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2D Seismic Interpretation of the Tumaco on-and offshore basin, SW Colombia. Implications for tectono-stratigraphic evolution and hydrocarbon exploration

by

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Dedication

A mis padres Gloria Inés y José Hernán.

A mis hermanos; Jose, Vivi, Nata y Linis.

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And for the last, but not least important; I would like to thank my family and my steamed friends Leonardo, Stine, Anita, Cesar and Alex, for their constant support throughout the duration of this study.

Abstract

The Tumaco on and offshore basin is located in the Pacific region of NW corner of South America, southwestern Colombia. It is classified as a forearc basin and it is considered a frontier exploration basin. The basin was formed during Paleogene-Recent convergence of oceanic derived terranes against South America. The stratigraphy consists of a volcano-clastic basement overlie by an Eocene to Recent clastic sedimentary cover. The last exploratory well, drilled in the 80's, showed non-commercial amounts of oil and gas. This study integrates new onshore outcrop data (e.g. biostratigraphy, stratigraphic and organic geochemistry) with more than 3000 Km of 2D seismic data on- and offshore.

Results based on seismic interpretation, plate tectonic models and surface geology indicate that the basement high, the Remolinogrande high, is the continuation of the Gorgona large igneous province to the north, which was accreted in the Late Eocene during subduction of the Farallon plate beneath South America. This accretion resulted in the development of the Tumaco onshore basin, located between the Remolinogrande high and the Western Cordillera of Colombia.

The Tumaco offshore basin is suggested as the fore-arc basin that results of the subduction of the Nazca plate beneath South America. The subduction affected the entire region, resulting in continuous uplift of the Remolinogrande high and the migration of the fore-arc basin eastwards.

Two main geological terranes were identified. The Tumaco South terrane (Gorgona terrane sensu Cediel et al., 2003) and the Tumaco North terrane. These terranes are separated by the Garrapatas Fault System and exhibit two diferent deformation styles. The structural style in the Tumaco South terrane is characterized by a thick skin deformation while the Tumaco North terrane has a thin skin deformation.

Eocene-Recent basin infill of the Tumaco onshore basin occurred mostly from the Western Cordillera of Colombia with the development of deep marine to continental deposition, whereas the Tumaco offshore consists of mostly marine sedimentation since Miocene. Source rocks mostly include gas prone Eocene marine shales in the Tumaco on - and off shore basin that are buried today to a depth of 8 km. Reservoir rocks include marine and continental sandstones of Miocene age.

Because the Tumaco basin has a sag type basin configuration most of the traps are pinchtouts against the uplifted Remolinogrande high and stratigraphic traps.

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1. INTRODUCTION

The geological history of the northwestern corner of South America is complicated. Its configuration is based on the accretion of different Cretaceous allocthonous blocks of mainly oceanic crust composition (Cediel et al., 2003; Escovar et al., 1992; Jaillard et al., 2006, 2009; Kerr et al., 2002). Despite the complicated geological history, few studies have been published in Colombia in order to constrain the geological history of the southwestern corner of the country and its relation with the geological history of northern Ecuador ((Kerr et al., 2002; Cediel et al., 2003)

The Tumaco on- and offshore basin several studies, including Ecopetrol and Agencia Nacional de Hidrocarburos (ANH) studies, have been conducted in the basin (Duque-Caro, 1984, 1990a, 1990b, 1991; Escovar, 1992; (Bueno et al., 1989; Bueno et al., 1974; Kerr et al., 2002; Marcaillou and Collot, 2008; Mountney and Westbrook, 1997; López, 2009; Ojeda, 1987). Most previous work in the region focuses on the on- and offshore area separately. No attempt to integrate the geological history of both areas, have been conducted, since it is difficult to extrapolate and correlate the onshore information to the offshore area.

This study integrates the study of the geology of the on- and offshore Tumaco basins and for the first time presents detailed analysis of the Pacific accretionary prism offshore structure in southwestern Colombia. It integrates 2-D local seismic lines and ten 2-D seismic regional profiles (published for first time), which were acquired from the present subduction zone up to the shoreline of the Pacific area and are interpreted in this work with the aim to:

1) Understand the tectono-stratigraphic evolution,

2) Its relation with terranes accretion and

3) The petroleum potential of the southwestern corner of Colombia. Tumaco on- and offshore basins in Colombia.

Previous studies

Most of the studies done in the Tumaco basin correspond to in-house studies completed by Ecopetrol (Ojeda, 1987; Escovar et al., 1992), (Ahmadi et al., 2003; Robertson Research U.S, 1981a, 1981b, 1988) and recently by ANH (2011). There are few publications relating to the tectono-stratigraphic evolution (Borrero et al., 2012) and the hydrocarbon potential of the basin. Generally, most of the published studies focus either northwards or southwards of the study area, as in the Gorgona Island (Kerr, 2005), the Atrato and Choco basin (Duque-Caro, 1984, 1990a, 1990b, 1991); and in the Borbon and Marañon basins in Ecuador (Kerr et al., 2002; Marcaillou and Collot, 2008; Mountney and Westbrook, 1997) comprises the study on the on- and offshore area separately.

Recently, the ANH has tried to increase the understanding of the basin and some Master and PhD studies have been conducted (López, 2009; Barbosa, 2012). In his study, López (2009) used seismic interpretation to determine the basin evolution of the Tumaco on- and offshore basins. However, he did not consider the possible accretion of the different terranes in the area; he assumed the Western Cordillera and the Remolinogrande high as a unique terrane. In addition, his study mainly focused on the description of the evolution of the sedimentary facies but little discussion regarding structural configuration was provided. The main focus of Barbosa (2012) was the understanding of the thermal history of the basin and its implications for the hydrocarbon generation. In his study, he uses apatite and zircon fission track to generate thermal models of the basin. However, he only recognizes the uplifting events of the Western Cordillera and by this neglecting the possible uplifting and subsidence events that may have occurred in the Remolinogrande high. This can have greater implications, not only in the tectono-stratigraphic model of the basin, but also in its hydrocarbon potential.

2. REGIONAL SETTING

The Tumaco basin is an elongated and asymmetric basin with an approximate N30°E trending; with a total area of 5828.5 km2. It is located in the Pacific coastal region of southwestern Colombia (**Figure. 1**). The basin corresponds to a fore-arc basin developed on and active convergent margin that extends from northwestern South America to Central America, formed during the subduction of both the Caribbean and Nazca plate (Duque-Caro, 1990; Escovar, 1992). It has been proposed that subduction along the margin started during the Mesozoic and was follow by the accretion of the several terranes until Cenozoic (Kellog and Vega, 1995).

The basin is divided into two sub-basins: on- and offshore basins (**Figure. 1**). The onshore basin is bounded to the east by the Western Cordillera, to the west by the present Pacific shoreline, to the north by the Garrapatas fault system and to the south by the Ecuatorian border (**Figure. 1**).

The Tumaco offshore basin is bounded to the north by the Garrapatas fault system, to the south by the Ecuatorian border, to the east by the present shoreline and to the west to the inner trench wall of the present subduction zone of the Nazca plate beneath South America (**Figure.1**).

Figure 2, shows the main structural elements and basins of the study area (López et al., (2008)). The Manglares basin and the Tumaco basin are considered fore-arc basins formed during the progressive subduction of the Nazca plate beneath the South American plate. These basins are separated by the Remolinogrande high (**Figure. 2**). The free-air gravity anomaly map (**Figure. 3**) shows the main basement paleo-highs, which include the Gorgona complex, the Tumaco on-and offshore basin and the Manglares basin.

Seismically, the study area is characterized as a very active zone related to the subduction process. Over the last 100 years, earthquakes of different magnitudes, up to 8 in the richer scale have been documented along the pacific margin in northern Ecuador and Southern Colombia. **Figure 4** shows the regional seismicity transects along the study area, illustrating the angle and deep variation of the subduction slab throughout the study area.

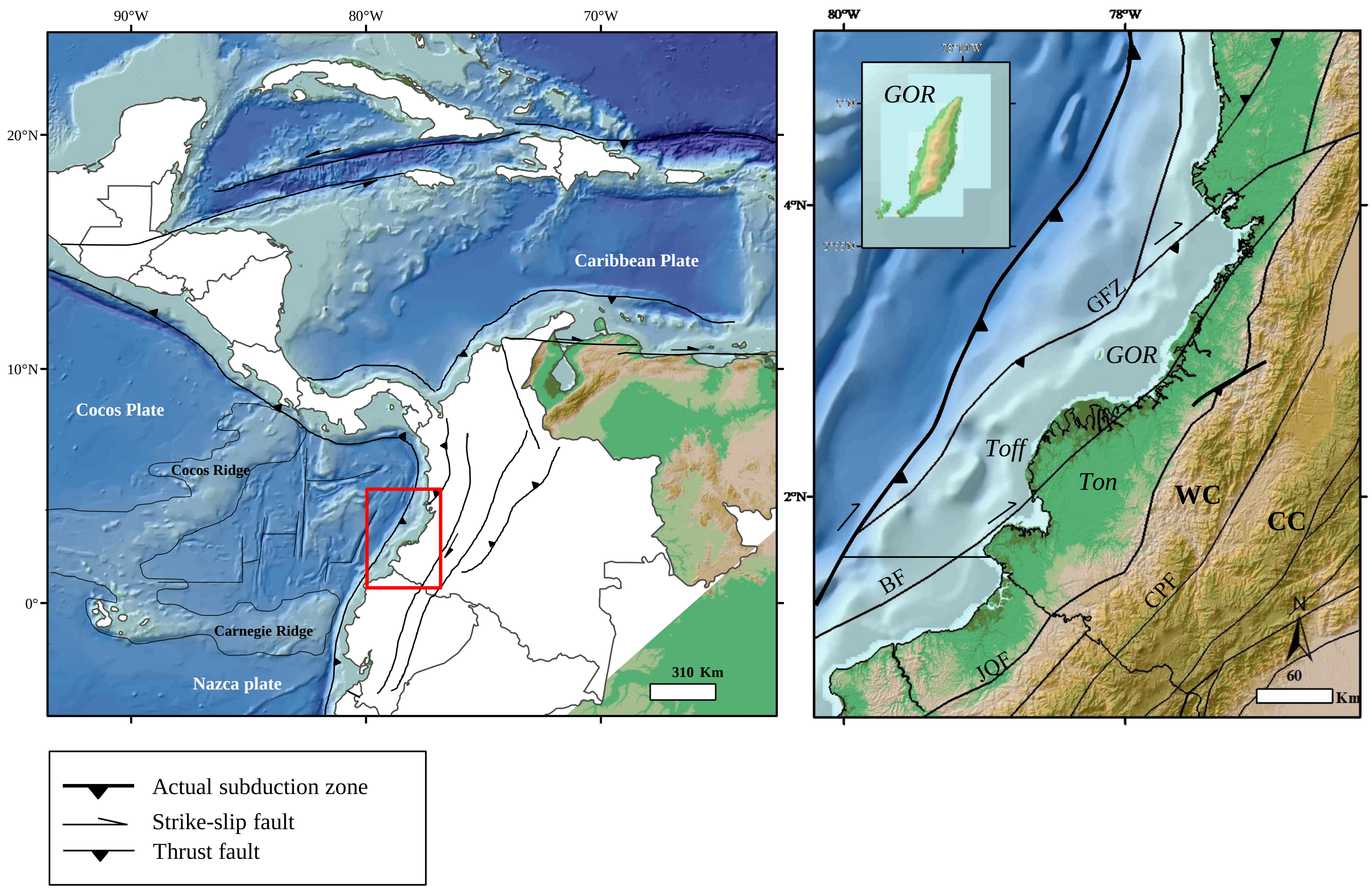

Figure 1. a) GEBCO digital elevation model of northwestern South America and surrounding tectonic plates. The red square indicates the study area b) Study area, showing main faults and major geographic features. WC: Western Cordillera, CC: Central Cordillera, GOR: Gorgona island, Toff: Tumaco offshore basin, Ton: Tumaco onshore basin, GFS: Garrapatas fault system, CPF: Cauca-Patía fault, BF: Buenaventura fault, JQF: Jama- Quininde fault.

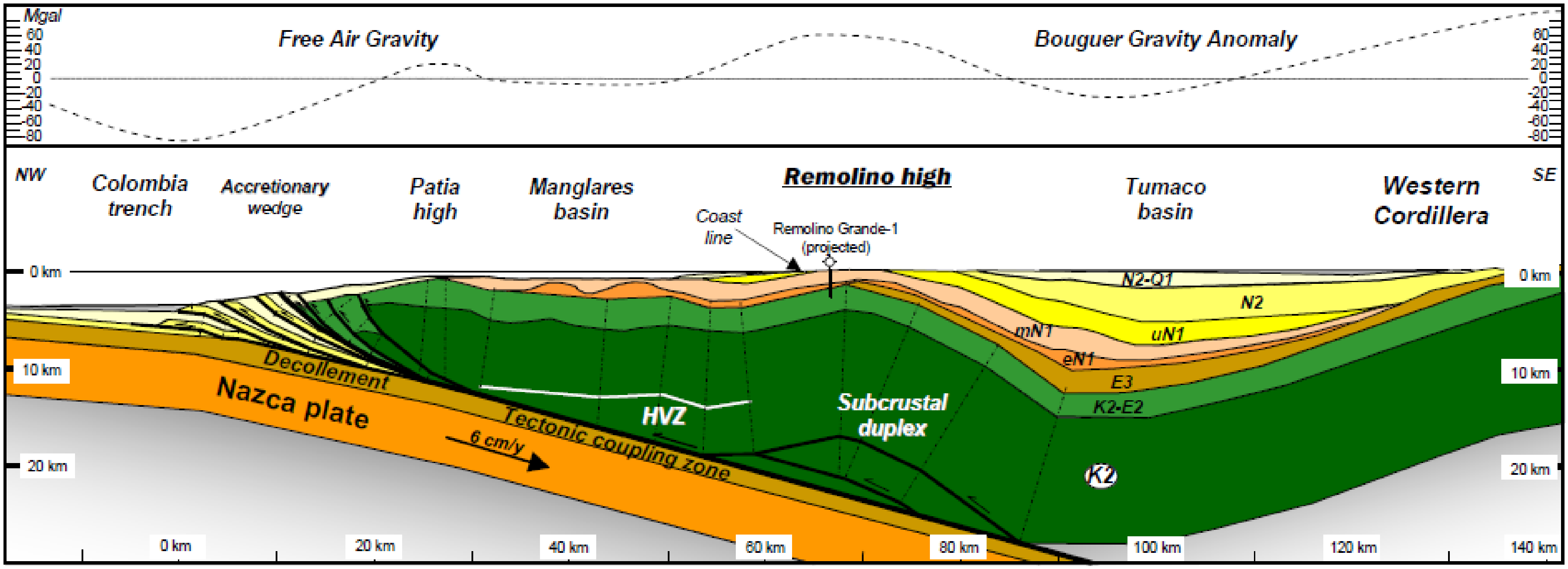

Figure 2. Structural cross section of Southern Colombia after López et al., (2008) showing main basins (Tumaco and Manglares basin) and basement paleo-highs (Remolino high) within the study area. Age of the units: K2, Late Cretaceous (basement); E2, Eocene; E3, Oligocene; N1, Miocene; N2, Pliocene; Q1, Pleistocene.

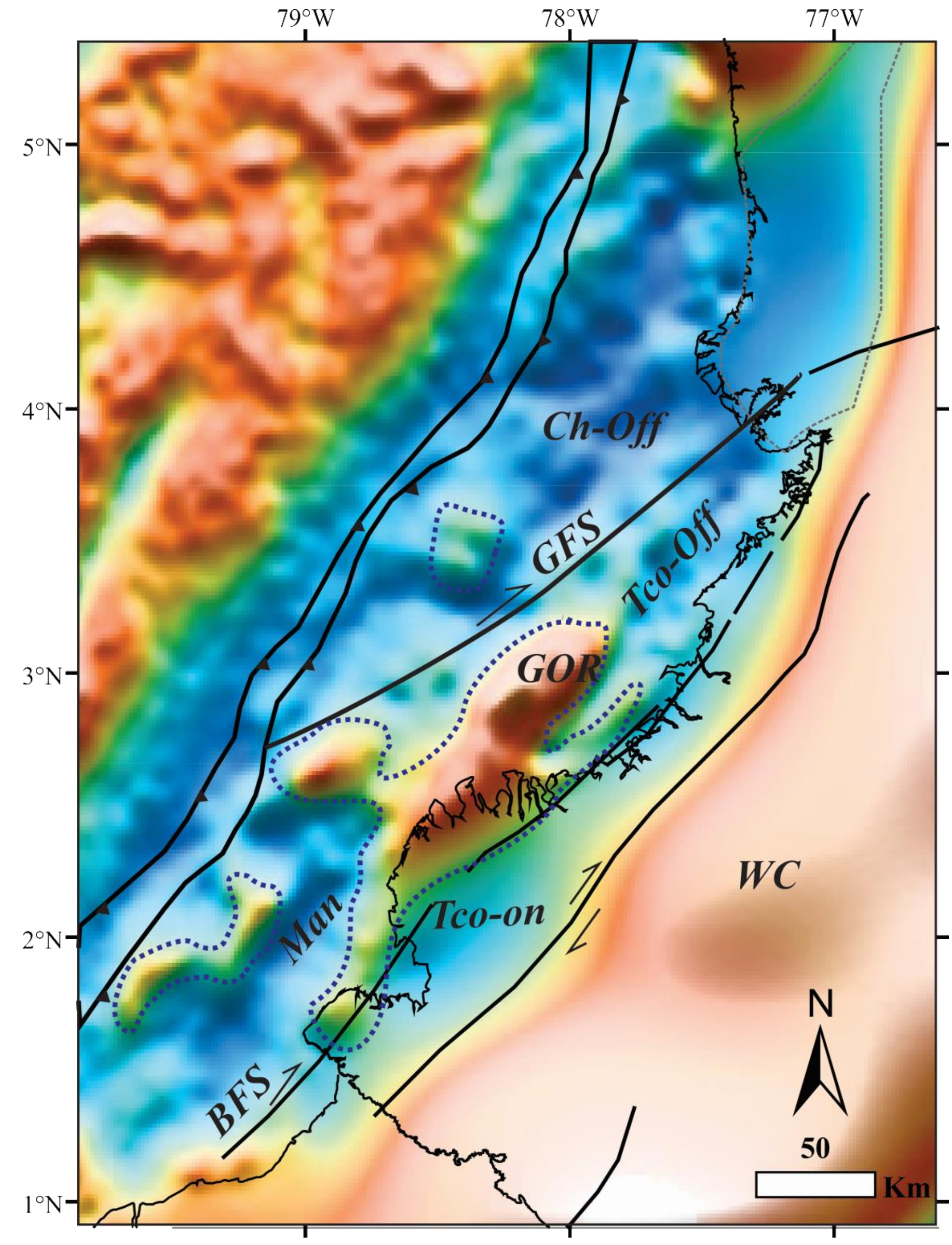

Figure 3. Regional free-air gravity anomaly map showing the distribution of the main basement paleo-highs and basins. Tco-off: Tumaco offshore basin; Tco-on: Tumaco onshore basin; Man: Manglares fore-arc basin; GOR: Gorgona basement complex; Ch-off: Choco offshore basin, GFS: Garrapatas fault system; BFS: Buenaventura fault system; WC: Western Cordillera; AC: actual accretionary prism. Dashed blue lines surrounds basement paleo-highs.

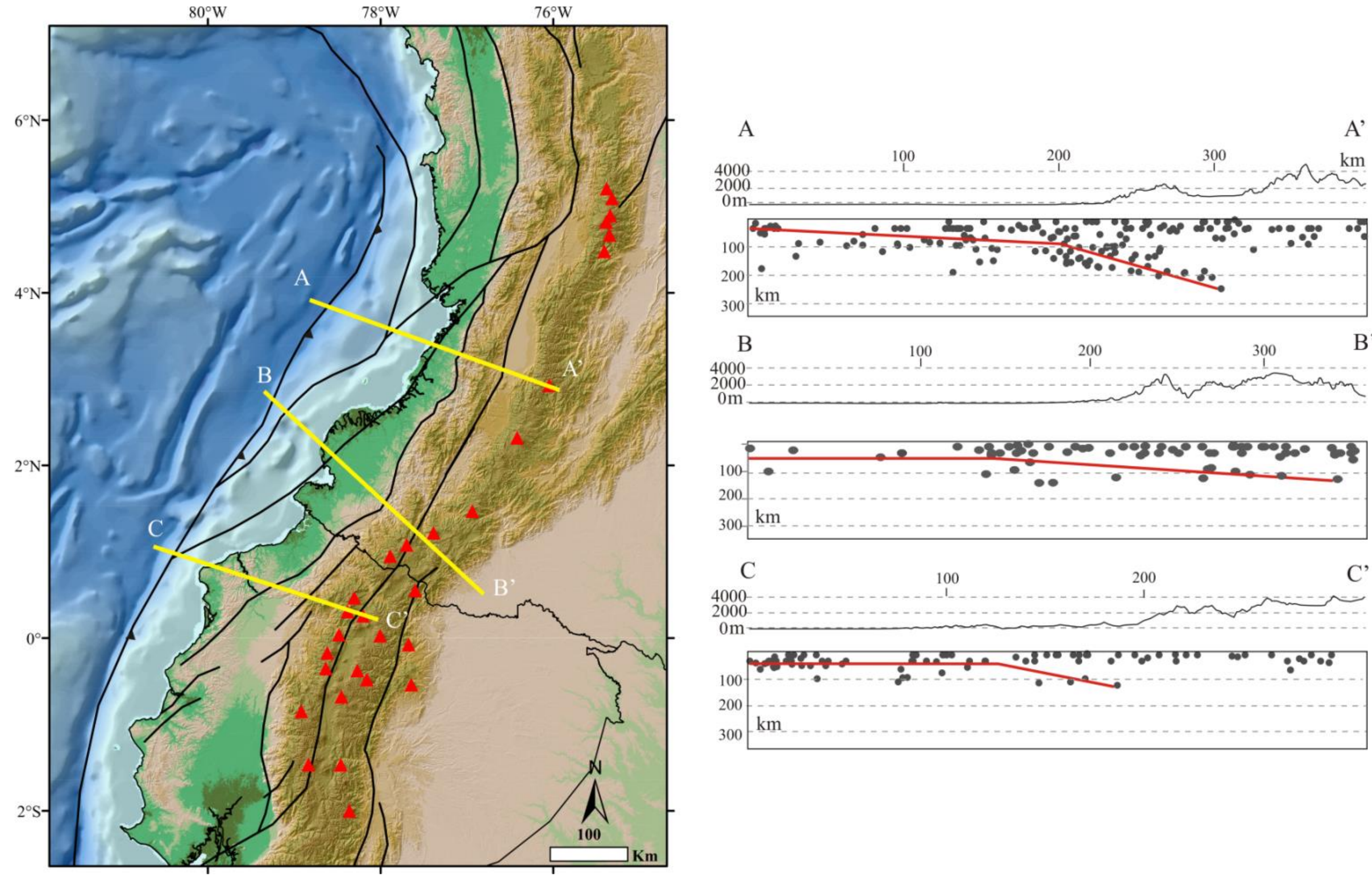

Figure 4. Regional seismicity transects from the study area and northern Ecuador. Black points indicate major hypocenter earthquakes. Red lines show the depth tendency of the earthquakes and red triangles indicates locations of volcanos.

Terranes configuration

The western margin of Colombia and Ecuador consist of a series of blocks of oceanic plateau and island arc affinity, accreted to the continental margin of the South American Plate (SOAM) from Mesozoic up to the Cenozoic times (**Figure. 5**).

In Ecuador, several terranes as the Macuchí, Naranjal, Piñón, and Pedernales terranes, among others are thought to constitute the Cretaceous basement of the western side of the country (**Figure. 5**). The Macuchí and Naranjal terranes, (represented by the Piñón Unit and the Pedernales-Esmeraldas sequences) have an island arc affinity and are believed to have accreted to the continental margin from the late Campanian up to Eocene time (Kerr et al., 2002). Jaillard et al. (2009) suggests that the Piñón and Naranjal units form a unique terrane which was accreted to the ecuadorian western margin during the late Paleocene.

According to Kerr et al. (2002) the Piñón-Pedernales terrane in Ecuador and the Gorgona and Serrania de Baudo terranes in Colombia cannot belong to the Colombian Caribbean Oceanic Plateau (CCOP). Reynaud et al. (1999) consider that the geochemical and geochronological data ages from the basement terranes of Colombia and Ecuador has different origins and cannot be considered as belonging to a unique oceanic plateau (CCOP). In contrast, Jaillard (2004), based on the geochemical analysis of the Piñón terrane suggest that this was form on the CCOP plateau and that it has similar affinities with the rocks found in the Gorgona island. Therefore the Gorgona island rocks do not have a Galapagos hot spot origin and more likely were form in the Farallon plate, South of Ecuador and close to the South America margin, forming a unique oceanic plateau which was separated by a subduction zone.

Others like Cediel et al. (2003)and Litherland et al., (1994) considered that the Dagua terrane (In Colombia) and Piñón terrane has the same origin and correlates them as a unique body (Cediel et al., 2003) denominated by the author as the Dagua-Piñón terrane.

Based on seismic, geochemical and palomagnetic interpretations (Cediel et al., 2003; Kerr, 2005; Kerr et al., 2002; Macdonald et al., 1997; McGeary et al., 1986) suggest that Gorgona is an isolated terrane that does not belongs to the CCOP and which was originated from southern Pacific latitudes and separated from the Dagua-Piñón terrane by the Buenavetura fault and from the Baudo terrrane by the Garrapatas fault (**Figure. 5**). However, the trace of the latter fault has been also a matter of debate since its trace has a lot of uncertainty in the offshore where it only had been observed in seismic and gravimetic maps near of the Buenaventura bay.

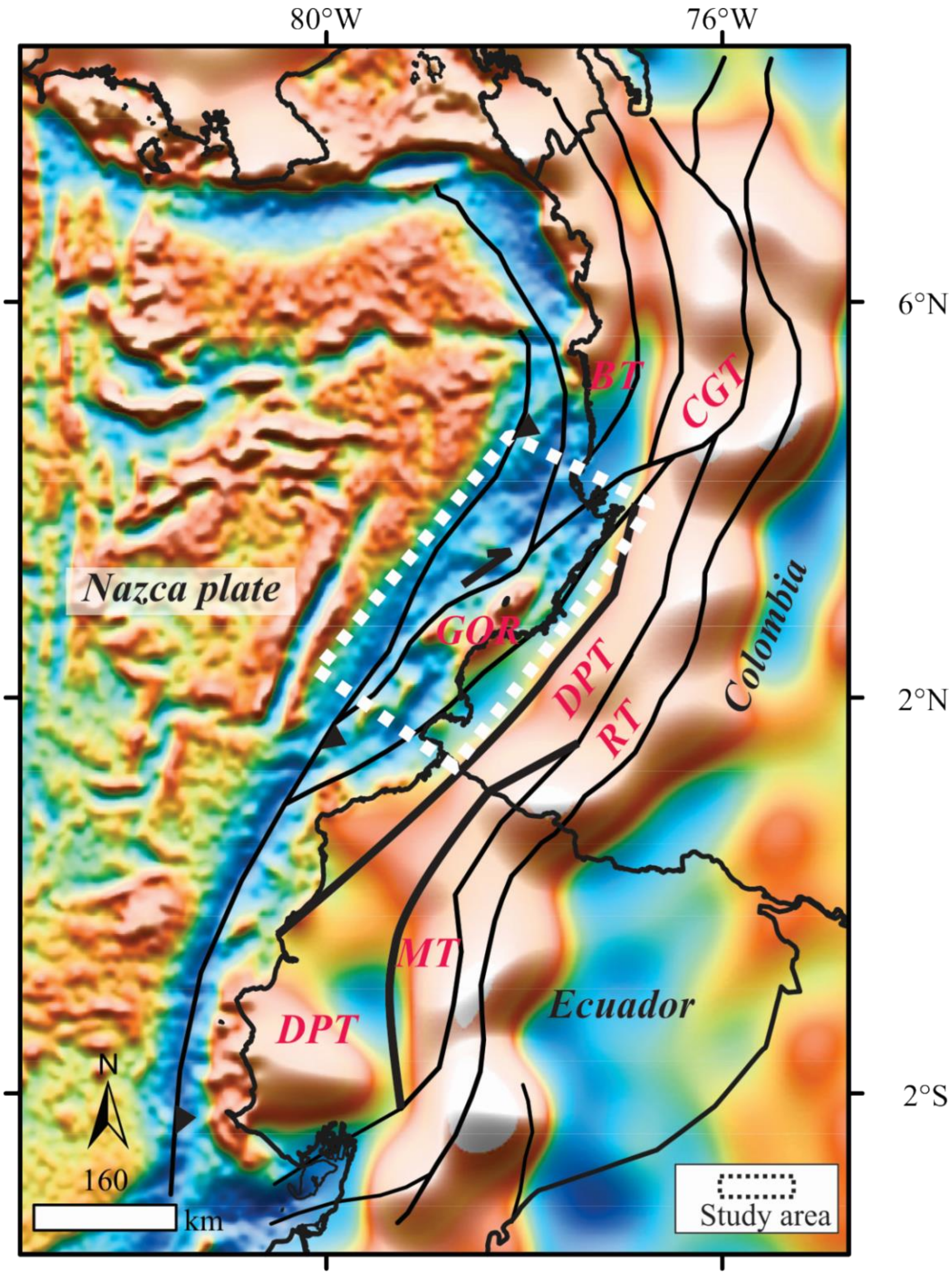

Figure 5. Regional free-air anomaly map showing the different Mesozoic terranes from the northwestern corner of South America. Names and location of terranes modified from Cediel et al., 2003; Jaillard et al., 2006 and Kerr et al., 2002. MT: Macuchí island arc terrane; RT: Romeral terrane; DPT: Dagua-Piñón terrane; GOR: Gorgona terrane; CGT: Cañas Gordas terrane; BT: Baudo terrane.

Tectonic framework

Based on plate tectonic reconstructions, thermochronology, geochronology and geochemistry data (Cediel et al., 2003; Duque-Caro, 1990; Kennan and Pindell, 2009; Moreno-Sanchez and Pardo-Trujillo, 2003; Villagómez et al., 2011; Pindell et al, 1998), four tectonic evolutionary stages are proposed (**Figure. 6**)

LATE CRETACEOUS – EARLY PALEOCENE

During the Late Cretaceous- early Paleocene the tectonic regime in southwestern Colombia changed from a passive margin to an active convergent margin as a result of oblique collision of the leading edge of the Caribbean plate and South American plate (SOAM) (Cediel et al., 2003; Duque-Caro, 1990; Kennan and Pindell, 2009; Moreno-Sanchez and Pardo-Trujillo, 2003; Villagómez et al., 2011; Pindell et al, 1998). Collision started in Ecuador and southern Colombia, resulting in the emplacement of the Western Cordillera range, around 75-70 Ma (Villagómez et al., 2011). The collision was followed by right-lateral strike-slip faulting along the Romeral fault system, as the Caribbean plate collision migrated diachronously to the north and northeast.

LATE PALEOCENE (~58 MA) – EARLY EOCENE

To the south, in Ecuador, the Piñón and Naranjal terranes were accreted to the western continental margin of Ecuador (Jaillard et al., 2009; Kerr, 2005) (**Figure. 6a**). According to Jaillard et al., 2006; these terranes are part of the CCOP. Cediel et al. (2003) suggested that the Western Cordillera and the Piñón terrane are part of the same oceanic plateau (CCOP) and conformed what he called as the Dagua-Piñón terrane.

MIDDLE EOCENE (45 MA) TO LATE EOCENE (~37–40 MA)

The collision of the Gorgona terrane with the Western Cordillera terrane occurred around 45 Ma (Cediel et al., 2003)**Figure. 6b**). According to (Franco and Abbott, 1999) the collision ended with a westward jump of the subduction zone.

The basement of the Tumaco basin is considered to be part of the Gorgona allocthonous block, derived from an oceanic plateau (CCOP) which was accreted to the continent during the initial Caribbean collision in northwestern South America (Escalona and Mann, 2012; Kerr et al., 2002; Pindell et al., 1998; Spikings et al., 2001).

OLIGOCENE – EARLY MIOCENE

The Nazca and Cocos plate consolidate and the Choco-Panama- arc terranes collided with the South American plate diachronously from southwestern to northwestern Colombia (Farris et al., 2011; Montes et al., 2012) (**Figure. 6c, 6d**), while the subduction of the Cocos plate generated arc magmatism in the Western Cordillera.

The discontinuous uplift of the Western Cordillera during the subduction cycle generated at least three periods of erosion and deposition.

1) Eocene (?) – Early Miocene

2) Early to Middle Miocene

3) Late Miocene – Recent.

These events gave origin to the thick sequences of sediments (~ 9 km) that have been deposited on the Western Cordillera and Gorgona terranes, forming the Tumaco on- and offshore basin.

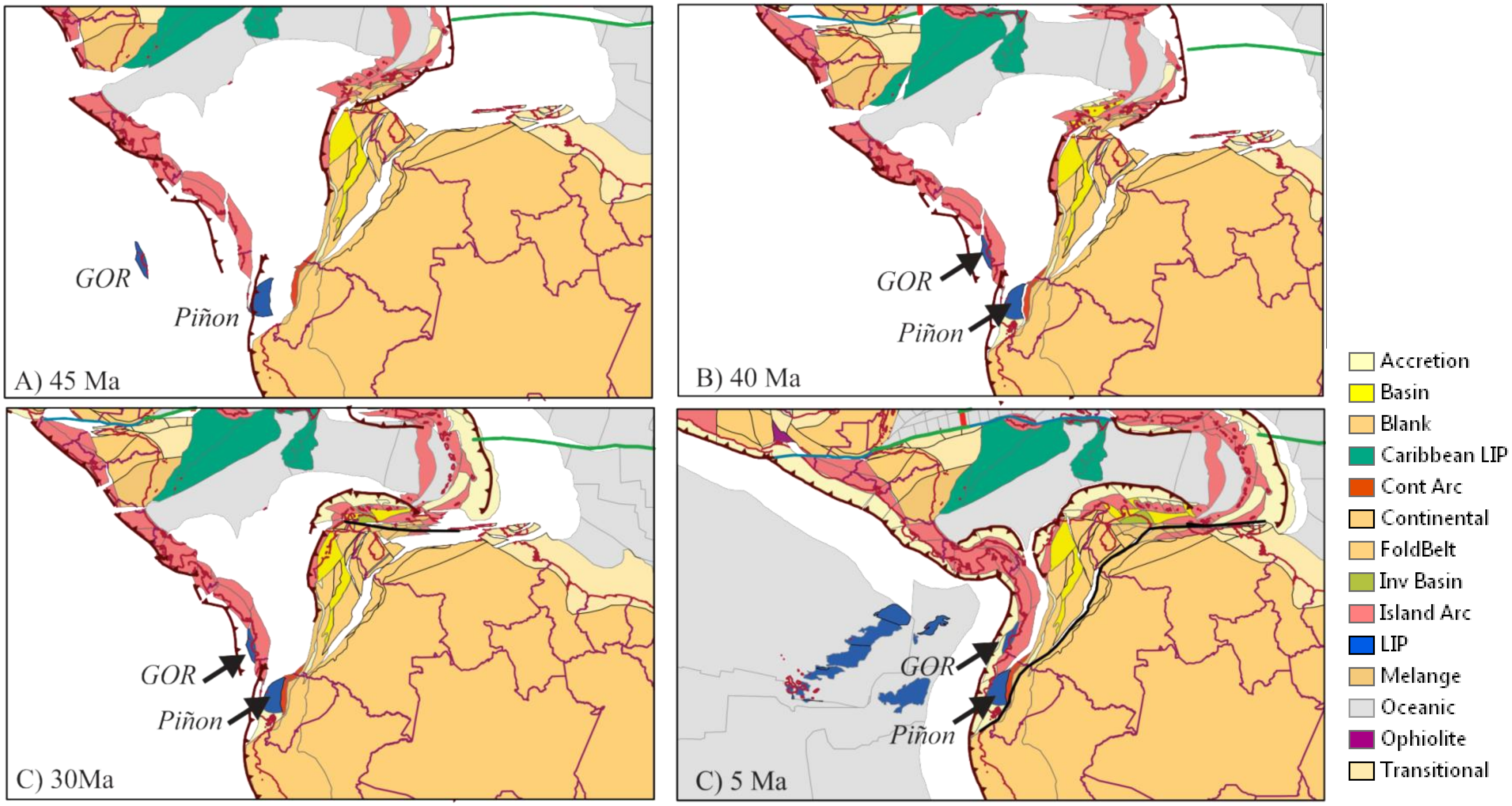

Figure 6. Plate tectonic reconstruction model of the Caribbean region from Middle Eocene to Recent (Escalona and Noron (2012) in progress. a) Middle Eocene, accreation of the Western Cordillera against the South American plate, b) Late Eocene, in Ecuador, accreation of the Piñón terrane, c) Late Eocene-Oligocene (?), collision of the Gorgona terrane - GOR- with Western Cordillera c) Actual configuration of the Caribbean

3. DATA AND METHODOLOGY

The well database for this study comprises two near shore wells drilled in 1967 (Tambora-1 and Sandi-1) and three onshore wells drilled from 1953 through 1981 (Remolinogrande-1, Chagüí -1 and Majagua-1) (**Figure 7**).

The geophysical database consists of more than 10.000 km of 2D seismic lines. The seismic coverage consist of 3.863 km of regional 2D offshore survey lines acquired by Wavefield-Inseis in 2005 and semi-detailed 2D coverage of 8424 km during 1973, 1982 and 1992 (**Figure7**).

The regional seismic lines were provided by *Spectrum ASA* and the semi-detailed coverage was providing by Universidad de Caldas, Colombia, in agreement with ANH. Table 1 resumes the parameters of the acquisition and processing of the different surveys. The quality of the data varies from regular to good due to differences in acquisition, sampling time, coordinate systems projections, seismic processing and target between seismic surveys and geological complexity.

In addition, a regional geological map from Gómez et al. (2007) a regional bouguer from ANH (2010), **Figure. 8** were used plus previous publications. The Regional bouguer anomaly gravity map has density corrections for the earth and water depth in the ocean of 2.67 g/cm3 and 1.03 g/cm3 respectively. The map shows variations between -235 mGal and 405mGal with a contouring interval of 20 mGal.

Stratigraphic descriptions from well and outcrop data follow the new stratigraphic proposal of the Tumaco onshore basin from Caldas-ANH (2011). The organic geochemical data was taken from (Caldas-ANH, 2011; Robertson Research U.S, 1981b, 1988)

The 2D seismic data was uploaded and interpreted in Landmark's Open Works TM. Due to the differences in the acquisition parameters of the different seismic surveys and in order to unify the seismic information resampling to 4 (s) was performed. Based on the well and stratigraphic descriptions of the basins, five major unconformities where identified. These unconformities were followed in the seismic interpretation and were used to define the stratigraphic and structural variations within the basin. To determine the main morphological characteristics of the basin, a seabed map was built.

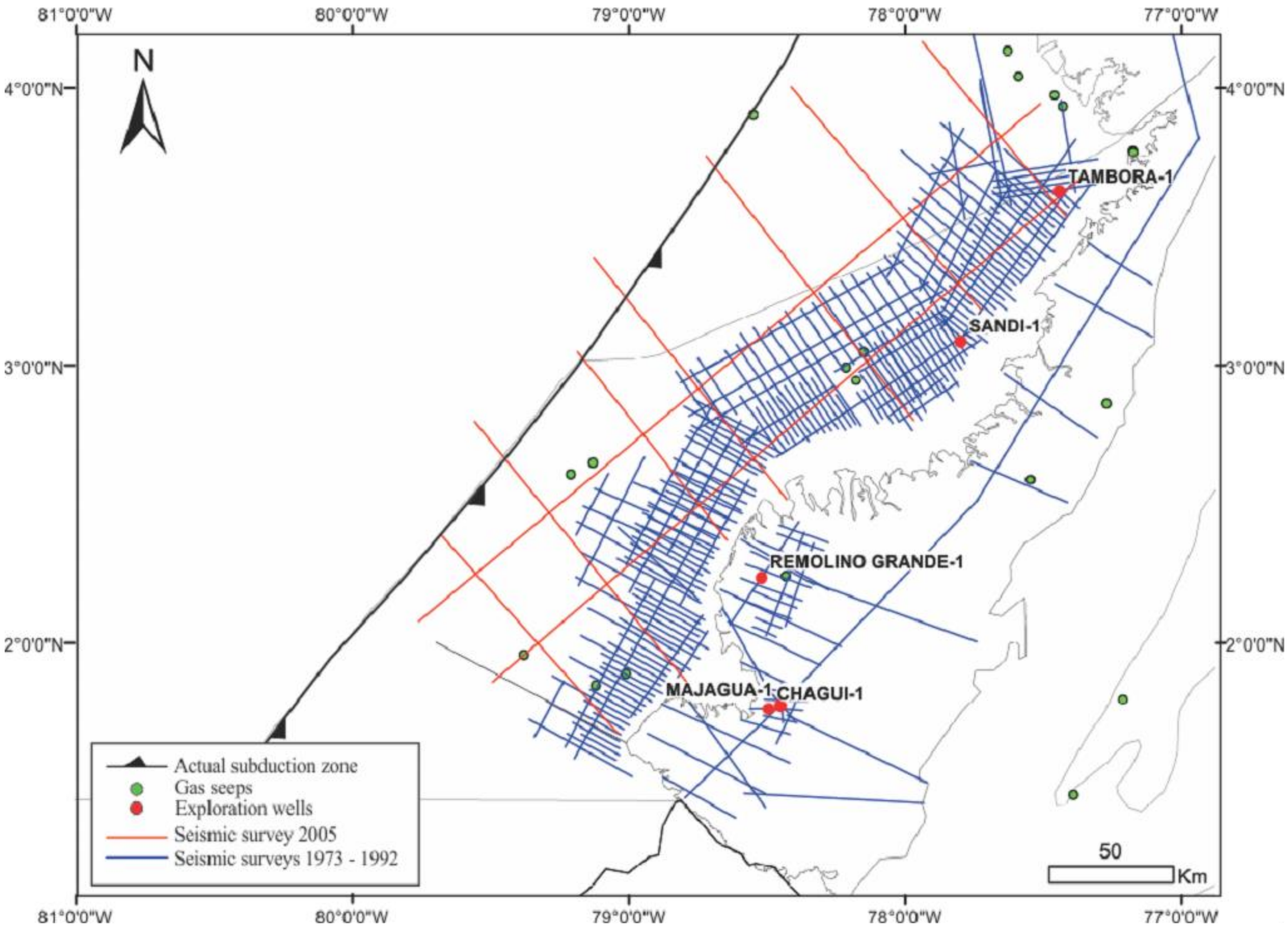

Figure 7. Well and seismic coverage map with the location of the different surveys lines used in this study and the location of the gas seeps within the basin.

4. OBSERVATIONS

Basin configuration

From the bouger gravity map (**Figure 8**) at least four different geological provinces are observed: two depocenters to the south, one depocenter to north, and a basement paleohigh in the central portion of the study area (**Figure 8**).

The onshore depocenter (**Figure 8 No1**) corresponds with the Tumaco onshore basin and it is characterized by a negative bouger anomaly up to ~50 mGal. It has an approximate N 30° E trend. The offshore depocenter corresponds to the Manglares basin (**Figure 8 No2)** it has positive Bouger anomalies.

The central portion of the basin is characterized positive bouger anomalies values (up to ~ 100 MGal) (**Figure 8 No3)**. It has an approximate N 30° E trend, 40 km of width and 140 km of longitude. This bouger anomaly corresponds to the Gorgona basement complex.

The last province is found in the northern area where anomalies values are the more negative of the whole basin reaching up to ~75mGal (**Figure 8 No4)**. This anomaly has a N40°E trending approximately and gets wider near Buenaventura city. It is also appreciated that the axis of this depocenter is slightly displaced to the west.

The bouger anomalies values increases towards the Western Cordillera, the subduction zone and the Gorgona complex. Deflection in the contours and elongate basement structures may indicate the presence of three different faults lineaments as shown in **Figure 8**.

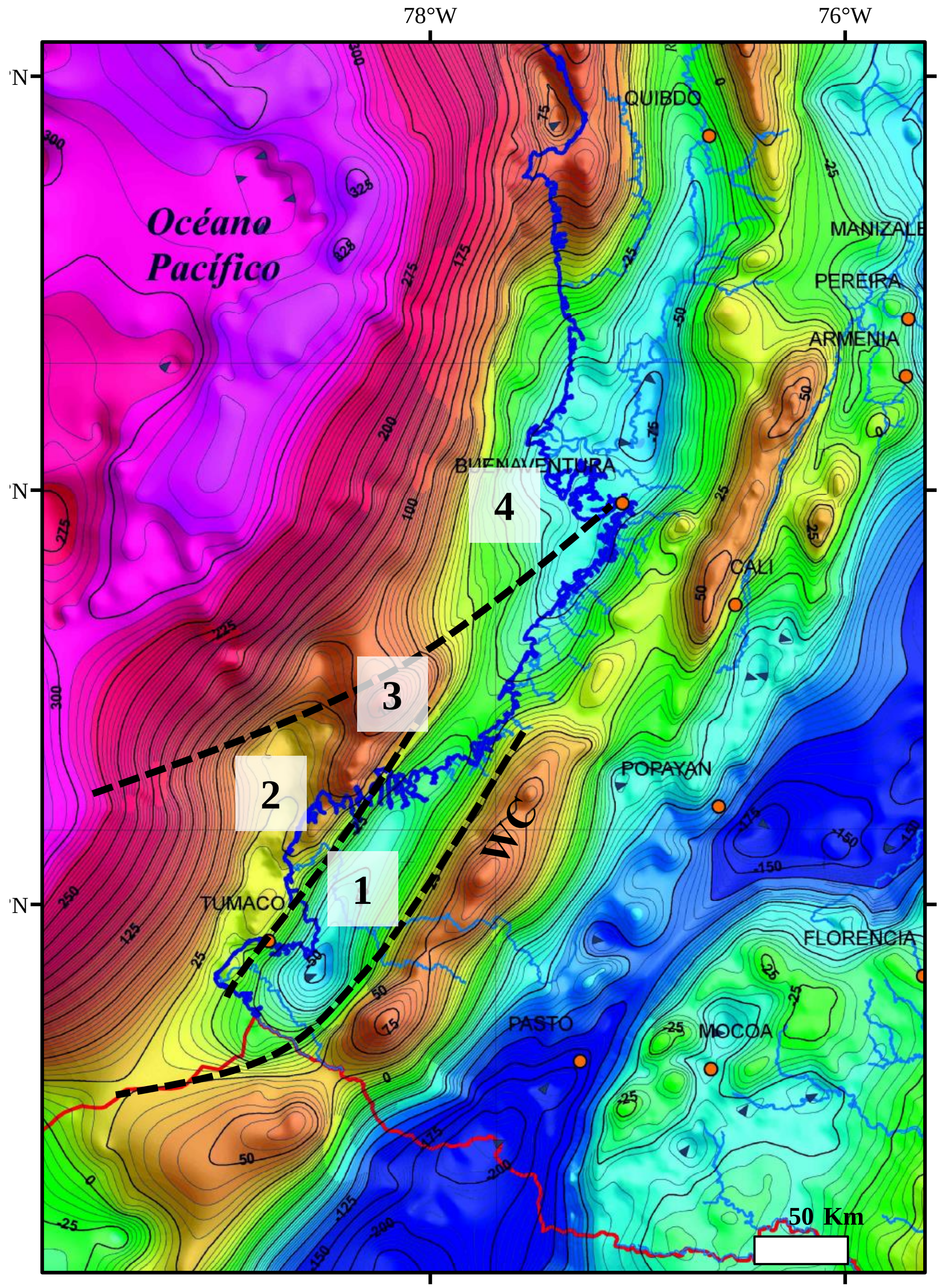

Figure 8. Bouger anomaly map modified after ANH (2010). The numbers indicates the different geological provinces. 1) Tumaco onshore basin, 2) Manglares basin, 3) Gorgona basement complex, 4) San Juan basin. Black dashed lines indicates fault lineaments. WC: Western Cordillera.

Geomorphology of the study area

With the aim of recognizing the main geomorphological features of the basin, the seabed reflector was mapped from all available seismic data (**Figures 9, 10**). On the seismic, it is characterized by high acoustic impedance and a negative polarity. Based on its interpretation, were identified in the Tumaco offshore basin, four main geomorphological domains: the continental shelf; the continental slope and the oceanic trench.

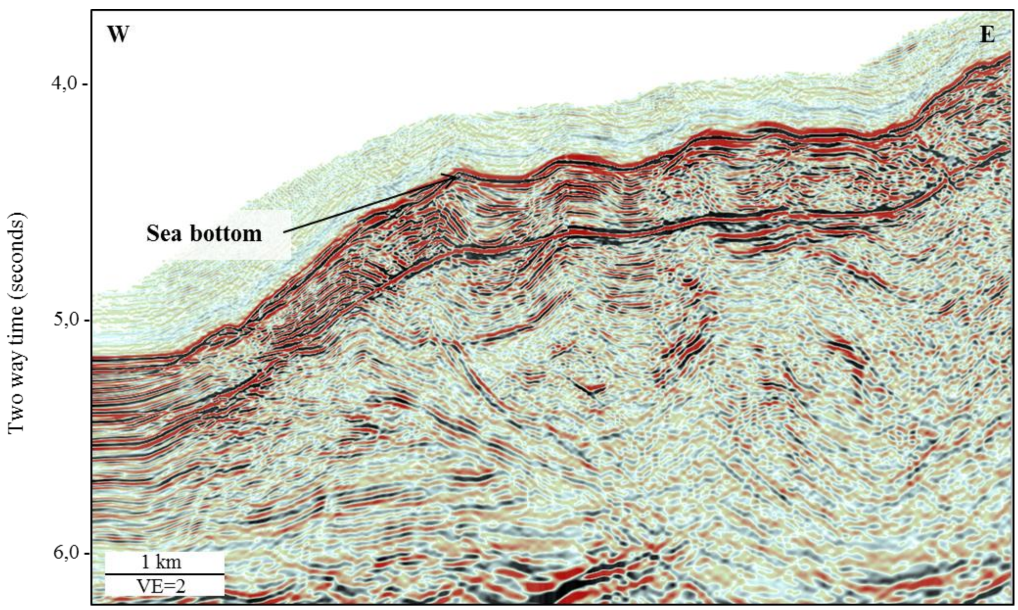

Figure 9. Seismic line showing the seabed reflector.

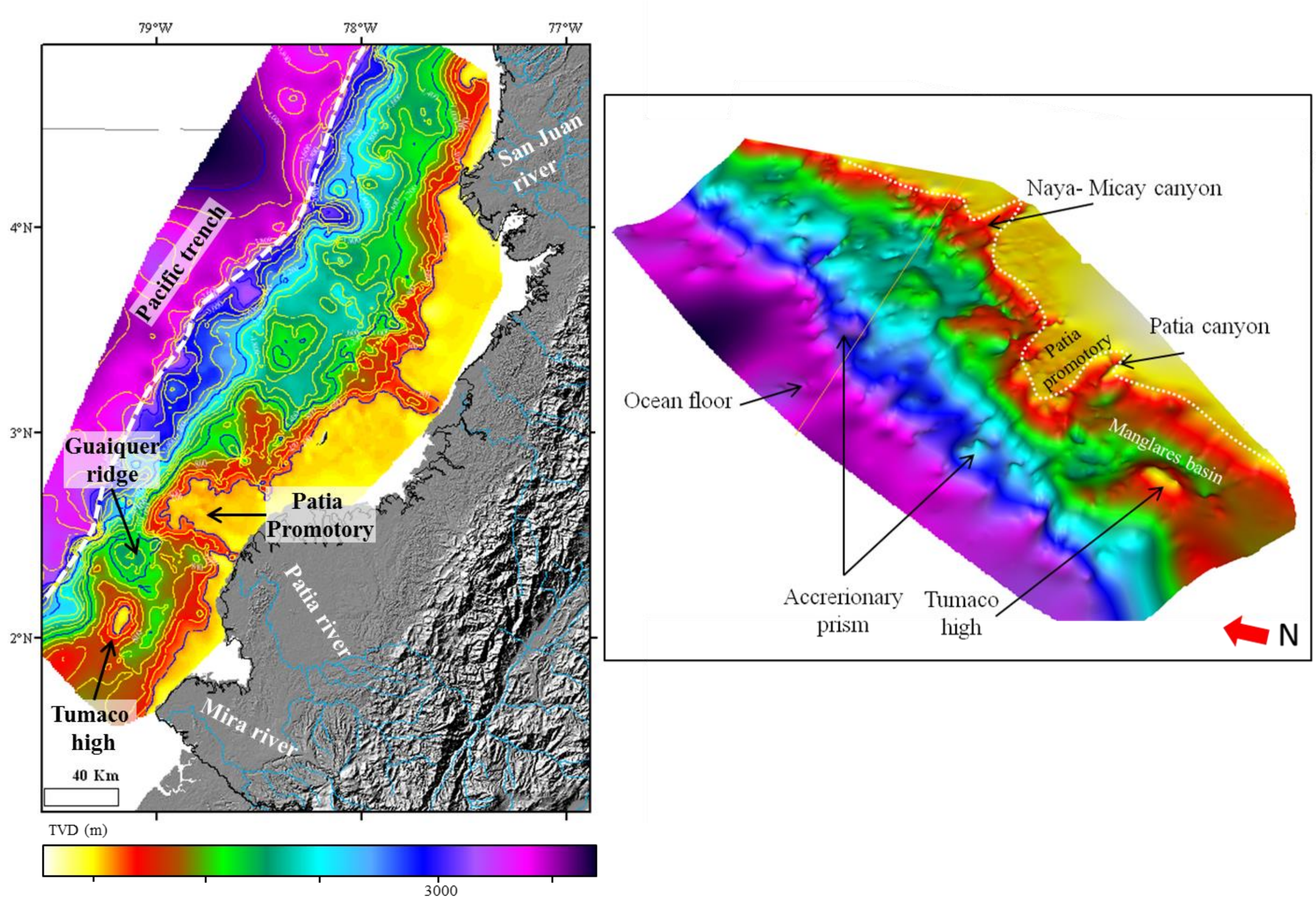

Figure 10. To the left, seabed depth map of the study area. To the right, 3D seabed depth map showing the main geomorphological elements of the basin as the shelf break (white dashed line), the Patía promontory, the Tumaco high, the Manglares basin, the accrecionary prism and Naya-Micay and Patía actual incised canyons.

CONTINENTAL SHELF BREAK

The present shelf area is defined approximately at the 200 m bathymetric line. It extends along the whole study area, with common variations in its width. The wider location is found in the central part of the study area, where it has an approximate width of 40 km and defines the Patía Promotory (**Figure 10**).

The geological processes affecting the shelf area are variable. In some areas the shelf is highly eroded by submarine canyon incisions (**Figure 10**) while in others the shelf exhibits gently dipping slope angles with downlapping reflectors over the upper continental slope (**Figure 11**).

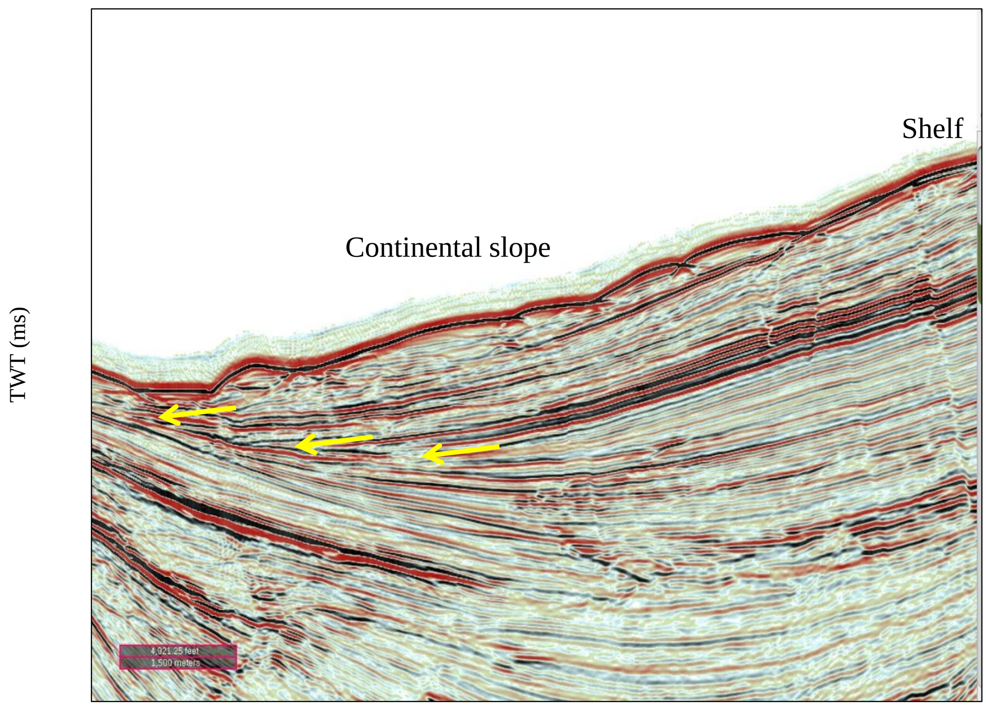

Figure 11. Close up over a dip seismic line showing how the shelf exhibits gently sloping angles with downlaps reflectors over the continental slope.

CONTINENTAL SLOPE

It is divided in upper, middle and lower continental slope. The upper continental slope has an N35°E trend and it extends from the shelf break approximately 200 meters below sea level (mbsl) basinwards to approximately ~ 1300 mbsl. The middle continental slope is located from the upper continental slope up to the Tumaco high to the south and between the 1300-2000 mbsl, to the north. It has N30°E direction with a prominent salient controlled by the Patía promotory. The lower continental slope is located between the 2000-3000 mbsl. It constitutes the accretionary prism of the study area.

The upper and middle continental slopes, to the south, are incised by the Mira and Patía Canyons while to the north are incised by the Micay and San Juan rivers (**Figure 10**). The Mira canyon exhibits a series of different bends. At the shelf break it has a westward direction, where it reaches the upper continental slope. In the Manglares basin, it changes to a NNE direction and in the Patía Promotory area its submarine direction changes to the NWW (**Figure 10**). The Patía Canyon exhibits a straighter path than the Mira Canyon. It incises the shelf and the continental slope to the south of the Patía promontory with an approximate W direction and it joins the Mira Canyon at the Guaiquer ridge (**Figure 10**). The Micay Canyon has almost the same behavior as the Patía Canyon. It incises the shelf and the continental slope with a NWW direction (**Figure 10**). These changes on its submarine paths are controlled by the basement paleo-highs found in the southern area as shown in figures 3 and 9.

Additionally, the upper and middle continental slopes are characterized by the presence of numerous basins as shown in **Figure 12**. The bigger basins are located towards the continental shelf.

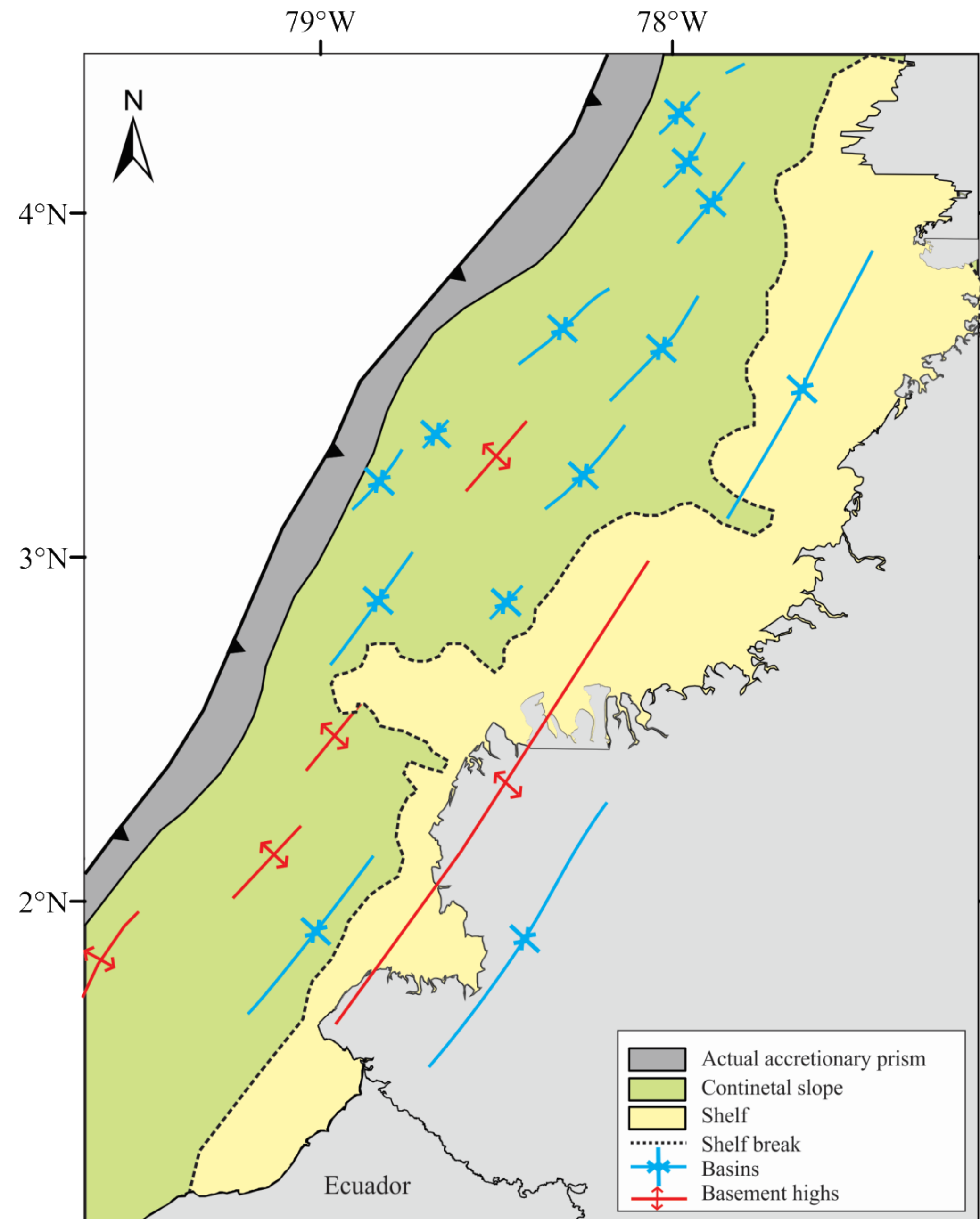

Figure 12. Main geomorphological features, basins and basement paleo-highs distribution, along the Tumaco offshore basin.

The lower continental slope is formed by the actual accretionary prism (**Figure 10**) which has an approximate N30°E continuous trend with local variations. It is located about 80-120 km west of the Pacific coast line with and approximate width of 15-20 km. To the south, the accretionary prism is wider with an approximate width of 30-35 km (**Figure 10**). In this area, the Guaiquer ridge has a width of about 40 km. The presence of small basins is also common through the entire accretionary prism

Figure 13 shows the bathymetric profiles of six seismic lines along the offshore basin. In the figure, it can be appreciated that the bathymetric profile changes from north to south. To the north, the continental slope is characterized by having a gentle slope angles while to the south the bathymetric profiles are more rough, exhibiting strong slope breaks and a bathymetric high eastwards of the accretionary prism (AC) which can be associated with the basement high observed in **Figures 3** and **8** and which could be associated either with a big seamount feature.

OCEANIC TRENCH

The oceanic trench is located westwards of the accretionary prism, at about 3600 mbsl. It is approximately 30 km wide and extends with a N30°W trend along the study area (**Figure 10**).

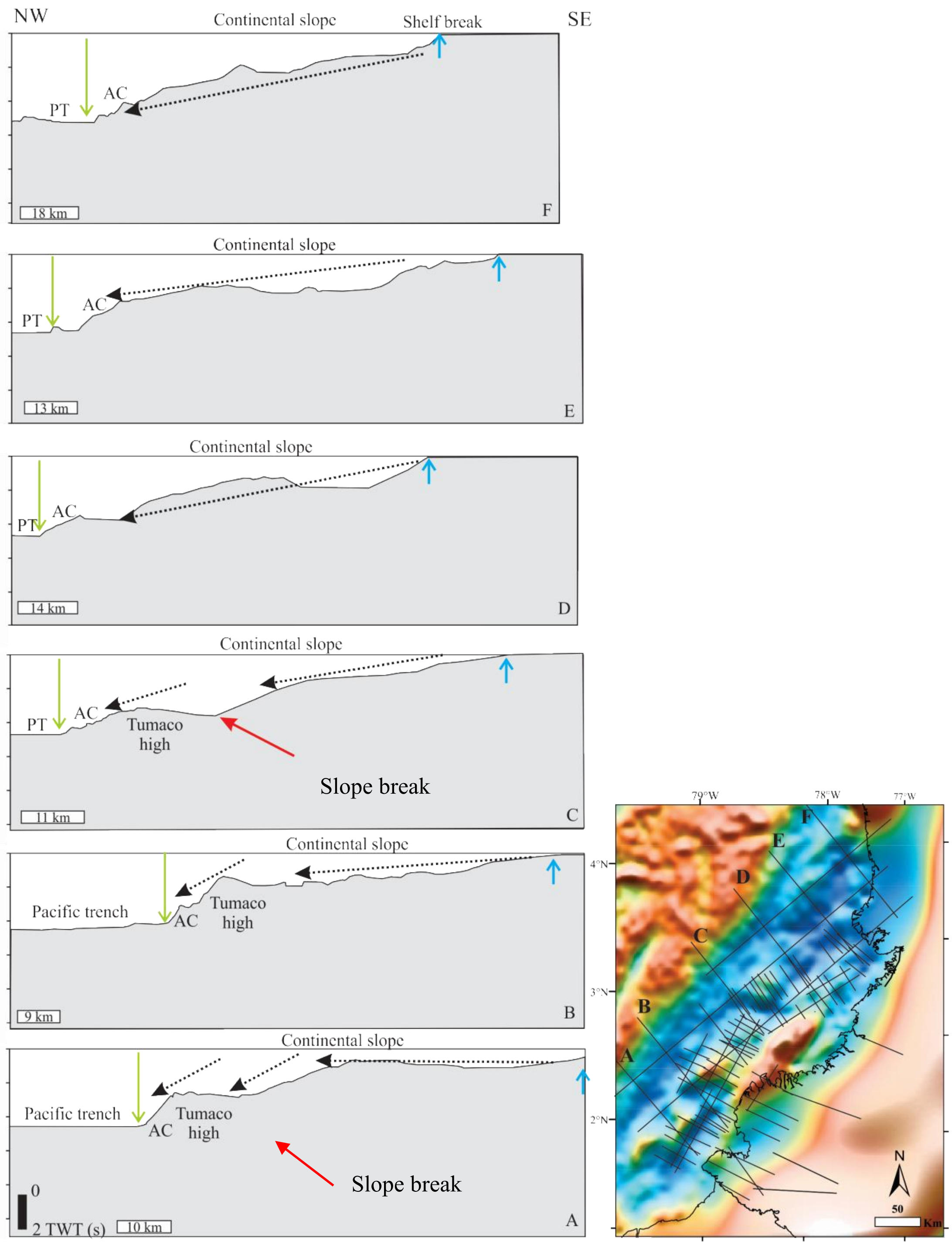

Figure 13. Bathymetric profiles along the Tumaco offshore basin. Profiles A, B, C shows rough bathymetric profiles related to basement paleo-highs. Profiles D, E, F exhibits gentler continental slope profiles than profiles A, B and C. Notice the strong slope breaks in profiles A and C.

Fault families

Based on seismic interpretation and gravity data eight fault families were identified.

FAULT FAMILY 1

Fault family one is the most difficult one to observe in the seismic lines. Its recognition is easier using gravity maps as shown in **figures 3 and 8.**

Consist of two main regional fault systems. The Buenaventura fault system (BFS) and the Garrapatas fault system (GFS).

The NE rectilinear trace that separates the Tumaco onshore basin, from the Tumaco offshore basin and the Gorgona complex was recognized in the gravimetric map as the Buenaventura fault system (**Figure 8**). According to Cediel et al., (2003) this fault has a dextral transpressive motion.

The trace of the Garrapatas fault system was done based on the free-air gravity map (**Figure 8**) and seismic interpretation (**Figure 14**). It corresponds to transpressional - transtenssional strike-slip fault. Its seismic expression near the Buenaventura bay is characterized by normal faulting defining a negative flower structure as shown in **Figure 15**. The fault divides the Tumaco offshore basin from the accretionary prism (to the west) up to the Buenaventura bay (to the east), into two blocks: The Tumaco South block (Tumaco offshore basin) and the Tumaco North block (Choco offshore basin).

FAULT FAMILY 2

Consist of NNW – SSE active normal flexural faults related to the Nazca subducting slab beneath the South American plate. Throws along these faults are normally low, but can reach up to 1000 TWT (ms) (**Figures 14, 16**). These faults, not only affects the basement of the Nazca subducting slab but also the sediments infill in the Pacific trench.

FAULT FAMILY 3

Eastwards-dipping thrust faults with a NNW –SSE direction that affects the entire sedimentary fill of the accretionary prism (**Figures 14, 16**). The deformation occurs progressively in 2 different stages: (1) folding and destruction of previous fold structures along an axes perpendicular to the Nazca plate-convergence direction and (2) new thrust faulting in the direction of Nazca plate-convergence.

FAULT FAMILY 4

NNW –SSE normal faults related to the paleo-basement highs, usually found in the SE offshore area, south of the GFS (fault family 1) and in the Tumaco onshore basin. Dip direction of these faults varies from W to E. Throws are usually low, reaching no more than 100 TWT (ms) (**Figure 16**).

FAULT FAMILY 5

Comprises thin-skinned thrust faults with an approximate N30W strike direction, related to the thrust and fold imbricate system, located northwards of the fault family 1 (GFS) (**Figure 14**). These faults commonly developed well fold structures. These faults have large displacement to the north-west reaching up to 500 TWT (ms), with indication of growth strata and well-developed and well-preserved piggy back basins.

FAULT FAMILY 6

Comprises thick-skinned thrust faults with an approximate N40W strike direction, related to the thrust and fold imbricate system, located southwards of the fault family 1 (GFS) (**Figure 16**). Most of these faults have small displacement of about 100 TWT (ms).

FAULT FAMILY 7

Normal gravitational faulting – Toe thrust faulting that occurs along the shelf break area, in the Manglares basin (**Figure 16**). The main dip direction of these faults is to the west. However some east dipping faults are appreciated to the north of the Garrapatas fault system. These faults are thought to occur as a mechanism of gravity collapse associated with the downfall of the shelf in the offshore area.

FAULT FAMILY 8

High angle normal faults with small throws values (less than 50 TWT (ms)) that generally dips landwards affecting almost the entire sedimentary sequence in the eastern side of the Manglares fore-arc basin (**Figures 14, 17**) . No evidence of growth strata is appreciated, suggesting that the extension activity occurs recently.

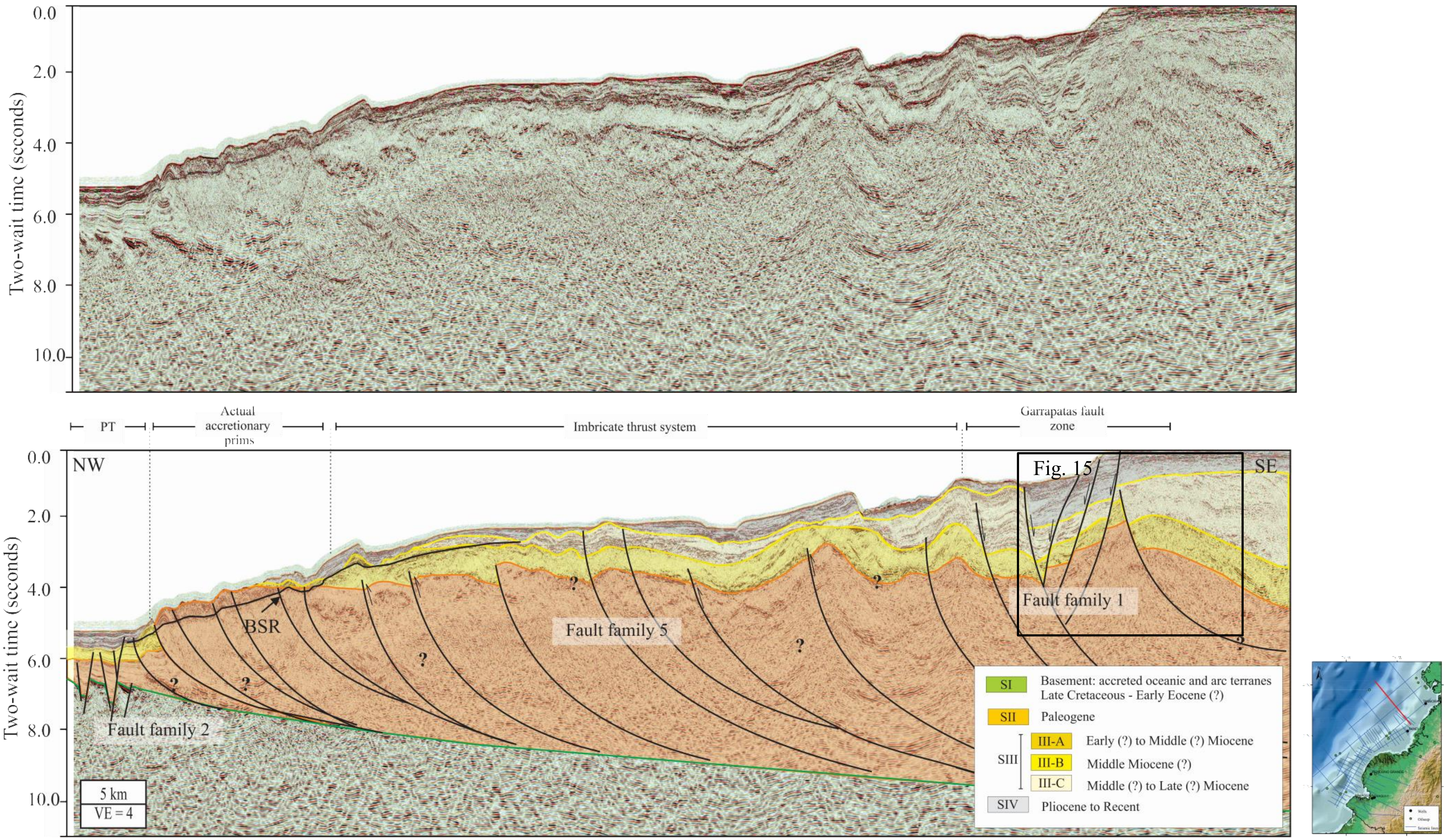

Figure 14. To the top un-interpreted seismic line from the Tumaco offshore basin, north Garrapatas fault system (GFS). To the bottom, interpreted seismic line, showing main subsurface regional features and fault families. 1) The basement is not involved in the deformation, 2) A wider and highly deformated accretionary prism, 3) Normal faulting due to occurrence of the GFS forming and narrow and transtensional basin 4) Bottom Simulator reflector (BSR).

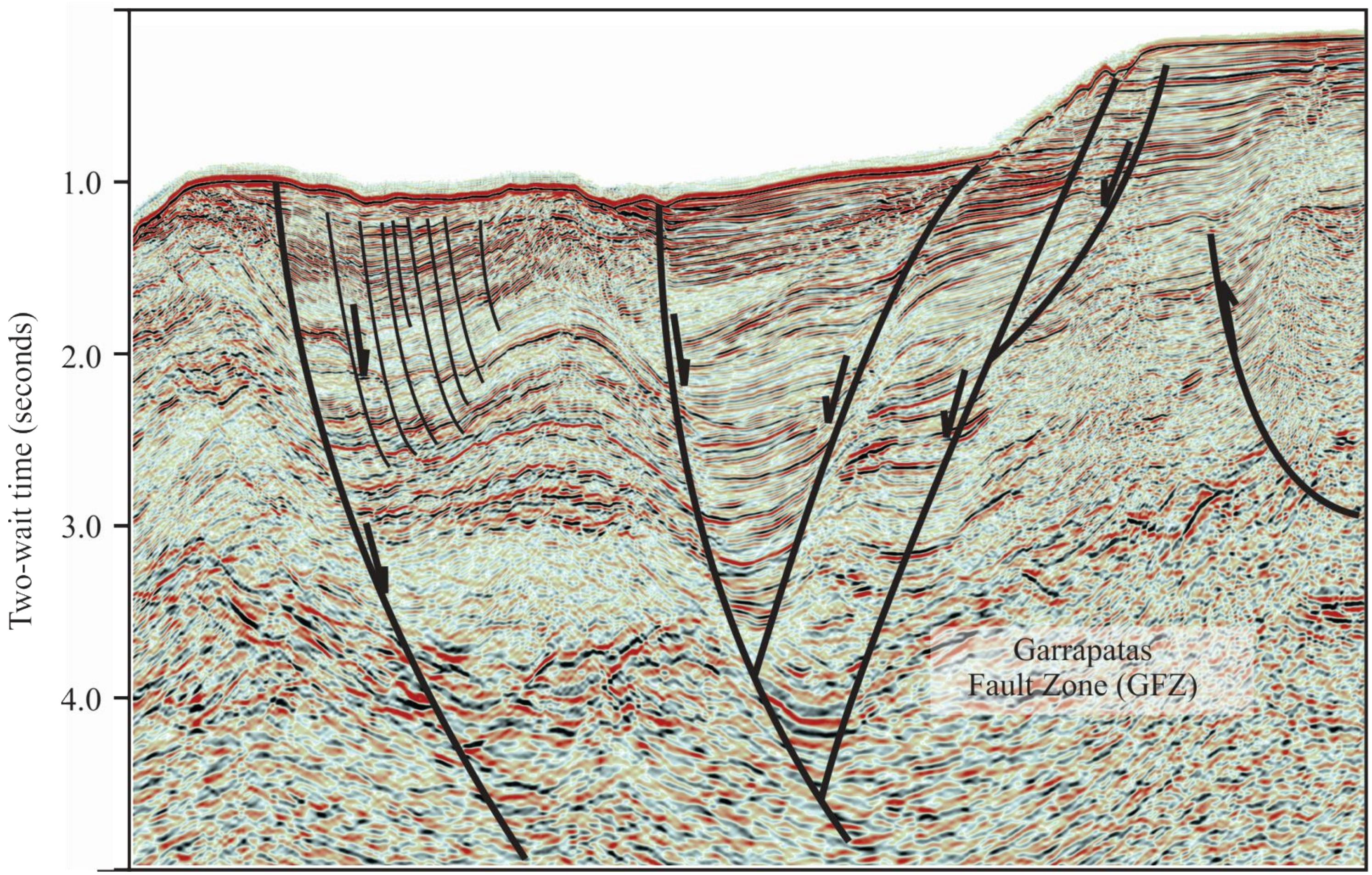

Figure 15. Close-up from figure 14 showing a deep transtensional sub-basin formed by normal faulting associated to the Garrapatas fault system (GFS, fault family 1).

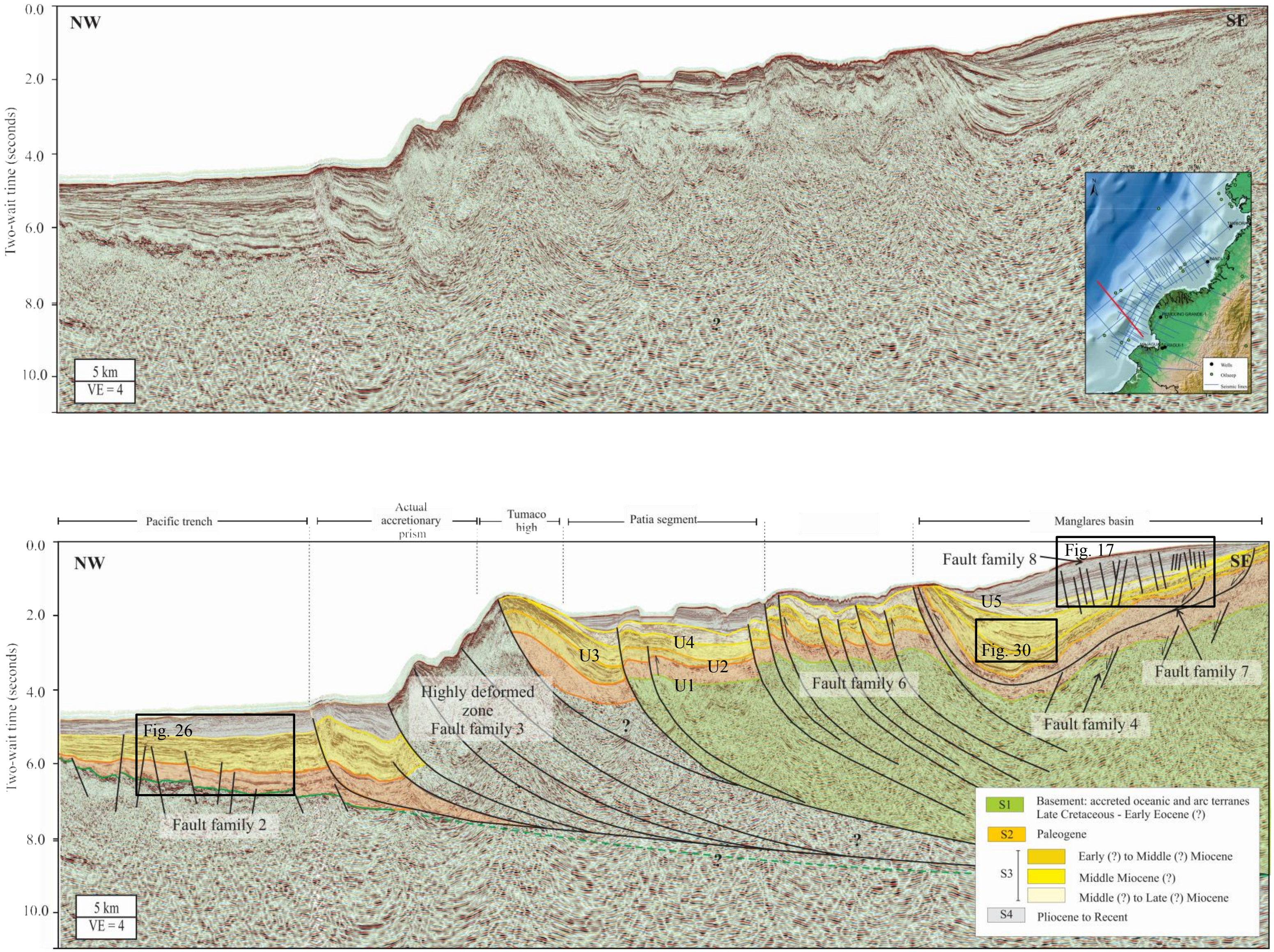

Figure 16. To the top un-interpreted seismic line from the Tumaco offshore basin, south of Garrapatas fault system (GFS).Interpreted seismic showing main subsurface regional features, fault families and thick-skin deformation. Eastwards fore-arc migration as the accretionary prism grows and imbricates.

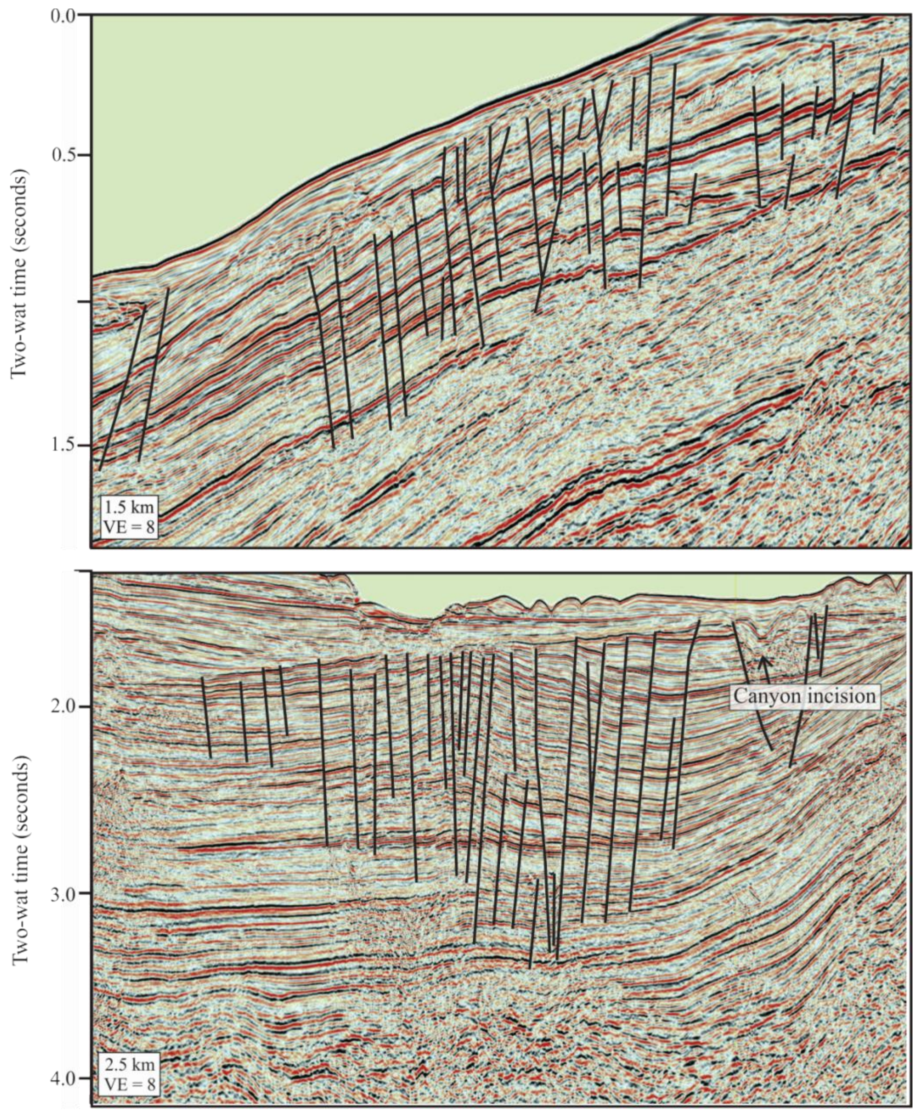

Figure 17. Close up from figure 16. Normal faults with small throw values, less than 50 TWT (ms) occurring only along the eastern side the Manglares basin. To the top, along-dip seismic line P-82-1800; to the bottom along-strike seismic line P-82-1700S.

Tectono-sequences

The identification of the principal tectono-sedimentary sequences, regional unconformities and their correlation across the Tumaco on- and offshore basin was carried out based on the interpretation and correlation of the existing outcrop descriptions, well data with the seismic profiles.

Four main tectono-stratigraphic sequences separated by major unconformities were identified. **Figures 18** and **19** shows the seismic and well log expression from the identified tectono-sequences in the Remolinogrande-1, Tambora-1 and Sandi-1 wells. Additionally, the stratigraphic distribution of the sedimentary and igneous sequences of the study area from well and outcrop data is shown in **Figure 20**.

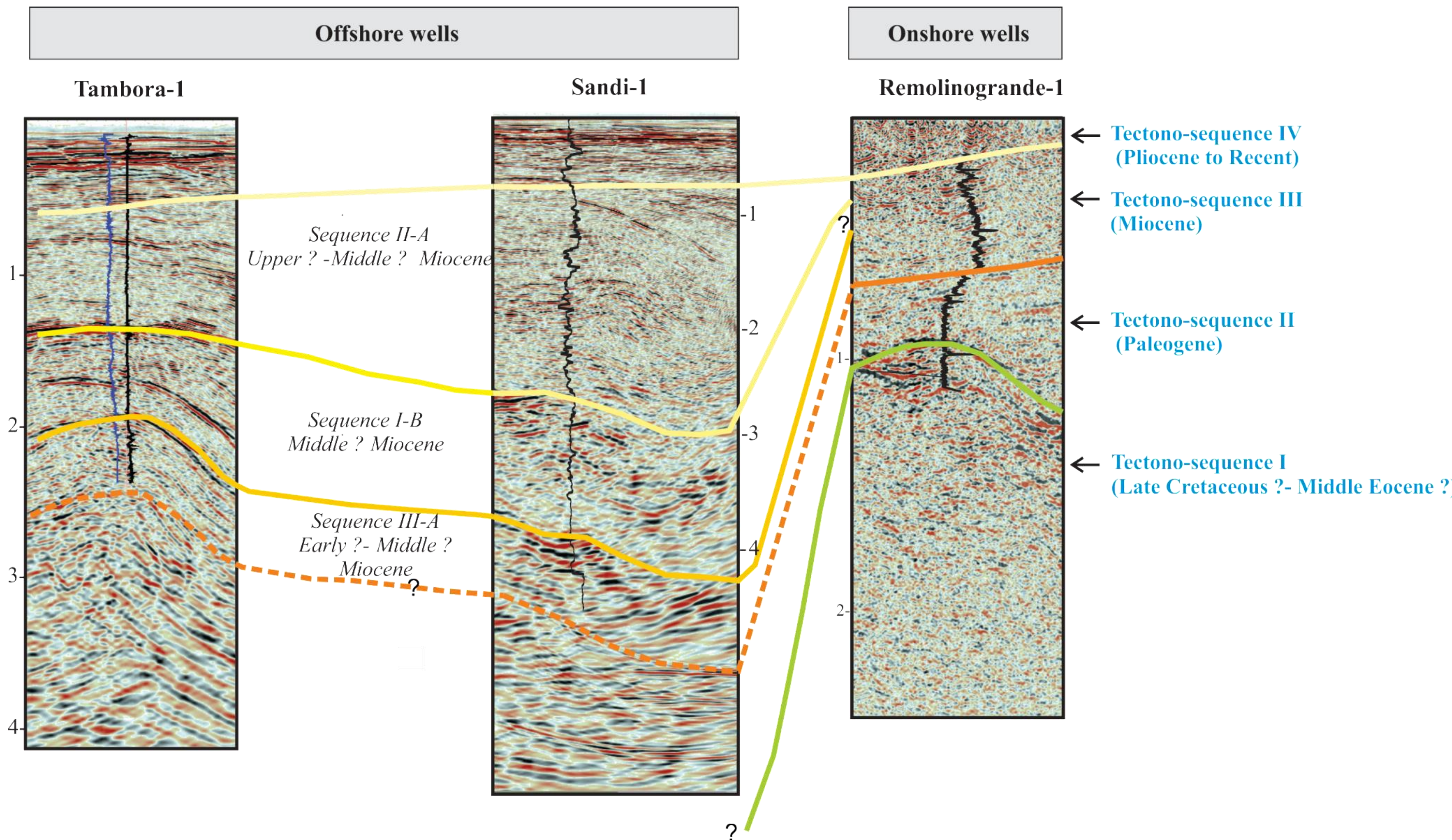

Figure 18. Well log and seismic correlation showing the main tectono-sequences identified in this study.

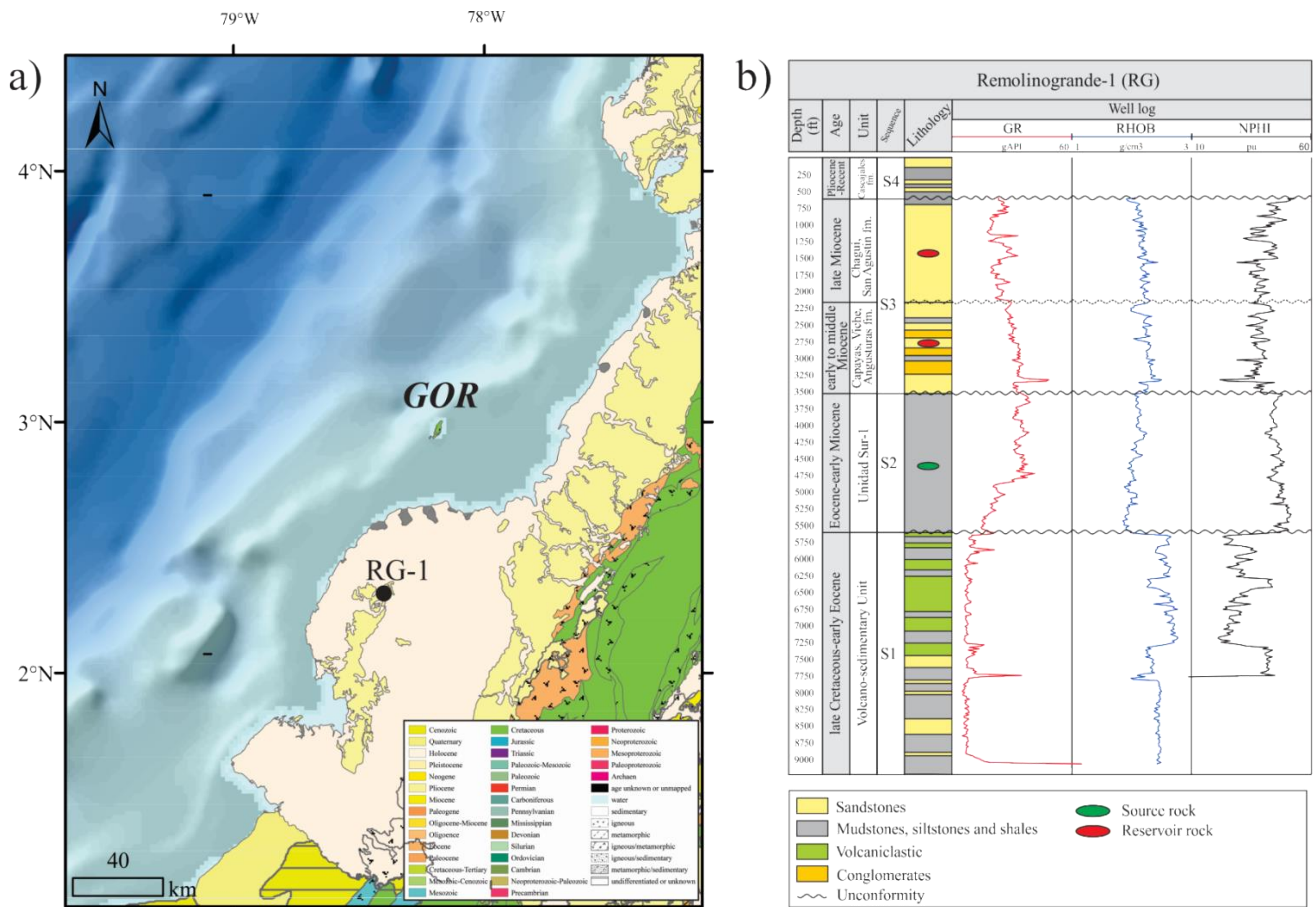

Figure 19. a) Generalized geological map of the Tumaco onshore basin (Modified from (Gómez et al., 2007)). b) Generalized stratigraphic column of the Tumaco on-and offshore basin, based on core and cuttings description from the Remolinogrande-1 well. The main source rocks in the Tumaco on-and offshore basin is Eocene (?) shale of the Unidad Sur-1 Formation. The main reservoirs are the Early to Middle Miocene sandstones

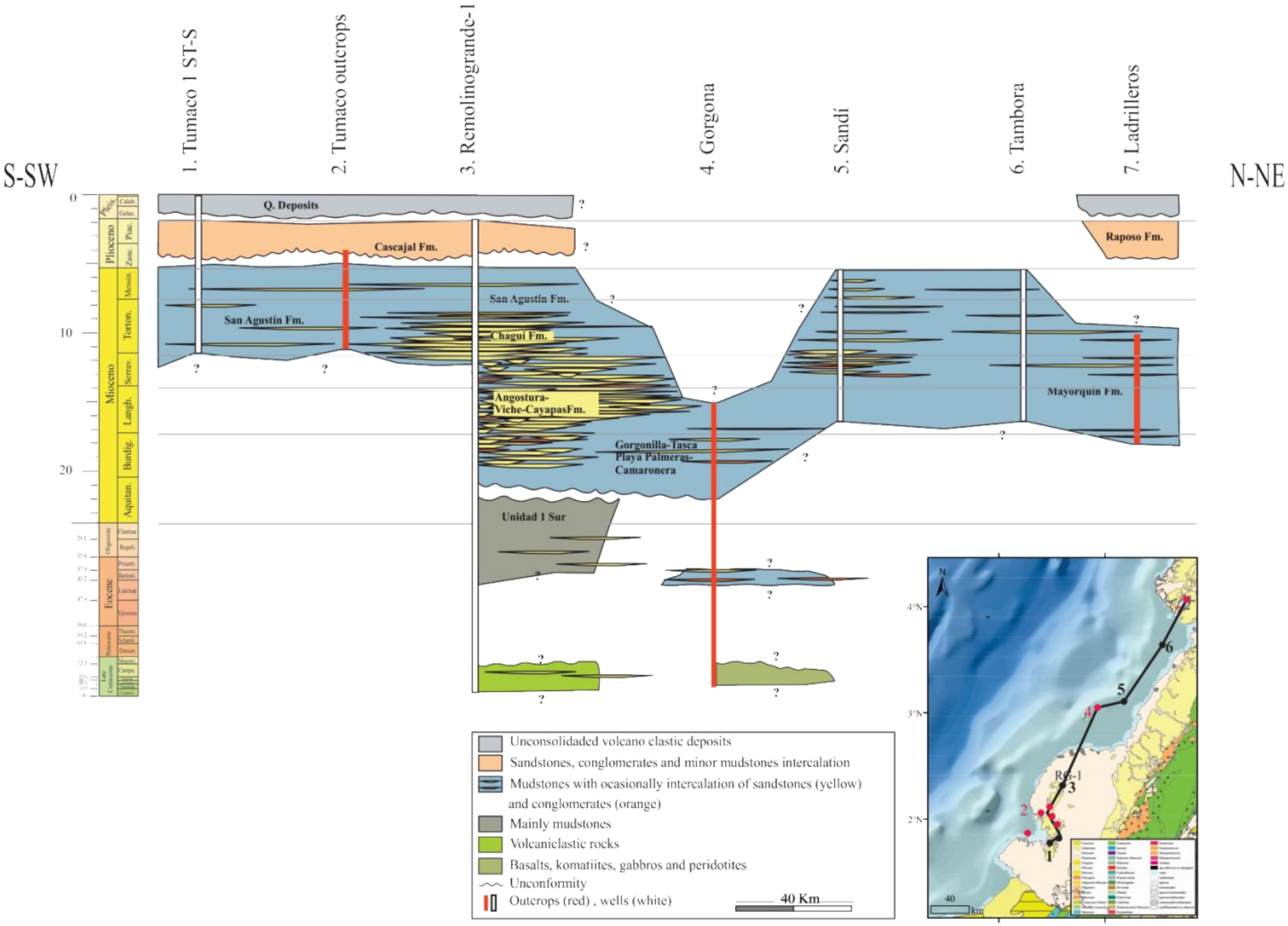

Figure 20. Well and outcrop correlation showing the stratigraphic distribution of the Tumaco on-and offshore basin The numbers on the map indicate the location of each well and outcrop sections.Modified from Caldas-ANH (2011).

TECTONO-SEQUENCE I: LATE CRETACEOUS – EARLY EOCENE (?)

It consists of a volcano-sedimentary succession and defines what we know of the basement of the basin from outcrop and well data. This sequence was drilled in the Remolinogrande high, in the western flank of the Tumaco onshore basin by the Remolinogrande-1 well and outcrops in the Gorgona Island. Based on free-air gravity and gravity maps is possible to follow a NE trending basement paleo-high from the Gorgona Island to Tumaco (**Figures 3, 8**).

Outcrop

As mention before, the only known outcropping locality is in the Gorgona Island. In this locality the basement is mainly composed by ultramafic sequences that include one of the few worlds Cretaceous occurrence of Komatiites (Echevarria, 1980; Serrano et al., 2011). In this locality, the basement sequence is mainly composed by dunites, peridotites and gabbros.

Well character

The gamma rays values from the Remolinogrande-1 well in this sequence are low and spiky (**Figures 18, 19**). Core descriptions from Caldas-ANH (2011); indicate the presence of a volcano-sedimentary succession consisting of two sequences. The lower sequences conformed by shales, mudstones and sandstones intercalated with basalts and micro gabbros, while the upper sequence is mainly composed by basalts and micro gabbros interbedded with thin mudstones and sandstones layers.

López (2009) interpreted this volcano-sedimentary tectono-sequence as the result of submarine volcanic activity that initially filled up the Tumaco onshore basin.

Seismic Character

A confident well tie was not possible to achieve from the well data. Some possible explanations to this are the anisotropy caused by the volcano-sedimentary lithology, seismic processing artifacts and weathering in the basement which can creates transition zones. Also, the differentiation of the two sequences described in the well reports was not possible using the seismic data. Nevertheless, it was possible to recognize the general seismic character of the basement in some areas, especially in the offshore basin, near the Gorgona Island, where it is characterized by chaotic and discontinuous seismic facies with high amplitude and low frequency reflectors (**Figure 21**). In some areas the top of the basement can be recognized by the occurrence of moderate and positive amplitude, however, in most of the areas in the Tumaco on- and offshore basin the top of the basement is no differentiable.

Time structural map

The TWT structural map of the sequence indicates that it is missing along the northern portion of the Garrapatas Fault System (GFS) (**Figure 22**). To the south of the GFS some few and non-continuous structures are observed (**Figure 21**). The longer structure is located near the coast line; it has a NE trending with an approximate extension of 120 km. This structure is also appreciated in the gravity maps (**Figures 3** and **8**) and can be associated to the southern extension of the Gorgona basement complex, including the Remolinogrande high. Normal faults bounding the NE trending basement paleo-high (Gorgona complex) are appreciated dipping in E and W direction (fault family 4). To the southeast, near the accretionary prism; two structural highs are observed. These structural highs correspond to the Tumaco high which is also observed in the bathymetric profiles (**Figure 13**). Among them, a basement low is observed, and defines the Guaiquer ridge which is also observed in the seabed map (**Figure 10**). Fault family 6 affects the basement in the area of the Tumaco high.

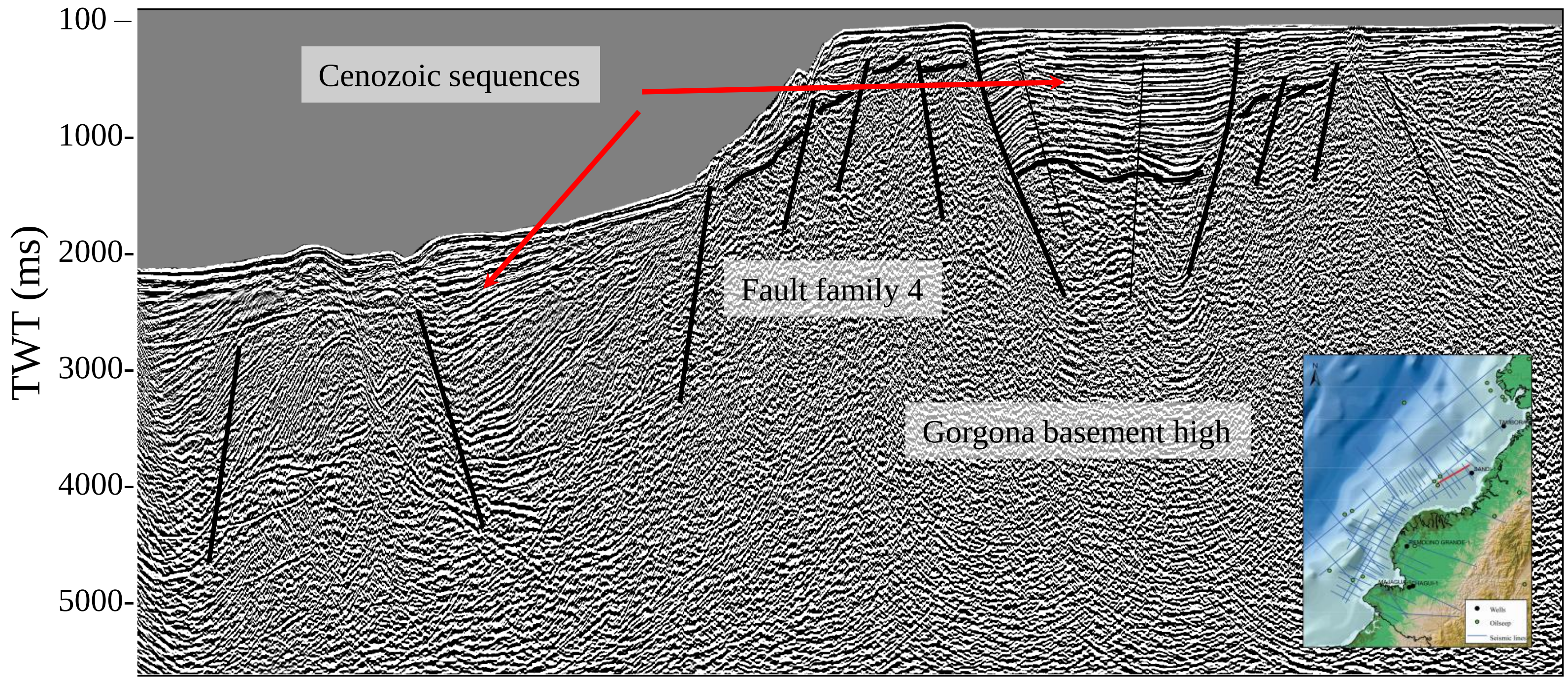

Figure 21. Seismic line showing the Gorgona Island basement and its main structural configuration.

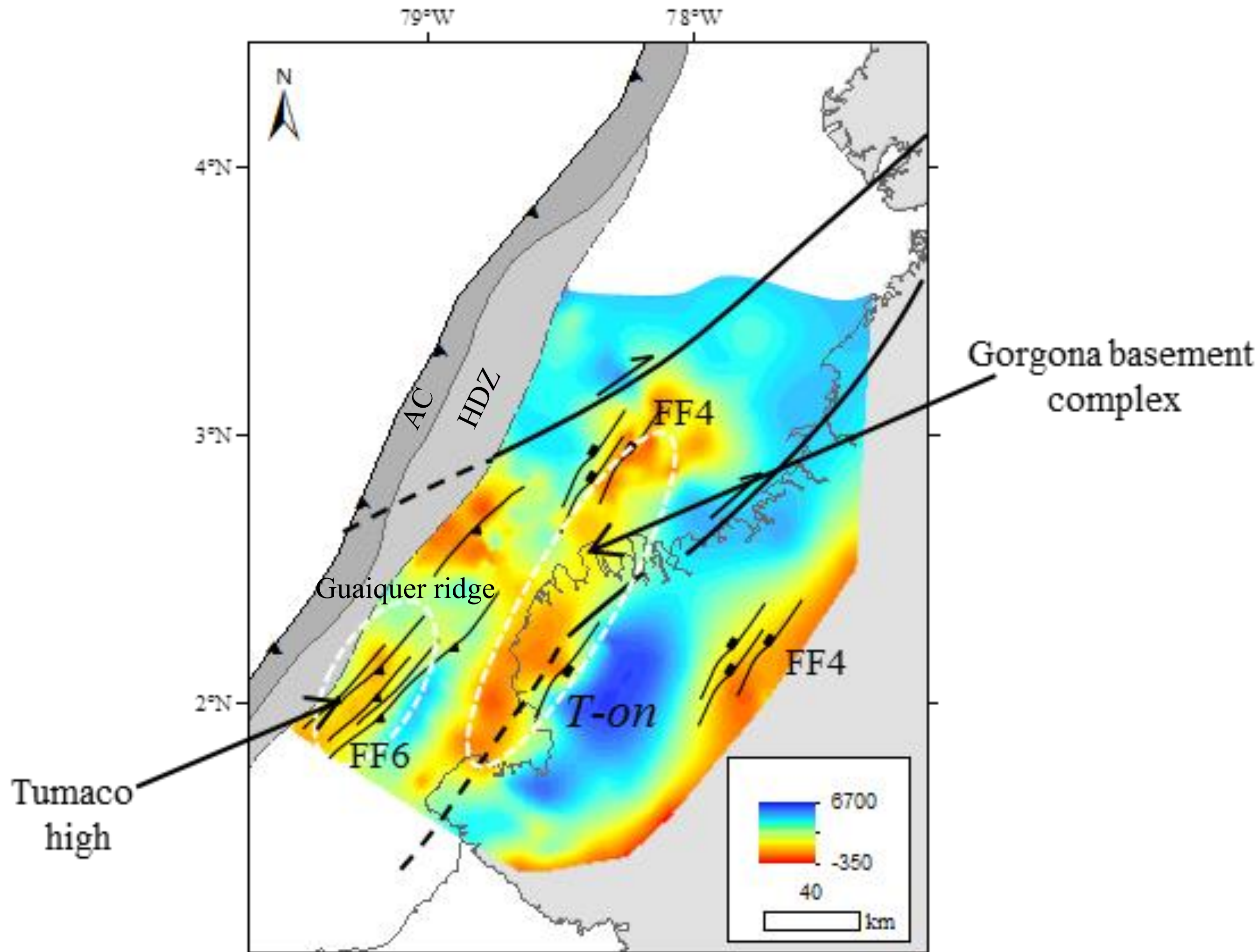

Figure 22. TWT (ms) structural map near the top of the Cretaceous basement showing the main structural highs associated with the southern extension of the Gorgona basement complex. T-on: Tumaco onshore basin. AC: accretionary prism, HDZ: highly deformed zone, FF: fault family.

TECTONO-SEQUENCE II: (PALEOGENE)

Well character

This sequence was only drilled by the Remolinogrande-1 well. The well character is spiky and variable; with medium to high gamma ray values at the base of the sequence to high gamma ray values at the top of the sequence, indicating high content of shales (**Figure 18, 19**). The thickness reported by the well data is approximately 600 m. Recent core descriptions from Caldas-ANH (2011) indicate that is mainly composed by siltstones intercalated with sporadic layers of sandstones from Unidad Sur-1 Formation (**Figure 19**).

Duque-Caro (1990) based on foraminifera analysis suggested that this unit was deposited in the upper continental slope. This unit has been interpreted as hemipelagic and turbidites deposits by López (2009).

Core analysis done by the Caldas-ANH (2011) indicates the presence of forams, algae, and radiolarians. Foraminifers analysis (Peñaloza and Sanchez, 2006) suggested an Oligocene age. Nanofossils studies by Caldas-ANH (2011) suggested a Late Oligocene age for the interval between 5400 and 4500 feet in the Remolinogrande-1 well.

Seismic character

The seismic facies are characterized by chaotic, discontinuous and blurry reflectors with lower amplitudes values than tectono-sequence I. It has a semi-transparent appearance with poor defined stratification with some local areas with well bedded and high amplitudes reflectors. It is characterized by landward on-laps and seaward down-laps reflectors. In the offshore area; to the south, this tectono-sequence exhibits a relative uniform thickness of about 1000 to 1500 TWT (ms) with some pinch-outs against the basement structures where its thickness varies (**Figures 14, 16, 23**); to the north, the real thickness of the sequence could not be determined.

Time structural map and time thickness map

This tectono-sequence yields unconformable over tectono-sequence I. It is the deepest sedimentary sequence found in the study area and it is affected by fault families 1 to 7 (**Figure 25**). To the north of the GFS is affected by fault families 1, 2, 5 and to the south of the GFS is affected by fault families 2, 3, 4, and 7. **Figure 25** shows the main structural elements of the Paleogene sequence. In the map, three main structural highs are observed. These highs matches with the structural highs mapped in tectono-sequence I (**Figure 23**) which suggest that the basement paleo-highs are controlling the sedimentation of tectono-sequence II.

Time thickness map (**Figure 25**) indicates that the thickness of the sequence varies along the whole basin and reveals the occurrence of three major depocenters.

The first depocenter is localized in the Tumaco onshore basin (**Figures 24, 25**). Based on the free-air gravity map is possible to determine that this depocenter has a NW-SW trending (**Figure 3**). The thickness of this sequence varies in this area. Towards the Western Cordillera and the Remolinogrande high the sequence is thinner while in the central portion of the basin the sequence is thicker (**Figure 24**). In the western side of the basin, the seismic patterns indicate the initial uplifting of the Remolinogrande high (**Figure 24**).

The second depocenter is located to the south of the offshore area, in the Manglares basin along (**Figure 16, 25**) where it reaches at maximum depth of 5000 TWT (ms). Based on the free-air gravity map is possible to determine that this depocenter has a NW-SW trending (**Figure 3**). The thickness of this sequence in this area is almost constant with approximate 1000 TWT (ms).

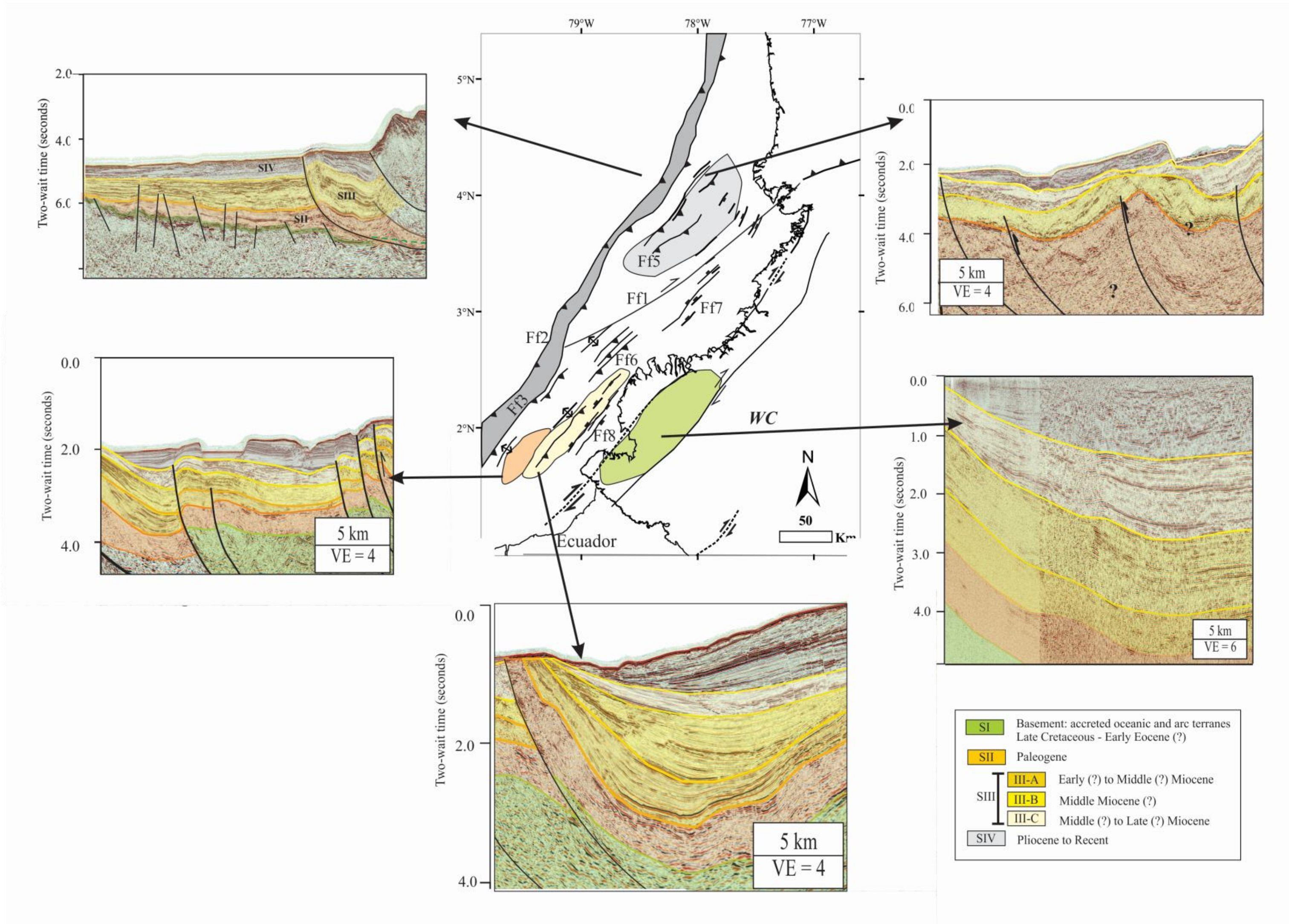

Figure 23. Fault families and seismic facies distribution map and inset seismic sections of the main tectono-sequences described in this study showing the distribution and seismic character of the different facies interpreted. TWT: two-way time.

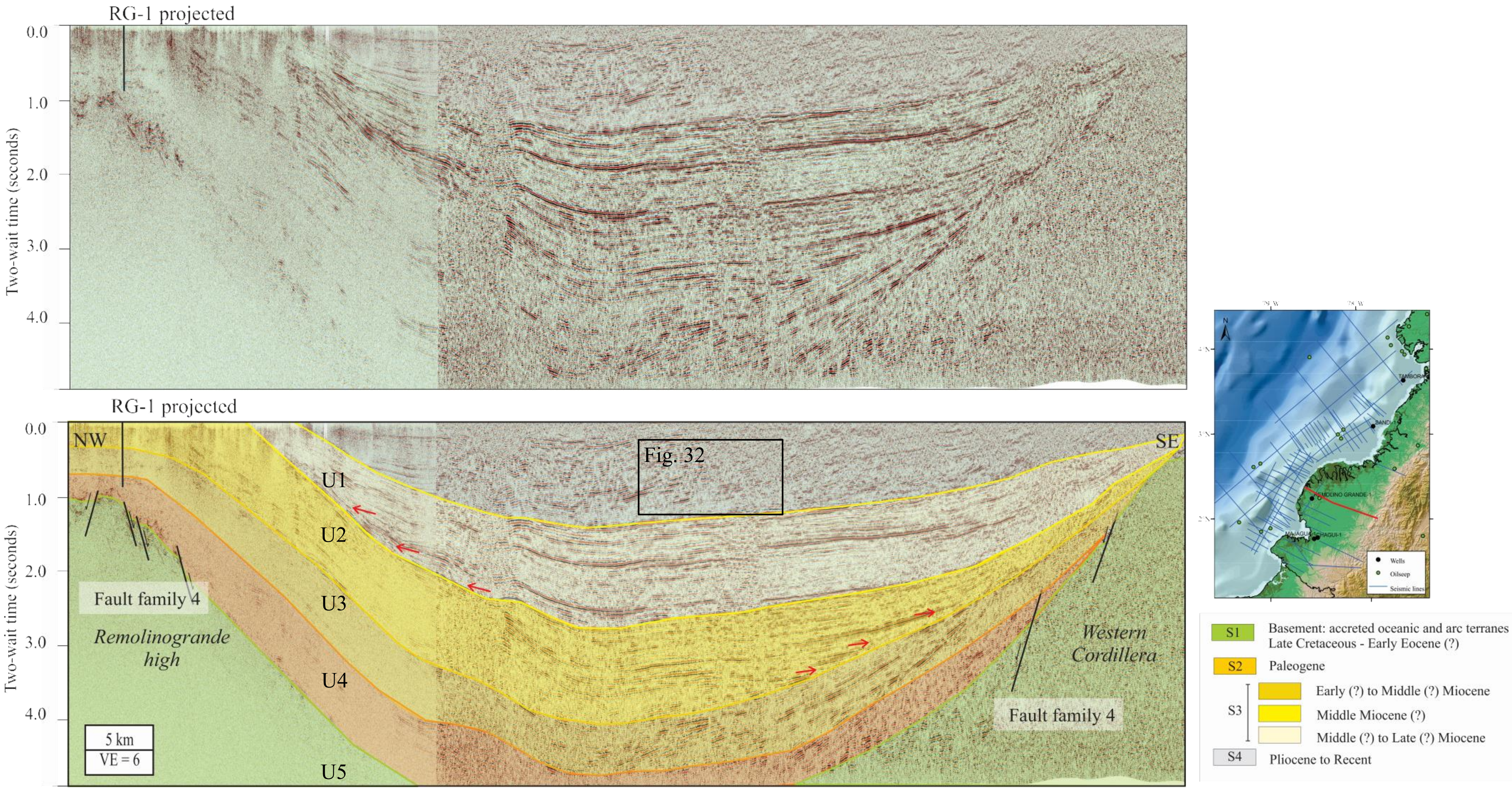

Figure 24. Composed seismic section along the seismic lines NT-1992-2840 and NT-1990-2870 of the Tumaco onshore basin showing the four main stratigraphic sequences interpreted in this study. The red arrows indicate onlapping reflector against the Western Cordillera and the Remolinogrande high

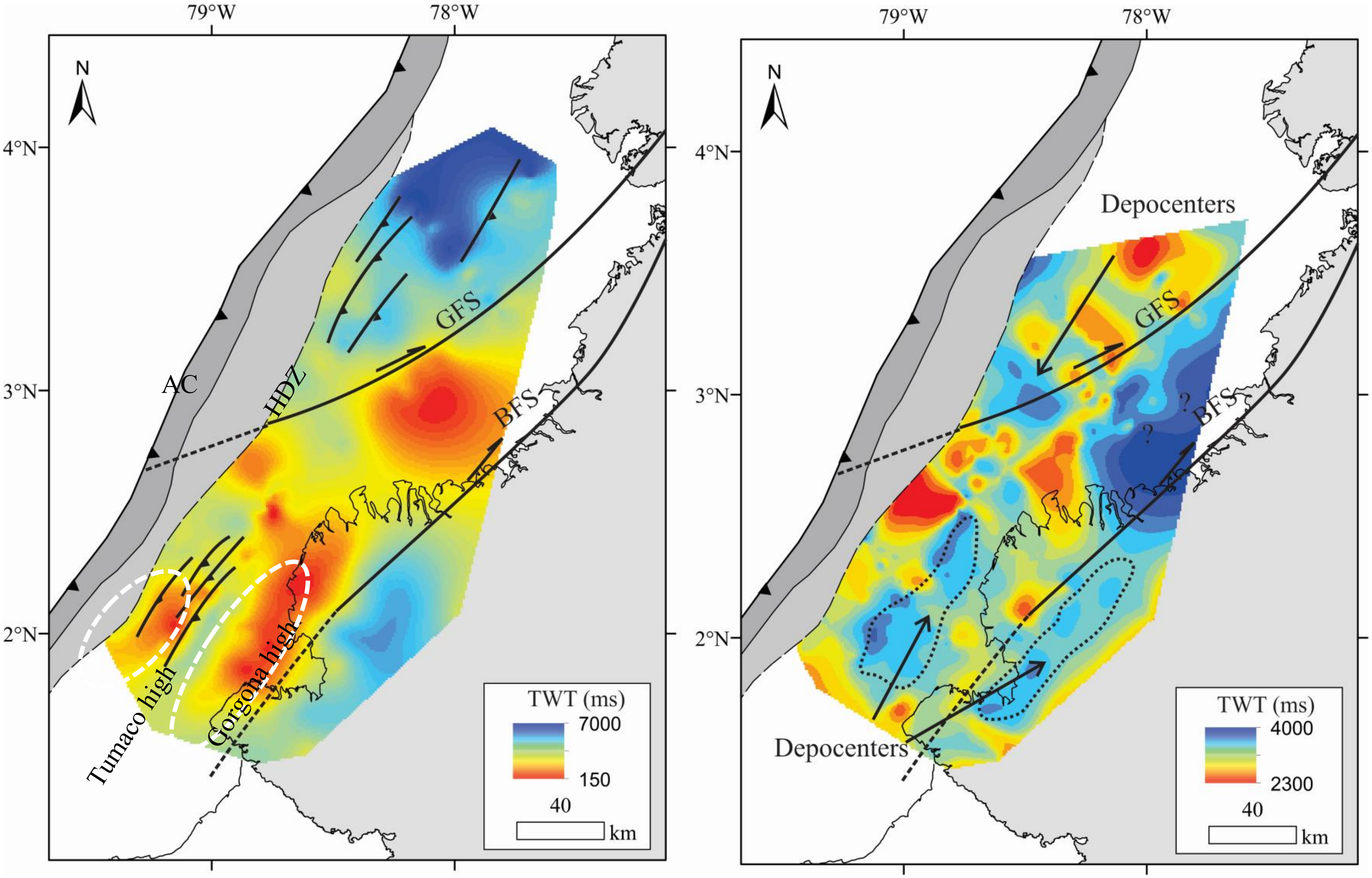

Figure 25. To the left, TWT structural map near the top of the Paleogene sequence. To the north of the GFS the structures are deeper than to the south of the GFS where the structures are controlled by the basement paleo-highs. To the right, Paleogene time thickness map showing the main depocenters and hydrocarbon possible kitchen (dashed lines) along the basin.AC: accretionary prism, HDZ: highly deformed zone, FF: fault family.

The third depocenter is located between the Manglares basin and the actual accretionary prism, in the Patía segment (**Figure 16, 25**). In this area the thickness of the sequence is approximately constant with about 800-1000 TWT (ms).

In the Pacific trench, it is characterized for having high amplitude, well-stratified, parallel and sub-continuous reflectors that onlaps against the Nazca subducting slab (**Figure 26**). In this area the thickness of the sequence varies from 200 ms to 1000 TWT (ms), with the deeper values where the accretionary prims starts. It is also affected by high angle normal faults with small throw values (50-100 TWT (ms)) related to the normal flexural faulting generated by subducting slab (fault family 2) (**Figures 16, 26**).

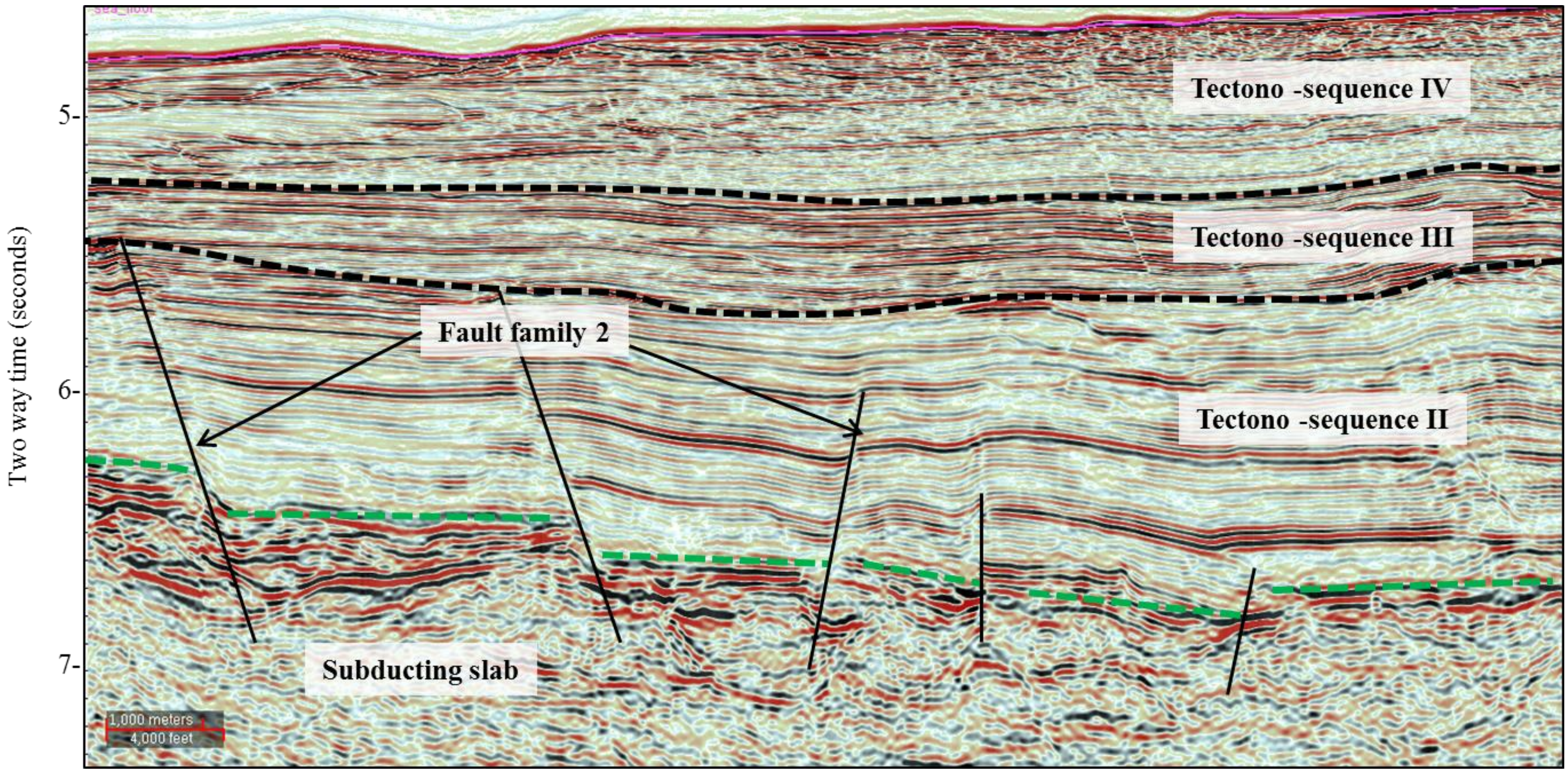

Figure 26. Close up to figure 16 showing the geometry and sediments infilling of the Pacific oceanic trench. Dashed green lines indicates the top of crust of the subducting Nazca plate. Black dashed lines indicates major unconformities.

TECTONO-SEQUENCE III (EARLY TO LATE MIOCENE):

This tectono-sequence lies unconformable over tectono-sequence II. It is mainly composed by sandstones and conglomerates with sporadic intercalations of mudstones and plutonic fragments from the Capayas, Viche, Angostura, Chagüí and San Agustín formations (**Figures 18, 19, 20**). Based on the sedimentary environments, and seismic character it was divided in three sequences:

1. Sequence III-A: (Early (?) to Middle (?) Miocene)
2. Sequence III-B: (Middle Miocene (?))
3. Sequence III-C: (Middle (?) to Late (?) Miocene)

Despite of the fact these sequences are described in detail in numerals in the following title, **Figure 27** shows a TWT structural map and a time thickness map of the top of the Miocene tectono-sequence.

The TWT structural map shows that the Miocene tectono-sequence is affected by fault all fault families, except fault family 4. Fault families 2, 3, 6, 7 are common south of the GFS, while fault family 5 dominates northwards of GFS.

Three main structural highs are found south of the GFS in the offshore area, with a common N~30°E trend. These structural highs matches with the basement paleo-highs mapped in tectono-sequence I which suggest that the Miocene sedimentation is also controlled by the basement highs.

Associated with fault family 6, north of GFS is common the formation of piggy-back basins is common. The most preserved and well-formed piggy back basins are located near the coast (**Figure 27**).

The time thickness map (**Figure 25**) shows the presence of three major depocenters (depocenter 1, 2 and 3). Depocenter 1 is located in the northern offshore area; it has an approximate 5000 TWT (ms) thickness (**Figure 25**). Depocenters 2 and 3 are located south of the GFS. Depocenter 2 is found along the Tumaco onshore basin. It has an N~35°E trend, and an approximate 5000-5500 TWT (ms) thickness (**Figure 25**). Depocenter 3, is found along the Manglares basin. It has the same structural trend as depocenter 2 and it has an approximate 4000 TWT (ms) thickness and is bound to the west by the Tumaco high and to the east by the southern extension of the Gorgona high (**Figure 25**).

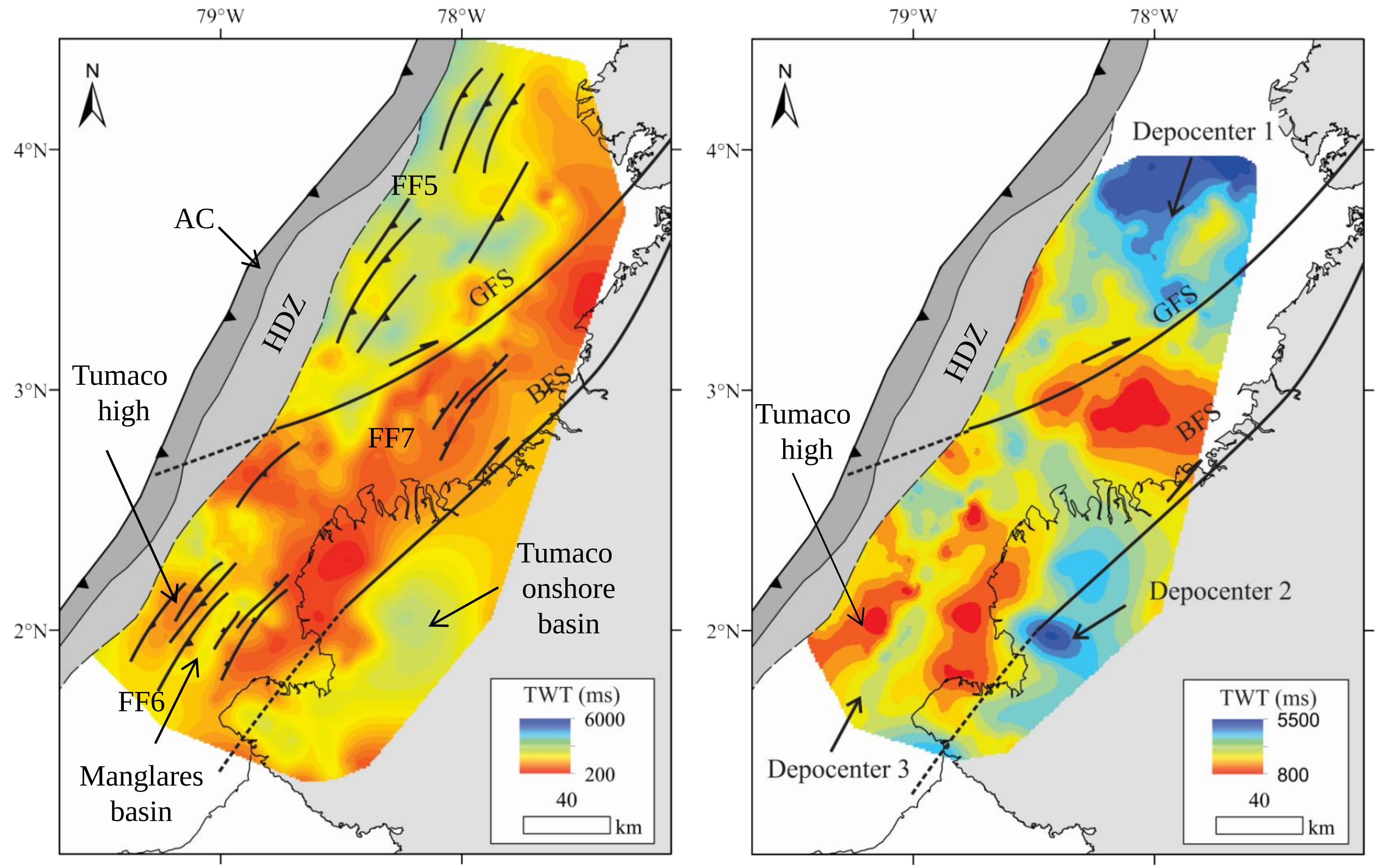

Figure 27. To the left TWT structural map at near the top of the Miocene sequence. The shallower structures are located to the south of the GFS and are controlled by the basement paleo-highs structures. To the right, Miocene time thickness map. Three main depocenters (1, 2, 3) can be identified as show in the figure.AC: accretionary prism, HDZ: highly deformated zone, FF: fault family.

Sequence III-A: (Early (?) to Middle (?) Miocene)

It comprises the Capayas and Viche formations.

Well character

This sequence was drilled by all the wells in the study area. However, the best well log data is from the Remolinogrande-1 well (**Figures 18, 19**). In this well, the gamma ray readings are spiky varying from medium to high values suggesting the intercalation of shales and sandstones (**Figures 18, 19**). Core descriptions from this sequence done by Caldas-ANH (2011) indicate that this sequence consists of sandstones and conglomerates. Sporadically, it presents levels of siltstones and limestones. The sandstones and conglomerate layers are mainly composed by cristaline quartz, igneous lithics (basaltic, porfiritic and plutonic lithics), sedimentary lithics and methamorphic lithics as phylites and serpentinites. Most of the layers are rich in bivalves, gasteropods and forams.

Based on foraminifers analysis, Duque Caro (1990) suggested an upper slope deposition. López (2009) based on seismic analysis, suggested that these units were deposited by a volcano-clastic fan at the toe of the continental slope.

Seismic Character

To the south, at the Tumaco onshore basin and Manglares basin, it is characterized by having high-amplitud, continuous and well-bedded reflectors that contrast with the blurry and chaotic reflectors of tectono-sequence II. The reflectors of these sequence onlaps over tectono-sequence II and define a major uniformity appreciated with the Tumaco onshore basin and the Manglares basin.

Time structural map

Figure 28 shows a TWT structural map near the top of the Early (?) to Middle (?) Miocene sequence. The TWT structural map shows that the Miocene tectono-sequence is affected by fault all fault families, except fault family 4. Fault families 2, 3, 6, 7 are common south of the GFS, while fault family 5 dominates northwards of GFS.

Four main structural highs are found south of the GFS in the offshore area (**Figure 28**). The three southernmost highs have a common N~30°E trend and matches with the basement paleo-highs mapped in tectono-sequence I which suggest that the Miocene sedimentation is also controlled by the basement highs. The northernmost high defines the initial formation of the Patía Promotory (**Figure 28**) which can also be appreciated in **Figure 10**.

Associated with fault family 6, north of GFS is common the formation of piggy-back basins. The most preserved and well-formed piggy back basins are located near the coast line as shown in **Figures 14** and **27**.

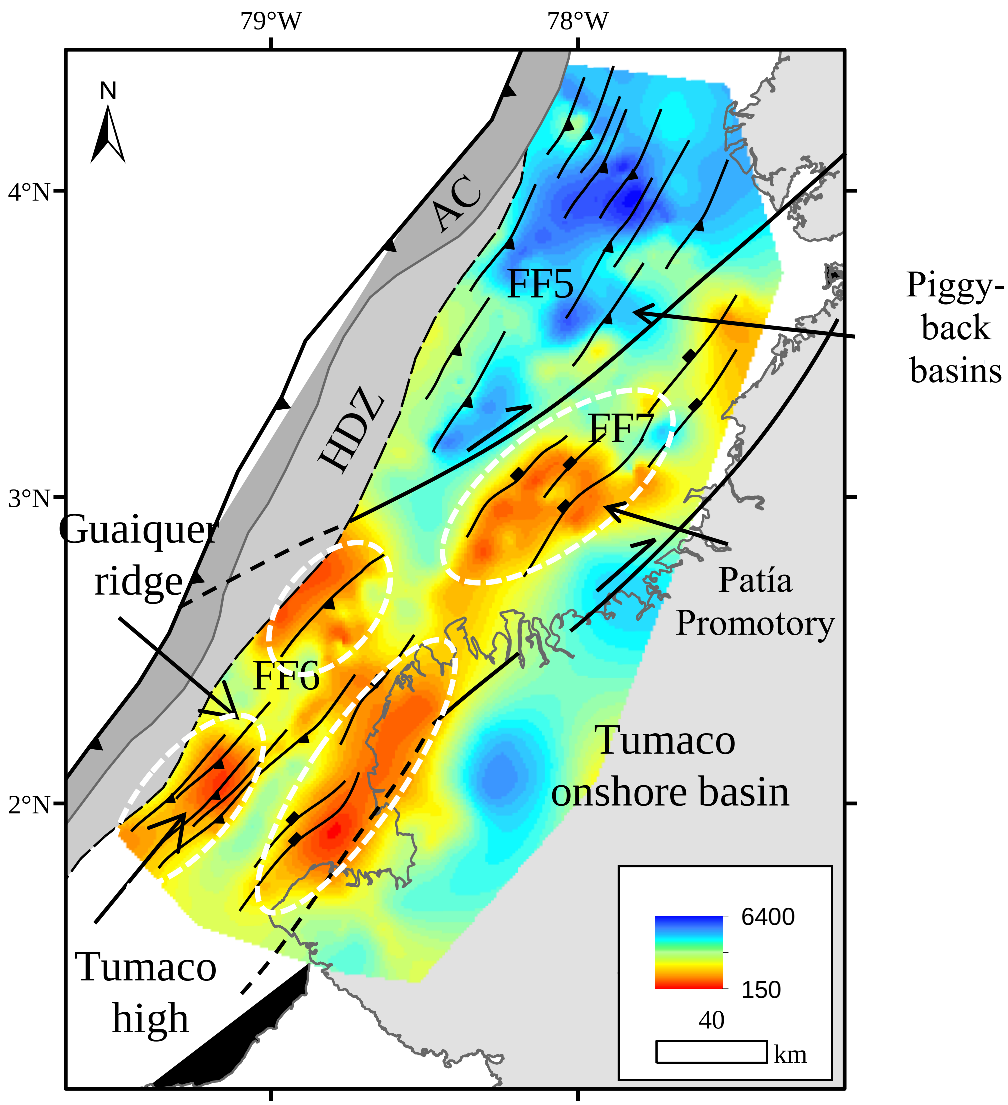

Figure 28. To the left TWT structural map at near the top of the Early (?) to Middle (?) Miocene sequence. To the right, Early (?) to Middle (?) Miocene time thickness map. AC: accretionary prism, HDZ: highly deformed zone, FF: fault family.

Sequence III-B (Middle Miocene (?))

Well character

Since it was not possible to separate sequence III-A and III-B from well log character the well character of this sequence corresponds to the same well character and core descriptions as in sequence III-A.

Seismic character

The seismic facies of this sequence is variable depending upon the location within the basin (**Figure 23**). In the Tumaco onshore basin the seismic facies are characterized by discontinuous to continuous parallel to sub-parallel reflectors with high frequency and low amplitudes values (**Figure 24**). In eastern side of the basin, the reflectors onlaps against sequence III-A, suggesting the uplifting of the Western Cordillera for this time and defining the occurrence of unconformity U3.

In the Manglares basin, is also characterized by discontinuous to continuous parallel to sub-parallel reflectors with high frequency amplitude values which changes laterally to low frequency amplitude values. Channelized features are also common in this sequence, which are characterized by having high amplitude reflection values (**Figure 30**). In this area onlapping against sequence III-A is appreciated, defining unconformity U3 (**Figure 14**).

In the Patía segment, is characterized for having chaotic and discontinuous reflectors with a transparent and ghostly appearance which makes difficult the description of a consistent seismic pattern. In the Tumaco high area the reflectors of this sequence are dipping landwards (**Figure 14**) suggesting the uplifting of the Tumaco high.

In the north Tumaco offshore area it is characterized for discontinuous, parallel to sub-parallel reflectors, with low to medium amplitudes. These reflectors downlaps against sequence III-A defining unconformity U3 (**Figure 14**).

Time structural map and time thickness map

Figure 29 shows a TWT structural map near the top of the Middle (?) Miocene sequence. The TWT structural map shows that this sequence is affected by fault families 1 to 8. To the south of the GFS is affected by fault families 3, 6, 7 and 8; to the north of the GFS is affected for fault families 1 and 5.

Four main structural highs are found south of the GFS in the offshore area (**Figure 29**). The three southernmost highs have a common N~30°E trend and matches with the basement paleo-highs mapped in tectono-sequence I which suggest that the Middle (?) Miocene sedimentation is also controlled by the basement highs. The northernmost high defines the Patía Promotory (**Figure 28**) which can also be appreciated in **Figure 10**.

Associated with fault family 6, north of GFS is common the formation of piggy-back basins. The most preserved and well-formed piggy back basins are located near the coast line as shown in **Figures 14** and **29**.

Time thickness map (**Figure 29**) indicates that the thickness of the sequence varies along the whole basin and reveals the occurrence of four major depocenters.

The first depocenter is localized in the Tumaco onshore basin (**Figures 24, 29**). Based on the free-air gravity map is possible to determine that this depocenter has a NW-SW trending (**Figure 3**). The thickness of this sequence varies in this area. Towards the

Western Cordillera and the Remolinogrande high the sequence is thinner while in the central portion of the basin the sequence is thicker (**Figure 24**).

The second depocenter is located to the south of the offshore area, in the Manglares basin along (**Figure 16, 25**) where it reaches at maximum depth of 5000 TWT (ms) and an approximate thickness of 2500 TWT (ms). Based on the free-air gravity map is possible to determine that this depocenter has a NW-SW trending (**Figure 3**).

The last two depocenters are located in the northern area of the Tumaco offshore basin (**Figure 29**). In this area, these depocenter are characterized by having approximately 2500 TWT (ms) thickness and are associated to piggy-back basins formed due to the deformation generation by fault family 5.

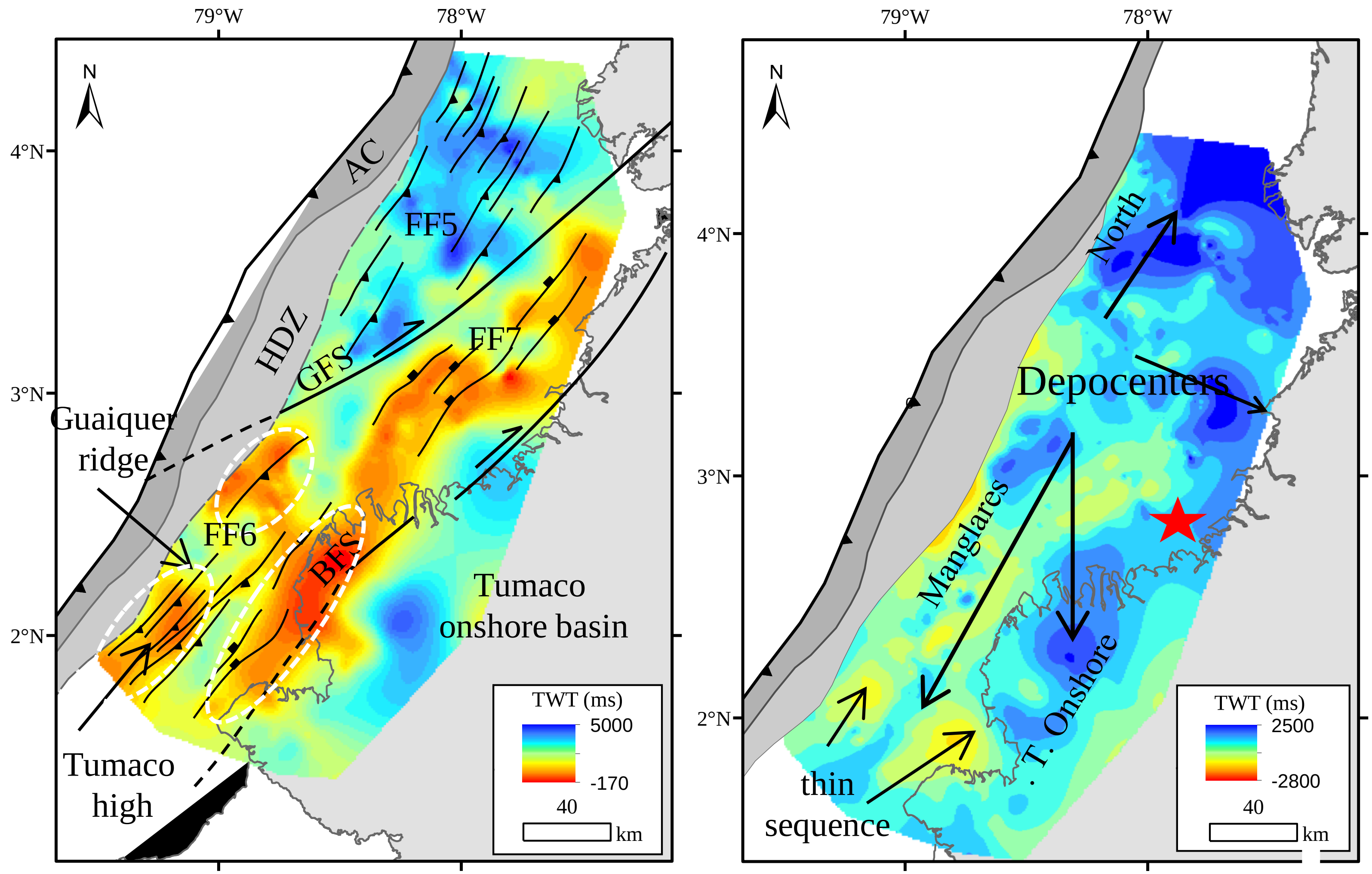

Figure 29. To the left TWT structural map at near the top of the Middle (?)Miocene sequence. To the right, Middle (?)Miocene time thickness map. AC: accretionary prism, HDZ: highly deformed zone, FF: fault family.

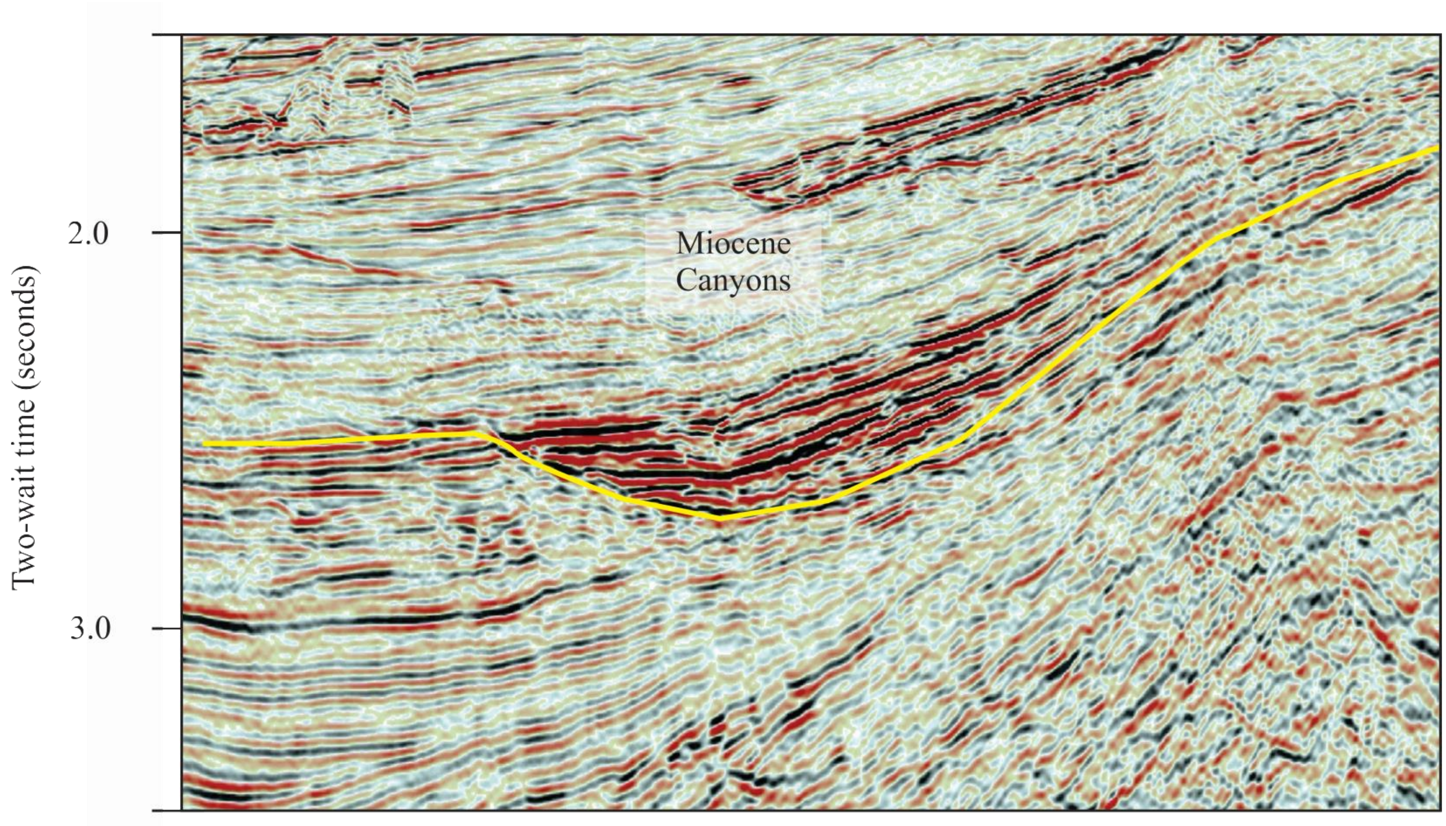

Figure 30. Close up from the figure 16 showing main Middle Miocene canyons.

Sequence III-C: (Middle (?) to Late (?) Miocene

It is constitute by the Chagüí and San Agustín formations.

Outcrop

The only outcropping formation from this sequence is the San Agustín formation. According to Caldas-ANH (2011), this unit is found along the Tumaco Bay with an approximate thickness of 300 meters. It is composed by a thick sequence of mudstones and siltstones with high concentration of forams and sporadic intercalation of fine sandstones.

Well character

It was drilled by all the wells in the study area. The base of this sequence is marked by medium gamma ray readings which increase towards the top of the sequence.

Based on core descriptions from the Remolinogrande-1 well, Caldas-ANH (2011) indicates that the Chagüí Formation is mainly composed by a series of thick sandstones layers intercalated with siltstones. According to Caldas-ANH (2011), this unit has high concentration of volcanic lithics of intermediate and plutonic composition, which are more common towards the top of the unit. In addition, the presence of methamorphic lithics (e.g. phylits) and minerals (e.g. amphibols), are common.

The San Agustín Formation consists of a thick sedimentary succession of claystones and siltstones rich in forams, and occasionally bioturbated intercalated with thick tobaceus sandstones beds of fine to medium grain size (Caldas-ANH, 2011). Caldas-ANH (2011) interpreted a prodelta to middle platform sedimentary environment of deposition to this unit.

Based on nanofossils studies, Universidad de Cadas (2011) established a Late Miocene age (Tortonian – Messianian); and based on the zonation of Jaramillo et al.

(2011) and palinomorfs studies, Caldas-ANH (2011) established a Late Miocene – Pliocene age (Tortonian – Zanclean).

Seismic character

The seismic facies of this sequence is variable depending upon the location within the basin (**Figure 23**). In the Tumaco onshore basin the seismic facies are characterized by discontinuous to continuous parallel to sub-parallel reflectors with high frequency and low amplitudes values (**Figure 24**). In both flacks of the basin, the reflectors onlaps against sequence III-B suggesting the uplifting of the Remolinogrande high and the Western Cordillera for this time and marking the occurrence of unconformity U4.

In the Manglares basin, is also characterized by discontinuous to continuous parallel to sub-parallel reflectors with high frequency amplitude values which changes laterally to low frequency amplitude values. In this area onlapping against sequence III-B is appreciated, defining unconformity U4 (**Figure 14**).

In the Patía segment, is characterized for having chaotic and discontinuous reflectors with a transparent and ghostly appearance which makes difficult the description of a consistent seismic pattern. In the Tumaco high area the reflectors of this sequence are dipping landwards (**Figure 14**).

In the north Tumaco offshore area it is characterized for discontinuous, parallel to sub-parallel reflectors, with low to medium amplitudes. These reflectors downlaps against sequence III-B, defining unconformity U4 (**Figure 14**).

In the Pacific trench (tectono-sequence III), it is characterized It is characterized by having higher amplitude reflectors than tectono-sequence II intercalated with chaotic, blurry and non-continuous reflectors (**Figure 26**).

Time structural map and time thickness map

Figure 31 shows a TWT structural map near the top near the top of the Middle (?) to Late (?) Miocene sequence. The TWT structural map shows that this sequence is affected by fault families 1, 3, 5, 6, 7 and 8. To the south of fault family 1 (GFS) the GFS it is affected by fault families 3, 6, 7 and 8; to the north of the GFS is affected for fault families 5.

Four main structural highs are found south of the GFS in the offshore area (**Figure 31**). The three southernmost highs have a common N~30°E trend and matches with the basement paleo-highs mapped in tectono-sequence I which suggest that the Middle (?) to Late (?) Miocene sedimentation is also controlled by the basement highs. The northernmost high defines the Patía Promotory (**Figure 31**) and the shelf which extends towards the north in the whole study area. The Patía promontory and the shelf break can be also appreciated in **Figure 10.**

Associated with fault family 6, north of GFS is common the formation of piggy-back basins. The most preserved and well-formed piggy back basins are located near the coast line as shown in **Figures 14** and **31**. Also, in the southwestern side of the basin, is possible to observe a better formation of the Guaiquer ridge during this time.

Time thickness map (**Figure 29**) indicates that the thickness of the sequence varies along the whole basin and reveals the occurrence of three major depocenters.

The first depocenter is localized in the Tumaco onshore basin (**Figures 24, 31**). Based on the free-air gravity map is possible to determine that this depocenter has a NW-SW trending (**Figure 3**). The thickness of this sequence varies in this area. Towards the Western Cordillera and the Remolinogrande high the sequence is thinner while in the central portion of the basin the sequence is thicker (**Figure 24**). And compared with sequences III-A and III-B its depocenter is wider and longer.

The second depocenter is located to the south of the offshore area, in the Manglares basin along (**Figure 16, 31**) where it reaches at maximum depth of 5000 TWT (ms) and an approximate thickness of 3000 TWT (ms). Based on the free-air gravity map is possible to determine that this depocenter has a NW-SW trending (**Figure 3**).

The last depocenter is located in the northern area of the Tumaco offshore basin (**Figure 31**). It has an approximate W-E trend. In this area, this depocenter is characterized by having approximately 3200 TWT (ms) thickness.

It is also important to notice, that towards southern highs the thickness of the sediments is thinner (**Figure 31**).

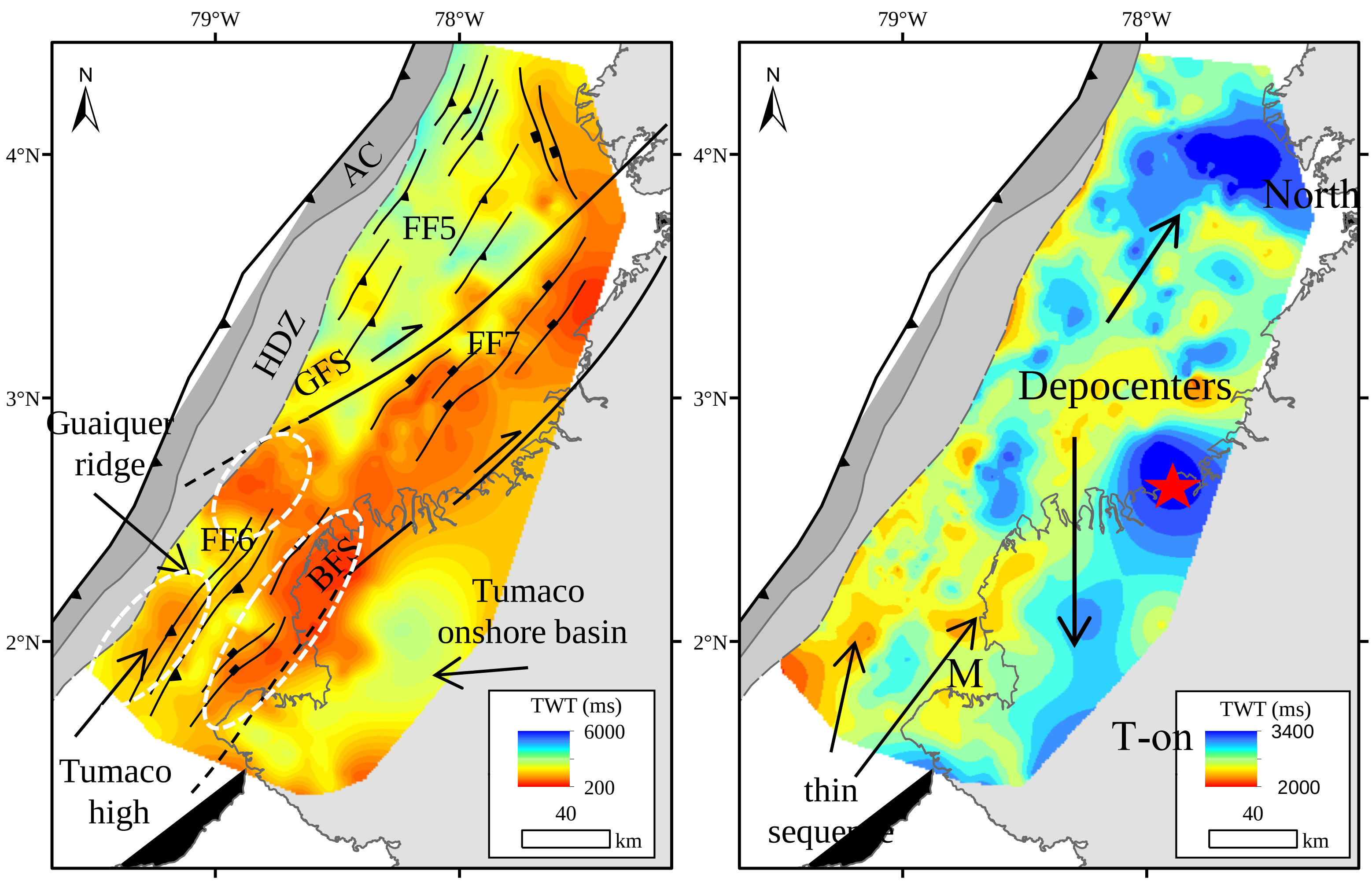

Figure 31. To the left TWT structural map at near the top of the Middle (?) to Late (?) Miocene sequence. To the right, Middle (?) to Late (?) Miocene time thickness map. AC: accretionary prism, HDZ: highly deformed zone, FF: fault family.

TECTONO-SEQUENCE IV (LATE MIOCENE -PLIOCENE TO RECENT):

Outcrop description

It represents the most recent and shallower sedimentary sequence in the basin. It consists of the Cascajal Formation (Late Miocene - Pliocene) and Recent sediments. According to the Caldas-ANH (2011) this unit outcrops in the Tumaco Bay and can be correlated with the Raposo Formation in the Ladrilleros area, north of the study area (**Figure 24).**

The Cascajal Formation consist of a succession of decimetric to metric sandstones, conglomeratic sandstones and conglomerates with lithic composition and lenticular geometry occasionally intercalated with mudstones with less than 2 meters of thickness (Caldas-ANH, 2011).

Based on the facies interpretation (Caldas-ANH, 2011) suggests that this unit was dominated by littoral environments of high energy (deltaic environments) like marine and distributary channels and coastal lagoons.

Based on the scarce palinological recovery, Caldas-ANH (2011) established and age of Late Miocene – Pliocene (Messinian – Zanclean?).

Well character

The sequence was drilled by the Remolinogrande-1, Sandi-1, Tambora-1 and Majagua-1 well. The well character shows low gamma ray readings, suggesting the presence of sandstones layers as indicated by the outcrop descriptions (**Figures 18, 19, 20**). The thickness of the sequence varies from 30 to 250 meters along the basin, where the major thickness is found in the central area of the study area, in the Remolinogrande-1 and Sandi-1 wells.

Seismic character

The seismic facies are characterized by well-bedded, continuous and high amplitude reflectors with different terminations patterns and types of discontinuities.

In the Tumaco onshore basin it is characterized by continuous parallel to sub-parallel reflectors, with low to medium amplitudes. Onlapping reflectors against the tectono-sequence II, the Western Cordillera and the Remolinogrande high are appreciated (**Figure 23, 24**). Also, onlap and downlap reflectors indicate the presence of a prograding shelf (**Figure 32**).

Across the Manglares basin, in the offshore area, it is characterized by continuous parallel to sub-parallel reflectors, with low to medium amplitudes with downlaps and onlaps against the western flank of the basin (**Figure 16, 23**). However, in some seismic lines, this sequence is pinching out against the western flank of this basin.

The Patía segment it is characterized by well-bedded, parallel to sub-parallel continuous high amplitude reflectors that onlaps and downlaps against tectono-sequence II (**Figure 16**). In the Patía area these reflectors are almost horizontal.

In the north Tumaco offshore area it is characterized for discontinuous, parallel to sub-parallel reflectors, with low to medium amplitudes that downlaps against tectono-sequence II, defining unconformity U5 (**Figure 14**).

In the Pacific trench, it is characterized for having low frequency, chaotic and burry reflectors that change laterally and vertically to higher amplitude and well defined reflectors (**Figure 26**). These reflectors gently dip 3-5° basinwards (**Figure 16**).

Time structural map and time thickness map

Figure 33 shows a TWT structural map near the top near op of the Pliocene to Recent sequence in the offshore area. The TWT structural map shows that this sequence is affected by fault families 1, 3, 5 6, 7 and 8. To the south of fault family 1 (GFS) the GFS it is affected by fault families 3, 6, 7 and 8; to the north it is affected for fault families 1 and occasionally by fault family 5.

Two main structural highs are observed (**Figure 33**). The first one is located along the western side of the coast line of the entire study area. It has an approximate N~30°E trend. This structural high is wider towards the north and thinner towards the south and the central area it extends up to the highly deformation zone (**Figure 33**). Its western side is highly affected by normal gravitational faults of fault family 7. This high clearly define the Patía promontory and the shelf break (**Figure 33**). The second one is located westwards of the Manglares basin and clearly define the Tumaco high as appreciated in **Figures 33** and **10.**

Time thickness map (**Figure 33**) indicates that the thickness of the sequence varies along the whole basin and reveals the occurrence of four major depocenters.

The first three depocenters are localized in the Tumaco offshore basin as shown in **Figure 33**. This depocenters have and approximate thickness of 2000 TWT (ms) and are located in the Manglares basin, the Patía segment and south of the Patía promontory. The northernmost depocenter has an N~30°E trend and an approximate 2000 TWT (ms) thickness. Most of the study area exhibits thinner depocenters localities with approximate thickness of 1000 TWT (ms) as shown in **Figure 33**.

In the Patía segment and in the Pacific trench the thickness of the sequence varies from 100 to 1000 TWT (ms) and it is slightly affected by the deformation (**Figures 16** and **26**).

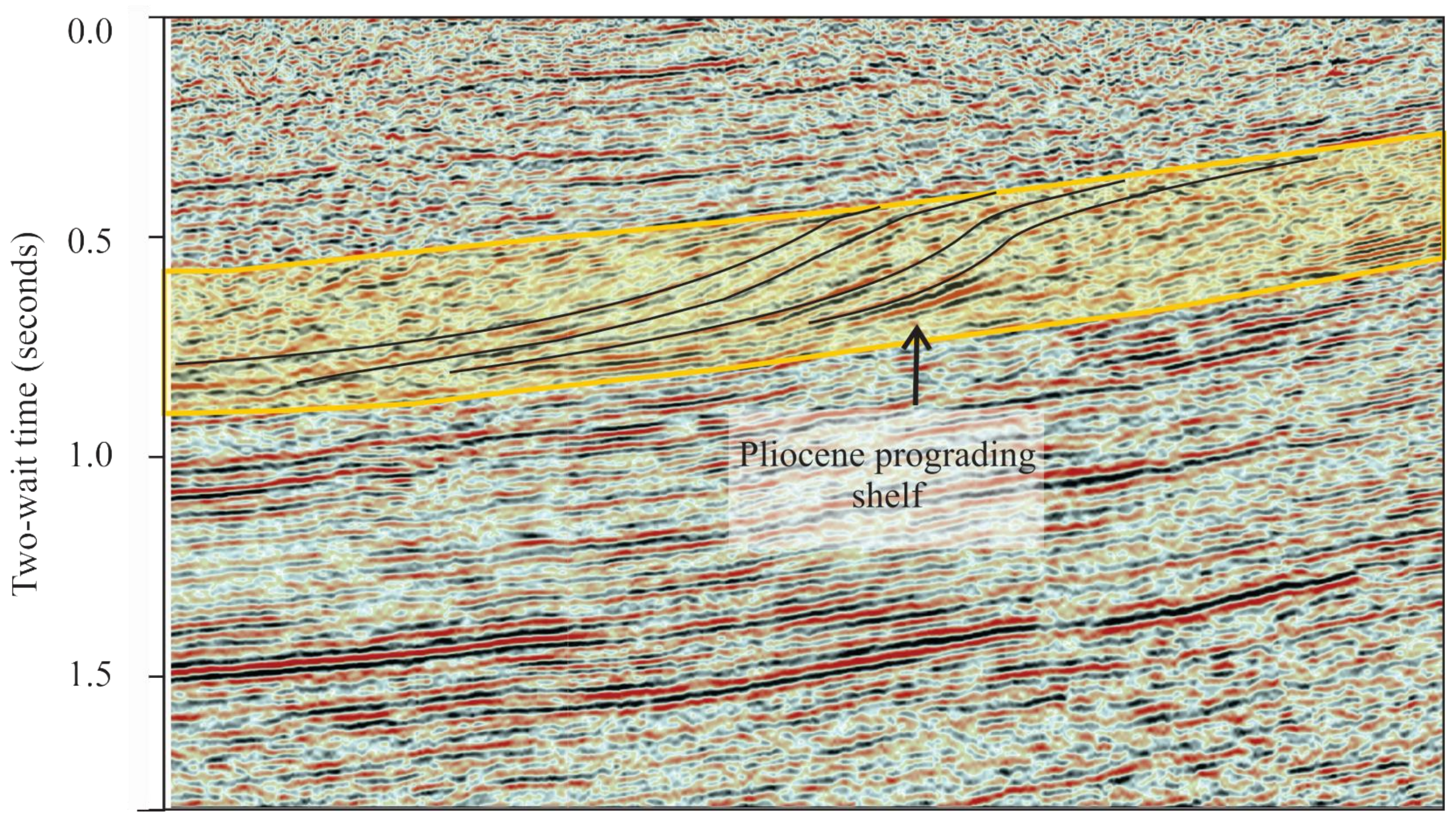

Figure 32. Close up from figure 24 showing the Pliocene prograding shelf.

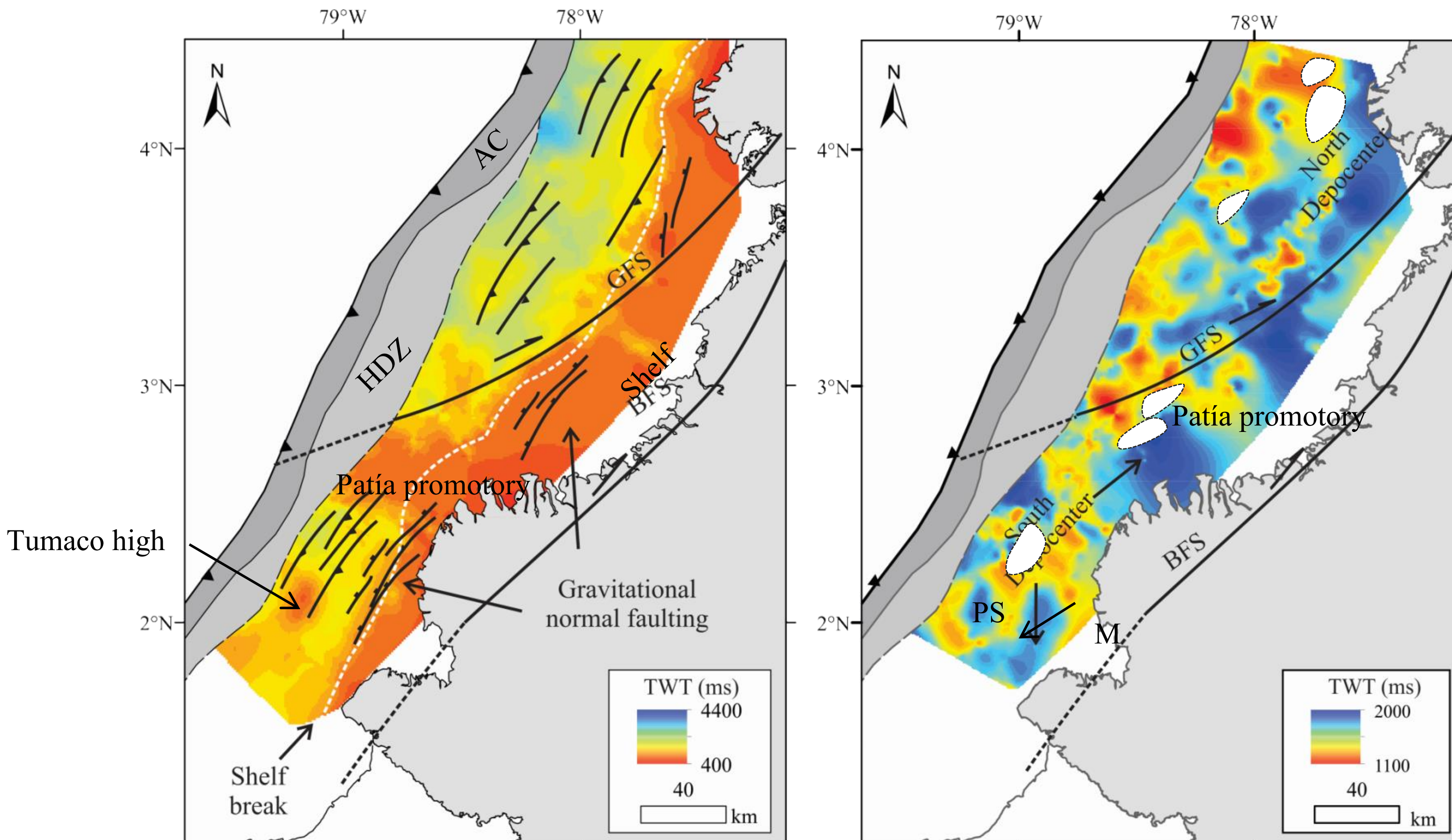

Figure 33. To the left TWT structural map from near the top of the Pliocene to Recent sequence in the offshore area. 1) White dashed line represent the shelf break, 2) Gravitational faulting along the shelf break. To the right time thickness map of the Pliocene-Recent sequence showing the main depocenters. White circles indicates areas of no deposition or erosion. AC: accretionary prism, HDZ: highly deformed zone, FF: fault family.

Hydrocarbon Indicators

BOTTOM SIMULATING REFLECTOR (BSR)

The new seismic reflection data collected along the offshore Pacific margin in Colombia exhibit a persistent seismic reflector in all the lines characterized by cross-cutting other seismic reflectors, having high amplitudes and reverse polarity. This reflector was identified as 'bottom simulated reflector' (BRS) (**Figure. 38**). It was mapped throughout the offshore area and it appears at depths 800-5600 TWT (ms) below the sea floor and can be traced from the actual accretionary prism at water depths of 3200 mbsl westwards up to 400 mbls slope, eastwards.

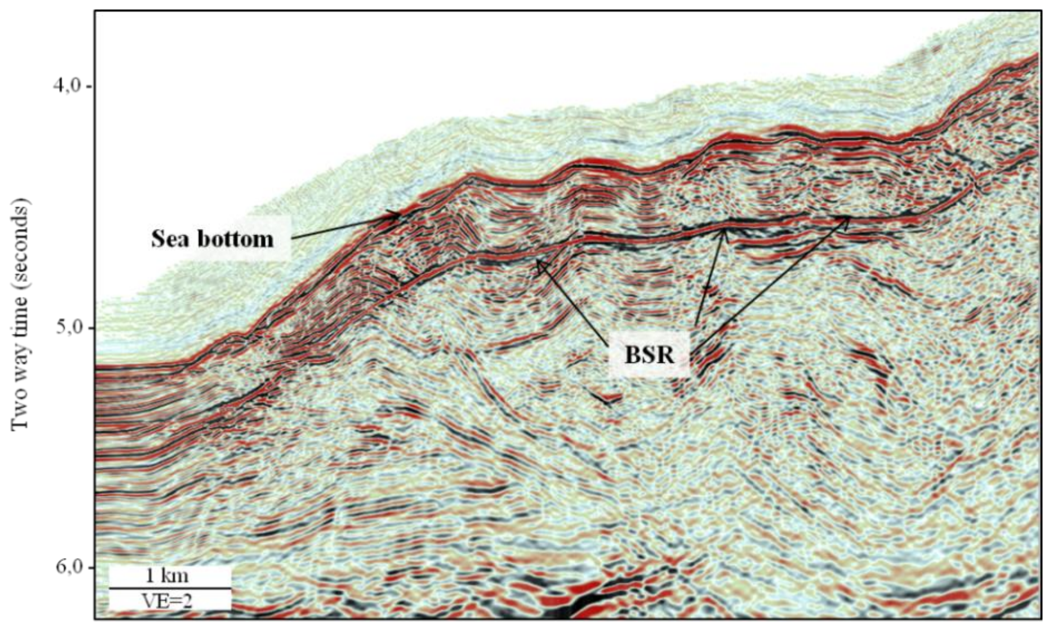

Figure 34. Bottom simulating reflector (BSR) example. Notice how closely parallels the sea bottom reflector. The gas hydrate must be found in the sediments above the BSR, and free gas in the sediments below.

A TWT structural map of the BSR and a time thickness map between the BSR and the sea bottom were done (**Figure 35**).

The TWT structural map (**Figure 35**) indicates that this reflector can be found from the continental slope, bellow 400 TWT (ms) depths up to the accretionary prism at about 6400 TWT (ms). The time thickness map (**Figure 35) s**hows how the thickness between the sea bottom and the BSR varies along the basin and that it is fairly constant along the study area. However, the thickness in the northern area is more constant that in the southern area.

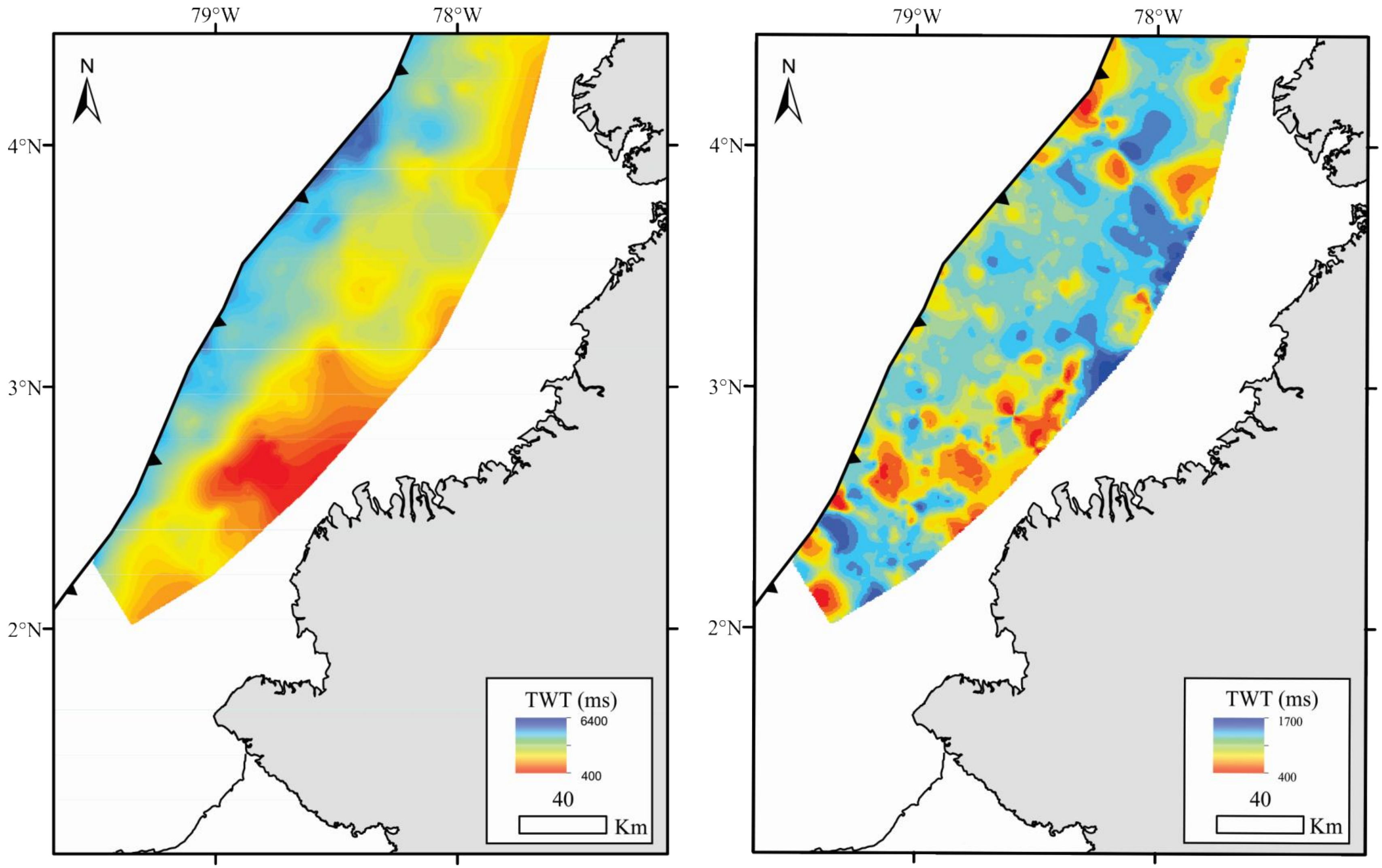

Figure 35. To the left TWT (ms) map of the BSR to the right time thickness map between the BSR and the sea bottom.

ORGANIC GEOCHEMICAL ANALYSIS

From the five wells drilled in the study area, only three contains Rock-eval analysis and Vitrinite Reflectance (Ro) data (Sandi-1, Tambora-1 and Majagua-1). The Remolinogrande-1 well only has Total Organic Carbon (TOC) and (Ro) values.

In order to determine the kerogen type and maturity of the samples from the Sandi-1, Tambora-1 and Majagua-1 the hydrogen index (IH), oxygen index (OI) and the maximum temperature (Tmax) values were plotted in **Figures 36, 37** and **38**. The modified Van Krevelen diagram (**Figure 36**) and the IH vs Tmax plot (**Figure 37**) indicates that most of the samples have kerogen type III and IV and only the well Tambora-1 has some samples with kerogen type II. **Figure 38** indicates that only one sample, from all the wells, reached the pick of the oil window.

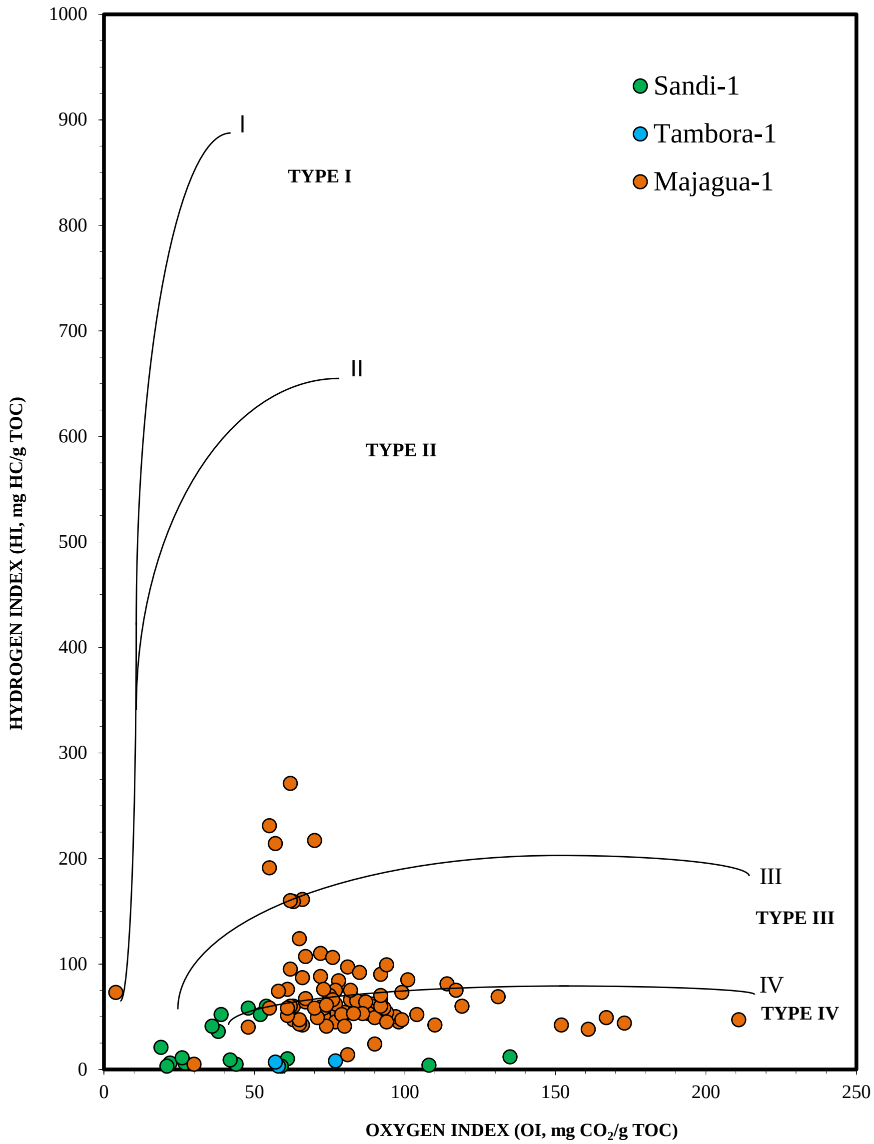

Figure 36. Modified van krevelen diagram for the Sandi-1, Tambora-1 and Majagua-1 wells. Notice that most of the samples have kerogen type IV associated with inert organic matter. The best kerogen characteristics are associated with the well Tambora, which has kerogens types IV (inert), III (terrestrial) and II (marine).

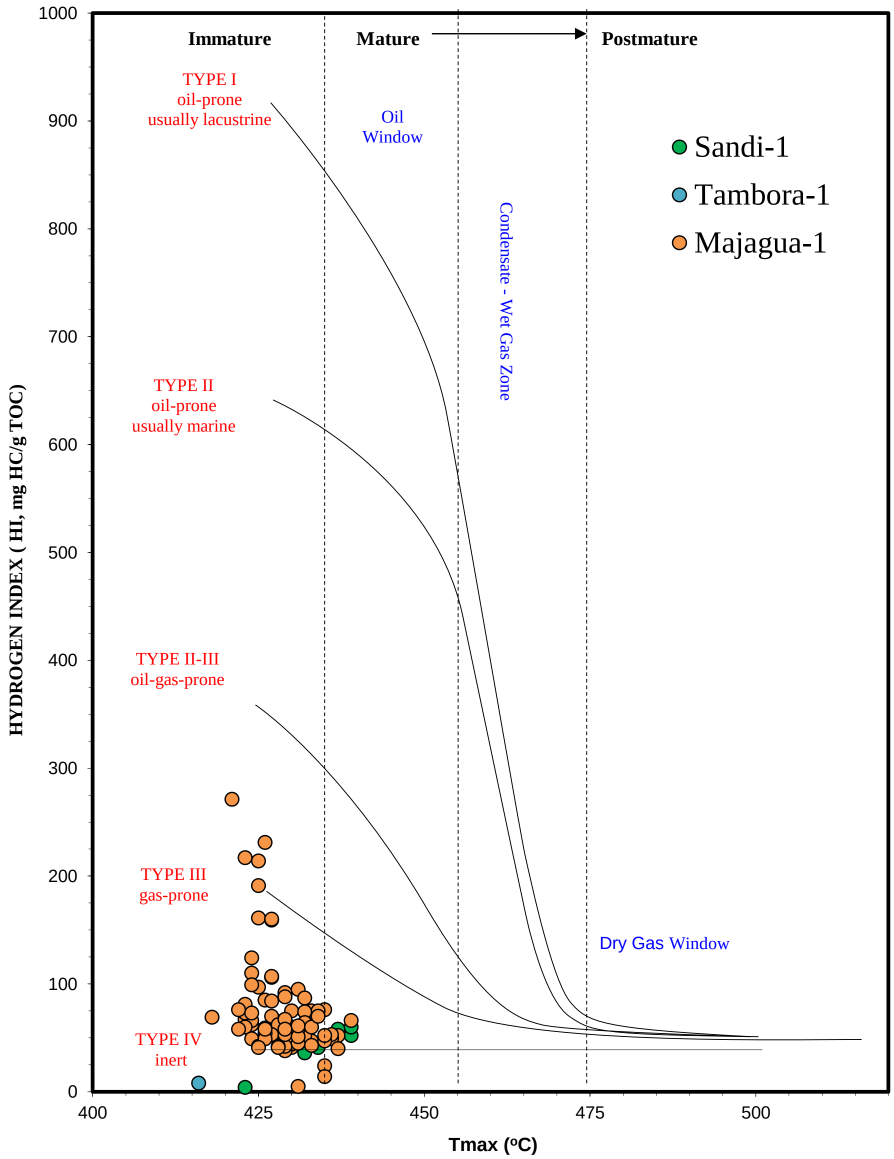

Figure 37. Crossplot diagram of HI vs Tmax. The diagram indicates that only the samples from the Tambora-1 wells have the potential to generate liquid and gas hydrocarbons, associate with kerogen types II and III respectively. However, most of the samples are still inmature to generate any kind of hydrocarbon. Only few samples from the Majagua-1 and Sandi-1 wells are located at the beginning of the oil generation windown.

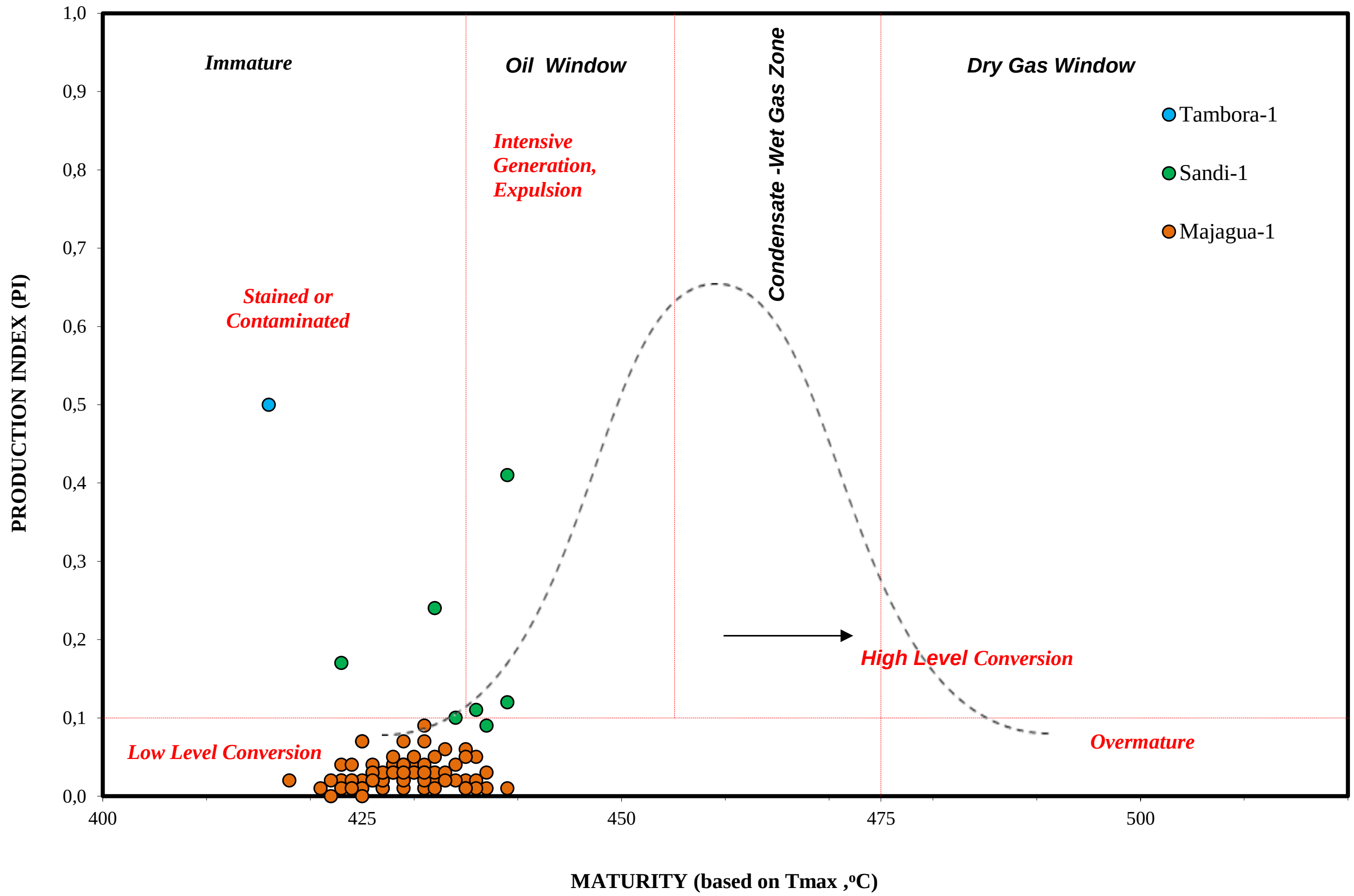

Figure 38. Crossplot diagram of Tmax vs Production Index (PI). The diagram indicates that all the samples of the Majagua-1 well area in a low level of hydrocarbon conversion and two of the seven samples of the Sandi-1 well are stained or contaminated, one is located within the oil window and the rest of the samples are still inmature to generate hydrocarbons.

5. DISCUSSION

The Gorgona Terrane accretion

Franco and Abbot (1999) based on the ages assign to the Gorgona basement by Sinton et al., 1993 (~89 Ma) and the ages of siliceous shales that unconformable overlie the basement of the Gorgona island dated by Gansser (1950) and Dietrich et al., 1981 as Upper Eocene (36.6 to 43.6 Ma) calculated that the age of the accretion of the Gorgona terrane was Early to Middle Eocene.

Based on deformed sandstones that unconformable overlies that basement in the Gorgona Island, paleomagnetic data and plate tectonic reconstructions, (kerr and Tarney, 2005) suggest that the Gorgona terrane is part of the Caribbean oceanic plateau that was carried by the Farrallón plate from 26°-30°S northwards until it was accreted to the Colombian continental margin during the Middle Eocene (~45 Ma).

Using seismic interpretation, Marcaillou and Collot (2008) suggest that the basement of the Manglares basin was accreted to the continental margin during the Late Cretaceous or Paleocene.

In this study seismic interpretation and gravity data allows defining that the Remolinogrande high corresponds to the southern extension of the Gorgona Island, defining a unique terrane of Cretaceous age ~ 90 Ma (based on radiometric ages from volcano-clastic rocks from Remolinogrande high and Gorgona dikes from Universidad de Caldas-ANH (2011)) with and approximate extension of 150 km (**Figure 3**).

Unconformity U1 identified on seismic data is suggested to be the time of accretion of the Gorgona terrane. Based on U-Pb dating in detritic zircons and nanofossils studies, Universidad de Caldas-ANH (2011) assigned an Upper Oligocene to Lower Miocene age (28-20 Ma) to the sandstones dated by Gansser (1950) and Dietrich et al., 1981 as Late Eocene and based on calcareous nanofosils analyses assigned and Eocene – Early Miocene to the Unidad Sur-1 (tectono-sequence II is this study).

The age difference between the Gorgona basement rocks (~ 89 Ma) and the overlying sedimentary rocks (~28 – 20 Ma) provides a minimum estimate of the time of the accretion of the Gorgona terrane. The age difference is 61 – 69 Ma, which suggest that the Gorgona Island was accreted during the Late Cretaceous – Paleocene in agreement with Collot and Marcalliou (2008); and related to the time of accretion of other oceanic plateaus in Ecuador (Jaillard et al., 2004; Luzieux et al., 2006) and rather the Middle to Late Eocene tectonic event proposed by Franco and Abbot (1999) and Kerr et al., (2004) can be the reason for unconformity U2 and the moderate deformation and folding observed in tectono-sequence II (**Figure 16**). This Middle to Late Eocene event can be correlated with a regional plate kinematic change known in the Andes as the Incaic compressive phase (Mégard, 1984; Jaillard and Soler, 1996; Noblet et al., 1996) as proposed by Marcalliou and Collot (2008).

Processes for seaward migration of the accretionary prism in response to oceanic plateau and seamount accretion.

Figure 13 shows the bathymetric profiles along the Tumaco offshore basin. The bathymetric data shows that the Tumaco offshore basin in the southern area does not exhibit a gentle topographic slope (**Figure 13, profiles A, B** and **C**), but rather a rough topographic profile with a "bulge" that extends towards the north and the south for almost 50 km. In this area, the sediments are strongly deformed, thrusts and vertical faults occur making difficult to follow the seismic sequences and generating complicated structures that are poorly resolve. This topographic “bulge” matches with an anomalous gravity high shown in **Figure 3**. This seismic and gravity signatures suggest that this topographic high may be related to seamount material that was accreted into the continental margin. In addition, the highly deformed area, related to fault family 6 westward of the Manglares basin (**Figure 16**), can be correlated with a previous accretionary prism related to the accretion of the Gorgona Island.

The accretion of oceanic plateaus and seamounts can take several forms. Large accretion events may cause the reversal in trench polarity and switch in the direction of subduction (Ben-Avraham et al., 1982; Kroenke et al., 1991). “Smaller accretion events can also produce seaward trench jumps. Because sufficiently buoyant lithosphere cannot subduct, the continued motion of the rest of the oceanic plate will cause a build up of forces near the buoyant feature. When these forces exceed the strength of its weakest part, the buoyant feature and some surrounding seafloor will break off from the subducting plate and a new trench will form seaward of the former trench.” (Franco and Abbot, 1999).

In this study, it is proposed that the Tumaco offshore basin not only experience the accretion of the Gorgona Island but also the accretion of a seamount feature. In both cases, the accretion was followed by a seaward trench jump which originates the migration of the accretionary prism and the formation of a new fore-arc system. **Figure 39** shows the proposed evolution and deformation model for the subduction of the seamount feature in the Tumaco offshore basin.

This model, can be correlated with sandbox experiments by Dominguez et al., (1998, 2000) where the topography of the continental slope in subduction systems could be highly affected by the accretion of seamount features. In his experiments he describes all the deformation stages affecting the accretionary prism and how this one migrates seawards as seamount features is incorporated into the subduction system. The main stages can be resuming in: 1) uplifting of the continental margin, 2) indentation of the accretionary wedge, 3) subsidence of the frontal margin 4) the formation of a new accretionary prism (**Figure 39**)

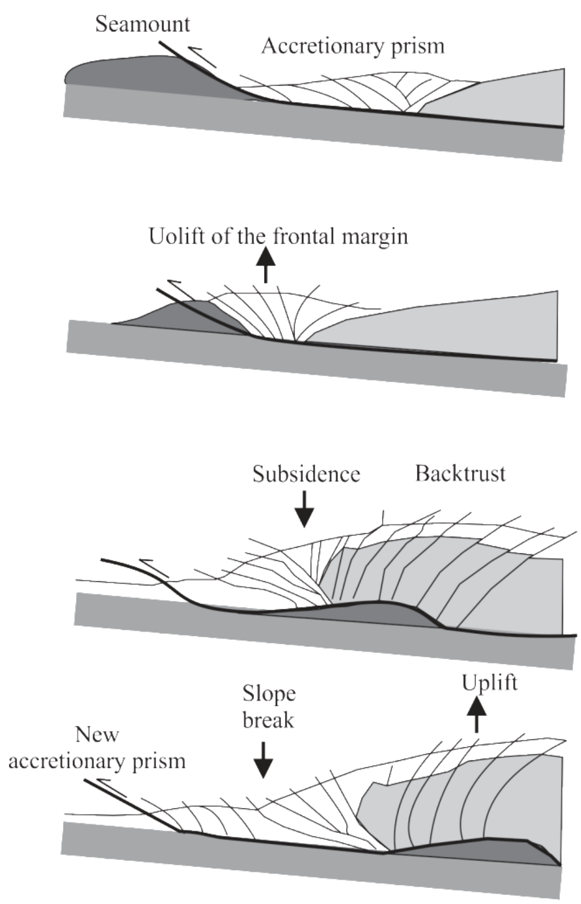

Figure 39. Schematic stages of the seamount subduction and seawards migration of the accretionary prism. Modified from Dominguez et al., (2000).

Tectono-stratigraphic evolution

LATE CRETACEOUS – PALEOCENE

By Late Cretaceous- early Paleocene the tectonic regime in southwestern Colombia changed from a passive margin to an active convergent margin as a result of oblique collision of the leading edge of the Caribbean plate and South American plate (SOAM) (Cediel et al., 2003; Duque-Caro, 1990; Kennan and Pindell, 2009; Moreno-Sanchez and Pardo-Trujillo, 2003; Pindell et al, 1998). Collision started in Ecuador and southern Colombia, resulting in the emplacement of the Western Cordillera range, around 75-70 Ma (Villagomez, 2010). The collision was followed by right-lateral strike-slip faulting along the Romeral fault system, as the Caribbean plate collision migrated diachronously to the north and northeast (Villagómez et al., 2011).

During the Late Cretaceous- Middle Paleocene the accretion of the Gorgona terrane against the western margin of southwestern Colombia took place (Marcalliou and Collot, 2008) (**Figure 40**). This terrane was carried by the Farrallón plate from 26°-30° northwards (Kerr et al., 2004) until it was accreted to the Colombian continental margin. The accretion was diagonal and probably driven by strike-slip faults related to fault family 1. The buoyancy of the basement terrene generates a basinwards jump in the subduction zone (Franco and Collot, 1999).

According to Gómez et al., (2005a) the oblique accretion of oceanic blocks against the Western Cordillera is the driving mechanism for the Late Cretaceous initiation of shortening and uplift in the Central Cordillera.

EARLY (?) EOCENE - EARLY MIOCENE ?

From Early to Middle Eocene convergence of the Farrallón plate below the South American plate was oblique, between 45° and 35° (Somoza, 1998) generating magmatism in the Western Codillera as evidenced by the Mandé Batholith ~43–44 Ma (Borrero et al., 2012) and the initial formation of the fore-arc basin. During this time calcareous turbidites from tectono-sequence II dominated the sedimentation (López, 2009) (**Figure 40**). This sedimentation was controlled by fault family 4 in the basement. The folding observed in the Manglares basin in tectono-sequence I and II suggest that a compressional episode occurs during the Oligocene (**Figure 16**). Which can be either correlated with a regional plate kinematic change known in the Andes as the Incaic compressive phase (Jaillard and Soler, 1996; Noblet et al., 1996); with the break-up of the Farallones plate (Lonsdale, 2005) or the collision between the Panama arc against the South American plate ~23- 25 Ma (Farris et al., 2011).

The Oligocene break-up of the Farallones plate into the Nazca and Cocos plates marked a period of plate kinematic reorganization (Farris et al., 2011). The new Nazca plate has an orthogonal subduction below the South American plate generating arc magmatism in the Western Cordillera as evidence by the Pierdrancha Batholith ~ 24 -23 Ma (Borrero et al., 2012).

EARLY MIOCENE -MIDDLE MIOCENE

During the Early – Middle Miocene, the Tumaco on-offshore basin was dominated by two main processes, high subsidence and high sedimentation rates indicated by the large topography extend of tectono-sequence III (**Figure 40**). Changes and migration of depocenter in the Manglares basin (**Figure 16**) can be explained as a consequence of high subsidence rates and different episodes of the formation of the Manglares fore-arc basin.

Based on foraminifers analysis, Duque Caro (1990) suggested an upper slope deposition. López (2009) based on seismic analysis, suggested that these units were deposited by a volcano-clastic fan at the toe of the continental slope.

MIDDLE – LATE MIOCENE

During the Middle to Upper Miocene, the Tumaco offshore basin was dominated by compressional process due to the convergence of the Nazca pate below the South American plate (**Figure 40**). This compressional process generates: 1) a thick-skin deformation style south of Garrapatas Fault Zone, folding tectono-sequence I-III (fault family 6); 2) a thin-skin deformation style north of GFS, folding and faulting tectono-sequence III (fault family 5).

This compressional event is well documented in Ecuador and Colombia and corresponds to one of the periods of exhumation of the Western Cordillera in Colombia (Villagomez, 2010) and Cordillera Real in Ecuador (Spikings 2001).

During this time, the subsidence rates in the basin decrease resulting in shallowing process with deposition of thick sandstones sequences with high concentration of volcanic lithics of intermediate and plutonic composition sourced by Western Cordillera (Sequence III-C).

EARLY PLIOCENE – RECENT

During the Early Pliocene to Recent the compressive phase is less intense and the basin underwent high subsidence and sedimentation rates (**Figure 40**) . In the Patía promontory, the onlapping reflectors of tectono-sequence IV against the basement “bulge” indicates ongoing uplift of this basement “bulge”.

Prograding reflectors of tectono-sequence IV over tectono-sequence III, suggest that sedimentation was dominated by deltas and continental fans, with volcano-clastics sourced by volcanos at the Western Cordillera during the time.

The Manglares basin is locally affected by the occurrence of fault families 7 and 8. Fault family 7, associated with basinwards dipping normal faults with larger throws ~500 TWT (ms), affects the southeastern corner of the Manglares basin. The fact that these faults are dipping basinwards, in the same direction of seafloor topography and strata dip direction, suggest that they can be associated to gravitational process affecting the sea floor and the shelf break. These fault faults detaches in the Paleogene sequence and generated compression in the western flank of the Manglares basin generating out of sequence deformation

In contrast, fault family 8, high angle normal faulting with small throws values that generally dips landwards affects tectono-sequence III and IV. No evidence of growth strata is appreciated, suggesting that the extension activity occurs recently, after deposition of tectono-sequence IV. The fact that the faults are dipping landwards and no seawards suggest that they are related to tectonic processes rather that to be associated with gravitational process, and can be related to the recent activity of the Buenaventura Fault Zone.

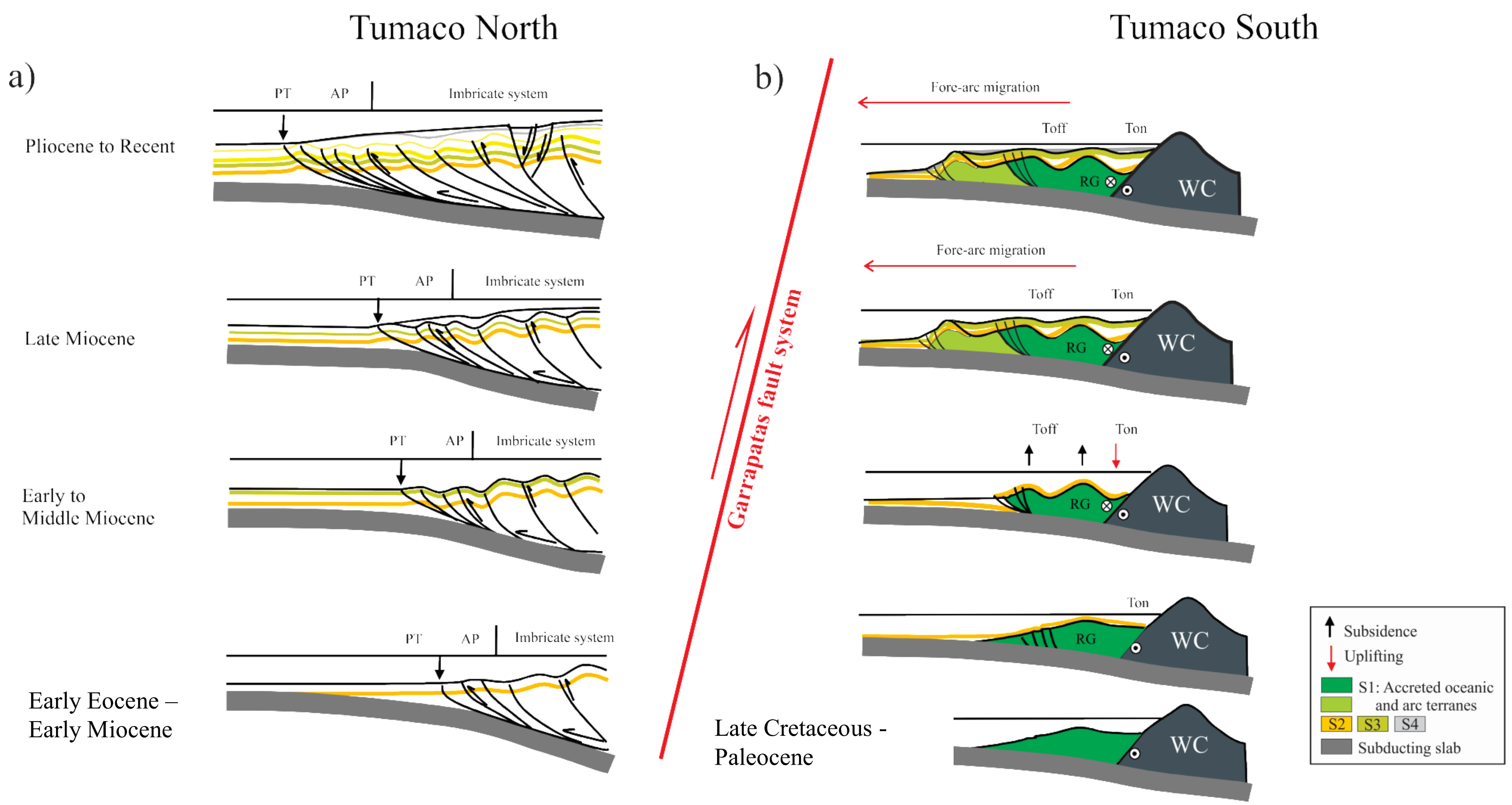

Figure 40. Simplified structural evolution model proposed in this study. a) Structural evolution for the Tumaco offshore basin, northwards Garrapata fault system (GFS) - Tumaco North b) Structural evolution model for the Tumaco on- and offshore basin, south Garrapata fault system (GFS) -Tumaco South. 1) The basement is involved in this model and 2) As the subduction advances and the terranes collides the fore-arc basins migrates eastwards. PT: Pacific trench; AC: Accretionary prism; RG: Remolinogrande high; WC: Western Cordillera; Ton: Tumaco onshore basin and Toff: Tumaco offshore basin.

Hydrocarbon Exploration Implications

SOURCE ROCKS

The mudstones and siltstones of the Unidad Sur-1 Formation which belongs to tectono-sequence II as shown are thought to be the source rocks in the basin. The organic geochemistry analysis done by Robertson Research (1981a), concluded that the Unidad Sur-1 Formation has potential to generate gas. However, the fact that the samples from this unit comes from the Remolinogrande high area and that these rocks are thought to be deposited and buried to deeper depths in the Tumaco onshore basin (**Figure 24**) and some areas in the Tumaco offshore basin (Figure.X) provides reasons to suggest that this unit may be mature enough at higher burial depths allowing the generation of liquid hydrocarbons.

In addition, source rock analysis from the shaly intervals of tectono-sequence III in the Tambora-1, Sandi-1 and Majagua-1 suggest that the main hydrocarbon potential of this sequence is gas related (**Figure 37**), associated with kerogen type III (**Figure 36**) but with a low level of conversion (**Figure 38**).

RESERVOIR ROCKS

The Middle to Late Miocene rocks, which belong to tectono-sequence III-B and III-C are thought to be the main reservoir units of the Tumaco basin. According to the onshore stratigraphic descriptions of these sequences are composed by a sandstones and conglomerates with lithic material deposited in deltaic environments.

TRAPS AND SEAL ROCKS

Based on seismic interpretation, stratigraphic and structural plays types have been identified in the study area as shown in **Figure 41**.

Two main types of structural traps are observed (**Figure 41**). 1) Structural traps associated with normal faulting in the flanks of the Cretaceous basement paleo-highs (Fault family 4) structural traps associated to the older and less deformed thrust and fold belt, near the Buenaventura Bay and related to fault family 6 (**Figure 41**).

Stratigraphic straps:

Mainly found in the northern part of the study area and in the Manglares basin. They are associated with submarine fans and incised canyons of Miocene age, sequence II-B and II C (**Figure 41**).

Figure 30 shows an example of canyon found in the Manglares basin which can be an excellent stratigraphic trap in the study area. Another play type includes Paleogene (?) Turbidites deposited within the depocenter axes of the Manglares basin.

MIGRATION

In the Tumaco onshore basin migration may occur from NWW or SEE, while in the north migration may have occurred from SW or NW filling up traps along the eastern and northern side of the N30°E Gorgona basement complex and in the north, traps west of the Buenaventura Bay, in the surrounding area of the Tambora-1 well (**Figure 41**).

The elongated Gorgona basement complex is likely to have acted as a migration barrier for the hydrocarbons migrating from the Tumaco onshore basin, the Manglares basin and from the north (near the Buenavantura Bay) during the Miocene. This may explain the gas seeps found in the Gorgona basement complex vicinities.

Figure 42 shows the hydrocarbon chart resume of the Tumaco on-and offshore basin.

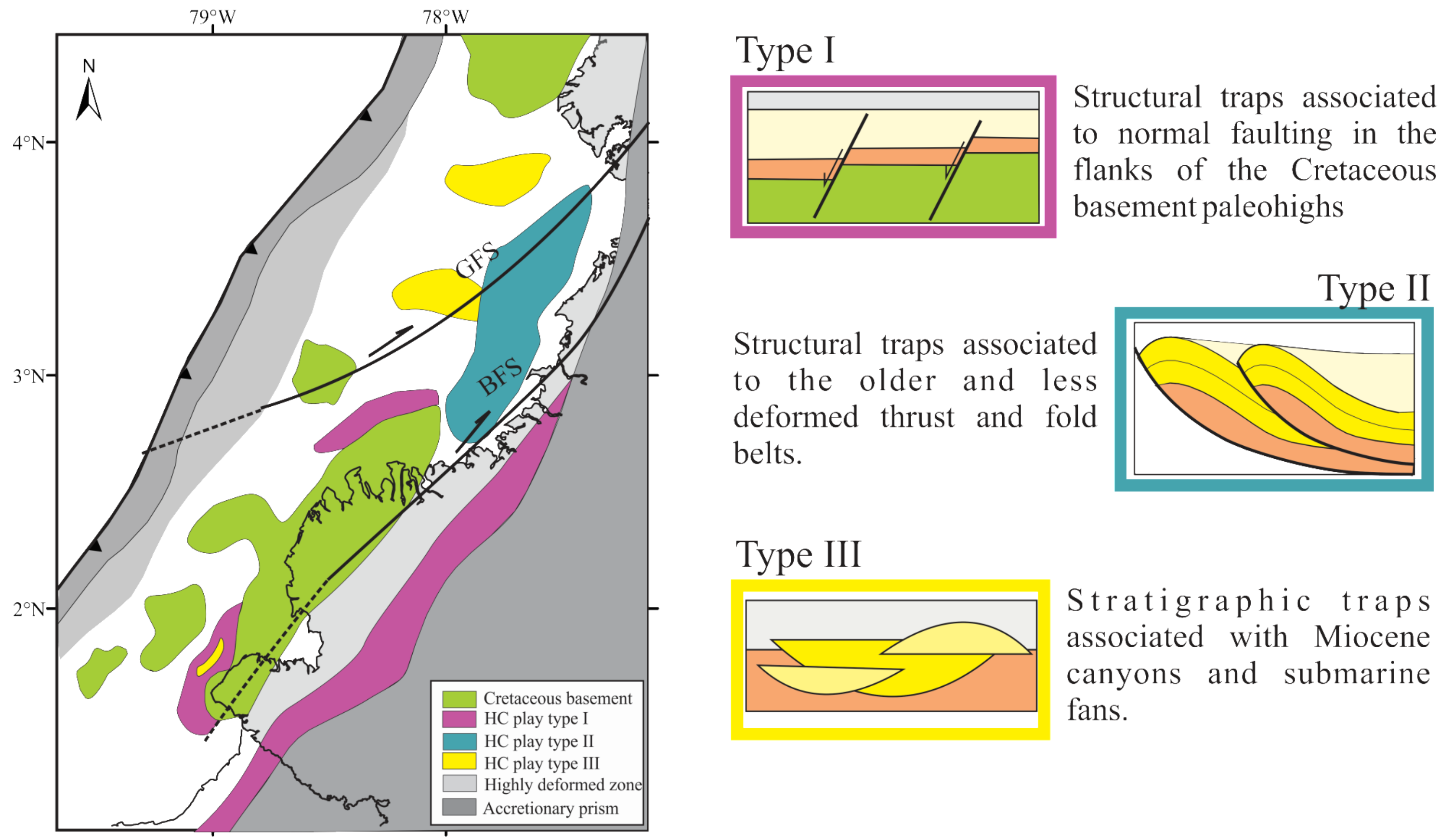

Figure 41. Schematic map of the Tumaco on- and offshore basin showing location of possible hydrocarbon accumulations and type of plays associated to it. Figure based on 2-D seismic interpretation. The figure also show non hydrocarbon prospective areas as the accretionaty prism and the highly deformed zone. HC: Hydrocarbon.

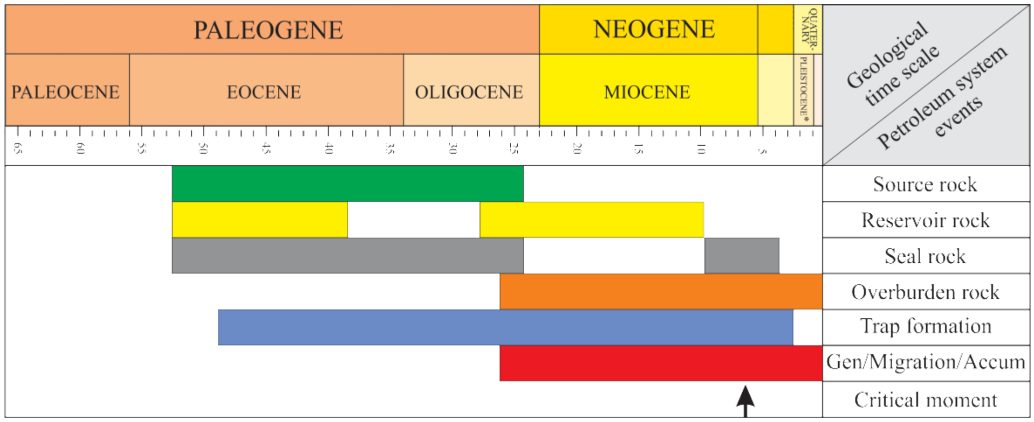

Figure 42. Hydrocarbon events chart summarizing the major petroleum system elements of the Tumaco on- and offshore basin. The critical moment is reached during the Late Miocene when the deposition of the seal rock occurred.

CONCLUSIONS

1. Four main tectono - stratigraphic sequences were interpreted ranging in age from Cretaceous to Recent.
2. Two main structural deformation styles were identified. 1. A thin-skin deformation style, north of the Garrapatas Fault System (GFS) and a thick- skin deformation style, south of GFS - named as Tumaco South.
3. To the south, in the Tumaco south area, it was possible to identify that the fore-arc basins are migrating eastwards as Cretaceous basement "terranes" collides while the subduction of the Nazca plate beneath the South American plate advances.
4. Based on the seismic interpretation and published data it is proposed that the Remolinogrande high is the southern extension of the Gorgona basement and together define a unique terrane which was accreted to the Colombian continental margin during the Late Cretaceous – Paleocene.
5. The source rock evaluation indicates that the main source rocks are the rocks of the Unidad Sur-1 Formation (tectono-sequence II) and the main hydrocarbon potential is gas related.
6. The main potential reservoirs rocks include Early to Middle Miocene sandstones (sequence IIA-IIB) with hydrocarbon plays related to canyons and submarine fans.

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