# UNIVERSIDAD DE INVESTIGACIÓN DE TECNOLOGÍA EXPERIMENTAL YACHAY

## Escuela de Ciencias de la Tierra, Energía y Ambiente

# TÍTULO: TECTONOSEQUENCE ANALYSIS OF THE MANABI BASIN, ECUADOR.

Trabajo de integración curricular presentado como requisito para la obtención del título de Geología.

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Urcuquí, Abril 2020

Urcuquí, 15 de abril de 2020

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## ACTA DE DEFENSA No. UITEY-GEO-2020-00009-AD

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# Dedication

"To my mother, father, and sister,
who survived to give me still their love
and unconditional support,
but especially,
to my brother David(+) thank you,
give me forces wherever you are.
I see you on the other side."

Milton Ruben Catota Villitanga.

# Acknowledgment

I want to express my thankfulness to my parents for their patience and support, while I finalize my university career. I thank you, mother Maria del Carmen Villitanga, for your love and to show strength after the happened us. I thank you, father Victor Catota, to show me responsibility and look after our family. Sister Jessie, I love you and thank you for helping me with this dream. I thankfulness that all you had survived, and I hope to give you joys because we have already suffered a lot.

I thank you, Brother David (+) because you believed and helped me while you were alive. I always remember you, and you are synonymous with force to face difficult situations of life.

I am grateful I had decided to come to Yachay Tech University because I lived good years among sciences, friendships, and adventures. Moreover, I thank Yachay Tech's professors because you are the best like person and professionals. Also, I appreciate I met friends and partners that will be great leaders of Ecuador. Thanks for all, Yachay Tech.

Milton Rubén Catota Villitanga

## Abstract

The Manabí basin situates in the Coastal Region of Ecuador, is constituted by a basement due to accretion of oceanic terranes that collided with the continental margin of South America, as well as Cenozoic sedimentary sequences that overlie the Cretaceous basement. These sedimentary sequences have deformed by the subduction between Nazca and South America plates. Thus, the stratigraphic succession of the Manabi Basin has divided into five tectonosequences through analyzing and interpreting data like seismic lines, wells, and geological maps to understand the Ecuadorian forearc basin and its evolution. Moreover, the tectonosequences produce isopach maps that show geometry and unconformities of the basin. The tectonosequences analysis carried out in this work has allowed inferring the tectonic development of the Manabi Basin, which considers three distinct geological phases: (a) Conformation of Cretaceous basement where deformation events are observed, (b) initiation of the formations of forearc basins due to rapid convergence in the active margin during the Middle and Late Eocene that caused drastic changes in forearc settings due to the extensional process. (c) Strong subsidence developed during Neogene age increased the thickness of the sedimentary infill and subsequent Carnegie Ridge subduction that triggered the inversion of the Manabi Basin.

**Key Words:** Tectonosequences, unconformities, sedimentary infill, evolution.

## Resumen

La cuenca del Manabí se encuentra en la Región Costera del Ecuador. Está formado por un basamento debido a la acumulación de terrenos oceánicos que colisionaron con el margen continental de América del Sur, así como de las secuencias sedimentarias Cenozoicas que se superponen al basamento Cretácico. Estas secuencias sedimentarias se han deformado por la subducción entre las placas de Nazca y América del Sur ha deformado estas secuencias. Entonces, la sucesión estratigráfica de la cuenca de Manabi se ha dividido en cinco tectonosecuencias a través del análisis e interpretación de datos como líneas sísmicas, pozos y mapas geológicos para comprender la cuenca de antearco ecuatoriano y su evolución. Además, las tectonosecuencias producen mapas de isopaca que muestran fallas, geometría e inconformidades de la cuenca. El análisis de las tectonosecuencias realizado ha permitido inferir el desarrollo tectónico de la cuenca del Manabi, que considera tres fases geológicas distintas: (a) conformación del basamento Cretácico donde se observa eventos de deformación. (b) inició de las formaciones sedimentarias de la cuenca de antearco debido a la rápida convergencia en el margen activo durante el Eoceno medio y tardío que causó cambios drásticos en la configuración del antearco debido al proceso de extensión. (c) La fuerte subsidencia desarrollada durante la edad de Neógeno aumentó el grosor del relleno sedimentario y la subsiguiente subducción de Carnegie Ridge que desencadenó en la inversión de la cuenca de Manabi.

**Palabras clave:** Tectonosecuencias, discordancias, relleno sedimentario, evolución.

**INDEX**

# CHAPTER 1

## 1. INTRODUCTION

The Western part of Ecuador has been built by the accretion of oceanic terranes to the continental margin during the Cretaceous time (Jaillard et al., 1997; Kerr et al., 2002), as well as, extensional and compressive tectonic events during Eocene-Pleistocene time have settled the Coastal Region. Many types of research describe the tectonic evolution and the configuration of Western Ecuador (Daly, 1989; Reynaul et al., 1999; Kerr et al., 2002; Jaillard et al., 2009), while other authors have studied the Ecuador Coastal basins (Benitez, 1995; Deniaud, 2000; Reyes, 2013; Jaillard et al., 1995).

Moreover, the subduction between Nazca and South America plate determines the geometry of the Ecuador forearc zone. This process triggers regional features like faults, structural highs, and subsidences that establish the current forearc basins. The main basins from south to north are: Progreso, Manabi, Manta-Jama, and Borbon. These basins have examined but one more than others. For example, the Progreso Basin has studied more because the first oil reservoirs of Ecuador exploited there.

Meanwhile, the other basins have been few explored, for example, the Manabi Basin locates in the central part of the Coastal Region has an extensive area that is covered by younger Quaternary and Miocene deposits, so it is not very easy to study. However, Benitez (1995) carried out studies about the lithostratigraphy of the basin, supported by seismic data. So, the subsurface data is the best method for a significant knowledge of the Manabi Basin.

The Ecuadorian forearc basins are important because they have studied to determine possible hydrocarbon potential (Rosania, 1990; Benitez, 1995; Jaillard et al., 1995), for example, in the Progreso basin has more proven hydrocarbon resources than other basins. The Manabi Basin may share similar geological features as well as hydrocarbon resources. For that, several studies made by oil companies have left subsurface and surface data of the Coastal region.

The subsurface data interpretations are relevant because it is possible to determine tectonosequences that allow understanding the geometry and tectonostratigraphy evolution of the forearc basin which have not ever been used in the Manabi Basin yet. This thesis focuses on the Manabi Basin because there is a robust dataset, which includes surface data (geologic, and gravimetric maps) and subsurface data (2D seismic profiles and boreholes). The results of this data constitute an excellent tool to define tectonosequences, strata geometries, unconformities, and lithostratigraphy of the sedimentary infill.

Therefore, this thesis aims to interpret seismic sections, establish tectonosequences of the Manabi Basin in order to increase our understanding of the sedimentary infill evolution.

## 1.1. Geographical Setting.

Continental Ecuador is between 1ºN and 4ºS latitudes in the northwest part of South America. It divides into three geographic regions, which from west to east are: Coastal, Highland, and Oriente regions (Fig.1.1a). The Manabi Basin situates in the Ecuador Coastal region (Fig.1.1a, b), and its geographical setting is related to the processes of the forearc zone.

The study area (Manabi Basin) has two main geomorphological features: the Coastal Cordillera (CC) and Chongon Colonche Cordillera (CCC) in the littoral zone, and Coastal Plain close to the Highland Region (Fig.1.1a). The elevations of the structural highs are 800 masl and show mainly Cretaceous rocks. Meanwhile, the Quaternary and Neogene sediments cover the Coastal Plain.

Specifically, the Manabi Basin is between 0ºN and 2º S latitudes in the Coastal Cordillera with NNE-SSW orientation (Fig. 1.1a, b). As a geographic reference, the study area is located mainly in the Manabi province located to the north of the Chongon Colonche Cordillera.

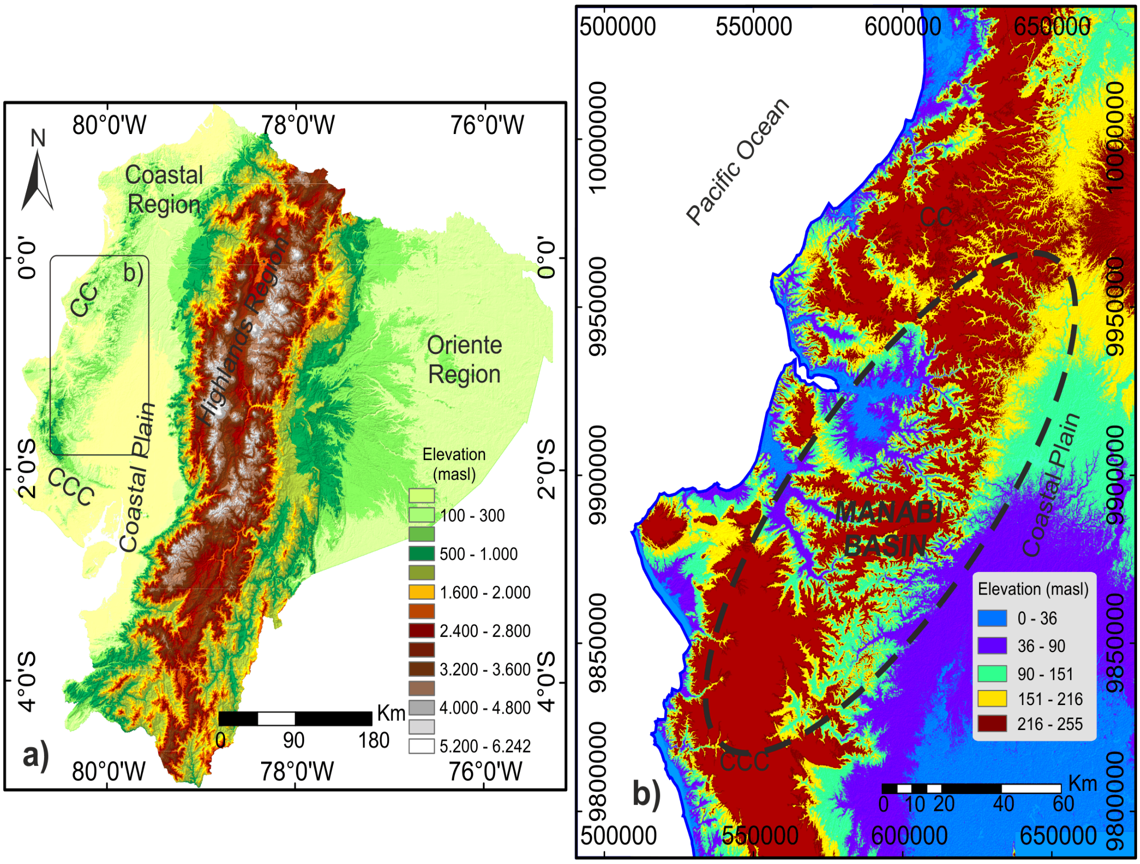

**Figure 1.1.** Localization Maps. a) Ecuador topographical map shows the main regions and structural highs of the Coastal region: Chongon Colonche Cordillera (CCC) and Coastal Cordillera (CC). The square delimits the study area. b) Digital Elevation Model of the Manabi Basin shows geomorphological features such as elevated areas and Coastal Plain. Dashed lines show the approximate location of the Manabi Basin. Coordinate System: WGS 1984, UTM Zone 17S. Projection: Transversal Mercator. Datum: WGS 84

## 1.2. Objectives

### 1.2.1. Principal Objective

Define and describe the tectonosequences of the sedimentary infill of the Manabi Basin and the tectonic structures to understand the configuration and evolution of the basin.

### 1.2.2. Secondary Objectives

Some activities must make to achieve the main objective like:

- Compile and describe the lithostratigraphy of the basin.
- Map the regional unconformities both at the surface and subsurface.
- Correlate seismic and well information.
- Interpret seismic lines to get isopach maps of each tectonosequence.
- Delimit the boundaries of the basin.
- Determine the tectonic evolution of the Manabi Basin.

## 1.3. Scope of the Study

This study uses seismic lines (2D) of medium resolution that were interpreted considering the followinf points:

- Geomorphological and structural analysis was carried out using digital elevation model (DEM) 30 meters resolution and geological map at 1:500.000 scale (Reyes, 2013).
- Seismic line analyses was done using the Kingdom Suite software. There the tectonosequences, geometries, and unconformities of the basin were determined.
- The lithostratigraphy description was accomplished by bibliographic review according to Benitez, (1995) and Deniaud, (2000).
- Isopach maps were done to interpret thicknesses, depocenters and existing structures of the basin.

## 1.4. Methodology and dataset

The methodology used to reach the thesis goals include 1) bibliographic compilation of previous works made in the study area like undergraduate thesis, doctoral thesis, papers and research projects; 2) compilation of the topographic and gravimetric maps allow defining the shape and location of the basin, and 3) compilation of the geological maps where contacts, main geological formations, and faults of the Manabi Basin are shown, for example, Geological Map of the Coastal Ecuador with scale 1:500000 by Reyes, (2013). Finally, the seismic and borehole data was provided by the thesis advisor. This data had manipulated only to be interpreted, and cannot be included in this work because there is a confidentiality agreement with Subsecretaria de Hidrocarburos of Ecuador.

After the bibliography review and data recompilation, the data processing carried out. The seismic lines interpretations and isopach maps were made in the Kingdom Suite software, interpreting unconformity-bounded tectonosequences according to published studies.

Additionally, Digital Elevation Models (DEM) with a resolution of 12.5 x 12.5 meters used to complete a geomorphological analysis of the region (Fig. 1.1). The gravimetric anomalies also give relevant information about structural highs and depocenters that constitute the Manabi basin.

On the other hand, the lithostratigraphy of the basin is defined from Benitez, (1995) and Deniaud, (2000). Finally, all these analyses result in five tectonosequences, five unconformities, and the shape of the sedimentary infill.

## 1.5. Previous work

The first works carried out in the Coastal Region were from oil companies such as ANGLO (Anglo-Ecuadorian Company) during seventy’s. Benitez (1995) and Deniaud (2000) are highlight works that detailed stratigraphic studies about Coastal Cordillera (Fig. 1.1a, b), inclusive of the Manabi Basin.

Benitez (1995) studied the geodynamic evolution of the coastal Ecuadorian province during the Upper Cretaceous to Tertiary and carried out stratigraphy, sedimentology, and structural studies to model the geodynamic evolution of the Coastal Region. The author shows studies about the forearc basin according to seismic lines data. So, this work is relevant because it defines lithostratigraphy and carries out a model about the evolution of the Coastal zone from Cretaceous to Neogene.

Deniaud, (2000) defined a set of sedimentary sequences in all Ecuador basins, including the forearc basins. The thesis work presents stratigraphic and tectonic records of the Neogene and determines mega-sequences of the Manabi Basin that shows the tectonic evolution of the Manabi Basin during Neogene.

Among other works about the Coastal Region are the Late Cretaceous–Late Eocene tectonostratigraphic evolution of the southern coast of Ecuador proposed by Jaillard et al., (1995). The work focuses on the Progreso Basin and identifies the Colonche fault as the boundary between Progreso and Manabi Basin. Furthermore, the authors present a stratigraphic framework of the Progreso Basin and suggest tectonic events from Late Cretaceous and Late Eocene of the basin. So, this work shows the Progreso basin development, but also, there are stratigraphic and tectonic data correlated to the Manabi Basin.

Reyes (2013) focuses on the genesis of the Coastal Cordillera during Plio-Quaternary in the Coastal Cordillera of Ecuador. The author presents a regional geological map of the Coastal Cordillera at 1:500.000 scale, and also concludes that there was a heterogeneous uplift because the Coastal cordillera segmented into several blocks. Finally, the author determined the faults of the zone and showed the stratigraphy of the Neogene Formations.

Egüez et al. (2003) described several faults and folds of the five morphostructural regions of Ecuador and showed several characteristics of these. The authors present a database with the geological setting, geometry, slip rate, and geological time of most recent movement of faults and folds. So, it is helpful to interpreter geological features of the Manabi Basin located in the Ecuadorian fore-arc.

Hernandez (2012) identifies a possible extension of the Jama fault system on Ecuadorian off-shore through seismic reflection profiles. Jama zone is an important area where sedimentary deposits associated with Manabi Basin Formation outcrops. Also, the author determines that the Jama fault extension is a neo-tectonic structure that acts from the Plio-Pleistocene boundary. This work confirms that Cañaveral fault, also known as Jama fault, is the northwest limit of the basin.

The Cretaceous accretion of the oceanic terranes has studied by Daly (1989); Jaillard et al. (1997); Reynauld et al. (1999), among others. For example, the geochemical and tectonic of the accreted oceanic terranes in Western Ecuador by Kerr et al., (2002) shows geochemical studies of Cretaceous terranes. Authors define the Western Cordillera as a complex tectonic melange of oceanic terranes accreted that has formed by subduction–accretion processes involving oceanic plateau basalts, through island-arc tholeiites. They conclude that two accretion phases occurred in western Ecuador. The second accretion is significant because Piñon Unit oceanic plateau sequences accreted in Late Eocene. So, this paper is useful to understand tectonic processes that occurred in western Ecuador related to its basement, and stratigraphy of the Manabi Basin during Cretaceous time.

Different studies carried out by previous authors, present a tectonic and stratigraphic analysis of all Coastal Cordillera. This work focuses on the Manabi Basin to increase knowledge about geometry, structures, and spatial distribution of the different geological formations that deposited in the sedimentary infill.

# CHAPTER 2

## 2. GEOLOGICAL CONTEXT.

The subduction process between Nazca and Soth America tectonic plates have triggered an active tectonic zone where volcanism, seismicity, uplifting, subsidence, and continental crust deformation has developed in Ecuador continental.

Ecuador belongs to a volcanic arc system with five morphotectonic regions: the Coastal Region, which has a forearc setting, the Andean Region represents volcanic arc that is integrated by the Western and Eastern Cordillera and the Interandean Depression, and finally, the Oriente Basin situated in the backarc zone (Figs. 1.1, 2.1). The Oriente Basin is a foreland sedimentary basin. Andean Cordillera composes by two mountain chains (Fig. 2.1): The Eastern Cordillera or the Cordillera Real which comprises pre-Cretaceous metamorphic rocks (Litherland & Aspden, 1992) and the Western Cordillera constituted by Cretaceous-Tertiary accreted oceanic terranes (Fig. 2.2, Jaillard et al., 1997; Kerr et al., 2002). These separated by an Inter Andean Valley or depression that mainly comprises Eocene-Quaternary sediments (Litherland & Aspden, 1992). Meanwhile, the Coastal Region constituted by the Cretaceous basement related to accreted oceanic terranes overlain by Paleogene–Quaternary sediments (Fig.2.2).

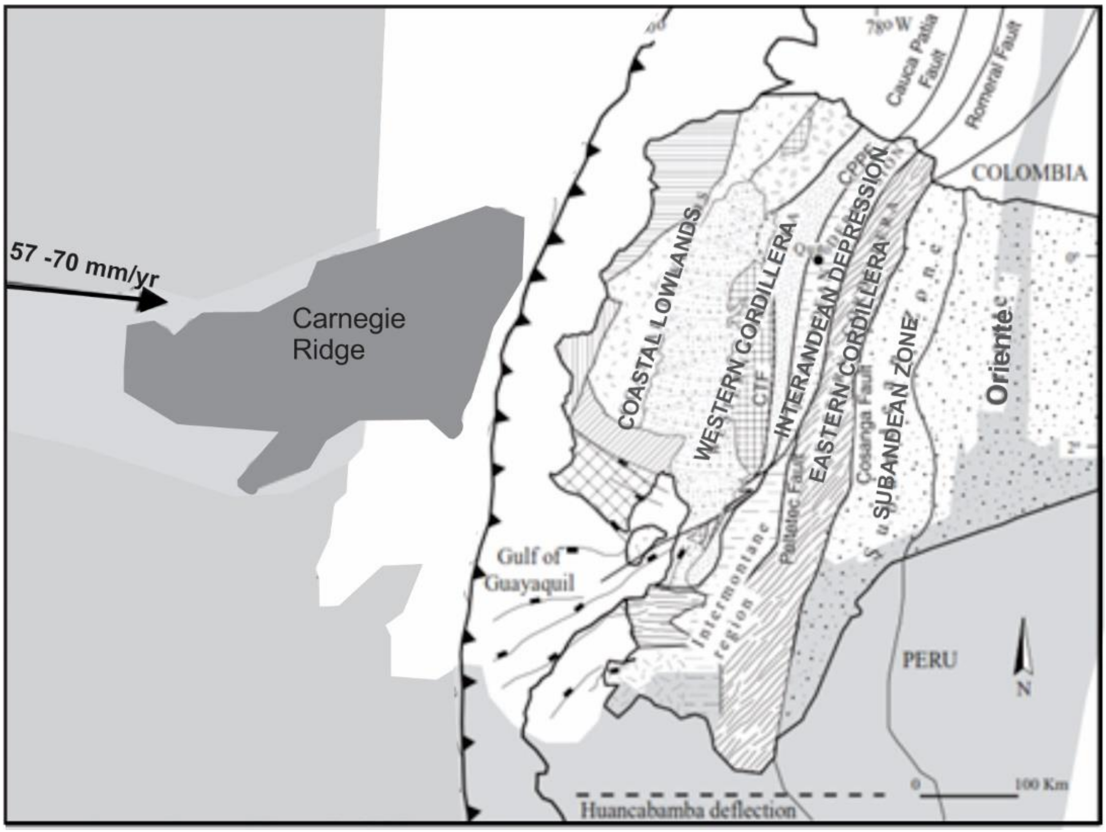

**Figure 2.1.** Geodynamic context of Ecuador shows morphotectonics regions and oceanic structures into convergence boundary between Nazca and South America plates. Modified from Vallejo et al., (2009).

### 2.1. Geodynamic Settings

There is active subduction of the oceanic Nazca Plate beneath the continental South America Plate along the Ecuadorian Coast (Fig. 2.1). This process provokes a deep and continuous offshore oceanic trench and volcanic arc system on continental crust. Some tectonic parameters to understand the geodynamic of Ecuadorian forearc are the convergence velocity across the subduction zone. This velocity is essential because the convergence rate had varied through the time that coincides with high tectonic activity, for example, a very high convergence rate had during Middle to Late Eocene (204±80 mm/yr, Daly, 1989). Currently, the velocity is approximately 58 ± 2 mm/a, which is considered rapid (Trenkamp *et al.*, 2002). Also, the oblique convergent motion between tectonic plates triggers strike-slip deformations like transpression and transtension (Dewey et al., 1998). The forearc is affected by transcurrent fault systems like the Carrizal and Jipijapa faults due to strike-slip displacement (Benitez, 1995).

Moreover, the subduction of the Carnegie Aseismic Ridge (Fig.2.1) initiates at around 8 Ma during Neogene time. Gutscher *et al.,* (1999) concluded that the subduction process between tectonic plates is profoundly affected by the subduction of the Carnegie Ridge. So, Carnegie Aseismic Ridge is an oceanic structure that affects the forearc region and is showed in the geological record through the uplifting and compressional process.

Therefore, the parameters mentioned latest determine that the Manabí Basin is a strike-slip basin developed in Neogene time with strong subsidence (Benitez, 1995).

#### 2.1.1. Regional Geology

The Coastal Region has been identified as an allochthonous terrane of oceanic origin that accreted to the Andean continental margin from Late Cretaceous to Eocene (Fig. 2.2, Jaillard *et al*., 1995; Reynaud *et al*., 1999; Kerr *et al*., 2002). The accreted terrane define as a mafic crystalline basement sequence (Jaillard *et al*., 1995; Reynaud *et al*., 1999) that is covered by intra-oceanic volcanic arcs (Jaillard *et al*., 1995). These Cretaceous sequences are covered by sedimentary sequences that deposited in different paleoenvironments from shallow marine to transitional environments during Paleogene-Quaternary time (Fig. 2.2).

The extensional tectonic processes during the Eocene time (Jaillard, 1995) and compressional processes during Neogene time (Benitez, 1995), both by Nazca and South America plates subduction, have deformed the Coastal Region and settled the current forearc basins (Fig. 2.2).

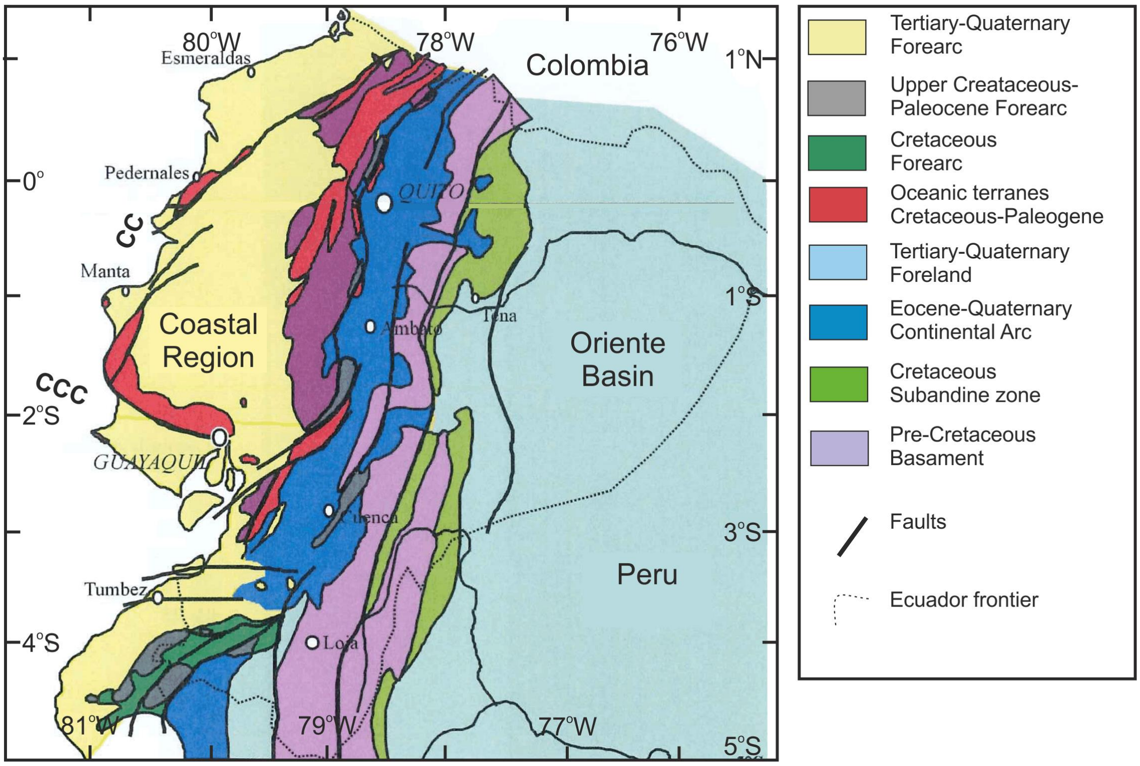

**Figure 2.2.** Geologic scheme of Ecuador show morphotectonic regions and stratigraphic ages. The Coastal region is represented by oceanic terranes from Cretaceous and Tertiary- Quaternary sediments. CC: Coastal Cordillera. CCC: Chongon Colonche Cordillera. Modified from Deniaud, (2000).

### 2.1.2. Forearc Basins

The main basins along the coastal region from north to south are Borbon, Manabi, Manta-Jama, and Progreso basins (Fig. 2.3). The establishment of forearc basins started from middle Eocene time due to a high tectonic activity period that is related by oblique convergent activity in front of the Coastal Region (Fig.2.1).

The obliquity between tectonic plates had developed strike-slip displacement, so that transcurrent faults like Guayaquil, La Cruz, Carrizal, and Jipijapa have formed (Benitez, 1995). These control the geometry and have deformed the forearc basins. The Manabi Basin is a strike-slip basin that had developed compressional and extensional processes due to subduction between tectonic plates. Furthermore, strong subsidence produced from Late Eocene to Neogene time has infilled the basin (Benitez, 1995).

On the other hand, the stratigraphy records show the basement and sedimentary sequences deposited in the forearc basin. Moreover, the Simplified Geological Map of Coastal region shows the geological formations of the Manabi Basin (Fig. 2.4).

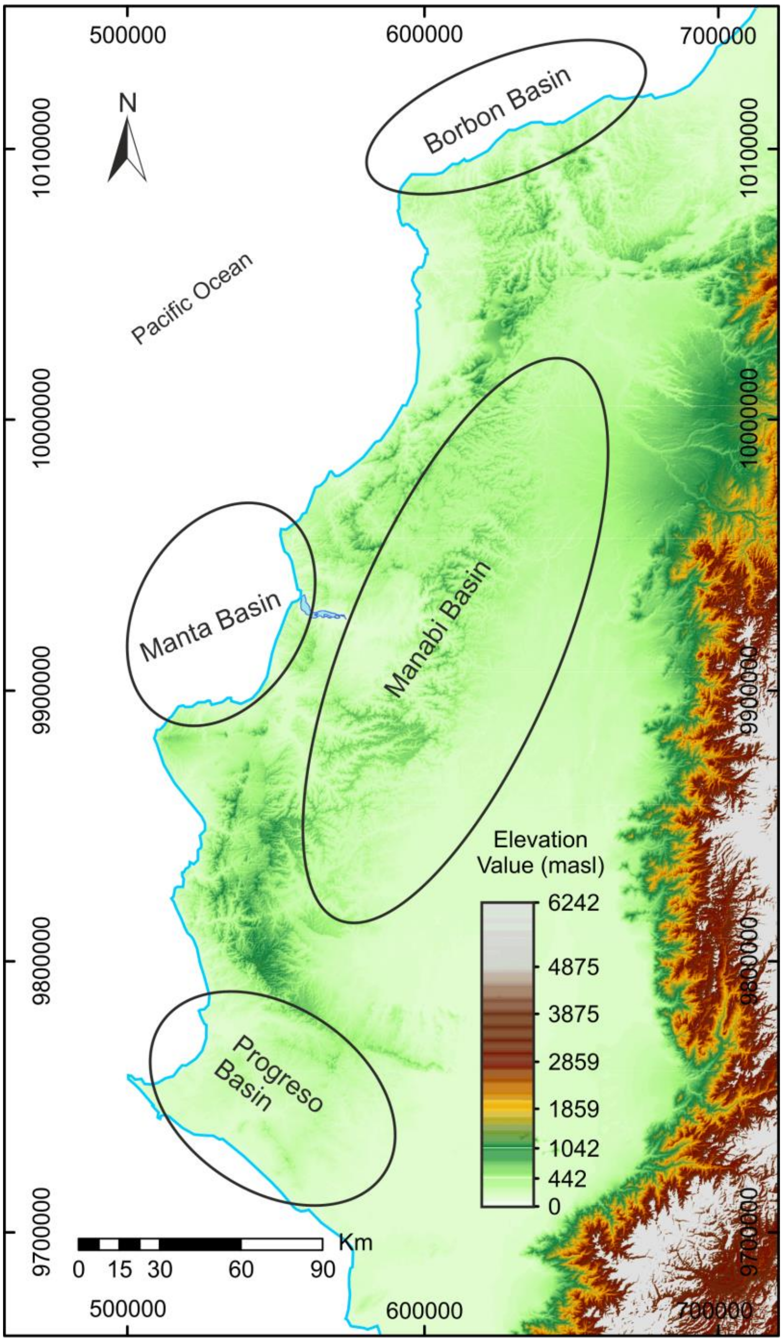

**Figure 2.3.** Digital Elevation Model of the Coastal region shows distribution of the main forearc basins.

## 2.2. Lithostratigraphy

The Paleogene and Neogene lithostratigraphy description is by earlier works like Benitez, (1995) and Deniaud, (2000). Meanwhile, the Cretaceous lithostratigraphy is by some authors like Kerr et al., (2002) and Jaillard et al., (1997). The next chronostratigraphic table shows the geological units of the basin, and tectonosequences describes in section 3 (Fig.2.4).

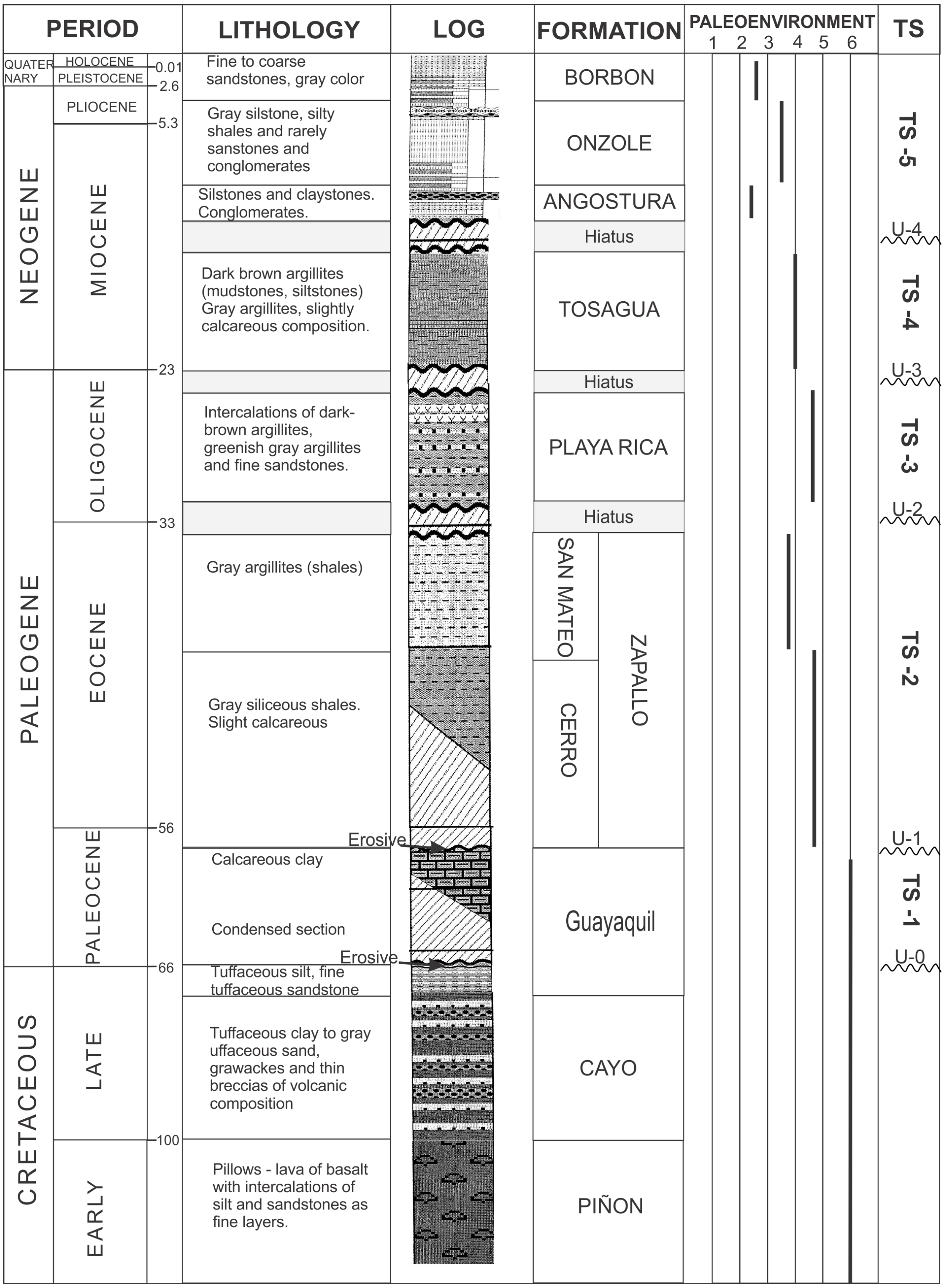

**Figure 2.4.** Chronostratigraphy of the Manabi Basin shows the geological units and tectonosequences division according to unconformities. Moreover, bold lines show the next paleoenvironments: 1. Continental, 2. Transitional, 3. Continental shelf, 4. Continental slope, 5. Continental rise (Bathyal zone), and 6. Abyssal. Modified from Benitez, 1995, and Deniaud, 2000.

### 2.2.1. Piñon Formation

It is the Cretaceous igneous basement of the Coastal region. The tectonic setting, according to geochemical analysis, is an oceanic plateau (Reynaud et al., 1999; Kerr et al., 2002). The name is due to the Piñón River located 20 km to the southwest of Portoviejo (Bristow & Hoffstetter, 1977). The Piñon Formation underlies in conformable contact with volcaniclastic sediments of the San Lorenzo Formation to the north of Manabi Basin. Instead, in Chongon Colonche Cordillera, volcaniclastic sediments of the Cayo Formation rest on in unconformable contact over Piñon Formation to southern (Kerr et al. 2002).

Lithologically constitutes a sequence of pillow basalts and associated hyaloclastite, together with associated massive dolerite sills and dikes (Kerr et al. 2002). The Piñon Formation age varies, for example, in the Manabi – Pedernales area dates dikes of San Lorenzo Formation (72.7 ± 1.6 Ma) to suggest that Piñon top has Campanian age (Kerr et al. 2002). Instead, Benitez, (1995) suggest Upper Aptian – Albian to the base. Likewise, radiometric studies attribute 88 ± 1.6 Ma age for the oceanic plateau of the Piñon Formation (Vallejo, 2009). So, Piñon Formation dates from Upper Aptian to Campanian (Fig. 2.4).

### 2.2.2. San Lorenzo Formation

It consists of coarse-grained volcaniclastic conglomerates associated with basalt flows and dikes that cover in concordant contact the Piñon Formation in the Jama zone. It dates from Upper Cretaceous (Kerr *et al.*, 2002). This formation has calc-alkaline characteristics that identify it as an island arc. (Kerr et al., 2002; Benitez, 1995). The outcrops are located close to Manta – Portoviejo, in the Coastal Cordillera.

According to Jaillard et al., (1995), in the southern of Manabi, there are intercalated sediments that contain Late Campanian–Maastrichtian microfauna, while in the northern outcrops contain Maastrichtian and Paleocene fossils.

### 2.2.3. Cayo Formation

Bristow and Hoffstetter (1977) describe the rocks as a thick sequence of volcanoclastic and sedimentary rocks. Jaillard et al. (1995) report a fining-upward sequence that also contains high and low-density turbidites that could be interpreted as a megaturbidite. So, the deposit environment is turbiditic with a high content of volcanoclastic origin.

Benitez (1995) dates the Cayo Formation from Upper Campanian according to radiolarians *Amphypindax pseudoconulus, A. tylotus, Archeodyctiomitra lamellicostata, Pseudoalophacus florensis, P. paregueraensis, Siphocampe daseia, Solenotryma dacroydes, Stylospongia verteroensis* and *Theocapsoma cf. comis.*

### 2.2.4. Guayaquil Formation

The main outcrops are located in the Progreso Basin, while in the Coastal Cordillera disappear because there is a change towards volcanic facies of the San Lorenzo Formation (Benitez, 1995). For that, the Guayaquil Formation does not crop out in the Manabi Basin, but the subsurface data maps it and correlates with the Manabi Basin. It has Lower and Upper members. Fine sediments of Lower Guayaquil from Maastrichtian overlie the Cayo

Formation, and black limestone silica content and locally sandy tuffaceous are belonging to Upper Guayaquil.

The fossil record dates Upper Paleocene at the top; meanwhile, no foraminifera fossil records establish a discordance during the Lower Paleocene (Benitez, 1995).

### 2.2.5. Cerro Formation

It is located in Cerro town, 13 km to the west from Portoviejo (Bristow & Hoffstetter, 1977). It contains calcareous and sandy tuffs (Feininger & Bristow, 1980). Moreover, according to (Benítez, 1995) Cerro Formation consists of grayish siliceous mudstones (argillites), slightly calcareous. Besides, Cerro Formation has considered a Lower member of the Zapallo Formation (Fig.2.4) mapped from the Borbon basin.

The Cerro Formation dates the Middle Eocene age (Benitez, 1995) corresponding to radiolarians *Podocyrtis ampla, P. diamesa, P. trachodes, P cf. dorus, Eusiringium fistuligerum and Lithapium plegmachanta*. Likewise, calcareous foraminifera and radiolarian content determine a marine paleoenvironment from central to the distal platform.

### 2.2.6. San Mateo Formation

It is the Upper member of the Zapalllo Formation (Fig. 2.4). It overlies in conformable contact on Cerro Formation. Besides, in some sites, the San Mateo Formation overlies in angular unconformity on the Piñon basement or Upper Cretaceous surface in the Coastal Cordillera.

The main outcrop located in San Mateo is 10 km west of Manta. It consists mainly of fine and medium sandstones deposited in shallow waters (Bristow and Hoffstetter, 1977).

Also, according to Benitez, (1995), consists of silico-clastic rocks that emerge in the San Mateo - Cabo San Lorenzo, Puerto López - Salango, Julcuy-Jipijapa, and Pedernales areas. It is composed of three members: the Lower member has sandstone and argillites, the middle member consists of conglomerates in channels and argillites and the Upper member by gray argillites. The basal part would correspond to deltaic sequences due to its increasing stratum character, while the middle member represents a deep continental shelf with a turbiditic environment. Finally, the Upper member represents turbiditic deposits due to the eustatic rise in sea level (Benítez, 1995). San Mateo Formation dates from Upper middle Eocene, according to radiolarians *Lithocyclia aristotelis, Lithocyclia ocellus,* and *Theocampe mongolfieri*.

### 2.2.7. Playa Rica Formation.

It crops out sporadically in the Jama zone and overlies in unconformable contact on the Cerro or San Mateo Formation (Zapallo Formation). The lithostratigraphy formed by intercalations of dark-brown argillites, greenish-gray argillites, thin banks of fine sandstone at the base, and light greenish-gray argillites, locally silty and slightly calcareous at the top.

Playa Rica Formation also outcrops on the edges of Borbon Basin and dates from Oligocene age. There are other shales formations like the Pambil and Viche in Borbon Basin, Tosagua in Manabi Basin, and Dos Bocas in Peninsula Santa Elena have Oligocene rocks at the base but contains Miocene rocks at the top. Benitez (1995) establishes the Playa Rica Formation belongs to Oligocene sedimentary cycle, and Tosagua Formation belongs to Miocene rocks to differentiate these rocks (Fig. 2.4).

Benitez (1995) reports that planktonic foraminifera: *Globorotalia opima opima, Globigerina ouachitensis, G. ampliapertura cancellaria, G. pseudoampliapertura, G. winkleri, G. yeguaensis, G. prasaepis, G. angiporoides,* and *G. praebulloides leroyi,* determine Oligocene age. Also, the author determines a bathyal depth paleoenvironment.

### 2.2.8. Tosagua Formation

Tosagua integrates by Dos Bocas and Villingota Formations (Fig. 2.4). This formation outcrops widely to the west of the Manabi Basin, and overlie in unconformity contact on Oligocene rocks.

Dos Bocas located 7 km close to Portoviejo – Montecristi and overlies in disconformity contact on San Mateo Formation in the Manabí Basin (Bristow & Hoffstetter, 1977). Meanwhile, the Villingota Formation located in the Sucre quarry at 1.5 km SE of the Villingota town shows a gradual transition with underlying Dos Bocas Formation.

In general, Tosagua Formation consists of dark brown shales, according to Bristow & Hoffstetter (1977). Likewise, Benitez (1995) establishes greenish-gray to gray argillites, slightly calcareous composition. It dates Lower Miocene age according to the foraminifera *Catapsidrax dissimilis, G. unicava, Globigerinoides obliquus,* and *Globoquadrina altispira* (Ordóñez, 2006). Finally, it deposited into open marine paleoenvironment due to abundant microfauna very rich in planktonic species.

### 2.2.9. Angostura Formation

The main outcrop is located in Santiago River in Esmeralda’s province close to Estero Angostura (Bristow and Hoffstetter, 1977). The basal part presents conglomerates and volcanic material, and at the top conformed from coarse to fine sandstones. This formation overlies in disconformity on Playa Rica Formations (Fig.2.4), while at the south overlies in disconformity on Villingota, Dos Bocas, Piñón or Cayo Formations (Bristow & Hoffstetter, 1977).

Angostura Formation dates middle-Upper Miocene due to abundant planktonic foraminifera of this age (Globorotalia fohsi peripheroronda, Orbulina suturalis, and Globorotalia continuosa) (Benitez, 1995). The author also indicates that the base and top were deposited in an external neritic environment (continental shelf), and the central part was deposited in a shallower environment between internal and transitional neritic (Fig 2.4).

### 2.2.10. The Onzole Formation

It is located in the Onzole River, affluent of the Cayapas River to the east of the Esmeraldas province. This Formation was described previously with several names (Bristow & Hoffstetter, 1977). The Onzole Formation consists of gray siltstones, silty shales, and rarely sandstones and conglomerates. It overlies Angostura Formation in conformity contact and underlies Borbon Formation with a transitional contact (Fig. 3.4, Benitez, 1995).

According to Deniaud (2000), planktonic foraminifera dates Upper Miocene – Pliocene age, according to *Globorotalia extremus*, *Globorotalia humerosa*, *Globorotalia continuous*, *and Pulleniata aff.*, that deposited a continental shelf environment.

### 2.2.11. Borbon Formation

It locates around Borbón town, close to the Santiago River around the Esmeraldas city. It represents by clastic rocks composed basically of massive sandstone sequences (Bristow & Hoffstetter, 1977).

According to Benitez (1995) consists of gray sandstones from fine to coarse grain, conglomerate lenses, and a basal conglomerate that rests on the Onzole Formation (Fig.2.4). Besides, the Borbon Formation dates from Upper Miocene to Pliocene times.

The depositional environment corresponds to a shallow marine environment and a transitional environment (Benitez, 1995).

## 2.3. Faults System.

In the Manabi Basin has developed compressional and extensional structures that are related by strike-slip faults. Normal faults had registered extensional or transtensional events during the Eocene time, where sedimentary sequences deposited. These normal faults change their settings to reverse fault due to an inversion process (Reyes, 2013).

Currently, reverse faults majority command the geometry and constitute the limits of the Manabi Basin. The Jama Fault delimits to the NW and the Jipijapa Fault to the SW of the basin (Fig.2.5). Meanwhile, the Western Cordillera foothills are the eastern boundary, but according to (Reyes, 2013) the Pichincha Fault is the limit because it separates the Manabí Basin from the Coastal Plain (Fig. 1.1a, b). Finally, the Colonche Fault delimits and separates the Manabi from the Progreso basin to the south.

### 2.3.1. The Colonche Fault

The Colonche Fault constitutes the south limit of Manabi Basin (Fig. 2.5). It has a WNW-ESE direction and likely dips to the south. This fault shows the contact between Cretaceous rocks from the basement and sedimentary rocks of the Paleocene - Oligocene located in the Chongon Colonche Cordillera.

Currently, it is a reverse fault where the Cretaceous basement uplifted in the north direction (Reyes, 2013) over the sedimentary infill. On the other hand, Eguez et al. (2003) infer the Colonche Fault as a reactivated fault that is associated with the formation of the Tertiary Progreso Basin. Moreover, the authors show an average strike of N59°W±22º.

### 2.3.2. The Jipijapa Fault.

The Jipijapa Fault locates to the SW of the Manabi Basin close to Jipijapa city (Fig. 2.5). It has an NNE-SSW orientation and probably a vertical dip (Reyes, 2013). This fault shows the contact between Cretaceous rocks (Piñon and Cayo Formations) and Miocene sedimentary rocks from the Manabí Basin (Fig. 2.3). Currently, it is a reverse fault with the strike-slip component (Reyes, 2013), so triggers uplift the Cretaceous basement against the Manabí basin. The Jipijapa fault constitutes the southwestern border of the Manabí basin.

According to Eguez et al. (2003), the kinematics of the fault could be related to the collision of the Carnegie Ridge with the South American Plate. Moreover, they consider N18°E±11° strike and also as a reverse fault.

### 2.3.3. The Pichincha Fault

The Pichincha Fault is located to the east of the Coastal Cordillera and constitutes the boundary between the Manabí Basin and the Guayas river watershed (Figs. 1.1, 2.5). It can follow from south Pichincha city through 140 km to the north. It has NNE-SSW direction and could perhaps extend further to the south (Reyes, 2013). It is a reverse fault that uplifting the west block and possibly an anticline flexure is formed by the fault (Reyes, 2013). On the other hand, Eguez et al. (2003) names it as Daule fault and present an average strike N32ºE±14º.

### 2.3.4. The Flavio Alfaro Fault

The Flavio Alfaro Fault locates near the Flavio Alfaro town. It has a NE-SW direction and likely dips to the southeast (Reyes, 2013). Also, it considered the southwest limit of the Jama fault system (Fig. 2.5). It is a reverse fault that occurred after the inversion of a normal fault (Reyes, 2013). On the other hand, Eguez et al., (2003) consider affects mainly Tertiary sedimentary rocks and denominated it as Calceta fault with N29°E±15° strike.

### 2.3.5. The Jama Fault

The Jama fault belongs to the Jama fault system. It is a relevant fault because of separates the Cretaceous basement located to the NW from the Miocene rocks to the SE (Fig. 2.5). This fault has a NE-SW direction and a dip to the east. Currently, it performs like an overlapping fault that controls the uplift of the Cretaceous basement (Reyes, 2013). On the other hand, Eguez et al. (2003) consider the Jama fault a discontinuous extension of the Cañaveral fault. This fault forms a lineament and could be related to transpressional movement. It has a strike N37ºE±12º.

### 2.3.6. Canande Fault

This fault forms the boundary between Manabi and Borbon Basins in the north. It has east-west direction and a dip to the north. The Canande fault shows the contact between the Cretaceous - Miocene and Plio-Quaternary rocks located in Manabi Basin (Fig.2.5). According to Reyes (2013) has a reverse component because of uplift basement rocks from the north against rocks in the Manabí basin to the south. On the other hand, Eguez et al., (2003) establish that the sense of the movement is Normal with the right-lateral (dextral) component and has an average strike N83ºW±18º.

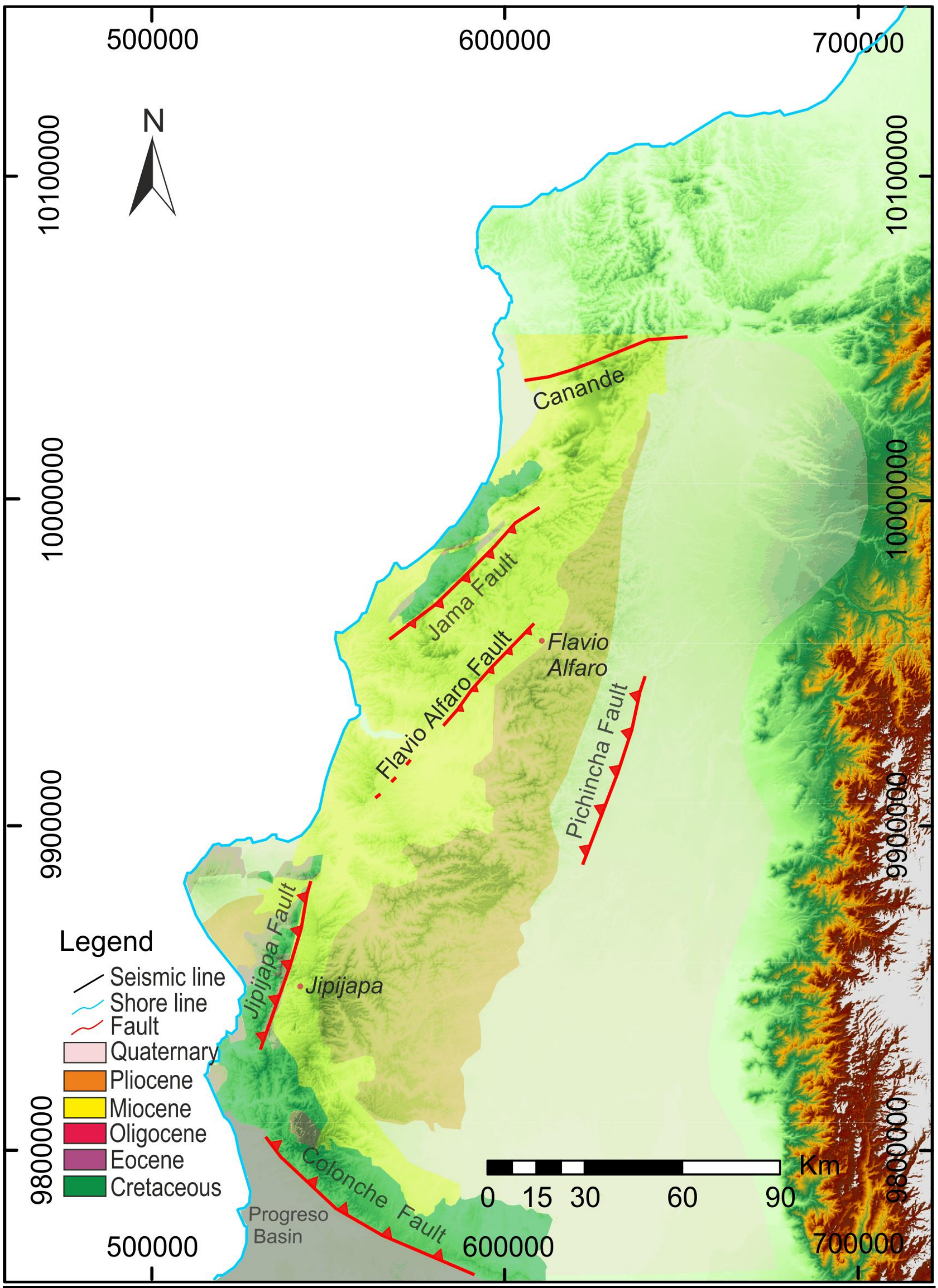

**Figure 2.5.** Map of faults of the Manabi Basin. Moreover, it shows geological formations that cover the study area.

# CHAPTER 3

## 3. The Manabi Basin.

The Manabi Basin is characterized by a Middle-Upper Eocene age sedimentary infill overlying unconformably the Cretaceous–Lower Paleocene interval (Jaillard et al., 1995). Meanwhile, the basement of the basin is an oceanic plateau that collides to margin continental during the Late Cretaceous, and an island arc developed in late Campanian–Maastrichtian times (Kerr et al., 2002).

### 3.1. Digital Elevation Model (DEM)

The DEM is a digital representation of topography or terrain and facilitates the mapping of significant structures, lineaments, and geomorphic features. The geological interpretation is through GIS software that enables multiscale visual interpretation from the terrain map.

The DEM used in this work represents a raster that downloaded from the web site: https://vertex.daac.asf.alaska.edu/. The dataset is ALOS PALSAR that presents the data in the GIS-friendly GeoTIFF format. Several scenes downloaded to make one raster that covers all study areas (Fig. 1.1a, b). The ArcGIS software together with the scenes allow view in multiscale visual to interpret the geomorphology of the Manabí Basin. The final raster has a spatial resolution of 12.5 x 12.5 meters and datum WGS-84.

The interpretations made in the DEM contains a geological map that also digitalized. This map draped over the DEM for structural and geomorphological interpretations (Fig. 3.1).

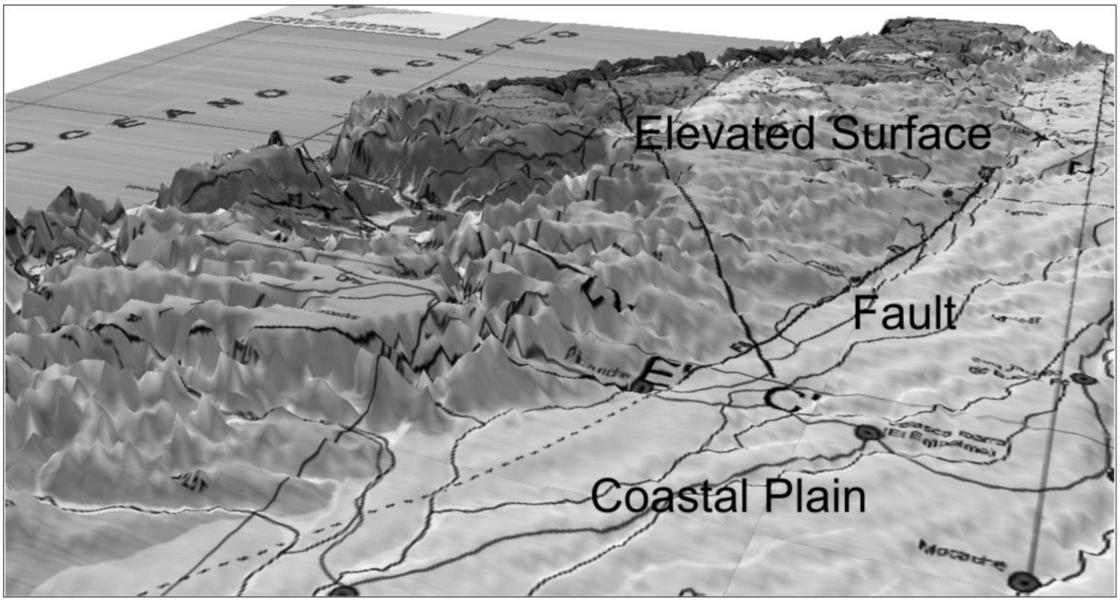

**Figure 3.1.** Digital Elevation Model (DEM) shows Pichincha fault in the east of the study area. It can see elevated surfaces and lowlands geomorphologies separated by the fault and concordance with data of geological map of the Coastal Region by Reyes, (2013).

The geomorphology of the study area displays elevated areas like the Chongon Colonche Cordillera that has NW-SE direction and a maximum elevation of 800 m. It is relevant because of some geological formation present in the basin crop out there. Moreover, it separates the Manabi and Progreso Basins because of is linked to the Colonche Fault activity.

Another structural high is the Coastal Cordillera located between 0ºN and 1ºS latitudes (Fig. 1.1a). It shows an elongated NNE-SSW shape with 400 km longitude and 75 km wide, and an average altitude of 450 m (Reyes, 2013). The Coastal Cordillera is situated in a very active zone because geomorphology shows inhomogeneous shapes (Benitez, 1995). For which, both Cretaceous and the Paleogene rocks crop up discontinuously

The areas of high relief and the Coastal plain show a drastic elevation change between them, and the difference in uplift is most probably due to fault (Fig. 3.1). Reyes (2013) describes the Pichincha fault is located in this zone. Therefore, this fault is the east boundary of the Manabi Basin according to DEM interpretation and corroborate with the geological map by Reyes, (2013). On the other hand, Jipijapa Fault related to the Coastal Cordillera uplift in the southeast and Jama Fault in the northwest, are not identified in the DEM because does not show a difference of elevation. However, the outcrops of Cretaceous formations indicate the presence of faults.

## 3.2. Gravimetric Anomalies related to the Manabi Basin.

Gravimetric anomalies help us to localize and describe subsurface structures from the gravity effects caused by anomalous densities. So, Bouguer anomalies provide insights to infer the limits of the basin and track faults, structural highs, and subsidence zones.

The subsidence zones and sedimentary basins are related to the local low Bouguer anomalies, whereas high values correspond to allochthonous oceanic units. Gravity crustal models suggest that the continental crust in the Coastal region is 20 to 40 km thick (Feinenger, 1983).

The Manabi Basin display both positive and negative values of Bouguer anomalies (Fig. 3.2). The positive values coincide with areas in which the basement Piñón Formation crop out, that is, there is high density in this zone. This located in the NW part of the basin. Meanwhile, negative values of Bouguer anomalies coincide with subsidence zones (depocenters) that filled with Eocene – Miocene sedimentary rocks (Fig. 3.2). Both positive and negative values shows NE - SW orientations.

The gravimetry anomalies vary between -70 to 200 mGal. The positive anomalies vary between 20-200 mGal, and the main structure shows 20 to 60 mGal values of positive anomalies (Fig. 3.2), where Jama Hills locates geographically. On the other hand, the zones of subsidence display values between -20 to -70 mGal (Fig. 3.2), where are located the depocenters of the basin.

The accordance with the gravimetric map the main depocenter of the basin are located to the center of the basin, with an NNE – SSW direction. The sedimentary infill of the Manabí Basin reaches up to 1-1.5 km thick (Feinenger, 1983).

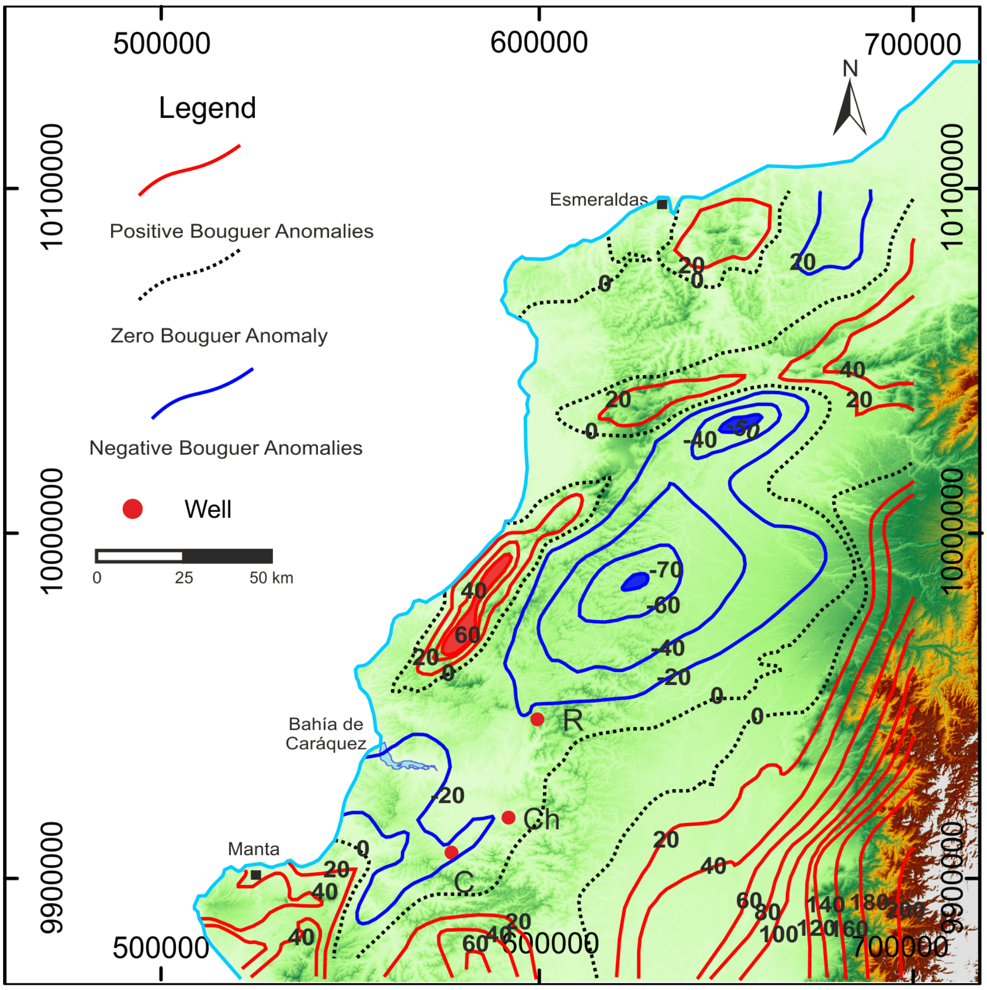

**Figure 3.2.** Gravimetric Map of the Manabi Basin showing positive anomalies (red lines) until 200 mGal, while negative anomalies reach -70 mGal (blue lines) display subsidence zones. Zero anomaly values (black dashes lines) shows the same orientation (NE-SW) of positive and negative values. Moreover, it shows the location of the oil-wells. R: Ricaurte, Ch: Chone and C: Calceta. Modified from Feininger (1977).

### 3.3. Lithostratigraphy of the Manabi Basin.

In the Manabi Basin, volcanic and volcaniclastic Cretaceous rocks underlie unconformity contact to the Eocene sedimentary rocks. The Simplified Geologic Map (Fig.3.3) shows the main lithostratigraphy of the sedimentary infill in the basin. So, the Upper Miocene and Quaternary sedimentary rock cover widely the Manabi Basin, while the Cretaceous – Oligocene rocks crop out majority to NW in the Jama fault zone and to SW in the Jipijapa fault zone. The Cretaceous-Oligocene outcrops crop out in these areas due to the Jipijapa and Jama reverse faults uplift the Piñon Formation to the west of the basin. Likewise, the Colonche fault shows Cretaceous rocks to the south of the basin.

The basement is represented by the Piñon Formation, meanwhile, the San Lorenzo and the Cayo arcs overlie the basement both conformably and unconformably (Fig. 3.3). Moreover, they indicate the end of the volcanic arc activity as well as the start of the sedimentary infill. All these formations date from Cretaceous time and crop out in the highlands of the study area. Meanwhile, the sedimentary infill is integrated by 8 lithostratigraphy units with ages from Upper Paleocene to Holocene. The next units described from bottom to top conform the sedimentary infill: Guayaquil, Cerro, San Mateo, Playa Rica, Tosagua (Dos Bocas and Villingota Formations), Angostura, Onzole and Borbon Formations. Upper Miocene and Pliocene Formations (Angostura, Onzole and Borbon) cover widely the surface of the study area, while Oligocene (Playa Rica Fm.) and Eocene (Zapallo Fm) crop out to west in the highlands of the basin.

In general, Cretaceous rocks are widely spread to the NW and SW, while Eocene and Oligocene formations sporadically are mapped in these zones of the basin. On the other hand, the stratigraphic thickness of the sedimentary infill is more significant to the north than to the south of the basin (Annex 1).

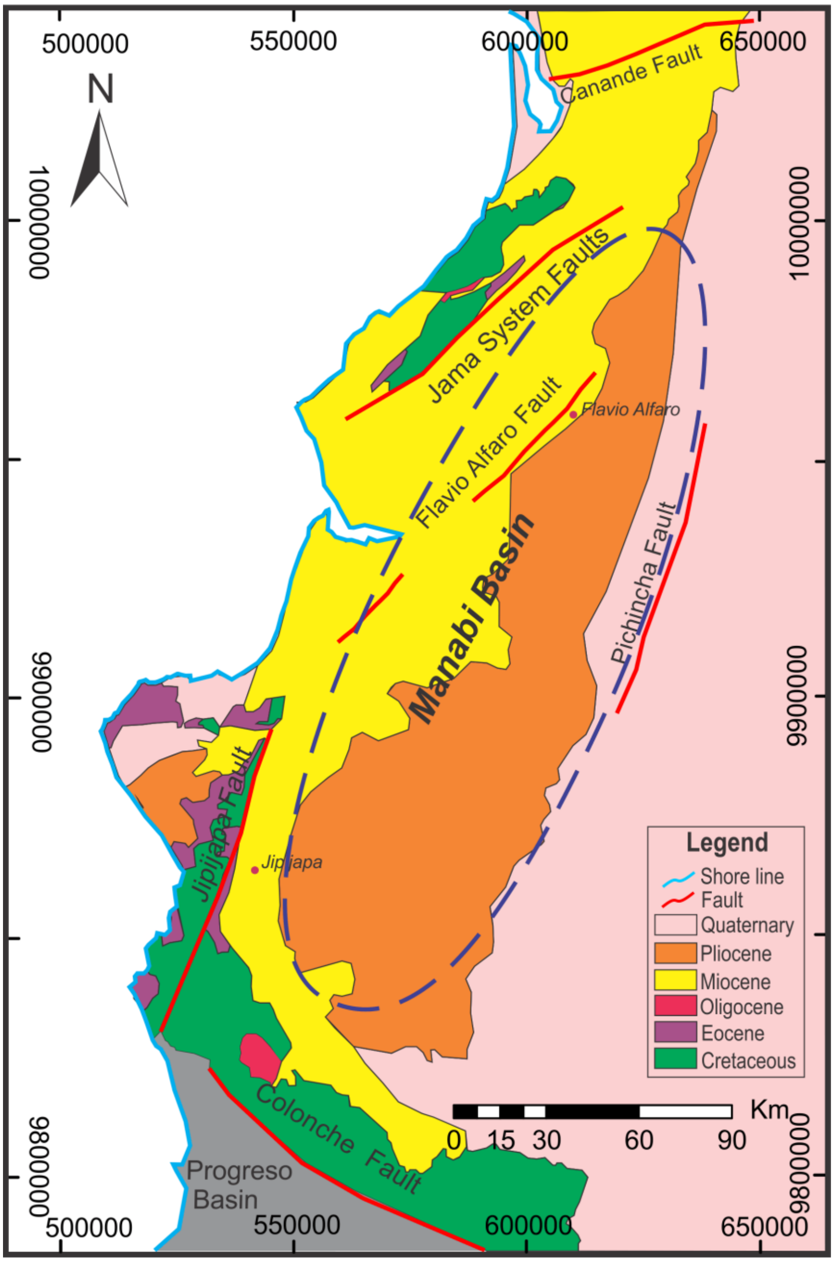

**Figure 3.3.** Simplified Geological Map of the Manabi Basin area shows lithostratigraphy sets according to geological epoch and main faults of the Manabi Basin. Modified from Reyes, (2013).

## 3.4. Seismic data and wells.

The Coastal region has studied to find hydrocarbon resources since the Progreso Basin first developed oil exploitation, 100 years ago. Oil companies have carried out exploration works, resulting in several geologic studies and geophysical datasets. Moreover, the Manabi basin is covered widely by Neogene sediments so that seismic data is necessary to interpret the basin. The seismic study surveys were mainly obtained during the seventies years.

Seventeen 2D seismic reflections lines and three exploration oil-wells (Ricaurte, Chone, and Calceta) are the dataset used to interpret the subsurface of the Manabi Basin (Fig.3.4). The seismic lines widely cover the study area, and wells data give information about geological formation tops. The seismic data show two-way travel time (TWT) reflections, so interpretations shown in milliseconds (ms). The seismic lines are of low quality. However, it is enough to differentiate structures and get isopach maps of each tectonosequence, allowing us to infer the geometry and depocenters of the basin.

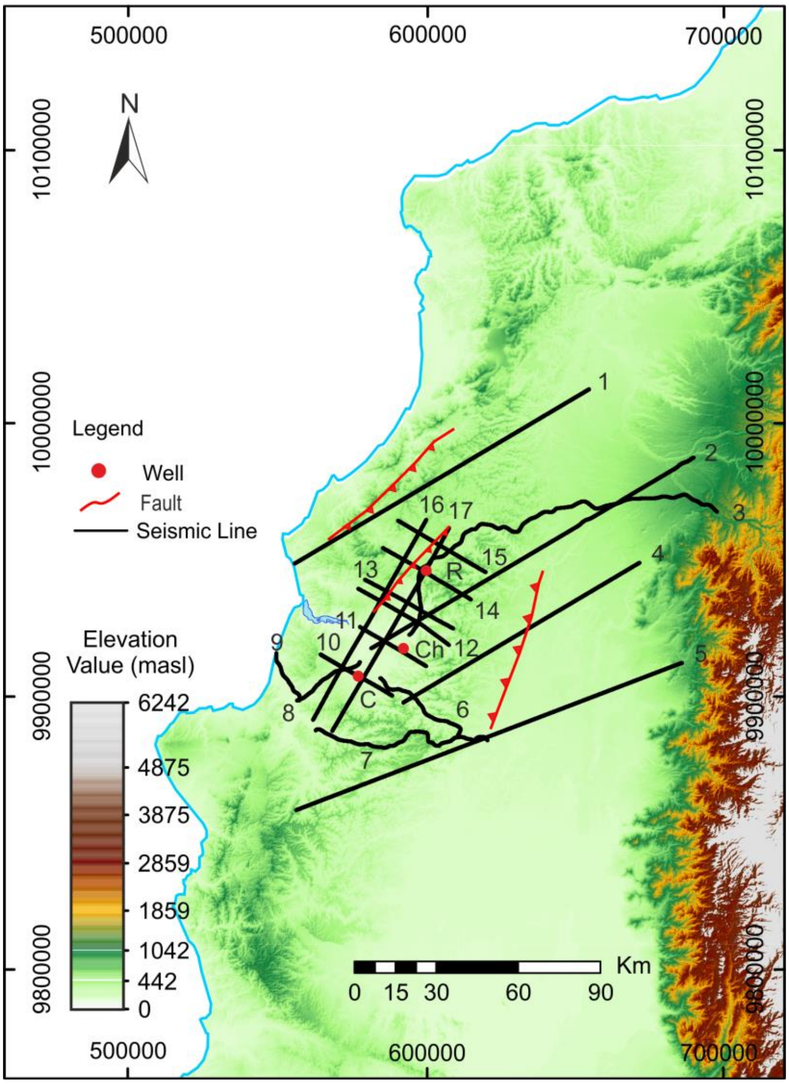

**Figure 3.4.** Location map of seismic data and wells (R: Ricaurte, Ch: Chone, C: Calceta) of the Manabi basin. Digital Elevation Model display geomorphology of the Coast region. Besides, the main faults of the zone.

The seismic and well data have different features. For example, seismic data are recorded in two-way travel time, whereas well log data are measured in meters along the boreholes. Furthermore, well log data has a limited resolution away from the borehole, while seismic data have excellent resolution away from the oil-wells. Thus, the correlation between them is relevant to show a synthetic seismogram, where well-to-seismic tie compares seismic data at a well location with log data from the well.

### 3.4.1. Wells

The seismic profiles data are not complete to interpret if they do not achieve a synthetic seismogram that is a seismic trace created from sonic and density logs (oil-well data) and is used to compare the original seismic data collected near the well location (Onajite, 2013). For that, the sonic log (velocity) and density log give a reflection coefficient log that is the difference of the acoustic impedance divided by the sum. The acoustic impedance is the product of velocity and density. After, a wavelet is necessary to generate a synthetic trace. Wavelet is obtained by software that convolved the reflection coefficient with wavelet to produce a synthetic seismogram. The Figure 3.5 shows an example, in which borehole data and the result of the convolution between the wavelet and the reflection coefficient (left part) are presented. This figure is to show a good example of the well-to-seismic tie because the synthetic seismogram of Calceta well and seismic line 10 do not have a good quality (Fig. 3.6).

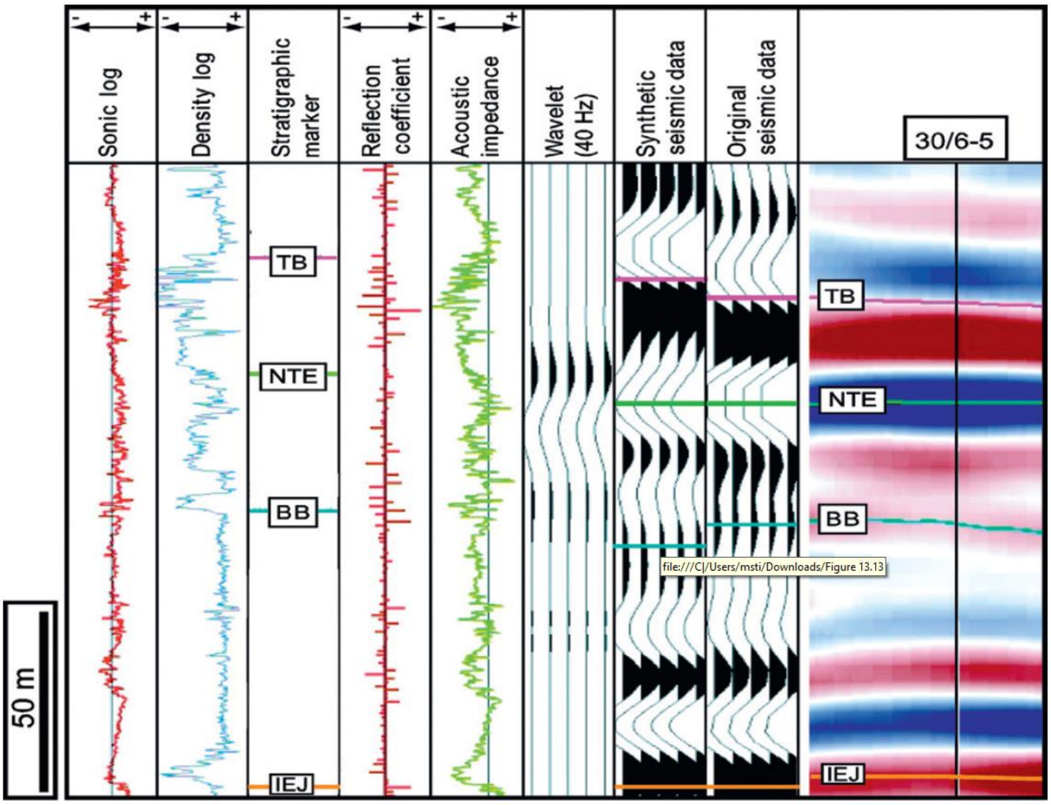

**Figure 3.5.** Example of well-to-seismic tie. Modified from Onajite (2013)

However, the synthetic seismogram of the Calceta borehole shows the geological formation tops because well-to-seismic tie correlates the stratigraphy sequence drilled in the well to the with specific reflectors on the real seismic section (Fig.3.6). These values are in millisecond (ms). The Cretaceous top has values around 1500 ms, Guayaquil top around 1000 ms, Zapallo top around 900 ms, Playa Rica around 700 ms and Tosagua around 350 ms. These values are taken to interpret the top of formation in the seismic lines.

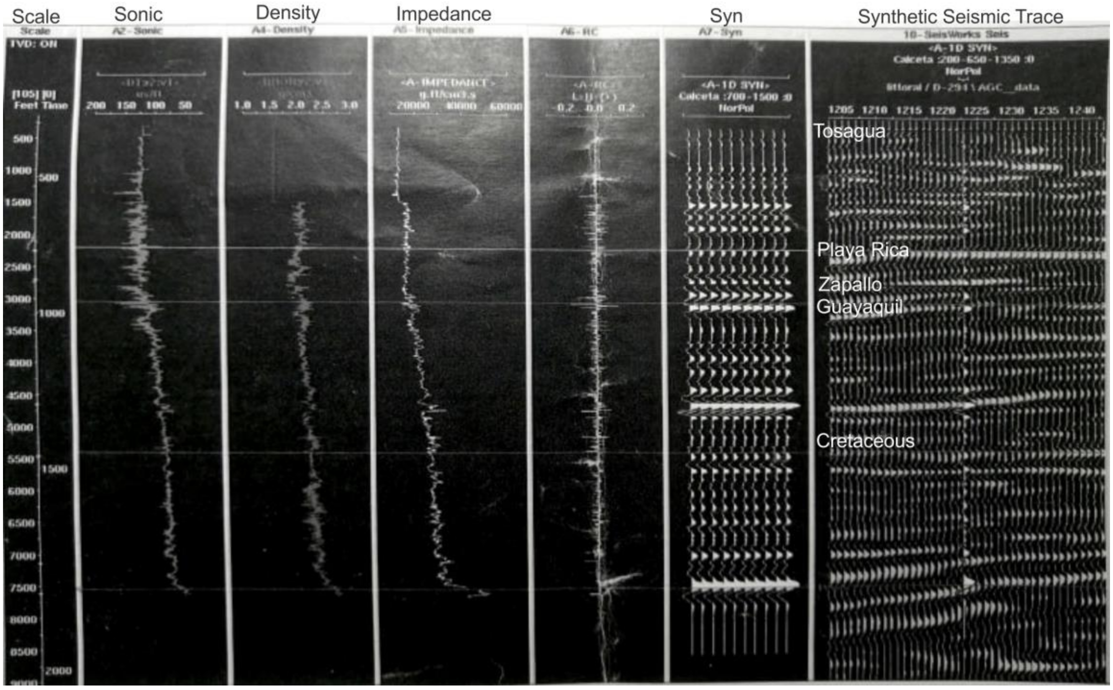

**Figure 3.6.** Synthetic seismogram of the Calceta borehole showing the tops of formations of the Manabi Basin.

On the other hand, the boreholes sketch of the Manabi Basin shows the formation tops (Fig. 3.7) that they are separated by regional unconformities (Fig. 2.4). For example, the Calceta well shows U2, U3, and U4 unconformities. It reaches 2,703 m depth and breaks through the Piñon and Cayo Formations. These constitute the Cretaceous sequences that underlie the Zapallo Formation in unconformity contact (Fig.2.4). Meanwhile, the Chone well possess almost 4,000 m depth and display the same unconformities of the Calceta well. Besides, the Ricaurte well is the deepest borehole with 4,500 m. It does not break through the Playa Rica Formation so that U3 unconformity does not show. Likewise, the Ricaurte well have recorded several fossils, detailed in the lithostratigraphy section. The benthic and planktonic foraminifera are main fossils found as well as remains of bivalves and gastropods.

In addition, the wells show two Cretaceous units: the Piñon and Cayo Formations. The Cayo Formation considers being a part of the Cretaceous basement because it overlies the Piñon Formation in conformably contact. It is relevant because determine the first unconformity to define tectonosequences.

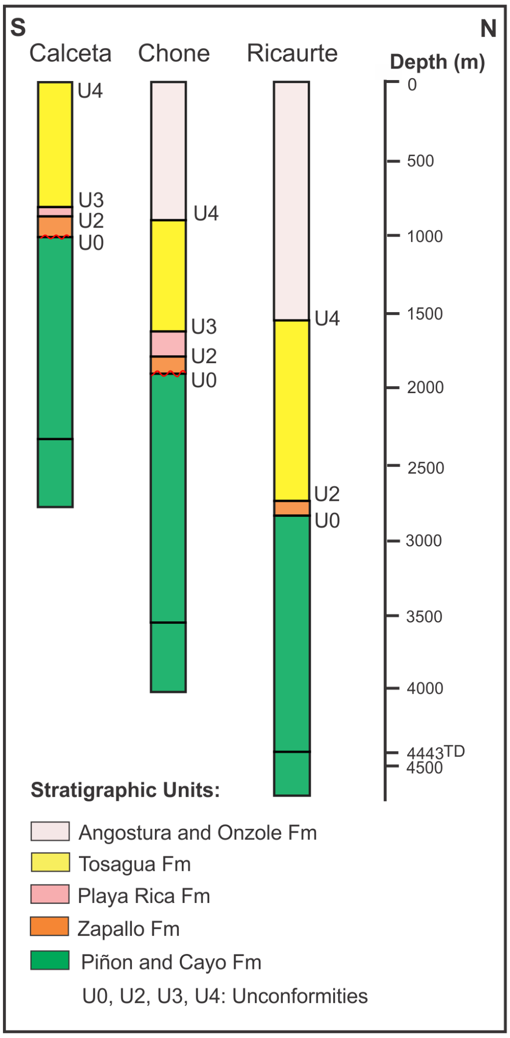

**Figure 3.7.** Sketch of the Calceta, Chone, and Ricaurte wells showing the tops of the lithostratigraphic units of the sedimentary infill of Manabi Basin and the unconformities that constitute the limit of each.Moreover, it shows that the thicknesses increase from the south to the north of the basin. The geographic localization is in figure 3.4. TD: True Deep. Modified from Benitez (1995).

### 3.4.2. Seismic Lines

The seismic-stratigraphic interpretation of the study area was based on the identification of regional unconformities that separate several packages that belong depositional events (Fig.3.8, 3.9). The basin-scale unconformities that subdivide the sedimentary infill correspond to seismic reflectors that constitute remarkable stratigraphic markers. Likewise, seismic lines show two marked patterns that allow differentiate the basement and sedimentary infill. The first pattern displays a chaotic setting where the basement is located (green color), and the second pattern sets parallel to subparallel and discontinuous reflectors that are interpreted as the sedimentary sequences deposited in the Manabi Basin (Figs.3.8, 3.9).

The seismic profiles used for seismic-stratigraphic interpretation were seismic line 10 and 17 (Fig.3.4). These correlate with Ricaurte and Calceta wells, respectively. In the north of the basin, the correlation has been carried out from the Ricaurte borehole and seismic section 17 (Figs. 3.4, 3.8), while the correlation in the south of the basin, Calceta well and seismic section 10 have been used (Figs. 3.4, 3.9). The use of these two wells has been necessary because seismic section 17 allows covering NE-SW direction and seismic line 10 covers WNW-ESE (Fig. 3.4). Moreover, the seismic line 10 intersect with the majority of other seismic lines to major control of the interpretation of seismic profiles.

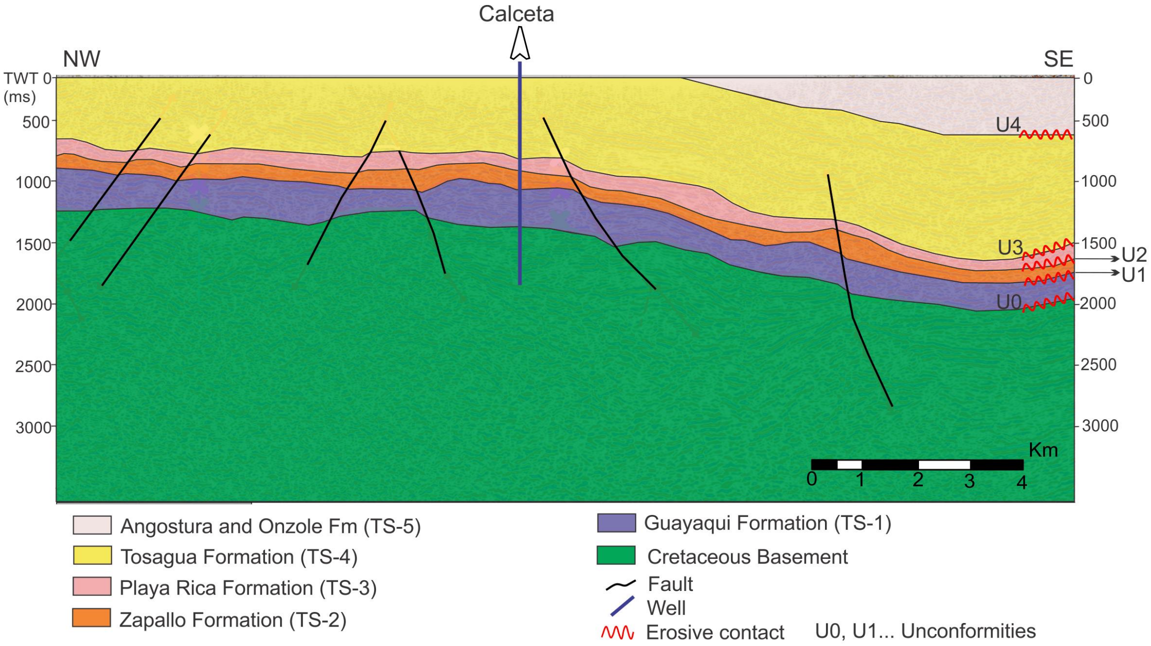

**Figure 3.8.** Interpretation sketch shows tectonosequences and unconformities from the correlation between the seismic line 10 and Calceta well, from NW to SE. The location of seismic line and well are in Fig. 3.4.

The seismic line 10 is in the south part of the study area. In the Calceta well shows mainly a reverse fault with NW-SE direction and dip to the south. This fault affects the basement and sedimentary cover until Playa Rica Formation (Oligocene). Other faults affect the sedimentary infill, but the seismic limits have a conformable setting. So, conformable seismic limits indicate no significant deformations in this zone of the study area. For example, in the SE of the profile can see the conformable seismic boundaries between formations.

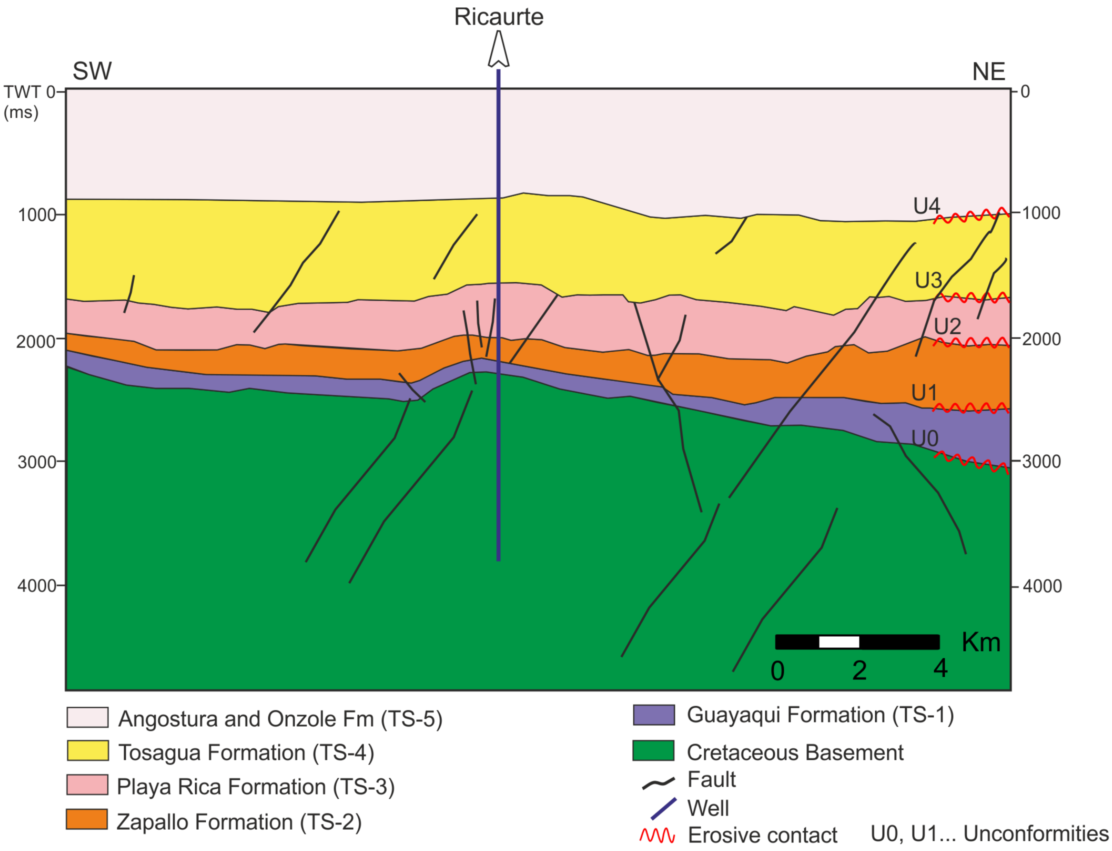

**Figure 3.9.** Interpretation sketch shows tectonosequences and unconformities from the correlation between the seismic line 17 and Ricaurte well, from NE to SW. The location of seismic line and well are in Fig. 3.4.

The Ricaurte well shows mainly a normal fault NE-SW strike and dip to the south. This fault affects the Cretaceous basement. Meanwhile, in the Eocene, Oligocene, and Lower Miocene, small geological faults are observed, which affect the sedimentary deposits of Zapallo, Playa Rica, and Tosagua Formations. Finally, this structure is covered or sealed by Upper Miocene deposits (Angostura and Onzole Formations). Furthermore, the seismic limits of Guayaquil and Zapallo Formations show an onlap setting.

The erosive contacts or unconformities are observed majority in the seismic lines. This settled the tectonosequences to define structures of the basin. Below, it describes each tectonosequence according to seismic and well interpretations.

## 3.5. Tectonosequences (TS)

A tectonosequence is a sequence of strata associated with compressional and extensional tectonic events. These events cause tilted and fold in the sedimentary sequences. Tectonosequences are recognized by an unconformity that limits both at the base and the top. The analyses of the Manabi Basin define five tectonosequences (TS-1, TS-2, TS-3, TS-4, and TS-5) that are delimited from the bottom to the top by regional unconformities (U0, U1, U2, U3, and U4; Figs. 2.4, 3.8, 3.9). Moreover, these allow creating isopach maps of each tectonosequence. Isopach maps show depocenters, geometry, and structural highs of the sedimentary infill. They have two-way travel time values.

### 3.5.1. Cretaceous Basement

Cretaceous rocks are underlying in the Manabi Basin area according to wells data (Figs.3.7, 3.8, 3.9). The borehole data indicates that the basement rock is Cretaceous igneous rocks and is interpreted as an acoustic basement. This interpretation supported by the unlayered and chaotic appearance of the lowest section in the seismic lines (Fig.3.7). Instead, the top of the basement has seismic reflections that are more coherent, subparallel and show a gently folded pattern that interpreted as a deformed basement. So, the U0 unconformity contact defined above this deformed basement. So, U0 separates Cretaceous rocks from Paleocene age strata, determining the TS-1.

### 3.5.2. Tectonosequence 1 (TS-1)

The contact between TS-1 and the Eocene TS-2 is the unconformity U1. Instead, the unconformity U0 delimits the base the Paleocene from the Cretaceous basement (Figs. 2.4, 3.8, 3.9, 3.10). This tectonosequence constitutes by the Upper Guayaquil Formation (Paleocene age).

The Paleocene unit presents parallel and subparallel reflections, which rest on the Cretaceous basement. The isopach map shows several small depocenters with irregular shapes and records a maximum of 700 ms (TWT) thick. Moreover, the thicknesses of TS-1 change in all study areas.

The depositional system of TS-1 is the abyssal paleoenvironment (marine environment). This consists of fine-grained sediments of siliceous argillites and calcareous composition at the top of the Upper Guayaquil Formation.

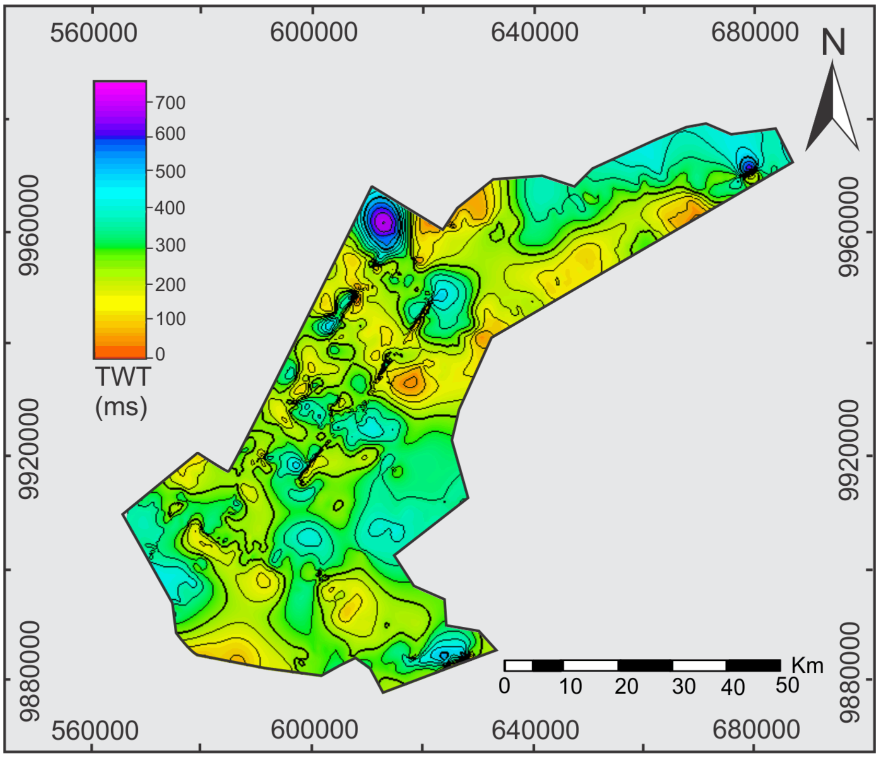

**Figure 3.10.** Isopach map of TS-1 shows several small depocenters with values that reach 600ms. The thicknesses vary across of the study area. The Moreover, few structural highs are observed.

### 3.5.3. Tectonosequence 2 (TS-2)

The contact between Eocene TS-2 and the Oligocene TS-3 is U2 unconformity that is represented by a hiatus between these two epochs (Fig. 2.4). In the Ricaurte well, the Eocene unit strata are 2800m depth (Fig. 3.7) and have a maximum 155m thick. On the other hand, the U1 delimits the base that separates Eocene from Paleocene Formation.

The TS-2 constitutes by Cerro and San Mateo Formations that date from Eocene age. The paleoenvironments include continental slope to Cerro Formation and continental shelf to San Mateo Formation (Fig.2.4).

Eocene age rocks form in the central deposit of the basin sub-parallel and continuous reflectors, which onlaps on or is in erosive discordance on the Paleocene deposits (Fig. 3.7, 3.8). The isopach map also shows small depocenters along the area but with more thickness than in the TS-1. They locate to NE and SW of the basin with irregular shapes. The depocenter thicknesses have maximum values of 600ms (TWT), while few structural highs until 100 ms (TWT) occupy the south of the area (Fig. 3.11) widely. The fast changes in thicknesses allow inferring that there is a significant deformation.

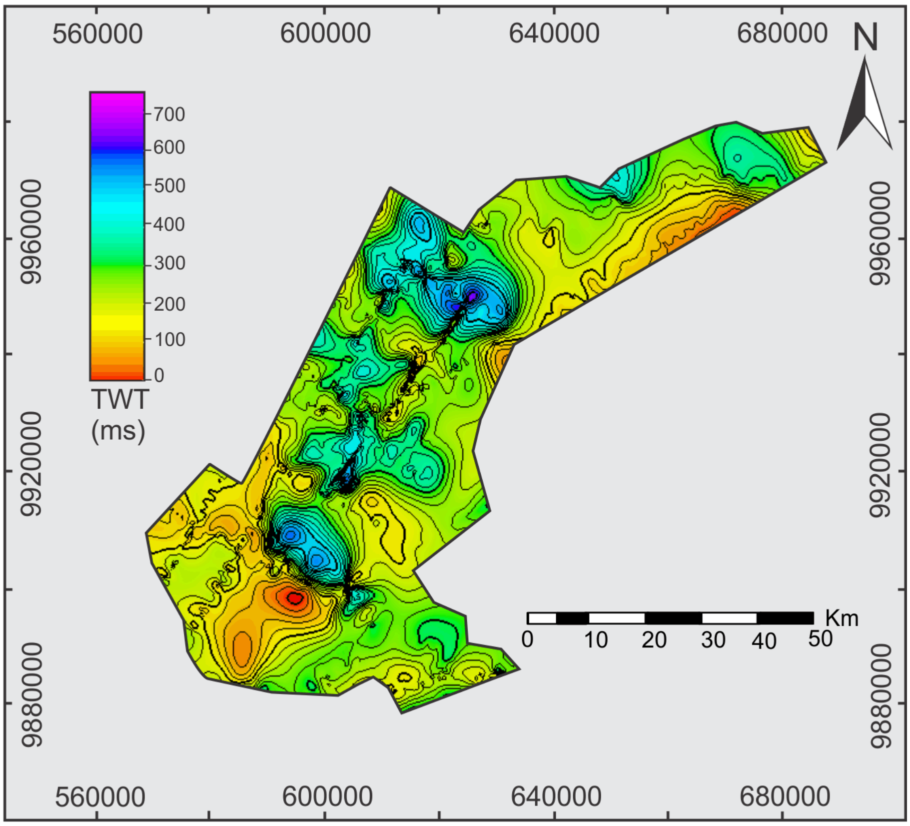

**Figure 3.11.** Isopach map of TS-2 (Eocene age) shows small depocenters with NE-SW orientation that reach 600mGal. Also, it shows structural highs located in the NE and SW of the study area.

### 3.5.4. Tectonosequence 3 (TS-3)

Oligocene TS-3 is represented by Playa Rica Formation that dates from the Oligocene age. The contact between TS-3 and the Oligocene TS-4 is the unconformity U3 represented by a hiatus (Fig. 2.4). On the other hand, the unconformity U2 separates the base of TS-3 from Eocene Formations (TS-2, Fig. 2.4).

The Playa Rica Formation in the Ricaurte borehole locate between 2000-2500 m depth. The Oligocene rocks sequence belongs to deep bathyal paleoenvironment.and are founded in Ricaurte, Chone, and Calceta wells (Fig. 3.7).

The isopach map displays more values of structural highs (100ms, Fig.3.12) than TS-2. The depocenter locates in the SW is smallest than TS-2 with 700ms (TWT) values of thicknesses. Meanwhile, in the NE of the basin, a significant depocenter with values until 900ms (TWT) is observed. So, depocenters of TS-3 occupy a reduced area while structures with less thickness cover the study area.

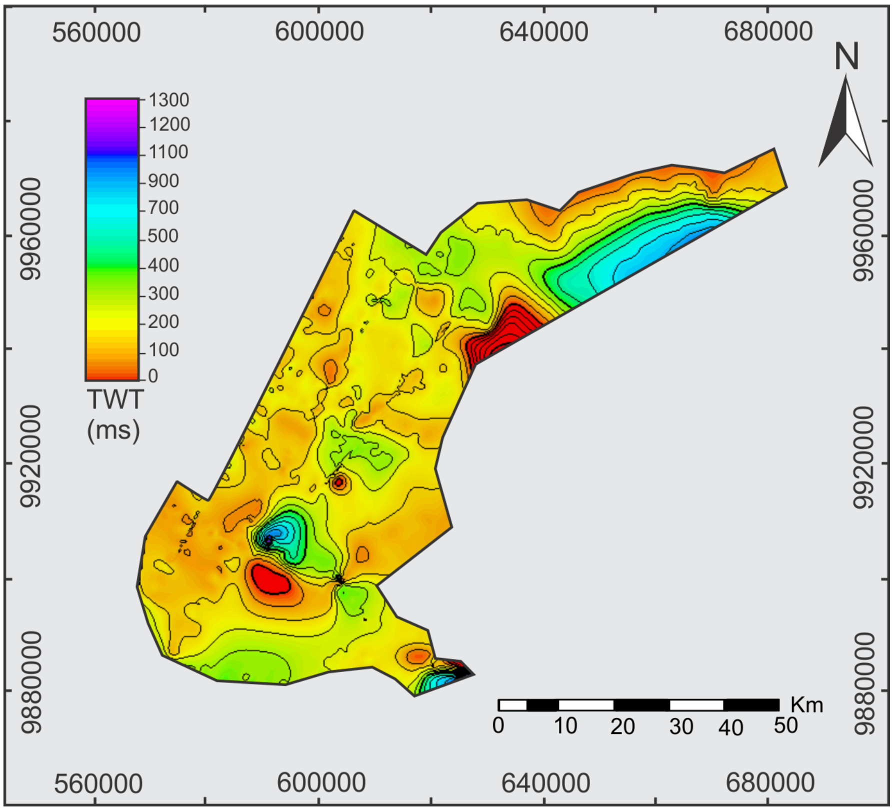

**Figure 3.12.** Isopach map of TS-3 (Oligocene age) shows depocenter until 800 ms (TWT) of thickness. Also, it show more values of low thickness that cover widely the areawith NE-SW orientation.

### 3.5.5. Tectonosequence 4 (TS-4)

The TS-4 dates Lower Miocene and constitutes by the Tosagua Formation. In the Ricaurte well, TS-4 is located approximately 1000m depth. The contact between TS-4 and the Upper Miocene (TS-5) is the U4 unconformity. Instead, the U3 unconformity separates Miocene Formations from Oligocene Formation (Fig. 2.4). The depositional environment is the continental slope.

The isopach map shows depocenters covering more area (Fig. 3.13) with values that reach 1400ms (TWT) in the SW of the basin. Meanwhile, the depocenter locates in the NE comparison with the depocenter of TS-3 moves more to the SW. Moreover, few structural highs observe. So, these indicate that the Tosagua Formation has a significant thickness.

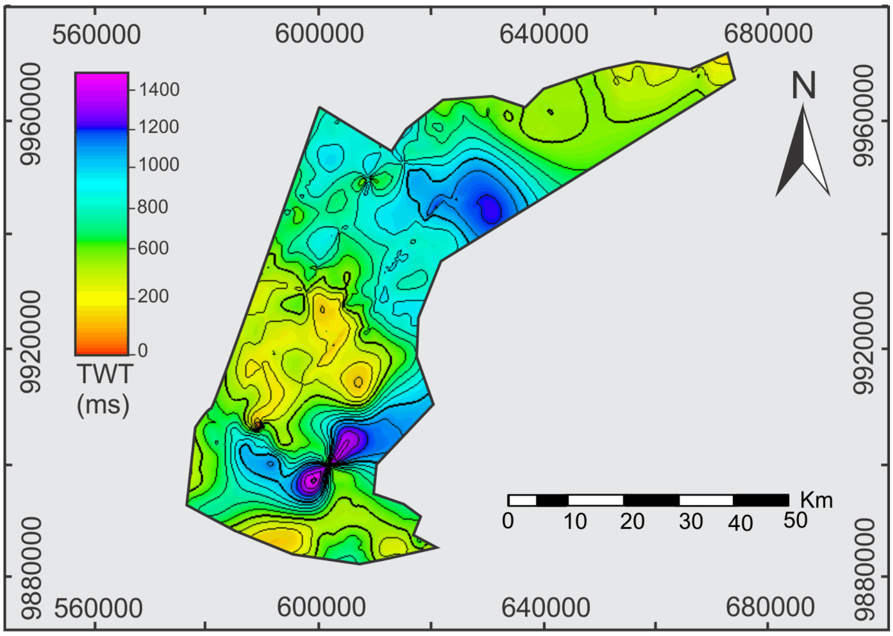

**Figure 3.13.** Isopach map of TS-4 shows two main depocenter with values until 1400 ms (TWT). Moreover, few structural high are observed.

### 3.5.6. Tectonosequence-5 (TS-5)

The last tectonosequence is constitute by Angostura, Onzole, and Borbon Formations that date mainly from Miocene. The contact between Upper Miocene tectonosequence and Lower Miocene Formations is the U5 unconformity that represents a hiatus (Fig. 2.4). The Ricaurte well establishes that this tectonosequence starts around 920 m depth.

The Angostura Formation dates the Middle Miocene age and has an external neritic environment (continental shelf). On the other hand, Onzole Formation dates Upper Miocene – Pliocene time. These facies deposited in the continental shelf and slope environments. Instead, the Borbon Formation dates Upper Miocene to Pliocene, and the depositional environment corresponds to the continental shelf environment.

# CHAPTER 4

## 4. DISCUSSION

The Manabi Basin interpreted according to seismic lines, gravity anomalies, stratigraphic record of the Ricaurte and Calceta boreholes, and surface maps. These show that tectonic events had affected more the north than the south of the basin. First, the gravity anomalies provide constraints for the deeper structures in the north than the south of the basin due to local gravity anomaly lows located there (Fig. 3.3). Second, the well-oil data shows strata thickness increases to the North of the study area (Fig. 3.7). Finally, the Manabi Basin show high and low zones, which correspond to structural uplifts and depocenters (Fig. 3.10-3.13), which are located along of the basin.

The tectonic regime of the study area was complicated to interpret because it is disturbed by old faults. These faults are not very evident because the reflectors of the oldest units are diffuse and do not allow to determine the fault traces, but some local faults are evident. In any case, the faults that control the depocenters are relatively old because they rule the Paleocene-Oligocene strata.

The oldest tectonic events are highlighted in the north of the basin (Fig. 3.9). The seismic line and Ricaurte well show to the southwest of the borehole, normal faults with probable NW-SE direction, which affect the Cretaceous basement and its Upper Paleocene cover; this structure is sealed by strata attributed to the lower Eocene which deposited in onlap. Moreover, the growth strata are to the NE of the seismic line indicates that the fault or faults were active while sediments were deposited, during Upper Paleocene and Eocene times (Fig.3.9). The isopach map of Eocene age (TS-2, Fig. 3.11) show small depocenters formed by the tilting of the blocks (high structures) that related along these faults mentioned before. Likewise, the tilting continued during the strata infill because the Oligocene deposits also show a seismic limit in onlap way.

The seismic line 14 perpendicular to the seismic line 17 (Fig. 3.4) shows reverse faults with probable NE-SW direction that affect the Cretaceous basement until the Lower Eocene. These faults probably continue tilting strata the rest of the Upper Eocene and finally are sealed by Oligocene and Miocene sediments. These reverse faults possibly are related to the Jama system fault.

The normal faults located to southwest (Fig.3.9) represent an extensive process that, according to Benitez (1995), could affect a distensible response from the NW-SE direction in relation to the probable NE-SW compression that would provoke a wedge condition. Likewise, Benitez (1995) observed complex structures as positive and negative flowers that this work does not find; however, these characterize the Jipijapa fault, which triggers the Coastal Cordillera uplifting that created pull-apart basins and controlled their evolution.

The more stable zone locates in the South of the Manabi Basin. The Paleogene and Neogene deposits show very few tectonic accidents (seismic line 10, Fig, 3.8). Moreover, the thickness is less than the North of the basin. Locally, the reverse faults affect the

Cretaceous basement and its cover-up to Paleocene rocks; they are sealed Eocene-Oligocene rocks. The stability of the South of the basin seems linked to the presence of a volcanic arc complex of probable Paleocene-Lower Eocene age, according to Benitez (1995).

The stratigraphic record shows that uplifted zones were condensed or eventually eroded, and considerable sedimentary thickness accumulated in the subsidence zones. The depocenters have northeast-southwest direction and slightly steep. The position and number of depocenters varied through time, as recorded in each tectonosequence (Figs. 3.10-3.13).

The sedimentary infill of the Manabi Basin dates from the Upper Paleocene to the Holocene, and it is not continuous, because it exhibits several unconformities that are regional unconformities (i.e., U0, U1, U2, U3 and U4. Figs. 2.4, 3.8). The regional unconformities allowed us to establish a sequential stratigraphy made up of five tectonosequences, which from base to top are named TS-1, TS-2, TS-3, TS-4, and TS-5. Although the relation of the sedimentary infill with the significant faults is not observable in the seismic lines, these faults do not cut the entire sedimentary infill; they are fossilized by it. Instead, the minor faults described from the seismic profiles, however, the upper tectonosequence (TS-4 and TS-5) generally fossilize the faults (Figs. 3.8, 3.9). For example, in the south part of the basin, it can be observed how the faults have been fossilized by the TS-4 (Fig. 3.8). Therefore, we can deduce the existence of a syntectonic sequence, predominantly formed by the four tectonosequences (TS-1, TS-2, TS-3 and TS-4. Figs. 3.8, 3.9), and therefore of Upper Paleocene-Lower Miocene age, and a post tectonic sequence mainly constituted by the tectonosequence TS-5 (Pliocene-Holocene, Figs. 3.8, 3.9). The deformations registered in the syntectonic sequence (TS-1, TS-2, TS-3) gradually decreased towards the upper part of sedimentary infill (TS-4).

The regional unconformities subdivide the basin into five tectonosequences: TS-1 constitutes Upper Paleocene time, TS-2 belongs to Eocene Formations, TS-3 from Oligocene age, TS-4 from Lower-Middle Miocene, and finally, TS-5 constitutes the Middle Miocene to Holocene strata. These tectonosequences show thickness variations (Figs.3.10-3.13) that indicate changes and movement of high and low subsidence zones. Tectonosequences described a stratigraphic evolution of the study area that together, the cartography and the bibliography review give a tectonic evolution of the sedimentary infill. For example, the seismic line 17 that crosses the Ricaurte well (Fig.3.9) displays normal faults that cause a depocenter. Meanwhile, the seismic line 10 with NW-SE direction (Fig. 3.8) shows a less tectonic activity because the thickness of sedimentary layers seems to keep a conformable seismic limit. Moreover, the isopach maps show depocenters that during the Upper Paleocene-Eocene age vary in size (Figs. 3.10-3.13). Meanwhile, depocenters of TS-3 are very thicknesses, and TS-4 depocenters show a little displacements to NE of the basin (Fig. 3.13).

### 4.1 Main geological events.

The tectonic events occurred from the Upper Paleocene to the Holocene were recorded in the sedimentary infill. The tectonosequences analysis and bibliography review summarize the structural evolution of the basin in the next phases.

Phase 1 (Upper Paleocene): Oceanic terranes accretion (Piñon Formation) and volcanic arc sediments constitute the Cretaceous basement (Fig. 4.1a) where the unconformity U0 defined in the top due to unconformity contact with Upper Paleocene strata.

Phase 2 (Middle Eocene): It characterizes by oblique convergence between the Nazca and South American plates. The middle to late Eocene basin-forming event and flysch sedimentation in the Ecuador forearc was coincident with the phase of rapid convergence between Nazca and South America plates (Daly, 1989). So, it can infer a syn-sedimentary tectonic deposition that is concordance with Benitez (1995).

The oblique convergence and shortening dominated most of the Manabi basin region during this period that triggers strike-slip motion (Benitez, 1995). Oblique convergence provokes significant deformations in the area that record more notable in the North of the basin. Likewise, Jaillard et al., 1995 mention diachronous processes that are associated with a period of unusual tectonic activity during this time. This diachronic resulted in numerous poorly defined stratigraphic units in the Manabi Basin during this time.

Phase 3 (Miocene- Holocene): As oblique convergence continued, the strike-slip motion accommodated more the boundaries of the basin where marine facies of the TS-4 deposited. At the same time, extension and subsidence increased, during the Miocene time (Deniaud, 2000). These are recorded in the isopach map of TS-4, where two significant depocenters registered. On the other hand, the subduction of the Carnegie Ridge contributes to the uplifting of the Coastal Cordillera during the Pliocene time. This event is considered of high tectonic activity because it provokes discontinuity of outcrops in both the basement and sedimentary covers (Benitez, 1995).

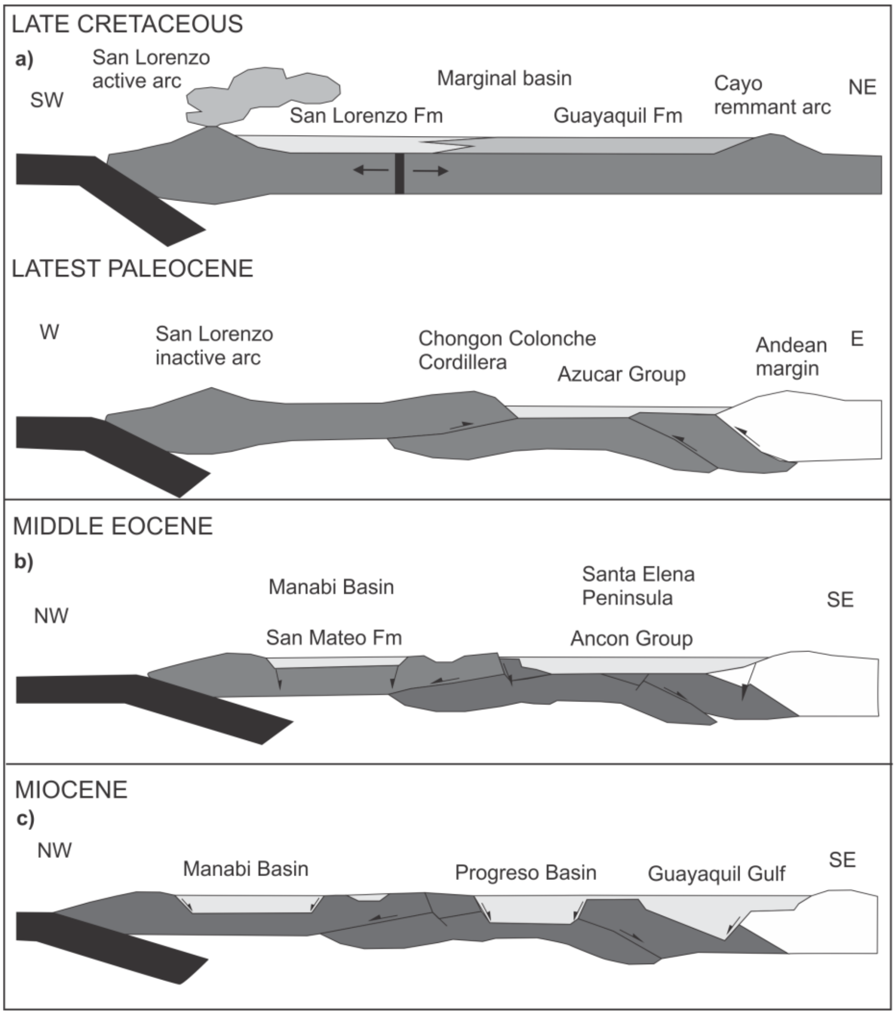

**Figure 4.1.** Schematic cross sections showing main tectonic domains of the Manabi basin evolution. (a) In the late Cretaceous, the San Lorenzo arc sediments are deposited on Piñon Formation into a marginal basin settings, while in the latest Paleocene strike slip faults provoke extensional processes. (b) The middle Eocene is represented by high activity tectonic due to convergence rate change, so that first sedimentary sequences are deposited (San Mateo Formation). (c) The forearc basins are settled and normal faults sink the sedimentary infill. Modified from Jaillard *et al*., (1995).

Therefore, the tectonic development of the Manabi Basin could divide into three stages (Fig. 4.1): (a) The Cretaceous basement determined by basalt and island arcs strata. (b) The Middle Eocene marked by the occurrence of significant tectonism that caused drastic changes in forearc settings due to the extensional process. Moreover, during Middle and Late Eocene was initiated the Formation of forearc basins due to rapid convergence in the active margin. (c) Instead, the Neogene age developed strong subsidence in transtensional forearc basins (Benitez, 1995), and the subduction of the Carnegie ridge results in the emersion of the Manabi forearc basin (Deniaud, 2000). So, these trigger current tectonostratigraphy setting of the sedimentary infill, as well as tectonic deformation, is controlled by strike-slip faults.

# CHAPTER 5

## 5. CONCLUSION

The Manabi Basin, located in the Coastal Cordillera, records the tectonosequences from the Upper Paleocene to Holocene. This sedimentation is recorded both in the highlands (Jama and Jipijapa) and in the depocenters of the basin. The forearc basin evolved due to rapid oblique convergence between Nazca and South America plates. The sedimentary infill is constituted by four tectonosequences (TS-1, TS-2, TS-3, and TS-4), delimited by regional unconformities (U0, U1, U2, U3, and U4). Each tectonosequence shows different geometries, although the elongated geometry in the NE-SW direction is predominant. Likewise, they show depocenters and structural uplifts, highlighting the complex evolution of the sedimentary infill. The tectonosequences determined by isopach maps that enable us to conclude that there are not main depocenters because tectonosequences show several small depocenters along the area.

On the other hand, the subduction between tectonic plates produces compression along the continental margin that originated the Jipijapa and Jama reverse NNE-SSW faults, limiting the Manabi Basin. The reverse faults are responsible for crustal thickening and local regions of extension, such as the Manabi Basin. Moreover, they are relevant faults because of show outcrops of the Manabi Basin.

Finally, the Manabi basin is a type of pull-apart basin developed by the subduction process in the active margin of Ecuador. The structural evolution of the basin shows three distinct stages—first, the Cretaceous basement. Second, the rapid convergence in the active margin during the middle and late Eocene caused drastic changes and synsedimentary deposition due to the compressional process, and finally, a strong subsidence infill the Manabi basin during Neogene age due to the Carnegie Ridge subduction.

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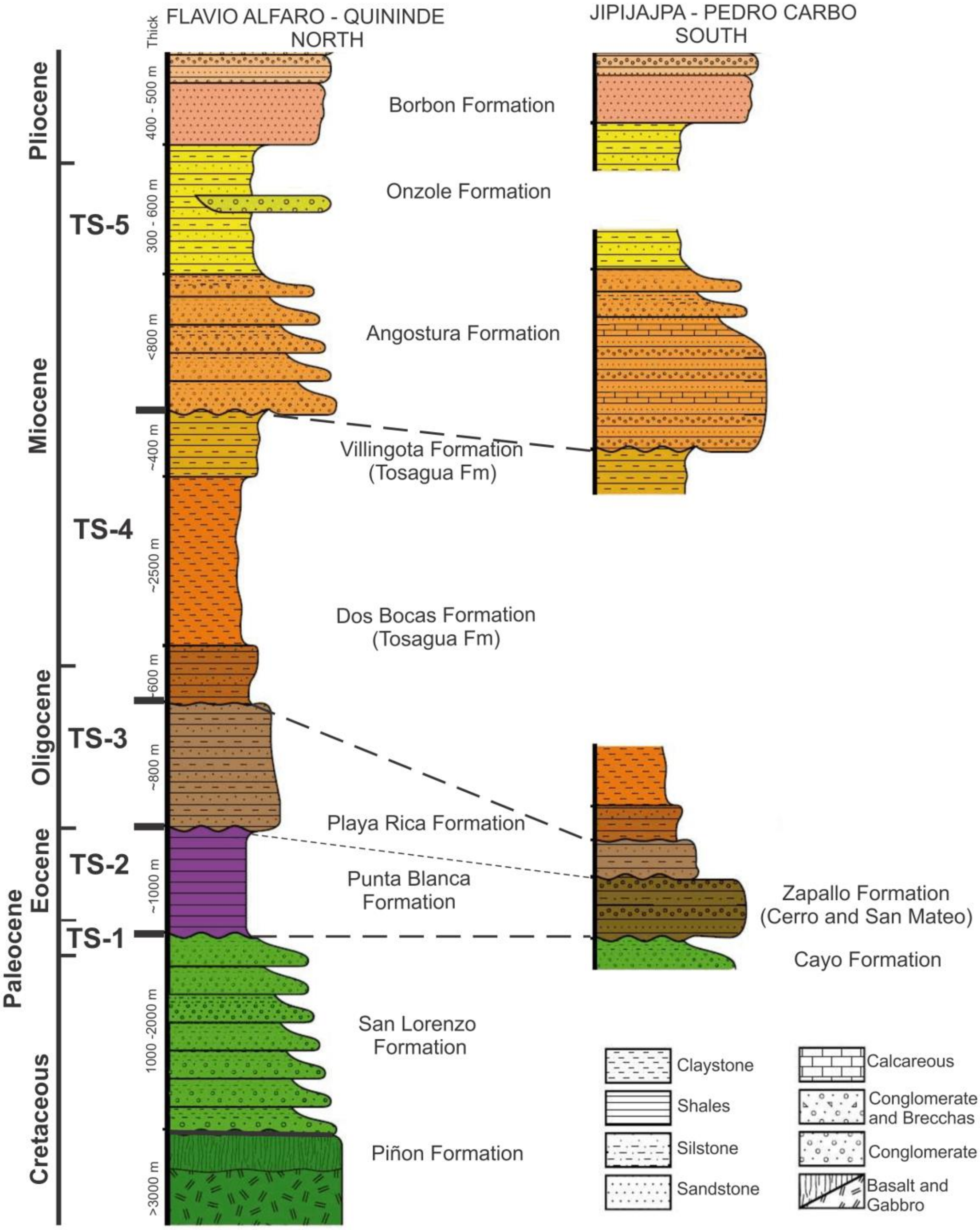
# ANNEX



**Annex 1.** Stratigraphic columns of the Manabi Basin shows the differences thickness between north and south of the basin. Modified from Reyes (2013).