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Recent sedimentation on northern Venezuela continental margin (central coastal district): imbricated record of climatic instabilities and earthquakes effects (landslides, tsunamis).

Sirel Colón

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THÈSE

Pour obtenir le grade de
**DOCTEUR DE LA COMMUNAUTE UNIVERSITE
GRENOBLE ALPES**

Ecole Doctorale **Terre - Univers – Environnement / TUE**
Arrêté ministériel : 7 août 2006

Présentée par
Sirel COLÓN

Thèse préparée au sein de **L'Institut des Sciences de la Terre (ISTERre)**, U.M.R. C.N.R.S. I.R.D. I.F.S.T.T.A.R.
A l'université Savoie Mont Blanc

La sédimentation récente sur la marge nord-vénézuelienne (littoral central): enregistrement superposé des instabilités d'origine climatique et des conséquences de l'activité sismique (glissements, tsunamis).

Recent sedimentation on the central northern Venezuela margin: combined record of climate – induced instabilities and seismic activity (landslides, tsunamis).

Thèse soutenue publiquement le « **27 Mars 2018** », devant le jury composé de :

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ABSTRACT

The northern South-America margin - i.e. the South-Caribbean margin - represents a main, EW-trending, part of the southern transform boundary of the Caribbean Plate. As the related tectonic activity is seismogenic, a general program of coastal and offshore investigation was developed along northern Venezuela margin. The present study concerns the North-Central part of this margin, from the Triste Gulf (*Golfo Triste*) to Cape Codera (*Cabo Codera*), and is essentially based on a high-resolution seismic survey, an approximately 250 km long and 50 km wide area. This study aimed to follow and complete similar investigations dedicated to the eastern part of the margin, especially the Gulf of Cariaco. The North-Central Venezuela coastal zone is bounded by the steep northern flank of the Coast Range, and almost exactly follows the right-lateral strike slip San Francisco Fault. Thus, the sedimentation along the margin is driven both by surface processes, and by the seismo-tectonic activity. Furthermore, catastrophic climatic events, as the 1999 Vargas flash flood may add specific accumulations.

The obtained seismic reflexion imagery permitted to investigate the Late Pleistocene-Holocene sedimentary cover, with an up to 400 ms penetration. The previously defined morphological subdivision into, from West to East, the Golfo Triste Platform, the Choróní Basin and the Guaira Platform, is confirmed by differences in sedimentation and deformation.

The Choróní basin is a deep depression, which is incised by submarine canyons which seem to be related to turbidity currents with greater flows during the Pleistocene wetter periods. To analyse seismic stratigraphy and subsidence, we focused on the Guaira Platform due to less deformation. Our set of profiles display three regional unconformity-bounded seismostratigraphic units. The two limits were attributed to MIS 2 (Last Glacial Maximum) and MIS 6, based on correlation with published data, especially from the Gulf of Cariaco. Using the global eustatic levels admitted for these two stages, and inferred passed water depth of the corresponding erosion surface, we estimated a 1.2 mm/yr mean subsidence rate.

Concerning active deformation of the imaged sedimentary pile, two contrasted zones have to be separated: 1) the La Guaira Platform slightly deformed along which the The San Sebastián fault shows a unique linear major offset, 2) the Choróní Basin which displays deformations across a broad zone, from the coastal area to the Bonaire Basin edge. For the Choróní Basins, two interpretations are proposed: large deep-seated gravity sliding, shortening component resulting into a flower structure. Along the San Sebastian Fault, local deformation and thick chaotic bodies are discussed in terms of gravity reworking (including climatic influences) *versus* direct tectonic effect.

In addition to the general purpose of the study, special attention was brought to a debate about the origin of the Major 1900 earthquake which stroke northern Venezuela. The previously proposed importance of the La Tortuga Fault and its implication for the mentioned event appear not supported by the new data. This work is here included as a published article.

RESUME

La marge septentrionale de l'Amérique du Sud - i.e. la marge Sud-Caraïbe – représente une partie majeure, d'orientation O-E, de la limite transformante méridionale de la Plaque Caraïbe. En raison de la forte activité tectonique sismogénique associée, un programme d'étude de la marge nord du Vénézuéla a été développé ; il inclut le domaine littoral et le domaine marin de plateforme au large. Le présent travail concerne le tronçon Nord-Central de cette marge, depuis le Golfe Triste (*Golfo Triste*) jusqu'au Cap Codera (*Cabo Codera*), et est essentiellement basée sur une étude en sismique-réflexion, couvrant une zone d'environ 250 km de long (O-E) et 50 km de large (S-N). Cette étude avait pour but de compléter des investigations similaires faites le long de la partie orientale de cette marge, en particulier dans le Golfe de Cariaco. La zone littorale Nord-Vénézuélienne longe le versant septentrional abrupte de la Cordillère Côtière, et suit presque exactement le tracé de la Faille, décrochante dextre, de San Francisco. Aussi, la sédimentation le long de cette bordure est gouvernée à la fois par des processus de surface, et par l'activité sismo-tectonique. De plus, des événements climatiques catastrophiques, comme les « flash flood » de Vargas en 1999, peuvent ajouter des dépôts spécifiques. L'imagerie en sismique-réflexion obtenue a permis d'analyser la couverture sédimentaire du Pléistocène supérieur et de l'Holocène, avec une pénétration atteignant localement 400 ms. Les subdivisions précédemment proposées de la plateforme marine à partir de la morpho-bathymétrie, sont confirmées par des différences dans la sédimentation et la déformation ; il s'agit, d'Ouest en Est : de la Plateforme du Golfe Triste, du Bassin de Choróní, et de la Plateforme de La Guaira. Le Bassin de Choróní est une dépression profonde, qui est incisée par des canyons qui seraient liés à des courants de turbidités avec une forte activité durant les périodes plus humides du Pléistocène. Pour réaliser une analyse en stratigraphie sismique et étudier la subsidence, nous nous sommes concentrés sur la Plateforme de La Guaira en raison de sa plus faible déformation. Notre ensemble de profils montre trois unités sismostratigraphiques limitées par deux discontinuités majeures. Ces dernières ont été attribuées aux MIS 2 (Dernier Maximum Glaciaire) et MIS 6, sur la base de corrélations avec des données publiées, notamment celles concernant le Golfe de Cariaco. En utilisant les valeurs admises pour le niveau marin global durant ces deux périodes, et les paléo-profondeurs postulées pour les surfaces d'érosion correspondantes, nous obtenons un taux de subsidence moyen de 1,2 mm/an. S'agissant de la déformation active affectant la pile sédimentaire étudiée, deux régions très contrastées doivent être séparées : 1) la Plateforme de La Guaira, peu déformée, le long de laquelle la Faille de San Francisco montre une trace majeure unique, 2) le Bassin de Choróní qui montre des déformations dans une large zone, depuis le domaine littoral jusqu'à la bordure méridionale du Bassin de Bonaire. Pour le Bassin de Choróní, deux interprétations sont proposées : un grand glissement à décollement profond, une composante en raccourcissement générant une structure en fleur. Le long de la Faille de San Francisco, la déformation locale et des corps sédimentaires chaotiques sont discutés en termes de remaniements gravitaires (y compris avec des influences climatiques) *versus* des effets tectoniques directs. En ajout au but général de notre étude, une attention particulière a été portée à un débat sur l'origine des séismes destructeurs majeurs qui a affecté le Nord du Vénézuéla en 1990. L'importance de la Faille de La Tortuga et son rôle dans l'événement mentionné n'apparaissent pas confirmés par les nouvelles données. Ce résultat est ajouté au présent mémoire sous la forme d'un article publié.

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Contents

Chapter 1 - Introduction and general purpose.....	1
Chapter 2 - General setting.....	6
2.1. Onshore geology (Central Coast Range).....	6
2.2 Geodynamic and tectonic setting.....	9
2.2.1. Transform fault system between the South American and Caribbean plates.....	9
2.2.2. Bonaire – Falcón Basin.....	11
2.2.3. San Sebastián, La Tortuga and Tacagua - El Ávila active faults.....	13
2.3. Bathymetry.....	15
2.4 Climate.....	17
2.4.1. Paleoclimate setting.....	17
2.4.2. Present-day climate.....	22
2.5. Historical and recent seismicity.....	23
Chapter 3 - High resolution seismic reflection offshore the Northern Venezuela margin: previous data and new acquisition.....	27
3.1. Previously published seismic reflection studies.....	27
3.1.1. Cariaco basin- trough coast seismic studies.....	28
3.1.2. Cabo Codera – Golfo Triste zone.....	34
3.2. The data acquisition 2007 Survey.....	38
3.2.1. Equipment.....	39
3.2.1.1. CENTRIPEDE Sparker.....	40
3.2.1.2. Single channel Streamer (SIG).....	41
3.2.1.3. Navigation and traces recording.....	41
Chapter 4 – Late Quaternary seismic stratigraphy and active structures of the North Venezuelan margin.....	43
4.1 Introduction.....	43
4.2. Seismic stratigraphy and structural interpretation.....	43
4.3. Description of the structure and the fractures.....	48
4.4. Combined Late Quaternary eustatic and tectonic impacts on the Northern Venezuela margin. First results of a high resolution seismic survey	49
4.4.1. Introduction.....	50
4.4.2. Geodynamic and geological setting.....	51
4.4.3. Sea floor morphology.....	54
4.4.4. Methods.....	56
4.4.5. Seismic Stratigraphy.....	56
4.4.5.1. Low-amplitude parallel stratified facies.....	57
4.4.5.2. Prograding clinoforms.....	57
4.4.5.3. High – amplitude parallel reflection.....	63

4.4.5.4. Transparent to very-low-amplitude mounded stratified facies.....	63
4.4.5.5. Chaotic high amplitude.....	65
4.4.6. Erosional unconformities.....	67
4.4.7. Offshore active faults.....	67
4.4.7.1. San Sebastián fault (SSF).....	67
4.4.7.2. La Tortuga fault (LTF)	71
4.7.8. Tentative estimation of mean subsidence of the La Guaira Shelf Interpretation in terms of sea-level changes and.....	73
4.7.9. Conclusion.....	75

Chapter 5 – Instabilities and gravity reworking interpretations....86

5.1 Introduction.....	87
5.2. Geological setting.....	88
5.2.1. Structural and seismotectonic context.....	88
5.2.2. Sea floor morphology.....	89
5.2.3. Morpho-sedimentary context.....	91
5.3. Methods.....	91
5.4. Results	92
5.4.1. Sismostratigraphic instabilities evidences.....	92
5.4.1.1. La Guaira shelf.....	95
5.4.1.2. Choróní basin.....	97
5.5. Discussion and Conclusion.....	100
5.5.1. Relationships between sedimentary/instability processes and structural heritage.....	100
5.5.2. Influence of paleoenvironmental-climatique changes on mass wasting processes.....	101
5.6. Conclusion.....	102

Chapter 6 – The 1900 Mw 7.6 earthquake offshore North-central Venezuela.....107

6.1. Article. The 1900 Mw 7.6 earthquake offshore North-central Venezuela: Is La Tortuga or San Sebastián the source fault?	108
---	-----

Chapter 7 – Conclusions and perspectives.....123

Chapter 8 - References125

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Chapter 1

Introduction and general purpose

Natural phenomena such as earthquakes, tsunamis, landslides, climate changes, etc; can impact severely on human society. The understanding of the nature and recurrence of the geologic process allows a correct evaluation and mitigation of their associated hazards.

The northern margin of Venezuela (Figure 1.1) is then exposed to three natural phenomena: 1) earthquakes and their direct effects (e.g. 1812, 1900 and 1967 historic seism in Caracas) these large earthquakes are mostly generated by large active fault systems, which are in a deformed belt of about 100 km wide, extending from southwest of Táchira with Boconó fault and continues in a northeasterly direction to connect to the San Sebastián fault in the north of Venezuela and then east to the Gulf of Paria with El Pilar fault; 2) tsunamis (linked to the faults in the north of Venezuela, Antilles activity, or submarine landslides), 3) landslides and flashflood, linked to extreme weather events (cf. flash flood Vargas, December 1999). The second and third type of phenomena directly affect both marine sedimentation (littoral and platform) as lagoon or lake. Moreover, the latest global changes (fast) sea levels have been subdivided and structured sedimentary stacking.

This study focuses on the system of San Sebastián fault which run almost completely offshore and very close to the coast in North-central Venezuela. Owing to the large uncertainties on the fault seafloor traces, the Venezuelan Foundation of Seismological research (FUNVISIS) decides in 2007 to acquire a first set of high-resolution shallow seismic profiles (HRP). The first campaign aimed westward to study the Gulf of Cariaco ([Audemard et al., 2007](#); [Van Daele et al., 2007](#); [Van Daele et al., 2011](#)) and the second acquisition correspond to the north central coasts between Cabo Codera and Gulf Triste. This HRP will have a range of sedimentary package observation of the mostly recent deposits nearly 130ka to present and how all process of deformation caused by the principal faults system affected this deposits using sismostratigraphic analysis tools.

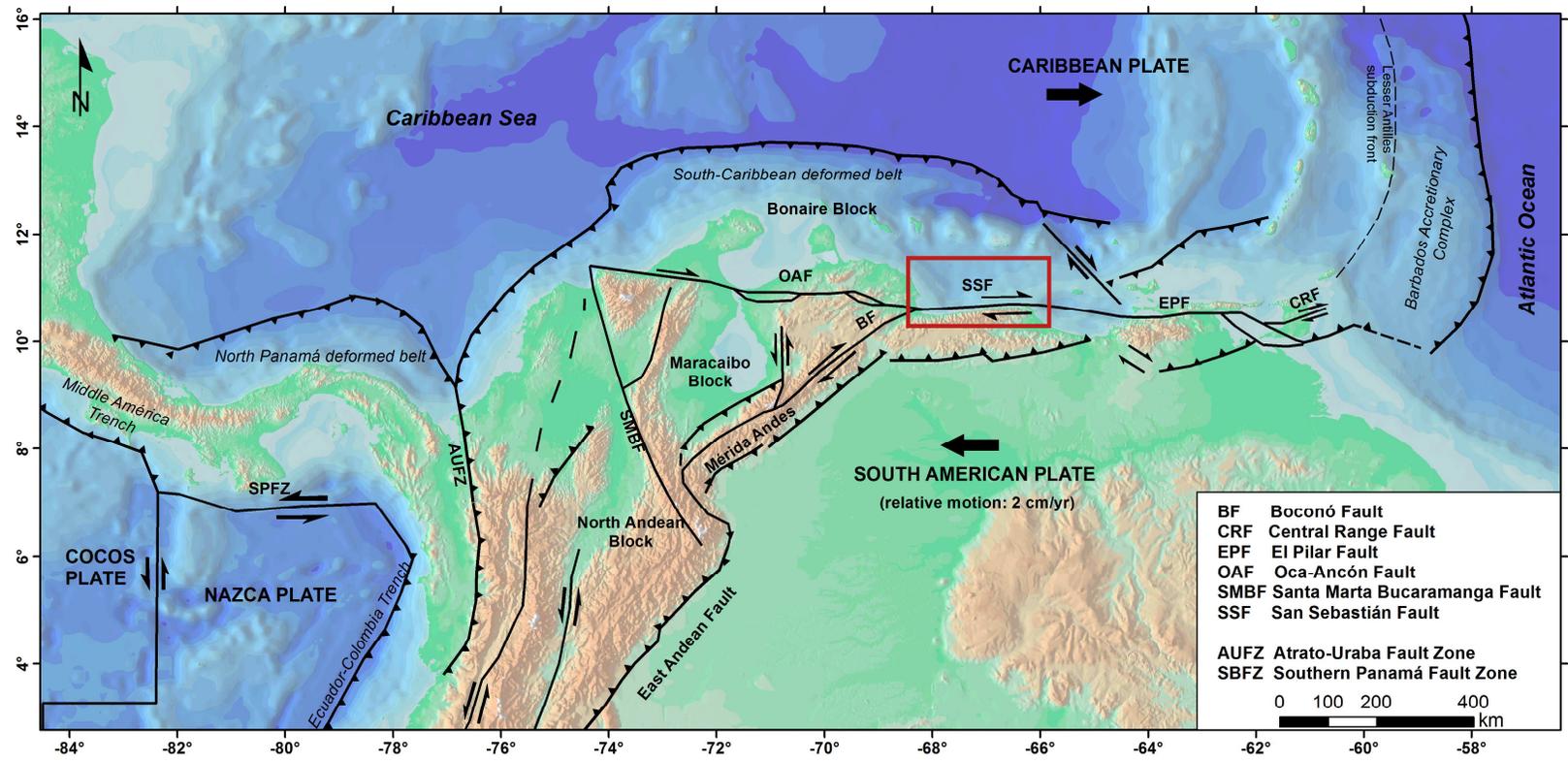


Figure 1.1. Geodynamic map of the southeastern Caribbean (Audemard, 1999b; Audemard et al., 2000; Weber et al., 2001; Trenkamp et al., 2002; Soto et al. 2007). The principal blocks are showing: Bonaire, Maracaibo, and North Andean interacting with the Caribbean, Nazca, and South American plates.

The sismostratigraphic analysis of high resolution profiles allows:

- to identify and characterize the San Sebastián fault and secondary active faults located in the area as well as La Tortuga fault, whose continuation trace in the zone is unclear. The first of these faults have deserved considerable attention because represents the main source of destructive earthquakes.
- to reconstruct the sedimentary process evolution and the influence of change climatic and the eustatic change for the last 130ka.
- to understand the spatial and temporal distribution (for a period of at least about 100,000 years) of major catastrophic events (earthquakes, tsunamis, flash floods) that have been inserted in the most characteristic sedimentation of this margin.
- to evaluate the possible impact of climatic and sismotectonic phenomena and their superposition on the deposits sedimentary as well as probable zones submitted to risk by tsunamis.

Organization of the manuscript

This study comprises general setting chapters, material and methods chapter, two chapters that include manuscripts containing the main results, and a conclusion chapter.

After the introduction I present the **second chapter** related with the general setting chapter, where I made an overview of the geological and geodynamic setting of the plate-boundary zone between Caribbean and South American plates. Because this study covers an important fault (San Sebastian fault) that forms part of this plate limit. In addition, I show the Bathymetry geomorphologic features described by [Sellier de Civrieux, \(1971 and 1977\)](#), [Rial \(1973\)](#), [Picard \(1974\)](#) and [Paolini \(2012\)](#). Paleoclimatic and present day climate setting is incorporated in this chapter with the sea level global and local curves showing the last 130ka eustatic fluctuations. Finally for this chapter, I compiled the important earthquakes generated by north-core offshore faults recorded (e.g. June 11, 1641, March 26, 1812, April 12, 1878, October 29, 1900, July 29, 1967 and the last one on September 12, 2009).

In the **third chapter** I introduce a recompilation of the previous studies made in the north margin of Venezuela related with reflection marine acquisitions with the new data incorporation for the last years. I describes the data used for this study, the methodology of acquisition, materials, software and equipment used and the institutions involved in the acquisition: ISTerre (Former LGCA) and Université de Savoie Mont Blanc (France), Fundación Venezolana de Investigaciones Sismológicas (FUNVISIS), Universidad de Oriente (Venezuela), and Renard Centre of Marine Geology (RCMG) - Universiteit Gent (Belgium).

In the **fourth chapter** I introduce a general idea of Seismic Stratigraphy interpretation and I make a detailed analysis of high seismic-reflection profiles. Here, I document the seismic-stratigraphic signature, geometry, dimensions, and depositional evolution of the north margin of Venezuela. This description was made in function of the different geomorphological features along to the coast, as it shows an important heterogeneity along the margin. Moreover, the actives faults was describes: San Sebastián, La Tortuga and secondary faults. In addition, using a series of sedimentary features, subsidence model and the relative sea level history, I have reconstructed the shelf paleo-bathymetry for the lowstand stages. This has led to propose an estimation for the vertical slip component of the San Sebastián fault. This chapter will be submitted for publication in “Marine Geology” (Colón et al., submitted).

The **fifth chapter** shows a detailed evaluation the instabilities linked to the faults deformation. The shallow deposits are clearly deformed, process dominated by the recent activity of the faults in the margin. This chapter will be submitted for publication in “Marine Geology” (Colón et al., submitted)

In the **sixth chapter** the paleoseismological content of the sedimentary sequences in Eastward north margin of Venezuela is examined using high-resolution seismic. We herein bring strong evidence to support that the San Sebastián fault is the source fault of 1900 major offshore earthquake, mainly based on the freshness of its submarine scarp

and recent fault throw, preserved as depicted in the profiles. This chapter has been published in Marine and petroleum geology ([Colón et al., 2015](#)).

In seventh, the main conclusions of this thesis are summarized and recommendations for future work are given.

Chapter 2

GENERAL SETTINGS

2.1. Onshore geology (Central Coast Range)

The Central Coast Range is an extensive igneous and metamorphic complex geological region in the Venezuela North (Figure 2.1). This region is composed largely of two major east-west trending belts: The Coastal Mountain Range and The Interior Range Napas (Urbani, 2008). This morphology results from rocks composition and tectonic control. The Coastal Mountain Range Napa includes: Costera, Ávila, and Caracas Napas. The Costera and Avila Napas contain a majority assemblage of igneous and metavolcanic rocks accumulated in subduction process and going through to greenschists facies, in Paleozoic and Mesozoic periods. The Caracas Napa is dominated by the Metasedimentary Suite, a regionally metamorphosed assemblage of the shelf and slope facies, in Jurassic- Cretaceous time.

The Interior Range Caucagua-El Tinaco, Loma de Hierro and Villa de Cura Napas are composed of Lower Cretaceous metasediments and igneous rocks accumulated in a tectonically and volcanically active environment. These rocks were metamorphosed to blueschist facies, and deformed by imbricated folds and thrust faults. A precise and comprehensive summary of the metamorphic history of the Central Coast Range is proposed by Urbani (2008).

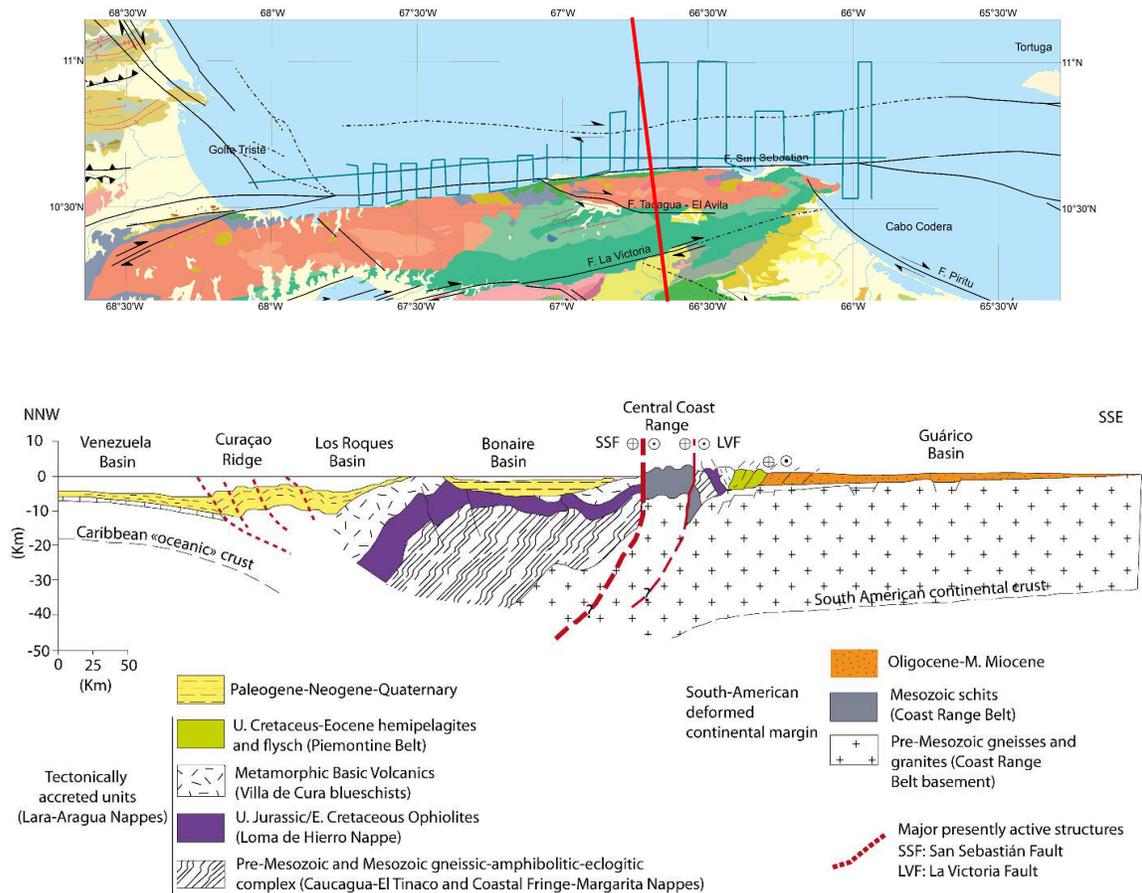


Figure 2.1. Above the geologic base map by Hackley et al. (2005). The color code of geologic units complies with the international nomenclature. Map of Quaternary faults taken from Audemard et al. (2000). Below simplified section (red line on the geologic map) across the southeastern Caribbean margin is based on maps and sections proposed by Bellizzia et al. (1976); Stéphan et al. (1980), Campos (1981), Beck (1986), Chevalier (1987).

Picard and Goddard (1975) describe preserved alluvial fans that flow into the sea with microclimatic origin between Mamo and Cabo Codera in the Pliocene–Pleistocene period. The La Sabana outcrop of the same period is identified as a sequence of heterogeneous torrential conglomerate, limolites and fanglomerate belong to La Playita formation which are tectonically deformed (Léxico Estratigráfico de Venezuela - L.E.V., 1997; Figure 2.2).

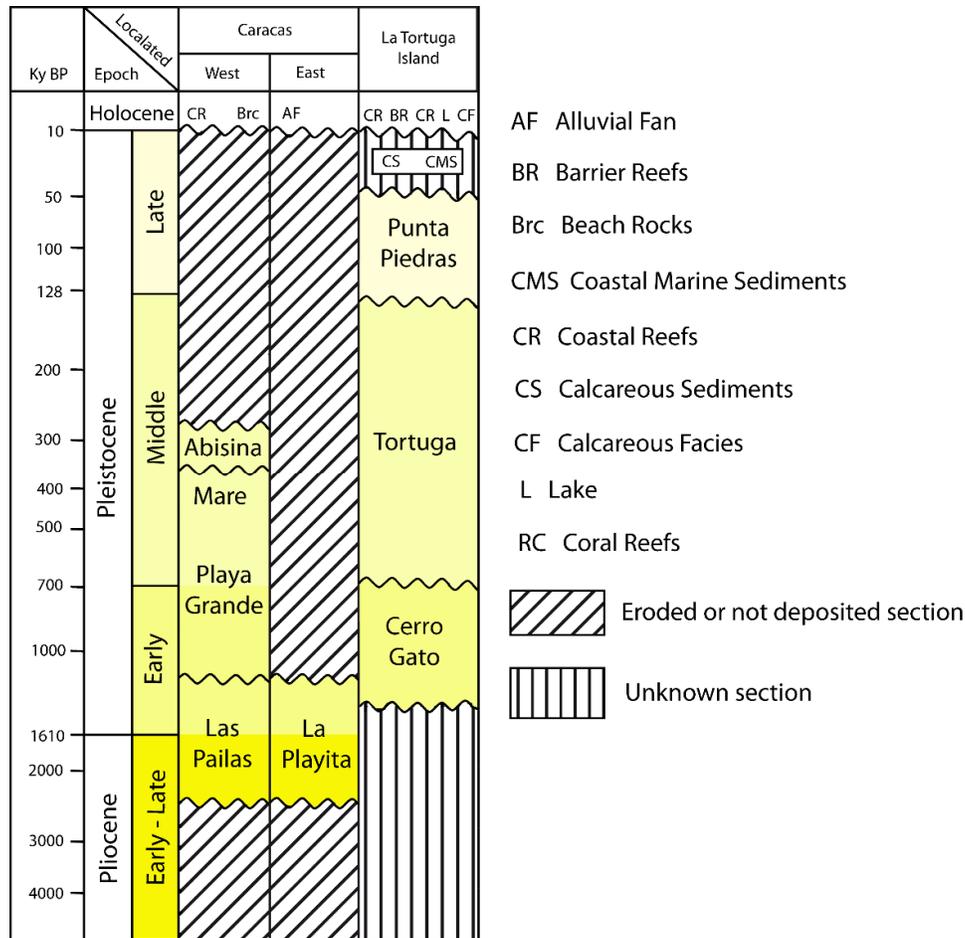


Figure 2.2. Stratigraphic correlation of Quaternary in the Northcentral Venezuelan Coast (Modified of Gonzalez de Juana et al., 1980).

In Cabo Blanco region, Las Pailas Formation (Inferior formation-Cabo Blanco Group) represents the transition from Pliocene to Pleistocene period. This formation presents at the bottom: silty clays, silts, and fine-grained sandstones intercalated with coarse-grained sandstones and conglomerates. The conglomerate and coarse-grained sandstones dominate the top of the formation (Picard and Goddard, 1975).

The Early Pleistocene is represented by the Playa Grande formation – Cabo Blanco Group located in the Cabo Blanco region. The Playa Grande formation shows an angular discordance with Las Pailas formation (Figure 2.2). Maiquetia and Catia Members of the Playa Grande formation present similar basal facies with the Las Pailas formation, but in Playa Grande Formation the beds are intercalated with micro and macro fossils and some calcareous beds (Picard and Goddard, 1975). The Catia Member composed of basal

conglomerated suggests fluvial sediment accumulation of the metasedimentary sequence of Caracas Group. This sediment was reworked in the shorelines (L.E.V., 1997). The Cerro Gato Formation in the Tortuga Island, included in the Early Pleistocene, shows a similar fossil content and stratigraphic features than Playa Grande Formation (Macsotay and Caraballo, 1976).

Mare Formation (Cabo Blanco Group) that belongs to the Middle- Pleistocene period begins in at the base with gravel upward gradation alternating with fine-grained sandstones and ends with a silt sequence. This facies suggests a continental ambient with alluvial fan where the gravel filled the shoreline with active reworking. At the top, the sequence shows features of depth sea to open shelf ambient (L.E.V., 1997). The Abisina Formation that overlies the Mare formation, consists of fossiliferous shales, silty clays, and gravels. The mollusks indicate an age of 300ky corresponding with the last interglacial of Middle Pleistocene (L.E.V., 1997).

The Tortuga Formation in La Tortuga Island is composed of two marine terraces developed in a reefal environment, and showing coralline limestone facies. The oldest upper terrace is formed by porous bioclastic limestone, with coral fragments, Foraminiferas, Pelycipods, and Echinoids spines. The lower terrace, called the Member Punta Piedra corresponds to reefal limestones. (Macsotay and Moore, 1974).

2.2 Geodynamic and Tectonic setting

2.2.1. Transform fault system between the South American and Caribbean plates

The Caribbean–South America Plate boundary from Colombia to Trinidad is over a 100 km wide active zone on and offshore northern Venezuela, where the geodynamic configuration results from a complex and evolving transpressive history (Audemard 1993; Singer & Audemard 1997; Stéphan, 1985; Stéphan et al., 1990; Pindell et al., 1988; Audemard et al. 2000, 2005; Ysaccis et al. 2000) that has occurred throughout the Tertiary and Quaternary (Audemard et al., 2005).

The boundary zone exhibits strain partitioning from the Mérida Andes in the west to the Interior range in the east (Figure 2.3). In the Andes, partitioning occurs between the dextral Boconó Fault and thrust faults on both mountain flanks (Audemard & Audemard 2002). The north-central Coastal Range also exhibits strain partitioning. Dextral slip occurs in the core along the San Sebastián, La Victoria faults and minor synthetic Riedel

shears while transverse shortening is accommodated by frontal thrust faults in the south (Audemard, 1999). A sub-sea, mirror thrust fault system may exist to the north and the easternmost portion of the Leeward Antilles Subduction zone must account for some shortening as well. Farther east, strain partitioning involves NNW– SSE-trending shortening over a 250 km wide zone from north of La Blanquilla to the active thrust front of the Interior Range. Slab detachment (Russo & Speed 1992; Russo 1999) associated with an incipient A-subduction, results in the largest onshore negative Bouguer anomaly in the world, south of the Interior Range. Dextral slip concurrently occurs along the main east–west striking El Pilar Fault and along the NW–SE striking Los Bajos– El Soldado faults and minor parallel and/or synthetic Riedel shear faults. Partitioning might also occur on Trinidad (Audemard, 2009).

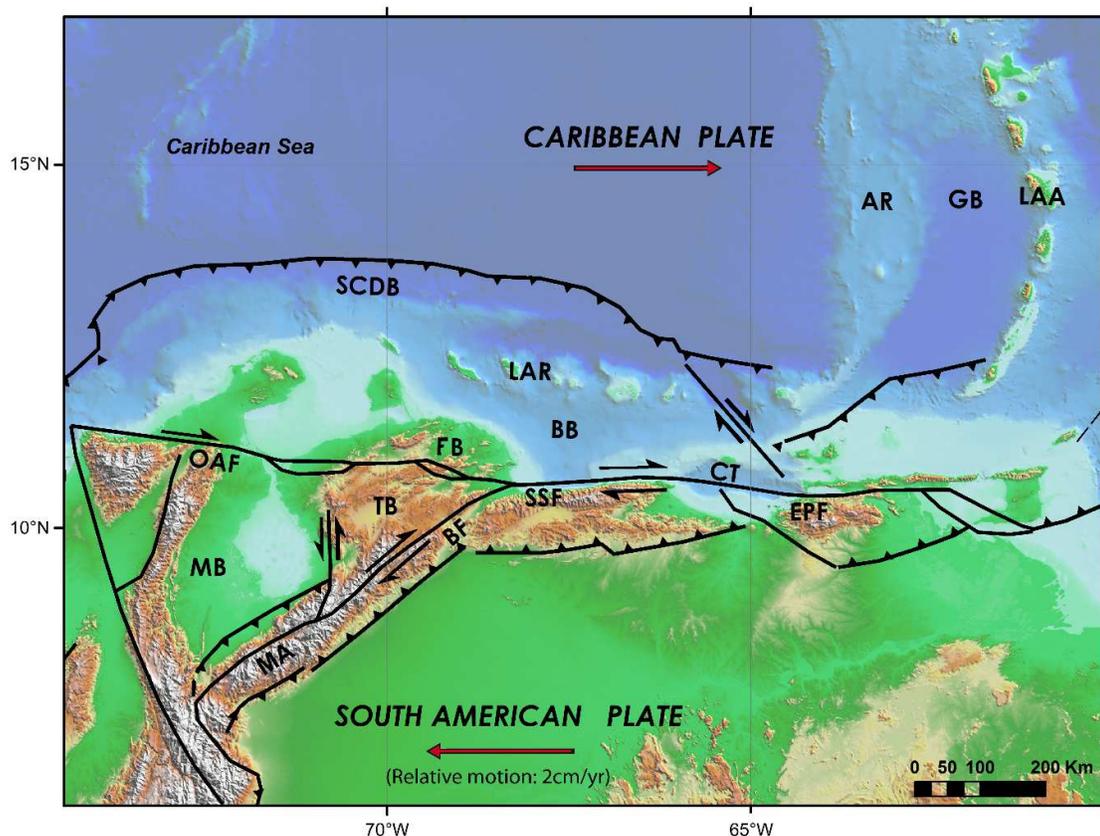


Figure 2.3. Present day geodynamic setting of the North-Venezuela margin along the transform boundary between the Caribbean Plate and South American Plate (Audemard 1999b; Audemard et al., 2000; Webber et al., 2001; Trenkamp et al., 2002). Tectonic Provinces - AR: Aves Ridge; GB: Granada Basin; LAA: Leseer Antilles Arc; SCDB South Caribbean Deformed Belt; LAR: Leeward Antilles Ridge; FB: Falcón Basin; BB: Bonaire Basin; CT: Cariaco Trough; MB: Maracaibo Block; TB: Trujillo Block; MA:

Mérida Andes. Quaternary faults - BF: Boconó Fault; OAF: Oca-Ancón Fault; SSF: San Sebastián Fault; EPF: El Pilar Fault.

The major part of present day dextral slip along the southern Caribbean boundary appears to be accommodated by the major Boconó–San Sebastián–El Pilar– Los Bajos–Warm Spring fault system where geological and geodetic data indicate slip rate of 8–10 mm/yr (Audemard, 2009). Several authors have predicted that the Caribbean Plate moves east at about 20 mm/annum relative to South America (Jordan 1975; Rosencrantz et al. 1988; Stein et al. 1988; Calais et al. 1992) and GPS studies have confirmed this (Pérez et al. 2001a, b; Weber et al. 2001; Trenkamp et al. 2002)(Figure 2.3). In the east, dextral slip along the plate boundary transfers to subduction in the Lesser Antilles.

2.2.2. Bonaire – Falcón Basin

The Bonaire basin is an elongate depression extending south of leeward Antilles islands from Curaçao to La Orchila (Silver et al., 1975) northward edge, and Cordillera de la Costa high and La Guaira Shelf southward ending. The Falcón basin, present-day inverted anticlinorium trending ENE-WSW, is a westward extension of the Bonaire basin (Silver et al., 1975, Case et al., 1984, Audemard 1993, 2001) forming Bonaire – Falcón basin. Two tectonic models are proposed for the origin of this basin (Figure 2.4): (1) pull-apart model suggests approximately 200 km wide east-west trending dextral faults stepover in the late Eocene – Oligocene, between the Oca Ancon and San Sebastián faults to the south and the South Caribbean deformed belt to the north (Stephan 1982, 1985; Pindell and Dewey, 1982; Muessing, 1984; Macelari, 1995) and (2) back arc basin model proposes extensional opening in the Late Eocene, of an east-west–trending back-arc basin in a subduction setting associated with the Great Arc of the Caribbean (Soulas et al., 1987; Audemard, 1993, 1995, 1997; Mann, 1999; Porras, 2000; Bezada et al., 2008, Audemard, 2009).

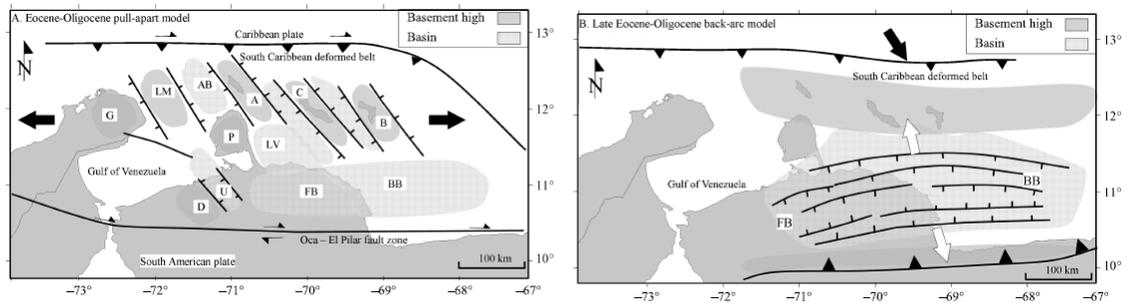


Figure 2.4. (A) Pull-apart model for Falcón and Bonaire region of northwestern Venezuela illustrating the distribution of Eocene–Oligocene highs and sub-basins. Northwest-striking normal faults control regional subsidence of deep-marine basins separated by emergent or shallow-water highs. (B) Paleocene–Eocene back-arc basin opening model for the Falcón and western Bonaire basins. East-west–striking normal faults time control the initial north-south basin opening during the Eocene–Oligocene, whereas the Leeward Antilles ridge remains a stable emerging or shallow-water high flanking the basin to the north. **Abbreviations:** A = Aruba; AB = Aruba Basin; B = Bonaire; BB = Bonaire Basin; C = Curaçao; D = Dabajuro high; FB = Falcón Basin; G = Guajira Peninsula; LM = Los Monjes islands; LV = La Vela Bay; P = Paraguaná Peninsula; U = Urumaco trough. (Modified of [Gorney et al., 2007](#)).

The Bonaire - Falcón evolution is described in four tectonic phases ([Porrás, 2000](#); [Gorney et al., 2007](#); [Paolini, 2012](#)): (1) Intra - arc extension: Caribbean plate slid around the northwest corner of South America and progressed eastward across Paleogene reaching the Bonaire - Falcón basin in the Eocene. The beginning of an extensional produced grabens and half grabens structures ([Porrás, 2000](#)), with higher energy reef and shelfal energy deposits accumulated in the basin flanks whereas lower energy marine deposits in the central basin ([Gourney et al., 2007](#)). Eocene south fluvio-deltaic depositional environment in the Golfo Triste becomes deep-marine setting in the north that suggest south-north sedimentation from La Cordillera de La Costa. Deposits are controlled by west-east striking normal faults ([Gourney et al., 2007](#), [Paolini, 2012](#)). (2) Transtension: The Bonaire - Falcón basin subsided strongly in the Oligocene - Early Miocene ([Gourney et al., 2007](#), [Audemard, 2009](#)). W-E to SW-NE-striking normal faults defined the central basin ([Porrás, 2000](#); [Gourney et al., 2007](#); [Escalona et al., 2011](#)). This regime created rifts that segmented the Leeward Antilles ridge (e.g. Aruba, West Curaçao, and East Curaçao). These basins accumulated thick, deep-water deposits derived from the South American craton ([Gourney et al., 2007](#)) and faults associated became SW-NE eastward (e.g. La Guaira shelf) ([Porrás, 2000](#)). (3) Transpression: The onset of inversion

of the Falcón Basin occurred in the middle Miocene (Audemard, 2001). Falcón inversion has been attributed to: (a) strain partitioning produced by the Andean orogeny (James, 2000); (b) a combination of North America and South America convergence since at least the middle Eocene and complex oblique deformation between the Caribbean and South American plates, resulting in transpression (Audemard, 2001; Audemard et al., 2005); and (c) deformation related to shallow subduction of the Caribbean slab (Kellogg, 1984; Van der Hilst and Mann, 1994). During middle Miocene, faults in the Falcón basin and faults closer to major E–W-striking strike-slip faults in the Bonaire basin were reactivated as high angle reverse and strike-slip faults (Gorney et al., 2007). As the inversion of Falcón progressed from southwest to northeast during the late early–middle Miocene, the eastern Falcón Basin and the rest of offshore northwestern Venezuela remained active sites of basinal deposition (Audemard, 2001). Porras (2000) proposed gravitational instability in Early Pliocene, induced by inversion and uplift of the Falcón Basin like results in a thin-skinned toe-thrust–style deformation in the La Vela fold-thrust belt. (4) Transtension – Transpression: Dextral trending in the south boundary assumed their present configuration and took place in the Pliocene (Audemard, 2009). This regime brought contemporaneous structures associated with transtension and transpression effects (Porras, 2000). The eastward motion of the Caribbean plate continues at a rate of 20mm/yr today (DeMets et al., 2000; Pérez et al., 2001).

2.2.3. San Sebastián, La Tortuga and Tacagua - El Ávila active faults

San Sebastián fault (SSF) runs nearly 500-km-long offshore along the north-central coast of Venezuela, bounding (on the north) the green schist metamorphic rocks of the Coast Range belt (Audemard 2000; Figure 2.3). This fault only crops out for a very short distance at the Caracas International Airport, where it is known as the Bruscas fault. In this area, the fault brings Miocene-Pliocene marine sedimentary rocks to the surface. Little is known about the age or activity rates of the SSF. At the moment, FUNVISIS is investigating recent paleoseismicity by mean of trenches. Towards the east, the connection with El Pilar fault along this series of strike-slip fault systems is realized across the Cariaco Basin, a 1200-m-deep pull-apart basin (Audemard et al., 2007). To the west the Cabudare to Morón section of the Boconó fault system connects to the east-west trending, predominately offshore SSF after undergoing a 45° clockwise bend. This bend

is responsible for the formation of the Yaracuy basin, although this basin was previously proposed to have a pull-apart origin (Audemard et al., 2000). The SSF ends westward in the Gulf Triste (Schubert & Krause 1984, Silver et al. 1975; Gonzales et al. 1980). The SSF appears to be a major tectonic boundary not only from the geodynamic and geodetic viewpoints, but also from a geophysical perspective. Magnani et al. (2009), from wide angle data are able to image the deep structure of North-central Venezuela at 67° W longitude (Caracas and Maiquetía longitude), as well as the attitude of SFF at depth (Figure 2.5). This fault appears to juxtapose a thick sedimentary package on the north, corresponding to the Neogene fill of the Bonaire basin, against the igneous-metamorphic nappes outcropping south of the SSF in the Coast range, as attested by their preferred velocity model. Here, the fault dips north at depth, which would support that this fault may well reflect an important tectonic inheritance. The SSF might have been a major extensional feature during the phase of orogenic collapse as proposed by Audemard (1993; 1998; 2009), responsible for the opening of several basins along the southern edge of the overriding Caribbean plate in the Late Eocene and Oligocene, among which the Falcón-Bonaire basin deserves mention.

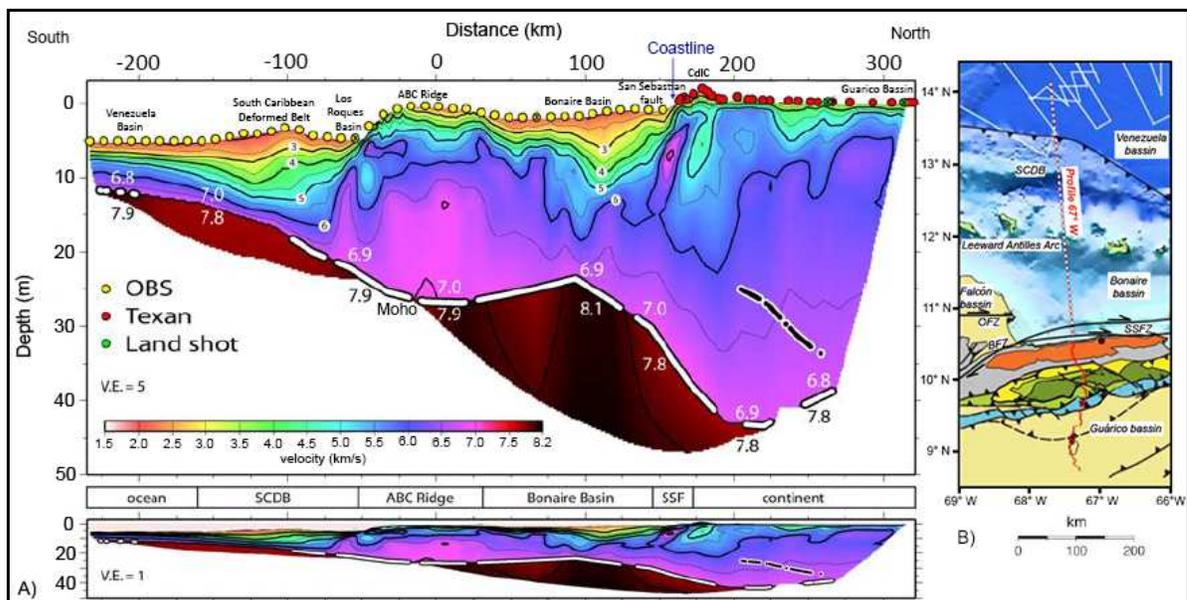


Figure 2.5. A) Velocity model and B) map of the area along profile 67°W modified of Magnani et al., (2009).

Beside, La Tortuga fault is a dextral strike-slip inferred fault (Figure 2.6), located parallel to and northward of SSF (Beltrán, 1993, Hernandez, 2009), however Paolini (2012) from deep seismic reflexion 2D profiles not found evidence of westward continuity of this fault. The Tacagua - El Avila fault system crosses the Coast Range of northern Venezuela in NW-SE trending (Figure 2.6). It is exclusively within the Coast Range belt, mainly cutting Mesozoic green schist meta-sedimentary rocks emplaced during the oblique collision of the proto-Caribbean arc and the South America passive margin. This fault system extends southeasterly from the Arrecife village (on the coast) to Araira village. The system bounds the Caracas and Guarenas-Guatire depressions on the north (Audemard et al., 2000). Rial (1973) suggested an extension northwestward offshore of this fault.

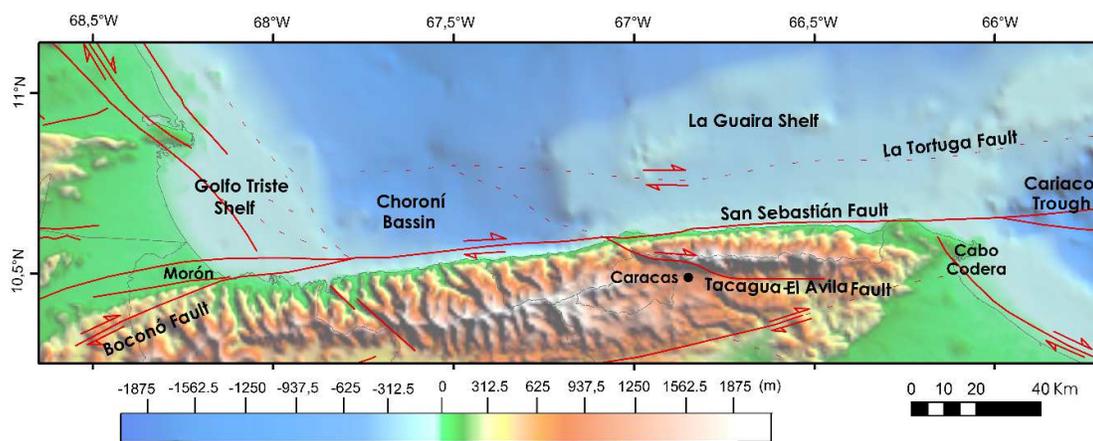


Figure 2.6. Bathymetry of the North of Venezuela (modified of Sellier de Civrieux, 1971). Topographic map surrounding onshore areas is based on SRMT30 and principal quaternary faults in the study area from Audemard et al. (2000).

2.3. Bathymetry

The continental shelf between Cabo Codera to Golfo Triste (Figure 2.6) shows an average of about 360 m depth shelf break. Based on the assumption that the modern ocean averages 130m of depth shelf break (Boggs, 2011), the Cabo Codera-Golfo Triste continental shelf is partially or completely structurally controlled, which suggest a major subsidence in certain marine zone contrasting with the stability of contiguous areas (Sellier de Civrieux, 1971).

Sellier de Civrieux, (1977) distinguishes, from east to west, three physiographic provinces: La Guaira Platform, Choroní Basin and Platform of Golfo Triste (Figure 2.7). The two mentioned platforms are erosional type and they are separated by Choroní basin, which this author describes as a deep depression Graben aspect, almost absent continental shelf with submarine canyons. The continental shelf of La Guaira platform extends to 360 m with a wide, gently and continuously sloping submarine plain down, which steeper between 0 and 200m. Three plateaus are interrupted abruptly rising from the bottom of the submerged plain (La Guaira, Los Caracas and Caruao) (Sellier de Civrieux, 1977; Paolini, 2012; Figure 2.6). The boundary with Bonaire basin corresponds to normal faults in the basement, allowing a south – north depth abrupt change since the continental shelf to the Bonaire Basin (Paolini, 2012). Westward, the zone of greatest subsidence seems to be the Choroní basin with almost nonexistent continental shelf. This depression is connected to the north with Bonaire Basin. The two well-characterized canyons have a close relationship with the current in the Serrania Del Litoral. Eastward of the Choroní basin, the Mamo river mouth discharges into the Canyon of Mamo, which is tectonically controlled by the northeast-seaward extension of the Tacagua-El Avila faults (Civrieux Sellier 1971; Rial, 1973). West of Choroní basin is located the Ocumare Canyon, in which discharge sediments of the Ocumare River (and perhaps the Cata River). These two submarine canyons join in the center of the basin to form a new canyon: "A" canyon which is directed north-seaward, connecting Choroní and Bonaire Basin (Sellier de Civrieux, 1971). Apparently, these canyons seem to be related to turbidity currents of the rivers which were carried out during the Pleistocene pluvial periods. Westward Choroní basin, the continental shelf in Golfo Triste Platform shows a shelf break at 170 m and 30 km wide. Sellier de Civrieux, (1977) observed three preserved submarine terrace levels on outer shelf which represents paleo shorelines. The deepest terrace is 146 m, above 133 m and finally 90 m. The second submarine terrace is related to Wisconsin shoreline (Sellier de Civrieux, 1977).

Picard (1974) described and classified coastal cliffs of the coast range into two sections: one west of Chichiriviche consisting in submerged cliffs up to 200 m, and one to the east of Chichiriviche cliffs formed by erosion platform tectonism possibly stable or slightly positive. Western cliffs (Puerto Cabello - Chichiriviche) were subdivided by the author in two parts: Cata section (Puerto Cabello - Chuao) with subsidence between 2 and 10 m,

and Puerto La Cruz section (Chuaó - Chichiriviche) with subsidence of up to 200m. This implies a slight subsidence western, central zone and a pronounced subsidence east (Eastward Chichiriviche) stable, or even rising. The continental shelf has been depressed apparently more pronounced (Sellier de Civrieux, 1973) calculated between 180m and 300m over.

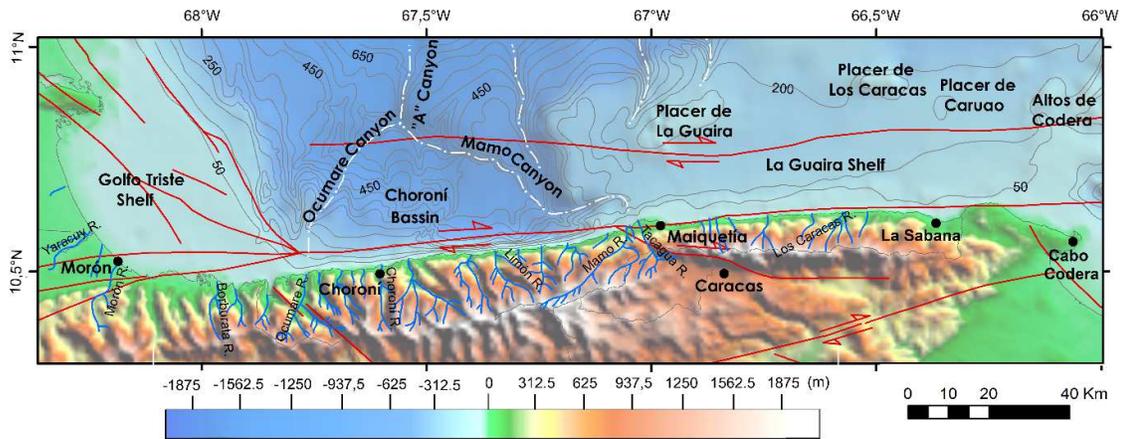


Figure 2.7. Offshore geomorphology of the North of Venezuela (modified of Sellier de Civrieux, 1971) that shows in white lines canyons and Placeres on the La Guaira shelf. Topographic map surrounding onshore areas is based on SRMT30.

2.4 Climate

2.4.1. Paleoclimate setting

Venezuela has a number of localities that have provided paleoenvironmental sequences in the Neotropical, the circum-Caribbean domain, such as the Cariaco basin, Lake Valencia, the Mérida Andes, and the Guayana region. At present, the most important area for Venezuela paleoclimatic investigations is the Gulf of Cariaco. Due to its anoxic conditions and biogenic sedimentation with deposition of seasonal laminations, the Cariaco Basin contains a uniquely preserved, high-resolution, sedimentary record of oceanographic and climatic history in the Caribbean region, influenced by latitudinal shifts of the ITCZ (Hughen et al., 2000, 1996; Peterson et al., 2000b; Haug et al., 2001; Lea et al., 2003; González et al., 2008).

Palynological and geochemical analysis of the marine and terrestrial record of this basin has been used for the reconstruction of climate variability for the last ~90 ka. High-

resolution reflectance measurements of the interval 60–25 ka BP (Figure 2.8), corresponding to MIS 3 (Marine Isotopic Stage 3), have documented the abrupt stadial-interstadial shifts that characterized the Dansgaard-Oeschger (D/O) cycles and Heinrich Events (HEs) described in North Atlantic marine cores and Greenland ice records (Hughen et al., 2004). Interstadials are characterized by enhanced marine productivity, and increased precipitation and river discharge (as deduced from the elevated Ti and Fe content), as well as expansion of semi-deciduous forests; while stadials show the opposite trends (Peterson et al. 2000a, 2000b; Haug et al., 2001; Peterson and Haug, 2006; Gonzalez et al., 2008). Furthermore, during stadials, the enhanced orographic precipitation probably caused by strongest upward winds promoted the expansion of mountain forests (González et al., 2008). Heinrich events are characterized by lighter sediments and lower terrigenous input, and are almost indistinguishable from stadials (Haug et al. 2001; Peterson and Haug 2006). However, HEs vegetation is clearly different and characterized by abrupt expansion of coastal salt-marsh vegetation, coinciding with peaks of carbon isotopes measured in leaf waxes (Gonzalez et al., 2008).

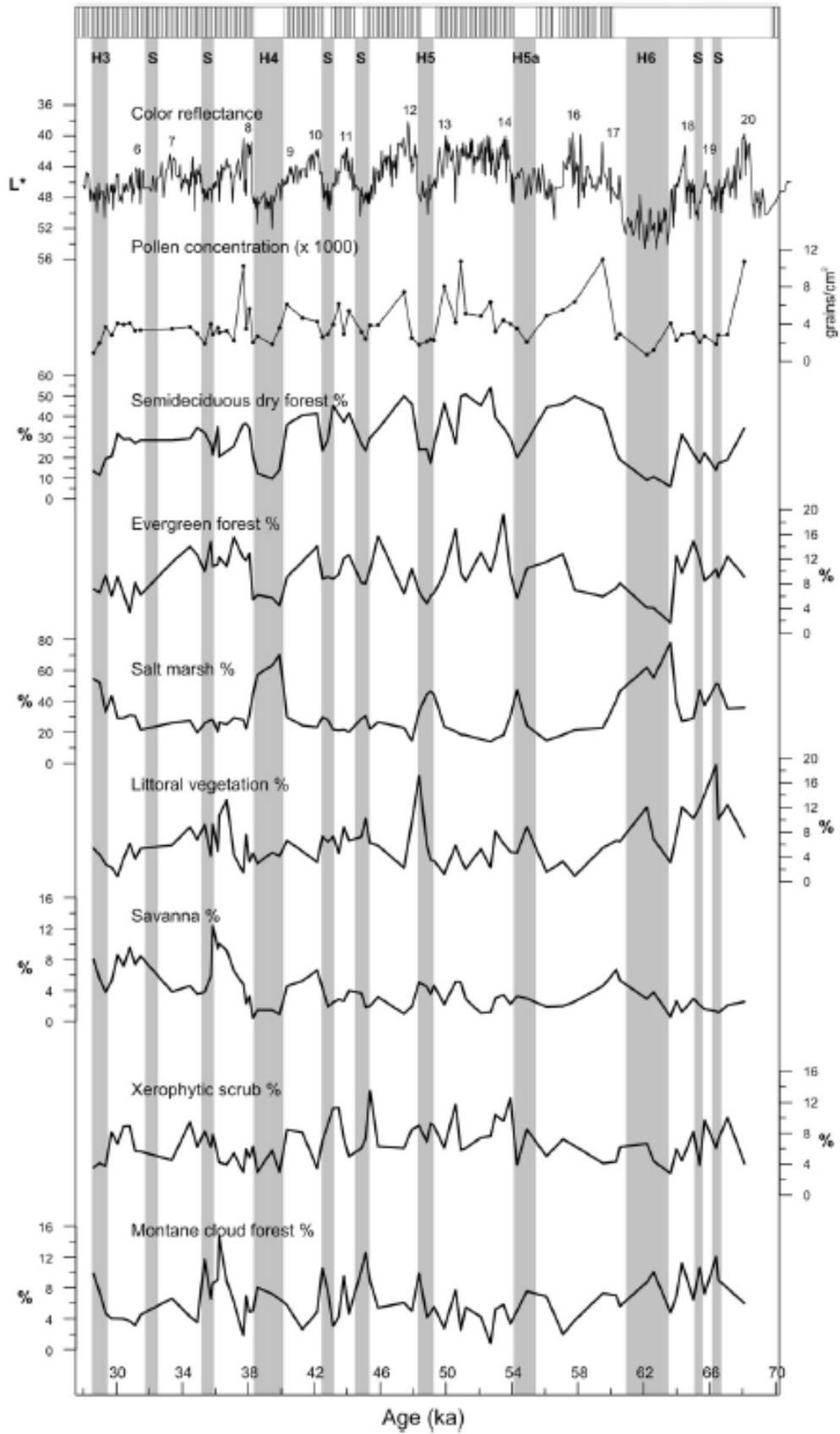


Figure 2.8. Downcore trends of vegetation change in the Cariaco Basin, comparing the color reflectance curve with the variations of C4/C3 ratios (log scaled), the relative abundance of the fungus *Tetraploa aristata*, the percentages of grains filled with pyrite, and the scores of the first CA ordination axis performed with the vegetation groups (Gonzalez et al., 2008).

In the LGM Cariaco Basin sea surface conditions (Clark et al., 2009), are documented cool (Lea et al. 2003), and the Younger Dryas (Muscheler et al., 2008) have been also documented in the Cariaco sea surface temperature reconstruction as cooling and dry periods, occurring between 23 and 21 cal ka BP and 13 and 11.8 cal ka BP, respectively (Figure 2.9). The last one was followed by a period of increased precipitation and riverine discharge that occurred during the Holocene thermal maximum (10.50 to 5.40 cal ka BP) (Haug et al. 2001; Lea et al., 2003; Hughen et al., 2004). Based on the previous results, the Cariaco paleoclimatologists concluded that the climate record of the Cariaco Basin is closely synchronized with the climatic events in the Northern hemisphere even with the rapid climate changes as D/O cycles and Heinrich events.

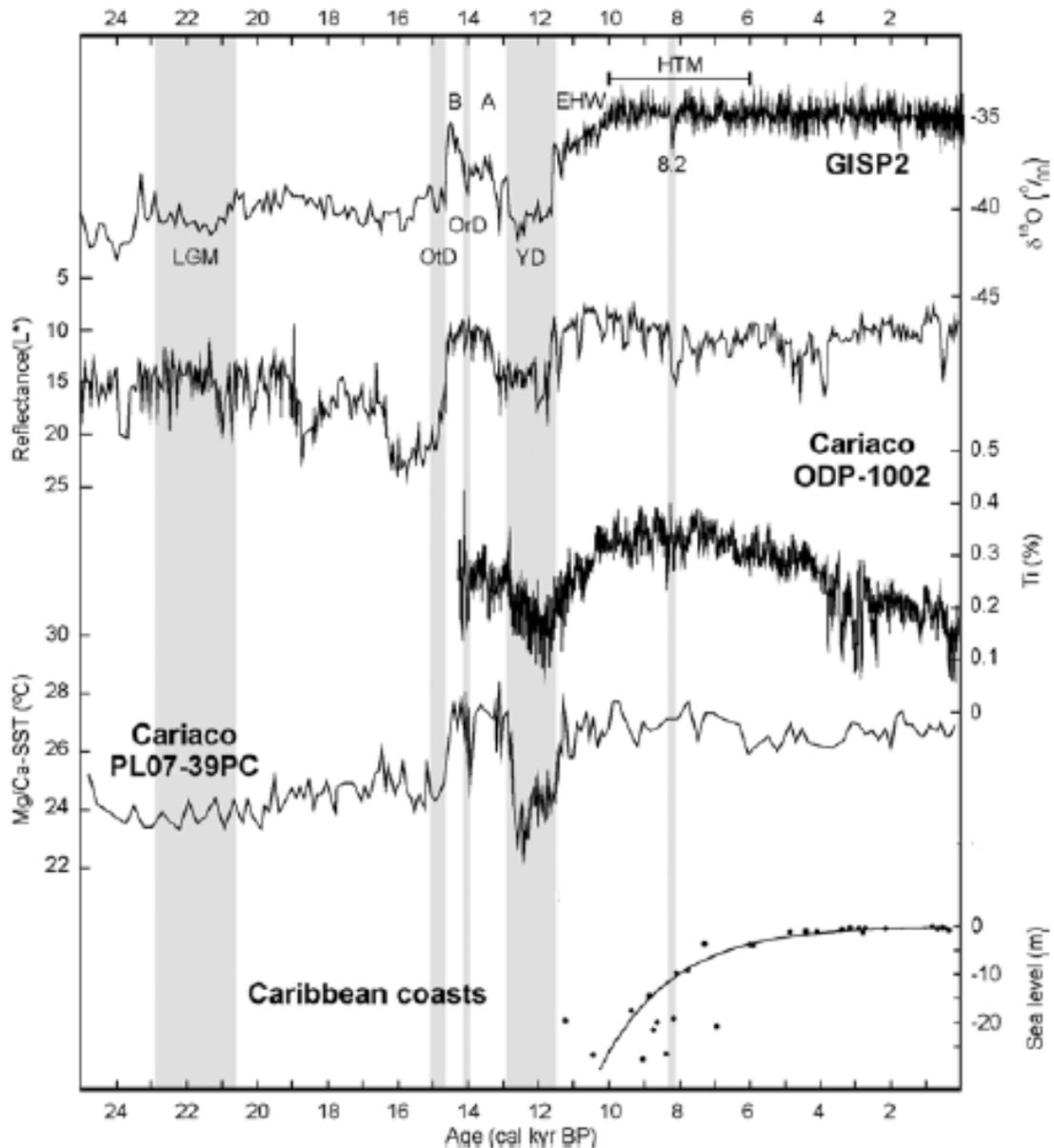


Figure 2.9. Summary of paleoclimate data since the LGM to the present, in Cariaco basin (from [Rull et al., 2010](#)). The oxygen-isotopic curve of the Greenland GISP2 ice core is shown for reference. Stadials and interstadials are from [Stuiver et al. \(1995\)](#): (B) Bølling; (A) Allerød; (OtD) Oldest Dryas; (OrD) Older Dryas; (YD) Younger Dryas. Early Holocene warming (EHW) and Holocene thermal maximum (HTM) according to [Haug et al. \(2001\)](#), [Björck et al. \(2002\)](#), [Kaufman et al. \(2004\)](#), and [Kaplan and Wolfe \(2006\)](#).

Additionally, [Van Daele et al. \(2011\)](#) from seismostratigraphic analysis proposed a sea/lake level curve for the last ~130 ka of the Gulf of Cariaco (200 km eastward to the Cariaco basin). The good fit of this curve with the eustatic sea-level curves ([Waelbroeck](#)

et al., 2002; Siddall et al., 2003) both in terms of amplitude and of timing suggests that this curve respond to regional climatic variation, and therefore can be used as a paleoclimatic proxy (Figure 2.10). An eustatic curve for the last 120 ka BP was constructed by Van Daele et al., (2012).

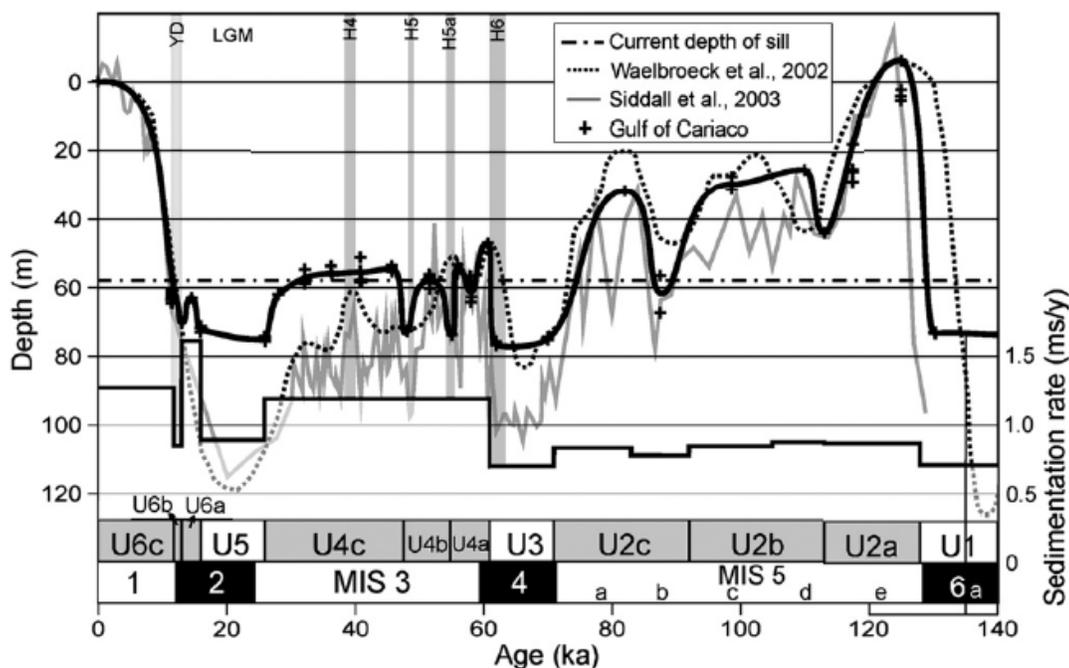


Figure 2.10. Sea/lake level curve for the last ~130 ka of the Gulf of Cariaco proposed by Van Daele et al. (2011). This curve is adjusted to the eustatic sea level curve (Waelbroeck et al., 2002; Siddall et al., 2003) and to Marine isotope Stages (MIS 2–MIS 4). Including the Heinrich Events (HE) recorded in the Cariaco Basin (Hughen et al., 2004; González et al., 2008).

2.4.1. Present-day climate

Venezuela has a tropical climate due to its geographical location over the Equator between 0° and 12° N. Although the country lies wholly within the tropics, its tropical climate varies from humid in the low elevation plains to glaciers tropical condition in the highlands with an average annual temperature from 24 to 27°C at sea level to slightly below 0°C in the highest Andean summits (Monasterio and Reyes, 1980). This climate is controlled by the seasonal migration of the Intertropical Convergence Zone (ITCZ), as a response to the annual insolation cycle (Poveda et al., 2006). The ITCZ is a low-pressure tropical belt of maximum cloudiness and rainfall, and its position is determined by

insolation and the convergence of the Northeast and Southeast tropical easterlies (McGregor and Nieuwolt, 1998). The ITCZ migration causes two distinct seasons in Venezuela: (1) when the ITCZ is South of Equator (December to May) a relatively cool and dry season with winds from the North is installed over Venezuela lands and, (2) while the ITCZ migrates northward near to Venezuelan coasts (June and November), a period of heavy rainfall and hot conditions occurred (Hastenrath, 1984; Rull et al., 2010). The Venezuelan Caribbean coast is throughout the year under the control of easterlies, which determine air stability and, as a consequence, dry climates with precipitation average of 300–600 mm/year (Rull et al., 2010).

2.5. Historical and recent seismicity

Several important earthquakes generated by offshore faults are recorded: June 11, 1641, March 26, 1812, April 12, 1878, October 29, 1900, July 29, 1967 and the last one on September 12, 2009 (Figure 2.11), an event in the coastal north-central Venezuela platform, 45 km from the city of Moron, Carabobo state. This seismic event of magnitude Mw 6.4 occurred offshore. An increase of the regional seismicity in the north-central part of the country was observed from early 2009: April 5th, Mw 4.3 northwest of La Guaira (SSF system), followed by a 4.2 Mw earthquake in Churuguara (fault system Oca-Ancon), on April 6th, Mw 4.4 east of Tucacas; and later on May 4th, Mw 5.4 south of Los Teques (Falla La Victoria) followed by two aftershocks of 4.4 Mw and Mw 4.0 (FUNVISIS, 2009).

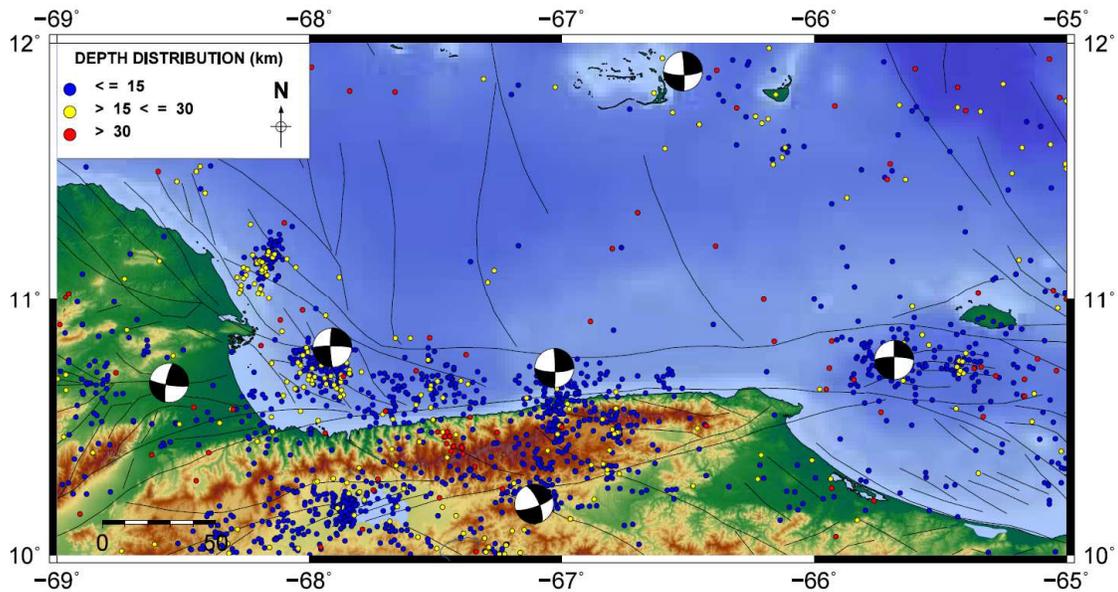


Figure 2.11. 1910-2010 seismicity from FUNVISIS catalog and Faults by [Beltrán \(1993\)](#). Focal mechanism by [Palma \(2010\)](#) and FUNVISIS web page. Topographic data from SRTM & Bathymetric from ETOPO1.

Jun 11, 1641. This seismic event was designated "disastrous" by [Centeno \(1940\)](#) who assigns intensities $I_M = 9-10$ and $I_{MCS} = 10$ to 11. This is the first event described in the catalogs ([Centeno, 1969](#); [Grases et al., 1999](#)). [Audemard \(2002\)](#) locate the epicenter with some uncertainty on the La Victoria fault system, and [Hernández \(2009\)](#) locate the event on La Tortuga Fault. [Hernández and Schmitz \(2011\)](#) assigned an intensity (IEMS) of 8-9.

March 26, 1812. This event hit mainly Barquisimeto, San Felipe, and Caracas. It resulted from a rupture made with at least two foci ([Audemard, 2002](#)). [Fiedler \(1961\)](#) places the two epicenters with magnitudes M_s 6.2 and 6.3. The coordinates were $10.2^\circ \text{ N } -69.1^\circ \text{ W}$ (between San Felipe and Barquisimeto) and $10.6^\circ \text{ N } - 66.9^\circ \text{ O}$ (north of Caracas) respectively. From the analysis of contemporary seismicity, [Audemard \(2002\)](#) proposes that this event should have occurred farther west on SSF, in a more intermediate position between Puerto Cabello and La Guaira in function of the intensities described by [Fiedler \(1961\)](#) for the villages of the north central region of the country. The second focus would be located at the northern termination of the Boconó Fault, along the valley of Yaracuy, in the segment of the fault (VE-06e in [Audemard et al., 2000](#)) extending from the traction basin of Cabudare towards the NE. This event should be located west of Caracas earthquake rupture of July 29, 1967 - 6.3 magnitude, to complete a seismic sequence

together with the 1812 and 1900 earthquakes, and geographically inserted between the breaks of both events (Audemard, 2002). Altéz (1998; 2005) argues that the event has two foci: a focus on the amount of the termination of Boconó system between San Felipe and Moron and the second focus between Puerto Cabello and La Guaira segment based on the distribution of sediment liquefaction phenomenon calculate the location of one of the focuses on the central region north of Choroní. Hernández (2009) places the earthquake on the west segment of the SSF and recently, Choy et al., (2010) located the event at north of La Guaira.

October 29, 1900. This earthquake affected the north central region of Venezuela producing numerous damages in the coastal towns and cities in the central region, depression of Barlovento, and so remote towns as Clarines and Barcelona (Grases, 1990). The event location is estimated on the sea by waves occurrence of several meters (paleotsunami) in Puerto Tuy - Barcelona Coast (Grases, 1990), but this epicentral location is considered very far north, although the magnitude assigned Ms 7.6 by the author seems to be appropriate to something overestimated (Audemard, 2002). This earthquake is assigned to the segment of SSF eastward to the rupture of the July 1967 Caracas earthquake, completing one seismic sequence from west to east over the SSF, comprising events 1812, 1967 and 1900. In turn, the event of 1900 seemed to come to complete a segment limited by the previous breaks of the events of 1812 and 1853 segments, all these with magnitudes $M_s \geq 7$, Although this not connecting both ruptures because it was required to the event 1967 Caracas seism, 1967; of magnitude lower (M_s 6.3) (Audemard, 2002). Rodriguez et al. (2006), from the relationship of the sites affected by the process of liquefaction, located the epicenter at the NE of Windward. Hernández (2009) located the epicenter in the La Tortuga fault.

July 29, 1967 Caracas Earthquake. Suarez and Nabelek (1990) evaluated the seismic information on this event and they propose that, despite being a multi-focal earthquake (3 sub-events dextral transcurrent with progression of the break to the east and a deeper inverse fourth and north), this earthquake occurs on a highly segmented and complex SSF portion, and the separation of about 95 km between the two sub-events do not represent the total length of the rupture.

September 12, 2009. A Moderate earthquake (M_w 6.4) occurred offshore northern Venezuela with geological effects spread around The Falcón coastline (Tucacas,

Chichiriviche and Boca del Tocuyo), as well as minor structural damage reports were attributed to inadequate construction techniques and/or soil liquefaction (Palma, 2009). In early 2009, a reactivation of the regional seismicity was observed in the north-central part of Venezuela. A sequence of events with a Mw 4.3 on April 5th (95 km east part of the current seismic event under study) accredited to SSF system, followed by a Mw 4.2 at Oca-Ancón fault system (Churuguara, 190 km west of the actual event) and a few hours later a Mw 4.4 event near Tucacas on April 6th (just 4 km away). These events were followed by an Mw 5.4 earthquake attributed to La Victoria fault (110 km further south) with two important aftershocks Mw 4.4 and Mw 4.0. The six-month time window for the previous mentioned seismic sequence demonstrates a possible interaction among the active faults prior to the Tucacas earthquake on September 2009. Palma (2010) from teleseismic data, extracts information about the source rupture process of Tucacas earthquake in 2009 (Table 2.1). The results also suggest a 40 x30 Km² EW main fault plane with a south dipping. The distribution of co-seismic slip shows a rupture propagation in depth.

Features	Values
Azimuth	39°
Dip	74°
Slip	.177°
Depth of initial rupture point	4,9 km
Event duration	18 s

Tabla 2.1. September 12, 2009 rupture parameters (Palma, 2010).

Chapter 3

High resolution seismic reflection offshore the Northern Venezuela margin: previous data and new acquisition

3.1. Previously published seismic reflection studies

In the offshore regions north and east of Venezuela, thousands of kilometers of oil-exploration seismic lines have been shot and interpreted for decades in the region under study, but very few of these studies have been actually published or made available (e.g., Pereira, 1985; Ysaccis, 1997; Di Croce et al., 1999; Ysaccis et al., 2000; Gorney et al., 2007; Magnani et al., 2009; Escalona and Mann, 2011; Escalona et al., 2011; Garciacaro et al., 2011). In a similar way, very few studies have aimed at characterizing the offshore seismogenic or Quaternary faults over the years, despite a significant amount of offshore seismic exploration carried out for larger scale and more geodynamic objectives in the 70's, which will be shown below (Figure 3.1).

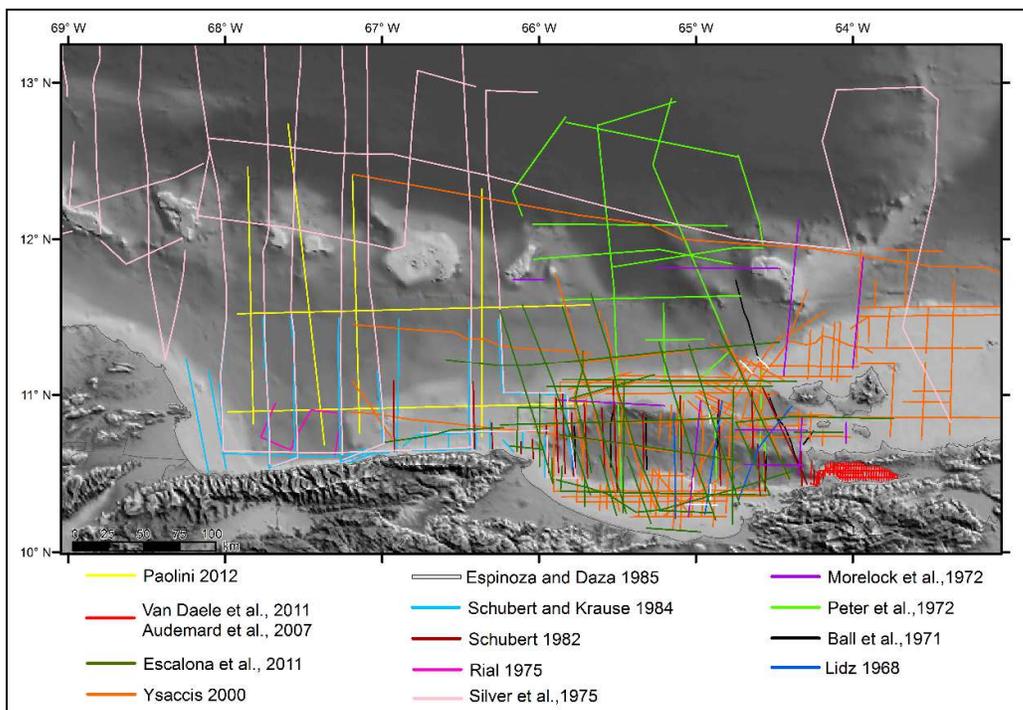


Figure 3.1. Seismic surveys made and published in the north of Venezuela from 1968 to the present.

3.1.1. Cariaco basin- trough coast seismic studies

The Venezuelan north borderland has been a focus of studies to understand its complex geological history. Several high-resolution seismic reflection studies have been published. Lidz et al. (1969) were the first to give the precision depth recording across the Cariaco basin. They published some echo sounding records (Figure 3.1) which have probably 30 m of penetration and this profiles show that the trench on the axis of the Cariaco basin is the trace of the seaward continuation of the El Pilar fault, and this trace continues westward (Rod, 1956). The trench presents offset at the south of the Tortuga Island, and the last mentioned authors interpreted this structure as a possible thrust faulting from the north during the Cenozoic. Northward edge of Cariaco basin, they found the Cenozoic igneous or metamorphic rocks at relatively shallow depth and a recent development of growth faulting of the sedimentary fill in the basin forming the graben on the floor of the Cariaco Basin. This style of faulting may represent a late stage in the sequence of geological events beginning with large strike-slip faults on the sea floor. The question of the amount of strike-slip movement on this fault is unanswered.

Ball et al. (1971) presented several acoustic reflection profiles across the Cariaco basin and one of their principal conclusions was that it is a zone with an east-west-striking, north dipping, normal faults belonging to a major fault system. These structures bounding shallow horsts and grabens, that control the island and strait topography of Margarita and Cubagua islands, the Araya Peninsula, and the Cariaco Gulf, through growth faulting of the sedimentary fill of the Cariaco Basin and a small scale slump faults on the slopes of Tortuga-Margarita Bank. They observed in the Cariaco Trench the thickening of sedimentary sections into both boundary faults. It has resulted in the formation of fault anticline which were modified by antithetic faults. They interpreted that in the blocks the predominant bedding dip is to the south and that major faults dip northward. Thus, each block is thrown up on the major fault forming its northern boundary and downthrown on the major fault to the south. The untilted corners of the rotated blocks give rise to horsts, while grabens form in the depressions on the downthrown sides adjacent to the faults.

Peter et al. (1972) published four acoustic reflection profiles across the Cariaco Basin. This work revealed the westward continuation of the structural Cubagua and Araya highs

and the westward extension faulting on the flanks of these structures. One of these faults cut the eastern deep of the Cariaco basin into two halves; the northern half is the basis of the down faulted sediments (or metamorphic) of the Araya block and the southern half is a deep trough filled with over 700m of sediments. The south bounding of these sediments is the El Pilar fault. In the western deep of the Cariaco basin the sediments are cut by numerous faults and they show stratification, faulting and slumping. The existence of the marked prograded scarps suggests probable subsidence in the order the hundreds meters, most likely during the Pleistocene and Holocene. The two depocentres of the Cariaco Basin are apparently offset in a right lateral sense and this is interpreted by Peter as an effect of the northward extension of the Urica fault towards to the Los Roques submarine canyon.

From the acoustic reflection profiles in the Paria gulf, [Lattimore et al. \(1971\)](#) interpreted three major structural-physiographic elements delineated within the Paria shelf: (1) The Carupano Valley, which extends eastward along the Paria-Araya shoreline forming a graben bounded on the south by a major fault system. (2) The Cumberland rise, a topographic and locally complex structural high north of the sea valley, is possible to reflect a positive element from Margarita Island east-northeast, and (3) Tobago trough, extend southwest across the shelf almost to the Paria-Trinidad coast. One of their conclusions is that the trends of the Lesser Antilles and Tobago Trough can be traced well into the Paria shelf. This implies that any recent transcurrent faulting within the area of the investigation could only occur near the Paria-Araya shoreline. [Lattimore et al. \(1971\)](#) pointed out that a great lateral fault bounding Caribbean-South American plate is possible located more southward Paria-Araya shoreline.

[Morelock et al. \(1972\)](#) presented three acoustic reflection profiles, one across Cariaco gulf and two profiles across the Cariaco basin showing the El Pilar fault as a narrow fault zone. They presented that the El Pilar fault can be traced through the Cariaco gulf into the offshore forming the southern boundary of the Cariaco basin. This is part of a system of the east-west faults bounding blocks that have been tilted, creating horst-graven system. The San Sebastian fault (SSF) appears to be a westward continuation of the El Pilar fault, showing a right-echelon step between them. The seismic records in the east of the Margarita Island show that the Tortuga-Margarita-Los Testigos high is underlain by igneous-metamorphic rock. The east Margarita shelf is a shoal terrace in topographical terms. There is a pattern of structural basins filled with more than 700m of sediments

between Araya-Paria peninsulas and the Los Testigos high. There is no direct evidence, but the sharp contact between these sediments and the igneous-metamorphic rocks bounding them suggests faulting in deep.

Schubert (1982) published several acoustic seismic profiles (Figure 3.1, 3.2) and interpreted the Cariaco basin as a pull - apart basin developed in the overlap region of the San Sebastian (referred as Morón fault by Schubert & Krause, 1984) and the El Pilar right-lateral “*en échelon*” faults, with an offset of less than 100 km and at least 25 km. The age estimation of the basin is most probably quaternary. Schubert considered that the Cariaco basin is a largest pull-apart basin developed along the Boconó – San Sebastian – El Pilar fault system, along which there are other basins. Finally, he concluded that this fault system is a part of the Caribbean – South America plate boundary.

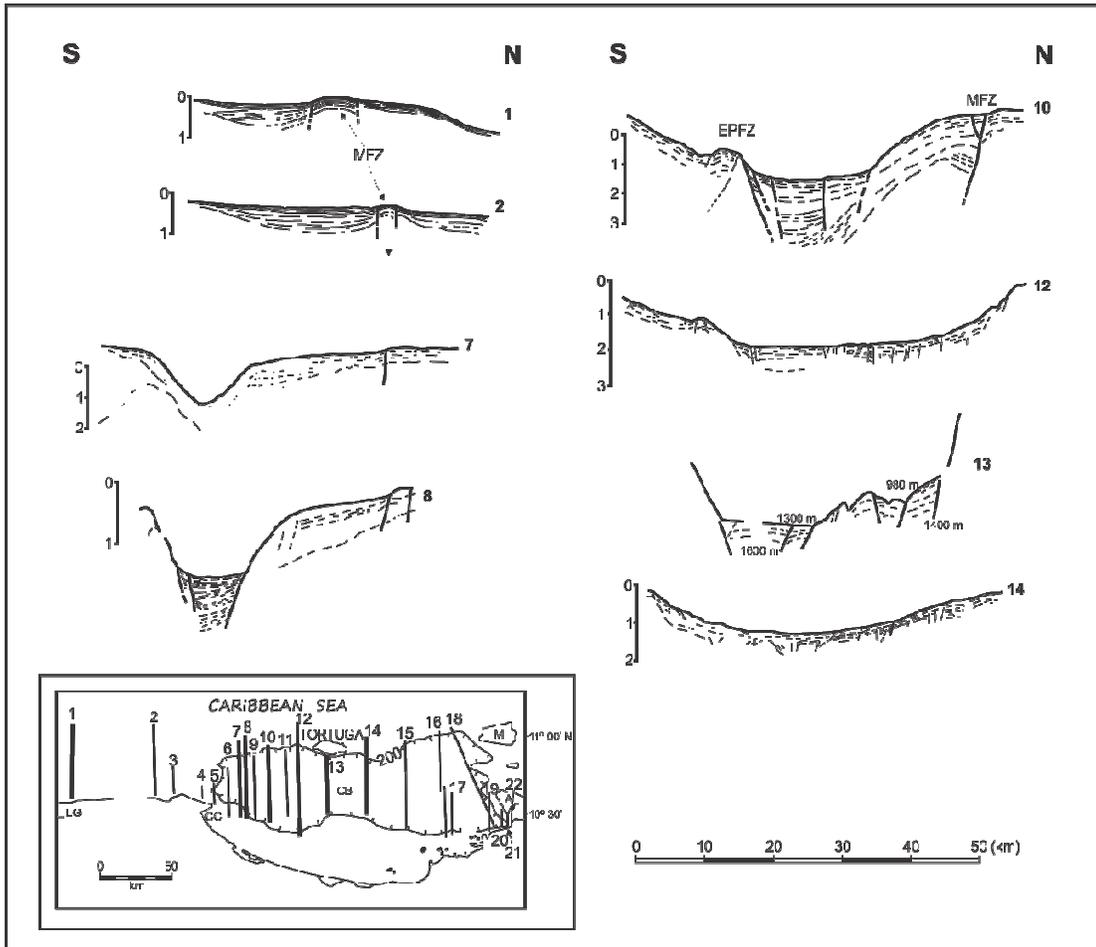


Figure 3.2. Line drawings of acoustic reflection profiles across the Cariaco basin. MFZ: Morón fault zone; EPFZ: El Pilar fault zone; CB: Cariaco basin; CC: Cabo Codera; LG: La Guaira; M: Margarita island; A: Araya peninsula. The vertical scale is in seconds

(two-way travel time) or in meters of depth. Vertical exaggeration varies between approximately 5 and 10 times. (Inset) The location map shows the outline of the Cariaco basin along the 200-m contour. Modified from [Schubert \(1982\)](#).

[Espinosa and Daza \(1985\)](#) presented several seismic profiles ([Figure 3.1](#)) in the Unare and Margarita – La Tortuga shelves which show prograding packages interpreted as fan deltas in Upper Pleistocene. The erosional unconformity surface is suggested as the Pleistocene – Holocene contact, developed by fluctuations in the sea level during this period. Both shelves have similar depositional processes, but sedimentary features are different. These authors identified the principal faults affecting the sedimentary process in these shelves (Urica, San Mateo, and Margarita faults of the Miocene, San Sebastian and El Pilar faults of the Pliocene – Pleistocene).

[Audemard et al. \(2007\)](#) published several high resolution seismic profiles acquired in the Cariaco gulf ([Figure 3.1, 3.3](#)) with the purpose to interpret the underwater Guaracayal depression, and these profiles reveal that this depression is an active pull – apart basin bounded by two subparallel traces of the El Pilar fault which lies inside a dextral transtensive overlapping. This stepover of about 2 km, may be a sufficient barrier to the fault rupture propagation, as evidenced by contemporary and historical seismicity.

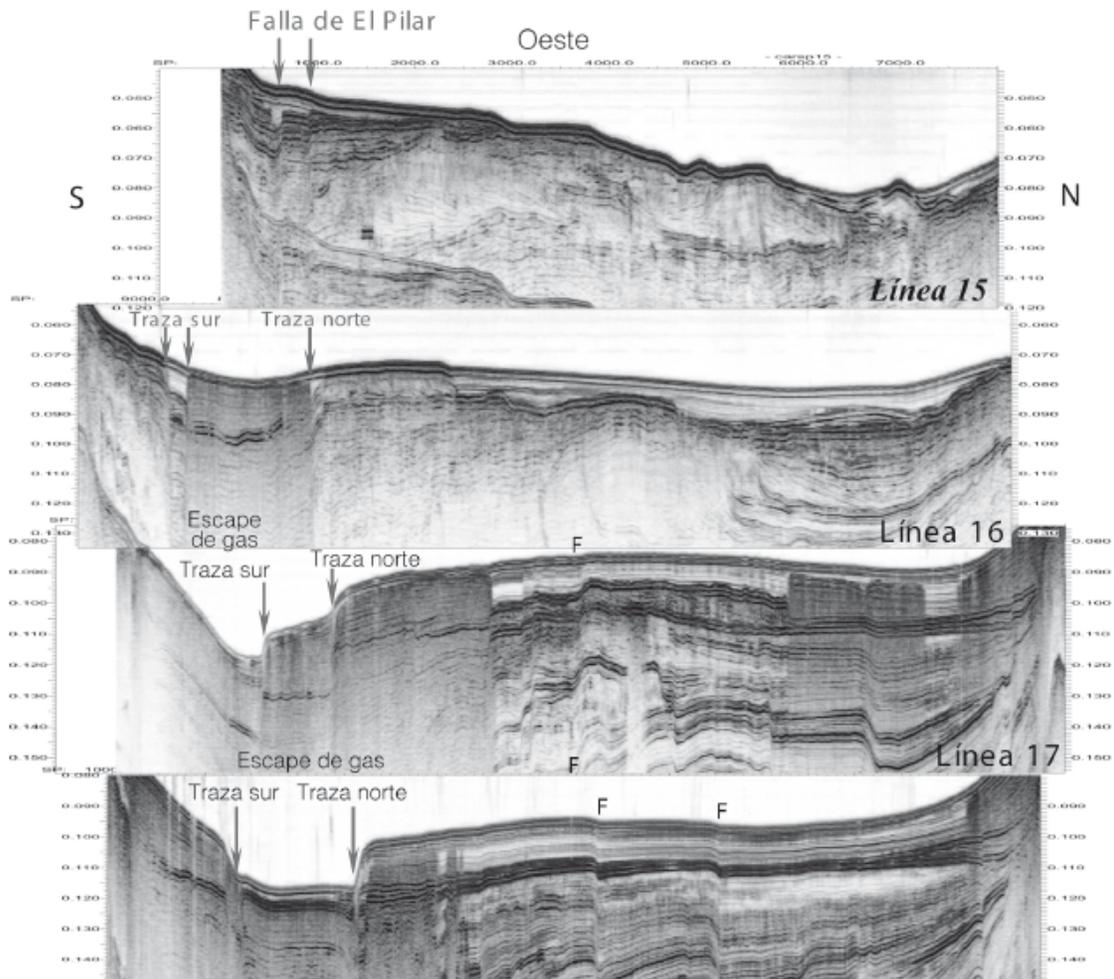


Figure 3.3. North–South sparker profiles across to the Gulf of Cariaco showing the El Pilar fault in the Guaracayal pull apart. Other faults in the north of the El Pilar fault are indicated with F. These faults exhibit recent activity. (Modified from [Audemard et al., 2007](#))

[Van Daele et al. \(2011\)](#) presented a dense grid of high resolution seismic profiles in the Cariaco Gulf to determine the overall tectonic structure of the gulf and to establish the seismic stratigraphy of its sedimentary infill ([Figure 3.1, 3.4](#)). Six unconformity-bounded seismic–stratigraphic units were identified in the upper ~200 m of the sedimentary infill. Detailed seismic–stratigraphic and seismic-facies analysis allowed defining a series of sedimentary features that can be used as indicators of past sea or lake level in the Gulf of Cariaco. From accurate measurements of these various indicators at several locations in the gulf and a simple total subsidence model, a relative sea/lake-level history

encompassing the last 130 kyr could be reconstructed. In periods of connection with the open ocean, reconstructed relative sea level correlates well with eustatic sea level. Distinct lake level fluctuations occurred in times of disconnection, which sometimes resulted in a total desiccation of the gulf. Lake-level fluctuations appear to correlate with major Heinrich Events, stadials and interstadials. MIS 4, the LGM and the Younger Dryas were thus identified in the Gulf of Cariaco sedimentary record. The last reconnection with the Caribbean Sea occurred ~ 11.5 kyr ago. The very good fit of the Cariaco sea/lake-level curve with the eustatic sea-level curves (both in terms of amplitude and of timing) underscores the potential for future paleoclimate research of the sedimentary record contained in this marginal basin, despite its active tectonic setting.

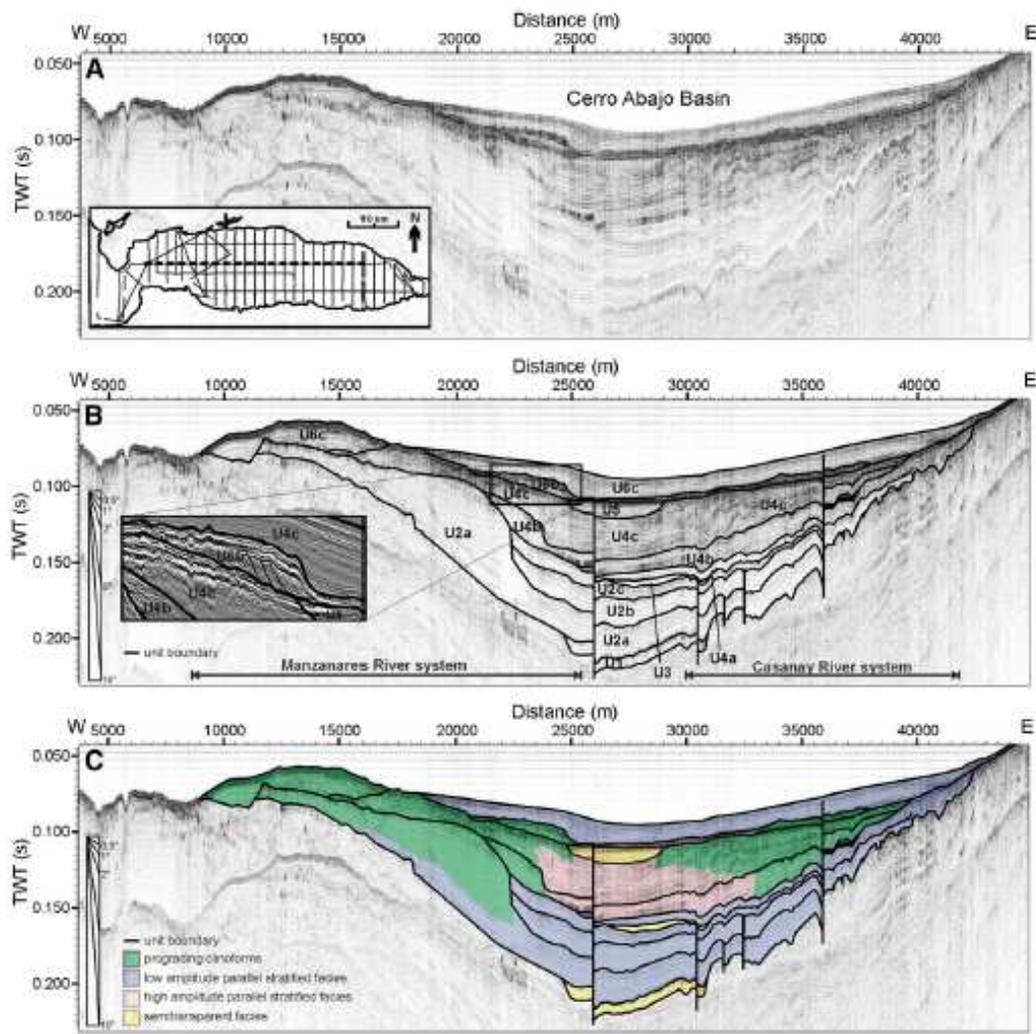


Figure 3.4. Portion of longitudinal (E–W) sparker profile. A: Non-interpreted profile. B: Interpreted profile showing unit boundaries and zoom of prograding clinofolds of Unit 6b. C: Interpreted profile showing different seismic facies. Two delta-fans complexes,

with several stacked clinoform units and subunits, prograde into the central Cerro Abajo Basin (e.g. a delta complex in the west associated with the Manzanares River and a delta complex in the east associated with the Casanay River). Most seismic–stratigraphic units are truncated at the seafloor in the west and are truncated or very condensed in the east. Seismic–stratigraphic units are offset by vertical faults in the central part of the basin and tend to become folded towards the east. In the westernmost part of the profile small canyons and gullies indicate currents between the Gulf of Cariaco and the adjacent Cariaco Basin (Van Daele et al., 2011).

3.1.2. Cabo Codera – Golfo Triste Coast zone

Rial (1973), based on analysis of seismic reflection profiles acquired in the Choróní basin (Sellier de Civrieux, 1971) concluded that Tacagua tectonic depression (Tacagua graben), which is aligned with the Tacagua fault, continues on the continental shelf to ~11°N latitude. This rule out the possibility of the continuity of major east-west strike-slip faults along north-central coast. Rial (1973) suggests that the Caracas 1967 earthquake may have produced by gravitational movement along the major faults of the Tacagua system.

Silver et al. (1975) presented an extensive acoustic reflection survey of the central Venezuelan boundary. Some profiles show a nearshore zone of deformation that begins along a sharp break that could be related to the trace of the SSF system (Figure 3.1, 3.5). The SSF system or deformation zone runs along the coast from Golfo Triste to Cabo Codera and the authors projected this fault eastward to intersect the Cariaco basin.

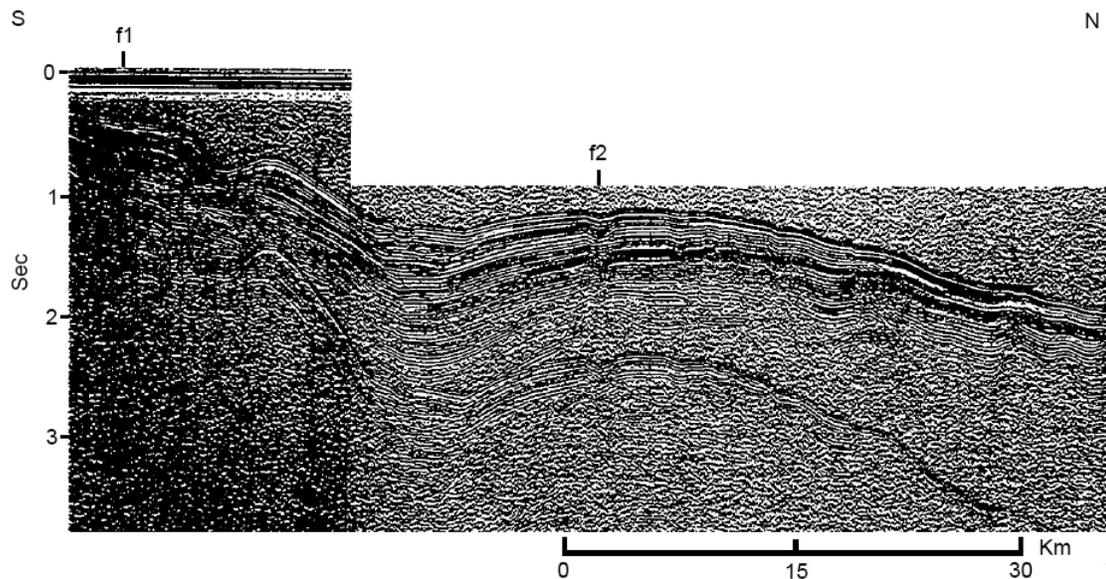
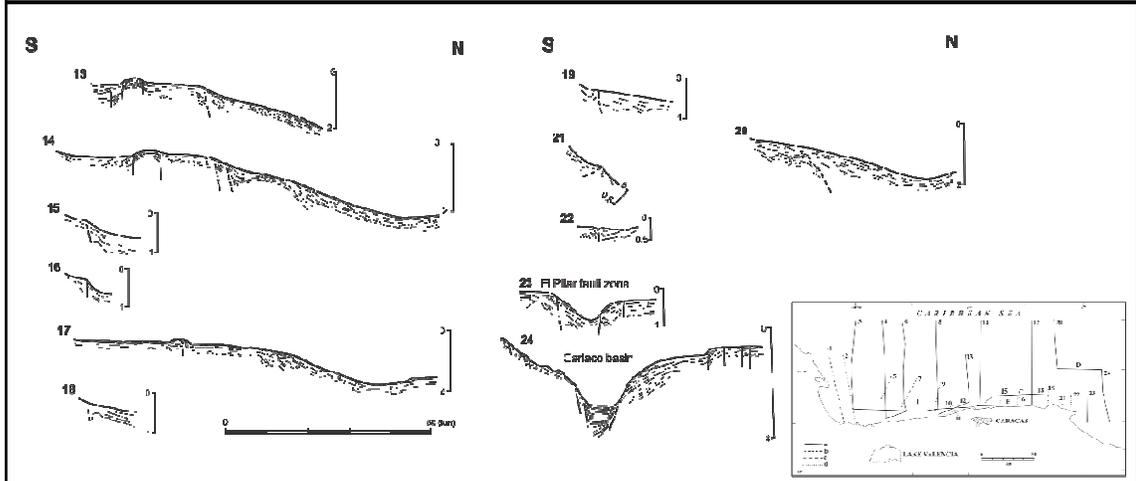
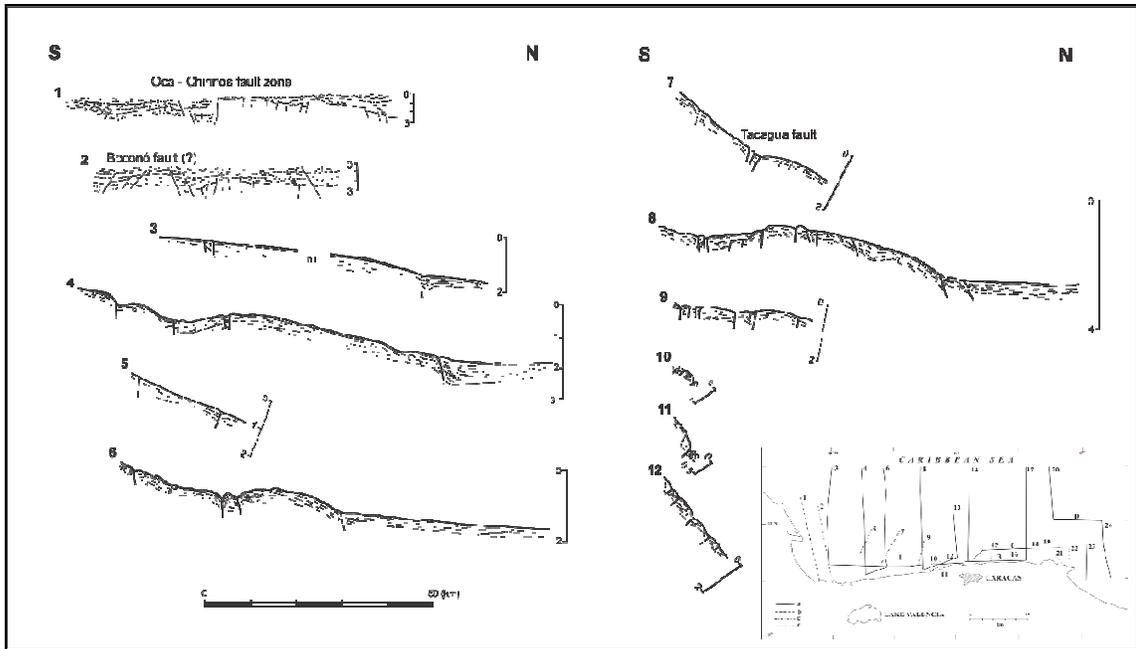


Figure 3.5. Portion of profile 26 in Silver et al. (1975) showing the San Sebastian fault (f1) and other parallel fault (f2).

Silver et al. (1975) for the first time stated that the Cariaco trench is an extensional basin between the San Sebastian and the El Pilar faults. This was interpreted as a long tectonic feature due to right-slip movement along two parallel but offset faults that have been active in Late Pleistocene – Holocene time. These authors suggest that there is no evidence for extending the Urica fault northward towards to the Los Roques submarine canyon to intersect the Cariaco basin, as was postulated by Peter (1972). Gonzalez et al. (1980) showed a profile seismic record in the north of Macuto where the deformation is located southward profile and this is an indicator of a great fault in the shoreline with compression component to the south.

Schubert & Krause (1984) analyzed 28 acoustic reflection profiles (Figure 3.1, 3.6) along the north – central Venezuelan borderland and suggested: 1) the Oca-Ancon fault zone extends eastward reaching the northern fault of the Cariaco pull-apart. Meanwhile, Beltrán (1993) considers that the eastward extension of the Oca-Chirinos fault keeps no more relation with this fault to the west and is then renamed La Tortuga fault (LTF). 2) This author considered that the Boconó – Oca – San Sebastián – El Pilar fault system forms a complex structural boundary along the northern and western Venezuela and suggest the whole system is since during Pleistocene-Holocene.



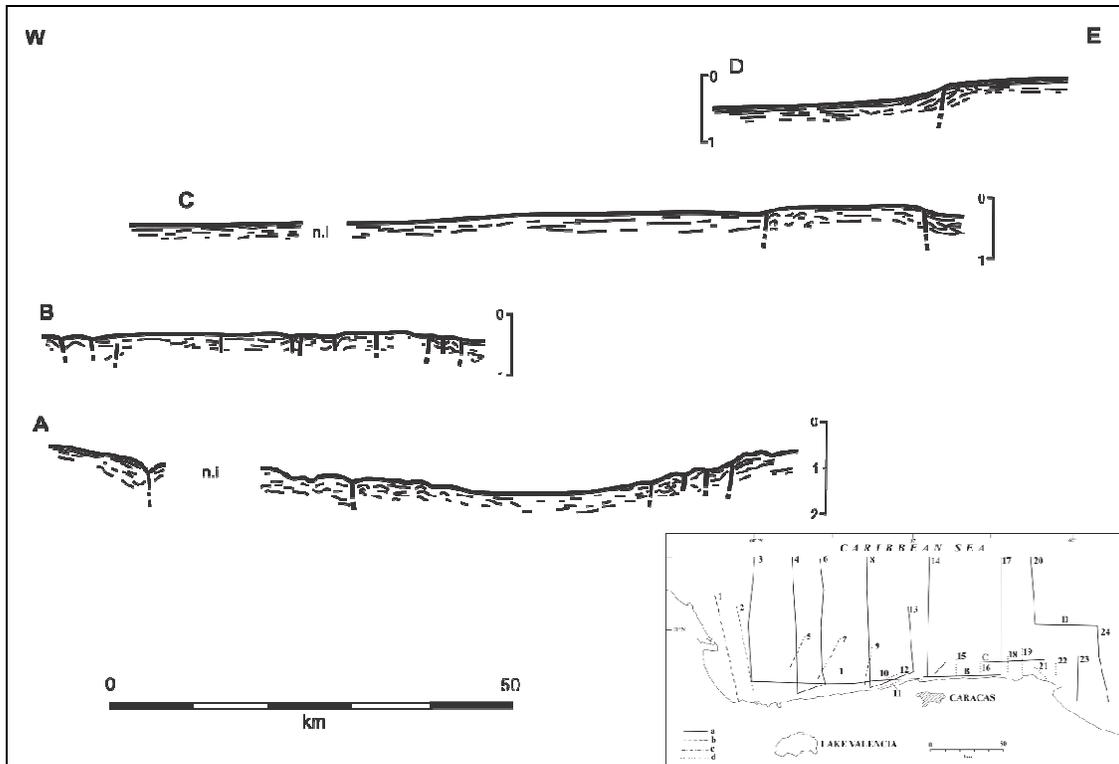


Figure 3.6. Acoustic reflection profiles (a) numbers 3, 4, 6, 8, 12, 13, 14, 17, 20, 23, and 24 (Silver *et al.*, 1975), profiles 22, 24, 26, 27, 28, 30, 31, 32, 34, 37, 39, 40 and 41); (b) numbers 1 and 2 from Gonzalez de Juana *et al.* (1980, p. 755, profiles A and B); (c) numbers 5, 7, and 9 are from Rial (1973, profiles A-A', C-C' and E-E'); (d) numbers 10, 11, 15, 16, 18, 19, 21, 22, and A, B, and C are from Planesa (1975, profiles 7, 10, 15, B, C, Naiguata, Los Caracas, and La Sabana). Emphasis was made on locating faults. Depth is shown as two-way travel time (sec). Modified from Schubert & Krause (1984)

Paolini (2012) used depth reflection seismic profiles, gravimetry, and magnetic aiming to understand the north shelf tectonic regime. On the seismic profiles the LTF was not identified, probably because of the limited number of seismic reflection profiles, offering little coverage information in the area. Therefore this author suggests to use marine seismic records that allow, on a scale more detailed, to check a possible impact of the LTF on the most recent sediments are affected or not by LTF. Gravity anomalies maps show an east-west alignment of maxima and minima in east-west direction, corresponding to the location of the SSF system, and the presence of a maximum and minimum alignment north of SSF, that was modeled as a lateral change of the crust, but uncut the sediments (Paolini; 2012)

3.2. The data acquisition 2007 Survey

In September, October, and November 2007, continuous (day and night) and nearly 1060 km of high-resolution reflection seismic profiles were acquired in the north central margin of Venezuela, between Golfo Triste and Cabo Codera (Figure 3.7; Table 1).

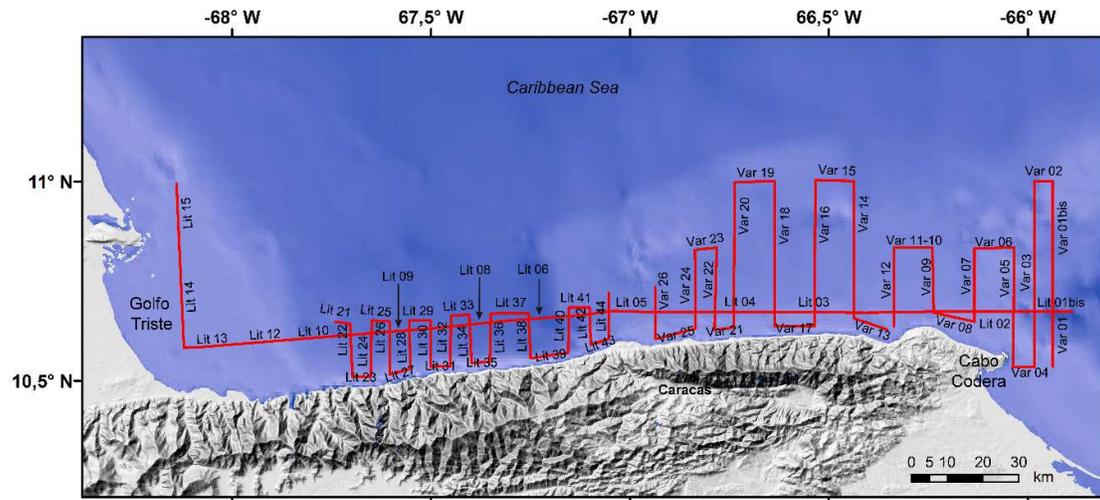


Figure 3.7. High-resolution reflection seismic profile survey.

This campaign was made possible by a collaboration of: ISTERre (Former LGCA) and Université de Savoie Mont Blanc (France), Fundación Venezolana de Investigaciones Sismológicas (FUNVISIS), Universidad de Oriente (Venezuela), and Renard Centre of Marine Geology (RCMG) - Universiteit Gent (Belgium).

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José Miguel Ramírez Márquez	Deck officer
Marcos Rafael Gutiérrez Conde	Machinist head
Lisandro José Gutiérrez Mendoza	Machinist
Jesús Francisco Córdova	Kitchener
Grubber Cordova	Kitchener assistant
Miguel Ángel Ramírez	Helmsman
Pedro Javier Trujillo Brito	Fuel provider
Edgar Ramírez	Assistant

Table 3.1. Team on board of the seismic reflection survey

3.2.1. Equipment

This survey was carried out aboard the R/V GUAQUERI II (Figure 3.7), an oceanographic vessel of the Oceanology Institute of the Universidad de Oriente. The reflection seismic equipment was provided and operated by the Renard Centre of Marine Geology (RCMG) at Ghent University (Belgium).



Figure 3.7. R/VsGuaiquerí II Boat of the Oceanographic Institute of the Universidad de Oriente in Cumaná

3.2.1.1. CENTRIPEDE Sparker

This is a source that consists of about 400 electrodes. When fired with an energy of 300 Joule this source generates a seismic signal with a frequency range 150 and 1500 Hz (Figure 3.8). The energy was supplied by a CSP-500 power supply connected to the generator of the ship. This resource has just been pulled under the water at 25 meters behind the boat (Figure 3.9). The subsoil penetration is about 200-300 m.



Figure 3.8. Multi-electrode CENTRIPEDE Sparker



Figure 3.9. View of the equipment behind the boat. The CENTRIPEDE Sparker is located to the right, and the single channel streamer (SIG) to the left.

3.2.1.2. Single channel streamer (SIG)

For the detection of the reflected signal a single-channel-SIG streamer was used (Figure 3.10). This streamer has an active length of 5 m, with 10 hydrophones at a mutual distance of 0.3 m. Dragged by 50-75 m of cable behind the boat on the sea surface, the streamer was towed as close as possible to the water surface (Figure 3.9).



Figure 3.10. High resolution streamer mono-channel.

3.2.1.3. Navigation and Positioning

The navigation was monitored with the aid of a Shipmate GPS. The Elics DELPH2 system allows to record together the acoustic signal and the GPS data of each shot in the header of the seismic trace. The navigation data can then later be easily recovered from this 'header' in order to make navigation files. Also, navigation data have been stored by the use of the FUGAWI- AVIGATION software package.

Chapter 4

Late Quaternary seismic stratigraphy and active structures of the North Venezuelan margin.

4.1. Introduction

Seismic stratigraphy is the observation that individual sedimentary reflections can be considered **timelines** representing a rather short time interval of continuous sedimentation conditions. This timeline concept equally signifies that seismic reflections tend to cross laterally through different depositional environments and therefore they can incorporate various lithofacies units (Veeken, 2007).

The seismic image reflects the interaction between the substrate geology and the seismic waves traveling through the rocks, modulated by the physical properties of the rocks. The seismic waves emitted by a source at the surface are characterized by specific physical attributes, including shape (spatial form as depicted by a seismograph), polarity (direction of main deflection), frequency (number of complete oscillations per second), and amplitude (magnitude of deflection, proportional to the energy released by source). Excepting for frequency, which is a constant parameter that depends upon the source of the seismic signal, all other attributes may change as the waves travel through the geological substrate (Catuneanu, 2006).

The physical properties which are most relevant to seismic data include the travel velocity of seismic waves, and the **acoustic impedance** (velocity multiplied by the rock's density) of the various layers and the contrasts thereof. Changes in acoustic impedance with depth are marked on seismic lines by reflections, which can signify changes in lithology, changes in fluid content within the same lithosome, or even diagenetic contrasts.

4.2. Seismic stratigraphy and structural interpretation

A seismic sequence is a relatively conformable succession of reflections on a seismic section, interpreted as genetically related strata; this succession is bounded at its top and

base by surfaces of discontinuity marked by reflection terminations and interpreted as unconformities or their correlative conformities (Mitchum et al., 1977). An unconformity surface either follows successive reflectors terminations by truncation; or joints their lateral termination. There are several types of lapout, depending on the position in which the reflectors ending against the uncoformable boundary and its relation with the upper and lower limit. Relationships between reflectors and the basal surface of the unit may be in onlap or downlap, where in first case, the termination of low-angle strata appear against a steeper stratigraphic surface, while the downlap is characterized by an initially inclined stratum terminates downdip against an initially horizontal or inclined surface. (Figure 4.1)

Reflection terminations (at unit boundaries)	Reflection configurations within facies units	External forms of facies units	Reflection characteristics
Lapout Baselap: Onlap  Downlap  Toplap 	Principal stratal configuration Stratified: Parallel  Subparallel  Divergent  Prograding Clinoforms: Sigmoid  Oblique  Parallel  Complex sigmoid oblique  Shingled  Hummocky clinoform  Unstratified: Chaotic  Chaotic deformed  Reflection free 	Sheet  Sheet drape  Wedge  Bank  Lens  Mound  Fan  Fill: Channel fill  Basin fill  Trough fill  other fill types: onlap fill mounded onlap fill divergent fill prograding fill chaotic fill complex fill slope front fill	Amplitude high low variable Continuity high low variable
Truncation Erosional Structural Concordance (no terminations)	Modifying terms: even hummocky regular disrupted wavy lenticular uniform variable irregular contorted		

Figure 4.1. Overview of the different criteria to describe seismic facies (Mitchum et al., 1977, Reading, 1980; Boggs, 2006).

The upper lapout include toplap, erosional and structural truncation. Toplap terminations characterized of inclined strata (clinoforms) against an overlying lower angle surface, mainly as a result of nondeposition (sediment bypass), \pm minor erosion (Figure 4.1, 4.4). In erosional truncation, termination of strata against an overlying erosional surface where older sediments are eroded by subarea or submarine erosion and removed over larger areas. In some case, there is no reflection from surface and only the systematic terminations of underlying reflections may define the surface. Structural truncation are associated to structural disruption produced by faulting, gravity sliding, diapirs, or igneous intrusion.

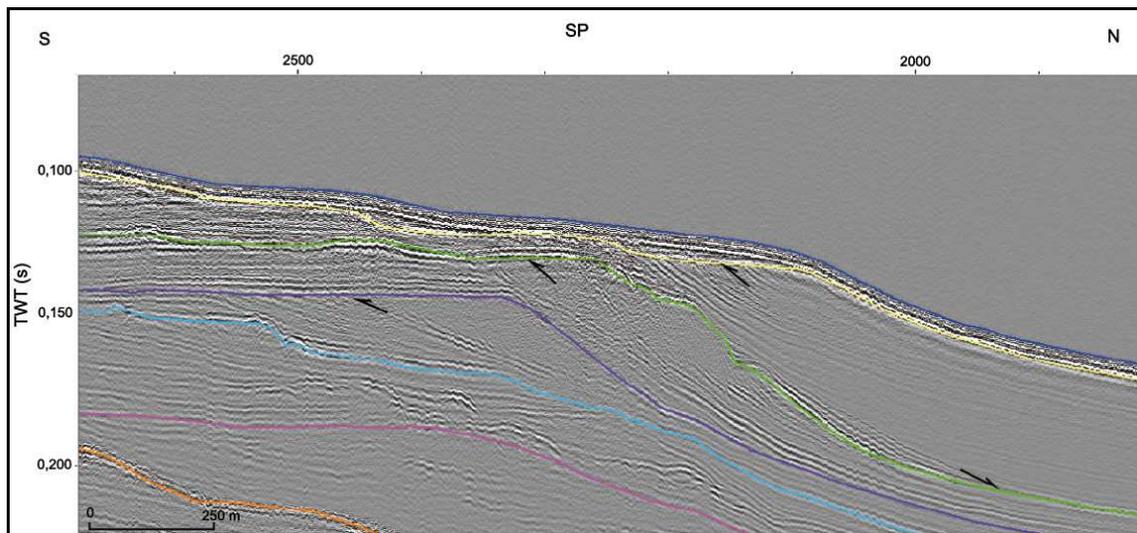


Figure 4.2. Seismic profile Vars07, showing discordances on La Guaira shelf. Black arrows underline truncation surfaces.

Seismic structural features

At abrupt discontinuities in interfaces, or structures which give rise to a radial scattering or hyperbole of incident seismic energy known as diffraction (Figure 4.3) (Kearey et al., 2002). Common sources of diffraction include the edges of faulted layers, unconformities, salt or shale diaper, igneous instruction, chaotic avalanches, etc. (Badley, 1985)

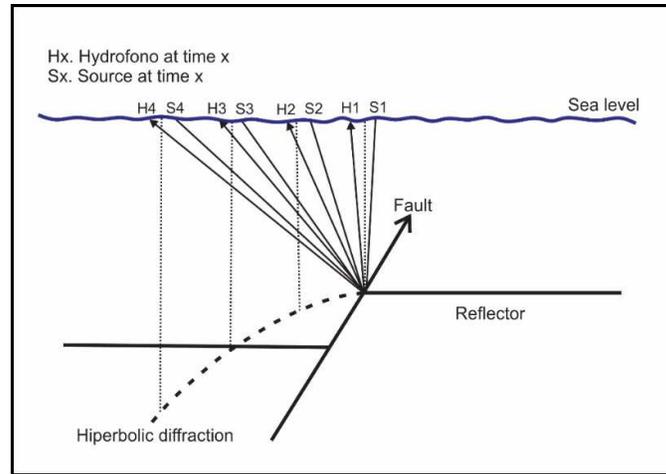


Figure 4.3. Hyperbolic diffraction from a fault (Badley, 1985).

Seismic reflections on fractures may occur apparent 'roll-over' (Figure 4.4). Reflectors in the foot block of a normal fault are to bend downwards against to the fault, but this effect can occur according to Badley (1985) for several reasons:

1. Real 'roll-over', caused by the inverse drag on the fracture surface of a listric normal fault;
2. a portion of a diffraction (Figure 4.3);
3. a velocity artefact caused by lower velocity wedge of rocks/sediments above the fracture surface, which overlie above the foot wall edge of the fault.

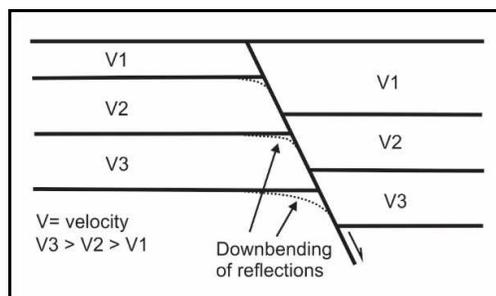


Figure 4.4. Dowbending of reflections into the fault. (Badley, 1985).

Velocity artefacts could occur in thrust faults and strike slip fault. Fractures with lateral displacement could have the very different reflectors pattern within the two separate blocks. Reflectors can be cut off losing the continuation along the other side of the fracture. Trenches, folds, channel, etc., within which the reflector curvature exceeds the curvature of the incident wavefront are represented on seismic sections by a 'bow-tie'

event resulting from the existence of three discrete reflection points for any surface location (Kearey et al., 2002; Figure 4.5). The two upper reflections come from both edges of the trench, and the trench in bending off downwards, but with a smaller slope than the slopes of the actual trench. The bottom reflector is a hyperbola, and its top is in line with the base of the trench (Badley, 1985).

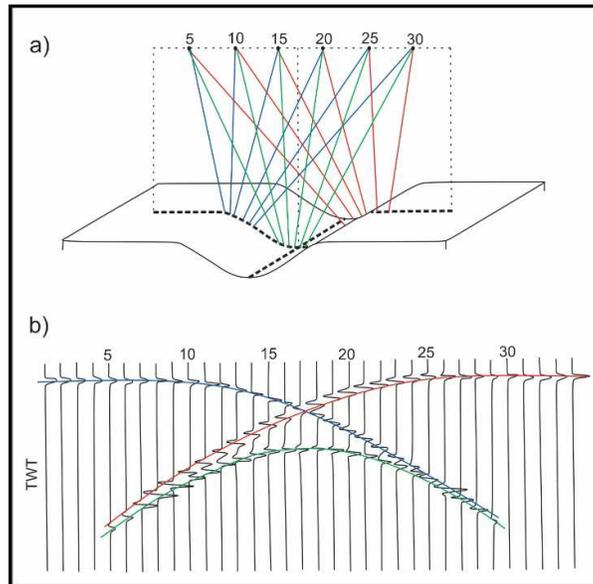


Figure 4.5. A trench feature in a reflecting interface, and the resultant ‘bow-tie’ shape of the reflection event on seismic section. (a) Beam path, (b) the reflection pattern where the blue line represents the reflection of the left edge of the trench, the right edge trench correspond to red line, and bottom of trench correspond to green line. Modified of Sheriff (1980) and Badley (1985).

Seismic facies

A seismic facies is defined on the basis of reflection configuration, continuity, amplitude, frequency and interval velocity together with the external form of the unit (Mitchum, et al., 1977) and may be mappable as a two- or three-dimensional unit. The most obvious feature of a seismic facies is the reflection configuration e.g. parallel, divergent, prograding clinoforms, shingled, etc, (Figure 4.1) which may yield information on bedding patterns, depositional and erosional processes, channel complexes and syn-depositional deformation. The external shape and spatial association of facies provide information on depositional environment, sediment source and sea level fluctuations. The most common shapes are sheets, wedges, banks and lenses (Figure 4.1). Topographic build-ups, due to organic growth or to clastic deposition, are known as mounds. There are many forms of fill above discordances (channel, trough, basin and slope front) which

have a variety of internal reflection configurations (Figure 4.1). Given beds of similar velocity and density, reflector continuity broadly reflects lateral depositional continuity and amplitude reflects the vertical contrast in facies; high amplitude, for example, indicate large-scale interbedding of shales with thick units of sandstone or carbonate rocks; low amplitude reflectors are the result of monotonous lithological profiles.

The facies distribution and its changes depend of a variety of factors that control depend on a variety of interrelated factors: sediment supply, climate, tectonic movements and subsidence, sea-level changes, biological activity, water chemistry, volcanic activity. The relative impact of these factors varies depending on the circumstances. The most universal factors are climate and tectonics where the climate is especially important in shorelines and continental surface conditions, and tectonics in deep marine conditions. In addition, sedimentation and sediment to play an important role in the delta and river conditions (Reading, 1996).

The accommodation space is controlled largely by external processes such as changes in sea level, climate, tectonic movements, volcanic activity, compaction and longer-term subsidence rates which together define a depositional base level. The supply of sediment varies in volume, composition and grain size, as well as in the mechanism and rate of delivery. These variations are the result of the climate, basinal water chemistry and the tectonics and bedrock geology of the source area. The sea-level fluctuation have a major impact in shallow situations (mostly passive continental margins) but less or none in deeper situation (shelf and oceanic plains) (Reading, 1996).

4.3. Description of the structure and the fractures

The Kingdom Suite 8.8 software was used for interpretation and description of the seismic profiles. Fractures or faults are recognized on seismic profiles by interrupt of the reflectors accompanied by hyperbolic diffraction (Figure 4.3). These fractures could cut young sediments until the surface or keep depth forming blind fractures which not reach the surface, and therefore has no surface trace. The main criteria for the correlation are the dip direction, the fracture activity and the degree of "roll-over" of the cut-off of reflectors. A part of the fractures could not be correlated with any other fraction as their

geographical distribution is not large enough. The well mapped fractures were divided into groups and then discussed by group.

Along northern shelf we observed faults which cut young sediments down to approximately 850 meters b.s.b. (used equipment maximum penetration). Some deformation and blind faults are recognized which is result of active deformation. The biggest fault system in the zone was improvement mapped.

4.4 Combined Late Quaternary eustatic and tectonic impacts on the Northern Venezuela margin. First results of a high resolution seismic survey

Paper to be submitted

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ABSTRACT

The continental shelf north of Central Venezuela is partially or completely structurally controlled by major right lateral strike slip active faults (e.g. San Sebastián and Tacagua faults), comprising three physiographic provinces, from west to east: the Golfo Triste Platform, the Choroní Basin and the Guaira Platform. The two mentioned platforms are of erosional type; the Choroní basin is a deep depression, which is incised by submarine canyons. These canyons seem to be related to turbidity currents with greater flows during the Pleistocene wetter periods. Following several authors, these submarine canyons are partially or completely structurally controlled by major structures present in the north-central coastal range of Venezuela.

We investigated the Late Pleistocene-Holocene sedimentary cover through high resolution seismic profiles acquired by a joint effort of several institutions (FUNVISIS with the Universities of Savoie –France-, Ghent –Belgium- and UDO –Venezuela). Five major regional unconformities and/or seismostratigraphic limits have been identified. We propose to correlate the most recent to MIS 2 (Last Glacial Maximum) lowstand. The chronological significance of the deepest detected major unconformity (strong erosion) is tentatively attributed to MIS 12 lowstand. Based on the present day position of the later one, we propose an estimation of the mean subsidence rate in the La Guaira Shelf, considering that the obtained value may locally represent a minor vertical component of the dominantly horizontal displacement along the San Sebastian Fault.

The San Sebastián fault shows a linear deformation in the eastern profiles. In contrast to the west, we observe in some profiles an intense deformation zone with two

possible fault traces that looks like a positive flower structure. Two alternate interpretations are viable for these features: they are of tectonic origin; or they correspond to large submarine gravitational instabilities.

4.4.1. Introduction.

The Quaternary period was characterized by climate variation, bring about changes in eustatic sea level and the growth of ice sheets and their deglation (Imbrie et al., 1992; Waelbroek et al., 2002; Clark et al., 2009; Shackleton, 1987). Base level fluctuations (eustatic sea level) coupled with the basin floor vertical motions (i.e. subsidence or uplift), and the rate of sediments deposited govern the accommodation space in the sedimentary basins (Boggs, 2011). Observation and analisis stacking of sedimentary facies allows to identify sequences within the series enables the reconstruction of paleoenvirenements and paleogeographies that describe the spacio temporal evolution of sediment deposition. Thus, if the sedimentation and subsidence are known, it's possible to reconstruct the base level fluctuations.

In recent years, studies have been made to reconstruct Quaternary sea level fluctuations with the help of the seismic stratigraphy, wich allowing know the accumulation and preservation of sediments through successive sea level cycles (e.g. 4th - order sea-level and 5th - order sea-level). In several continental passive margins, Quaternary sea level variations was reconstructed by using deposits that show shoreline positions in the Gulf of Lion (Rabineau et al., 2005, 2006; Jouet et al., 2006), deposits during the Holocene transgresión from the Great Barrier Reef (Larcombe and Carter, 1998), evolution of the delta shoreface in Barcelona shelf (Liquete et al., 2008), in the eastern Mediterranean sea (Piper and Aksu, 1992; Skene et al., 1998), in the black sea (Aksu et al; 2002), in the western Mediterranean sea (Chiocci, 2000), regressive deposits in the Adriatic basin (Trincardi and Corregiari, 2000; Ridente and Trincardi, 2002), in the Gulf of Mexico (Anderson et al., 2004) and in the Gulf of Gökova (Ulug et al., 2005). The preservation of the sea level eustatic indicators is assured by the subsidence and burial in those environments.

The Venezuelan northern margin is a region along a system of active right lateral strike slip faults which edge the transform boundary between the Caribbean Plate and the South American Plate (Audemard et al. 2000). This strike-slip fault system along Caribbean-South America plate boundary zone extends offshore for over 400 km. As a result of this setting, the Venezuelan northern margin is affected by a series of active faults (e.g. San

Sebastian fault) (Audemard, 2007; Audemard et al., 2000). In a tectonically active, transtensional region, subsidence is an important—and complex—factor controlling accommodation space and shelf modelling. The Venezuelan north margin evidences this structural control by its heterogeneity along the shelf from east to west (66°-68°), where Sellier de Civrieux, (1977) distinguishes: La Guaira shelf; the Choróní basin, which shows a narrow shelf with a steep margin slope as a deep depression graben aspect, with submarine canyons; and Golfo Triste shelf. The both mentioned shelf are shallow and erosional type (Sellier de Civrieux, 1971).

We investigated using a dense grid of single-channel high resolution sparker seismic profiles to 1) improve our understanding of remarkable active faults that cut across the shelf development 2) the recent history of sedimentary infilling of the margin, 3) the along-shelf variation of the relationship between recent sea level fluctuations and vertical tectonics.

4.4.2. Geodynamic and geological setting

Northern Venezuela lies in the interaction zone between the South America and Caribbean Plate (Figure 1). The Caribbean-South America Plate boundary from Colombia to Trinidad is over a 100-km-wide active compressional right-lateral strike-slip zone onshore and offshore northern Venezuela (Audemard, 1993; Singer and Audemard, 1997; Pindell et al., 1998; Audemard et al., 2000, 2005; Ysaccis et al., 2000).

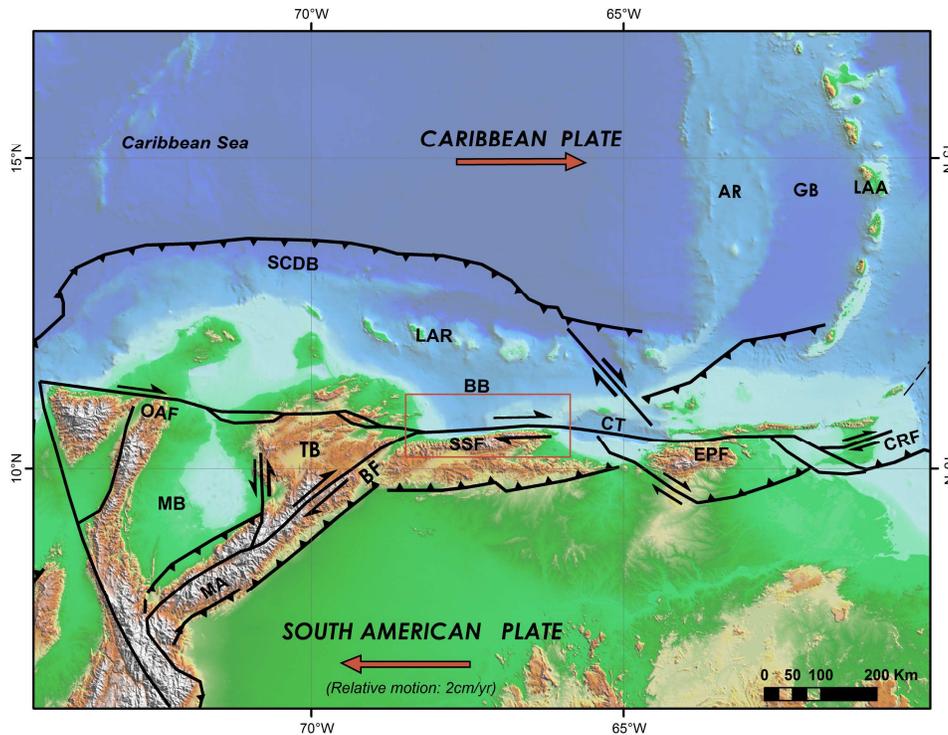


Figure 1. Present day geodynamic setting of the North-Venezuela margin along the transform boundary between the Caribbean Plate and South American Plate (Audemard 1999b; Audemard et al., 2000; Webber et al., 2001; Trenkamp et al., 2002). Study zone enclosed with a red rectangle. Tectonic Provinces - AR: Aves Ridge; GB: Granada Basin; LAA: Leseer Antilles Arc; SCDB South Caribbean Deformed Belt; LAR: Leeward Antilles Ridge; FB: Falcón Basin; BB: Bonaire Basin; CT: Cariaco Trough; MB: Maracaibo Block; TB: Trujillo Block; MA: Mérida Andes. Quaternary faults - BF: Boconó Fault; OAF: Oca-Ancón Fault; SSF: San Sebastián Fault; EPF: El Pilar Fault; CRF: Central Range fault

Seismicity along this plate boundary (Figure 2) is moderate both in frequency and magnitude and the dominant types of faulting, based on focal mechanism solutions, are strike-slip and reverse (Audemard et al., 2005; Palma et al., 2010). Much of present-day dextral slip along the southern Caribbean boundary seems to be focused along the major Boconó -San Sebastián -El Pilar-Los Bajos-Warm Spring-Central Range fault system where geological and geodetic data indicate slip rate of about 10 mm/yr (Figure 1).

Most authors see this system as the plate boundary (Hess and Maxwell, 1953; Schubert, 1979; Stephan, 1985; Perez et al., 2001 a, b). A large portion of this strike-slip fault system lies offshore, comprising the entire San Sebastián fault (SSF) and most of the EPF, with the rare exception of the EPF portion outcropping on the land bridge between

the gulfs of Cariaco and Paria, in Eastern Venezuela. In other words, the major strike-slip fault system along this Caribbean-South America plate boundary zone extends offshore for over 400 km between longitude 68° and 64°, north of North central Venezuela. The Quaternary faults onshore are rather well mapped and tectonically characterized and their seismogenic potential is appropriately estimated, accordingly to the present state of the art (Soulas, 1986; Beltrán, 1993, 1994; Audemard et al., 2000), the current situation differs very much for the offshore regions north and east of Venezuela (Audemard, 2012), even in a country where thousands of kilometers of oil-exploration seismic lines have been shot and interpreted for decades in the region under study, but very few of these studies have been actually published or made available (e.g., Pereira, 1985; Ysaccis, 1997; Babb and Mann, 1999; Di Croce et al., 1999; Ysaccis et al., 2000; Gorney et al., 2007; Magnani et al., 2009; Escalona and Mann, 2011; Escalona et al., 2011; Garciacaro et al., 2011).

Significant positive relief is present along the Coastal and Interior ranges of Northcentral and Northeastern Venezuela. Further west, the southern Caribbean boundary broadens to as much as 600 km and includes several small tectonic blocks or microplates. The Coastal Cordillera rises parallel to the coast and barely 6–10 km inland, exceeds 2000 m elevation and reaches its maximum altitude at Pico Naiguatá (2765 m) and the lithology mainly consist of igneous and metamorphic rocks. The linear, east-to-west, emergent coast is controlled by faults and characterized by steep cliffs and terraces (Dengo, 1953). In the present, the sediments of the North flank of the coastal cordillera drained by short streams that flow northward for 7–12 km while descending precipitously through narrow, deeply dissected V-shaped valleys (Larsen et al., 2001b, Perez, 2001). For most of the year, these small streams are unimposing and exhibit a low discharge. The sediments are transported by drift currents westward (Picard 1974). The average speeds in the surface of the Caribbean Sea in front of the Venezuelan coast can reach to 70cm / s (Fratantoni, 2001). There could be bottom currents and upwelling phenomena or vertical movement of the water masses from Cabo Codera to NW, due to temperature difference and the action of the trade winds present in the area (Castellanos et al., 2002)

Precipitation in coastal Venezuela shows a pronounced seasonality. As in other equatorial regions, rainfall variability is closely tied to migration of the Inter-Tropical Convergence

Zone (ITCZ) the rainy season (May–November) coincides with the northward displacement of the ITCZ, while the dry period (December–April) occurs as the area comes under the influence of the NE trade winds (Riehl, 1973; Snow, 1976). Infrequent atmospheric disturbances, however, can cause severe rainfall episodes.

4.4.3. Sea floor morphology

The continental shelf between Cabo Codera (Miranda) to Golfo Triste (Falcón) shows an average of about 360m depth shelf break which. In the modern ocean the average depth shelf break is about 130m (Boggs, 2011), this suggest that continental shelf is partially or completely structurally control that suggest a major subsidence in certain marine zone contrasting with stability of contiguous areas (Sellier de Civrieux, 1977).

Sellier de Civrieux, (1977) distinguishes, from east to west, three physiographic provinces: Platform of La Guaira, Choroní Basin and Platform of Golfo Triste (Figure 4). The two mentioned platforms are erosional type and they are separated by Choroní basin, which he describes as a deep depression graben aspect, almost absent continental shelf with submarine canyons (Sellier de Civrieux, 1971). The continental shelf of **La Guaira platform** extends with a wide, gently and continuously sloping submarine plain down to 360m, which steeper between 0 and 200m. Three plateaus interrupted abruptly rising from the bottom of the submerged plain (La Guaira, Los Caracas and Carua) (Sellier de Civrieux, 1977; Paolini, 2012) (Figure 3). The boundary with Bonaire basin corresponding to normal faults in the basement, allowing an south – north depth abrupt change since the continental shelf to the Bonaire Basin (Paolini, 2012). Westward, the zone of greatest subsidence seems to be the **Choroní basin** with almost nonexistent continental shelf. This depression is connected to the north with Bonaire Basin. The two well-characterized canyons are a close relationship with the current in the Serrania Del Litoral. Eastward Choroní basin, Mamo river mouth discharge into the Canyon of Mamo, wich is tectonically controlled by the northeast-seaward extension of the Tacagua-El Avila faults (Rial, 1973; Civrieux Sellier 1971). Westward Choroní basin is located the Canyon of Ocumare, in which discharge sediments of the Ocumare River (and perhaps the Cata River). These two submarine canyons meet in the center of the basin to form a new canyon: "A" canyon which is directed north-seaward, connecting Choroní and Bonaire Basin (Sellier de Civrieux, 1971). Apparently, these guns seem to be related to

turbidity currents of the rivers which were carried out during the Pleistocene pluvial periods. Westward Choroni basin, the continental shelf in **Golfo Triste Platform** shows a shelf break at 170m and 30 km wide. [Sellier de Civrieux, \(1977\)](#) observed three preserved submarine terraces levels on outer shelf which represents paleo shorelines. The deepest terrace is 146m, above 133m and finally 90m. The second submarine terrace is related to Wisconsin shoreline ([Sellier de Civrieux, 1977](#)).

[Picard \(1974\)](#) described and classified coastal cliffs of the coast range into two sections: one west of Chichiriviche consisting submerged cliffs up to 200 m, and one to the east of Chichiriviche cliffs formed by erosion platform tectonism possibly stable or slightly positive. Western cliffs (Puerto Cabello - Chichiriviche) were subdivided by the author in two tranches: tranche Cata (Puerto Cabello - Chuao) with subsidence between 2 and 10m, and stretch of Puerto La Cruz (Chuao - Chichiriviche) with subsidence of up to 200m. This implies a slight subsidence western, central zone and a pronounced subsidence east (Chichiriviche eastward) stable, or even rising. The continental shelf has been depressed apparently more pronounced ([Civrieux Sellier, 1973](#)), calculated between 180m and 300m over.

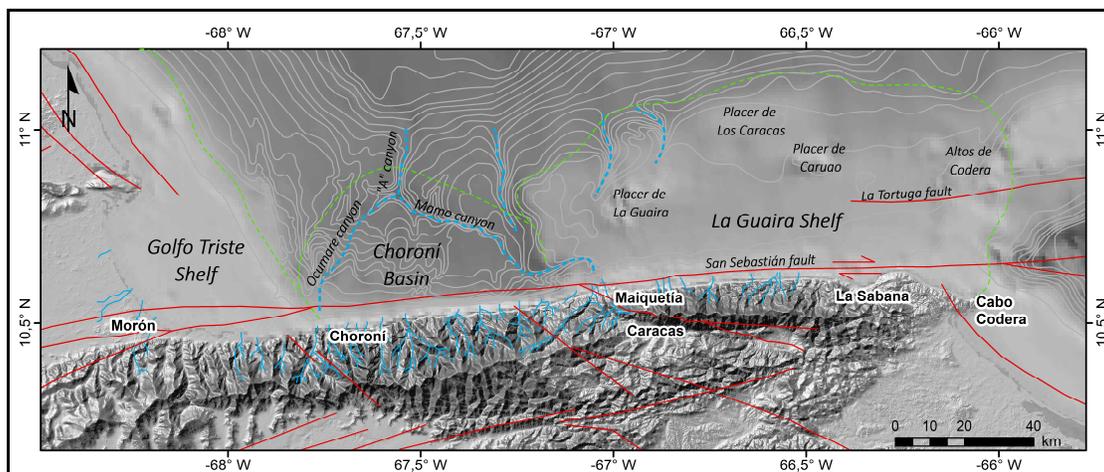


Figure 4. Offshore geomorphology of the North of Venezuela (modified of [Sellier de Civrieux 1971](#)). Green dotted lines, enclose the estimated geomorphology features. The blue dotted lines showing canyons. Active fault map of [Audemard et al., 2012](#). Relieve map surrounding onshore areas (based on SRMT30).

4.4.4. Methods

In this study was collected ~1064 km of high resolution (HR) on seismic reflection profiles on board of R/V Guaqueri II of the Oceanographic Institute of the Universidad de Oriente in Cumaná in September, October and November 2007 (Figure 5). These profiles were shot with RCMG's "centripede" multi-electrode sparker opered at 300 or 400 J. The sparker generate a broad-spectrum seismic signal, with a frecueny at ~1.3 kHz. The signal was received by a single channel streamer with 10 hydrophones. The expected vertical resolution at depth is ~ 1m. The maximum penetration depth below the seafloor is about 560 ms two way travel time (TWTT)

The navigation grid was acquired at an average survey speed of 4 knots and the positioning was done by GPS. Data were digitally and converted to SEG-Y format with Elics™ Delph-II software and they were interpreted using KingdomSuite™ software. The grid consists of north-south lines separated by 6 'in longitude and an east-west lines to correlate all previous lines. The aim of the grid disposition is to reconstruct the 3D geometry of the sedimentary sequences and to map the different traces of the San Sebastian fault in the North of Venezuela.

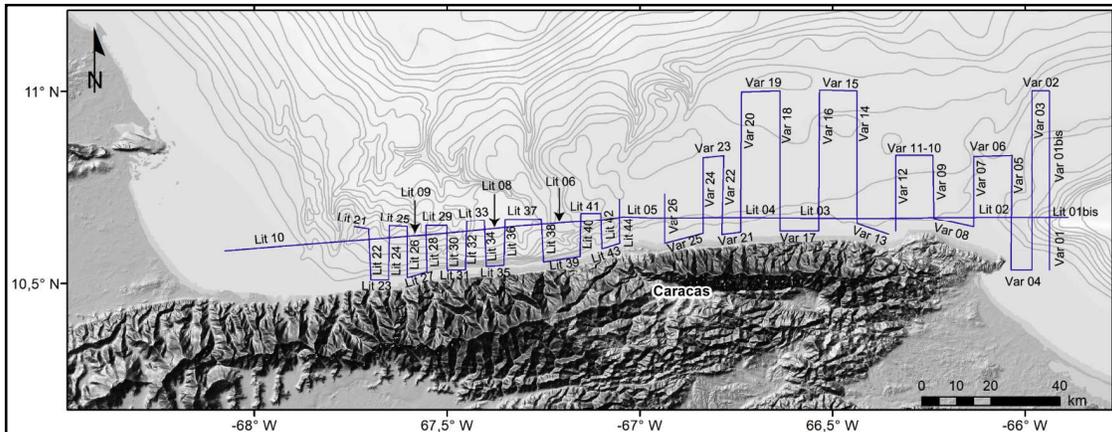


Figure 5. Bathymetry of the North of Venezuela (modified of [Sellier de Civrieux 1971](#)), relieve map surrounding onshore areas (based on SRMT) and seismic grid acquired in the survey expedition.

4.4.5. Seismic Stratigraphy

On the North of Venezuela margin, the seismic stratigraphy of La Guaira shelf, Choróní basin and Golfo Triste self is different. The sedimentary infill in La Guaira shelf is punctuated by several erosional unconformities named horizons (e.g. H5), all of them used to define seismic 6 main seismic–stratigraphic units basically. These erosional

unconformities occur mainly at the top of Units where they are most pronounced at the south margin of the shelf and they grade into correlative conformities towards deepest north margin shelf, indicating that the unconformable character is clearly depth-controlled.

4.4.5.1. Low-amplitude parallel stratified facies

The 6 deepest unit consist of a parallel-subparallel stratified facies with low-amplitude reflections in the base which we interpreted hemipelagic facies and for the top we found some high amplitude reflection associated with coarser terrestrial particles. The unit base is not perceptible because the resolution vertical of seismic reflection is not enough and the top called horizons 1 (H1).

The facies for the Unit 3 is similar to the Unit 6, parallel-subparallel stratified facies with low-amplitude reflections. The top of this unit is identified by horizons 4 (H4) characterized by truncation of reflection caused by shallowing shelf exposure related with lowstand of MIS 2, (LGM).

4.4.5.2. Prograding clinofolds

On N-S profiles, numerous lens-shaped or mounded sediment bodies are intercalated between the parallel stratified, vertically aggrading sequences. These sediment bodies with prograding clinofolds are located mainly on the shelf. Mostly in the La Guaira shelf and La Tortuga shelf. These are present in Units 2, 3, 4 and 5. Los sedimentos que llegan a la plataforma provienen de las pequeñas quebradas o ríos que drenan desde la Cordillera de la costa que vierten la Cuenca de sedimentos en dirección N-S. La cantidad de sedimentos es escasa y es sabido que épocas glaciares hay una fuerte acumulación de ellos que es descargada en épocas interglaciares. Estas facies progradantes pueden corresponder a estos niveles bajos de nivel de mar. Estas facies progradantes no se observan en todos los perfiles, pudiendo la tectónica de la falla de San Sebastián tene un papel importante en el proceso sinsedimentario de estos depósitos, permitiendo el no desarrollo de estas estructuras. Así mismo, las corrientes oceánicas que llevan dirección O-E pueden erosionar parte de estos sedimentos transportándolos hasta la cuenca de Chorón y de allí a la cuenca de Bonaire al norte.

Unit 5, 4 and 2 suggesting that these units represent north-prograding packages, rather than tilted, exhumed and eroded strata.

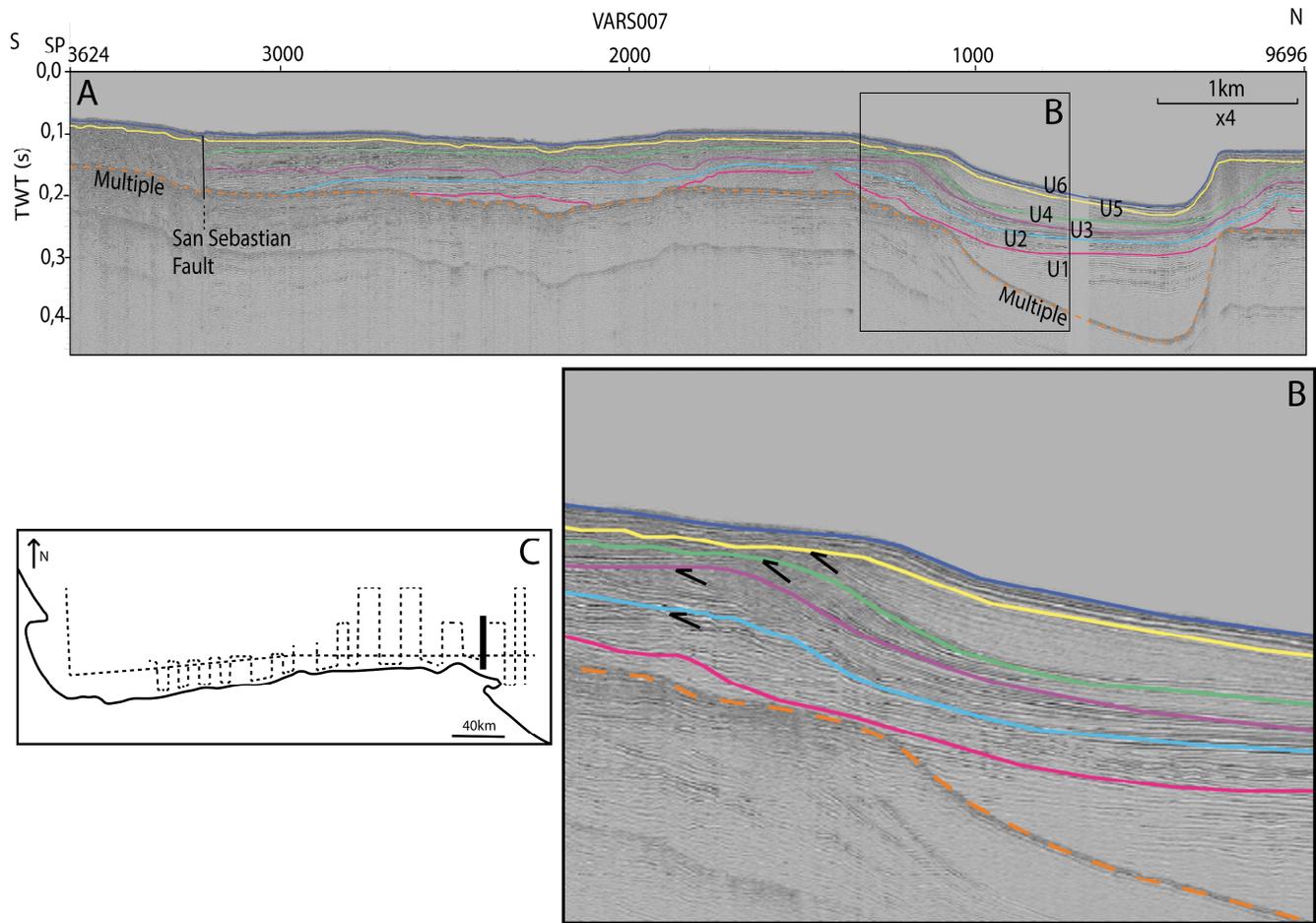


Figure 6. Interpreted Vars07 profile showing horizons and units in La Guaira shelf

On Vars001 and Vars003 profiles which are located eastward of La Guaira shelf are observed Sigmoid progradation reflector patterns corresponding with possible contourite drifts according with seismic features diagnostic of used by [Faugeres et al., \(1999\)](#). (Figure 7 and Figure 8)

Depositional units in contourite drifts that can be recognised on U2 and U4 of the seismic profiles with lenticular in shape, with more or less smooth to irregular bounding surfaces. They delineate an upwardly convex geometry that is nonparallel to the accumulation surface created by the preceding erosional event. The extent and detailed geometry of the units are limited on these profiles, suggesting a slow and a localized intensity of the erosion and degree of reworking that has taken place. U4 shows most clearly the nature of progradation oblique downlapping reflections than U2.

The flow E-W is directed alongslope, as with bottom currents and the Coriolis effect again deflects the flow to the right, effectively constraining the flow against the slope. Being so constrained the flow intensifies, erosion occurs and a channel develops. Lower velocities to the left of the flow favor deposition and drift construction, with the drift tending to migrate upslope as well as prograde alongslope.

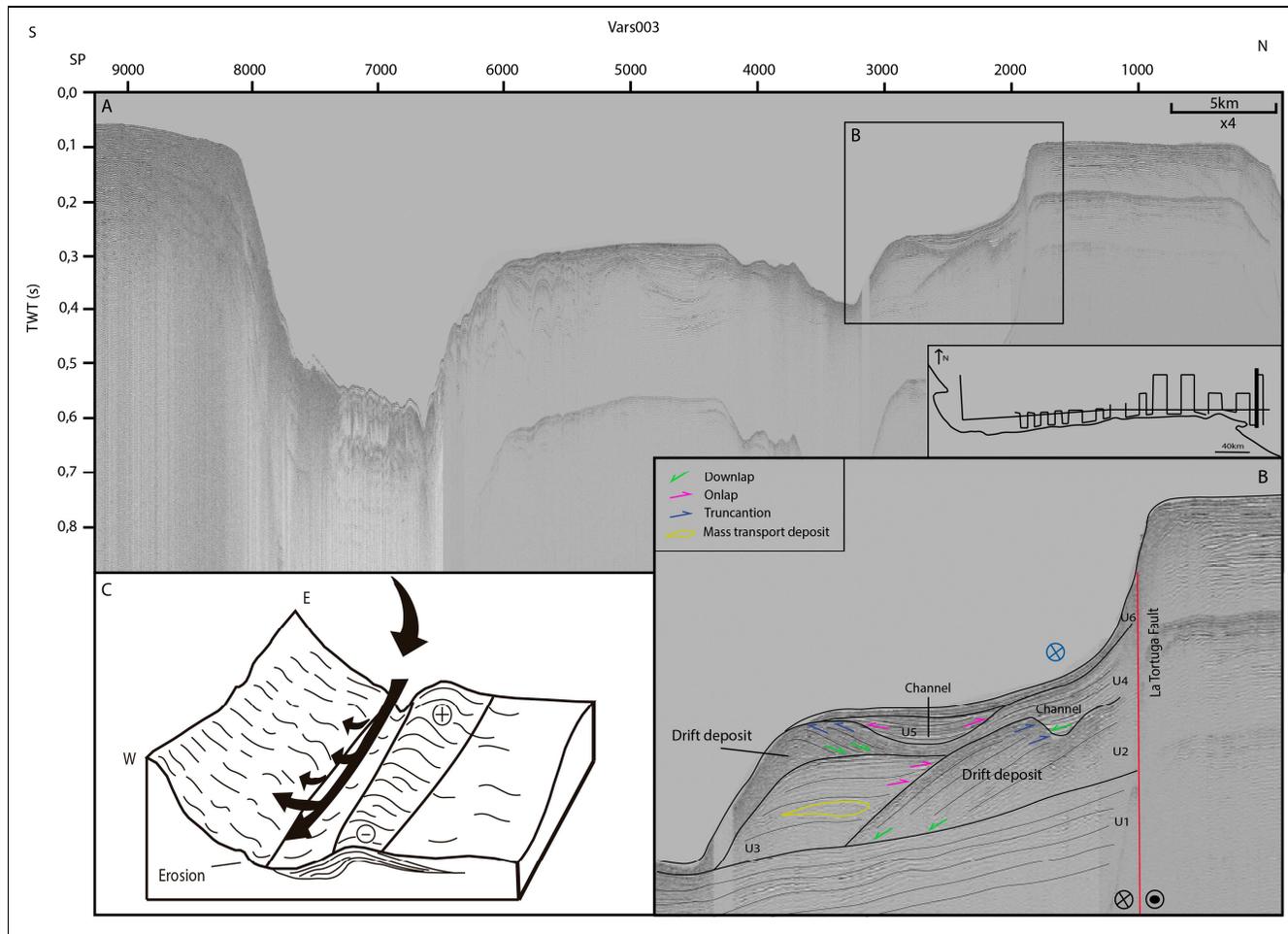


Figure 7. A) Vars003 seismic interpreted profil. B) Zoom on Vars003 profile possible drift contourite deposits and channel associated of the erosion by the bottoms currents C) Scenario illustrating the possible relationships between the slope trend, the current trend and the sediment levee pattern when contour current are involved in sediment deposition in the N hemisphere (Faugères et al., 1999)

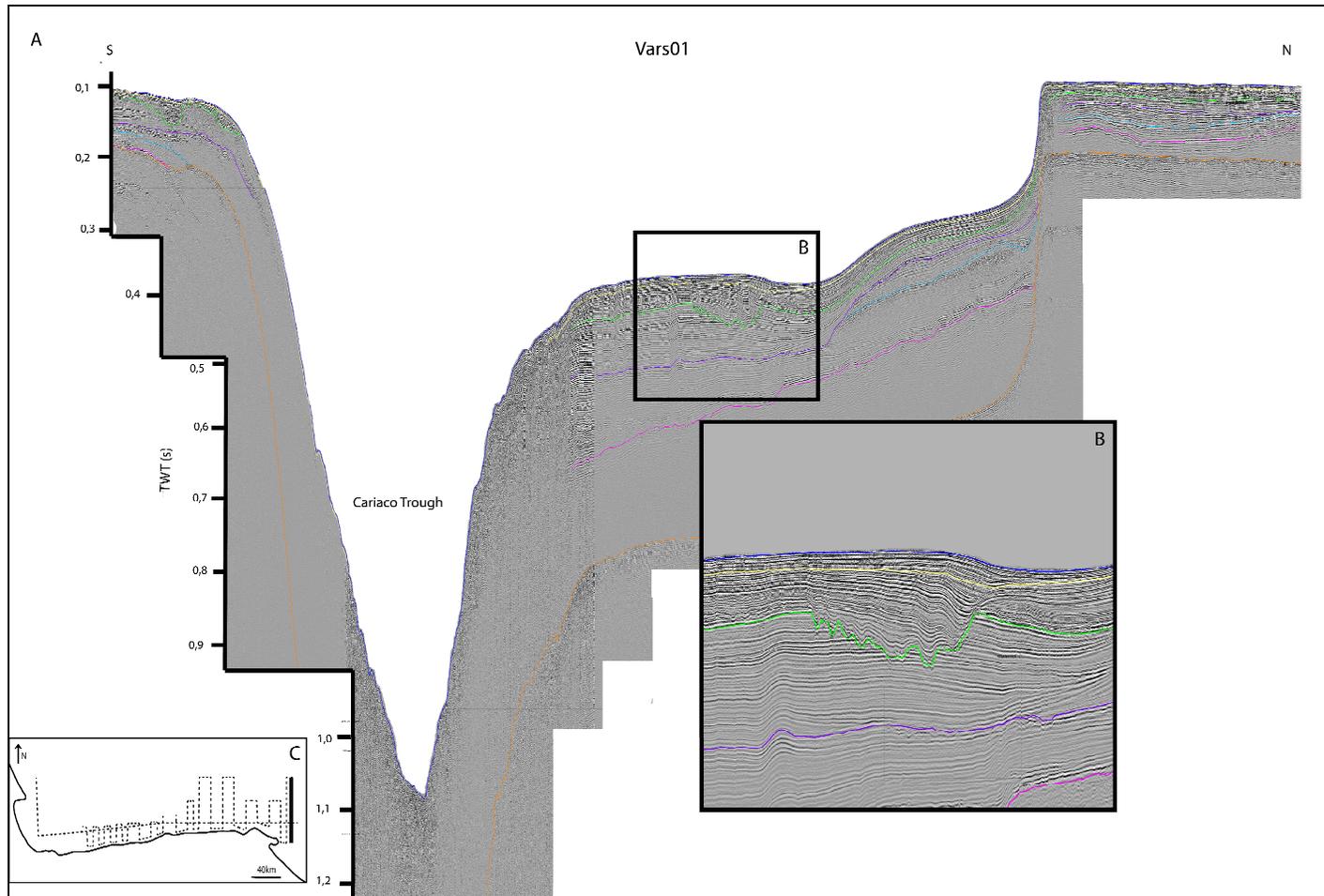


Figure 8. A) Vars001 interpreted seismic profil. B) Zoom on Vars001 profile swowing possible contournite deposits with strong erosion on the base generated by the bottoms currents

4.4.5.3. High – amplitude parallel reflection

Finally the unit 1, imaged high – amplitude parallel reflection package corresponding to transgressive Holocene to Present deposits.

Comparing with the high resolution seismic data of the Unare platform ([Espinosa and Daza, 1985](#)), located further east of the Guaira shelf, a similarity is found in the Holocene deposits with the La Guaira shelf Holocene deposits. For both deposits we had interpreted the unit constituted of clay and silt little consolidated in the upper part and clayey sand in the surfaces of erosion. Finally both shelves show a very similar thickness of 0,025s.

4.4.5.4. Transparent to very-low-amplitude mounded stratified facies

Another facie recognized in the unit located in the beginin of the slope between Vars014-Vars026 profiles, is represented by mounded, chaotic-reflection free reflectors wich we interpreted like Banks of reef facies. This similar facies is observed on the northward margin in La Guaira shelf, documented by [Sellier de Civrieux \(1977\)](#) for Los Placeres (La Guaira, Los Caracas and Caruao) like a layers of sand with calcareous bottom and reef fauna type.

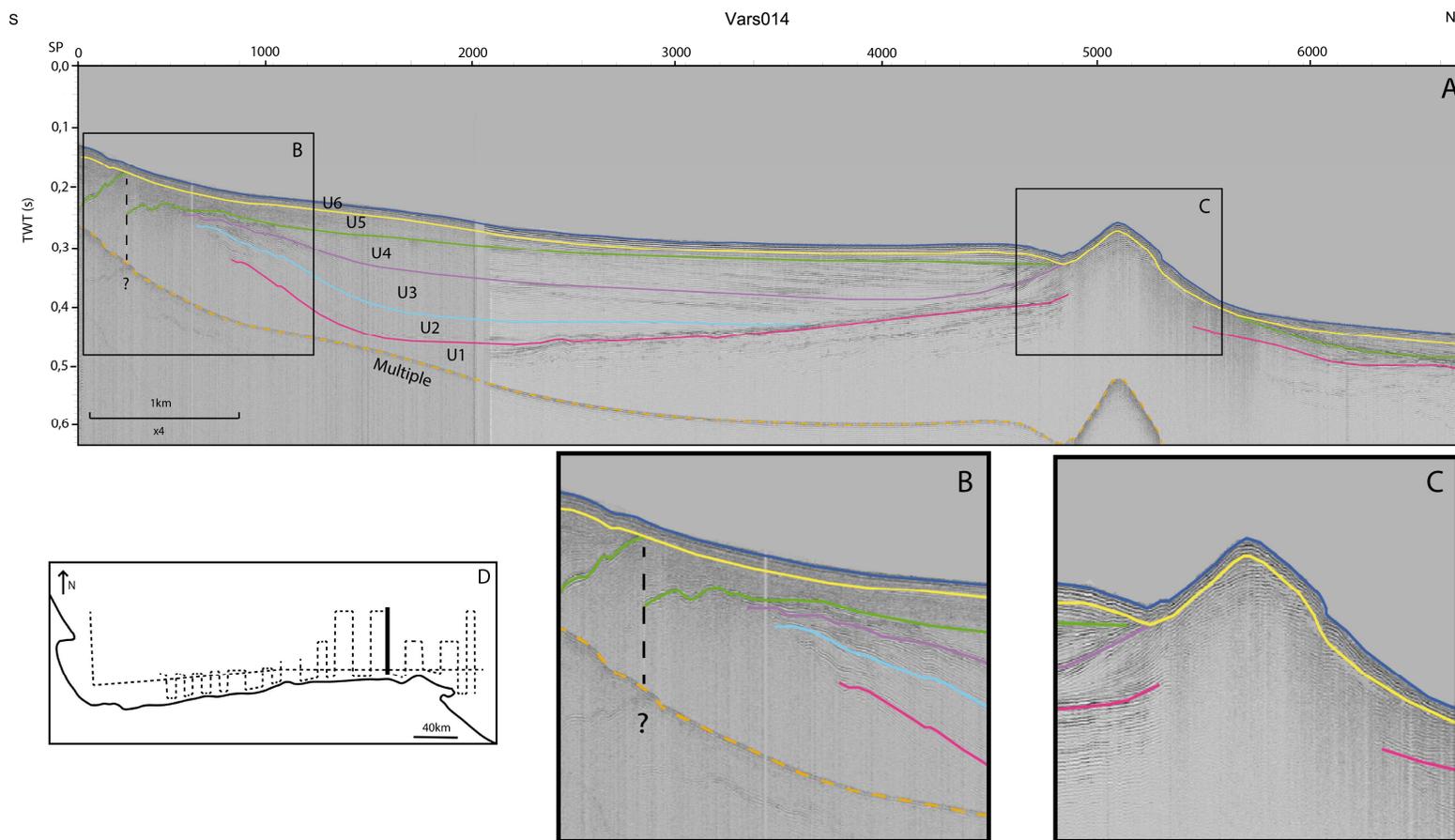


Figure 8. A) Vars014 interpreted seismic profil. B) Zoom on seismic profile showing banks of reef facies on the shelf. C) Zoom on seismic profile showing banks of reef facies associated to El Placer los Caracas

4.4.5.5. Chaotic high amplitud

For the Choróní basin our data do not image any deeper extended horizons and seismic units, despite a penetration depth of 560ms that should allow reaching the MIS 5 highly-reflective units described in the eastern La Guaira shelf. In addition to this, [Sellier de Civrieux, \(1977\)](#) described westward shelf has major changes, where it experimented deepening-narrowing in Choróní basin. The transition between both is marked by the Mamo submarine canyon. Previous bathymetry data show that the canyon from the mouth of the Mamo River until the upper slope the canyon shows both linear and highly sinuous segments with a remarkable and abrupt change in direction from NS to NW -SE. The new NS-trending, Lit040 profile (Figure 7) we identified the six units correlated with La Guaira shelf units are affected by numerous subvertical normal faults. The horizons are slight angular, subparallel unconformities deeping in a canyon floor. U1 and U2 show deformed reflections reflections when U3, U4, U5 and U6 exhibits well-stratified oblique reflections prograding in a seaward direction. U5 units are deeply incised by an irregular surface at the base of U6, which underlines a possible paleocanyon floor.

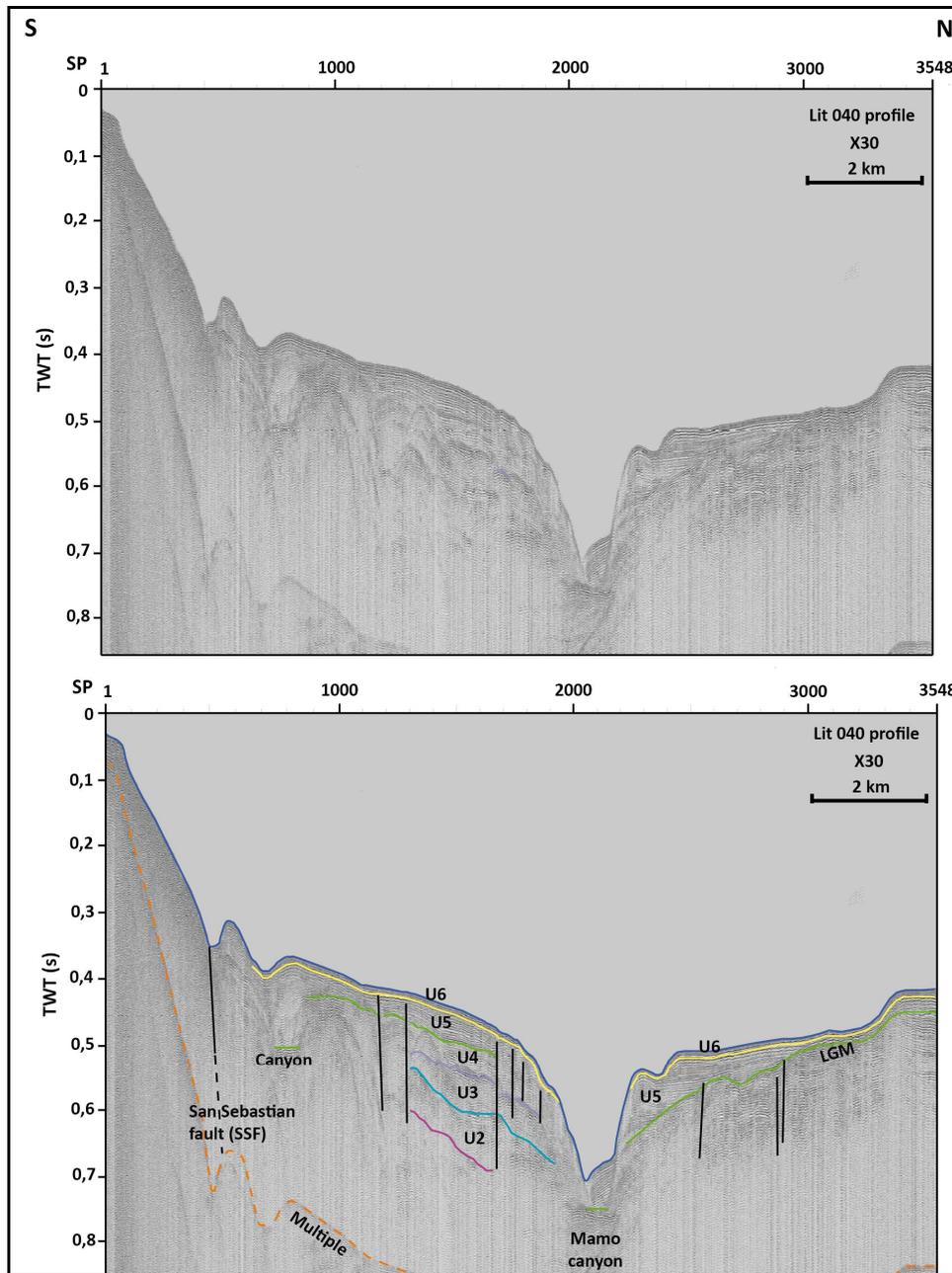


Figure 10. Uninterpreted (above) and interpreted (below) sparker profile (LIT 40). Relative location is shown in Figure 5. A complex SSF, comprising several active splays, is imaged, on which the Mamo canyon is superimposed and fossil canyons as well.

Low amplitude reflection in the basin of Choróní suggest silts and silty clay facies. Mamo canyon is the way for the turbidite flows. The recurrence in time of climatic cycles is feasible, with high volumes of rainfall, that the impact on the flow regime of rivers accumulated sediments in the valleys submerged to produce instability and collapse mass to trigger avalanches into the system of submarine canyons of Choróní basin.

4.4.6. Erosional unconformities

The major here-defined unconformities (truncations of prograding units or strong erosion, locally scarving surfaces; Figure 6, Figure 8) could be correlated through the whole studied area. To convert this seismostratigraphic frame into a chronological one, we first envisaged a comparison with the Gulf of Cariaco, part of the same margin and built on the prolongation of the San Sebastian Fault: the El Pilar Fault. Based on a detailed seismic stratigraphy, [Van Daele et al., \(2011\)](#) proposed a chronological frame where the lowest unconformity is attributed to MIS 6. Nevertheless, the situation is rather different as, due to a shallow entrance, the Gulf of Cariaco is disconnected from open sea during low stands; evaporates characterize these stages.

To discuss the sea-level fluctuations over the La Guaira Shelf, we considered global curves ([Waelbroek et al., 2002](#); [Van Daele et al., 2011](#)). Refined methods for the identification of sea-level fluctuations and different analyses of passive margins (e.g. [Mauffrey et al., 2017](#)) have shown that the different MIS (excentricity, obliquity, and precession) may not have similar impact on global sea-level. Regional frameworks (in terms of clastic input for example) have their influence. Thus, we propose to attribute the deepest (and oldest) observed discontinuity (Unit 1/ Unit 2) to MIS12 rather than to MIS 6.

4.4.7. Offshore active faults

4.4.7.1. San Sebastián fault (SSF)

The San Sebastián fault (SSF) runs nearly 500-km-long offshore along the north-central coast of Venezuela, very close to the shore of the Coastal range (Figure 1, 4 and 10), for this reason very few seismic lines have in fact depicted the fault plane of the main strand at depth. The previous surveys have mainly captured the same strand identified by [Magnani et al. \(2009\)](#) and have failed to image the main strand at the shore. In this shallow seismic lines of our data, these lines have actually cut the main strand of the SSF where the fault plane can be seen in some lines. Beginning with the west zone (Choroní Basin), the fault plane in the lines LIT 26 - 38 is on the very left edge (southern end) of the line, indicating that the fault lies almost below the coastline, on a very steep seabottom, which seems to be the submarine extension of the up to 20° steep northern flank of the Coastal range. The fault is almost perfectly vertical.

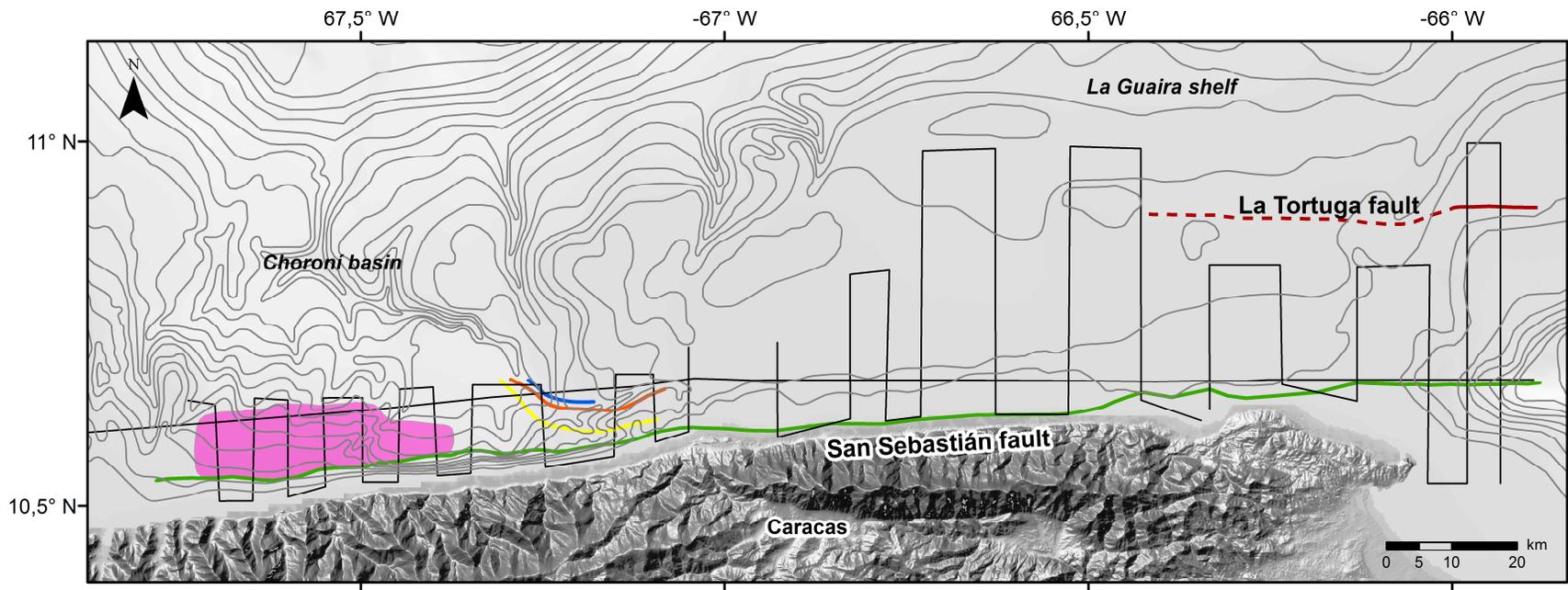
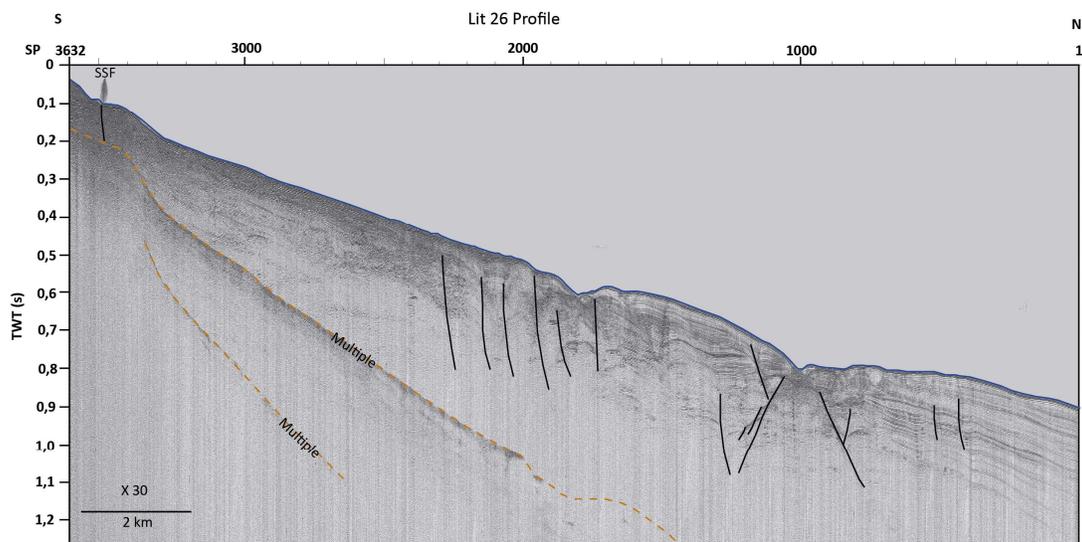


Figure 11. Interpretation of faulting along the North-central Venezuelan coast, from acoustic reflection profiles. Red line: San Sebastian fault. Green line: La Tortuga fault. Blue line: Active faults from Paolini et al, 2012.

From the fault in Figure 9a, it appears that some gas venting or seepage was escaping during the line acquisition, pinpointing accurately the sea-bottom location of the fault plane. The seep is perfectly located at the contact of a bench with the steep sea-bottom (Figure 9a). The fault is less prominent in LIT-38 (Figure 9b), although it appears to be at the first slope break. Farther away from the shore (towards the right), several other subvertical fault strands, in a number up to 4 major planes, are contained in a 10 - 12 km wide tectonic corridor or strip (Figure 9b). This seems to coincide with the mapping of Schubert and Krause (1984) for the region just west of Maiquetía. All of them are equally active because present-day sea-bottom is affected by these fault planes. LIT 40, closer to Maiquetía than the 2 previous ones, also exhibits several active fault planes, on which submarine canyons have developed nowadays and on the past (Figure 9). The active zone of deformation here (LIT-40) is as wide as to the west (LIT-26 and -38).



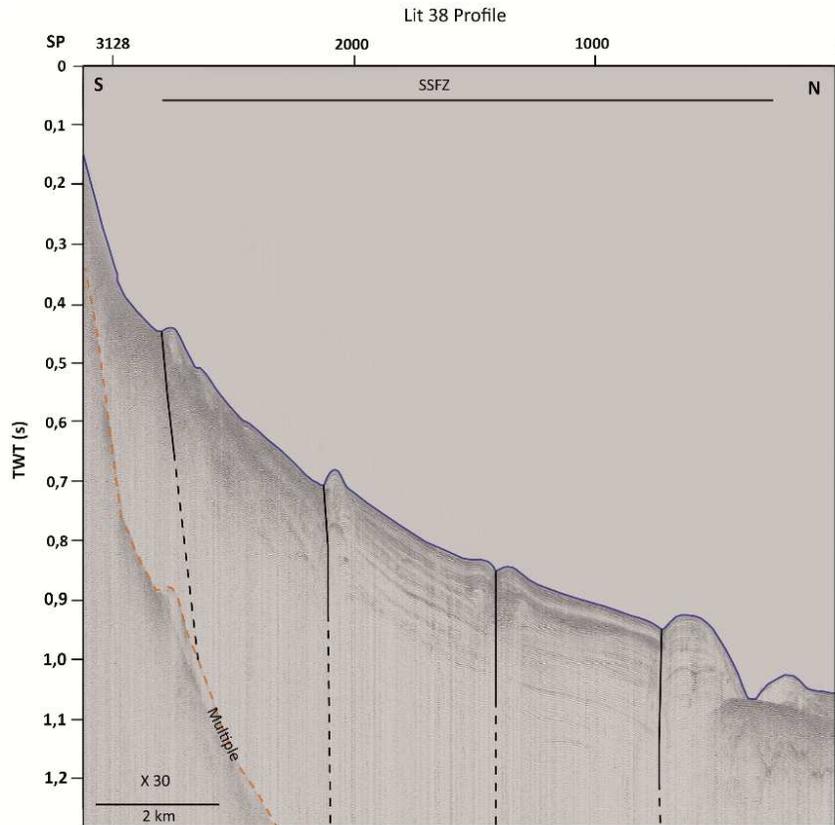


Figure 12. High resolution shallow seismic profiles: Above LIT 26 and below LIT 38. Both sparker profiles show the multiple active fault splays composing the SSF, as evidenced by disruption of sea-bottom. The main strand, exhibiting a sub-vertical fault plane, is at the very left of both profiles, very close to southern profile tip.

Conversely to the western part, the fault east of Maiquetía seems much simpler and all deformation seems accommodated by a very sharp and conspicuous single fault plane (Figures 10 through 12; refer to Figure 5 for location). Between Maiquetía and Chuspa (profiles VARS 14 through 20), the SSF runs at the northern edge or break of a rather narrow hanging submarine shelf, which resembles to a huge fault bench (Figures. 11 and 12). It is here confirmed that the fault near sea-bottom is perfectly vertical to subvertical. Here, the coastline is also straighter, paralleling the bench break, with less embayments and salients than west of Maiquetía, if discarding the few coastal salients associated with modern sedimentation of alluvial fans.

Only the particular configuration of the shore, with a large embayment at Chuspa, close to Cabo Cadera, made possible the best imaging of SSF east of Maiquetía along the Coastal range in Northeccentral Venezuela (Figures. 5 and 10), in which the R/V Guaiquerí II could actually navigate across the submarine fault trace, as evidenced by the

seismic line VARS 12. As a matter of fact, it is at this embayment where the fault also appears to be the freshest as it exhibits a very well-preserved north-facing 1.5-m-high fault scarp (Figure 10).

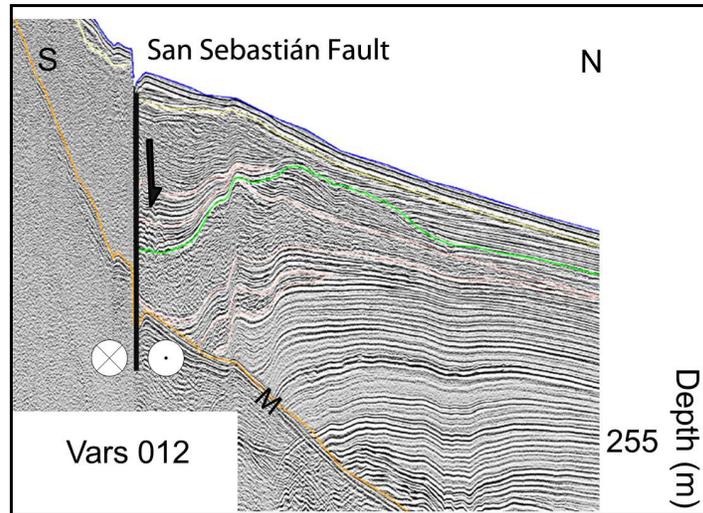


Figure 13. The SSF appears as a very sharp single vertical fault plane, conversely to the structural style exhibited west of Maiquetía. This visualization is possible because the coast has a large embayment at Chuspa, several kilometers west of Cabo Codera (easternmost tip of the Coastal range), allowing the vessel crossing across. Note the freshness and preservation of the north-facing fault scarp in unconsolidated sediments

In turn, this fault attitude could be inherited from the prior southeast-directed nappe overthrusting during the oblique subduction-collision phase between the Caribbean and South America plates that predated the orogenic collapse, justifying somehow the low dip of this structure at high depth.

4.4.7.2. La Tortuga fault (LTF)

This dextral strike-slip fault (Figure 4.6), is located parallel to and northward of SSF. This fault appears on Var01bis and Var03 profiles and, westward the seismic data (Var05, 07, 09 and 12 profiles) did not reach the west lateral extension of the fault, thus the LTF is inferred until the Var14 profile where LTF trace disappears of the profiles. Therefore the fault running along the southern edge of La Tortuga shelf (Figure 4.6) where its lateral extent is limited to several tens of kilometers at most, being restricted to a position roughly east of Cabo Codera, where the LTF exhibits a very important vertical offset (Figure 4.7), which does not exclude that the LTF may also have a dextral component of slip. Certainly, it does not prolong into the Oca-Chirinos fault, as once proposed by [Schubert and Krause, 1984](#); and as much westward as maintained by Beltrán

(1993, 1994) in his compilation map of Quaternary Faults of Venezuela. East of la Tortuga high, it does not appear to extent very far either. However, comparing the LTF trace of [Paolini et al., 2012](#), on the Var profiles the LTF runs northward.

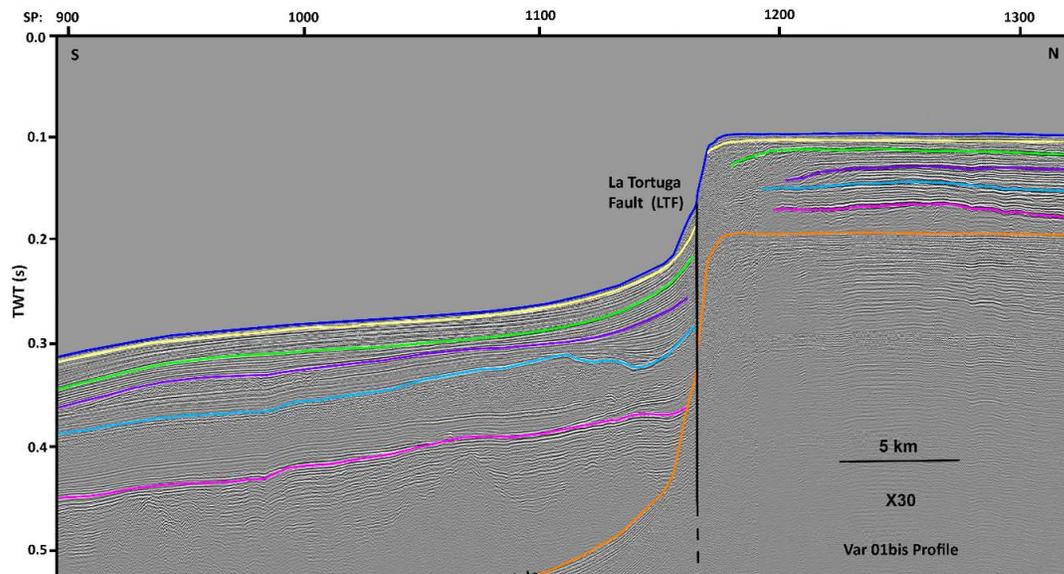


Figure 14. Var001BIS profile showing La Tortuga fault cut off the La Tortuga shelf

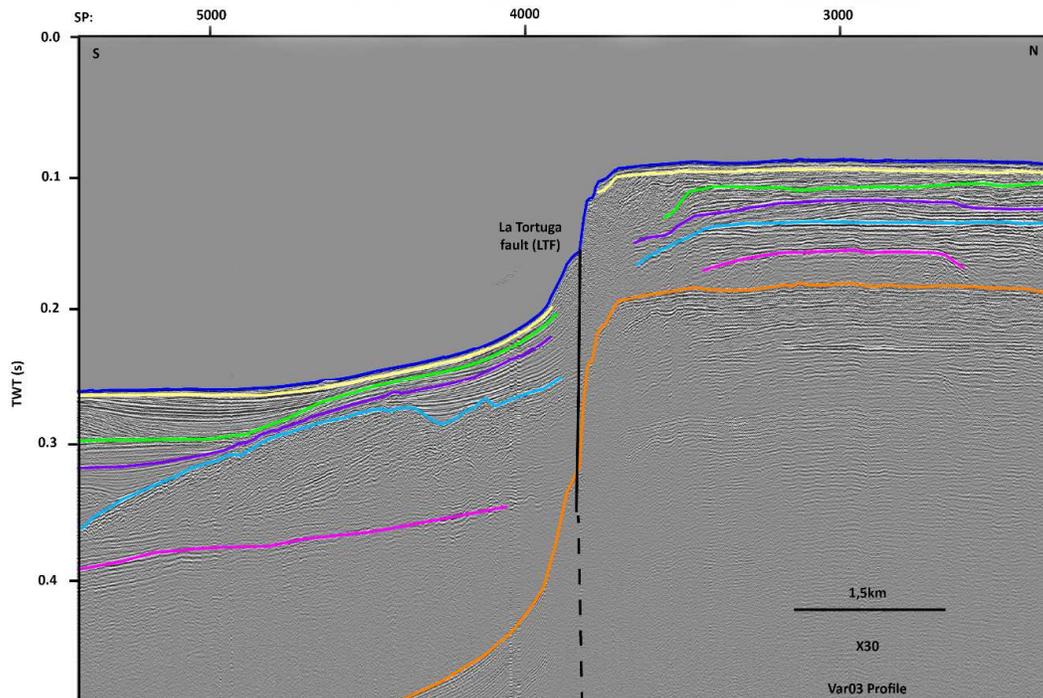


Figure 15. Var03 profile showing La Tortuga fault cut off the La Tortuga shelf.

4.7.8. Tentative estimation of mean subsidence of the La Guaira Shelf

Both previous bathymetric data and our own HR seismic survey display a major subdivision of central northern Venezuela margin into: The la Guaira Shelf, the Choroni basin and Golfo Triste shelf, all of them being limited to the south by the San Sebastian fault. Which the Choroni Basin appears tectonically complex, the Golfo Triste and La Guaira Shelf represent a rather simple homogeneous block. Thus we choose the central part of the La Guaira Shelf to calculate an estimation of the subsidence vertical displacement which can be considered as a component of the dominantly strike slip San Sebastián fault.

On most of the HR profiles, the strongest and widely developed discontinuity is considered as corresponding to MIS12 sea level lowstand (Figure 12 and 13). Based on correlation with global curves (Waelbroeck et al., 2002; Siddall et al., 2003) and with results concerning the Gulf of Cariaco (Van Daele et al., 2011). A 130 ky BP is given to this event, the sea level being considered as 130 m deeper than at Present. A 20 ky BP is given to MIS2 lowstand, the sea level being considered as 120 m deeper than at Present. For our estimation, we used a 1.5 km.s^{-1} velocity for the sea water, a mean 1.6 km.s^{-1} for the post-MIS2 sediments, and a mean 1.8 km.s^{-1} for the sediments accumulated between the MIS2 and MIS12 discontinuities.

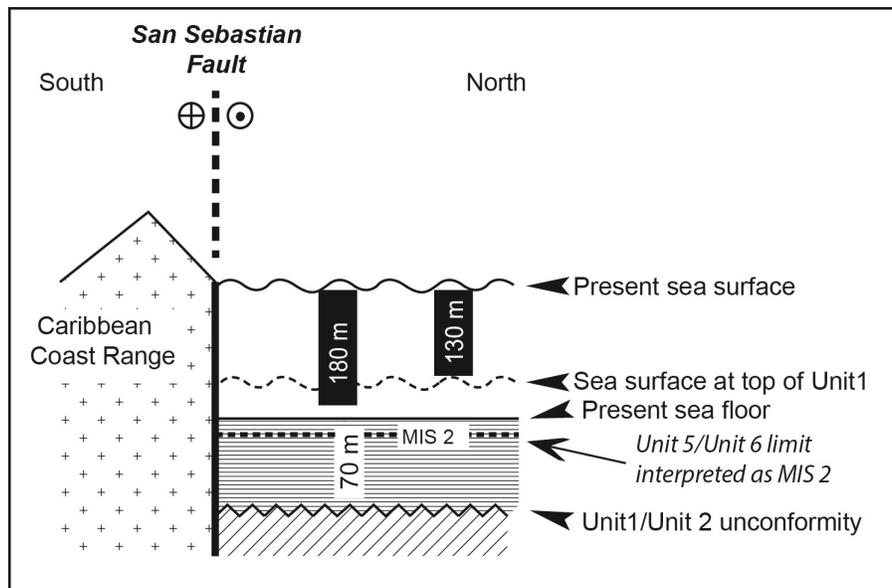


Figure 12. Schematic La Guaira shelf situation at unconformities Unit 1/Unit 2 and Unit 5/Unit 6.

The vertical motion was estimated using reef facies show on northward Vars014 and recognized by [Sellier de Civrieux \(1977\)](#) on the Placer de La Guaira which live on 10-20m depth water, if the eustatic level were stated 120m, the subsidence is $1,2 \text{ mm.yr}^{-1}$. Is the value for the last 24ka (Figure 14) and estimates made by [Sellier de Civrieux \(1977\)](#) where recognize to a depth of 183m at the pleasure of the Guaira a Pleistocene reef facies for the LGM who lived between 10 to 20m above sea level.

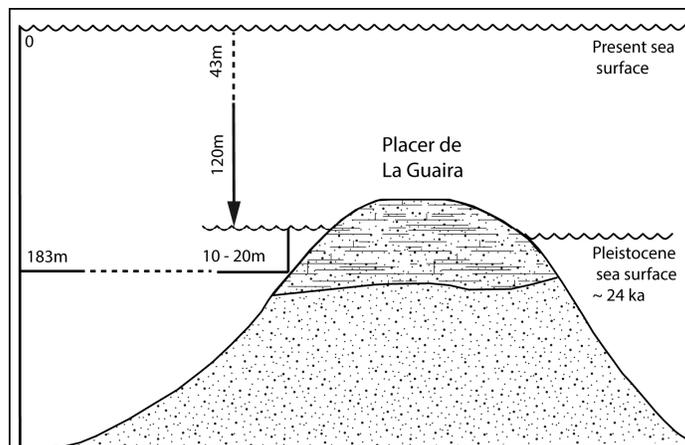


Figure 14. Reef facies on the Placer de La Guaira formed during MIS 2 lowstand. The subsidence is 43m for the last 24 ka, approximately $1,2 \text{ mm/ka}$. (Modified of [Sellier De Civrieux, 1977](#))

Other data interesting for this estimation is two earthquakes associated with the San Sebastian fault motion, their respective data of the focal mechanisms (Table 1 and 2), allowed us calculated the pith value then using trigonometrie we found the vertical displacement for these events is between $0,5 - 1 \text{ mm.yr}^{-1}$ with respect to the horizontal movement of this fault on the La Guaira shelf.

	Azimuth	Dip	Slip
A	90	74	176,4
B	181	86,5	16

Table 1. Solutions of proposed focal mechanisms for seismic events that occurred in Venezuela and neighboring areas between August 2005 and December 2008. ([Palma et al., 2010](#))

	Azimuth	Dip	Slip
A	81	70	180
B	171	90	20

Table 2. Focal mechanisms for seismic event that occurred in North margin of Venezuela April, 2009. (http://www.funvisis.gob.ve/old/mecanismos_focales.php?pag=7)

4.7.9. Conclusion

The large uncertainties on the fault seafloor traces and their extent in North-central Venezuela. High resolution seismic allowed us to deter problems continuity of La Tortuga fault located north of the San Sebastian faults and corroborate the existence of the latter with clear evidence of recent activity, apart from seismic activity record (e.g. Colón et al, 2015) we have in the most of high seismic profiles a clearly evidence of recent deformation caused by SSF.

Using our lowest unconformity (Fig 12 and 13) we infer that the La Guaira shelf was expose to aerial erosion during MIS12 and MIS12 periods (Figure15). The present depth of the oldest unconformity in the center of the shelf and global eustatism data led to a 0.14 mm/y subsidence for the last 700 Myr. This rate only concerns the La Guaira Shelf.

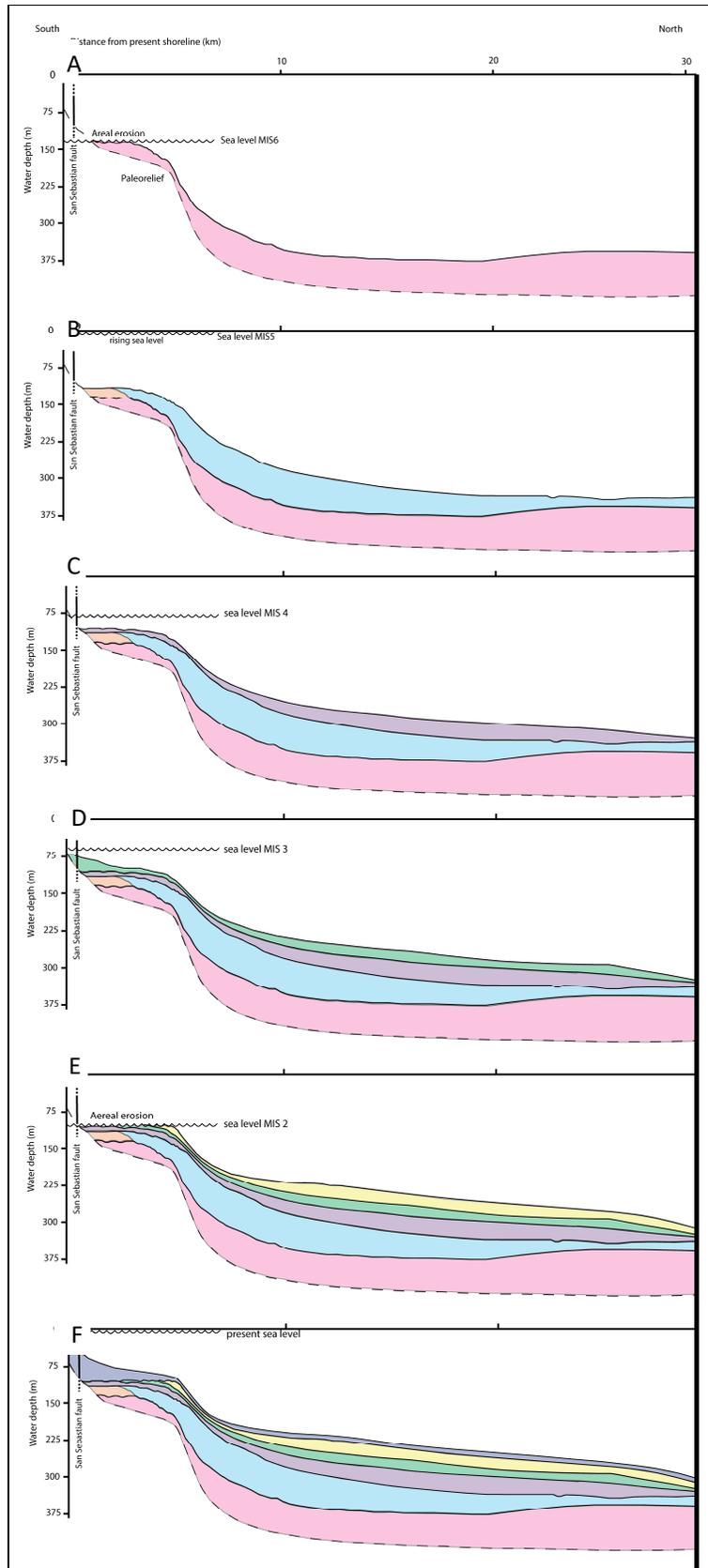


Figure 15. Scenario based on observed geometries for the deposition of the last 130 ka sequence of (from MIS 5 to present) in the La Guaira shelf (Vars018 profile see position in Figure 5). Depths are in meters. The black surface corresponds to major discontinuity for every unit. A) Rose: Unit 1. Correspond to MIS12 period where the shelf had aerial exposure because the sea level descends 130m respect to present. Top deposits Unit 1 show a strong eroded surface B) Orange-blue: Unit 2. Transgressive deposits characterized this period. The reef facies (orange) appear when the sea rise C) Violet: Unit 3. The sea level descends but only 75m and the shelf is not expose in this period and. D) Green: Unit 4. The transgressive sediments are restricted to a thin veneer of reworked sandy materials on the shelf E) Yellow: Unit 5. Correspond to LGM, where a situation similar to MIS12 occurred. The exposure of the shelf occurred and strong discontinuity is marked in the unit 5. F) Depth-blue: Unit 6. The sea level rise until the present level. Unit 6 deposit are cut by San Sebastián fault. The thickness is major in the inner-shelf

The subsidence measured in the HR profiles a cross the central part of the La Guaira Shelf is $0,14 \text{ mm.yr}^{-1}$. For the Choróní basin is not possible calculated the same way because is not possible to correlate the discontinuities seen in the La Guaira shelf but the vertical motion is clearly higher than for the later one. The Golfo Triste shelf is more stable rather than the other shelves.

According with Paolini 2012, the North margin could be divided into 4 provinces (Figure13) with different sedimentological and tectonic features. In the high of Codera is influenced by the active north La Tortuga fault and south failure is observed San Sebastian. Westward, La Guaira shelf, an erosive and shallow platform with a gently and continuously sloping submarine plain down to 360m, which steeper between 0 and 200m. Three plateaus or banks of reef interrupted abruptly rising from the bottom of the submerged plain (La Guaira, Los Caracas and Carua). To the west, the Choróní basin appears with an abrupt deepening of the platform, this influenced by a series of normal faults affecting up early Miocene deposits. These normal fault defined by Paolini 2012, are responsible for the submarine canon "A" (Sellier de Civrieux 1971; Paolini 2012), which is connected with the canon Mamo in surface. Through these canyons they are transported sediments to the Bonaire basin. Finally, Golfo Triste shelf have the similar features of La Guaria shelf, in other words an erosive and shallow platform with a gently and continuously sloping.

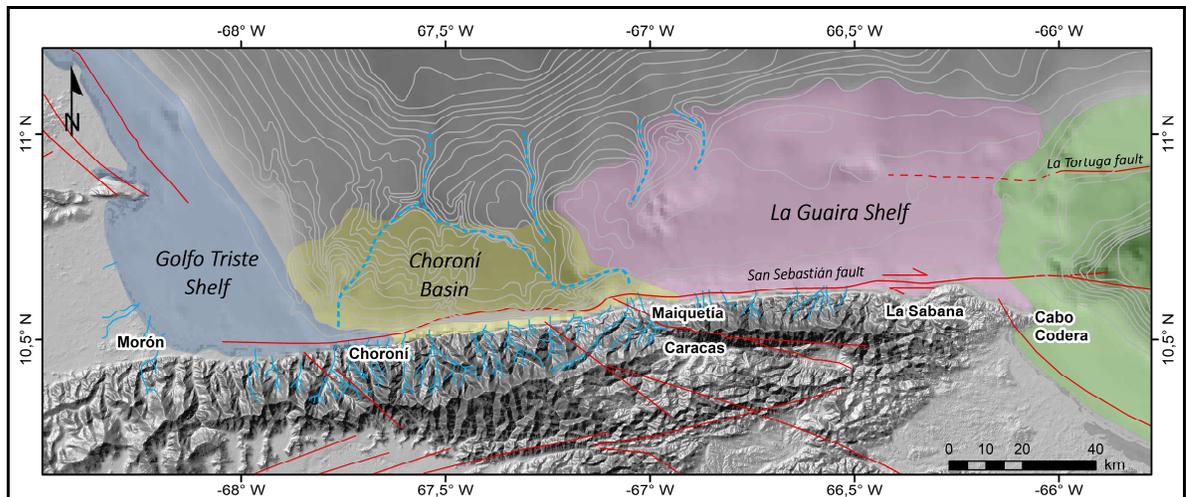


Figure 13. Tectonic provinces on the North central margin of Venezuela. Blue zone: correspond to Golfo Triste shelf. Yellow zone: Choroní basin. Rose zone: La Guaira shelf and Green zone: High of Codera.

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Chapter 5

Instabilities and gravity reworking interpretations

This chapter is presented as a first version of a paper to be submitted in a few months in Marine Geology

Instabilities and gravity reworking interpretations of sedimentary deposits on the Margin North of Venezuela

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Abstract

An overview is given of mass wasting features along the North margin on Venezuela shelf, where this is characterized by active tectonics along the San Sebastian Fault and by eustatic sea level changes controlling the sedimentary, geomorphologic and structural process on this zone. A high resolution bathymetric data is have been used to identify, map and date submarine slope failures and mass wasting deposits. Gravity mass movements are widespread on the steep slopes of north margin of Venezuela, centered mostly east and west of La Guaira shelf, where the slope plays an important role due to its increase, allowing more easily the development of these events e.s. Choróní basin. Thus, the mass wasting features, have been analysed in connection with crustal deformation. These gravitational gliding masses are probably induced by the transtensional deformation within the crust. Moreover, age relative estimation of landslides and debris flows indicate that they were more frequent during the last transgressive phase, when the rate of terrigenous sediments supplied by the canyons to the deep basin was higher and the exposure of the shelf. We discuss these results taking into account activity, pre-conditioning and trigger mechanisms for slope instability with respect to tectonics and paleo-environmental changes induced by sea-level oscillations.

5.1. Introduction

Along continental margins, and especially on their slopes, an important part of sediments is mobilized through gravity instabilities leading to slope failures and associated mass movements. Their importance and recurrence depend on various factors (i.e. lithology, presence of fluids, overpressures, seismicity, tectonic activity, structural inheritance, sedimentary input, eustatism, etc.). Studying slope instabilities have two main issues: to better perform risk assessments (tsunamis) and more conceptually, to better understand how they participate to the evolution of submarine reliefs and to deep-sea sedimentation processes. Many studies of submarine slope instabilities are focused either on tectonically active areas (see the examples of Marmara sea or Nankai, [Zitter et al., 2012](#); [McHugh et al., 2006](#); [Gazioglu et al., 2002](#); [Yalciner et al., 2002](#)), or on passive margins, nearly exclusively along highly sedimented divergent segments (e.g., [Sager et al., 2004](#); [Tripsanas et al., 2004a and b](#); [Sultan et al., 2004](#); [Loncke et al., 2009 a and b](#)). Although several shear margins exist in the world (30% of passive margins) and present very specific structurations (e.g., Equatorial Atlantic margins: in [Gouyet, 1988](#); [Basile et al., 1993](#); [Benkhelil et al., 1995](#), Davie Fracture Zone: in [Masclé and Blarez, 1987](#), Southern Exmouth plateau: [Lorenzo et al., 1991](#); [Lorenzo, 1997](#), Agulhas-Falkland Fracture Zone: in [Lorenzo and Wessel, 1997](#), northeastern Canada: in [Reid and Jackson, 1997](#), and probably a part of the Gulf of Mexico: in [Buffler and Thomas, 1994](#); [Pindell, 1985](#)), few studies have up to now focused on the distribution and importance of slides along these margins.

The Venezuelan northern margin is a region along a system of active right lateral strike slip faults which edge the transform boundary between the Caribbean Plate and the South American Plate ([Audemard et al. 2000](#)). This strike-slip fault system along Caribbean-South America plate boundary zone extends offshore for over 400 km. As a result of this setting, the Venezuelan northern margin is affected by a series of active faults (e.g. San Sebastian fault) ([Audemard, 2007](#); [Audemard et al., 2000](#)).

In this area there are historical evidences of earthquakes with tsunamigenic reports on the shores of the northern margin of Venezuela (eg 1300, 1812, 1900) ([Schubert 1994](#), [Oropeza et al 2016](#)) with an important occurrence of landslides or deposits associated with these events. Another important factor that can participate in the sediment reworking and to contribute to the landslides are torrential avalanches from Avila with a significant

sedimentary load (eg 1798, 1914, 1938, 1944, 1999) (Rodriguez et al., 2006, Urbani, 2008; Perez, 2001; Audemard, 2007) This last event recorded an important volume of sediments (8-10m thick) even modified the coastline making it gain ground of about 100m.

We investigated using a dense grid of single-channel high resolution sparker seismic profiles to understand the relationship between the sedimentary process/instabilities and climatic or structural heritage (tsunamis)

5.2. Geological setting

5.2.1. Structural and seismotectonic context

Northern Venezuela lies in the interaction zone between the South America and Caribbean Plate (Figure 1). The Caribbean-South America Plate boundary from Colombia to Trinidad is over a 100-km-wide active compressional right-lateral strike-slip zone onshore and offshore northern Venezuela (Audemard, 1993; Singer and Audemard, 1997; Pindell et al., 1998; Audemard et al., 2000, 2005; Ysaccis et al., 2000). Significant positive relief is present along the Coastal and Interior ranges of Northcentral and Northeastern Venezuela. Further west, the southern Caribbean boundary broadens to as much as 600 km and includes several small tectonic blocks or microplates.

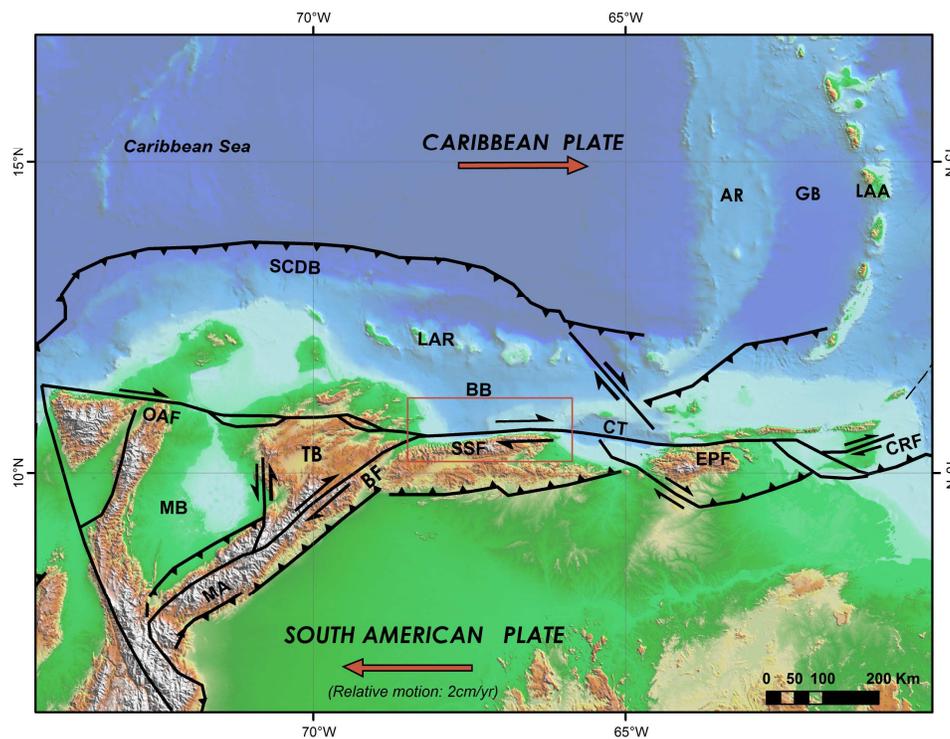


Figure 1. Present day geodynamic setting of the North-Venezuela margin along the transform boundary between the Caribbean Plate and South American Plate (Audemard 1999b; Audemard et al., 2000; Webber et al., 2001; Trenkamp et al., 2002). Study zone enclosed with a red rectangle. Tectonic Provinces - AR: Aves Ridge; GB: Granada Basin; LAA: Leseer Antilles Arc; SCDB South Caribbean Deformed Belt; LAR: Leeward Antilles Ridge; FB: Falcón Basin; BB: Bonaire Basin; CT: Cariaco Trough; MB: Maracaibo Block; TB: Trujillo Block; MA: Mérida Andes. Quaternary faults - BF: Boconó Fault; OAF: Oca-Ancón Fault; SSF: San Sebastián Fault; EPF: El Pilar Fault; CRF: Central Range fault

The most important structural local right-lateral strike-slip fault located between Cabo Codera and Golfo Triste is the San Sebastián fault (SSF) which runs nearly 500-km-long offshore along the north-central coast of Venezuela, very close to the shore of the Coastal range. On the HR profiles, this fault show vertical and subvertical dip. Along the northern margin can be seen in the La Guaira shelf a clear and net trace of SSf wich cuts the sediments that reach the surface. Eventually deformation of the sediments can be observed. Westward, on the Choroní basin the morphology changes, SSfF show the parallel traces and subparallels to the principal estructure and its observed that the sediments are much more deformed in this area, with a tendency to landslides, which will be discussed in this section.

5.2.2. Sea floor morphology

Sellier de Civrieux, (1977) distinguishes, from east to west, three physiographic provinces: Platform of La Guaira, Choroní Basin and Platform of Golfo Triste (Figure 2). The two mentioned platforms are erosional type and they are separated by Choroní basin, which he describes as a deep depression graben aspect, almost absent continental shelf with submarine canyons (Sellier de Civrieux, 1971). The continental shelf of **La Guaira platform** extends with a wide, gently and continuously sloping submarine plain down to 360m, which steeper between 0 and 200m. Three plateaus interrupted abruptly rising from the bottom of the submerged plain (La Guaira, Los Caracas and Caruaó) (Sellier de Civrieux, 1977; Paolini, 2012) (Figure 2). The boundary with Bonaire basin corresponding to normal faults in the basement, allowing an south – north depth abrupt change since the continental shelf to the Bonaire Basin (Paolini, 2012). Westward, the zone of greatest subsidence seems to be the **Choroní basin** with almost nonexistent continental shelf. This depression is connected to the north with Bonaire Basin. The two well-characterized canyons are a close relationship with the current in the Serrania Del

Litoral. Eastward Choróní basin, Mamo river mouth discharge into the Canyon of Mamo, which is tectonically controlled by the northeast-seaward extension of the Tacagua-El Avila faults (Rial, 1973; Sellier de Civrieux 1971). Westward Choróní basin is located the Canyon of Ocumare, in which discharge sediments of the Ocumare River (and perhaps the Cata River). These two submarine canyons meet in the center of the basin to form a new canyon: "A" canyon which is directed north-seaward, connecting Choróní and Bonaire Basin (Sellier de Civrieux, 1971). Apparently, these canyons seem to be related to turbidity currents of the rivers which were carried out during the Pleistocene pluvial periods. Westward Choróní basin, the continental shelf in **Golfo Triste Platform** shows a shelf break at 170m and 30 km wide. Sellier de Civrieux, (1977) observed three preserved submarine terraces levels on outer shelf which represents paleo shorelines. The deepest terrace is 146m, above 133m and finally 90m. The second submarine terrace is related to Wisconsin shoreline (Sellier de Civrieux, 1977).

Picard (1974) described and classified coastal cliffs of the coast range into two sections: one west of Chichiriviche consisting submerged cliffs up to 200 m, and one to the east of Chichiriviche cliffs formed by erosion platform tectonism possibly stable or slightly positive. Western cliffs (Puerto Cabello - Chichiriviche) were subdivided by the author in two tranches: tranche Cata (Puerto Cabello - Chuao) with subsidence between 2 and 10m, and stretch of Puerto La Cruz (Chuao - Chichiriviche) with subsidence of up to 200m. This implies a slight subsidence western, central zone and a pronounced subsidence east (Chichiriviche eastward) stable, or even rising. The continental shelf has been depressed apparently more pronounced (Civrieux Sellier, 1973), calculated between 180m and 300m over.

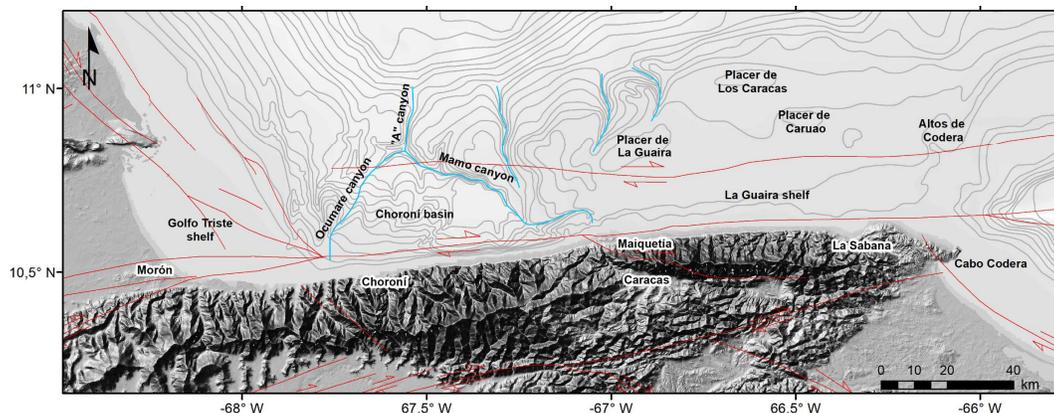


Figure 2. Offshore sea floor morphology of the North of Venezuela (modified of Sellier de Civrieux 1971), showing in white lines canyons and Placeres on the La Guaira shelf. Relieve map surrounding onshore areas (based on SRMT30).

5.2.3. Morpho-sedimentary context

The Guaira platform according to maps of gravimetric anomalies (Siever, 1975, Paolini, 2012) presents the basement close to the surface and a thin layer of sediments on it. In the Guaira platform, the present sedimentation is characterized by a low contribution of materials, since the rivers in the Cordillera de la Costa drain only an area of 8500km² and have little volume with little fine material, which is trapped by the coastal stream and dragged into the Choróní basin. In the Guaira platform, facies of sands can be known especially in the pleasures, with calcareous bottoms being swept by marine currents that travel from west to east, circulation of the typical Caribbean sea in this zone at a speed of 70 cm / sec (Frantantoni et al., 2001), calcarenites and Amphistegine reefs; this facie is covered locally by a thin layer of terrigenous silts. In the Choróní Basin, the sediments present in the slope are clay loam and silty clays. In the underwater canyons there is sedimentation by currents of turbidity. It is feasible the recurrence in time of climatic cycles, with high volumes of precipitation, that on the river regime of these rivers accumulated sediments in the submerged streets until produce instability and mass collapse to trigger avalanches towards the canyon system of the basin of Choróní (Sellier de Crieux, 1969)

In the Triste Gulf, the Yaracuy and Aroa rivers flow and there the sedimentary dynamics has built a wide coast of beaches and coastal barriers, where the fine material passes in part towards the platform. The very recent sediments consist of soft clays, silty clays, silty fine sands and clayed fine sands; the underlying and locally outcropping sediments consist of compacted partially cemented sands and stiff clays with dispersed small old reefs formations (Barbot et al., 1979)

5.3. Methods

In this study was collected ~1064 km of high resolution (HR) on seismic reflection profiles on board of R/V Guaquerí II of the Oceanographic Institute of the Universidad de Oriente in Cumaná in September, October and November 2007 (Figure 5). These profiles were shot with RCMG's "centripede" multi-electrode sparker opered at 300 or 400 J. The

sparker generate a broad-spectrum seismic signal, with a frequency at ~1.3 kHz. The signal was received by a single channel streamer with 10 hydrophones. The expected vertical resolution at depth is ~ 1m. The maximum penetration depth below the seafloor is about 560 ms two way travel time (TWTT). The navigation grid was acquired at an average survey speed of 4 knots and the positioning was done by GPS. Data were digitally and converted to SEG-Y format with Elics™ Delph-II software and they were interpreted using KingdomSuite™ software. The grid consists of north-south lines separated by 6 'in longitude and an east-west lines to correlate all previous lines.

Mass wasting must be identified on high resolution seismic data attempt their facies expressions:

Transparent (T), Chaotic (C), Hyperbolic (H) facies also correspond to deposits generated by mass wasting processes (Damuth, 1980a; Embley, 1980; Loncke et al., 2006; Loncke et al., 2009a; Loncke et al., 2009b). Well-stratified continuous and parallel reflections that usually characterize pelagic and hemipelagic sediments may also correspond to cyclic deposition by turbidity currents (Domzig et al., 2009, Figure 11 in Zitter et al. 2008).

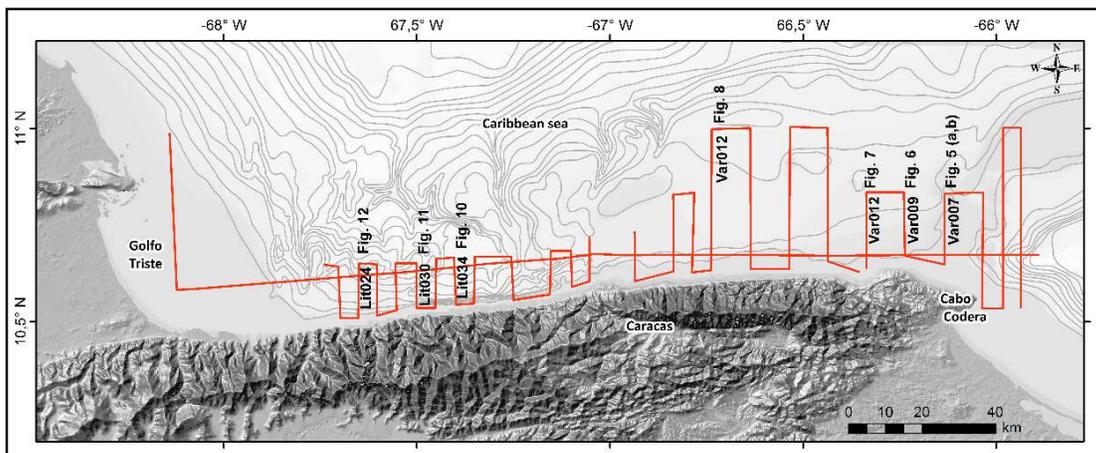


Figure 3. Bathymetry of the North of Venezuela (modified of Sellier de Civrieux, 1971), relieve map surrounding onshore areas (based on SRMT) and seismic grid acquired in the survey expedition.

5.4. Results

5.4.1. Sismostratigraphic instabilities evidences

The slopes of the western margin of Venezuela north are generally steeper than the eastern ones. The steepest slopes are located side of Choróní Basin where the average

gradient is 12° and on the La Guaira shelf with 3° average gradients. Figure 4 presents a map of morphological evidence of slope instabilities and the network of canyons in the North margin of Venezuela. At the present there not previous studies available of submarine mass wasting features in this zone, so all instabilities identified on the seafloor of the in this study should be the first one being published in 2018.

As can be seen in Figure 4, the distribution of landslides is heterogeneous. The highest concentration of them are presented east and west of the platform of the Guaira, where the slopes are much more pronounced. A few are identified in the center of the Guaira platform.

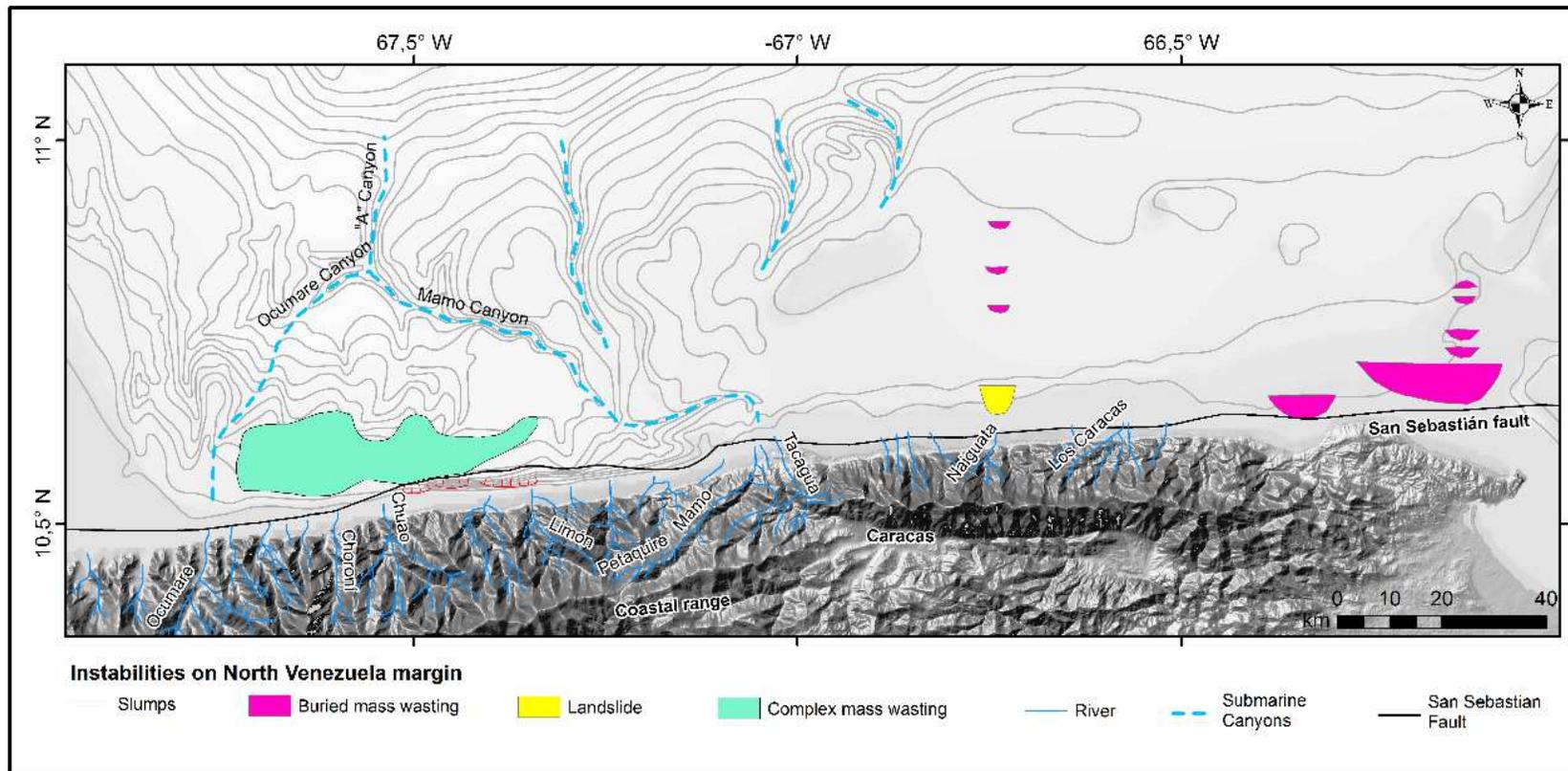


Figure 4. Map of the mass wasting features, active faults and canyons in the north margin of Venezuela, bathymetric data from [Sellier De Civrieux \(1971\)](#), active faults of Chapter 3. Relief map surrounding onshore areas (based on SRMT30)

5.4.1.1. La Guaira shelf

In the west of La Guaira shelf there are some buried landslides identified by high amplitude chaotic facies north of the San Sebastian fault (Fig 5 a and b) and 6) and it is estimated that they may correspond to relative ages of eustatic level falls MIS 2, 4 and 6) according to the seismo-stratigraphic units identified in Chapter 3 on the area. In this area the slope does not have a large angle of dip.

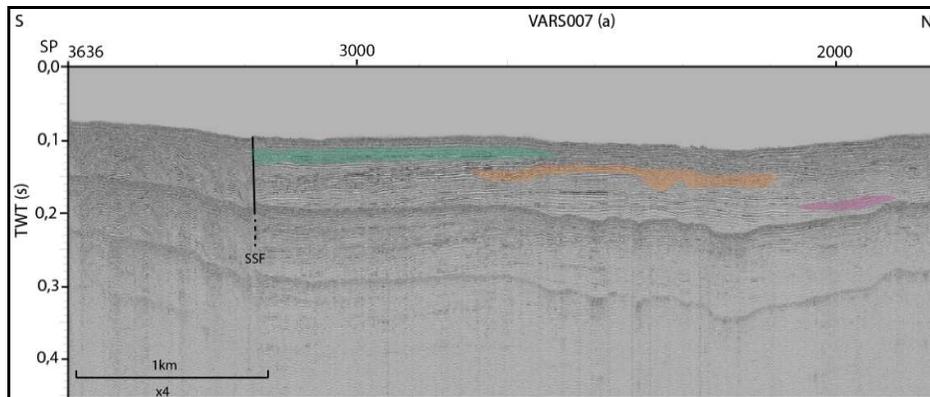


Figure 5. Vars 007 (a and b) profiles showing buried mass wasting. Fuchsia polygon most buried mass wasting, orange correspond to intermediate buried mass wasting and green polygon is the less buried instability.

The slope on this shelf vary between 1-3%. The most recent deposits observed (identified by a green polygon) cover an approximate area of about 20 km wide with a length in the most distal part of approximately 3 km (Fig 6).

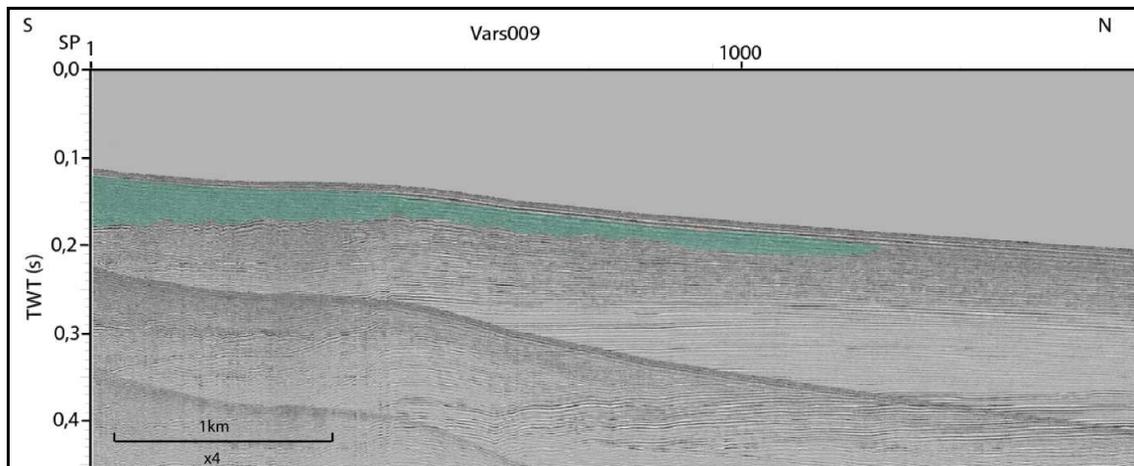


Figure 6. Vars 009 profile whit hummocky expression facies for the buried landslide

Deeper instabilities are also observed (enclosed with the orange and fuchsia polygons) in this same zone, where the influence of the San Sebastian fault on them can be noted. This area is located above a deep-seated transtensional shear zone, and the deformation of the seafloor may result from tectonic motion more than the slope failure.

In this zone, the fault, despite its mostly horizontal movement, has a vertical - subvertical component, which deforms the landslides by changing the slope of its original deposit (Figure 7 and 8). On the Vars007 line (Figure 7) it can be seen how the older deposits are tilted with respect to the most recent deposits, with which we can infer that the vertical movement of the fault was more accentuated in the first. Due to the proximity of these landslides to the San Sebastian fault, it can be inferred that they could be associated with movements of this, which generated these deposits.

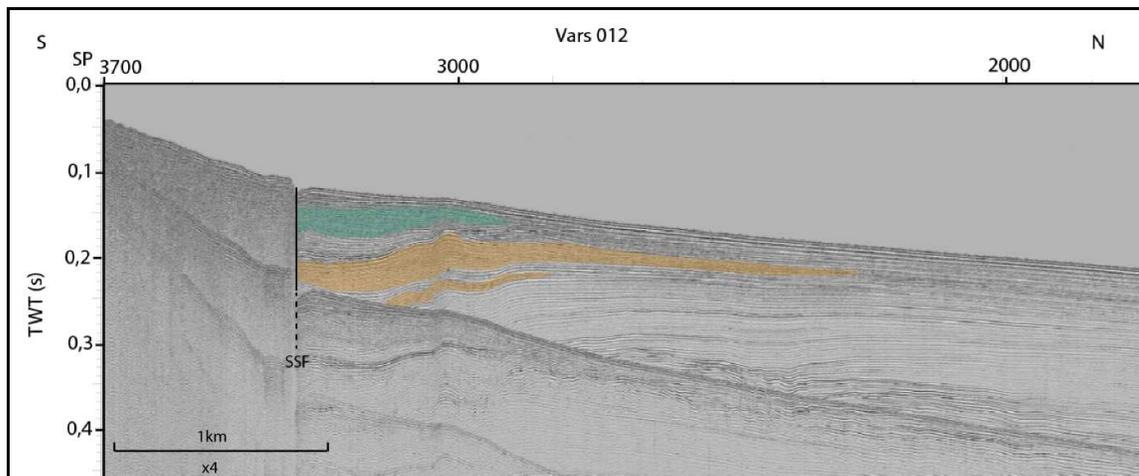


Figure 7. Vars 012 profile where buried mass wasting were observed on North site of San Sebastian fault

Some acoustically transparent are seen directly at the seafloor indicating recent deposition. It can be observed in Figure 8, that this type of deposits in the line Vars 020. This event could be associated to a climatic event of intense rainfall occurred in the area, Flash food of Vargas 1999, where a large volume of deposits were hauled from the El Ávila massif by the hydrographic basins that flow into the sea, in this profile from the Naguayá river.

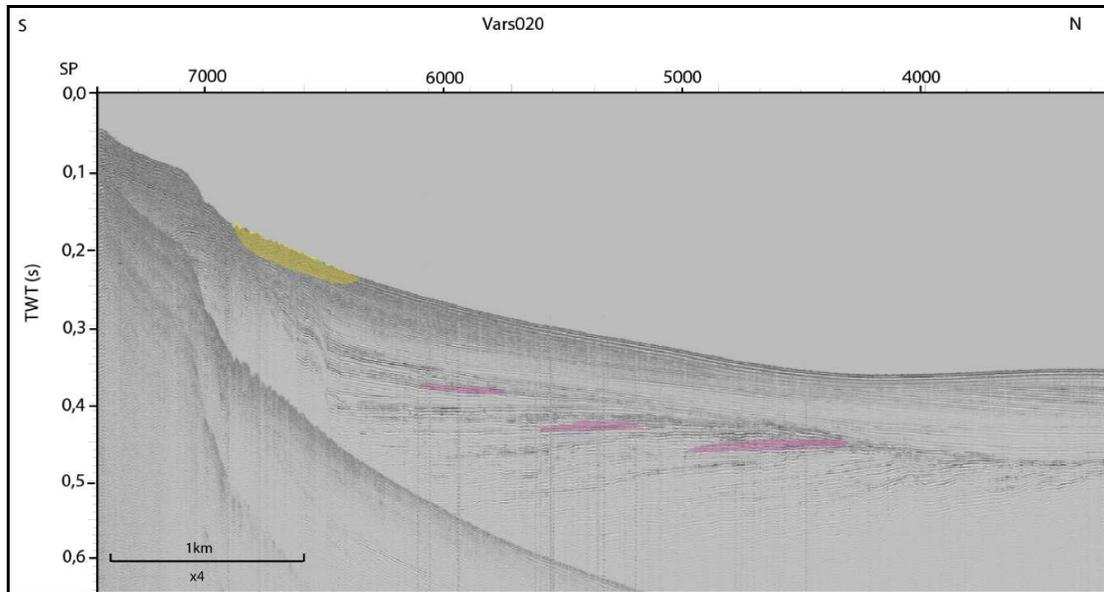


Figure 8. Vars 020 profile show some buried mass wasting deformed and a recent process of instability.

This climatic event carried a large amount of sediments, the volume has been incalculated but there is a record of deposits of 8 to 10m of sperm and blocks dragged with diameters greater than 7m (Singer, 2000, Audemard, 2002 and Larsen, 2002). This accumulation of sediments has favored in some sectors the advance of the coastline to the sea about 100m approximately.

5.4.1.2. Choroní basin

This basin with almost nonexistent continental shelf exhibits a slope steeper than the platform of the Guaira, with 12% of average. It's clear the mass wasting in this area, with caotic, hummocky and deformed expression of reflectors. To the east of the basin we can observe the presence of slumps with deposit of unstable material towards the north (Fig 10).

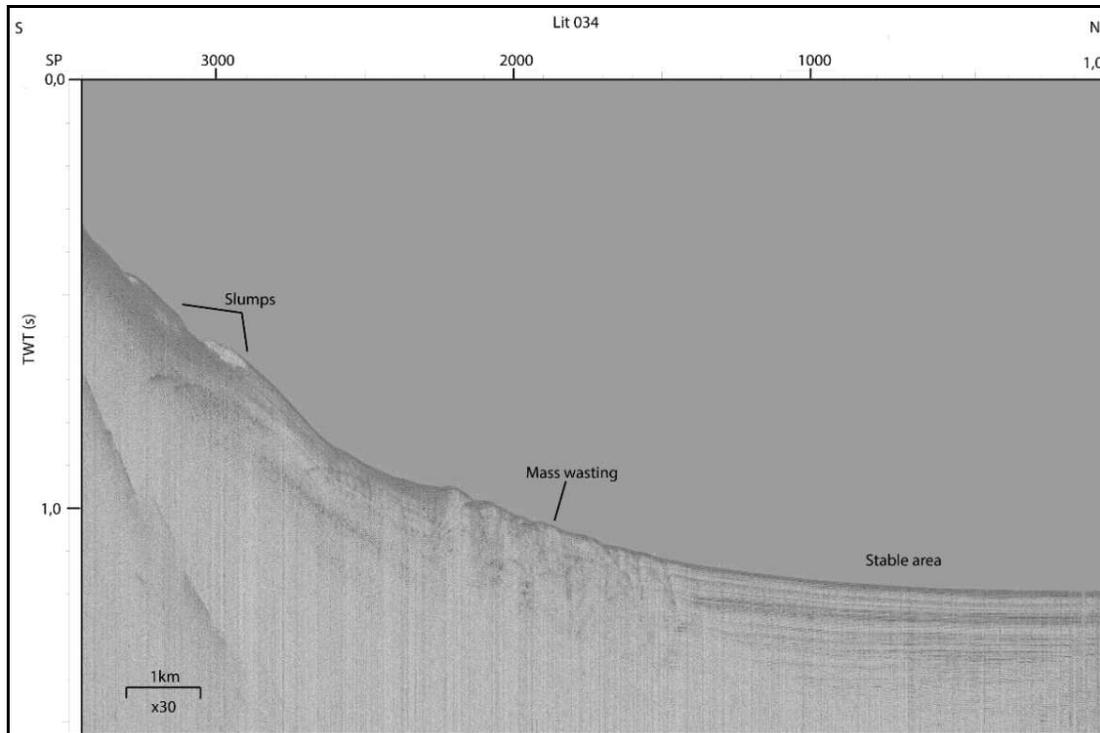


Figure 10. Lit 030 profile with slumps and mass wasting process in the Choróní basin

Towards the center we can observe mass wasting with greater thicknesses with chaotic facies towards the center of the deposit, reaching 1.5 s without having access to a greater depth range limited by the resolution of the seismic (Fig 11). In this area there is the influence of the submarine canyons Ocumare and Mamo that provide an important sedimentary deposit. Apparently, these guns seem to be related to turbidity currents of the rivers and avalanches which were carried out during the Pleistocene pluvial periods (Sellier de Civrieux, 1977).

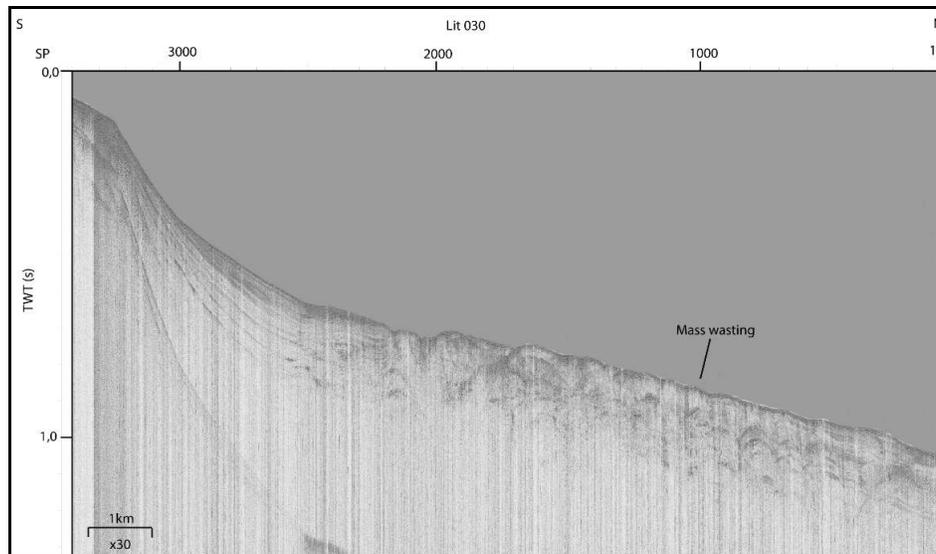


Figure 11. Lit 034 profile show mass wasting and fluidization process of sediments in Choróní basin

To the east of the Choróní Basin the continuity of the mass was seen in the middle of the basin, showing the reflectors a chaotic facies and to the south of the landslide the trace of the San Sebastian fault can be observed cutting the sediments until reaching the most recent deposits including the bathymetry. It is important to emphasize that this area is located above a deep-seated transtensional shear zone, and the deformation of the seafloor may result from a combination of slope failure and tectonic motion

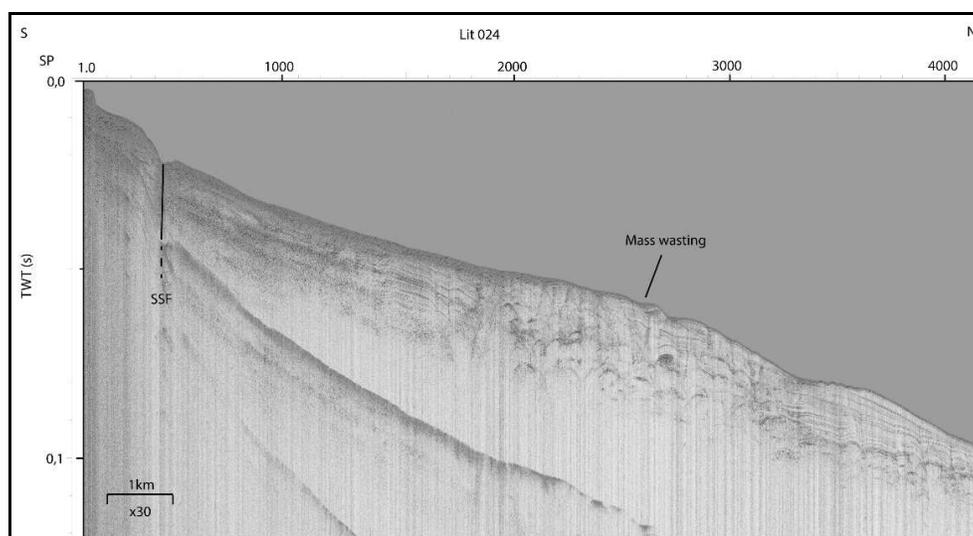


Figure 12. Lit 024 profile show mass wasting and fluidization process of sediments in Choróní basin on north site of San Sebastian fault

5.5. Discussion and Conclusion

5.5.1. Relationships between sedimentary/instability processes and structural heritage

As we have seen, the San Sebastian fault and minor faults are an important structural modeling factor for the northern margin of Venezuela, as well as an agent triggering eventual instability events. The evidence of recent seismicity (Figure 14) and historical, shows us an important activity of the faults present in the area. The high resolution seismic profiles have a depth of approximately 350 m, and there is no micro seismicity data, which would allow us to correlate the events marked in the profiles with earthquakes. However, the Occurrence of large earthquakes on major faults is an obvious trigger of instability, but distributed strain and fracturing could also contribute to weaken the material above, eventually leading to catastrophic failure

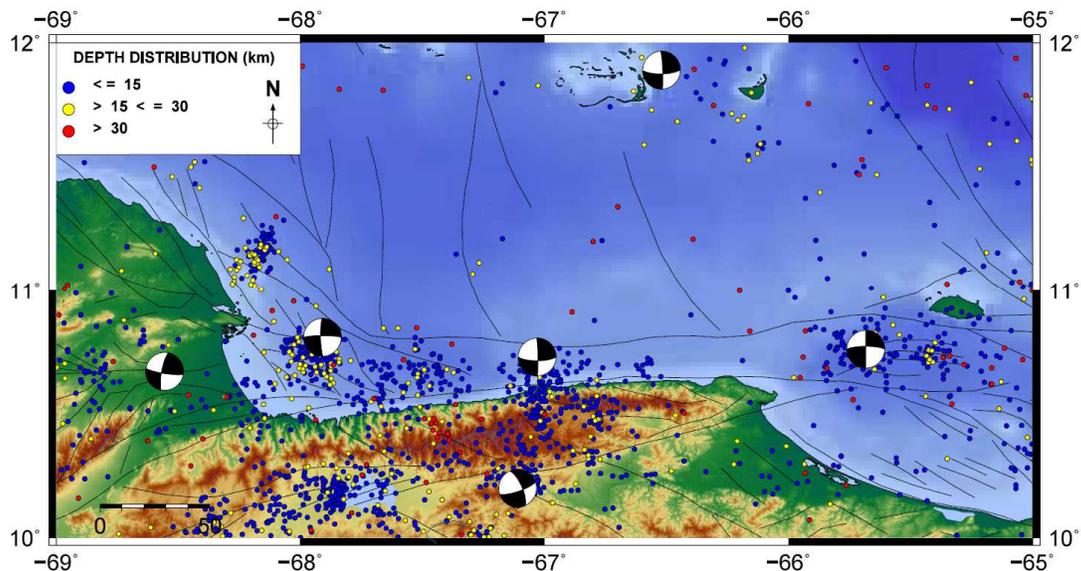


Figure 14. Topographic data from SRTM & Bathimetric from ETOPO1. Seismicity 1910-2010 from FUNVISIS catalog & Faults by Beltrán (1993). Focal mechanism by Palma (2010) & FUNVISIS web page.

On the La Guaira platform, some instability events may be noted lying on the northern edge of the SS fault, some horizontal or following the inclination of the platform as in Vars 009, and others with some inclination in the opposite direction which is estimated is caused by vertical movement of the fault which deforms the landslides subsequent to its occurrence as in Vars 12. These events could be associated with a movement of the fault, especially those closest to these structural accidents.

For the Choróní basin, the scenario is different from the Guaira platform because the slope in this area is much higher with an almost non-existent platform. The landslides involve much greater thicknesses. The presence of structural effect and slope are the predominant factors to trigger mass wasting features.

Additionally, from the observations on the seismic profiles in the Choróní basin, a marked process of instability can be seen in line LIT034 and Lit024 (Figure 11 and 12), which could be described according to [Morneaut et al \(2010\)](#), as follows:

1. When an earthquake is generated, the acceleration generates a sudden increase in the pressure of fluids in the pores in the sediments until the liquefaction takes place in the buried mass transport tanks.
2. Subsequent hydraulic fracturing in the overlying layer of sedimentation of the bottom with / without a transport associated with turbidites at its base.
3. Fluidization of sediments

These processes can be associated to the same seismic event, that is to say the traces of the sliding and the expulsion of fluids linked to a seismic event, or to be separated by consecutive events, with the occurrence of the landslide and the subsequent occurrence of an earthquake generates the acceleration of the particles allowing the escape of sediments / fluids to the upper layers.

5.5.2. Influence of paleoenvironmental-climatic changes on mass wasting processes

Sea-level oscillation modulates the sediment supply and consequently the activation of gravity mass movements. Near the end of lowstand period, coarse shelly sand was transiting the shelf to the deep basin through the canyons

For the northern landslides away from the faults, they could be influenced by these processes of sea level descent, where the platform was partially discovered favoring the erosion and transport of these sediments aided by exceptional weather events such as flahs food Vargas 1999.

5.6. Conclusions

On North Venezuela margin the mapping mass wasting features demonstrates the occurrence of instabilities process. The Choroní basin presents more favorable conditions for submarine mass movement than La Guaira shelf, with high sedimentation rates, dominated by silico-clastic deposits, drastic paleo-environmental changes caused by global sea-level oscillations with partial exposure of shelf carried out exceptional process of accelerated sedimentation by drastic climatic process, and active tectonic deformations maintaining very steep slopes ranging from 3 to 12 ° on average.

The vertical component of slip along the SSF contributes to steepen the slopes and consequently favors slope instability. This combination of factors may account for the observed concentration of large landslides near fault. Cyclic sea level variations also influence the mass wasting processes. Several mass wasting deposits observed in the sedimentary record appear to date back 11-24ka BP, i.e. corresponding to the end of the LGM and the early marine period. Morphological observations and high resolution profiling of the canyons also indicate variations in the rate of sediment transfer processes over the same time interval. This study highlights that landslide triggering is dependent on contextual factors that influence the probability of occurrence of slope instabilities in space and time, for instance, the distribution of crustal stress and strain, paleo-environmental conditions and sea-level change.

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Chapter 6.

The 1900 Mw 7.6 earthquake offshore North-central Venezuela

In the morning of October 29, 1900, an earthquake, whose magnitude was estimated at 7.7 (Fiedler, 1988), shook the Venezuelan coastal center-north. The greatest material damages were concentrated in Anzoátegui, Aragua, Carabobo, Capital District, Miranda and Vargas (Leal et al., 2014, Leal, 2018). Additionally, the geological effects has been identified according to the ESI - 07 scale, remarking an important extension of them in the northern margin of Venezuela (Figure 6.1). The effects most notable are the tsunami record on the north coast, specifically in front of Macuto coast (Oropeza et al, 2015). Despite of this, in the high resolution seismic profiles, deposits associated with this type of phenomena have not yet been determined.

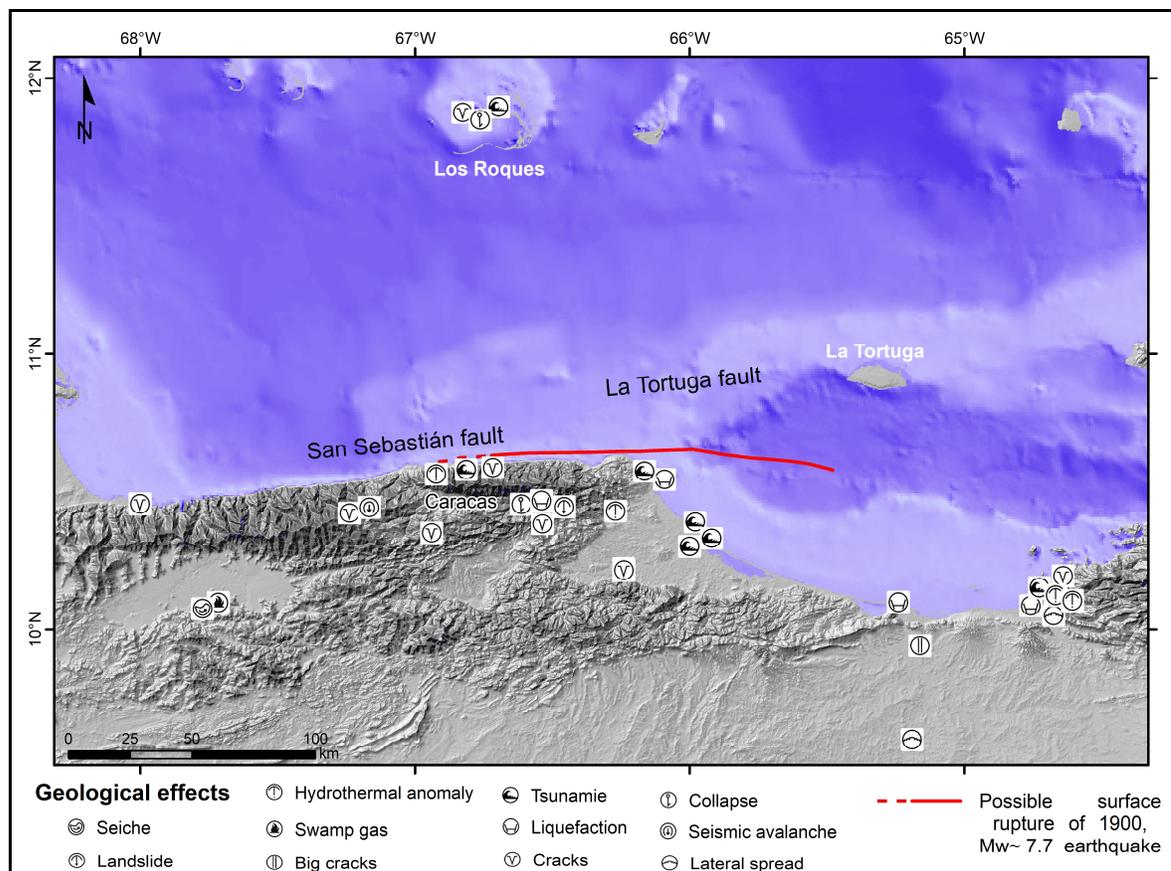


Figure 6.1. The 1900 earthquake geological effects using ESI-2007 scale.

The 1900 earthquake epicenter location has been a subject so much discussed. There are currents that locate this epicenter to the north of the San Sebastián fault (e.g. [Fiedler, 1961](#); [Hernandez, 2009](#); [Colón et al., 2015](#)), however our data of high resolution seismic profiles allows us to propose its location on the San Sebastian fault trace and this will be explained in the published article located in the next section.

6.1. The 1900 Mw 7.6 earthquake offshore North-central Venezuela: Is La Tortuga or San Sebastián the source fault?

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Research paper

The 1900 Mw 7.6 earthquake offshore north–central Venezuela: Is La Tortuga or San Sebastián the source fault?

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ABSTRACT

A new high resolution shallow marine seismic survey provides further insights on the fault source of the October 29th, 1900 earthquake, which affected a large region of North–central Venezuela, both offshore islands and mainland. This Mw 7.6 to 7.7 seismic event has been indistinctly ascribed to either the La Tortuga or San Sebastián fault, which has installed a live debate among different authors. These two faults allegedly run roughly east–west offshore, along the Coastal range. The San Sebastián fault (SSF) bounds this range to the north, being responsible for its linearity and the steep slope of its northern flank, whereas the La Tortuga fault (LTF) would do about the same, but some 20–30 km farther north, based on acoustic surveys carried out in the late 70's and early 80's. We herein bring strong evidence to support that the SSF is the source fault of this major offshore earthquake, mainly based on the freshness of its submarine scarp and recent fault throw, preserved at the Chuspa bay (close to Cabo Codera, eastern end of the Coastal range in central Venezuela), as depicted by one of the profiles. In addition, it is shown that most of the previous extent ascribed to LTF is not so. The LTF, besides exhibiting mainly normal slip, is much shorter than originally proposed. This precludes that LTF may have the seismic potential for an earthquake as big as the 1900 event. Finally, available reflection seismic data reveal the existence of a major fault system bounding the La Guaira shelf on the north, which exhibits tectonic inversion of pre existing extensional faults, shortening and strong syn-tectonic deformation during the Plio-Quaternary deposition. Sedimentation in the Bonaire basin during the Plio-Quaternary time is strongly controlled by this system activity.

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1. Introduction

The large and destructive October 29th, 1900 earthquake struck a large region of continental north–central Venezuela, and some leeward Antilles islands lying north of that coast, early that

morning, just before dawn, around 4:30–4:45 am local time (Centeno Graü, 1949) or 09:11 am GMT (Pacheco and Sykes, 1992). Its intensity center has been placed offshore (e.g., Centeno Graü, 1949; Fiedler, 1961; Jacobowicz and Larotta, 1974; Lugo, 1984; Grases, 1990; Pacheco and Sykes, 1992; Grases et al., 1999; Audemard, 2002; Hernández, 2009a, 2009b; Hernández and Schmitz, 2010, Fig 1). Since the active tectonic framework offshore this region of Venezuela is still poorly known (see Audemard et al., 2000; as a reference), regardless of the significant past efforts of acoustic seismic imaging of the continental shelf and offshore regions in central Venezuela carried out by Schubert (1982) and Schubert and Krause (1984), a debate about the source of this offshore event at the brink between historical and instrumental seismicity, has grown with time. In spite of being the largest crustal earthquake in Venezuela, being its magnitude

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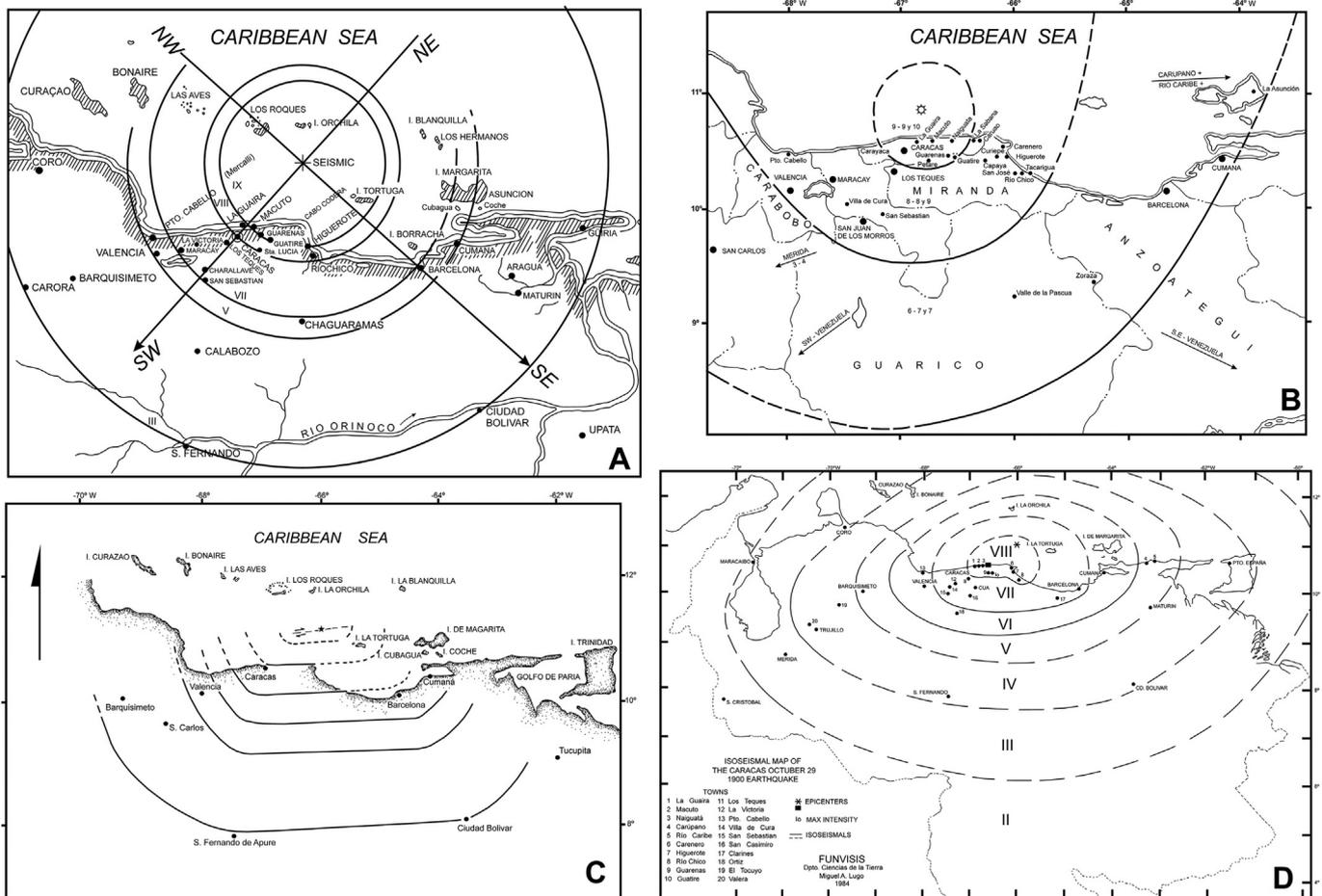


Fig. 1. Isoseismal maps for the October 1900 earthquake: A) Centeno-Grä (1949); B) Fiedler (1961); C) Jacobowicz and Larotta (1974); and D) Lugo (1984). The 3 first maps place the macroseismic epicenter of this event offshore north–central Venezuela, while Lugo (1984) pulls it to shore.

estimated from two far-distant seismograms (at Pasadena station-California, USA and Kew Observatory-England; the first two instrumental records of their kind for any given Venezuelan earthquake, after Fiedler, 1988), at $M_s = 7.7$ (Abe and Noguchi, 1983) and $M_w = 7.6$ (Pacheco and Sykes, 1992), Hernández and Schmitz (2010) from a reassessment of the macroseismic intensities for several historical earthquakes affecting Caracas (1641, 1766, 1812, 1900 and 1967 AD), conclude that the 1900 event reached a $M = 7.7$ and thus must lie farther away than the smaller ($M = 7.5$) 1812 event because the latter one happens to be the most destructive for Caracas in historical and instrumental times. In that sense, Hernández (2009a, b) and Hernández and Schmitz (2010) assigned the 1900 earthquake to La Tortuga fault (LTF), thus validating the intensity centers proposed by Centeno Graü (1949), Fiedler (1961), Jacobowicz and Larotta (1974) and Grases (1990), as well as the instrumental relocation obtained by Pacheco and Sykes (1992), placing the event at 11° N and 66° W, west of La Tortuga island. On the contrary, Lugo (1984), after reassessing the macroseismic intensity data for that event, pulls it closer to both Caracas and shore (Fig. 1), adscribing it to the San Sebastián fault (SSF). Audemard (2002) does alike from applying the concept of seismic gap to the Venezuelan catalog of instrumental seismicity 1910–April 2002. Instead of providing an epicenter, this author proposes the extent of the surface rupture that may have generated the 1900 event. This rupture would have largely filled the gap along the easternmost portion of the SSF, lying between the ruptures of the 1812 earthquake to the west and the 1853 event on the El Pilar

fault (EPF) to the east. The latter event epicenter should have been on the EPF segment bordering the Cariaco trough on the south Audemard (2002, 2007). This contribution pretends to bring additional supporting evidence to a source on the SSF for the 1900 earthquake, as well as arguments against a source on the LTF.

2. Tectonic framework

Northern Venezuela lies in the interaction zone between the South America and Caribbean Plate, while western Venezuela and northern Colombia cover several interplaying tectonic blocks or microplates (refer to Audemard, 2014 for further details; Fig. 2). The Caribbean–South America Plate boundary from Colombia to Trinidad is over a 100-km-wide active compressional right-lateral strike-slip zone onshore and offshore northern Venezuela (Audemard, 1993; Singer and Audemard, 1997; Pindell et al., 1998; Audemard et al., 2000, 2005; Ysaccis et al., 2000). Significant positive relief is present along the Coastal and Interior ranges of North–central and Northeastern Venezuela. Further west, the southern Caribbean boundary broadens to as much as 600 km and includes several small tectonic blocks or microplates (Fig. 2). Seismicity along this plate boundary is moderate both in frequency and magnitude and the dominant types of faulting, based on focal mechanism solutions, are strike-slip and reverse (Audemard et al., 2005; Palma et al., 2010).

Much of present-day dextral slip along the southern Caribbean boundary seems to be focused along the major Boconó-San

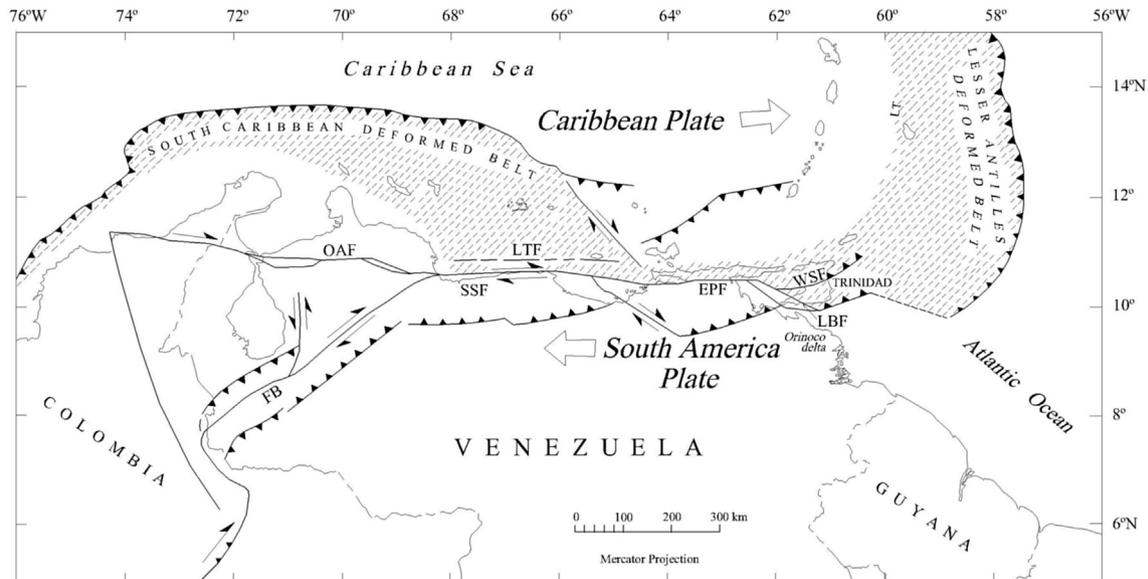


Fig. 2. Simplified geodynamic framework of Northern South America (modified from Audemard et al., 2000), where the alleged La Tortuga fault trace has been incorporated. Abbreviations: BF Boconó fault; EPF El Pilar fault; LBF Los Bajos-El Soldado fault system; LTF La Tortuga fault; OAF Oca-Ancón fault system (also named Oca-Chirinos fault by Schubert and Krause, 1984; but with a different fault trace); SSF San Sebastián fault; WSF Warm Spring fault of Trinidad.

Sebastián-El Pilar-Los Bajos-Warm Spring fault system where geological and geodetic data indicate slip rate of about 10 mm/yr (Fig. 2). Most authors see this system as the plate boundary (Hess and Maxwell, 1953; Schubert, 1979; Stephan, 1985; Pérez et al., 2001a, b). A large portion of this strike-slip fault system lies offshore, comprising the entire SSF and most of the EPF, with the rare exception of the EPF portion outcropping on the land bridge between the gulfs of Cariaco and Paria, in Eastern Venezuela. In other words, the major strike-slip fault system along this Caribbean–South America plate boundary zone extends offshore for over 400 km between longitude -68° and -64° , north of North–central Venezuela (Fig. 2). The intensity center of the 1900 earthquake lies in this poorly explored and still unknown offshore region; reason for which since 2006 an exploration program has been led by FUNVISIS (Audemard, 2012).

While the Quaternary faults on continental Venezuela are rather well mapped and tectonically characterized and their seismogenic potential is appropriately estimated, accordingly to the present state of the art (Soulas, 1986; Beltrán, 1993, 1994; Audemard et al., 2000), the current situation differs very much for the offshore regions north and east of Venezuela (Audemard, 2012), even in a country where thousands of kilometers of oil-exploration seismic lines have been shot and interpreted for decades in the region under study, but very few of these studies have been actually published or made available (e.g., Pereira, 1985; Ysaccis, 1997; Babb and Mann, 1999; Di Croce et al., 1999; Ysaccis et al., 2000; Gorney et al., 2007; Magnani et al., 2009; Escalona and Mann, 2011; Escalona et al., 2011; Garciacaro et al., 2011). In a similar way, very few studies have aimed at characterizing the offshore seismogenic or Quaternary faults over the years (e.g., Morelock et al., 1972; Caraballo, 1982; Schubert, 1982; Schubert and Krause, 1984; Espinosa and Daza, 1985), despite a significant amount of offshore seismic exploration carried out for larger scale and more geodynamic objectives in the 70's (Ball et al., 1971; Peter, 1972; Case, 1974; Silver et al., 1975; Biju-Duval et al., 1978; Mascle et al., 1979) and in more recent times (e.g., Gorney et al., 2007; Escalona et al., 2011; Magnani et al., 2009; Escalona and Mann, 2011; Garciacaro et al., 2011). Most of the shallow seismic surveys are of local coverage, low density or poor data quality. In recent years,

particularly since 2006 as indicated by Audemard (2012), the Earth Sciences Department of FUNVISIS, with the collaboration of ISTERRE (former Laboratoire de Géodynamique des Chaînes Alpes—LGCA) from Université de Grenoble (France) and the Renard Centre for Marine Geology—RCMG from University of Ghent (Belgium), has launched and carried out an ever-growing program of single-channel high-resolution shallow seismic reflection acquisition (e.g., Audemard et al., 2007; Van Daele, 2007; Van Welden, 2007; Audemard et al., 2011; Van Daele et al., 2011), a more modest campaign of core recovery offshore (Aguilar et al., in prep.) and onshore (Leal and Scremin, 2011; Oropeza et al., 2011, 2012; Leal et al., 2014) so far, and a growing paleo- and historical tsunami recognition program along our exposed low-lying inhabited seashores (Audemard, 2012; Audemard et al., 2012; Audemard and Leal, 2013; Leal et al., 2014).

3. Offshore active tectonics

The tectonic structure and style of the Cariaco trough, an active pull-apart basin at the dextral stepover between the right-lateral strike-slip SSF and EPF (e.g., Schubert, 1982; Audemard et al., 2000; Escalona et al., 2011), and surrounding shelves (e.g., Morelock et al., 1972; Espinosa y Daza, 1985; Goddard, 1986) have deserved considerable attention over the years. Conversely, the submarine extent of the Moron Fault Zone—MFZ—, as defined by Schubert and Krause (1984), has received little exploration effort, except for the work by these latter authors. The MFZ extending underwater all along north–central Venezuela, as defined by Schubert and Krause (1984), comprises (Fig. 3): a) an eastward extension of the Oca-Chirinos fault zone running at about $10^{\circ}50'$ N latitude, b) a probable continuation of the Boconó and Morón faults bordering the Venezuelan coast, which splits into the Avila and Macuto faults; 3) The Tacagua fault, which is a southeastward trending splinter of the Oca-Chirinos fault zone; and 4) the westward extension of the Cariaco pull-apart basin and the EPF. In the same way as Schubert and Krause (1984), Beltrán (1993, 1994) makes the Boconó and Morón faults merge in a single fault north of Caracas (Fig. 3). This author names it San Sebastián fault (SSF), whose name was attributed after the town of San Sebastián de

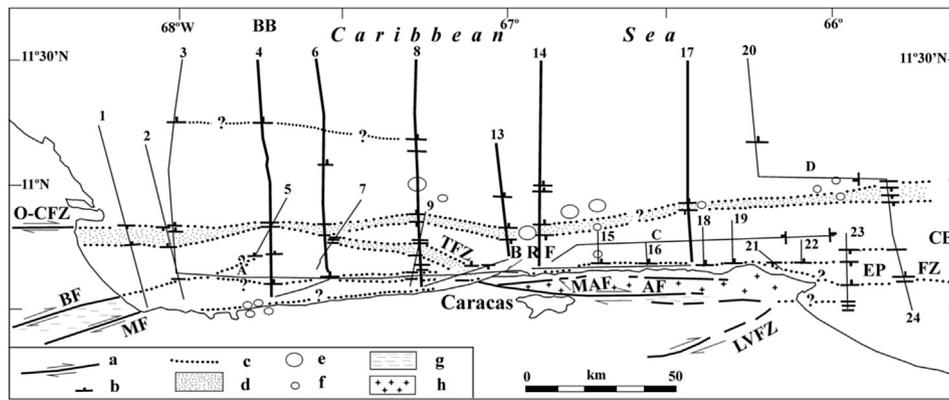


Fig. 3. Regional interpretation of faulting along the North–central Venezuelan coast, from acoustic reflection profiles (simplified from Schubert and Krause, 1984). Legend: a. strike-slip fault; b. direction of dip of fault plane in seismic line; c. inferred connection between faults in profiles; d. fault zones; e. epicenter of earthquake ($5.5 \leq M \leq 7.2$) f. epicenter of earthquake ($4.5 \leq M \leq 5.4$); g. basin; h. area of uplift. Abbreviations: AF Ávila fault; BB Bonaire basin; BF Boconó fault; BRF Bruscas fault; CB Cariaco basin; EPFZ El Pilar fault zone; LVFZ La Victoria fault zone; MAF Macuto fault; MF Morón fault; O-CFZ Oca-Chirinos fault zone; TAF Táchata fault zone; TFZ Tacagua fault zone. Seismic lines shown in Fig. 4 are in bold line.

Maiquetía, where the fault crops out for only a single few-kilometer-long stretch across the International Airport Simón Bolívar (also known as Maiquetía Airport, serving Caracas). At the airport, the fault is named Bruscas fault (BRF in Fig. 3). Meanwhile, Beltrán (1993) considers that the eastward extension of the Oca-Chirinos fault of Schubert and Krause (1984) keeps no more relation with this fault to the west and is then renamed La Tortuga fault (LTF). Audemard et al. (2000), based on the very little control points on which the fault had been originally defined by Schubert and Krause (1984; Fig. 3), in addition to the limited quality of the acoustic profiles (Fig. 4), roughly keep the same fault trace as Beltrán (1993) but cautiously include it in the compilation of year 2000 as an inferred fault trace.

Owing to the large uncertainties on the fault seafloor traces and their extent in North–central Venezuela, FUNVISIS decides in 2007 to acquire a first set of high-resolution shallow seismic profiles. The aim of this paper is not to unravel the active faulting in this offshore tectonically complex region but pretends to use some of the new-shot profiles to explore what fault may be held responsible for the largest and first crustal earthquake ever recorded instrumentally in Venezuela so far: the October 29th, 1900 Mw 7.6–7.7 earthquake.

4. High-resolution shallow seismic profiling

The shallow seismic data used in this study were collected during the VARGAS Seismic (VARS) and LIToral (LIT) expeditions, which took place in September and October 2007, respectively, onboard of R/V Guaiqueri II, the research vessel of the Oceanographic Institute of the Universidad de Oriente in Cumaná. A first-order grid of high-resolution seismic reflection profiles (Fig. 5) was shot with a RCMG's "Centipede" multi-electrode sparker operated at 300 or 400 J. The sparker produces a broad-spectrum seismic signal ranging between 400 and 1500 Hz, with a mean frequency at ~1.3 kHz. A single-channel streamer with 10 hydrophones was used as receiver. Both the source and streamer were towed behind the R/V, near sea surface.

Data were acquired at a survey speed never faster than 4 knots, and positioning and navigation was done by GPS (with a GPS SIMRAD Shipmate, complementing the vessel own GPS system). Seismic and GPS data were digitally recorded and converted to SEG-Y format with Elics™ Delph-II software. The acquisition parameters were set at a firing rate of 0.75 s, a recording window of 0.5 s and a sampling frequency of 4 kHz. Previous to recording, the seismic

signal was filtered with a Rockland 751A band pass filter to remove frequencies <200 Hz and >2000 Hz. Data were subsequently interpreted using The Kingdom Suite™ software. The navigation grid (Fig. 5) was designed and dimensioned with the aim of reconstructing the 3D geometry of the sedimentary sequences and mapping the tectonic features present under the seafloor off the North–central Venezuela coast. In that sense, lines were shot normal and parallel to the roughly east–west trending coast of North–Central Venezuela. The more frequent north–south lines were apart either 6' or 3' of longitude (11 or 5.5 km apart, respectively). All these lines were tied up with an over-220-km-long roughly east–west line (Lit 01 through 10; Fig. 5). For the purpose of this work, we are not herein presenting a local seismo-stratigraphic interpretation of the used lines, since it is the aim of another contribution by the main author in the frame of her PhD thesis. Therefore, the sedimentary sequences are not correlated to any geologic time units so far. However, we assume that the age of the more superficial sedimentary units may not differ much from that obtained by Van Daele et al. (2011), which continuously record sedimentation to the present.

5. The San Sebastian fault (SSF)

As mentioned earlier, the SSF essentially extends offshore along and near the coastline of North–central Venezuela, except for a very short stretch along the southern foothill of Cerro Machado at the International Airport Simón Bolívar at San Sebastián de Maiquetía. Here the fault cuts outcropping Pliocene and Pleistocene marine sediments, which were described by Weisbord (1957) and Gibson-Smith (1971). This is by far the most conspicuous geologic evidence of the Quaternary activity of the SSF. In turn, Weisbord (1957) named this fault splay as Bruscas (Fig. 3). The cropping out of this body of young marine deposits at a coastal salient (Fig. 5) should result from a restraining bend or left-lateral stepover of the fault, opposed to the right-lateral strike-slip sense of motion of this fault, determined from seismologic (e.g., Suárez and Nabelek, 1990; Audemard et al., 2005) and geodetic (e.g., Pérez et al., 2001a, b) data. This structural configuration still remains undetermined but it seems to play a significant role in the seismogenic segmentation of SSF, if Audemard (2002)'s proposals regarding rupture length and location of the 1812 and 1900 earthquakes happens to be correct. A current and also active analog to this structural geometry has been described for the El Pilar Fault –EPF– at the Caguire Hills in Cumaná (state of Sucre, Venezuela; e.g., FUNVISIS, 1994; Beltrán et al., 1996;

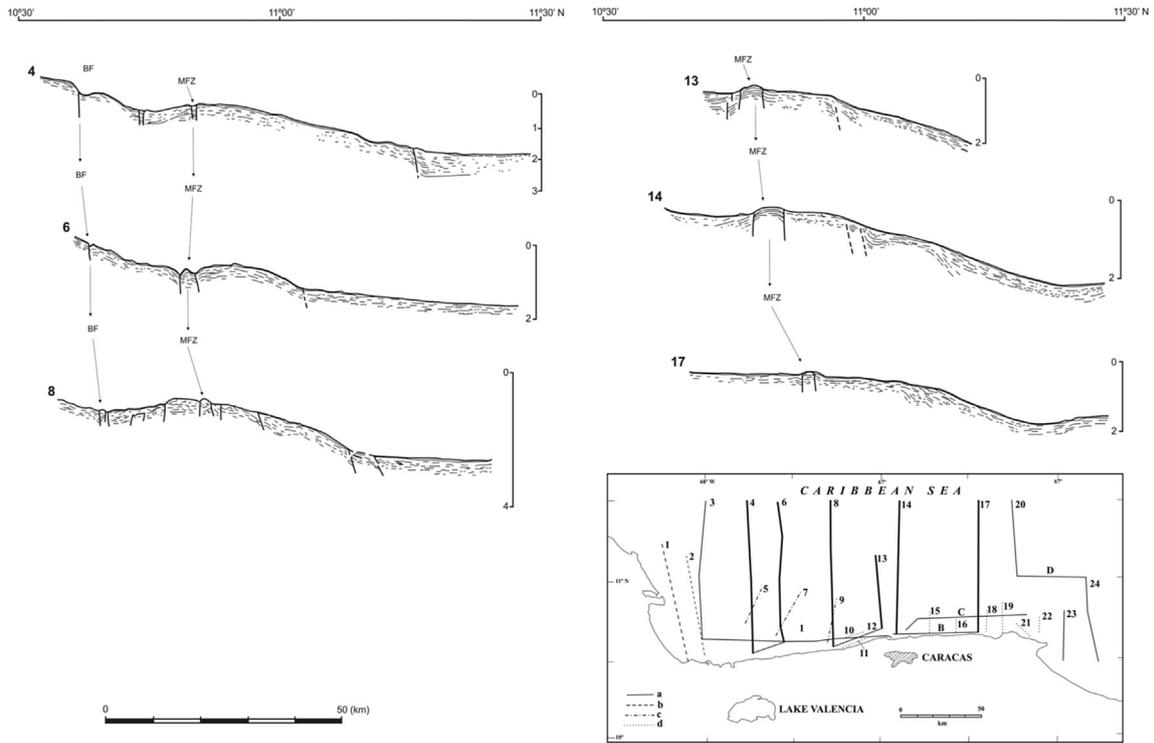


Fig. 4. Selection of simplified line-drawings from north-south trending acoustic reflection profiles (simplified from Schubert and Krause, 1984). Inset figure provides relative location of profiles (after Schubert and Krause, 1984; also shown in Figs. 3 and 5). The Morón Fault Zone –MFZ–identified in these profiles, which is in fact the eastern extension of OCFZ of Schubert and Krause (1984), corresponds to La Tortuga fault –LTF– of Beltrán (1993). The latter one is the definition adopted in this work. EPFZ stands for El Pilar Fault Zone.

Audemard et al., 2000; Audemard, 2006). The similarity in structural style is also transposable to the seismogenic segmentation of the fault (e.g., Audemard et al., 2000; Audemard, 2006, 2007).

The SSF appears to be a major tectonic boundary not only from the geodynamic and geodetic viewpoints, but also geophysically. Magnani et al. (2009), from wide angle refraction data, are able to image the deep structure of North–central Venezuela at 67° W

longitude (Choroni longitude; 67.61° W), as well as the attitude of SSF at depth (Fig. 6). This fault appears to juxtapose a thick sedimentary package on the north, corresponding to the Neogene fill of the Bonaire basin, against the igneo-metamorphic nappes outcropping south of the SSF in the Coast range, as attested by their preferred velocity model (Magnani et al., 2009, Fig. 6). Here, the fault dips north at depth, which would support that this fault may

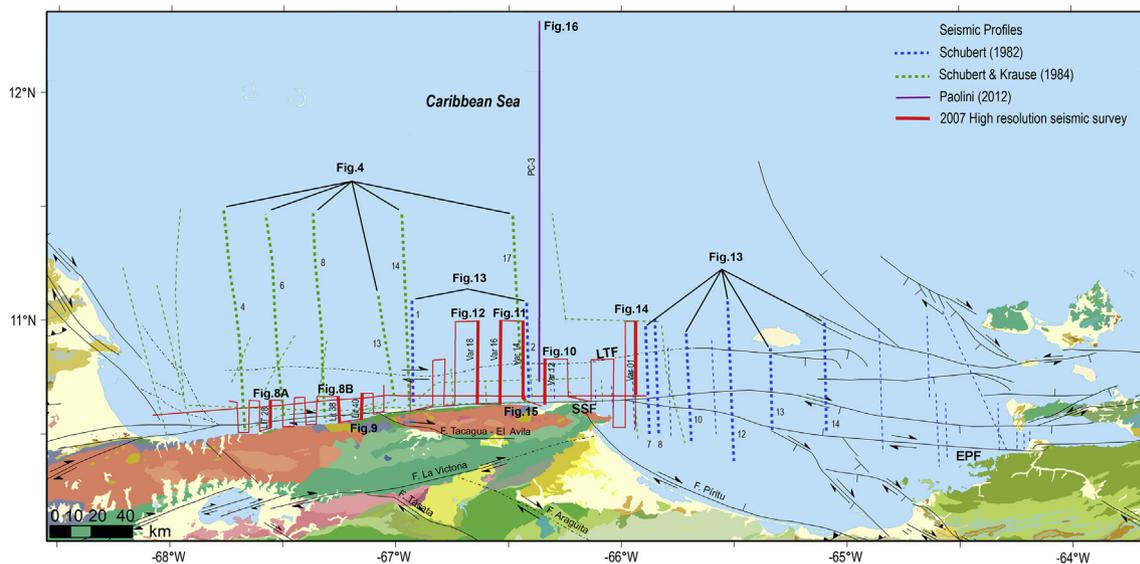


Fig. 5. Location map of high resolution shallow seismic profiles acquired in September–October 2007 during the Vargas (VARS) and Litoral (LIT) campaigns by a joint international effort (FUNVISIS–ISTerre–RCMG). The lines used in this contribution are highlighted as thick lines and labeled by the figure number accordingly. Geologic base map by Hackley et al. (2005). Color code of geologic units complies with the international nomenclature. Map of Quaternary faults taken from Audemard et al. (2000). Note that the LTF submarine trace is inferred from Cabo Codera longitude towards the west. In addition, this interpretation does not consider the LTF as the prolongation of the Oca–Ancón fault system. This figure also provides the location of seismic lines displayed in this study from previous surveys (Schubert, 1982; Schubert and Krause, 1984 and Paolini, 2012).

well reflect an important tectonic inheritance. The SSF might have been a major extensional feature during the phase of orogenic collapse proposed by Audemard (1993, 1998, 2009) responsible for the opening of several basins along the southern edge of the overriding Caribbean plate in the Late Eocene and Oligocene, among which the Falcón-Bonaire basin deserves mention. The extensional phase is clearly imaged in the seismic line of Fig. 7, where basement involved normal faults controlled the thickness of the Paleogene-Oligocene sequence in the basin. In turn, this fault attitude could be inherited from the prior southeast-directed nappe overthrusting during the oblique subduction-collision phase between the Caribbean and South America plates that predated the orogenic collapse, justifying somehow the low dip of this structure at high depth. In addition, this velocity model supports that the main splay or strand in the fault zone of the SSF runs very close or at the coastline (Fig. 6). Besides the straightness of the coastline between Morón (Golfo Triste) and Cabo Cordera, this is also locally supported, west of Maiquetía, by the structural relief of over 2500 m difference in elevation between the Coastal range (rising up to 2000 m above msl) and the submarine depression lying north of the fault with water depths higher than 500 m. Consequently, since the seismic line shot during the BOLIVAR-GEODINOS projects did not reach the coast (refer to Fig. 6B, for seismic line extent), the SSF labeled in Fig. 7 does not coincide with the main strand imaged in their preferred velocity model shown in Fig. 6A. On top of this, this same profile also images in 2D a set of imbricated high-angle faults with vertical thrust component, whose updip terminations do not attain seabottom, but are definitely active since they control sedimentation of the thick Plio-Pleistocene package, which is clearly thicker to the north (in the apparently downthrown block). The fact that these thrust-like splays do not reach seabottom implies that their degree of activity is less than the fault south of it with sea-bottom expression, both shown in Fig. 7, and even lower than the main fault strand located at the seashore. This fault system to the east seems to run at the northern edge of the La Guaira platform and would be responsible for the current elevation of this

submarine shelf. Therefore, SSF comprises a rather wide active fault zone, of several kilometers in width (Fig. 7), at least between Morón and Maiquetía. This seems to agree with the underwater mapping of the prolongation of the Boconó and Morón faults by Schubert and Krause (1984; Fig. 3), comprising the fault system identified by Magnani et al. (2009; Fig. 7) and the main strand flanking the northern straight coast of the Coastal range.

Since the SSF trace runs offshore very close to the shore of the Coastal range in North-central Venezuela, very few seismic lines have in fact depicted the fault plane of the main strand at depth. The previous surveys have mainly captured the same strand identified by Magnani et al. (2009; compare Figs. 4 and 7) and have failed to image the main strand at the shore. During this survey, few lines have actually cut the main strand of the SSF. We show 7 shallow seismic lines of the 2007 acquisition where the fault plane can be seen. The 3 first lines are located west of the Maiquetía salient (lines LIT-26 and -38 in Fig. 8 and LIT-40 in Fig. 9) and the other four ones (VAR-12, 14, 16 and 18) are east of Maiquetía (Location of all our shown profiles provided in Fig. 5).

The fault plane in both lines LIT 26 and 38 is on the very left edge (southern end) of the line, indicating that the fault lies almost below the coastline, on a very steep sea-bottom, which seems to be the submarine extension of the up to 20° steep northern flank of the Coastal range. The fault is almost perfectly vertical. From the fault in Fig. 8a, it appears that some gas venting or seepage was escaping during the line acquisition, pinpointing accurately the sea-bottom location of the fault plane. The seep is perfectly located at the contact of a bench with the steep sea-bottom (Fig. 8a). The fault is less prominent in LIT-38 (Fig. 8b), although it appears to be at the first slope break. Farther away from the shore (towards the right), several other subvertical fault strands, in a number up to 4 major planes, are contained in a 10–12 km wide tectonic corridor or strip (Fig. 8b). This seems to coincide with the mapping of Schubert and Krause (1984) for the region just west of Maiquetía. All of them are equally active because present-day sea-bottom is affected by these fault planes. LIT 40, closer to Maiquetía than the 2 previous

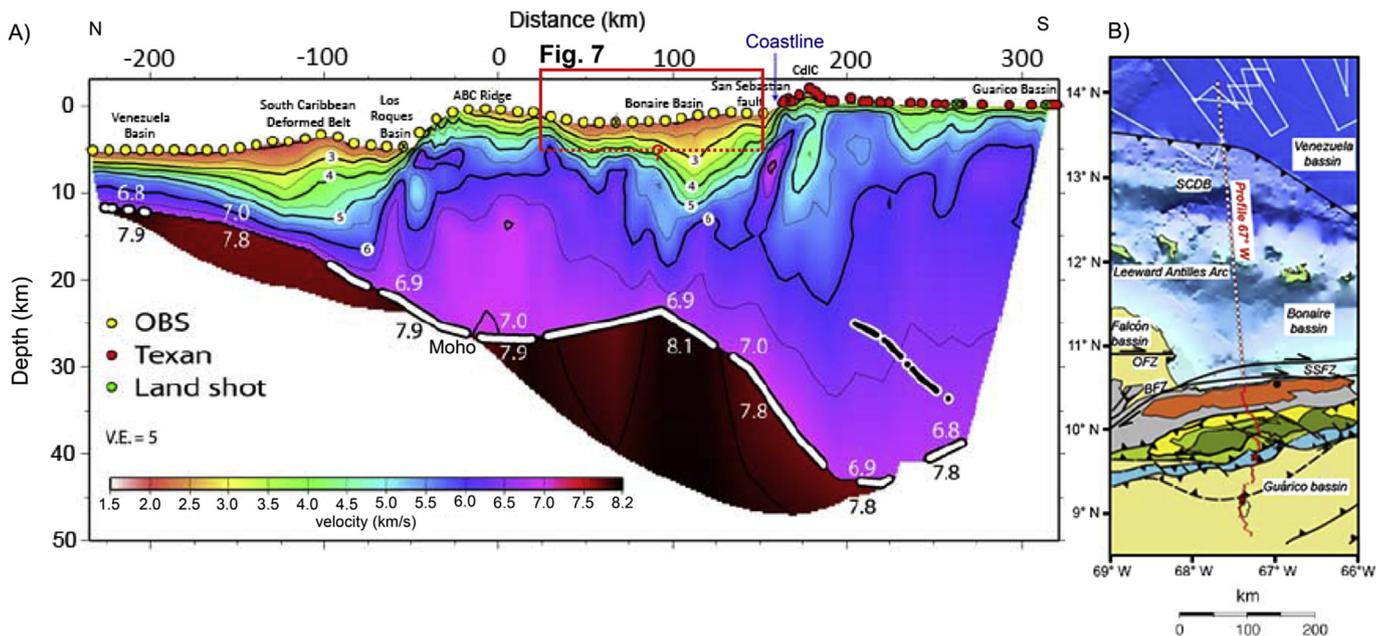


Fig. 6. A) Preferred velocity model along profile at 67° W (from Magnani et al., 2009). Vertical exaggeration = 5. OBS, Texan, and land shot locations used to constrain the model are shown atop of profile. Moho is white where constrained by reflections and black where unconstrained. Contour interval is 0.5 km/s; thick contour interval is 1 km/s as labeled. Lowermost crust and uppermost mantle velocities (km/s) are labeled above and below the Moho. ABC Dutch Leeward islands (Aruba, Bonaire and Curacao); CdC Cordillera de la Costa belt; VdC Villa de Cura belt; SCDB South Caribbean Deformed Belt; SSF San Sebastián dextral strike-slip fault. Horizontal extent of seismic reflection line shown in Fig. 7 is indicated. B) Location and extent of velocity model at 67° W depicted in Fig. 6A (from Magnani et al., 2009).

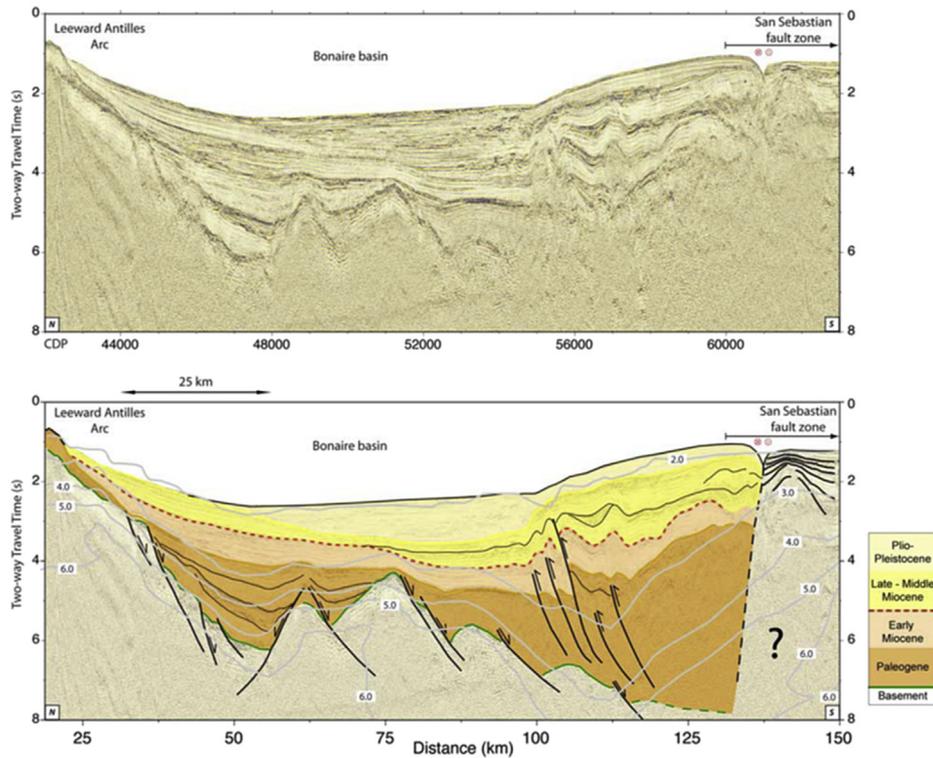


Fig. 7. Seismic reflection data uninterpreted (top) and interpreted (bottom) of southern portion of profile 67° W across the Bonaire basin with wide-angle velocity contours (gray lines) overlaid (from Magnani et al., 2009). The profile images the basement blocks rifted during the Paleogene buried under the Neogene sequences. To the south, normal faults are inverted in Plio-Quaternary times, with north-directed vergence. Extent of seismic reflection line in Fig. 7 is indicated in model shown in Fig. 6.

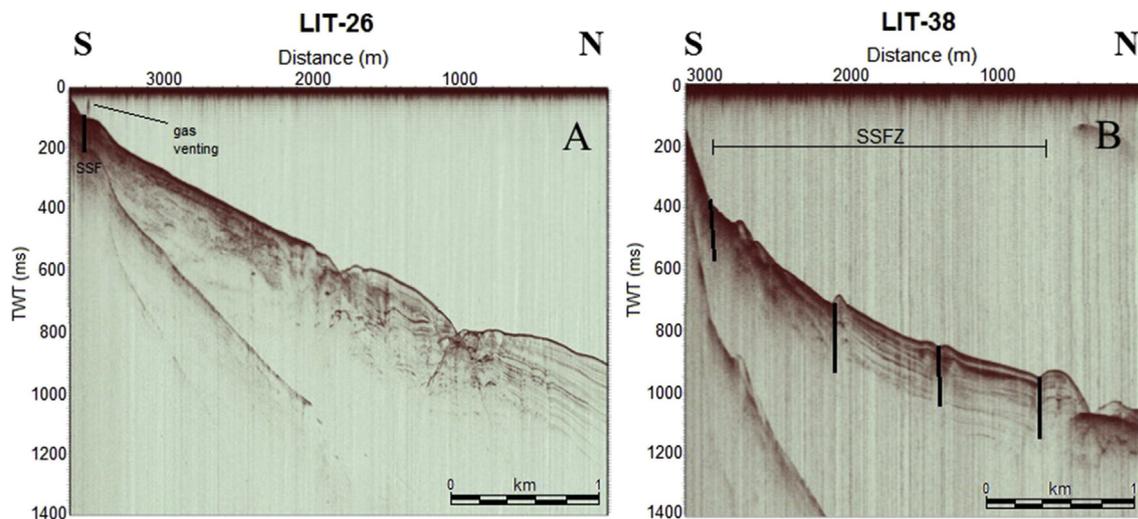


Fig. 8. Uninterpreted high resolution shallow seismic profiles of the Litoral –LIT-campaign: A) LIT 26 and B) LIT 38. Relative location is depicted in Fig. 5. Both sparker profiles show the multiple active fault splays composing the SSF, as evidenced by disruption of sea-bottom. The main strand, exhibiting a sub-vertical fault plane, is at the very left of both profiles, very close to southern profile tip.

ones, also exhibits several active fault planes, on which submarine canyons have developed nowadays and on the past (Fig. 9). The active zone of deformation here (LIT-40) is as wide as to the west (LIT-26 and -38).

Conversely to the western part, the fault east of Maiquetía seems much simpler and all deformation seems accommodated by a very sharp and conspicuous single fault plane (Figs. 10 through 12; refer to Fig. 5 for location). Between Maiquetía and Chuspa (profiles VARS 14 through 20), the SSF runs at the northern edge or break of a rather narrow hanging submarine shelf, which resembles to a huge

fault bench (Figs. 11 and 12). It is here confirmed that the fault near sea-bottom is perfectly vertical to subvertical. Here, the coastline is also straighter, paralleling the bench break, with less embayments and salients than west of Maiquetía, if discarding the few coastal salients associated with modern sedimentation of alluvial fans. Only the particular configuration of the shore, with a large embayment at Chuspa, close to Cabo Cadera, made possible the best imaging of SSF east of Maiquetía along the Coastal range in North-central Venezuela (Figs. 5 and 10), in which the R/V Guaiquerí II could actually navigate across the submarine fault trace, as

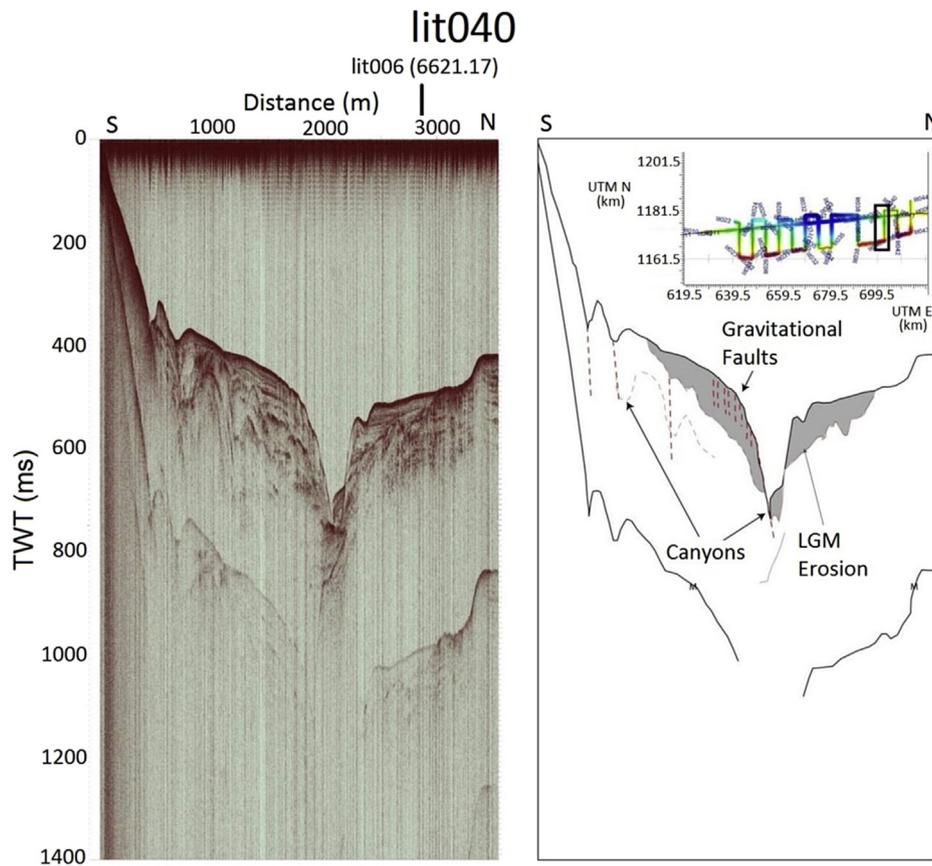


Fig. 9. Uninterpreted (left) and interpreted (right) sparker profile (LIT 40). Relative location is shown in Fig. 5. A complex SSF, comprising several active splays, is imaged, on which the Tacagua canyon is superimposed and fossil canyons as well.

evidenced by the seismic line VARS 12. As a matter of fact, it is at this embayment where the fault also appears to be the freshest as it exhibits a very well-preserved north-facing 1.5-m-high fault scarp (Fig. 10).

6. The La Tortuga fault (LTF)

La Tortuga fault (LTF) takes its name from the island and bank (platform or rise) of equal name, located at the edge of the northern rim of the Cariaco trough or basin. This roughly east–west striking fault bounds the La Tortuga platform on its southern side. It is as well the bounding fault of the northernmost part of the Cariaco basin. Using a small set of N–S trending acoustic lines, Schubert and Krause (1984) extends it to the west for over 220 km until connecting it to the Oca-Chirinos fault at the eastern Falcón coast (Figs. 3, 4 and 13). The expression in seismic lines of this fault is very conspicuous south of the island (Fig. 14). Recent sedimentation is controlled by the fault and essentially restricted to the southern compartment where the sedimentary packages are much thicker. The fault planes reaches surface, and deforms sea-bottom (Fig. 14). A selected set of the original line drawings from Schubert (1982) are herein presented for comparison. Lines 1, 2 and 8 from Schubert (1982; Fig. 13) roughly coincide geographically speaking with our lines VARS 18 (Fig. 12), 14 (Fig. 15) and 1 (Fig. 14), respectively. LTF in line 2 of Schubert (1982) is bounding a “basement” high that protrudes through younger sediments. Our equivalent line (VARS 14; Fig. 15) clearly shows that sediments are overlapping such “basement” on both southern and northern side; and only a minor fault appears cutting the surface sediments on the northern flank of the “basement” high. Further to the west, lines VARS 16 (Fig. 11) and 18

(Fig. 12) do not show any fault on the western prolongation of the alleged LTF, which is otherwise very conspicuous in line VARS 1 (Fig. 14), south of the homonym island. The same “basement” high imaged by VARS 14 is also visible in VARS 16 (Fig. 11), but not any longer in VARS 18 (Fig. 12). Surrounding younger sedimentary units keep overlapping the high. This high is known to the fishermen as a “Placer”, because of the high quality professional sport fishing.

In order to visualize the eventual prolongation of the LTF at depth west of la Tortuga island and off north of the North–central Coastal range, we include a conventional oil-exploration north-south trending seismic line shot at the longitude of the Chuspa embayment ($-66^{\circ} 20'$; Fig. 16; location also provided in Fig. 5). If any prolongation of LTF crosses La Guaira platform is definitely a fault of lesser importance since it is not that evident on any of the conventional seismic profiles interpreted by Paolini (2012), such as the one shown in Fig. 16. East of La Tortuga island, the situation about this fault is not much different. Already few kilometers east of the island, as depicted by profile 14 in Fig. 13, the expression of the fault in seismic lines vanishes (refer to Morelock et al., 1972 for further details).

7. Discussion

The pioneering exploration of Schubert by acoustic profiling, among other methods and explorers, revealed the occurrence of Quaternary deformation affecting offshore regions in North–central Venezuela. From previous works and our own investigations, we can confidently state that the San Sebastián fault (SSF) is a prominent structural feature offshore North–central Venezuela, regardless of the depth of investigation considered. This

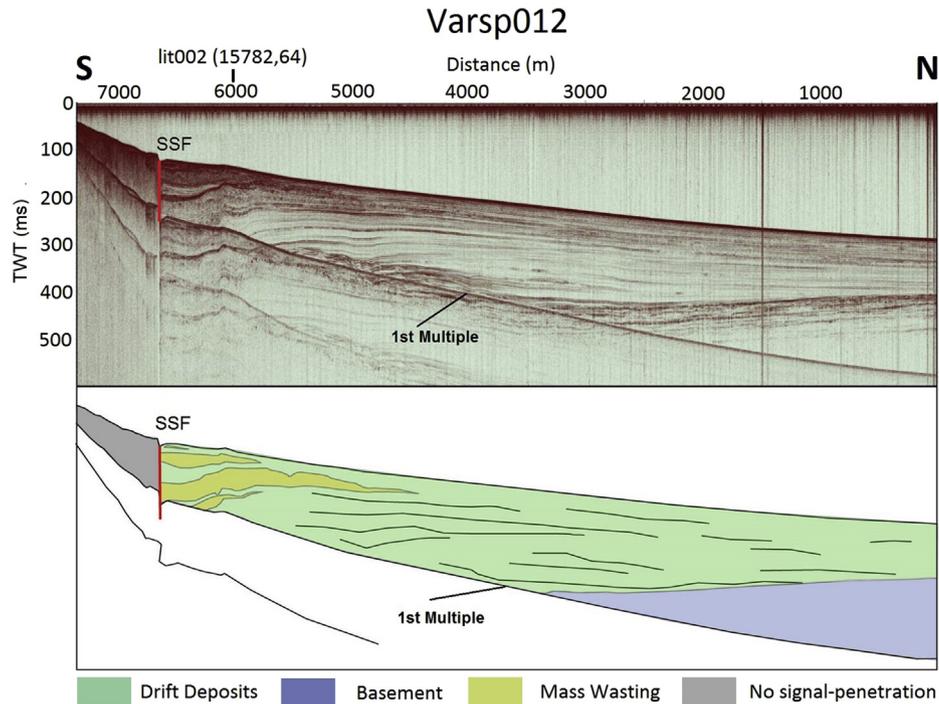


Fig. 10. Uninterpreted (top) and interpreted (bottom) sparker profile (VARS 12). For relative location, refer to Fig. 5. The SSF appears as a very sharp single vertical fault plane, conversely to the structural style exhibited west of Maiquetía. This visualization is possible because the coast has a large embayment at Chuspa, several kilometers west of Cabo Codera (easternmost tip of the Coastal range), allowing the vessel crossing across. Note the freshness and preservation of the north-facing fault scarp in unconsolidated sediments. Interpretation is only provided above first multiple.

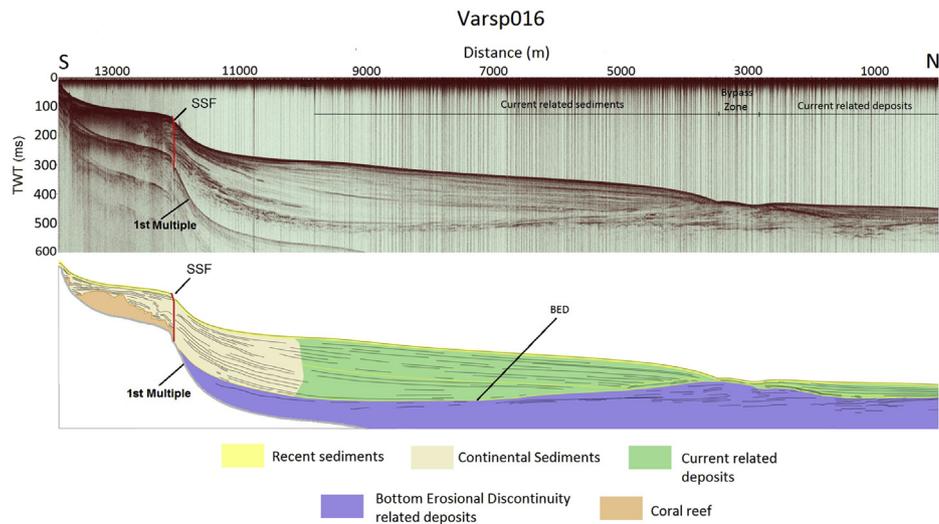


Fig. 11. Uninterpreted (top) and interpreted (bottom) high-resolution shallow seismic line VARS 16. Relative location is given in Fig. 5. The SSF appears as a single vertical fault plane at the edge of a narrow elevated platform, looking much alike to a fault bench. Also note the protruding “basement” through a younger onlapping sedimentary package to the right of the profile. Interpretation is only provided above first multiple.

fault can be identified from seismic velocity modeling, such as the one derived by Magnani et al. (2009), conventional oil-exploration seismic data with imaging depths of TWT 6–8 s and high-resolution seismic profiling with shallower investigation depths of only a few hundreds of milliseconds of penetration, as the one shot by us in 2007 and shown in this contribution. As mentioned earlier, this fault abruptly juxtaposes rock packages of velocities typical of sedimentary rocks against faster igneo-metamorphic complexes (Fig. 6). The SSF is equally conspicuous in conventional seismic lines, as shown in Fig. 7, despite that one not being the main

strand but a subsidiary northern splay. In fact, by analyzing Fig. 6 more carefully, Magnani et al. (2009) could have deduced themselves that the imaged fault by reflection seismic (Fig. 7) was not the main fault splay. The northern inclined boundary of the high velocity body identified in Fig. 6 still lies south of the surface expression depicted in Fig. 7, whose updip termination lies right below the coastline. Furthermore, these geophysical tools prove the Quaternary and even Holocene activity of this fault, since the sea-bottom is clearly offset tectonically. This is particularly valid for the high-resolution seismic lines (Fig. 8 through 12). In addition,

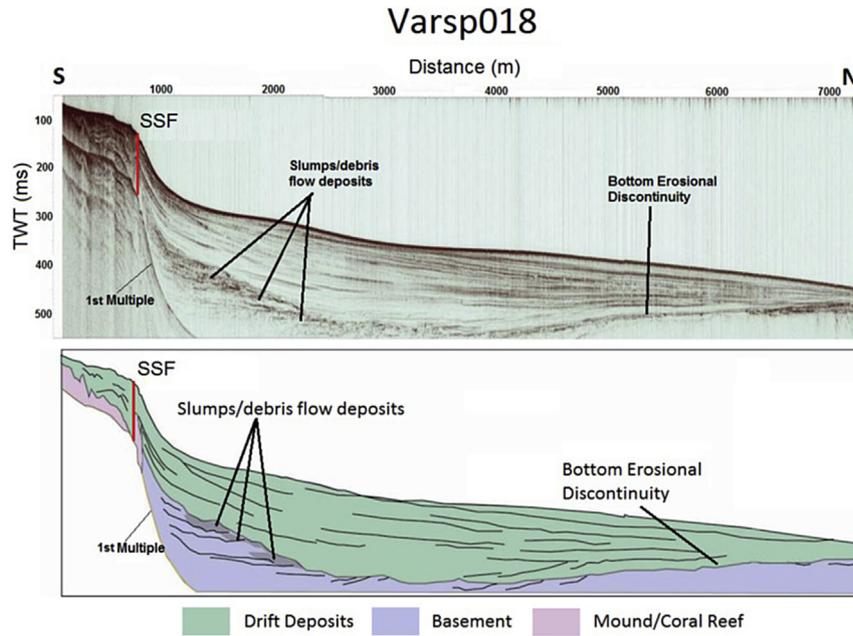


Fig. 12. Uninterpreted (top) and interpreted (bottom) profile VARS 18. Refer to Fig. 5 for relative location. The sub-vertical SSF runs at the edge of a narrow elevated bench, much in the same way as shown in line VARS 16 (compare to Fig. 11), located 11 km east of VARS 18. Interpretation is only provided above first multiple.

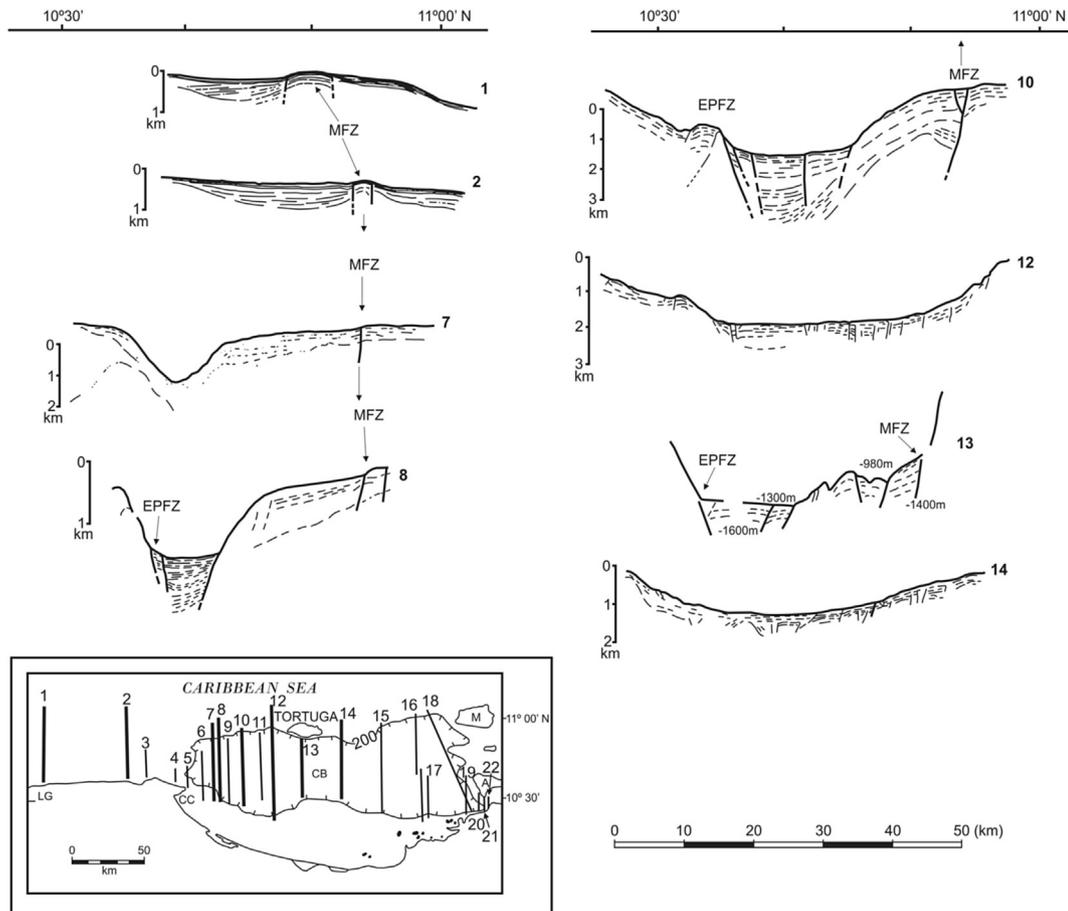


Fig. 13. Selection of simplified line-drawings from north-south trending acoustic reflection profiles of the Cariaco basin and adjacent shelves, compiled by Schubert (1982). Inset figure provides relative location of profiles (from Schubert, 1982). Relative location to other surveys is provided in Fig. 5. Numbers in line 13 are water depths. Vertical scale is variable between profiles. Compare lines 1, 2 and 8 from this figure to our VARS 16 (Fig. 11), 14 (Fig. 15) and 1 (Fig. 14) sparker lines. The Morón Fault Zone –MFZ–identified in these profiles corresponds to LTF of Beltrán (1993). The latter one is the definition adopted in this work. EPFZ stands for El Pilar Fault Zone.

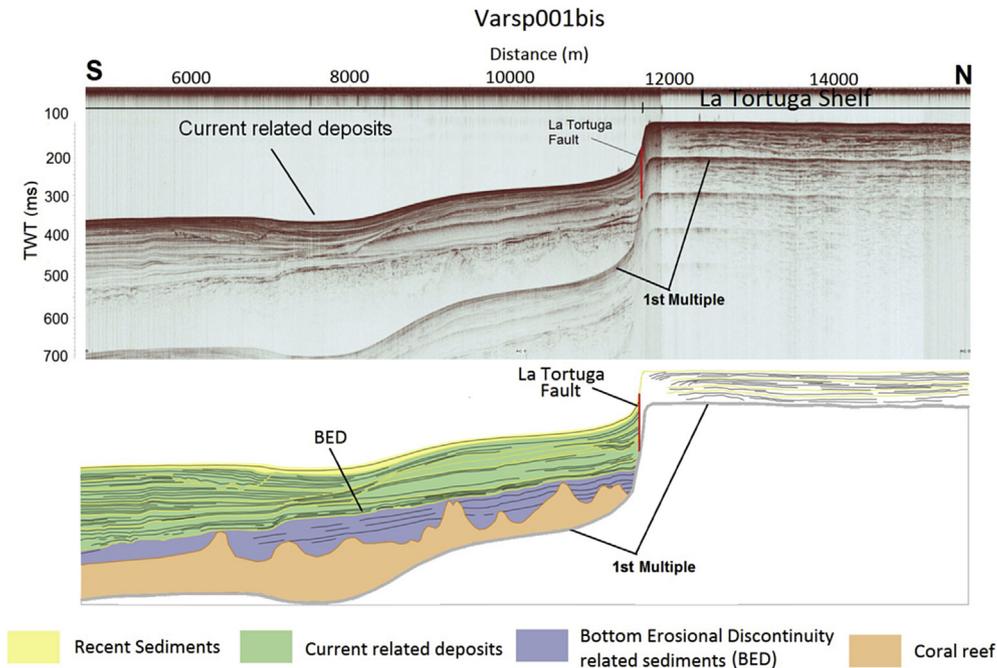


Fig. 14. Uninterpreted (top) and interpreted (bottom) profile VARS 1, across the western sector of La Tortuga high. Relative location is provided in Fig. 5. The sub-vertical LTF defines the southern edge of this high, and exhibits significant vertical component of slip, restraining the younger sedimentary packages to the Cariaco basin located south of LTF. Interpretation is only provided above first multiple.

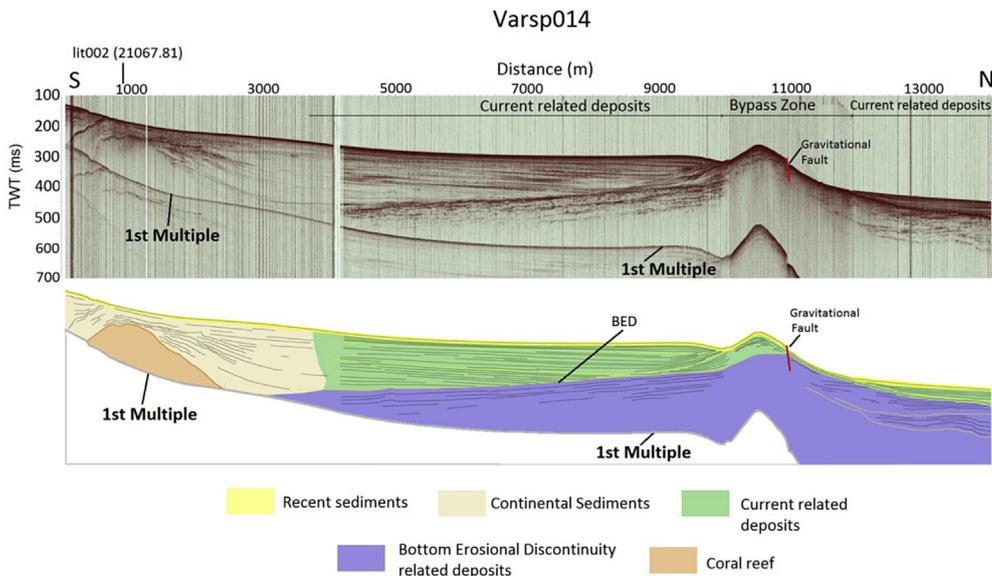


Fig. 15. Uninterpreted (top) and interpreted (bottom) high-resolution shallow seismic line VARS 14. Relative location is given in Fig. 5. Note the protruding “basement” through a younger onlapping sedimentary package to the right of the profile. Compare to profile VARS 16 (Fig. 11), located 11 km west of this one, where a similar high is also visible. It disappears at the longitude of profile VARS 18, 22 km west of this one (Fig. 12). Interpretation is only provided above first multiple.

the gathered seismic data also pinpoints that the SSF trace is much more complex west of Maiquetía than the almost single strand east of there, which actually controls the linearity of the coastline and rather steep slope of the northern flank of the Coastal range.

On the contrary, the La Tortuga fault (LTF), except for the portion of fault running along the southern edge of La Tortuga shelf (Fig. 14), is never that prominent. It also appears that its lateral extent is limited to several tens of kilometers at most, being restricted to a position roughly east of Cabo Codera, where the LTF exhibits a very important vertical offset (Fig. 14), which does not

exclude that the LTF may also have a dextral component of slip. This is supported on the fact that it does not show up where it had allegedly been mapped, like across the Guaira platform, in the past (Fig. 10 through 12; comparable to line drawings 1 and 2 by Schubert, 1982; in Fig. 13). Definitely, it does not prolong into the Oca-Chirinos fault, as once proposed by Schubert and Krause, 1984; and as much westward as maintained by Beltrán (1993, 1994) in his compilation map of Quaternary Faults of Venezuela. East of la Tortuga high, it does not appear to extent very far either (profile 14 in Fig. 13).

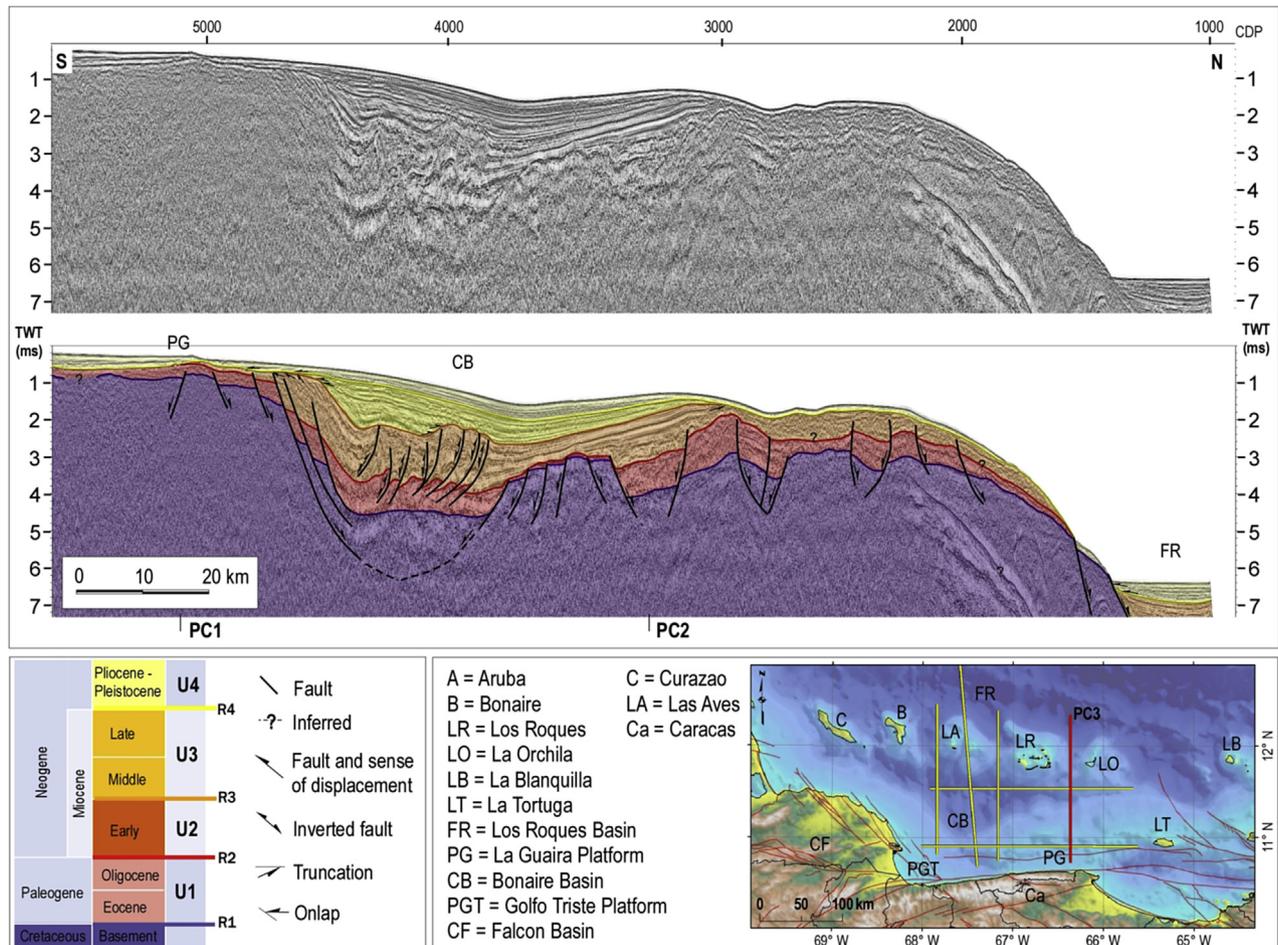


Fig. 16. Seismic reflection data uninterpreted (top) and interpreted (bottom) of profile at 66° 22' W across eastern Bonaire basin (from Paolini, 2012). Relative location is provided in inset map in bottom right corner and in Fig. 5. The profile images the southern bounding fault system of the basin, which controls and raises the La Guaira shelf. Also note the absence of a larger brittle structure in the prolongation to the west of the LTF.

This has fundamental implications in terms of seismic potential. A strike-slip fault of less than 60–70 km in length can hardly generate a Mw 7.0 earthquake, applying the Wells and Coppersmith (1994) relationships. Depending on the accepted magnitude (Mw 7.6 to 7.7) for the October 29th, 1900 earthquake, the required fault rupture on a strike-slip fault would vary between 220 km (Mw 7.6) and 270 km (Mw 7.7), assuming an average rupture depth of 15 km. This does not take into account the fact that LTF seems to slip with a dominant vertical displacement, for which earthquakes larger than Mw 7.0 are very rare to very unlikely worldwide.

Nevertheless, in spite of the fault rupture length needed for an event Mw 7.6+, the authors do believe that the most supportive evidence that the SSF was responsible for the October 29th, 1900 event is the freshness of the sea-bottom deformation introduced by the most recent slip. In that sense, we would like you to compare the fault scarps imaged for both SSF and LTF faults in Fig. 10 (VARS 12) and 14 (VARS 01), respectively. This would imply that the 1900 earthquake occurred on the SSF close to Cabo Codera. Taking into account the needed rupture length longer than 220 km, it is very likely that a large part of the 1900 rupture took place on the SSF east of Maiquetía (and east of the Caracas 1967 earthquake) and along the northern edge of the Cariaco trough (Audemard, 2002) thus giving a reliable explanation for the occurrence of accompanying tsunami waves affecting the Ensenada de Barcelona coast and Los Roques Archipelago (Audemard et al., 2012; Audemard and Leal, 2013).

On the other hand, the conventional oil-exploration seismic profiles, as those studied by Magnani et al. (2009; Fig. 7) and particularly Paolini (2012; Fig. 16), reveal the presence of another important tectonic structure in the Quaternary deformational process of this offshore region north of the Coastal range in North–central Venezuela. The La Guaira platform is raised by this fault, which runs along its northern edge. To the west (67° W longitude), it clearly exhibits significant north-verging thrust component, as interpreted by both Magnani et al. (2009) and Paolini (2012; her Fig. 37 in page 67: profile PC5). However, this latter author interprets normal component farther to the east, at the longitude (66° 20' W) of Cabo Codera (Fig. 16), although we herein favor that the La Guaira platform is raised during the Plio-Pleistocene (even starting sometime earlier in the Late Miocene) by shortening along its northern margin, differing from Paolini (2012)'s interpretation (Fig. 16). This feature could account for a significant amount of uplift that the Coastal range exhibits in North–central Venezuela, which does not appear to be accommodated by the SSF on its own. In terms of seismic hazard, this feature urgently needs to be assessed owing to its potential extent in ENE–WSW direction, from somewhere near Maiquetía to even as far as Los Roques canyon (west of Margarita island), for several tens of kilometers. It is not excluded that this major active structural boundary prolongs, although not necessarily continuously, into the Blanquilla basin southern marginal fault (see Fig. 2 and refer to Ysaccis, 1997; for more details). On top of that, in terms of risk, it

would run close to the north of the largest and most inhabited of the Venezuelan islands (Margarita), with a lively touristic industry.

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Chapter 7

Conclusion and perspectives

The large uncertainties on the fault seafloor traces and their extent in North-central Venezuela. High resolution seismic allowed us to determine problems continuity of La Tortuga fault located north of the San Sebastian faults and corroborate the existence of the latter with clear evidence of recent activity, apart from seismic activity record (e.g. [Colón et al, 2015](#)) we have in the most of high seismic profiles a clearly evidence of recent deformation caused by SSF.

The review and comparison of eustatic sea-level curve ([Van Daele et al., 2007](#)) with our low base level (LGM and MIS12) (Fig 12 and 13).on the profiles allows us to infer that the La Guaira shelf was exposed during MIS12 and MIS2 period (Figure 15). The depth of this horizon on mi-shelf is approximately 117m, if the sea level during LGM corresponding with 120m, the exposure until mi shelf was around 2km measured from the shoreline until mi-shelf.

The subsidence measured in the HR profiles is $1,2 \text{ mm.yr}^{-1}$. For the Choroní basin is not possible calculated the same way because is not possible to correlate the discontinuities seen in the La Guaira shelf but the vertical motion is obviously because the quickly deepening of the shelf. Golfo Triste shelf is more stable rather than the other shelves.

According with Paolini 2012, the North margin could be divided into 4 provinces (Figure13) with different sedimentological and tectonic features. In the high of Codera is influenced by the active north La Tortuga fault and south failure is observed San Sebastian. Westward, La Guaira shelf, an erosive and shallow platform with a gently and continuously sloping submarine plain down to 360m, which steeper between 0 and 200m. Three plateaus or banks of reef interrupted abruptly rising from the bottom of the submerged plain (La Guaira, Los Caracas and Caruao). To the west, the Choroní basin appears with an abrupt deepening of the platform, this influenced by a series of normal faults affecting up early Miocene deposits. These normal fault defined by Paolini 2012, are responsible for the submarine canon "A" ([Sellier de Civrieux 1971](#); [Paolini 2012](#)),

which is connected with the canon Mamo in surface. Through these canyons they are transported sediments to the Bonaire basin. Finally, Golfo Triste shelf have the similar features of La Guaria shelf, in other words an erosive and shallow platform with a gently and continuously sloping.

The most supportive evidence that the SSF was responsible for the October 29th, 1900 event is the freshness of the sea-bottom deformation introduced by the most recent slip. In that sense, we would like you to compare the fault scarps imaged for both SSF and LTF faults in VARS 12 and VARS 01, respectively. This would imply that the 1900 earthquake occurred on the SSF close to Cabo Codera. Taking into account the needed rupture length longer than 220 km, it is very likely that a large part of the 1900 rupture took place on the SSF east of Maiquetía (and east of the Caracas 1967 earthquake) and along the northern edge of the Cariaco trough (Audemard, 2002); thus giving a reliable explanation for the occurrence of accompanying tsunami waves affecting the Ensenada de Barcelona coast and Los Roques Archipelago (Audemard et al., 2012; Audemard & Leal, 2013).

We recommend the densification of the seismic to corroborate the extension of the landslides present in the zones of study as well as the taking of nuclei that allow to give the absolute ages of the stratigraphic units and of the observed events in the seismic profiles.

Chapter 8

References

A

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