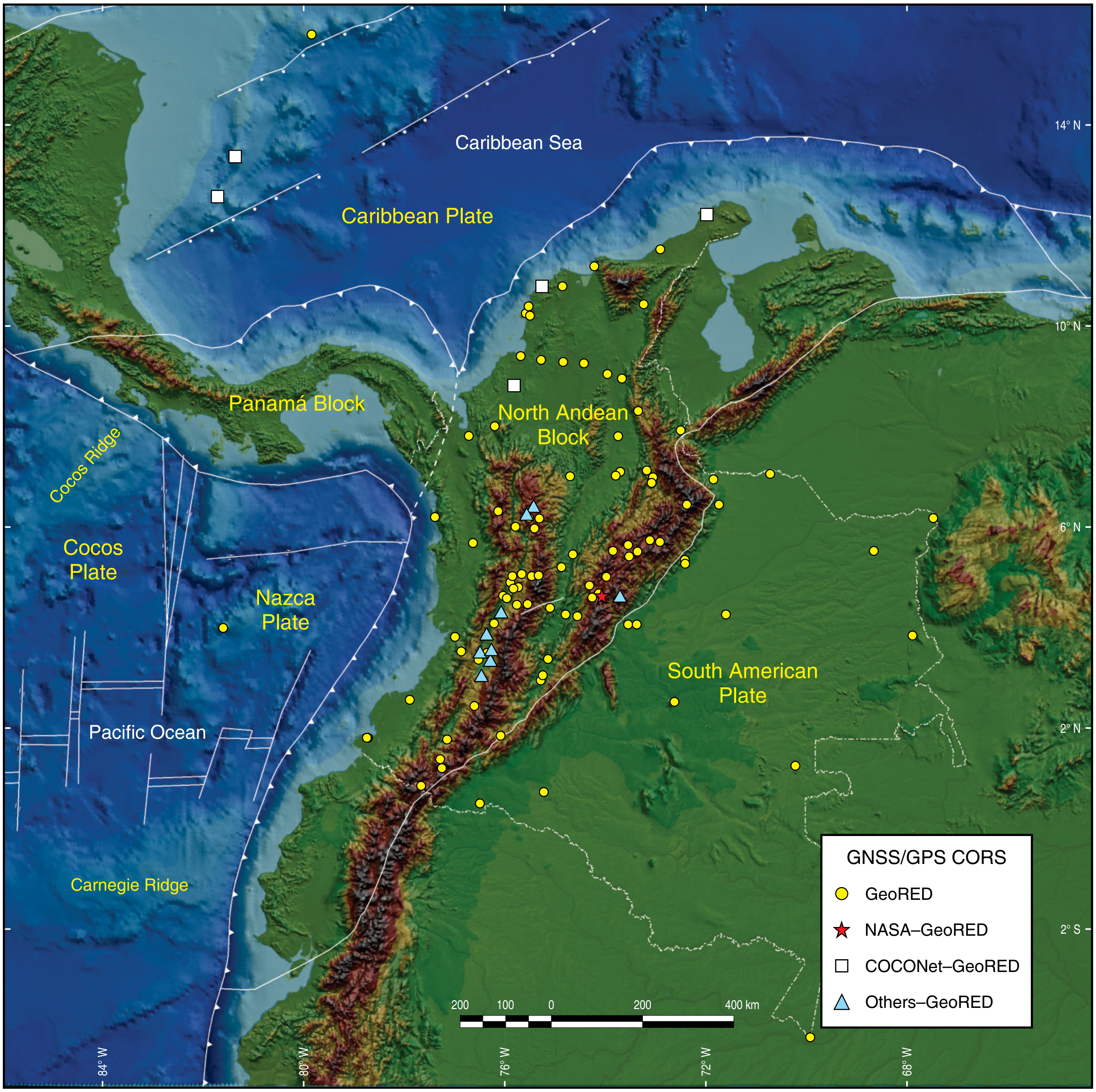

Figure 4. GNSS CORS stations of GeoRED Network.

tion in the stochastic modelling of the GPS time series. It has implemented the following type of models: white noise, power–law noise, ARIMA, generalized Gauss–Markov. The estimated parameters are tectonic rate, seasonal signal, specified frequencies, offsets and outliers (Xiaoxing et al., 2017). HECTOR computes the secular motion observed at each GPS station, together with periodical signals using a power law plus white noise model to take into account the existing noise signals in the trend. It has different functions that permit estimations of linear trends and the power spectral density from the data or residuals using a periodogram method. It also computes the associated power spectral density for given frequency ranges, and removes outliers, among other routines (Bos & Fernandes, 2016). Table 1, Supplementary Information shows the estimated velocity values expressed in millimeters per year based on site coordinates computed in the non–fiducial frame and transformed to the ITRF2008 (Altamimi et al., 2011, 2012).

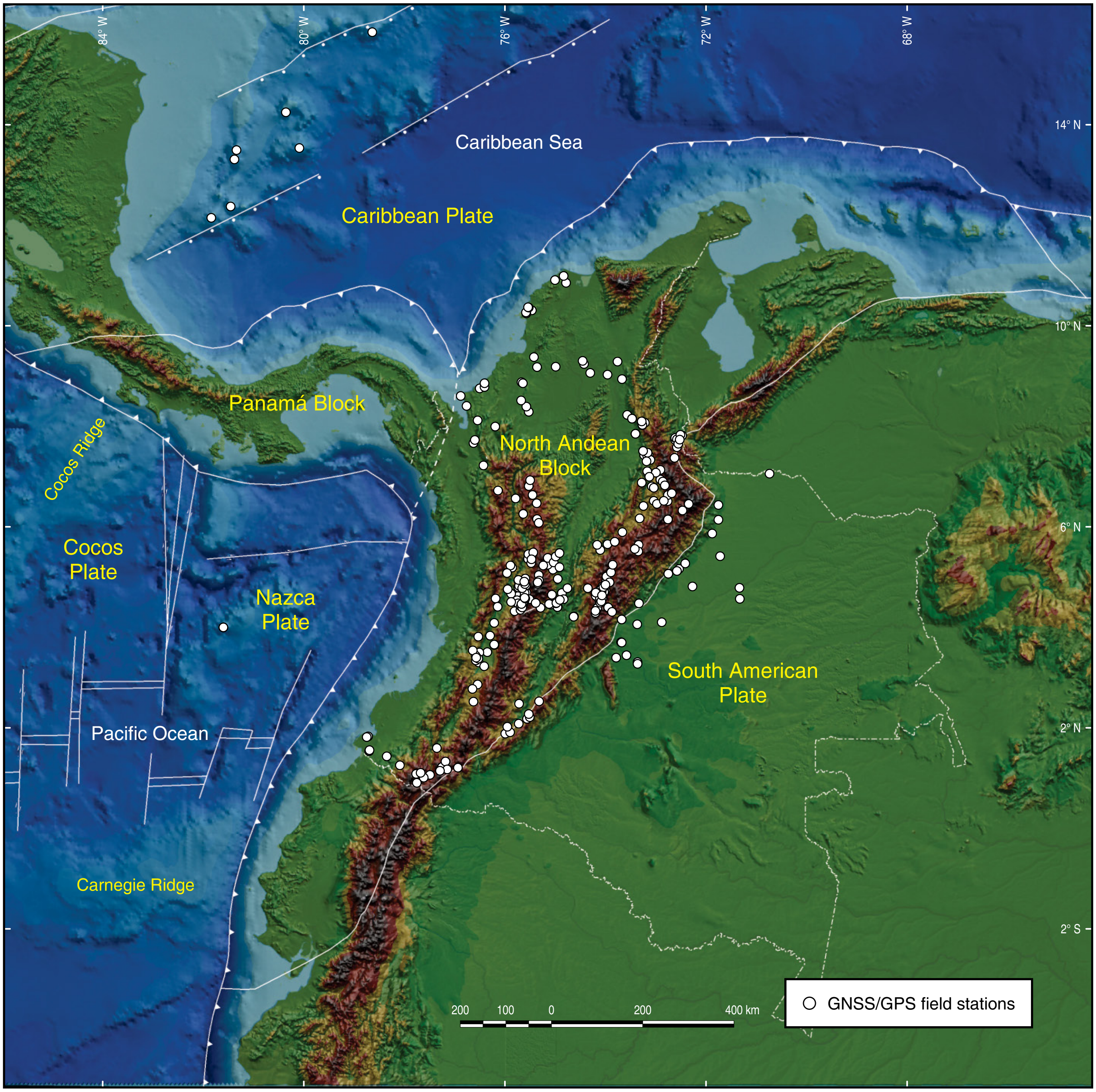

Figure 5. Field stations of GeoRED Network.

2.2. COCONet Regional Data Center

The Servicio Geológico Colombiano through the Space Geodesy Research Group, that runs the Center for Processing and Analysis of Geodetic Scientific Data, received a grant to host a Regional Data Center headquartered in Bogotá, Colombia, and serve the entire circum–Caribbean community. The center functions as a mirror for COCONet data and metadata with capabilities for local data and metadata management, such as downloading stations and archiving GNSS data are available at URL: http://coconet1.sgc.gov.co/coconetgsac/gsacapi/.

UNAVCO provided hardware, software, installation, and training to develop this site. The center supports open access to data, data integration, high impact research, and graduate–level training in the Earth Sciences in the circum–Caribbean region, where there is a significant need for more expertise and study to meet immediate concerns and provide longer–term benefits to the COCONet community. The benefits include educational advancement; professional workforce development; hazard

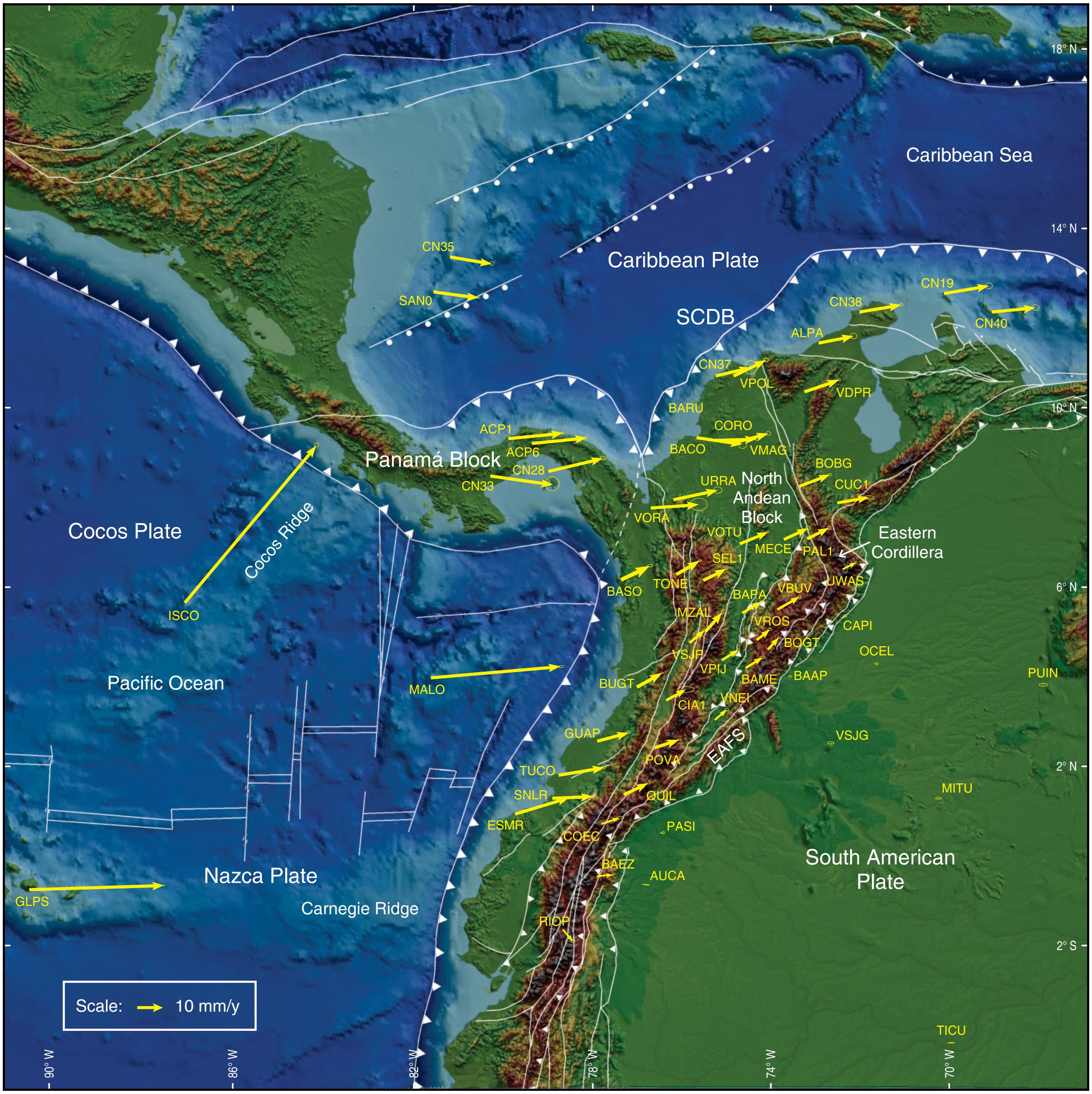

Figure 6. GPS vectors relative to stable South America (Mora–Páez et al., 2019). One sigma error ellipses. Station names in yellow. (EAFS) East Andean Fault System; (SCDB) South Caribbean deformed belt; Table 2, Supplementary Information.

preparedness, response, and mitigation; development and planning; and understanding and living with Earth processes.

3. Results

3.1. Precise Velocity Field – North Andean Block

Mora–Páez et al. (2019) presented the first precise velocity field for northwestern South America and the southwest Caribbean based on GPS CORS (Continuously Operating Reference Stations) in Colombia (GeoRED, COCONet), Ecuador (ESPONA), Panamá (ACP, COCONet), Costa Rica (COCONet), and Venezuela (COCONet), with a minimum of 2.5 years of observations (Figure 6). This was the first comprehensive precise model of North Andean Block motion. Previous estimates by Chlieh et al. (2014) and Nocquet et al. (2014) were based on data from a small area (mainly in Ecuador, plus two sites in Colombia) and thus may not be appropriate to extrapolate

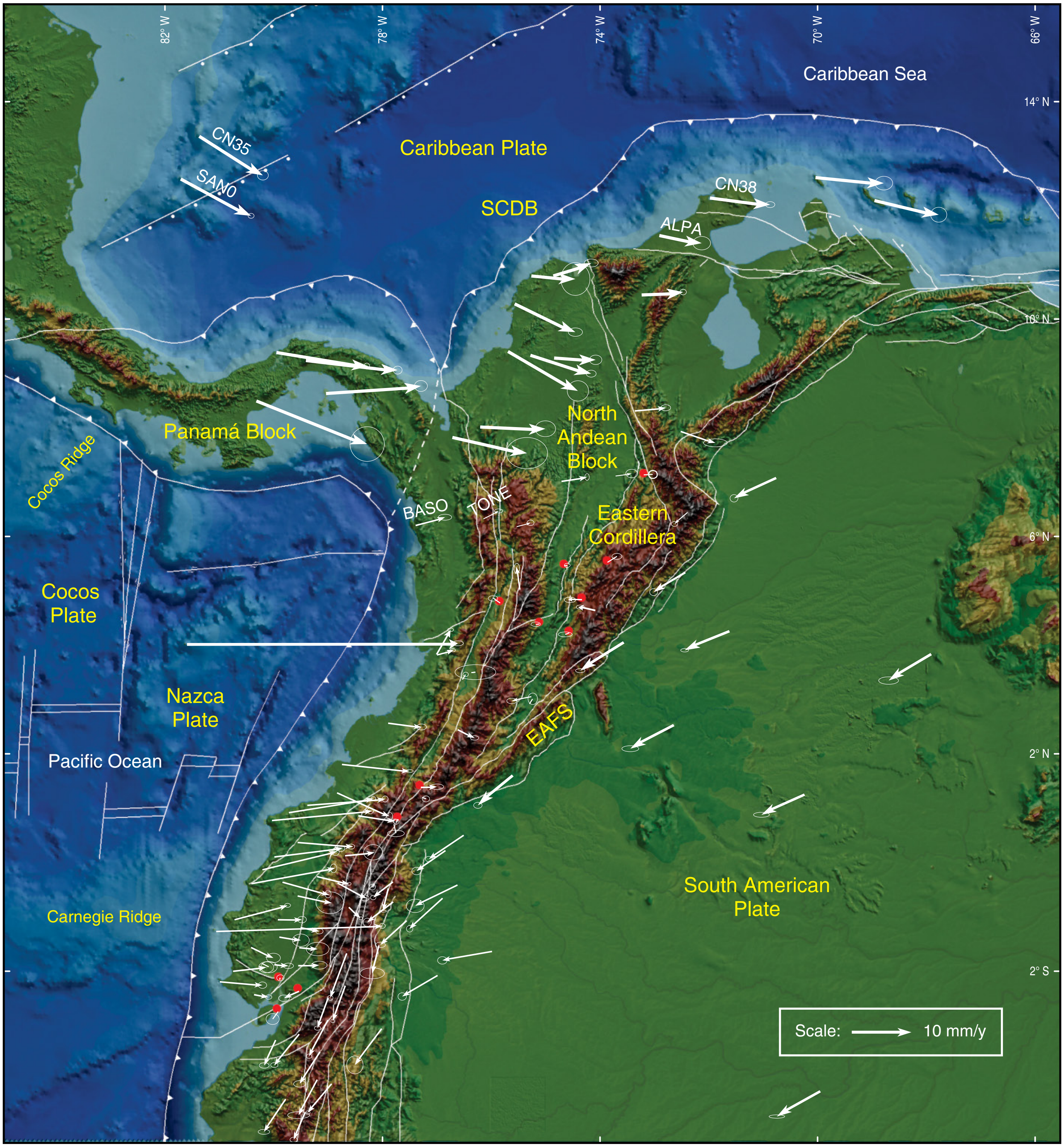

Figure 7. Velocities relative to the North Andes Block (Mora–Páez et al., 2019), one sigma error ellipses; Table 3, Supplementary Information. Red circles: sites used to re–estimate the North Andes motion. (EAFS) East Andean Fault System; (SCDB) South Caribbean deformed belt.

farther to the north. Determining North Andean Block motion relative to stable South America was important to accurately estimate slip partitioning into margin–parallel rigid body translation along the broad East Andean Fault System (EAFS, Figure 6), margin–normal elastic strain accumulation on the Ecuador–Colombia trench, and permanent shortening and mountain building. Mora–Páez et al. (2019) estimated that the North Andes Block rotates counter–clockwise at a rate of 0.072°/Ma about a pole located at 58.6° N, 174.8° W. Because the pole of rotation is located far away, the block motion of all

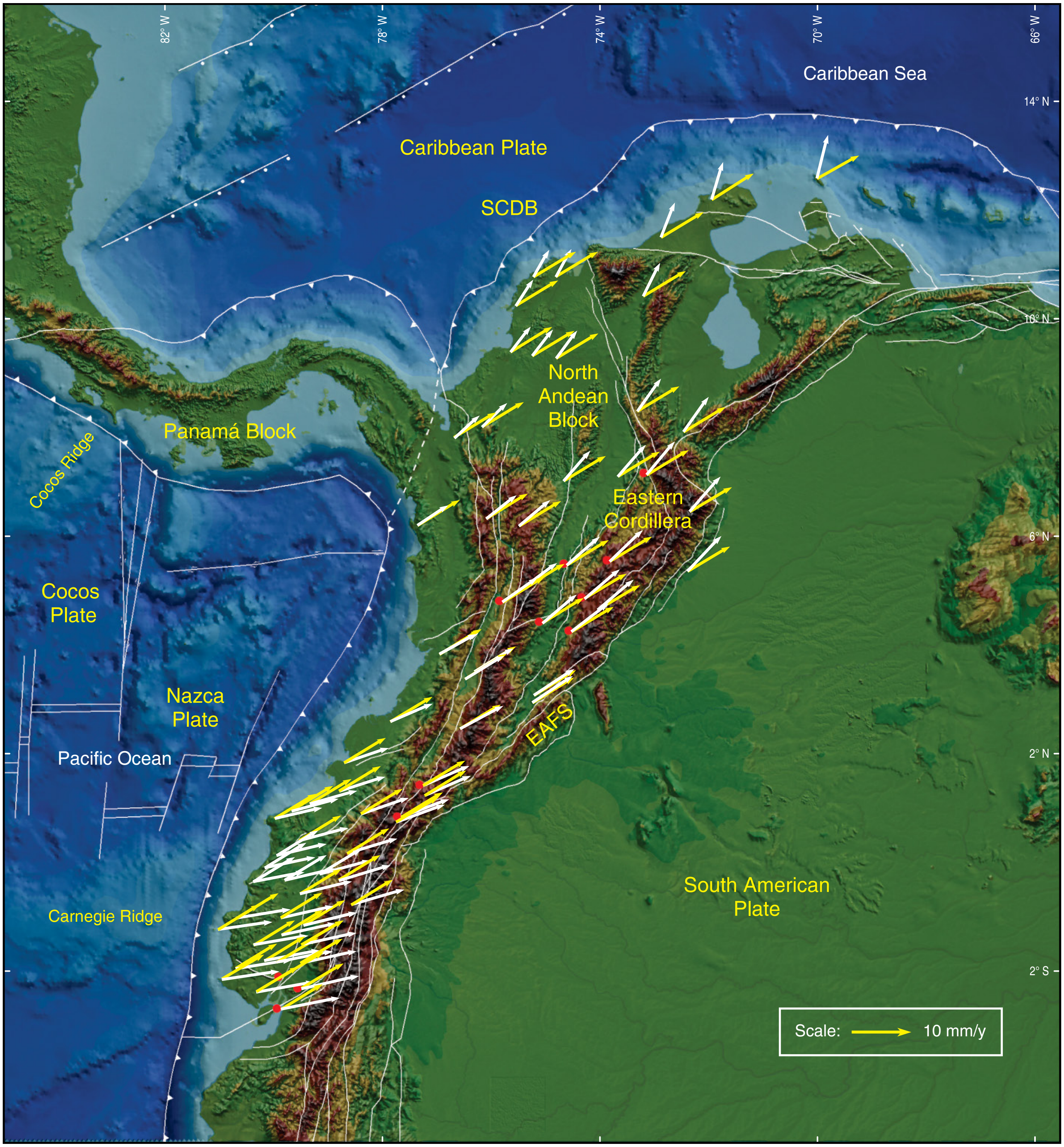

Figure 8. Predicted motion of the North Andes Block relative to stable South America from Mora–Páez et al. (2019) (yellow arrows) and Nocquet et al. (2014) (white arrows). Red circles: sites used to re–estimate the North Andes motion. (EAFS) East Andean Fault System; (SCDB) South Caribbean deformed belt.

sites across the North Andes Block are very similar, with minimal rotation about a local vertical axis. As it is common for small plates or blocks, the pole location is highly correlated with the angular speed. Velocities relative to the North Andes Block and the predicted block motion are shown in Figures 7 and 8, respectively, and clearly show the elastic strain signal from the Nazca plate subduction, oblique convergence across the Eastern Cordillera, and the effects of Panamá arc collision and Caribbean Plate subduction. The North Andean Block is moving to the northeast (060°) at a rate of 8.6 mm/y, and the

North Andean Block vector can be resolved into a margin–parallel (035°) component of 8.1 mm/y rigid "escape" and a margin–normal (125°) component of 4.3 mm/y.

3.2. Nazca Subduction

Sites on the Pacific coast of Colombia and Ecuador show substantial inland–directed motion relative to South America and the North Andes (Figures 6, 7). Kobayashi et al. (2014) modeled the eastward motion of these coastal sites as being due to pre–earthquake 100% coupling at the trench, decreasing to 50% by 20 km depth in a 3D model of elastic strain accumulation. Just to the north at Guapi (GUAP) eastward movement at the coast drops to 5.5 ± 0.7 mm/y. White et al. (2003) interpreted the reduction in apparent locking in southwest Colombia relative to northern Ecuador as the result of viscoelastic relaxation in the lower crust following the 1979 Mw 8.2 subduction earthquake.

3.3. Caribbean Subduction

San Andrés and Providencia islands (SAN0 and CN35, two of the very few sites unequivocally located on the stable Caribbean Plate) obliquely converge east–southeastward with stable South America at 18.2 mm/y and 17.2 mm/y respectively (Figure 6) and southeastward with respect to North Andean Block at 13.2 mm/y and 12.4 mm/y (Figure 7) respectively. Slow amagmatic Caribbean subduction under the North Andes has been proposed by numerous authors based on a weak Wadati Benioff zone (e.g., Dewey, 1972; Kellogg & Bonini, 1982; Bernal–Olaya et al., 2015), seismic tomographic evidence for a south–dipping, high velocity slab (van der Hilst & Mann, 1994; van Benthem et al., 2013), seismic reflection profiles that show Caribbean acoustic basement underthrusting the deformed belt (e.g., Silver et al., 1975; Ladd et al., 1984; Bernal–Olaya et al., 2015), and plate motion models that require convergence (Boschman et al., 2014; Kobayashi et al., 2014). The new GPS velocity vectors presented here suggest subduction–related deformation in the overriding North Andean Block. Even though we estimate a significant eastward motion of the North Andes Block relative to South America, Caribbean coastal sites still show large motions relative to the North Andes. CN38 and ALPA are moving eastward at 9.9 mm/y and 7.0 mm/y relative to the North Andes (Figure 7).

3.4. Arc–Continent Collision

The Panamá arc is rapidly colliding eastward with the North Andean Block at approximately 15–18 mm/y, but surprisingly, the present deformation associated with the Panamá arc collision is confined to the North Andes north of 7.5° N latitude (Figure 7; Mora–Páez et al., 2019). Mora–Páez et al. (2019) propose that the Panamá arc is acting as a rigid indentor. The Colombia–Panamá border area is a zone of active seismicity with earthquake focal mechanisms consistent with compression normal to the Panamá–North Andes suture (Freymueller et al., 1993; Wallace & Beck, 1993). Geodetic evidence for active Panamá–North Andes collision was first reported by Kellogg et al. (1995). Kobayashi et al. (2014) interpret the eastward motion of the Panamá Block as tectonic escape from the subducting Cocos Ridge at the Middle America Trench and modeled the Panamá–North Andes blocks convergence as 12.2 mm/y to the southeast (124°). Since the Panamá–North Andes convergence zone involves the collision of two thick buoyant crustal blocks, the resulting deformation is collision–like, unlike subduction zones where most of the convergence in the overriding plate is recoverable elastic strain associated with the earthquake cycle. The new Mora–Páez et al. (2019) vectors are consistent with the Trenkamp et al. (2002) model for Panamá collision related deformation in northern Colombia over a locked east–dipping thrust fault zone. The present on–going collision poses a major earthquake hazard from the Panamá border to Medellín, Colombia.

3.5. Margin–Parallel "Escape"

McCaffrey (1996) has shown that about half of all modern subduction zones have mobile forearc blocks. Slip partitioning into margin–parallel and margin–normal components within the overriding plate at oblique subduction zones frequently results in lithospheric blocks being detached from the overriding plate. The forearc blocks are driven by plate coupling and are displaced relative to the overriding plate (McCaffrey, 2002). The Mora–Páez et al. (2019) estimate of the average motion of the North Andean Block (8.6 mm/y toward 060°, can be resolved into a margin–parallel (035°) component of 8.1 mm/y (Figure 9) and a margin–normal (125°) component of 4.3 mm/y (Figure 10), assuming that the average trend of the North Andes–South America margin is 035° between 1° and 7° N latitude. Mora–Páez et al. (2016) estimated right–lateral strike–slip shear along the northeast trending Eastern Cordillera of 8.0 ± 1.7 mm/y. Most of the northeastward "escape" is accommodated along the broad East Andean Fault System (EAFS). Near Panamá and north of 6° N latitude the margin–parallel rates increase up to 10.4 mm/y (CORO, VMAG, VORA, VPOL), probably due to the Panamá arc–North Andes collision. This rate is comparable to the slip rate of 8–10 mm/y along the Boconó Fault zone in Venezuela from geological and geodetic data (e.g., Audemard, 2009, 2014). Egbue & Kellogg (2010) compiled field geologic estimates of northeastward displacement rates for the North Andes with a mean estimated geologic slip rate for the last 86 000 years of 7.6 mm/y. The earliest measurements date back to the opening of the Gulf of Guayaquil at 1.8 Ma, and the northeastward displacement of the North Andes has been interpreted as tectonic escape from

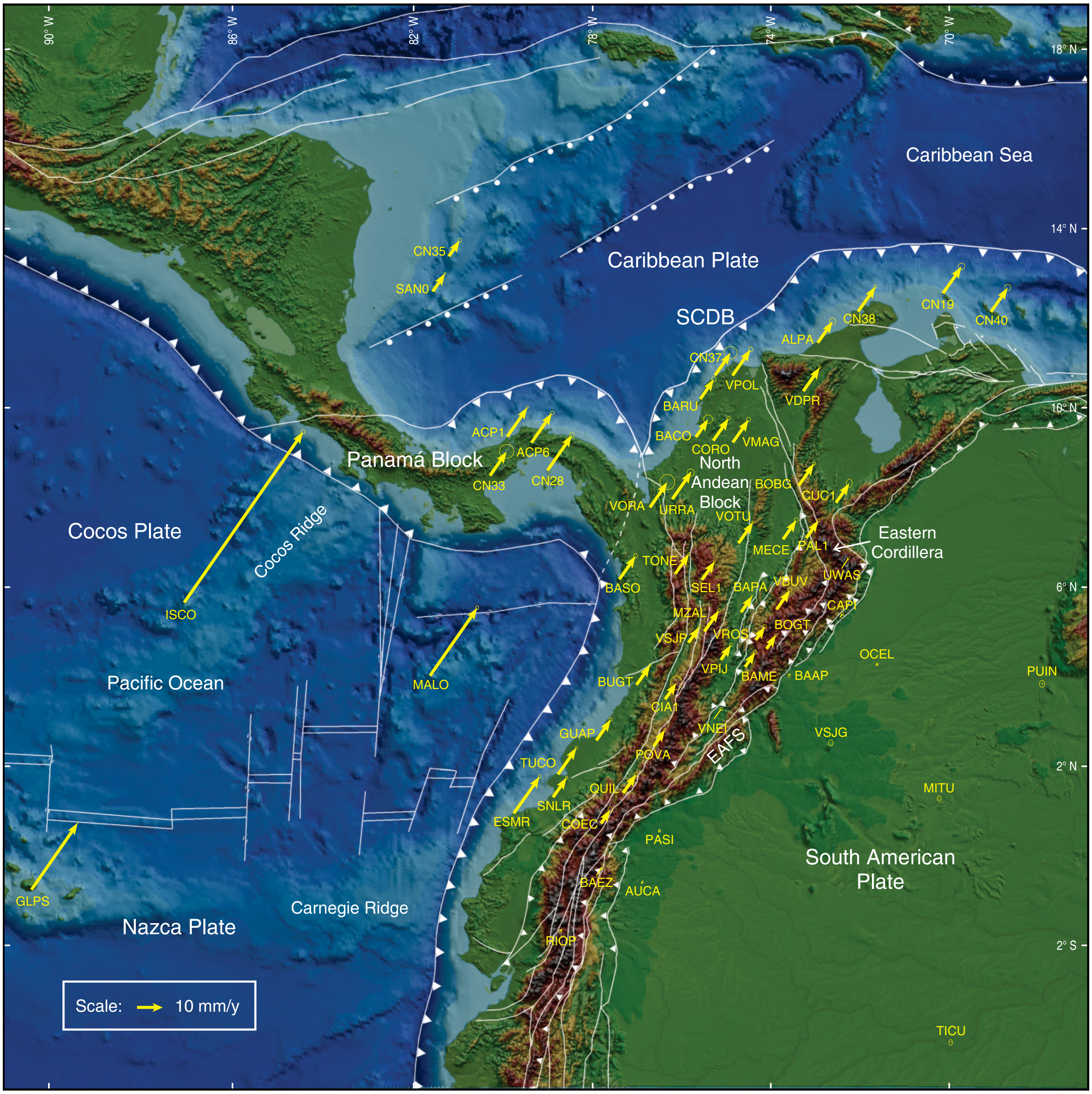

Figure 9. Margin–parallel component of the North Andes Block; Table 2, Supplementary Information. Station names in yellow. (EAFS) East Andean Fault System; (SCDB) South Caribbean deformed belt.

the Carnegie Ridge subducting at the Ecuador Trench (Egbue & Kellogg, 2010; Chlieh et al., 2014; Nocquet et al., 2014). Presently, in the Eastern Cordillera the northeastward margin–parallel "escape" rate (8.1 mm/y) is greater than the rate of range–normal shortening (4.3 mm/y). Therefore, northeast trending right–lateral strike–slip faulting is an increasing component of the seismic hazard for the Eastern Cordillera and the 8 million inhabitants of Bogotá, the capital city of Colombia.

4. Discussion

4.1. Margin–Normal Mountain Building "Broken Indenter"

Margin–normal velocities within the North Andes, assuming that the average trend of the North Andes–South America margin is 035° between 1° and 7° N latitude, vary from 0.9 to 16.6

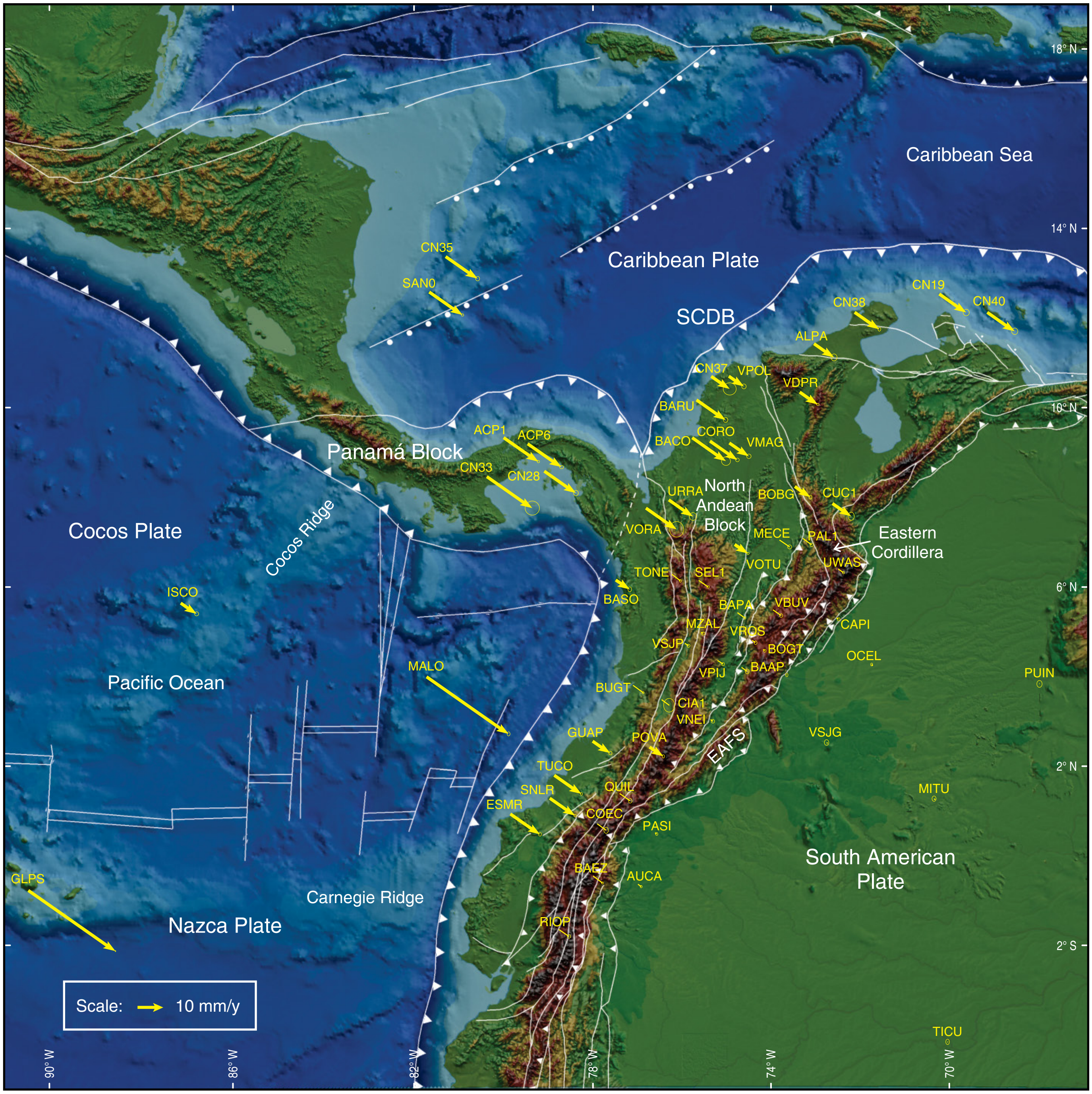

Figure 10. Margin–normal component of the North Andes Block; Table 2, Supplementary Information. Station names in yellow. (EAFS) South Caribbean deformed belt; (SCDB) East Andean Fault System.

mm/y. There are much greater variations in margin–normal displacement in the North Andes than variations in margin–parallel displacement, because margin–parallel vectors are dominated by escape–related translation while margin–normal vectors are dominated by the subduction earthquake cycle and permanent deformation (mountain building). In Colombia's Eastern Cordillera (BAME, UWAS, VBUV, VROS), the shortening rates are less than 4.1 mm/y. The margin–normal component of the average North Andes Block vector is 4.3 mm/y (Mora–Páez et al., 2019).

There is an apparent discrepancy between the small GPS measured margin–normal shortening in the Eastern Cordillera of Colombia and paleobotanical, radiometric, and geologic evidence for recent rapid shortening and uplift of the cordillera. Mora–Páez et al. (2016) interpreted the small GPS measured shortening as evidence for slow formation of the Eastern Cordillera over a period of up to 40 my. They argue that the paleobotanical evidence for recent rapid uplift may represent local uplift or may have been influenced by climate change or invasive species from North America.

The apparent dichotomy of rapid Miocene shortening in the Eastern Cordillera and very slow range normal shortening at present (new GPS results) may be explained by a "broken indenter" model (Mora–Páez et al., 2019). The rigid Panamá–Chocó collision with the North Andes (15–18 mm/y at present) produced rapid permanent deformation in the North Andes, especially after the closure of the Central American Seaway and formation of the land bridge in the last 10 Ma. The present–day GPS vectors at BASO and TONE (Figures 6, 7), however, suggest that the Chocó Block is no longer part of the rigid Panamá indenter but has been accreted to the North Andes. The new velocity field presented in Mora–Páez et al. (2019) highlights the increase in North Andes deformation north of 7.5° N (Figure 7) related to present day Panamá–North Andes convergence. If this interpretation is correct, the break in the Panamá–Chocó indenter and Chocó accretion to the North Andes must have occurred very recently (in the last 1–2 Ma) to explain the rapid Late Miocene shortening and uplift.

Rapid margin–normal shortening of 9 to 14 mm/y in northern Colombia north of 7° N, reflects mountain building and seismic hazard across the broad plate boundary, including the Western and Central Cordilleras of Colombia and the Mérida Andes of Venezuela (e.g., Kellogg & Bonini, 1982; Audemard & Audemard, 2002). The permanent shortening in northern Colombia and Venezuela is driven by the Panamá collision and Caribbean subduction.

5. Conclusions

Colombia has experienced substantial progress in the understanding of the dynamics of the Earth's crust through the use of space geodesy technology. Important steps have been taken to generate a reference frame for geodynamic studies, starting with the 1988 GPS CASA project. The global success of continuously operating permanent stations inspired the establishment of the Colombia GeoRED network of permanent stations by the Servicio Geológico Colombiano, a key component of the Latin American geodetic reference frame. National and international cooperation made possible the acquisition of scientific software, high–precision instruments, and advice, and ensured the consolidation of a high–precision geodetic network. Rigorous procedures for the installation of the geodetic stations on the Earth's surface guarantee the quality of the data obtained at each of the stations. In this way, the results obtained correspond to the state of the art in scientific geodetic applications for the study of earth´s dynamics in Colombia, and permit advances in other scientific fields of knowledge.

Thus, the Servicio Geológico Colombiano through the GeoRED project is creating a high–quality GNSS infrastructure that serves as an essential framework for the study of crustal and atmospheric dynamics of the entire Colombian territory, and, at the same time sharing data and research results with neighboring countries. Data products include raw GNSS observations, and measurements of atmospheric water vapor, that facilitate the construction of time series of high precision daily geodetic positions. These data permit the compilation of surface velocity fields that register crustal dynamic behavior of direct relevance to geohazard research in earth and atmospheric sciences. We are planning to increase the density of the national GNSS network in an effort to address specific geoscience measurement of plate kinematics and crustal dynamics, the recording of active fault slip rates, and plate boundary interaction and deformation, including the understanding of the earthquake cycle.

It is expected that under the framework of the SATREPS (Science and Technology Research Partnership for Sustainable Development) project, with the support of JICA (Japan International Cooperation Agency), the analysis of geodetic data performed together with researchers of the University of Nagoya, will contribute to obtaining more scientific products from the application of space geodesy in Colombia. One of the main results obtained up to now, is the coupling model for the Pacific subduction zone, at the Ecuador–Colombia boundary, that is also presented in Sagiya & Mora–Páez (2019).

5.1. Challenges

GNSS Geodesy has great relevance for all aspects of Earth Science research at the Servicio Geológico Colombiano, including the application of new space geodesy technology that permits the active observation of crustal and atmospheric dynamics that shape the Earth's surface and processes at depth. The crustal deformation that the GNSS network can measure includes seismic and volcanic movements, measurements that are needed to estimate and prepare for geohazards and to limit the damage from future natural disasters in Colombia.

The main challenges for the future are:

- Obtain geodetic rates of fault displacements to characterize the kinematics of active faults and their seismogenic potential.
- Generate crustal sub–block and regional deformation models for Colombia, through the integration of geodetic, geological, and geophysical data.
- Maintain a dense GNSS network composed of continuously–operating long–term stations, most of them transmitting data in near real–time, as well as a network of field stations for campaign data collection.
- Study and understand the ionosphere behavior and its relationship with other phenomena such as earthquakes (lithosphere–atmospheric coupling, tsunamis, etc.).
- Continue performing activities related to subsidence, mass movement, and mud–diapirism studies, promoting the integration of geodetic imaging (InSAR) techniques with positioning geodesy (GNSS), and also the

collaboration with other research institutions carrying out projects to install and occupy field geodetic stations on local networks focused on displacements related to mass movements.

- Provide support to atmospheric and ionospheric studies for different applications (navigation, surveying, etc.), through the collocation of meteorological sensors at selected CORS stations, and the estimation of daily total electron content (TEC) values.
- Continue doing geodetic ties with tide gauges in a collaborative project with the Armada Nacional and Dirección General Marítima (Dimar) to support sea level studies.
- Collaboration should involve data exchange, comparison of geodetic processing procedures and reference frame analysis, as well as fostering international cooperation on geoscience research in the fields of geodynamics and atmospheric science.
- Colombian investigators should continue to cooperate and interchange with international organizations.

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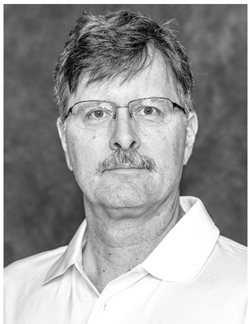
Explanation of Acronyms, Abbreviations, and Symbols:

ACP	Autoridad del Canal de Panamá
CASA	Central And South America GPS Project
Cenicaña	Centro de Investigación de la Caña de Azúcar
COCONet	Continuously Operating Caribbean GPS Observational Network
CORS	Continuously Operating Reference Station
Dimar	Dirección General Marítima
EAFS	East Andean Fault System
ESPONA	Escuela Politécnica Nacional de Quito
FLINN	Fiducial Laboratories for an International Natural Science Network
GeoRED	Geodesia: Red de Estudios de Deformación
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IGC	International GNSS Service
Ingeominas	Instituto Colombiano de Geología y Minería
JICA	Japan International Cooperation Agency
JPL	Jet Propulsion Laboratory
MLE	Maximum likelihood estimation
NAB	North Andean Block
NASA	National Aeronautics and Space Administration
NSF	National Science Foundation
SATREPS	Science and Technology Research Partnership for Sustainable Development Project
SEGAL	Space & Earth Geodetic Analysis Laboratory at the University of Beira Interior
SGC	Servicio Geológico Colombiano
TEC	Total electron content
UNAVCO	University NAVSTAR Consortium

Authors' Biographical Notes

Héctor MORA–PÁEZ has been linked for more than 30 years to tectonic and volcano geodesy research projects to study the deformation of the Earth's crust. He graduated as Cadastral and Geodetic Engineer from the Universidad Distrital of Bogotá, Colombia, obtained a MSc from the University of South Carolina, USA, and a PhD from the University of Nagoya, Japan. He is currently the coordinator of the Space Geodesy Research Group at the Servicio Geológico Colombiano, under which the project named Implementation of the GNSS National Network of permanent stations for geodynamic purposes — GeoRED is carried out, a proposal that he presented in 2006. He started working in tectonic geodesy in the CASA project, under the leadership of the second author and advice of the third author of this article, gathering data in the field, coordinating field campaigns, and processing data from stations located in Costa Rica, Panamá, Colombia, Venezuela, and Ecuador. At the end of the CASA project, he led a construction plan for GPS field stations and data collection, with loan of geodetic equipment from UNAVCO.

James KELLOGG has studied the geology and tectonics of the southwest Caribbean and northern Andes for over 40 years. He is Distinguished Professor and Director of the Andean Geophysical Laboratory at the University of South Carolina, and associate editor of the *Journal of South American Earth Sciences* for which he served as editor–in–chief for 22 years. His research specializes in seismic, geodetic, gravity, and tectonic studies of active margins and orogenic belts. He was principal investigator for the Central and South America (CASA) GPS Geodesy Project, and the Colombia, Perú, and Bolivia Geophysical Projects. CASA was the first GPS project at a convergent plate boundary and the first with a global civilian tracking network. He is especially proud of his many accomplished students, including the two coauthors. Jim is a member of the South Carolina Academy of Science, a Distinguished Fulbright Lecturer, and member of the American Geophysical Union, Society of Exploration Geophysicists, American Association of Petroleum Geologists, and Geological Society of America.



Jeffrey T. FREYMUELLER graduated from the University of South Carolina with a PhD in geology in 1991, followed that with postdoctoral work at Stanford University. He was on the faculty at the University of Alaska Fairbanks from 1995–2018, and now holds and endowed chair faculty position at Michigan State University. He was named a Fellow of the American Geophysical Union in 2014 for his career contributions to geodesy and its application to tectonic and volcanic problems. Dr. FREYMUELLER's research focuses on the measurement and modeling of solid earth deformation caused by a variety of sources, including active tectonics and earthquakes, volcanism, hydrological, and cryospheric mass variations, and sea level change. He began his career studying the plate motions and active tectonics of the North Andes with the Central and South America (CASA) GPS Geodesy project, and since then has done similar work in tectonically active regions such as California, Alaska, and China. From 2003–2011 he was a member of the US National Committee for Geodesy and Geophysics and the official US National Correspondent to the International Association of Geodesy, and was chair of the committee from 2011–2016 and the official US Council Delegate to the International Union of Geodesy and Geophysics (IUGG).