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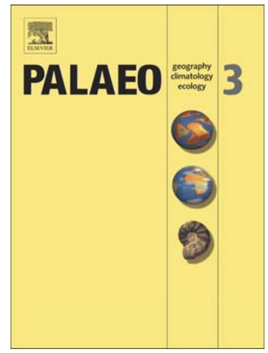


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# LATE EOCENE MARINE INCURSION IN NORTH-WESTERN SOUTH AMERICA

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## ABSTRACT

During the late Eocene in the Colombian Subandean basins, one of the most important oil-bearing rocks of the country was deposited: the Mirador Formation. Palaeogeographical models have interpreted a typically fluvial environment for the lower Mirador Formation and marginal to marine environments for its upper layers. The potential of marine influence in the upper Mirador beds and the overlying lower Carbonera formation as a correlation tool, and the palaeogeographic distribution of the event have not yet been defined. In order to determine the palaeogeography of this probable incursion, 80 wells and four sections were analysed using palynological techniques. The presence of a marine influence in the sediments was determined by using a Salinity Index (SI) that describes the negative relationship between continental and marine palynomorphs. The marine influence has been recognized in two areas: the first, in the Putumayo basin, and the second, in the Eastern Cordillera and Central Llanos Foothills. In the Putumayo basin the Salinity Index pattern reveals a southern provenance of the marine incursion, flooding the Colombian territory in a South-North trend through the Ecuadorian coast. The marine influence of the Eastern Cordillera and the Central-Eastern Llanos Foothills is more difficult to explain. We propose a possible corridor through the proto-Lower Magdalena Valley that connected the Caribbean Sea and the Central Llanos Foothills. Palaeogeographic models for the late Eocene of north-western South America should consider this marine incursion and its geographical distribution.

Key Word(s): Late Eocene; Palynology; Salinity Index; Marine Influence; Mirador Formation, Carbonera Formation

## INTRODUCTION

Depositional models for the late Eocene in north-western South America have considered most of the sedimentary sequences deposited during this period to be of fluvial origin (Notestein *et al.*, 1944; Van der Hammen, 1957; Van der Hammen, 1960; De Porta, 1962). However, recent data have shown some evidence of deltaic and sporadic marine influence (Cooper *et al.*, 1995; Villamil, 1999) associated with an increase in the subsidence rate (Bayona *et al.*, in press). Palaeogeographical models proposed by Cooper *et al.* (1995), Pindell *et al.* (1997) and Villamil (1999) have interpreted a marine ingression that flooded the Llanos basin through Lake Maracaibo. However, sedimentological analysis carried out by Higgs (1997) in upper Eocene cores and outcrops from the Llanos Foothills did not support a marine influence, rejecting any marine incursion in this area. Information from cores, well logs and palynological analysis has shown that during the late Eocene, a marine incursion also flooded south-western Colombia (southern Llanos Orientales basin and western Putumayo basin), and probably came from the south, through the Ecuadorian coast (Osorio *et al.*, 2002).

This work uses the palynological information from 84 localities to establish the palaeogeographical distribution of a marine incursion during the late Eocene in Eastern Colombia.

## REGIONAL TECTONIC SETTING OF EOCENE SEDIMENTARY UNITS

The study area encompasses the Eastern Cordillera and the following surrounding basins: Catatumbo, Llanos, Upper Magdalena Valley, Middle Magdalena Valley, and Putumayo basins (Figure 1). All these basins and the Eastern Cordillera record the evolution of a complex broken foreland basin since latest Cretaceous time. The foreland basin was bounded to the west by uplifts along the Central Cordillera that controlled deposition along the Magdalena basin during the Palaeocene (Cooper *et al.*, 1995; Gómez *et al.*, 2005). Internal reactivated structures toward the east (structural blocks presently involved in the axial zone of the Eastern Cordillera) controlled tectonic subsidence, sediment supply and depositional systems of the foreland basin toward the Catatumbo and

Llanos basins (Bayona *et al.*, in press). During the Eocene, extensive deformation affected the Magdalena basin and the western flank of the Eastern Cordillera, as documented by Eocene conglomeratic sandstones resting upon pre-Palaeocene rocks in an angular unconformity in the Magdalena basin (Villamil *et al.*, 1995; Restrepo-Pace *et al.*, 2004; Gómez *et al.*, 2005). Angular unconformities have not been reported toward the east. Lower-middle Eocene strata in the Eastern Cordillera, Catatumbo, Llanos and Putumayo basins consist of amalgamated quartzarenite beds with thicknesses ranging from 100 to 200 m. These beds accumulated in a period of approximately 15 m.y. (Bayona *et al.*, in press). During the late Eocene–Oligocene, the growth of structures along the present Eastern Cordillera and Llanos Foothills controlled thick (>1 km thick) synorogenic deposition in the Magdalena foreland basin (Gómez *et al.*, 2005), as well as in the foreland basin along the Catatumbo, Llanos and Putumayo basins (Bayona *et al.*, in press).

Eocene strata in the study area include the Mirador Formation (or Picacho Formation in the Eastern Cordillera), and the lower Carbonera Formation (or Concentración Formation in the Eastern Cordillera). The Mirador-Picacho is composed of clean sandstones, moderately hard and friable, fine- to medium-grained and locally conglomeratic, with internal sedimentary structures that are massive and cross-bedded and wavy-laminated to the top (Notestein *et al.*, 1944; Hubach, 1957; Van der Hammen, 1960; De Porta, 1962). In the Mirador Formation, two members have been distinguished: the lower, comprising medium- to coarse-grained sandstones, with a thinner stratification than the upper member. The upper member, one of the subjects of this research, is composed of quartzitic-conglomeratic sandstones alternating with light grey massive sandy mudstones and locally laminated, organic mudstones with plant remains, which become thicker upwards (Fajardo *et al.*, 2000).

The depositional environment for the upper member of the Mirador has been widely discussed, as sedimentary structures change from north to south. Outcrops and core descriptions in the northern Llanos Foothills indicate that upper Mirador sandstones show complete fining-upward successions and coal interbeds (Reyes, 2004). In the central Llanos Foothills, fine- to medium-grained quartzarenites have more mudstone interbeds and show evidence of deposition in a brackish-water environment including a diverse ichnofacies association comprising *Ophiomorpha, Thalassionoides, Psilonichnus and Diplocraterion* (Pulham *et al.*, 1997), couplets in foreset laminations, and wavy and flaser lamination. Several authors have proposed a coastal to marginal-marine environment, owing to the presence of dinoflagellates, microforaminifera and ichnofossils (Cazier *et al.*, 1995; 1997). On the contrary, Higgs (1997) discusses the depositional model proposed by Cazier *et al.* (1995) and Cooper *et al.* (1995), interpreting the "stunted" ichnofauna (*Planolites*, *Ophiomorpha* and *Arenicolites* associations) and facies (sandstones, siltstones and mottled, rootlet-bioturbated mudstones) as having been deposited in a fluvial environment including fluvial channels, overbank palaeosols and lakes.

The Carbonera Formation overlies the Mirador Formation. The contact between the two formations is transitional. Carbonera strata in the northern and central Llanos Foothills consist predominantly of 250m-thick dark green and grey laminated and poorly bioturbated mudstones (Jaramillo and Dilcher, 2001; Mora and Parra, 2004) grading to coarsening-upward successions. The lower Carbonera Formation has been interpreted as coastal plain deposits with brackish influence (Fajardo *et al.*, 2000) that accumulated during the late Eocene (Jaramillo and Dilcher, 2001).

In the Upper Magdalena Valley and Putumayo basins (Figure 1), Eocene strata consist of interbedded conglomeratic-dominant and mudstone-dominant lithological units

(Gualanday Group - Pepino Formation). In the upper Magdalena basin, age control of the Gualanday group is poorly constrained because the dominant facies are varicolored and mottled mudstones that accumulated in oxidized alluvial plains and contain poorly preserved palynomorphs and organic matter. In the Putumayo basin, the Pepino Formation is overlain by the Orteguaza Formation (Osorio *et al.*, 2002), which consists of green-brown siltstones and limestones at its base, and carbonaceous limestones and sandstones at the top. In both the Putumayo basin and the Oriente basin in Ecuador, this formation has been interpreted as deposited in a subtidal zone (Ecopetrol and Beicip, 1988; Western Atlas, 1995; Baby *et al*., 1997; Rivadeneira and Baby, 1999; Osorio *et al.*, 2002).

## LATE EOCENE PALYNOLOGY

The late Eocene in Eastern Colombia can be recognized by the presence of palynological zone T07, *Echitriporites trianguliformis orbicularis* of Jaramillo *et al.* (in press). The top of the zone is recognized by the extinction of the pollen taxon *Echitriporites trianguliformis* var. *orbicularis*. This palynological zone has been recognized throughout Colombia and Venezuela (Muller *et al.*, 1987; Osorio *et al.*, 2002; Jaramillo and Rueda, 2004).

The top of zone T07 in the Catatumbo, Llanos Foothills and Southern Llanos has been found at the base of the Carbonera Formation, just a few metres above the Mirador Formation (Jaramillo and Rueda, 2004; Jaramillo *et al.*, in press). In the Upper Magdalena Valley and Putumayo basins, the top of zone T07 occurs at the base of the Orteguaza Formation (Osorio *et al.*, 2002).

## METHODS

Eighty wells and four outcrop sections, distributed in a SW–NE pattern were analysed palynologically (Figure 1, Table 1). Well names cannot be given because of confidentiality issues. The analysis at each site followed two steps: In the first step several samples were analysed in order to determine the top of the palynological zone T07. In the second step, several samples spanning zone T07 were analysed to calculate the proportion of marine versus terrestrial palynomorphs for each sample. Palynomorphs were grouped into two categories: continental (pollen and spores) and marine (dinoflagellate cysts, microforaminifera lining and marine acritarchs). Three hundred palynomorph grains were counted per slide, when possible, to standardize the data (Buzas and Hayek, 1997).

A Salinity Index (SI) was calculated for every sample as SI = M/T, where M is the number of marine palynomorphs and T is the total count (marine plus terrestrial palynomorphs). A similar index has been used in paleoecological and sequence stratigraphy studies elsewhere (e.g. Rull, 2000; 2002). As the environment of deposition moves away from the shoreline, the proportion of terrestrially derived palynomorphs generally decreases and the proportion of marine-derived palynomorphs increases (e.g. Hoffmeister, 1954; Muller, 1959; Williams, 1971; Heusser, 1983; Traverse, 2007) mainly because a pollen grain behaves as a sedimentary particle and is water-transported (Traverse, 2007). We computed the Salinity Index for the data published by Muller (1959, his table 1) from his study in the Orinoco delta (Figure 2). The correlation between the Salinity Index and the distance to the shoreline was significant (Spearman rho = 0.8632643, p-value $< 2.2 * 10^{-16}$, N=118). However, it has proven very difficult to quantitative assess the significance of the marine/terrestrial ratio in terms of absolute water-depth or absolute distance to the shoreline, because many factors in a particular basin can affect the value, including the size of the drainage, offshore currents, tidal currents and bottom morphology (Muller, 1959;

Cross *et al.*, 1966; Williams and Sarjeant, 1967; Chowdhury, 1982; Mudie, 1982; Hofmann, 2002; Traverse, 2007). Here, we use the Salinity Index as a qualitative assessment of the degree of marine influence. Sites farther from the shoreline would in general have a lower proportion of terrestrially derived palynomorphs and a higher proportion of marine-derived palynomorphs.

The index that had the highest value within the upper part of zone T07 was used as the value indicating the maximum marine influence for that site. Maximum SI values per site were plotted on a geographic map, and an isosalinity map was produced using the software Surfer 6.02. Samples with fewer than 169 palynomorphs counted per slide were not used to calculate the salinity index, ensuring a confidence level of 95% and a confidence interval of ± 5%.

Palynological slides were prepared at the Colombian Petroleum Institute using the standard palynological technique (Traverse, 1988). Palynological analyses were carried out using Axioskop Zeiss and Zeiss ICS KF2 microscopes.

## DISTRIBUTION OF THE MARINE INFLUENCE IN UPPER EOCENE STRATA

Upper Eocene strata (palynological zone T07) were recognized in a north-eastern – south-western trend located along the western side of the study area including the Eastern Cordillera and Llanos Foothills, Catatumbo, Middle Magdalena Valley (MMV), Upper Magdalena Valley (UMV) and Putumayo basins (Figure 3, Table 1). In most of the Llanos basin, upper Eocene rocks either did not accumulate or accumulated and were later eroded (Figure 3).

There are two areas with a notable marine influence (SI > 0.07, Figure 3); the first is in the central Llanos Foothills (SI = 0.19 to 0.24), and the second is located toward the south-west, in the Putumayo basin (SI = 0.07 to 0.1) (Figure 3). The Central Llanos Foothills exhibit the highest SI values: 0.24 at site 51 and 0.2 at site S44 (Table 1). The overall pattern of the SI shows a decrease both northward and southward of the central Llanos Foothills (Figure 3). The Putumayo basin also shows a marine influence (SI = 0.1 at site 80), with SI decreasing northward (0.07 at site 79; 0.02 and 0.04 at sites 77 and 78, respectively, Figure 3).

Either minimal or no marine influence was recognized in the Catatumbo (0-0.02), Middle Magdalena Valley (0) and Upper Magdalena Valley (0.02-0.04) basins (Figure 3). The Catatumbo basin shows very low SI values: 0 in sites 1, 3, 4 and 6, and 0.02 at site 7. In the Middle Magdalena Valley, the marine influence is null (SI = 0), and in the Upper Magdalena Valley, it is low (SI = 0.02 at site 77). Likewise, in the Eastern Cordillera, SI is low (0.02 at site S24, in the area of Paz del Río, Table 1).

## PALAEOGEOGRAPHIC IMPLICATIONS

The Salinity Index data show two clear patterns, a marine influence towards the central Llanos Foothills, and a separate marine influence in the Putumayo basin (Figure 3). Palaeogeographic models for the late Eocene in north-western South America (Cooper *et al.*, 1995; Villamil, 1999) suggest a marine ingression flooding the Llanos Foothills and Llanos basin from Lake Maracaibo through the northern Llanos. These models show a marine influence in the central Llanos Foothills that is in agreement with the data presented here (Figure 3). Cazier *et al.* (1995; 1997) report evidence from trace fossils and palynology that indicates a marine influence in the Cusiana Oil Field (central Llanos Foothills). In Cusiana, ichnofacies composed of *Teichichnus, Arenicolites, Thalassinoides, Ophiomorpha, Diplocraterion, Paleophycus, Macaronichnus, Skolithos, Gyrolithes and*

*Planolites* were identified. According to Pemberton and MacEachern (1995) such an assemblage is generally associated with marginal marine environments including intertidal zones, shallow lagoons, estuaries and deltaic platforms. The palynological evidence for a marine influence in the Cusiana Oil Field includes the dinoflagellate cysts *Spiniferites*, *Polysphaeridium*, *Operculodinium*, *Cordosphaeridium*, and *Homotryblium* and microforaminiferal test linings (Cazier *et al.*, 1997).

Beyond the central Llanos Foothills our findings diverge significantly from earlier studies. The models of Cooper *et al.* (1995) and Villamil (1999) propose that the marine incursion should be recorded in the upper Eocene strata of the southern Maracaibo, Catatumbo and northern Llanos because that was the communication pathway to the Caribbean Sea during the late Eocene flooding. Our results do not support this hypothesis. The data set presented above shows those areas with a minimal to null marine influence. None of the sites analysed in the Catatumbo, northern Llanos Foothills and northern Llanos showed a marine influence (Figure 3). Published data from the southern Maracaibo basin also do not indicate a marine flooding in upper Eocene strata. The Carbonera Formation, which lies across most of the southern Maracaibo basin, was accumulated in a coastal plain environment and does not record any marine influence during the late Eocene (Colmenares and Teran, 1990; 1993). Upper Eocene formations from the western Perija Range also record no evidence of a major marine flooding (e.g. La Sierra and Ceibote formations; Cien, 2007), and there is a major unconformity in the middle of Lake Maracaibo where upper Eocene sediments are not recorded (Mann *et al.*, 2006).

We propose an alternative hypothesis to explain the marine influence in the central Llanos Foothills that is based on a dynamic model for north-western South America proposed by Montes *et al.* (2005). This model divides north-western South America into three blocks: Maracaibo, Central Cordillera and Eastern Cordillera blocks. Because of the deformation associated with the north-eastward movement of the Caribbean plate along the border of the South American plate, the Maracaibo and Central Cordillera blocks rotated and translated north-eastward in a clockwise direction (Figure 4a). According to Montes's model, during late Eocene, the Central Cordillera and Santa Marta massif were located to the south-west of their present position. Those two blocks started to separate from each other, giving rise to a corridor (proto Lower Magdalena Valley) between the Santa Marta massif and the northern Central Cordillera-Middle Magdalena basin (Figure 4A and B) (Reyes *et al.*, 2002; Niño *et al.*, 2006). A late Eocene marine ingression could have occurred south-eastward, through the Lower Magdalena Valley, producing the onset of marine to marginal deposition in the Lower Magdalena Valley (Casanova and Hernández, 2006), and marine influence in the Paz del Río area (site S24) and in the central Llanos Foothills (Figure 4B). This ingression could have flooded Colombia in a NW-SE trend (Figure 4A) and because of the rotation and translation of these blocks, the flooding trend would now be fragmented (Figure 4b). Although there is scarce information from the Eocene strata of the southern segment of the Lower Magdalena Valley as a result of wells being drilled on palaeohighs (Casanova and Hernández, 2006), there is evidence of early Oligocene limestones and turbidites in the region **(**Reyes *et al.*, 2002; Niño *et al.*, 2006). In the Paz del Río Area (Eastern Cordillera), a marine event has been recognized in the Upper Eocene Concentración Formation using sedimentological and biostratigraphical proxies (Kimberley, 1980; Cazier *et al.*, 1997; Villamil, 1999; Bayona *et al.*, in press). The lowermost Concentración Formation is composed of fine-grained sandstones and black-grey mudstones, sometimes bioturbated, and contains a red oolitic ironstone bed. The oolitic ironstone bed has been interpreted as deposited in a shallow-marine epicontinental seaway (Villamil, 1999).

The late Eocene marine incursion can be a good tool for correlation across and within basins. It was used to correlate strata between the Llanos Foothills (lowermost Carbonera Formation) and the axial Eastern Cordillera (Concentración Formation, site S24, Paz de Rio). In the Eocene, the palinspastic distance between these two sections was at least 90 km apart (Bayona *et al.,* in press). Additionally, the increase of accommodation space associated with this marine incursion is also recorded in continental strata 200 km farther north in the Llanos Foothills. Similar biostratigraphic studies in other sites in Venezuela and Ecuador, that are not yet available, could allow tracing this marine incursion event along the northern South American basins.

The Salinity Index pattern shows an increase in the marine influence toward the south-west, indicating possibly that this event flooded south-western Colombia from the Ecuadorian Coast, in a south-western to north-eastern trend, as Cooper *et al.* (1995) and Villamil (1999) recognized in their models. Rivadeneira and Baby (1999), working in the Oriente basin (the southern extension of the Putumayo basin into Ecuador), recognized a flooding surface in the upper Eocene Orteguaza Formation. This event is recorded in black shales with pyritic nodules that suggest a shallow marine platform.

## CONCLUSIONS

Sediments with marine influence accumulated during the late Eocene (palynological zone T07) in the central Llanos Foothills and Putumayo basins. In the Catatumbo, Middle Magdalena Valley, north-west and south-west Llanos basin and Upper Magdalena Valley, there is no record of marine influence.

In the Putumayo Basin, the southward increase in Salinity Index values suggests that a marine incursion could have come from the south, from the Ecuadorian coast. The marine ingression in the central Llanos Foothills is more puzzling, because the flooding seems to be surrounded by more continental deposits. We propose that block rotations during the Cenozoic could have disrupted and displaced the marine corridor that probably connected the open Caribbean Sea with the central Llanos Foothills through the initial opening of the Lower Magdalena Valley during the late Eocene. More data from the northern Middle Magdalena Valley and southern Lower Magdalena Valley basins would be needed to test this hypothesis.

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FIGURE 2. Salinity Index in relation to the distance from the shoreline for the Orinoco delta. (Data from Table 1. Muller, 1959).

FIGURE 3. Geographical distribution of the Salinity Index values from upper Eocene sediments, north-western South America.

FIGURE 4. Marine ingression during the late Eocene in north-western South America (Colombia). 4A. Late Eocene reconstruction of the flooding and position of the tectonic blocks of northern Colombia. 4B. Present-day reconstruction of north-western Colombia showing the modern location of the Eocene flooding (tectonic model after Montes *et. al.*, 2005).

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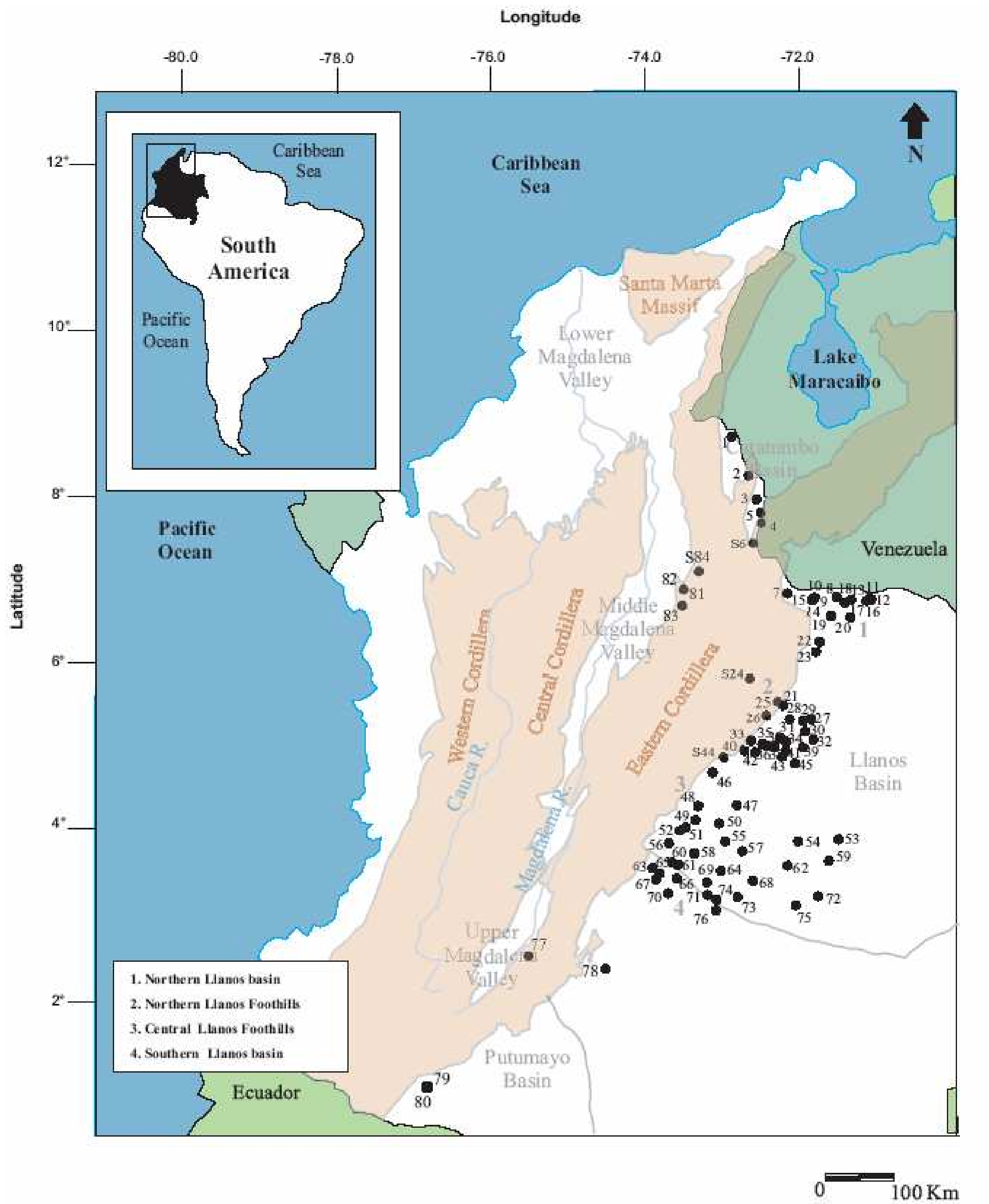
| Well / Section | Latitude (N) | Longitude (W) | Salinity Index |
|---|---|---|---|
| 1 | 9° 5´ 47" | 72° 54´ 17" | 0 |
| 2 | 8° 35´ 19" | 72º 40´ 38" | 0.009 |
| 3 | 8° 16´ 41" | 72° 34´ 44" | 0 |
| 4 | 8° 12´ 46" | 72° 44´ 33" | 0 |
| 5 | 8° 6´ 3" | 72° 30´ 56" | 0.004 |
| S6 | 7° 42´ | 72º 37´ 00" | 0 |
| 7 | 7° 2´ 36" | 72° 10´ 36" | 0.02 |
| 8 | 6° 59' 29" | 71° 31' 50" | Upper Eocene is not present |
| 9 | 6° 59' 07" | 71° 41' 19" | Upper Eocene is not present |
| 10 | 6° 58' 56" | 71° 50' 07" | Upper Eocene is not present |
| 11 | 6° 58' 06" | 71° 06' 13" | Upper Eocene is not present |
| 12 | 6° 57' 27" | 71° 04' 35" | Upper Eocene is not present |
| 13 | 6° 57' 24" | 71° 20' 33" | Upper Eocene is not present |
| 14 | 6° 57' 30" | 71° 50' 37" | Upper Eocene is not present |
| 15 | 6° 57' 17" | 71° 51' 25" | Upper Eocene is not present |
| 16 | 6° 56' 46" | 71° 05' 54" | Upper Eocene is not present |
| 17 | 6° 56' 34" | 71° 08' 22" | Upper Eocene is not present |
| 18 | 6° 54' 46" | 71° 25' 26" | Upper Eocene is not present |
| 19 | 6° 44' 47" | 71° 36' 26" | Upper Eocene is not present |
| 20 | 6° 43' 35" | 71° 21' 04" | Upper Eocene is not present |
| 21 | 6° 26' 26" | 73° 06' 09" | Upper Eocene is not present |
| 22 | 6° 24' 22" | 71° 45' 29" | Upper Eocene is not present |
| 23 | 6° 16' 38" | 71° 48' 17" | Upper Eocene is not present |
| S24 | 6° 03' 25" | 72° 59' 09" | 0.01 |
| 25 | 5° 37´10" | 72° 18´ 20" | 0 |
| 26 | 5° 26´ 32" | 72° 27´ 22" | 0.009 |
| 27 | 5° 23' 47" | 71° 52' 25" | Upper Eocene is not present |
| 28 | 5°23' 37" | 72° 09' 14" | Upper Eocene is not present |
| 29 | 5° 22' 27" | 71° 58' 33" | Upper Eocene is not present |
| 30 | 5° 14' 08" | 71° 57' 05" | Upper Eocene is not present |
| 31 | 5° 09' 08" | 72° 16' 38" | Upper Eocene is not present |
| 32 | 5° 07' 39" | 71° 50' 47" | Upper Eocene is not present |
| 33 | 5° 6´ 50" | 72° 39´ 37" | 0 |
| 34 | 5° 06' 11" | 72° 12' 03" | Upper Eocene is not present |
| 35 | 5° 04' 29" | 72° 30' 51" | Upper Eocene is not present |
| 36 | 5° 03' 01" | 72° 27' 28" | Upper Eocene is not present |
| 37 | 5° 02' 46" | 72° 21' 08" | Upper Eocene is not present |
| 38 | 5° 01' 52" | 72° 21' 29" | Upper Eocene is not present |
| 39 | 5° 01' 21" | 71° 58' 45" | Upper Eocene is not present |
| 40 | 4° 59´ | 72° 44´ 46" | 0 |
| 41 | 4° 58' 26" | 72° 12' 23" | Upper Eocene is not present |
| 42 | 4° 57' 55" | 72° 36' 24" | Upper Eocene is not present |
| 43 | 4° 54' 30" | 72° 15' 10" | Upper Eocene is not present |
| S44 | 4° 54´ | 73° 1´ | 0.199 |

| | | | |
|---|---|---|---|
| 45 | 4° 48' 52" | 72° 05' 05" | Upper Eocene is not present |
| 46 | 4° 41´ 52" | 73° 9´ 49" | 0 |
| 47 | 4° 16' 14" | 72° 50' 46" | Upper Eocene is not present |
| 48 | 4°15´34´´ | 73° 21´ 3´´ | 0.035 |
| 49 | 4° 4´ 23" | 73° 23´ 16" | 0 |
| 50 | 4° 01' 50" | 73° 04' 48" | Upper Eocene is not present |
| 51 | 3° 58´ 39" | 73° 30´ 48" | 0.241 |
| 52 | 3° 56´ 16" | 73° 35´ 11" | 0 |
| 53 | 3° 49' 06" | 71° 31' 10" | Upper Eocene is not present |
| 54 | 3° 47' 49" | 72° 02' 46" | Upper Eocene is not present |
| 55 | 3° 47' 54" | 72° 59' 51" | Upper Eocene is not present |
| 56 | 3° 46´ 22" | 73° 44´ 1" | 0.06 |
| 57 | 3° 40' 01" | 72° 46' 39" | Upper Eocene is not present |
| 58 | 3° 38´ 28" | 73° 24´ 6" | 0 |
| 59 | 3° 32' 10" | 71° 38' 47" | Upper Eocene is not present |
| 60 | 3° 31´ 13" | 73° 41´ 38" | 0.027 |
| 61 | 3° 29´ 22" | 73° 36´ 53" | 0 |
| 62 | 3° 28' 35" | 72° 11' 05" | Upper Eocene is not present |
| 63 | 3° 26' 45" | 73° 56' 48" | 0.021 |
| 64 | 3° 24´ 28" | 73° 3´ 17" | Upper Eocene is not present |
| 65 | 3° 22´ 45" | 73° 51´ 20" | 0.036 |
| 66 | 3° 18´ 36" | 73° 38´ 1" | 0 |
| 67 | 3° 17´ 54" | 73° 54´ 2" | 0 |
| 68 | 3° 16' 44" | 72° 38' 11" | Upper Eocene is not present |
| 69 | 3° 15´ 26" | 73° 14´ 17" | 0 |
| 70 | 3° 6´ 55´´ | 73° 44´ 419´´ | 0.041 |
| 71 | 3° 05' 45" | 73° 13' 50" | Upper Eocene is not present |
| 72 | 3° 04' 29" | 71° 47' 23" | Upper Eocene is not present |
| 73 | 3° 04' 08" | 72° 50' 23" | Upper Eocene is not present |
| 74 | 3° 01' 51" | 73° 06' 49" | Upper Eocene is not present |
| 75 | 2° 57´ 30" | 72° 4´ 48" | Upper Eocene is not present |
| 76 | 2° 53' 25" | 73° 07' 23" | Upper Eocene is not present |
| 77 | 2° 16´ 46" | 75° 33' 31" | 0.017 |
| 78 | 2º 7´ 31" | 74° 33´ 35" | 0.035 |
| 79 | 0° 34´ 28" | 76° 52´ 49" | 0.068 |
| 80 | 0° 34´ 6" | 76° 53´ 39" | 0.097 |
| 81 | 7° 5´ | 73° 31´ 54" | 0 |
| 82 | 7° 8´ 12" | 73° 32´ 34" | 0 |
| 83 | 6° 53´ 3" | 73° 33´ 1" | 0 |
| S84 | 7° 20´ | 73° 20´ | 0 |



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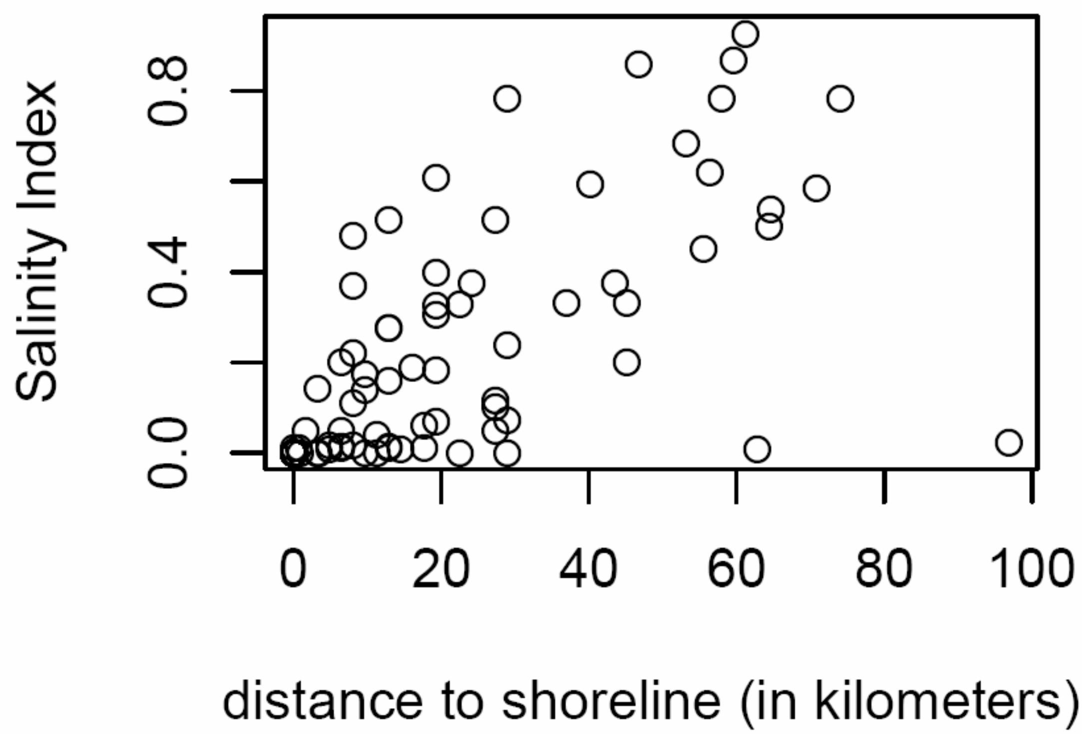
-76.0
-74.0
-72.0
Latitude
12°
10°
8°
6°
4°
2°
N
Caribbean Sea
South America
Pacific Ocean
Caribbean Sea
Pacific Ocean
Santa Marta Massif
Lower Magdalena Valley
Lake Maracaibo
Venezuela
Middle Magdalena Valley
Western Cordillera
Central Cordillera
Eastern Cordillera
Cauca R.
Magdalena R.
Llanos Basin
Upper Magdalena Valley
Putumayo Basin
Ecuador
1. Northern Llanos basin
2. Northern Llanos Foothills
3. Central Llanos Foothills
4. Southern Llanos basin
0
100 Km


524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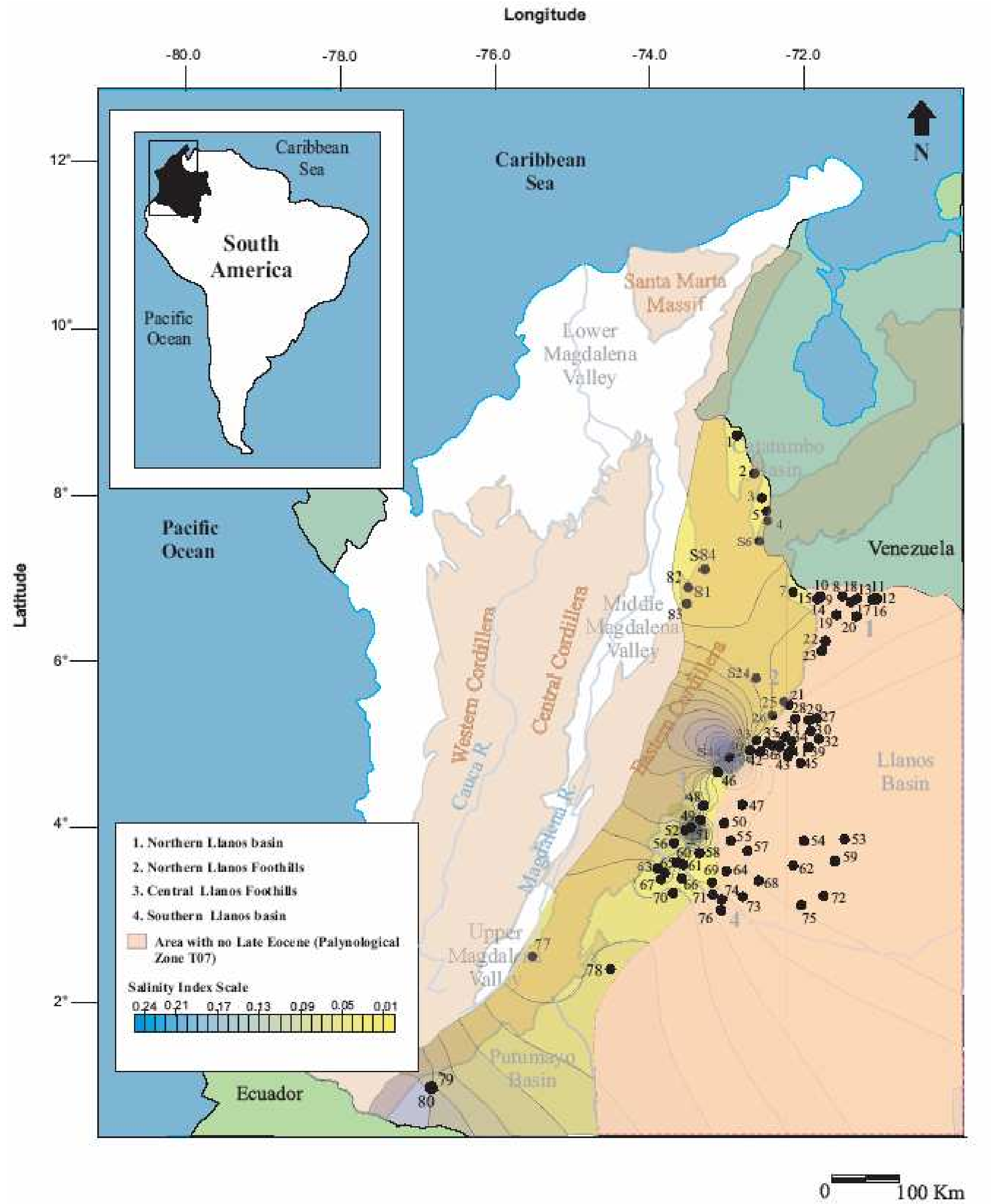
0.4
0.8
0
20
40
60
80
100
distance to shoreline (in kilometers)

525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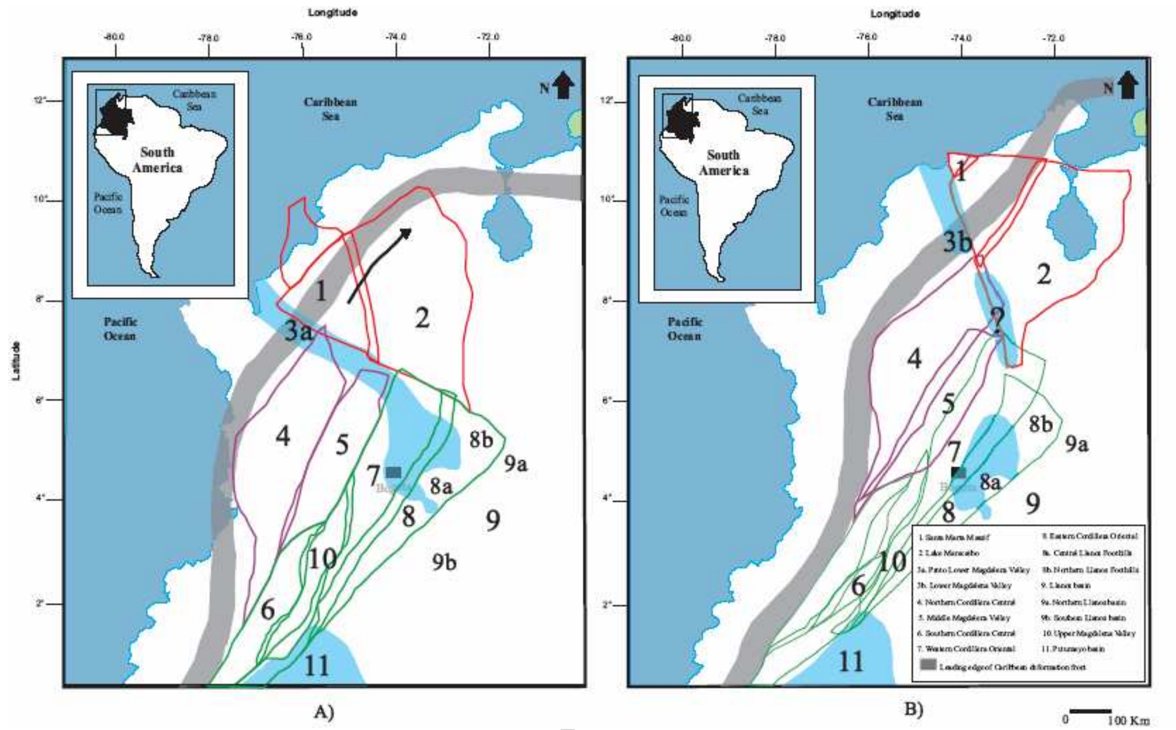
Latitude
12°
10°
8°
6°
4°
2°
N
Caribbean Sea
South America
Pacific Ocean
Caribbean Sea
Santa Marta Massif
Lower Magdalena Valley
Pacific Ocean
Venezuela
Middle Magdalena Valley
Western Cordillera
Central Cordillera
Eastern Cordillera
Cauca R.
Magdalena R.
Llanos Basin
Upper Magdalena Valley
Putumayo Basin
Ecuador
1. Northern Llanos basin
2. Northern Llanos Foothills
3. Central Llanos Foothills
4. Southern Llanos basin
Area with no Late Eocene (Palynological Zone T07)
Salinity Index Scale
0.24 0.21 0.17 0.13 0.09 0.05 0.01
0
100 Km

526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Latitude
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-78.0
-76.0
-74.0
-72.0
12°
10°
8°
6°
4°
2°
Caribbean Sea
Pacific Ocean
South America
N
1
2
3a
3b
4
5
6
7
8
8a
8b
9
9a
9b
10
11
A)
B)
1. Santa Marta Massif
2. Lake Maracaibo
3a. Pinto Lower Magdalena Valley
3b. Lower Magdalena Valley
4. Northern Cordillera Central
5. Middle Magdalena Valley
6. Southern Cordillera Central
7. Western Cordillera Oriental
8. Eastern Cordillera Oriental
8a. Central Llanos Foothills
8b. Northern Llanos Foothills
9. Llanos basin
9a. Northern Llanos basin
9b. Southern Llanos basin
10. Upper Magdalena Valley
11. Putumayo basin
Leading edge of Caribbean deformation front
0
100 Km