Chapter 10
Cretaceous Stratigraphy and Paleo-Facies Maps of Northwestern South America

Luis Fernando Sarmiento-Rojas

10.1 Introduction

The northwestern corner of South America (Fig. 10.1) had a complex geological history during the Cretaceous time, with interaction of at least three major tectonic plates along the active continental margin extending from Peru to Colombia and including a passive margin along the northern margin, extending into Venezuela. Some generalized paleogeographic reconstructions have been presented for the region (e.g., Etayo et al. 1976; Macellari 1988; Geotec 1992; Sarmiento-Rojas 2001; Cediel et al. 2003a, 2011; Villamil 1994, 1999, 2012; and Villamil and Pindell 2012, among others), but an integrated map set encompassing Venezuela, Colombia, Ecuador, and northernmost Peru, and including several regional stratigraphic sections and paleo-facies reconstructions spanning the Cretaceous period, has yet to be attempted. The purpose of this paper is to present 12 paleo-facies maps covering various ages of the Cretaceous period, supported by a regional sequence stratigraphic framework, and to summarize the Cretaceous tectonic/geological history of the northwestern South American region. I refer to "paleo-facies" maps as opposed to "paleogeographic" maps, because no attempt has been undertaken herein to do palinspastic restorations. Notwithstanding, in order to facilitate understanding of the complex tectonic history involving the accretion of oceanic terranes to the continental margin, schematic tectonic reconstructions are integrated within the paleo-facies maps. One fundamental condition in the construction of paleogeographic interpretations is the construction of accurate and correlatable stratigraphic sections. In the study region, there are many applied lithostratigraphic names, with varying local synonyms, and few biostratigraphic studies to make accurate regional stratigraphic correlations. In order to overcome this difficulty, I attempt to integrate

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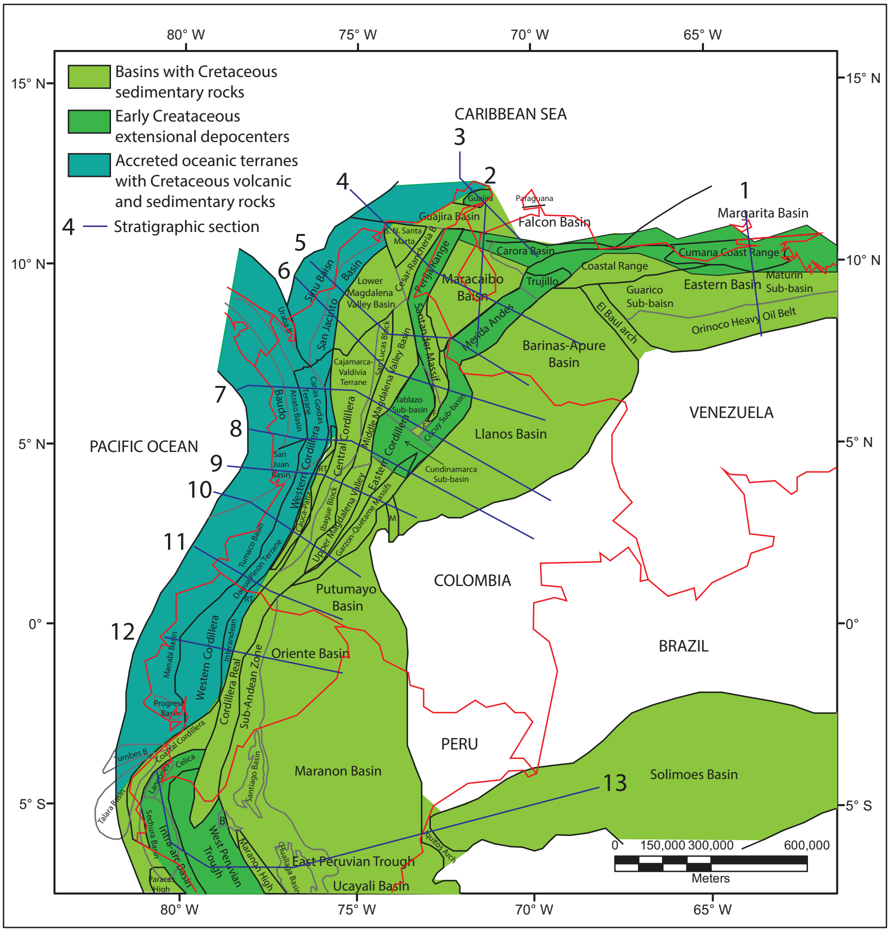

Fig. 10.1 Map of northwestern South America showing location of sedimentary basins and stratigraphic sections discussed in text. Basins indicating Cretaceous sedimentary rocks include those presently containing Cretaceous deposits, as well as those where the existence of such deposits in the past may be inferred. East-west trending Early Cretaceous depocenter in northern Venezuela is inferred from the rift system generated during separation of the Yucatan block from northern South America, based upon some plate tectonic interpretations (e.g., Pindell and Keenan 2009). F: Floresta Massif and Floresta High. M, Sierra de la Macarena; RT, Romeral Terrane as defined by Cediel et al. (2003b, 2011); B, Bagua Basin of Peru. The east-west trending Early Cretaceous depocenter in Northern Venezuela is inferred to be present below oceanic terranes accreted to the northern Venezuelan margin during the Cenozoic (not shown in this map). The maximum thicknesses for the Cretaceous sedimentary record occur in the Trujillo depocenter of northwestern Venezuela, the Tablazo, Cocuy, and Cundinamarca sub-basins of the Eastern Cordillera of Colombia and the Western Peruvian Trough of western Peru

the stratigraphy of the region into a sequence stratigraphic framework, based partially on ages reported by biostratigraphic studies, previous sequence stratigraphic studies, and in good part, using lithological and facies data from available literature and sequence stratigraphy concepts.

10.2 Methodology

I prepared several stratigraphic cross sections perpendicular to the structural grain of the Northern Andean region, including several paleo-facies maps. In order to do this, I applied the following methodology:

(a) Compilation from available literature of (a) more than 100 stratigraphic columns and stratigraphic cross sections and (b) previous paleogeographic maps
(b) Preparation of stratigraphic sections and paleo-facies maps for the studied region

10.3 Geological Setting

The northwestern corner of South America (northern Peru, Venezuela, Colombia, and Ecuador) includes litho-tectonic and morpho-structural features (Fig. 10.1) summarized below.

1. *The pre-Cambrian shields*. In south of Venezuela and east of Colombia and Ecuador lies the Guiana Shield. In east of Peru lies the Brazilian Shield. Between them, in northern Brazil, the Solimoes Basin represents an intracontinental rift developed during the Paleozoic. The Solimoes Basin trends EW along the course of the Amazon River. During the Late Cretaceous and/or earliest (?) Cenozoic, it received sediments from a west-flowing river system.
2. *The sub-Andean foreland basins bounding the Northern Andes*. These include from NE to SW: in Venezuela, the eastern Venezuela Basin, including the eastern Maturin sub-basin and the Western Guárico sub-basin, to the south of which the Orinoco Heavy Oil Belt is located. The Barinas-Apure Basin is separated from the eastern Venezuela Basin by the El Baul Arch. The Barinas-Apure Basin continues into Colombia in the Llanos Orientales Basin, south of which is located the Caguán-Putumayo Basin, which is separated from the Llanos Orientales Basin by the Sierra de La Macarena high. The Putumayo Basin of southern Colombia continues into Ecuador in the Oriente Basin and further south into Peru in the eastern part of the East Peruvian trough which contains the Marañón, Ucayali, and Madre de Dios basins. All these basins contain local Paleozoic fill and craton-ward thinning Upper Cretaceous fill, covered by Cenozoic fill which also thins toward the craton. It is possible to consider all of these basins as a single sub-Andean foreland basin with craton-ward thinning Cretaceous and Cenozoic sediments, resulting from flexural subsidence of the lithosphere due to the weight of the growing Andean orogen during the Late Cretaceous-Cenozoic time and, partially, due to Cretaceous thermal subsidence of back-arc rift basins, subsequently captured by the Andean uplift.
3. *The Northern Andes including mountainous relief and intermontane basins*. At the present time the Northern Andes may be considered a single mountain range, in Peru, consisting of the Eastern and Western cordilleras separated by the Altiplano and in Ecuador consisting of the Real and Western cordilleras

> separated by the Interandean Valley. In Colombia the Andes diverge to the north of the Colombian Massif to form three distinct mountain ranges: the Eastern, Central, and Western cordilleras. The Magdalena Valley separates the Eastern and Central cordilleras, and the Cauca Valley separates the Central and Western cordilleras. The Colombian Eastern Cordillera diverges northward forming two mountain ranges: the Sierra de Perijá along the northern Colombia-Venezuela border and the Mérida Andes of Venezuela. There are also lesser coastal ranges: the Coast Range of Venezuela, the Sierra Nevada de Santa Marta and the Baudó Range in Colombia, and the Coastal Cordillera of Peru. Several intermontane basins throughout the region contain Cretaceous sediments, such as the Maracaibo Basin of Venezuela, the Middle and Upper Magdalena basins of Colombia, and several basins in Peru (Santiago, Bagua, and Huallaga, among others). Many of these basins had different Paleozoic histories or were part of different tectonic blocks. In Colombia, Etayo et al. (1983) proposed the existence of several tectonic terranes.

During the Early Cretaceous, prior to uplift of the continental-rooted Anden ranges, basin development initiated as local rifts or extensional back-arc basins bounded by normal faults, inherited from Early Mesozoic structures. These sub-basins began to coalesce due to flexural thermal subsidence, into a regional, interconnected basin by the Aptian time. The Early Cretaceous sub-basins that constituted important, rapidly subsiding depocenters included Trujillo, Machiques (Perijá Range), Uribante (Mérida Andes), Cundinamarca (Eastern Cordillera of Colombia), and the Western Peruvian Trough (Western Cordillera of Peru; Macellari, 1988). Some of these extensional basins contain grabens separated by horst blocks, for example, the Western Peruvian Trough and the Eastern Peruvian Trough separated by the Marañón High, the Machiques (Perijá) and Uribante (Mérida Andes) rifts separated by the Maracaibo high, and the Cocuy and Tablazo sub-basins separated by the Floresta paleo-high. However, since the Aptian and during most of the Cretaceous, sedimentation covered most of the continental margin due to an elevated sea level combined with thermal subsidence. In this context, Etayo et al. (1983) proposed the name Cretaceous supraterrane in Colombia, encompassing the whole of the Cretaceous basin resting upon continental crust. This idea can be extrapolated over northwestern South America, from Venezuela to northern Peru. During the Cenozoic, the extensive basin was segmented into several compartments separated by structural highs, some of them resulting from inversion of Mesozoic normal faults which limited the original grabens. These Cenozoic compartments are now independent intermontane basins with differing and variable Cenozoic sedimentary fill.

Within the Andes of northern Peru, Ecuador, and Colombia, subduction-related magmatic arcs were developed along/within the margin of the continental plate during the Cretaceous. In Colombia and Ecuador, such magmatic arcs, although poorly developed, were located in the area of the Colombian Central Cordillera and its continuation to the south in Ecuador. In southernmost Ecuador and Peru, however, the Cretaceous magmatic arc was very well developed in the intra-arc Celica basin and in the intra-arc Casma basin developed in the western part of the Western Peruvian Trough. In Colombia, Ecuador, and Peru, most of the Cretaceous basins located craton-ward (to the east) of the magmatic arc can be considered "back-arc basins." In southernmost Ecuador and northern Peru, some basins (Tumbes, Talara, and Sechura, among others offshore of Peru) developed ocean-ward (west of) the magmatic arc and can be considered fore-arc basins.

4. *Terranes containing pre-Cretaceous rocks* representing the continental margin such as sections of the Central Cordillera of Colombia, the Real Cordillera of Ecuador, and portions of the Peruvian Andes and the coastal Cordillera of Peru.
5. *Cretaceous oceanic terranes in the Northern Andes (Venezuela, Colombia, and Ecuador)* which are petrologically and lithochemically similar to the Caribbean Plate. These are interpreted as fragments of the Caribbean/Farallon Plate, accreted to the continental margin during Cretaceous (Ecuador and Colombia) and Early Cenozoic (Venezuela), including the Coastal Range of northern Venezuela and Western cordilleras of Colombia and Ecuador.

10.3.1 Note on Southernmost Ecuador and Northern Peru

There is an important difference between the Andes of southern Ecuador and northernmost Peru and the Ecuadorian and Colombian Andes to the north. During the Meso-Cenozoic, the Ecuadorian-Colombian Andes were subject to collision and accretion of oceanic terranes of the Pacific and Caribbean Plate affinity. By contrast, the Peruvian Andes do not contain accreted oceanic terranes. During Cretaceous times, the Peruvian Andes were dominated by subduction of the Farallon and Phoenix plates beneath the western margin of the continent, which itself had undergone important deformation.

10.4 Summary of Mesozoic Plate Tectonic Interpretations

10.4.1 Jurassic

According to some Jurassic plate tectonic reconstructions (e.g., Ross and Scotese 1988; Pindell and Kennan 2009), the western margin of Colombia, Ecuador, and northern Peru constituted an active convergent margin related to subduction of Pacific (i.e., Farallon Plate) lithosphere and the development of a subduction-related magmatic arc in western Colombia, Ecuador, and northern Peru (Pindell and Dewey 1982; Bourgois et al. 1982a, b; McCourt et al. 1984; Pindell 1990, 1993; Pindell and Barret 1990; Pindell and Erikson 1993; Pindell and Tabbut 1995; Pindell et al. 2005; Toussaint 1995a, b; Toussaint and Restrepo 1989, 1994; Meschede and Frisch 1998). In Colombia and Ecuador, continental arc magmatism spanned most of the

Jurassic and is preserved along the length of the Central Cordillera (e.g., Ibague Batholith, Villagómez 2010; Villagómez et al. 2011) and elsewhere (see detailed discussion of Jurassic are related magmatism by Leal-Mejía et al. 2018). The youngest pulse of Mesozoic continental arc magmatism occurred at 145 Ma (Villagomez, 2010). Such an interpretation explains at least some of the Jurassic rift basins from western Colombia to Peru as back-arc basins.

In addition to continued subduction of the Farallon Plate along the western margin of South America, some tectonic plate interpretations (e.g., Pindell and Kennan 2009) suggest separation of North and South America started during the Middle to Late Jurassic, along the northern margin of South America (Venezuela and northern Colombia). As a result, a new, "Proto-Caribbean" oceanic basin began to open between northern and western Colombia, the Chortis block and Venezuela and the Yucatan block (Fig. 10.2). Such an interpretation explains Jurassic rift basins in northeastern Colombia and Venezuela.

10.4.2 Cretaceous

10.4.2.1 Venezuela

Despite the arrival of Pacific-Caribbean terranes in NW Colombia during the Late Cretaceous, generated some degree of tectonic loading and flexure in the western Maracaibo region, Venezuela, since the Jurassic and during the Early Cretaceous, much of northern South America behaved as a passive continental margin, as evidenced by subsidence curves, the age of synorogenic flysch units, stratigraphic and structural studies, and plate motion histories (e.g., Villamil and Pindell 2012). During the Meso-Cenozoic, west-to-east-directed Caribbean plate motion caused allochthonous terranes of Jurassic-Cretaceous rocks, many of which were deformed and metamorphosed during the Cretaceous, to be abducted onto the Venezuelan passive margin.

10.4.2.2 Western Colombia

Villagomez (2010) and Villagómez et al. (2011) studied the thermochronology, geochronology, and geochemistry of the Western and Central cordilleras of Colombia and proposed a model for the tectonic evolution of western Colombia from the Jurassic to Paleocene (Figs. 10.2 and 10.3):

- From ca. 145 Ma (Jurassic-Cretaceous boundary) to 130 Ma (Hauterivian) uplift and exhumation occurred due to rebound of the continental margin (Central Cordillera of Colombia) and retreat of subduction west of Colombia, including backstepping of the subduction zone to a more westerly position. According to Nivia (2001) and Nivia et al. (1996, 2006), this corresponds to the opening of the Quebradagrande marginal basin to the west of the Central Cordillera. An oceanic

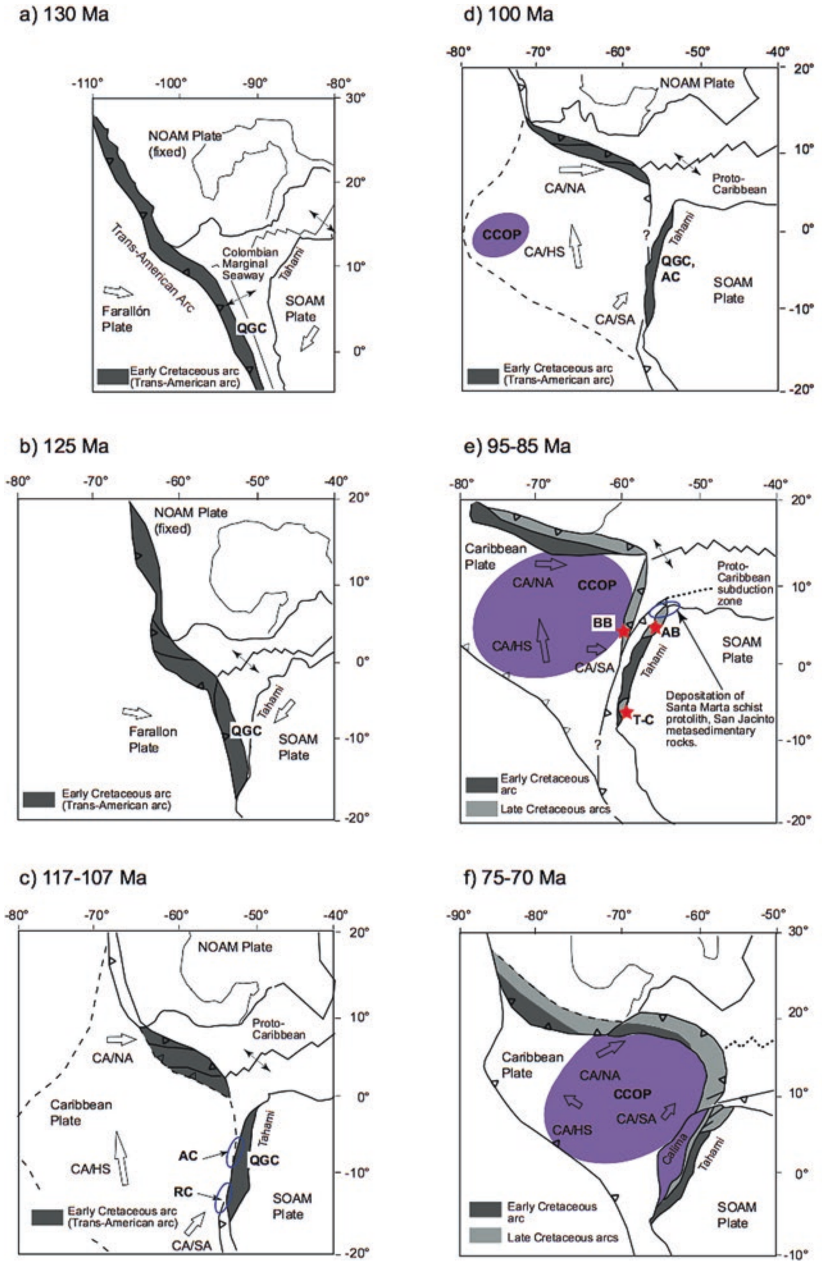

Fig. 10.2 Paleotectonic reconstructions during the Cretaceous including relative paleo-positions of North and South America, modified and simplified from Pindell and Kennan (2009). Reference frames: (**a**, **b**) North America, (**c**–**f**) Indo-Atlantic using hotspot reference frame of Müller et al., in Villagomez et al. (2011). Relative convergence direction: *CA/HS* Caribbean Plate/hotspot, *CA/NA* Caribbean Plate/North America, *CA/SA* Caribbean Plate/South America. Abbreviations: *AB* Antioquian Batholith, *AC* Arquía Complex, *BB* Buga Batholith, *CCOP* Caribbean-Colombian Oceanic Province, *NOAM* North American Plate, *QGC* Quebradagrande Complex, *RC* Raspas Complex in Ecuador, *SOAM* South American Plate, *T-C* Tangula-Curiplaya intrusions. The Early Cretaceous Trans-American Arc is shown in dark gray, Late Cretaceous arc is shown in medium gray, and the CCOP is shown in purple. (From Villagomez et al., 2011)

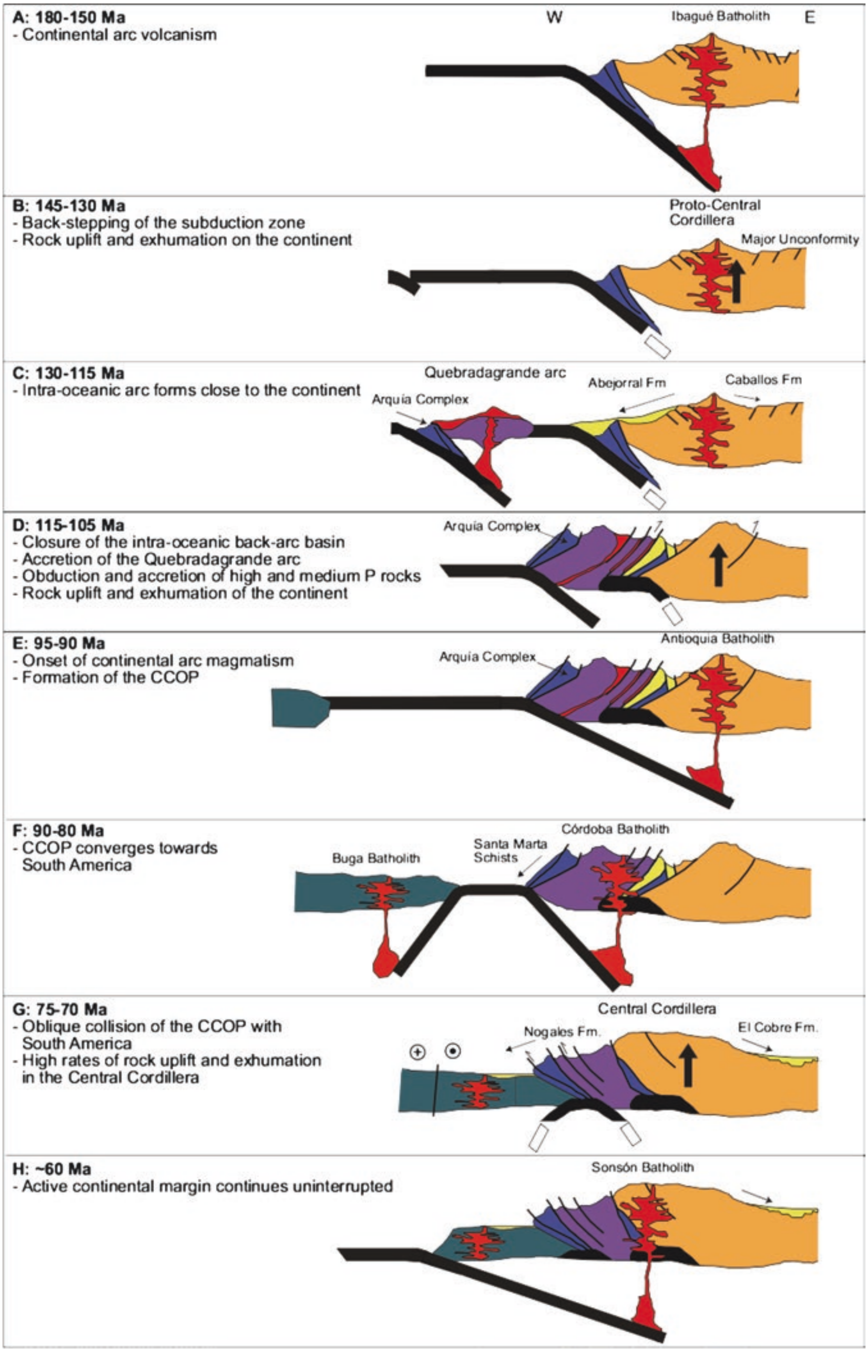

Fig. 10.3 Schematic paleotectonic reconstruction of western Colombia during the Jurassic, Cretaceous, and Paleocene (ca. 150 to 60 Ma). Black arrows indicate exhumation periods. From Villagomez et al. (2011)

marginal basin and intraoceanic arc, represented by the Quebradagrande Complex, formed during the Early Cretaceous, and its inception may have been caused by backstepping of the Jurassic slab due to the introduction of buoyant seamounts (Villagomez, 2010). The coexistence of both MORB-like gabbros and basalts in close association with pillowed arc basalts, locally covered by marine sediments with both an oceanic and continental provenance, suggests an oceanic arc origin for the Quebradagrande Complex, with a back arc located proximal to the continent. The Quebradagrande marginal basin corresponds to the Colombian marginal seaway basin of Pindell and Kennan (2009). Subduction of oceanic crust beneath the Quebradagrande marginal basin may have approached the continent. Alkali-feldspar 40Ar/39Ar cooling ages obtained from crystalline rocks located to the south of the laterally extensive Ibagué Fault yield ages of ca. 138–130 Ma (Valanginian-Hauterivian), suggesting uplift and exhumation of the southern part of the Central Cordillera, contemporaneous with the cessation of Jurassic arc magmatism.

- From 130 Ma (Hauterivian) to 115 Ma (Aptian), an intraoceanic arc forms at the western border of the Quebradagrande marginal basin, and it migrates toward the continent.
- From 115 Ma (Aptian) to 105 Ma (Albian), closure of the intraoceanic back-arc basin (Quebradagrande marginal basin of Nivia, 2001 and Nivia et al., 1996, 2006, or Colombia seaway of Pindell and Kennan, 2009). Remnants of this basin and the associated arc constitute the Quebradagrande Complex along the Romeral-Peltetec suture zone. The Quebradagrande Complex accreted against metamporphic basement of the Tahami Terrane (sensu Restrepo and Toussaint, 1988; Toussaint and Restrepo, 1989, 1994; Toussaint, 1995a, b) or Cajamarca-Valdivia Terrane (sensu Cediel et al., 2003b, 2011) in Colombia's Central Cordillera during the Late Aptian. That event was accompanied by the obduction of medium-high P-T metamorphic rocks of the Arquía Complex onto the Cretaceous fore-arc to the west. These rocks may represent abducted remnants of subduction channel sediments. In the Central Cordillera north of the Ibagué Fault, medium-temperature thermochronometers reveal the presence of a younger cooling event at 107–117 Ma (Aptian-Albian).
- From 95 (Cenomanian) to 90 Ma (Turonian), the onset of continental arc magmatism in central Colombia is observed (see discussion by Leal-Mejía et al. 2018). To the west, in the Pacific domain, the Caribbean oceanic plateau was formed (*e.g*., Kerr et al. 1997a, b; Sinton et al. 1998). Accreted fragments of this plateau were referred to as the PLOCO (i.e., *Provincia Litosferica Oceanica Cretacica Occidental: Western Cretaceous Lithospheric Province*) by Nivia (2001). Geochronological analyses of plateau rocks from throughout NW South America and elsewhere range from ca. 105 to 72 Ma (see summary of radiometric and biostratigraphic ages in Kerr et al. 2003).
- From 90 Ma (Turonian) to 80 Ma (Campanian), the Caribbean Plate (CCOP sensu Kerr et al. 1997a, b) converged upon NW South America. The remnant ocean basin located between South America and the Caribbean Plate was consumed via double-vergent subduction, giving rise to continental- and oceanic-rooted

arcs (see summary and reconstruction by Leal-Mejía et al. 2018). The Antioquian and Cordoba batholiths are representative continental arc segments, while the Sabanalarga, Mistrato, Buga, and Jejenes plutons are representative of the oceanic arc formed along the leading edge of the CCOP.

- From 75 Ma (Campanian) to 70 Ma (Maastrichtian), the Caribbean Plate collided against the NW South American margin, along the dextral compressive Cauca-Almaguer fault system, and fragments of the CCOP, including the leading-edge arcs, were accreted to the continental margin, forming the basement of the Western Cordillera of Colombia and Ecuador. This resulted in the extinction of both magmatic arcs. High rates (ca. 1.6 km/My) of uplift and exhumation of the Central Cordillera were observed at this time there, driven by collision and accretion of the CCOP.
- From ca. 60 to 50 Ma (Paleocene), subduction was briefly reestablished beneath the western continental margin, as revealed by limited occurrences of granitoid plutons to the south of the Antioquian Batholith (Sonsón, Manizales, El Hatillo, El Bosque; Leal-Mejía et al. 2018). Along the northern continental margin, in the Sierra Nevada de Santa Marta Province, Paleo-Eocene subduction-related magmatism appears to have been driven by separate and distinct tectonic mechanisms (Duque-Trujillo et al. 2018; Cediel 2018). At the same time (ca. 65–58 Ma), the southernmost Sierra Nevada de Santa Marta was exhumed at elevated rates ($\geq$0.2 Km/My), in response to the interaction between the CCOP and northern South America.

10.4.2.3 Western Ecuador

Based upon geological fieldwork and thermochronological, geochronological, and lithochemical data, Vallejo (2007) and Vallejo et al. (2009) proposed the following tectonic history of the Western Cordillera of Ecuador (Fig. 10.4).

- The ca. 123 Ma (Aptian) age reported from a set of basalts, basaltic andesites, and gabbros in western Ecuador suggest they may represent fragments of Jurassic to Early Cretaceous oceanic crust, which accreted against South America during the Early Cretaceous (*e.g.*, Litherland et al. 1994). This could represent the southern continuation of the Quebradagrande marginal basin in Colombia, as interpreted by Nivia (2001) and Nivia et al. (1996, 2006).
- From approximately 85 Ma to 83 Ma (Santonian), subduction of oceanic crust occurred west of the continental margin (as represented by the Cordillera Real of Ecuador). This oceanic plate (proto-Caribbean? Farallon?) separated the Caribbean plateau farther west from the South American margin. A remnant oceanic basin with pelagic sedimentation developed and was consumed via a double-vergent subduction system, giving rise to continental and oceanic arcs, similar to the case interpreted for western Colombia. Granitoid rocks of the La Portada and Paujíl plutons are interpreted to represent the oceanic magmatic arc developed on the leading edge of the Caribbean Plate.

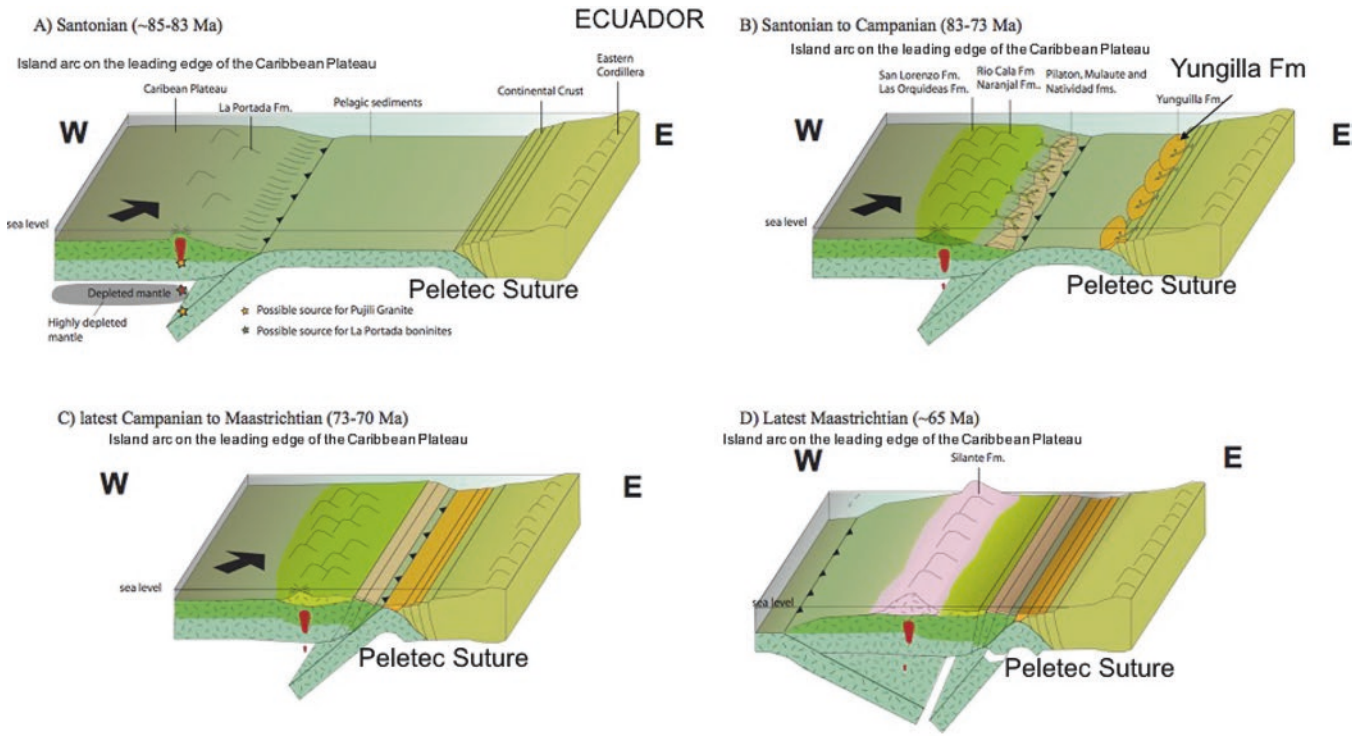

Fig. 10.4 Schematic Late Cretaceous paleotectonic reconstruction of the Western Cordillera of Ecuador and neighboring areas. From Vallejo (2007)

- From 83 Ma (Santonian) to 73 Ma (Campanian), the marginal basin was narrowing. The magmatic arc on the leading edge of the Caribbean Plate continued. Volcanic rocks of the San Lorenzo, Las Orquideas, Rio Cala, and Naranjal Fms. are representatives of this arc. Between this arc and the subduction zone, trench fill turbidites were deposited (Pilaton, Mulaute, and Natividad Fms.). To the west of the continental margin, turbidites of the Yungilla Fm. were also deposited. Intraoceanic island arc sequences (Pujilí Granite, Rio Cala Group, Naranjal Unit) intrude/overlie the CCOP and yield crystallization ages that range between ca. 85 and 72 Ma. The lithochemistry and radiometric ages of lavas associated with the Rio Cala Arc, combined with the age range and geochemistry of their turbiditic and volcanoclastic products, indicate that the arc initiated by westward subduction beneath the CCOP and are coeval with other island arc rocks (Las Orquideas, San Lorenzo, and Cayo formations).
- From 73 Ma (Campanian) to 70 Ma (Maastrichtian), the Caribbean Plate dextrally collided along the South American continental margin, along the Pujilí-Pallatanga suture zone (Cediel et al. 2003b). As in Colombia, fragments of plateau rocks were accreted to the continent, forming a basement to the Western Cordillera of Ecuador. Paleomagnetic analyses of volcanic rocks, of the Piñon and San Lorenzo units of the southern external fore-arc (Luzieux et al. 2006), indicate their pre-collisional extrusion at equatorial or shallow southern latitudes. Furthermore, paleomagnetic declination data from basement and sedimentary cover rocks in the coastal region (Luzieux 2007) indicate 20–50° of clockwise rotation during the Campanian, which was probably synchronous with the collision of the oceanic plateau and arc sequence with South America. Island arc magmatism terminated. The initial collision between the South American Plate and the Caribbean plateau was synchronous with accelerated surface uplift and exhumation (>1 km/my) along the buttressing continental margin at ca. 75–65 Ma (Campanian-Maastrichtian), in an area extending as far inland as the Cordillera Real. Rapid exhumation coincides with the deposition of continental siliciclastic material in both the fore- and back-arc environments (Yunguilla and Tena formations, respectively). This situation is analogous to events interpreted by Villagomez (2010) for western Colombia between ca. 75 and 70 Ma.
- At approximately 65 Ma (Cretaceous-Paleocene boundary), subduction beneath the composite continental margin resumed. Arc-related rocks of the Silante Fm. are representative of this magmatism. This situation is similar to that interpreted by Villagomez (2010) for western Colombia at ca. 60–50 Ma. During the Paleocene to Eocene, marine conditions were dominant in the area now occupied by the Western Cordillera in Ecuador and Colombia, and volcanic rocks of the Macuchi Unit (Ecuador) were deposited, possibly as a temporal continuation of the Silante volcanic arc. This submarine volcanism was coeval with the deposition of siliciclastic rocks of the Angamarca Gp. and the Saguangal Fm., which were mainly derived from the emerging Cordillera Real.

Tectonic models presented by Villagomez (2010) and Villagómez et al. (2011), and Vallejo (2007) and Vallejo et al. (2009) are based upon analyses from widely spaced rock samples of the Western and Central cordilleras of Colombia and the Western Cordillera of Ecuador, respectively. Due to the spaced location of the samples, and regional nature of the studies, some geological domains remained unsampled and hence are not accounted for in the above tectonic interpretations. Two examples of this include the Cretaceous tectonic evolution of southernmost coastal Ecuador and the Guajira Peninsula in northeasternmost Colombia/Venezuela.

In southernmost western Ecuador, Jaillard et al. (1995) proposed that "an accreted terrane underlain by oceanic crust formed during the Aptian-Albian." To the southeast, the oceanic crust is overlain by Cenomanian-Coniacian fine-grained pelagic deposits, coarse-grained volcanoclastic turbidites of Santonian-Campanian age, and Maastrichtian-Middle Paleocene tuffaceous shales. To the northwest, Late Campanian-Paleocene volcanoclastic beds and lava flows of island arc composition resting upon oceanic crust resulted from the opening of a marginal basin between an Early Late Cretaceous island arc (Cayo arc) and a latest Cretaceous-Paleocene island arc (San Lorenzo arc). In the latest Paleocene-Earliest Eocene, the accretion of the remnant arc to the Andean continental margin caused a major but localized deformation phase that affected the southern part of coastal Ecuador (Fig. 10.5, after Jaillard et al. 1995).

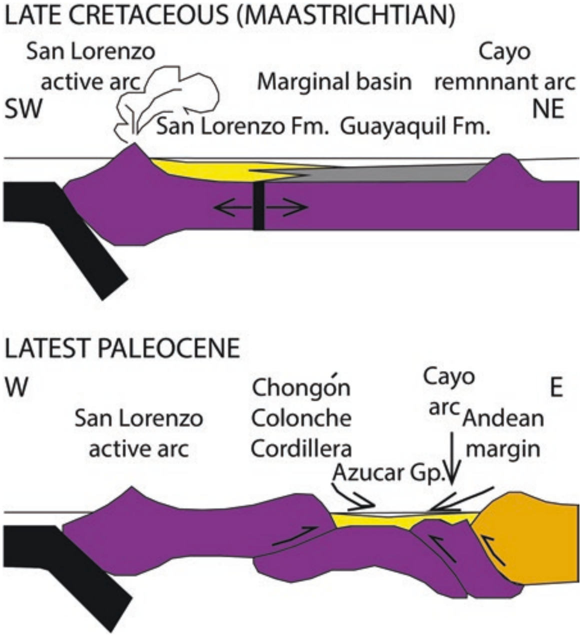

Fig. 10.5 Paleotectonic reconstruction of southern coastal Ecuador during the Late Cretaceous to Paleocene. (**a**) In the Late Cretaceous, a marginal basin opened between the Early Late Cretaceous Cayo arc and the latest Cretaceous-Paleocene San Lorenzo island arc. (**b**) In the Late Paleocene–Earliest Eocene, the Cayo remnant arc collided with the Andean continental margin and caused intense deformation of the Santa Elena Peninsula, emergence of the Chongón Cordillera, and infilling of the Santa Elena basin by coarse-grained turbidites. Modified after Jaillard et al. (1995)

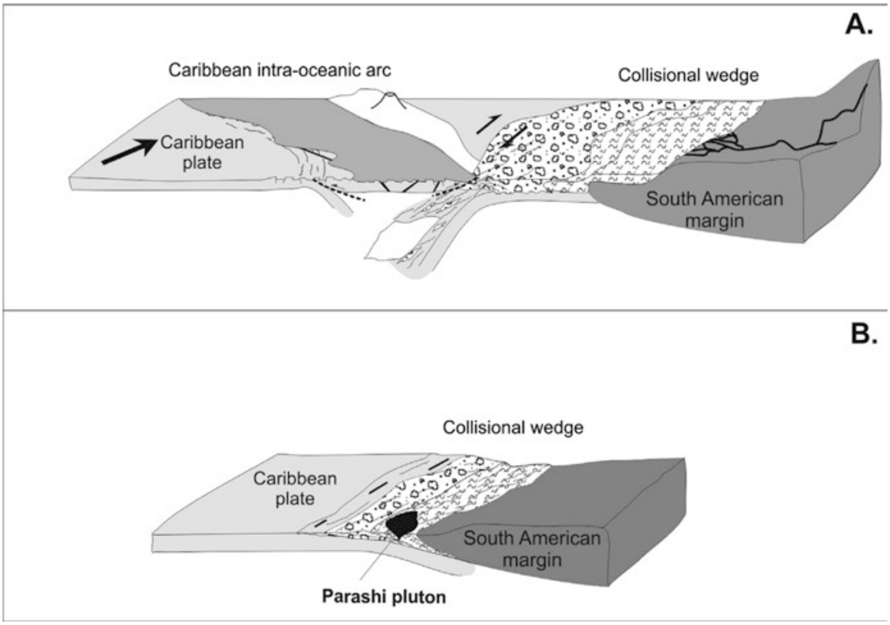

Fig. 10.6 Paleotectonic model reconstruction of the northern Colombia Guajira peninsula during the Maastrichtian to Eocene. (**a**) Maastrichtian to Paleocene oblique arc-continent collision, followed by subduction initiation. (**b**) Emplacement of the Eocene Parashi Stock. From Cardona et al. (2014)

In the Colombian Guajira Peninsula, Cardona et al. (2007) and Cardona et al. (2014) interpreted the existence of an intraoceanic oblique subduction-related arc (Jarara Fm.) active prior to and during the Campanian, including an oceanic back-arc basin to the south (Cabo de La Vela mafic and ultramafic rocks). This arc approached the continent during the Campanian and Maastrichtian and was later accreted to the continent (Fig. 10.6, after Cardona et al. 2007, 2014).

10.5 Cretaceous Stratigraphy and Paleo-Facies Distribution

10.5.1 Continental Margin Domain

An important percentage of the outcropping rocks in the Northern Andean region are of Cretaceous age. Figure 10.1 shows the sedimentary basins considered within this study, including the location of the stratigraphic sections constructed herein. Figures 10.7, 10.8, 10.9, 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.19 and 10.20 include 13 traverse time-stratigraphic cross sections of these basins. I constructed the sections from available literature, including but not

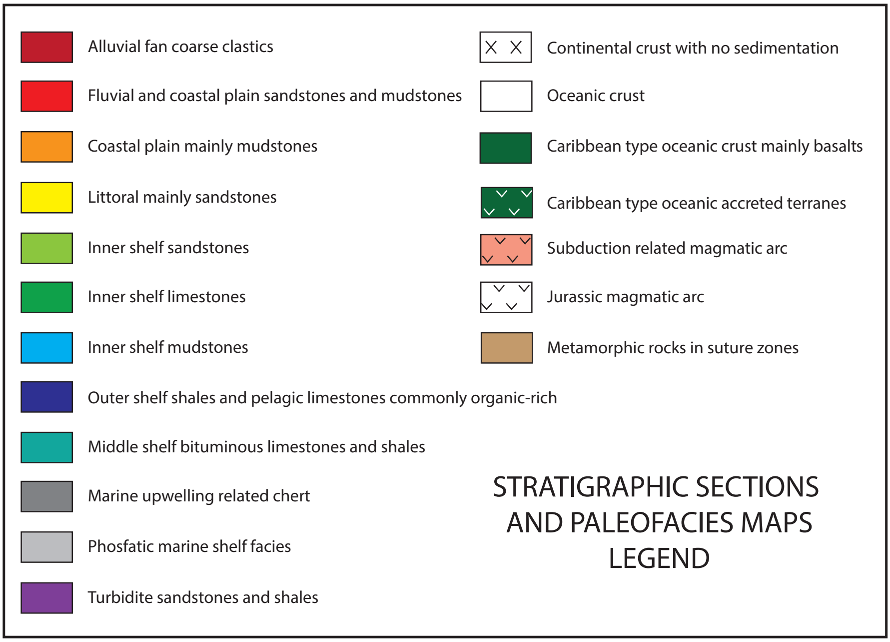

Fig. 10.7 Color legend for the stratigraphic sections depicted in Figs. 10.8, 10.9, 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.19 and 10.20 and for the paleo-facies maps depicted in Figs. 10.21, 10.22, 10.23, 10.24, 10.25, 10.26, 10.27, 10.28, 10.29, 10.30, 10.31 and 10.32. In the paleo-facies maps, the color-filled "x"s for some facies signify these areas were covered by the sedimentary environments corresponding to the respective color, but the lack of subsidence or very reduced subsidence did not permit enough accommodation space for sediment accumulation, or if sediment accumulated it was later eroded

restricted to Fabre (1985, 1986, 1987), Macellari (1988), Cooper et al. (1995), Sarmiento-Rojas (2001), Lopez-Ramos (2005), Villamil (2012), Villamil and Arango (2012), Guerrero (2002), and Sarmiento (2015) in Colombia; Rod and Maync (1954), González de Juana et al. (1980), Lugo and Mann (1995), Parnaud et al. (1995), Mann et al. (2006), and Villamil and Pindell (2012) in Venezuela; Barragan et al. (2004) in Ecuador; and Macellari (1988), Jaillard and Sempere (1989), Jaillard (1993), and Jaillard et al. (1990, 2000, 2005) in southern Ecuador and Peru. In these stratigraphic sections, I identify sequences bounded by unconformities recognizable in some parts of the basin (usually proximal areas) or correlative conformities in other areas of the basin (usually distal areas) which were generated during times of relative (tectono-eustatic) low sea level. These unconformities are proposed sequence boundaries (SB) and are shown in the stratigraphic sections as red horizontal lines and labeled with odd numbers. I also identify maximum flooding surfaces (MFS) within these sequences generated during times of relative high sea level. Maximum flooding surfaces are shown in the stratigraphic sections as blue horizontal lines and labeled with even numbers. I assume that SB and MFS are surfaces generated regionally at specific times (time surfaces).

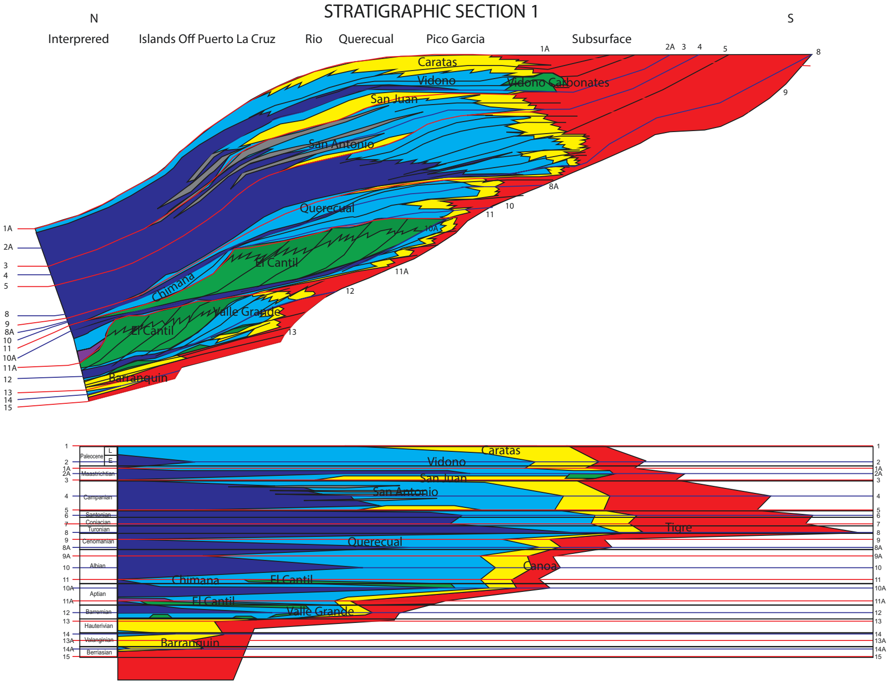

Fig. 10.8 Stratigraphic Section 1 through eastern Venezuela. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. (**a**) Section modified from Villamil and Pindell (2012). (**b**) Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

Although this assumption probably is only a first approximation due to differential tectonic subsidence of graben blocks, especially during the earliest Cretaceous and the initial inversion of these grabens at the end of Cretaceous, this assumption is a useful tool for regional correlation.

Cretaceous rocks, including (locally) uppermost Jurassic and Paleocene deposits, form a mega-sequence bounded by regional unconformities that are at least locally angular. On a broad scale, Cretaceous rocks represent a major transgressive-regressive cycle with the maximum flooding surface close to the Cenomanian-Turonian boundary (MFS 8), corresponding to the maximum Cretaceous, and even Mesozoic, eustatic level (Fabre 1985; Villamil 1994, 2012; Sarmiento-Rojas 2001; Figs. 10.7, 10.8, 10.9, 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.19 and 10.20). Superimposed on this large- scale trend, several smaller transgressive-regressive cycles are present, suggesting an oscillating relative tectono-eustatic level. These minor cycles correspond to the several proposed stratigraphic sequences.

Particularly in Colombia, Venezuela, and Ecuador, I have identified several of these small transgressive-regressive cycles, which can approximately be correlated throughout the region and could possibly be extended further into southern Ecuador and northern Peru, although in this southern region, the ages of the surfaces have minor

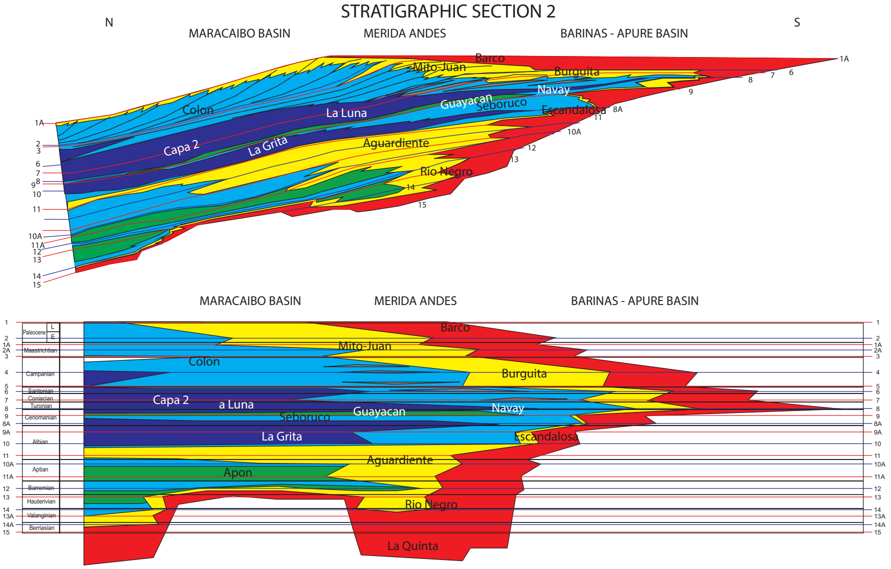

Fig. 10.9 Stratigraphic Section 2 through western Venezuela. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. (**a**) Section modified from Villamil and Pindell (2012). (**b**) Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

changes possibly resulting from more active tectonics and basin inversion at the end of Cretaceous, as compared to the northern region. The earliest Cretaceous surfaces are more difficult to correlate regionally because differential vertical subsidence of different blocks limited by normal faults. In the stratigraphic sections (Figs. 10.7, 10.8, 10.9, 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.19 and 10.20), these surfaces are numbered from top to bottom. In the following sections the stratigraphic description is mainly based on Villamil and Pindell (2012) for Venezuela, Sarmiento-Rojas (2001) for Colombia, and Barragan et al. (2004) for Ecuador.

10.5.1.1 Venezuela

Jurassic red beds are present in the extensional grabens of the Mérida Andes (the Uribante and Trujillo rifts) and Serranía de Perijá (Machiques rift) and in several subsurface grabens in the Maracaibo, Barinas-Apure, and eastern Venezuelan Basins (Espino and Apure-Mantecal Grabens).

According to plate tectonic interpretations, a Jurassic marine shelf section is expected in northernmost South America and particularly Venezuela. Some occurrences are apparent in northern salients of the continent, in the Colombian Guajira (Cocinas Gp.) and Caracas area. Villamil and Pindell (2012) speculated that a major (<2 km thick) section of Jurassic marine shelf section probably exists beneath the Serranía del Interior and northernmost Venezuela.

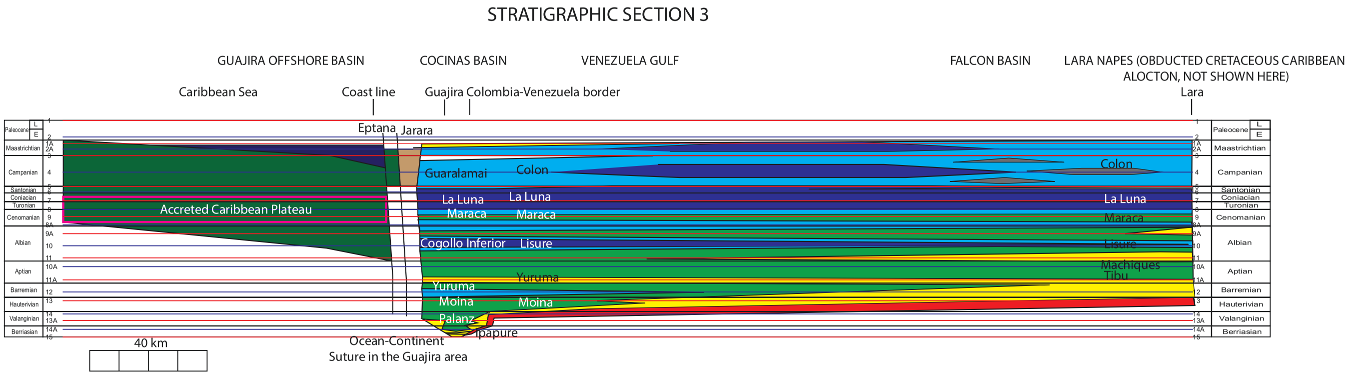

Fig. 10.10 Stratigraphic Section 3 through northernmost Colombia and western Venezuela. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

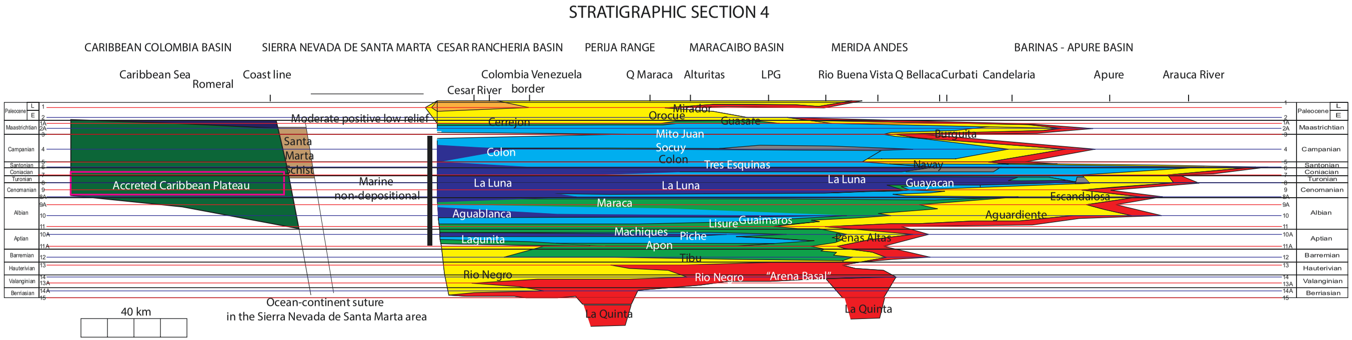

Fig. 10.11 Stratigraphic Section 4 through northern Colombia and western Venezuela. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

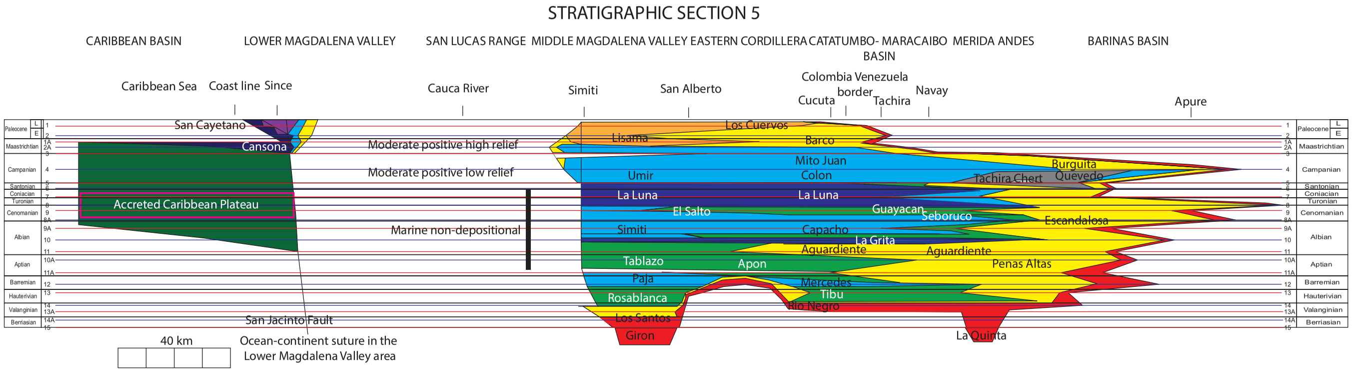

Fig. 10.12 Stratigraphic Section 5 through northern Colombia and western Venezuela. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

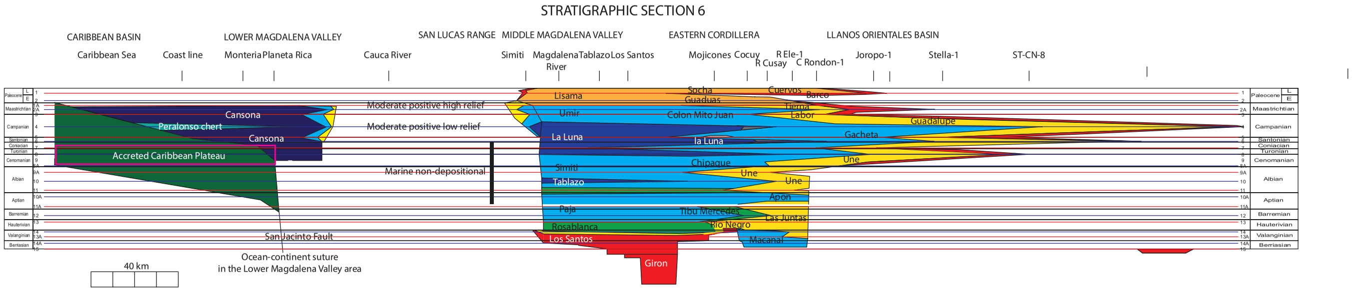

Fig. 10.13 Stratigraphic Section 6 through northern Colombia. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

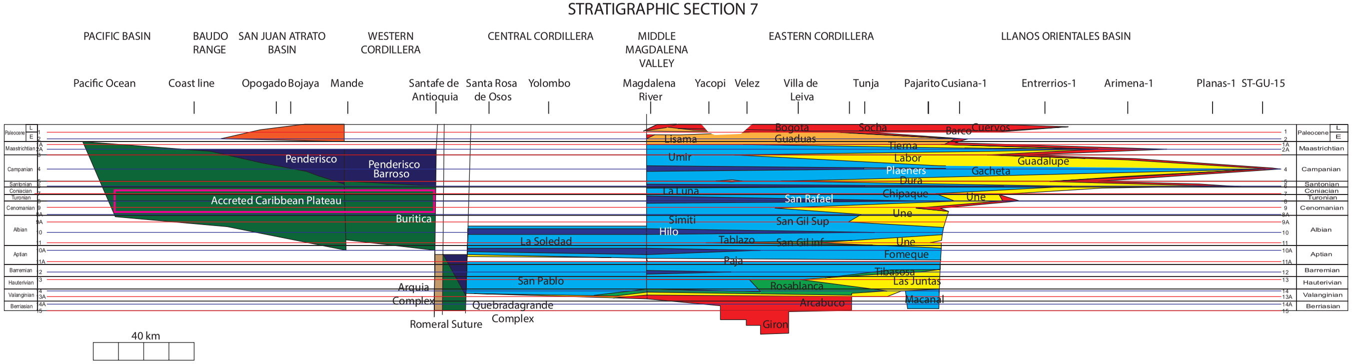

Fig. 10.14 Stratigraphic Section 7 through central Colombia. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

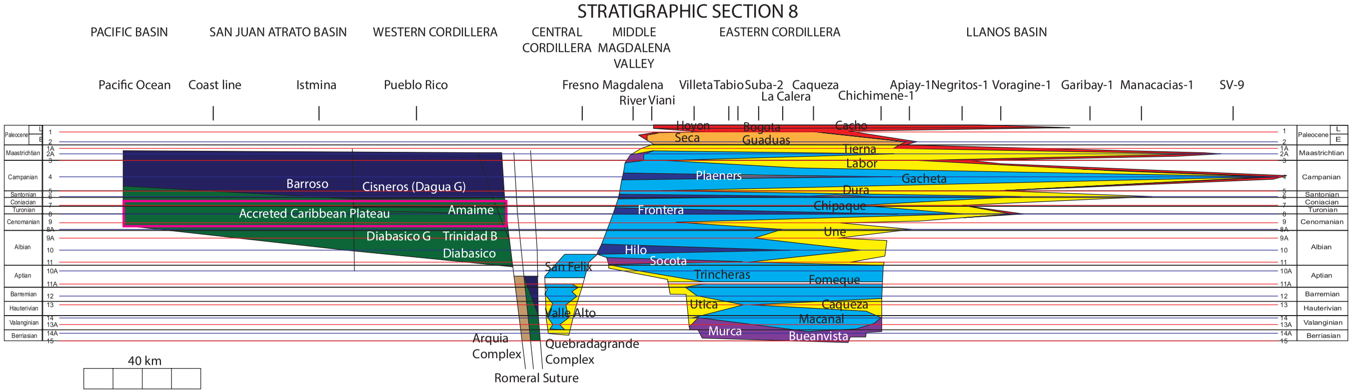

Fig. 10.15 Stratigraphic Section 8 through central Colombia. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

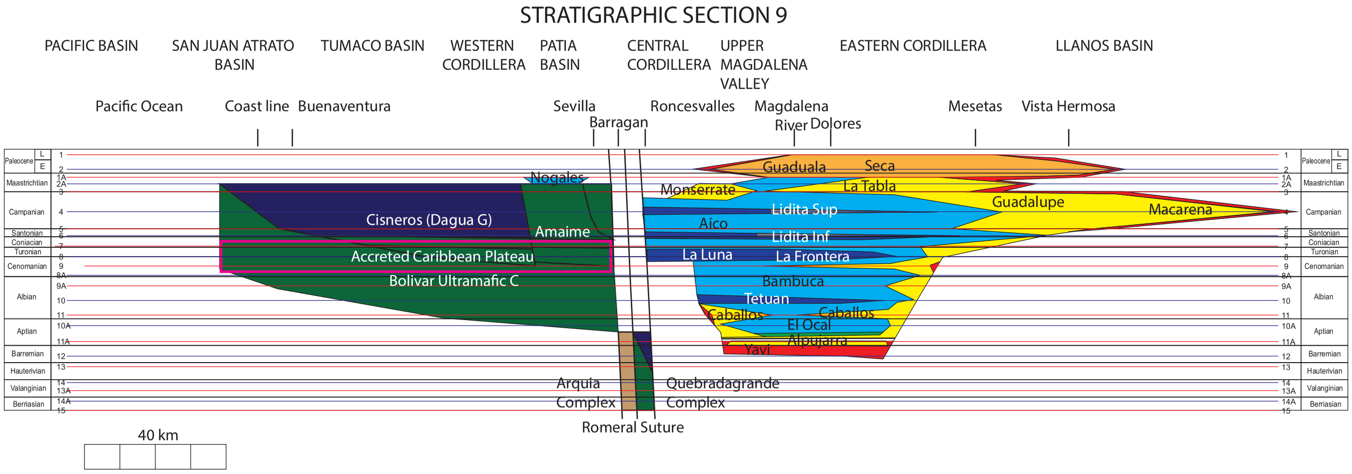

Fig. 10.16 Stratigraphic Section 9 through southern Colombia. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

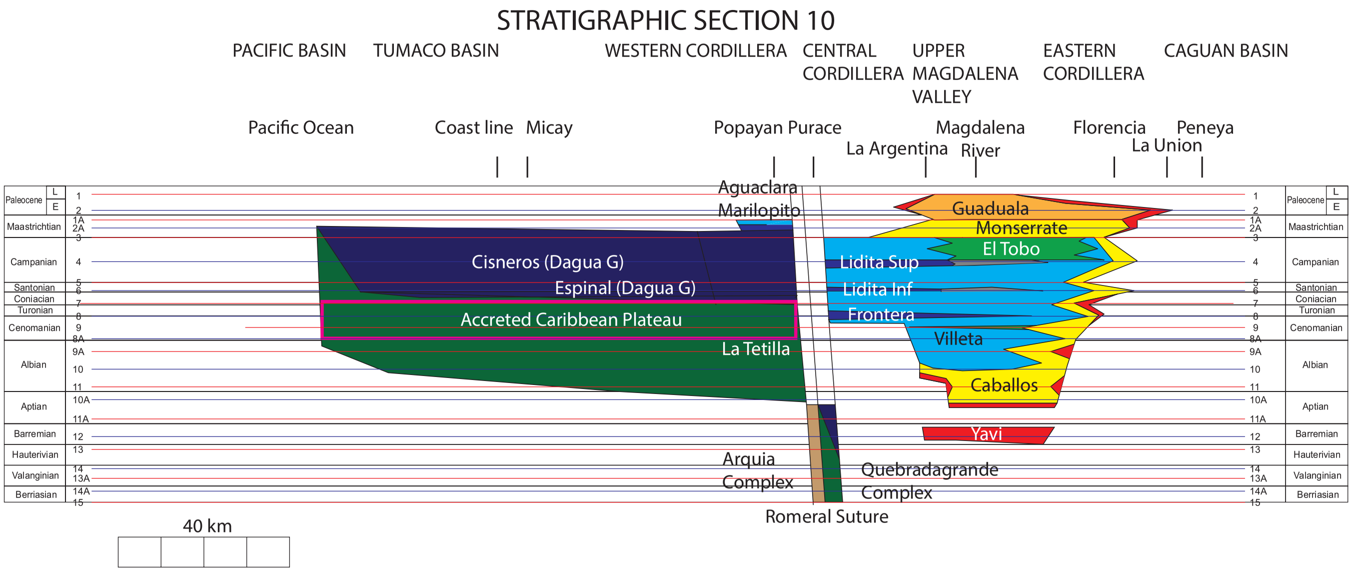

Fig. 10.17 Stratigraphic Section 10 through southern Colombia. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

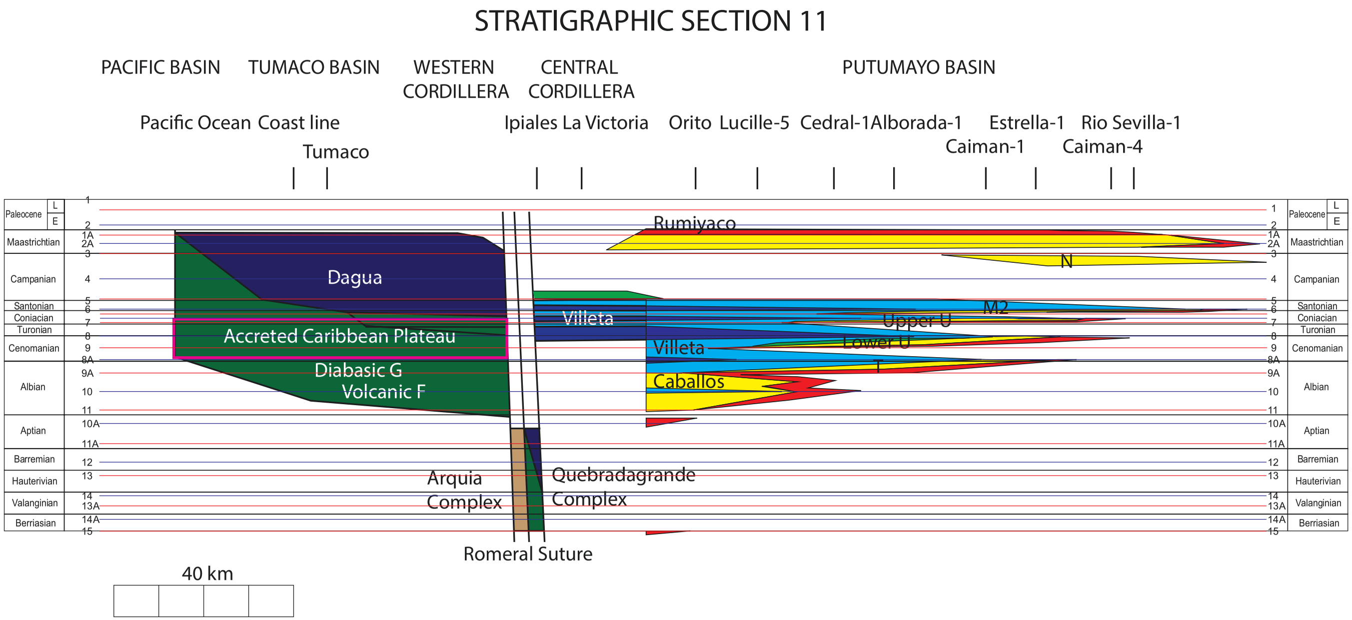

Fig. 10.18 Stratigraphic Section 11 through southern Colombia. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

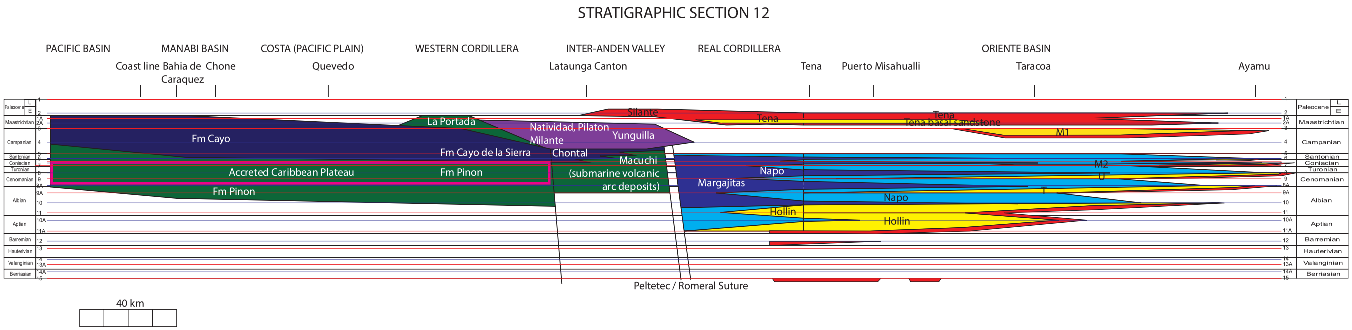

Fig. 10.19 Stratigraphic Section 12 through Ecuador. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

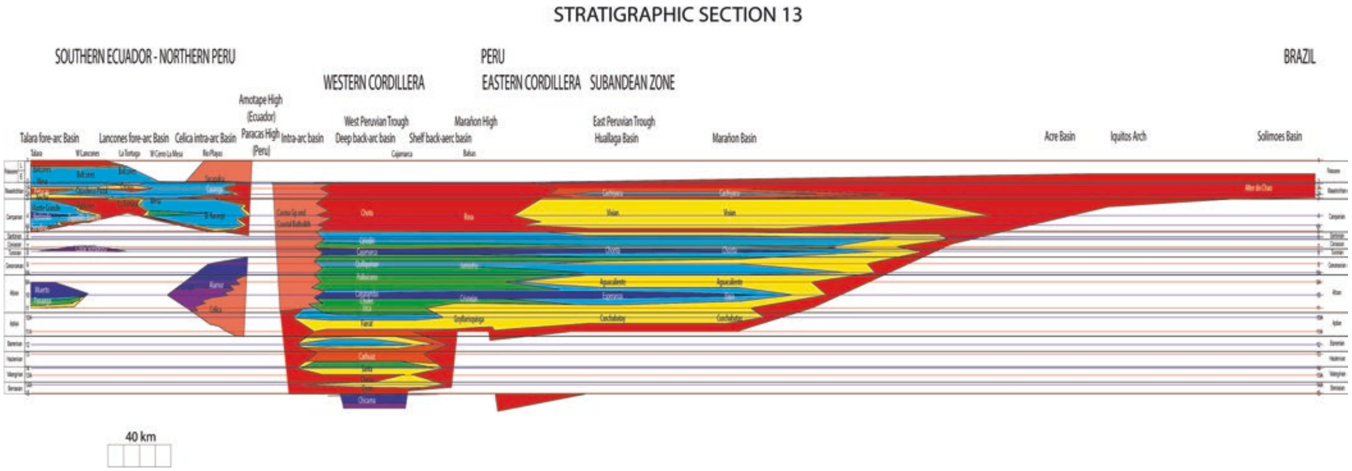

Fig. 10.20 Stratigraphic Section 13 through northern Peru and northwestern Brazil. See Fig. 10.1 for section location and Fig. 10.7 for facies color legend. Section with geological time in vertical axis. Horizontal red lines indicate proposed sequence boundaries (SB); horizontal blue lines indicate maximum flooding surfaces (MFS) for the proposed stratigraphic sequences. See additional explanation in text

Early Cretaceous Sedimentation

In northern Venezuela, Early Cretaceous sedimentation (Figs. 10.8, 10.9, and 10.21) took place in grabens inherited from Jurassic times, localized within the Machiques and Uribante rifts. During the earliest Cretaceous (Berriasian? Valanginian?), these rift basins were still active or initiated subsidence by thermal cooling following active Jurassic extension. In the Guajira Peninsula, shallow marine sedimentation (basal clastics followed by carbonates of the Palanz Fm.; Figs. 10.10 and 10.21) is recorded; however, with the exception of northernmost Venezuela, where it is possible to predict deposition of shallow marine facies, sedimentation was dominantly

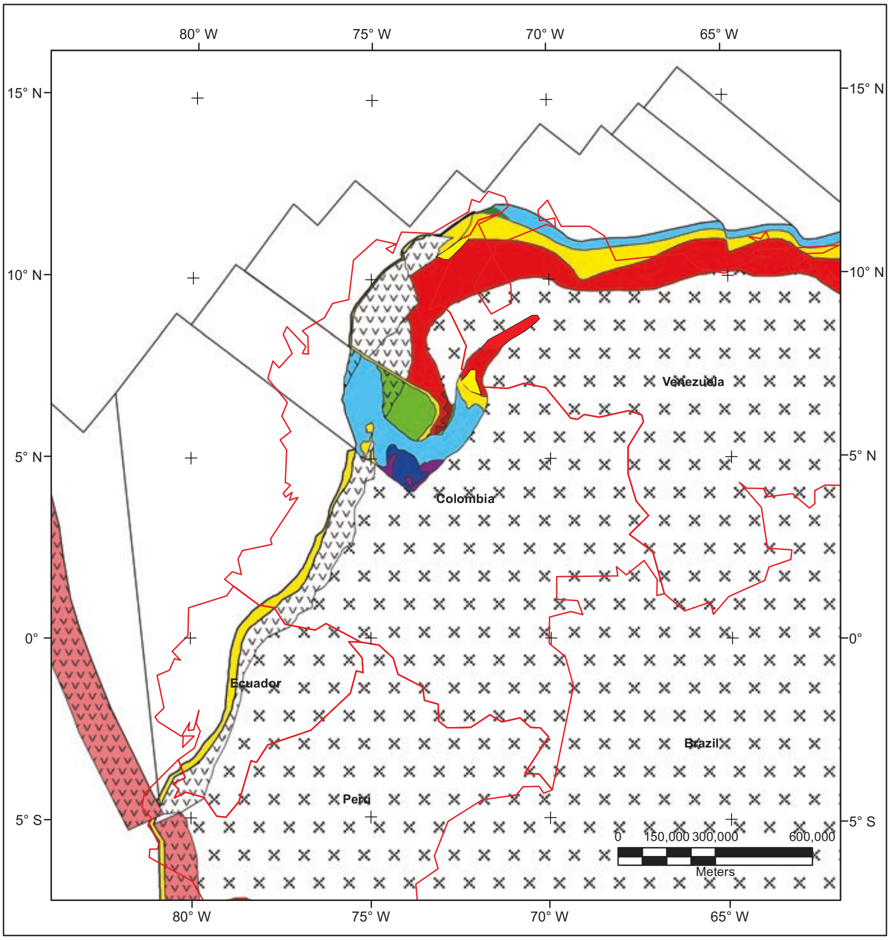

Fig. 10.21 Schematic paleo-facies map of northwestern South America during the Berriasian-Valanginian. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

continental. In the Machiques and Uribante grabens, Cretaceous sedimentation initiated within fluvial environments (*e.g.*, Rio Negro Fm. in western Venezuela and Barranquín Fm. in eastern Venezuela). During the Hauterivian (Figs. 10.8, 10.9, and 10.22), this fluvial sedimentation gradually onlapped onto the craton, while in the grabens, littoral or shallow marine sedimentation was initiated (littoral portions of the Rio Negro Fm. in western Venezuela and Barranquin Fm. in eastern Venezuela). Due to post-Jurassic tectonic or thermal subsidence, thicker sections were accumulated in the Uribante, Machiques, and Barquisimeto troughs. In general, Cretaceous rocks are separated from Jurassic rocks by an unconformity (SB 15). During the Barremian (Figs. 10.8, 10.9, and 10.22), marine transgression in general

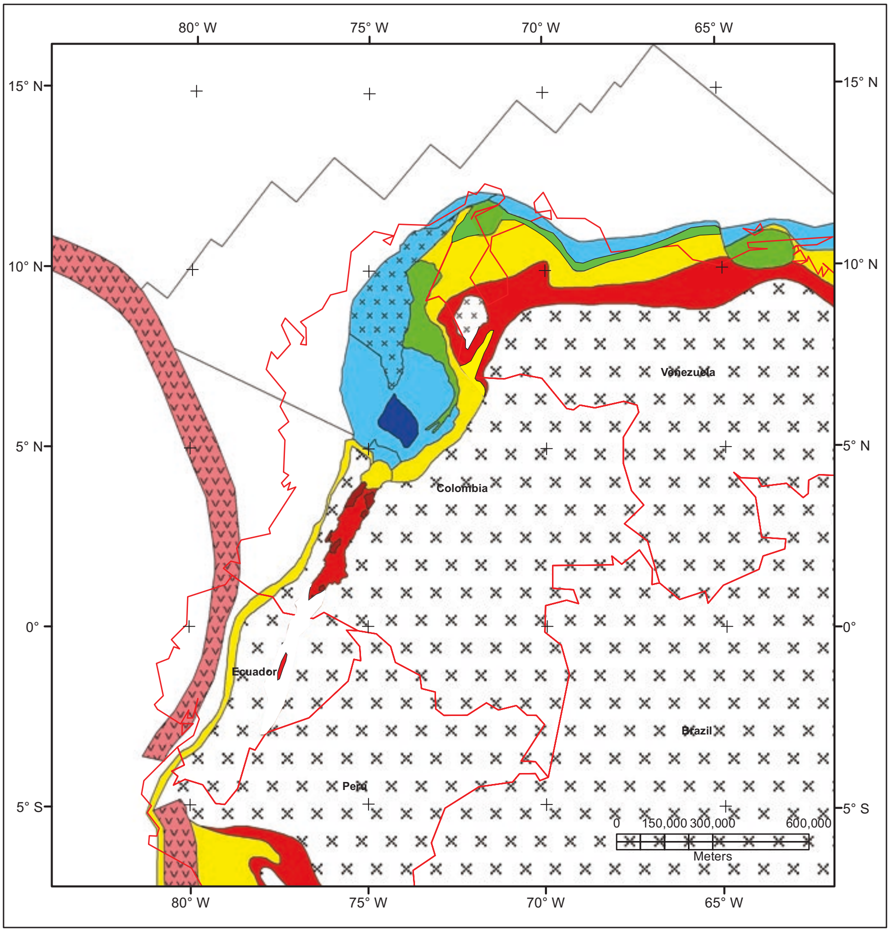

Fig. 10.22 Schemantic paleo-facies map of northwestern South America during the Hauterivian-Barremian. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

advanced southward, and continental facies were covered by littoral siliciclastic marine facies (Barranquin Fm. and Valle Grande Fm. of eastern Venezuela and upper part of Rio Negro Fm. of western Venezuela), and locally some carbonate marine shelf facies were deposited, some with isolated carbonate buildups (Villamil and Pindell 2012; Morro Blanco and Taguarumo members of Barranquín Fm. of eastern Venezuela and lower part of Apón Fm. in western Venezuela and Yuruma Fm. in Guajira northernmost Colombia; Figs. 10.10 and 10.22). In general, since Berriasian to Barremian times, a general marine transgression occurred.

During Aptian (Figs. 10.8, 10.9, and 10.23), open marine inner shelf carbonate platforms were established (Apón Fm. in western Venezuela and El Cantil Fm. of

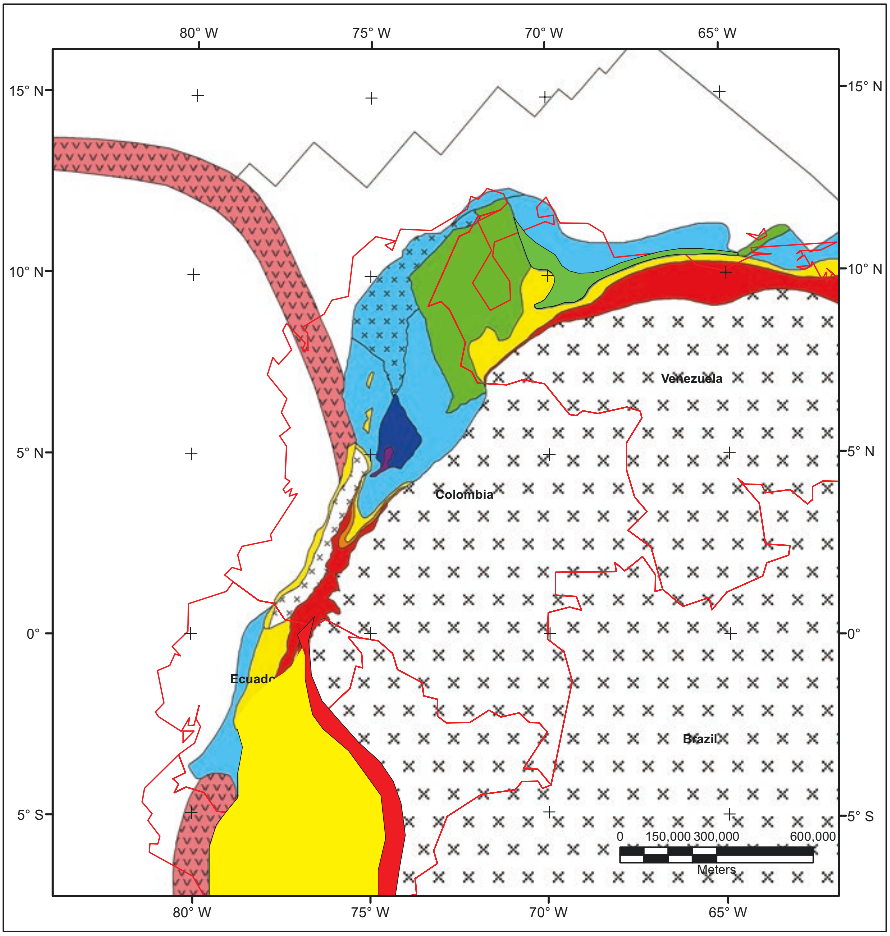

Fig. 10.23 Schematic paleo-facies map of northwestern South America during the Aptian. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of the oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

eastern Venezuela), with local carbonate buildup developments dominated by rudist bivalves and corals. In western Venezuela carbonate shelf facies interfinger with clastics as mixed carbonate platforms (Villamil and Pindell, 2012). In other places clastic supply inhibited carbonate development. To the south, continental littoral and continental clastics continue to onlap onto Jurassic rocks or the craton (Valle Grande Fm. in eastern Venezuela and Peñas Altas Fm. and lower part of Aguardiente Fm. in western Venezuela). Fine-grained clastic shelf facies were deposited over carbonate shelf facies (shales of Valle Grande Fm. and García Fm. over Barranquín Fm. in eastern Venezuela, Apón Fm. in western Venezuela). As a consequence of the transgression, general retrogradation of siliciclastic (*e.g.*, Aguardiente Fm. over Rio Negro Fm. in western Venezuela) and carbonate facies (*e.g.*, El Cantil Fm. older in the north than in the south in eastern Venezuela) is observed. The lower Aptian contains a sequence boundary (SB 11A), and the upper Aptian contains a condensed section (MFS 10A, Guaimaro shale of western Venezuela). Above the lower Aptian sequence boundary, Villamil and Pindell (2012) have interpreted the Aptian as a general transgressive system tract with the development of a condensed section maximum flooding surface (MFS 10A) and a short regression episode at the end of the stage. Creation of accommodation space during the Aptian favored aggradation of carbonate platforms where siliciclastic input was low.

During the Early Albian (Figs. 10.8, 10.9, and 10.24) in general, sedimentation continued onlapping onto the craton, with facies aggradation and transgression. In western Venezuela progradation of sands of a deltaic system (Aguardiente Fm.) over carbonate or mixed platform deposits is recorded (*e.g.*, Lisure and Machiques Fms., which were considered as Early Albian by Villamil and Pindell (2012), based on paleontological evidence instead of Aptian as earlier workers proposed). In eastern Venezuela aggradation prevailed. At the end of the Early Albian, an abrupt transgression was associated with widespread deposition of starved intervals and the termination of siliciclastic and shallow-water carbonate shelf environments in Venezuela. Carbonate buildups also terminated by an abrupt transgression. Carbonate banks and shoals were isolated by fine-grained siliciclastic sediments. To the south a coarse-grained siliciclastic littoral to shallow marine facies belt is recorded (Aguardiente and Peñas Altas Fms.). The coarse-grained siliciclastic belt was fringed southward by continental facies which onlap onto the craton (upper part of Rio Negro Fm. in western Venezuela and Canóa Fm. in eastern Venezuela). Villamil and Pindell (2012) proposed two sequence stratigraphy hypotheses for the carbonates of El Cantil Fm. of eastern Venezuela: the first is a highly diachronous interpretation for the El Cantíl Fm., with two prograding carbonate build up developments, one Aptian and another Albian in eastern Venezuela, separated by a condensed section (MFS 10A). This interpretation is shown in stratigraphic section 1 (Fig. 10.8). The second interpretation involved a less diachronous Aptian El Cantíl Fm., lacking the two carbonate bodies separated by a shale.

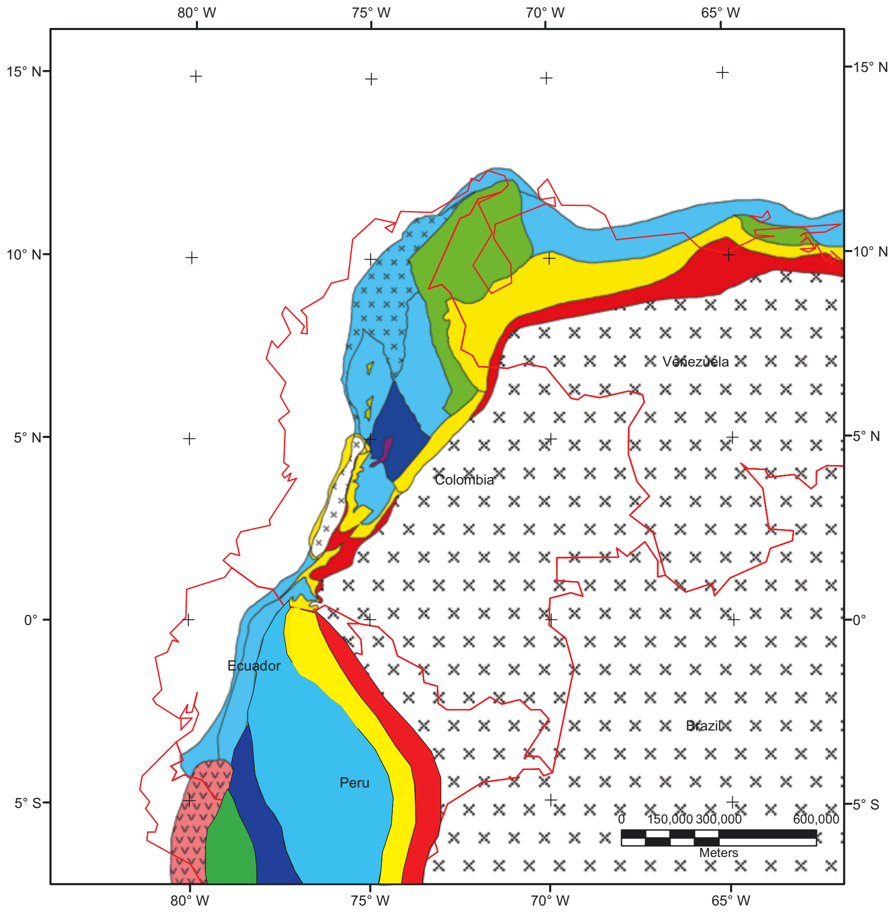

Fig. 10.24 Schematic paleo-facies map of northwestern South America during the latest Aptian-Early Albian. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

Middle Albian and Late Cretaceous Sedimentation

An abrupt, widespread transgression is observed during the Middle to Late Albian (Figs. 10.8, 10.9, and 10.25), resulting in the development of condensed sections and maximum flooding surfaces, including an important petroleum source rock interval. Two maximum flooding surfaces include:

1. A lower Middle Albian surface (MFS 10) that marks the termination of the platform carbonates and records an abrupt landward shift of facies. In eastern

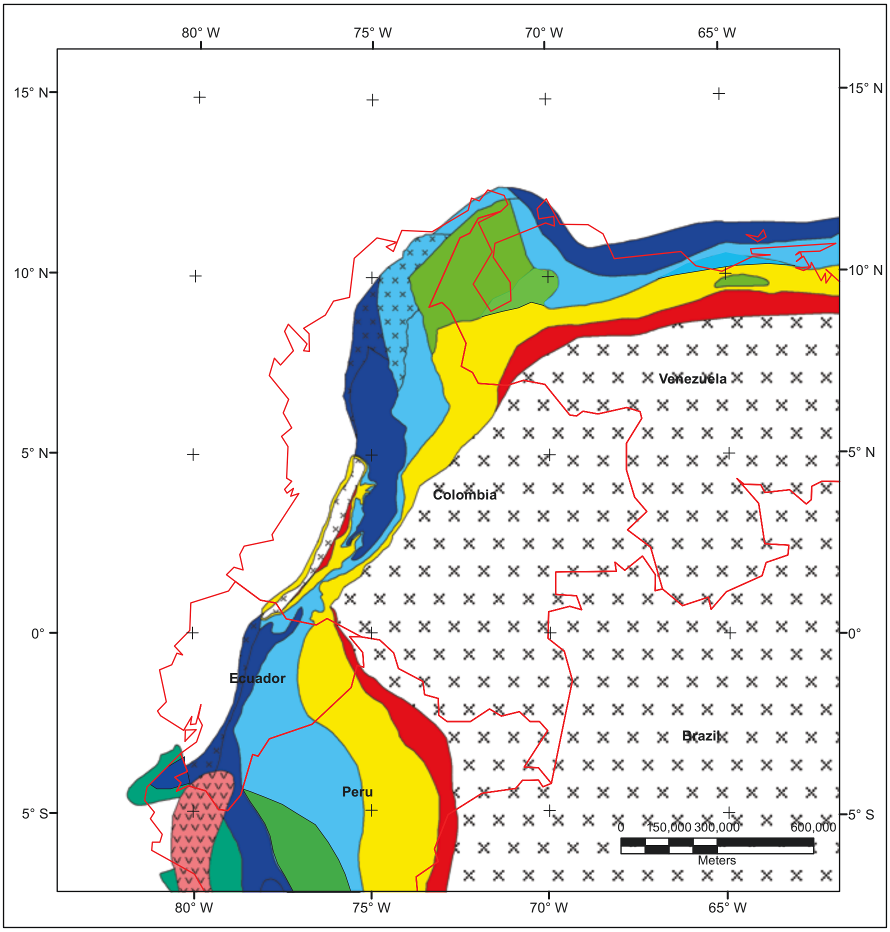

Fig. 10.25 Schematic paleo-facies map of northwestern South America during the Late Albian. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

Venezuela, MFS 10 is within a condensed section of glauconite-rich greensand at the base of Chimana Fm. In western Venezuela, the transgressive surface and maximum flooding surface (MFS 10) are condensed at the top of the Aguardiente Fm. and the middle greensand of the Escandalosa Fm. of the Barinas Basin.

2. A Late Albian maximum flooding surface (MFS 8A). The interval between the transgressive surface and the MFS 8A maximum flooding surface is condensed at the base of the Querecual Fm. in eastern Venezuela and the base of the isopic facies of the La Grita member of the Capacho Fm. in western Venezuela. In northern

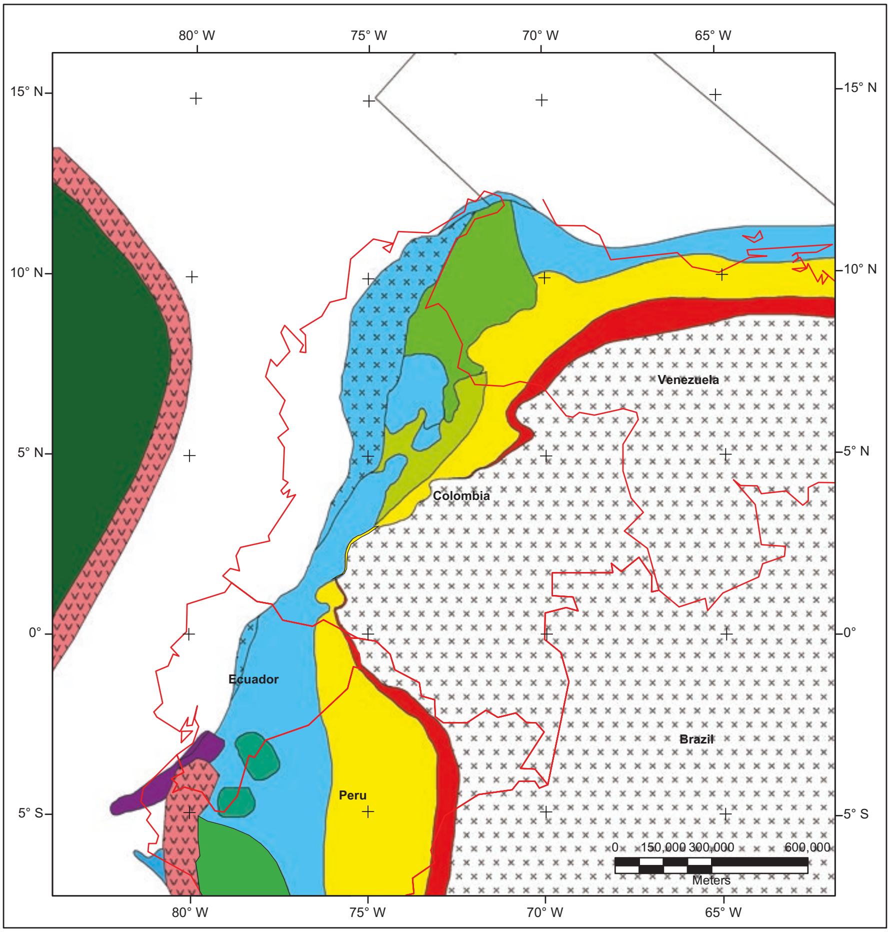

Fig. 10.26 Schematic paleo-facies map of northwestern South America during the Cenomanian. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

Venezuela (Isla La Borracha, offshore Puerto La Cruz), the MFS 8A event occurs at the contact between the Chimana Fm. and the base of the Querecual Fm. The base of the Querecual Fm is diachronous in eastern Venezuela (Late Middle to Early Late Albian in the north and Late Albian in the south).

During the Cenomanian (Figs. 10.8, 10.9, and 10.26), in eastern Venezuela, noncalcareous shales were deposited on an inner to outer marine shelf (Querecual Fm.). In western Venezuela noncalcareous shales were deposited on a marine shelf (Seboruco Fm.), and sands were deposited in littoral to shallow marine environments to the south (Escandalosa Fm.). In western Venezuela the noncalcareous Seboruco Shale represents high stand deposition with a high sedimentation rate. Above the Seboruco Shale rests the shallow-water carbonate of the Guayacán Member, and between the two, there is a sequence boundary unconformity (SB 9). This unconformity represents an abrupt shift in facies, from distal shale (Seboruco) to proximal shallow-water limestone (Guayacán Member) or even sandstone (Tocuy), as a consequence of a relative sea level drop that forced shallow-water depositional system basinward.

In westernmost Venezuela (Maracaibo Basin and Serranía de Perijá), shallow-water carbonates were deposited (Maraca Fm.). The Maraca Fm. is considered by Villamil and Pindell (2012) as Cenomanian, instead of Late Albian as proposed by earlier studies. If the Maraca Fm. is Late Albian, there has to be an unconformity with a Cenomanian hiatus of ca. 4 m.y. between the top of the Maraca Fm. and the base of La Luna Fm., which marks the Cenomanian-Turonian boundary. Villamil and Pindell (2012) propose that the Maraca Fm. is Cenomanian and correlates to the Guayacán Member, based on the observation that in other regions of Venezuela (i.e., Mérida Andes), the Guayacán Member is overlain by the La Luna Fm. and in many regions of Colombia, shallow-water carbonates of the Late Cenomanian (Caliza Mermeti) are overlain by La Luna Fm. equivalents. The same stratigraphic relation applies to the Maraca-La Luna. In addition, there is no field evidence of an unconformity representing a hiatus of 4 m.y. Rather, from the middle of Maraca Fm. to the base of La Luna Fm., facies indicate a gradual upward deepening of the basin, and at the Maraca-La Luna contact, there is a transgressive surface without an abrupt interruption of sedimentation (Villamil and Pindell 2012).

The transgressive surface at the base of the La Luna Fm. is just a few feet below the Cenomanian-Turonian boundary. The interval between the Cenomanian-Turonian boundary and the lower Turonian is a condensed section that contains the maximum flooding surface (MFS 8). This surface represents maximum flooding during the entire Cretaceous and perhaps including the entire Phanerozoic. During deposition of this stratigraphic interval, relative low rates of sedimentation favored accumulation of organic matter during times of a global marine anoxic event, allowing deposition of the best petroleum source rock in northwestern South America. The MFS 8 surface lies within a 10 m section of basal La Luna Fm., and it is characterized by a widely distributed concretion interval in western Venezuela (Villamil and Pindell 2012). Similarly, in eastern Venezuela, the Cenomanian–Turonian boundary lies within the lowest 100 m of the Querecual Fm., with similar facies.

During the Middle Turonian to Coniacian (Figs. 10.8, 10.9, 10.27, and 10.28), calcareous shales, hemipelagic limestones with micro-calcite concretions with local development of cherts, were deposited in an outer marine shelf representing a prograding high stand. This interval (La Luna Fm. in western Venezuela and Querecual Fm. in eastern Venezuela) contains cherts, indicative of vigorous upwelling conditions.

An additional transgressive event occurred during the Early Coniacian time. This event generated a highly fossiliferous laterally continuous concretion level containing abundant ammonites, planktic foraminifera, and *inoceramus* bivalves. In western

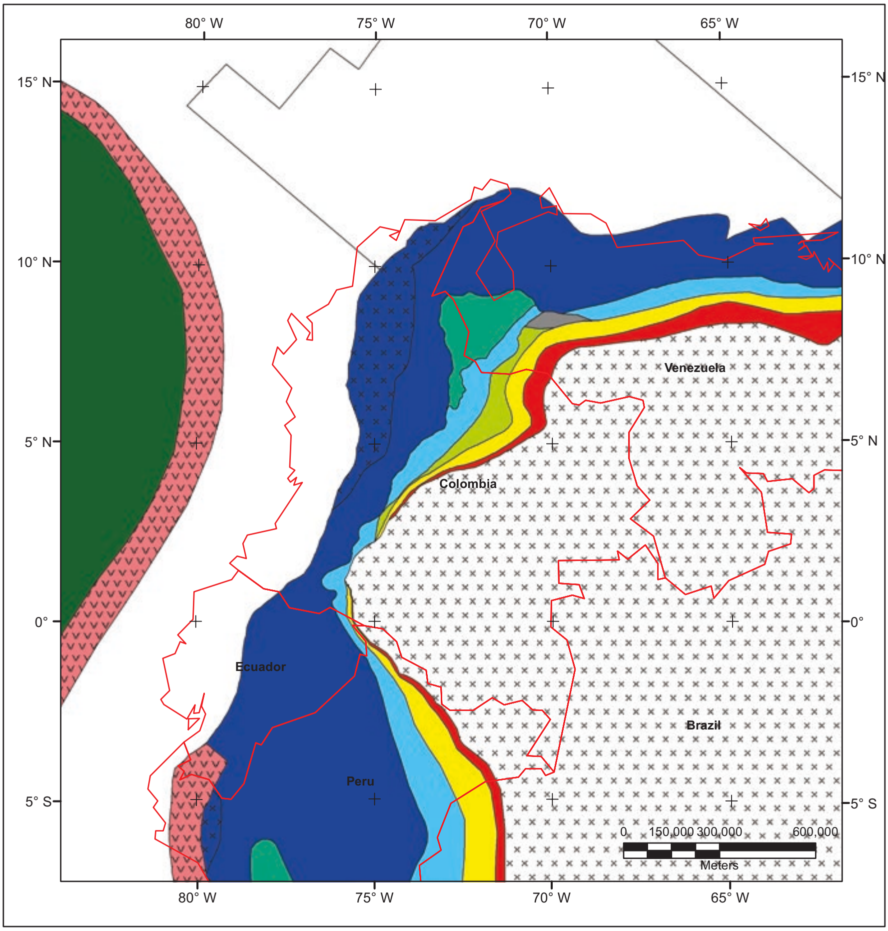

Fig. 10.27 Schematic paleo-facies map of northwestern South America during the Turonian. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

Venezuela this event lies within the La Luna Fm. while in eastern Venezuela, within Querecual Fm. (Villamil and Pindell 2012).

During the Santonian to Campanian (Figs. 10.8, 10.9, 10.29, and 10.30), intensive upwelling conditions were established over northwestern South America with deposition of chert (upper part of La Luna Fm., Ftanitas del Táchira, Tres Esquinas phosphorites in western Venezuela, and cherts of the San Antonio Fm. in eastern Venezuela). The location of active chert deposition shifted from specific locations to a regional distribution over the entire open marine shelf. During this time,

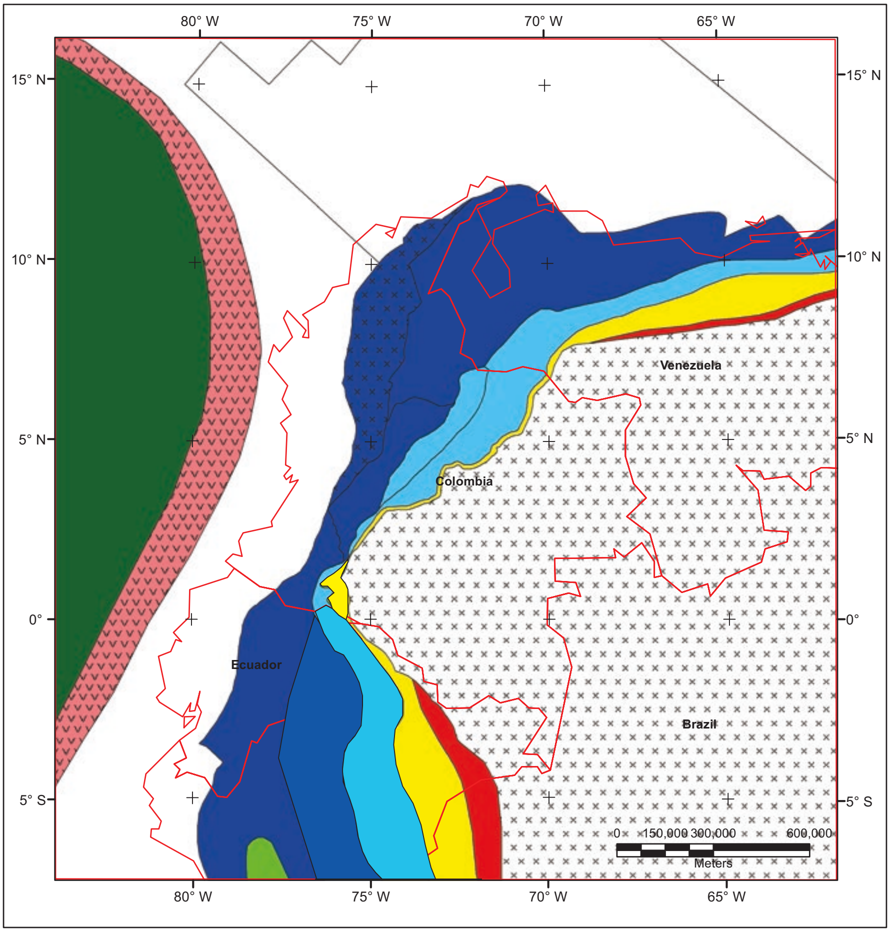

Fig. 10.28 Schematic paleo-facies map of northwestern South America during the Coniacian. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

shallow-water facies were deposited for the first time in the Barinas Basin. These facies prograded over Early Turonian maximum flooding shallow-water cherts of the Navay Fm. The upper part of the La Luna Fm. contains a phosphate-rich level called "Capa 2" in phosphate mines. Capa 2 overlies, in abrupt contact, cherts and calcareous shales of the La Luna Fm. and represents a drop in relative sea level (SB 7), followed by a rise and winnowing of siliceous fine-grained sediment. Capa 2 is overlain by cherts of the Ftanitas del Táchira, which cover large-scale ripples of the Capa 2. Another condensed section which recorded transgression and maximum

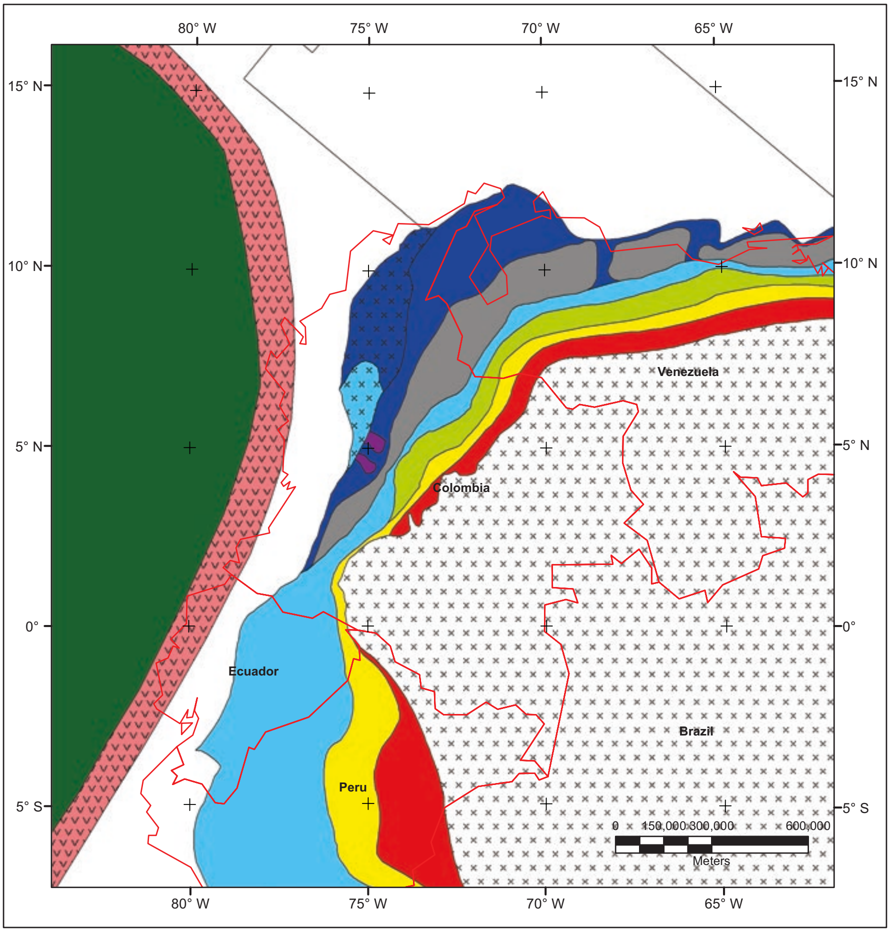

Fig. 10.29 Schematic paleo-facies map of northwestern South America during the Santonian. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

flooding (MFS 6) is the Tres Esquinas Fm. (Ghosh 1984). Downlapping of the overlying Colon shale is interpreted from outcrop and seen in seismic sections (Villamil and Pindell 2012). The condensed section of the Tres Esquinas Fm. contains glauconite and pyrite and phosphate-rich shales, abundant mosasaur and other marine reptile bones, and abundant fish debris. In eastern Venezuela, a drop in relative sea level (SB 5) is interpreted at the base of San Antonio Fm. by Villamil and Pindell (2012), with sand input in the distal basin previously dominated by fine-grained sediments of the Querecual Fm. The sequence boundary 5 at the base of the San

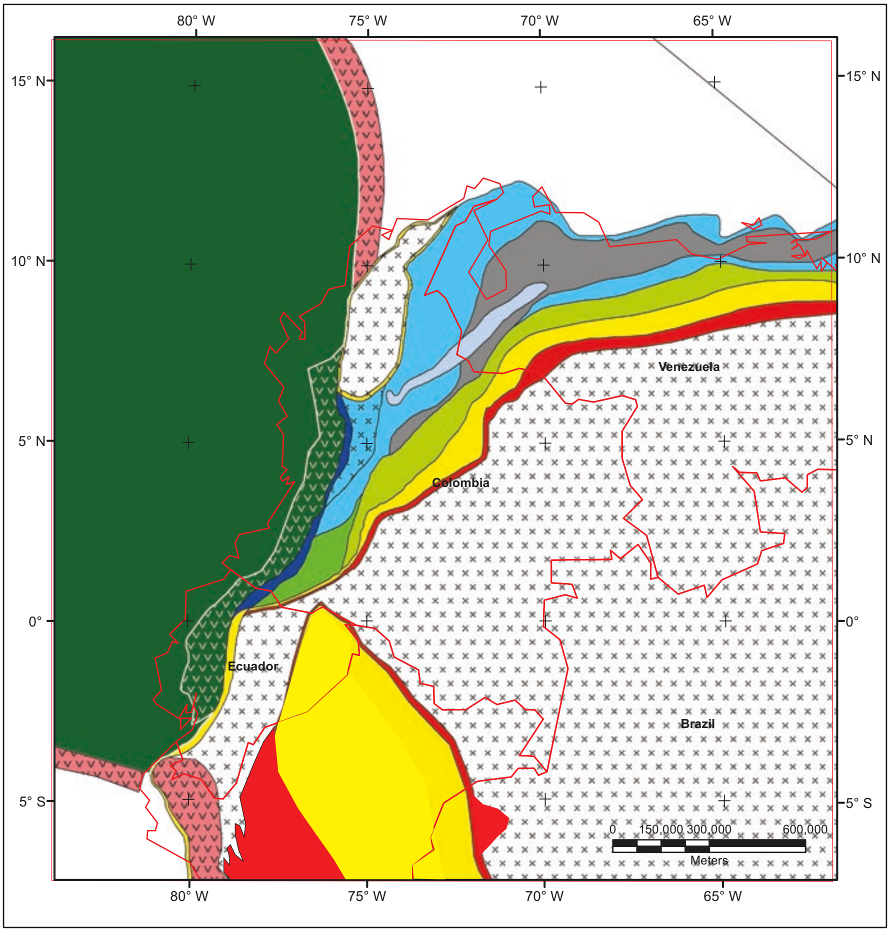

Fig. 10.30 Schematic paleo-facies map of northwestern South America during the Campanian. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

Antonio Fm. correlates with a biostratigraphic hiatus of lower Campanian plankton foraminiferal biozones, evidenced by Conney and Lorente (2009), in some basins of western Venezuela (Lake Maracaibo, Trujillo-Lara, and Barinas-Apure).

During the Maastrichtian (Figs. 10.8, 10.9, 10.31, and 10.32), sediment distribution changed in Venezuela. In western Venezuela, progradation of shallowing upward and coarsening upward shales of the Colón and Mito-Juan Fms. occurred, downlapping over the Tres Esquinas condensed section (MFS 6). In western Venezuela and Colombia, an Upper Maastrichtian and Paleocene regression and

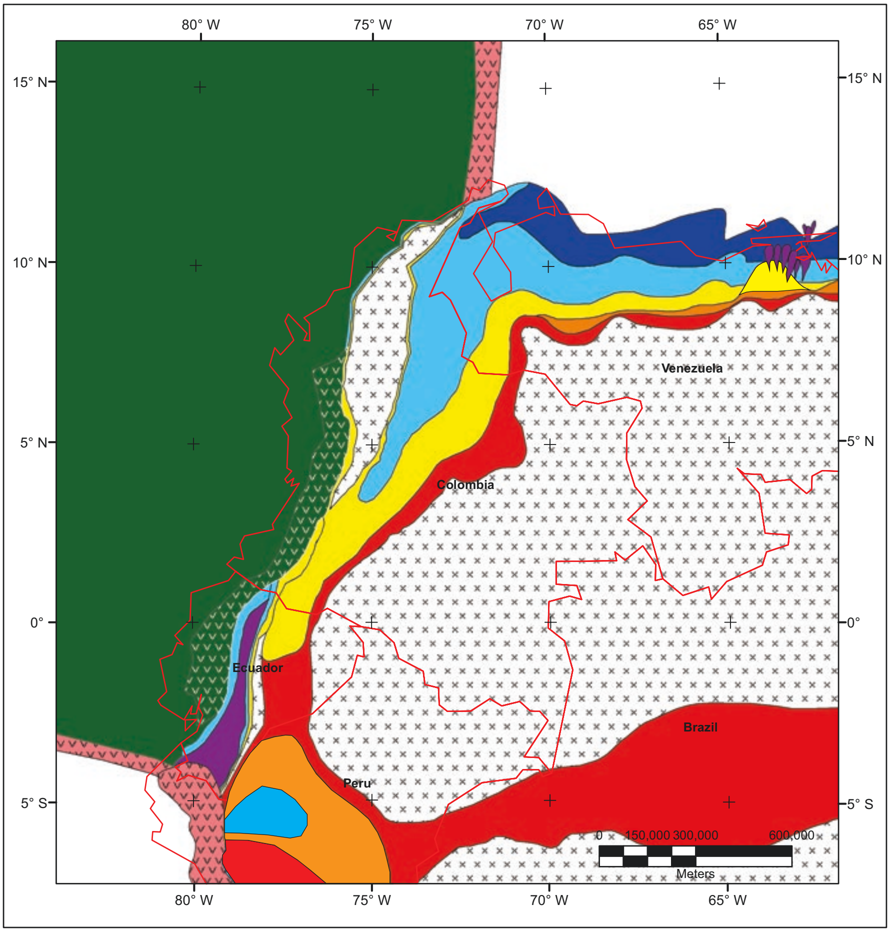

Fig. 10.31 Schematic paleo-facies map of northwestern South America during the Early Maastrichtian. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

basinward shift of facies are recorded. Inner marine shelf shales (Colón Fm.) were followed by coarser shallow marine shales (Mito Juan Fm.) ending with progradation of littoral sands (Barco Fm.) The progradation and regression filled the accommodation space, ending open marine sedimentation. The Colón and Mito Juan sedimentation high stand infilled the basin at high sedimentation rates. However, in the distal part of the basin, in western Venezuela (Lake Maracaibo and Trujillo-Lara), downlapping and condensation at the bottom of the Colón Fm. precluded deposition of several Campanian plankton foraminiferal biozones recognized by

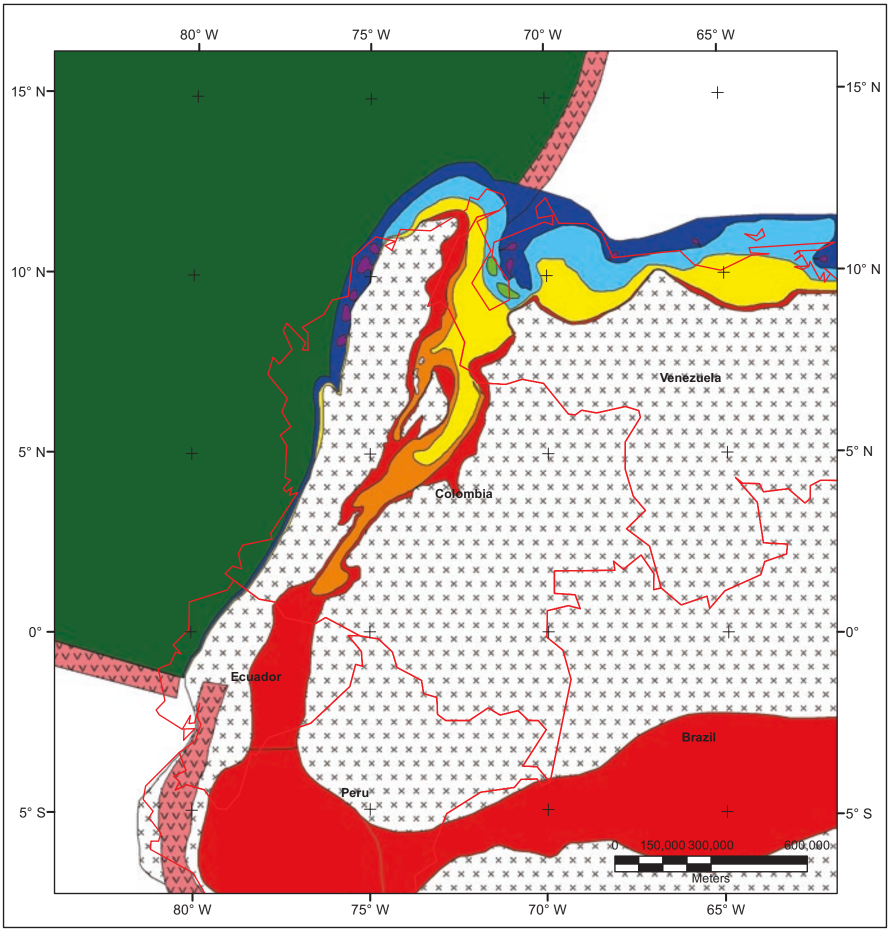

Fig. 10.32 Schematic paleo-facies map of northwestern South America during the Late Maastrichtian-Early Paleocene. See Fig. 10.1 for location and Fig. 10.7 for facies color legend. The schematic tectonic map reconstruction has been integrated to aid the reader in understanding the complex tectonic history of oceanic terranes accreted to the continental margin. Compiled after Etayo et al. (1976), Macellari (1988), Geotec (1992), Sarmiento-Rojas (2001), Cediel et al. (2003a, 2011), Villamil (1994, 1999, 2012), and Villamil and Pindell (2012)

Conney and Lorente (2009). In these areas, the stratigraphic interval between the surfaces represented by sequence boundaries 5 and 3 is condensed. Sediment input was derived from uplift of the Colombian Central Cordillera, probably increased by subtle uplift of the peripheral bulge associated with flexural subsidence, generated by the approaching Caribbean plateau in western Venezuela. In eastern Venezuela the unconformity between the chert-rich San Antonio Fm. (below) and the basal sand-rich San Juan Fm. (above) records a relative drop in sea level (SB 3), which terminated chert deposition in the basin. Sequence boundary 3, at the bottom of the

San Juan Fm. of eastern Venezuela, correlates with a hiatus evidenced by the lack of some Upper Campanian planktonic foraminiferal zones, as recognized by Conney and Lorente (2009) in western Venezuela. The San Juan Fm. of eastern Venezuela terminates with a transgressive surface that defines the base of the Vidoño Fm. The stratigraphic interval between this transgressive surface and the maximum flooding surface (MFS 2A) records relatively deep-water facies deposition of calcareous shales rich in planktonic radiolarians and foraminifera. The structureless San Juan Fm. basal sandstones could represent basin floor fans or alternatively shallow marine sands. If the basal San Juan sandstones are basin floor fans, the contact with the overlying Vidoño Fm. would be a progradational surface of slope deposits; if they are shallow marine sands, the contact with Vidoño Fm. would be a transgressive surface. In both cases the Vidoño Fm. represents a transgressive portion and a regressive progradational portion of marine deposits (Villamil and Pindell 2012).

The base of the San Juan Fm. records a fall in relative sea level (SB 3; Erikson and Pindell 1993). This was probably caused by tectonic uplift due to compressive stress on the plate during a time when the motion between North and South America changed (Villamil and Pindell 2012). In eastern Venezuela, the transgressive system tract of the lower Vidoño Fm. possibly records tectonic loading to the north. The Caratas Fm. records prograding sand during the final regression at the end of the Cretaceous. During deposition of the upper Vidoño and Caratas Fms., high stand possibly terminated with the arrival of the Caribbean forebulge in the Late Eocene, at the top of the Caratas Fm. (Erikson and Pindell 1993).

10.5.1.2 Colombia

Early Cretaceous Syn-Rift Sedimentation

Jurassic red beds are present in extensional grabens in the Guajira Peninsula, Serranía de Perijá, Serranía de San Lucas, Eastern Cordillera, and Upper Magdalena Valley and possibly in the Arauca Graben in the Llanos Basin, as a continuation of the Espino Graben of the Venezuelan Barinas Basin. In the Guajira Peninsula, shallow marine sediments of the Cocinas Gp. are also observed.

The Early Cretaceous sedimentary history in Colombia is illustrated in Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.19, 10.20, 10.21, 10.22 and 10.23. Sedimentation started in the Tablazo sub-basin in Jurassic times and continued during the Early Cretaceous (Figs. 10.13, 10.14, 10.15 and 10.21), locally without a tectonic-related angular unconformity (*e.g.*, at the Rio Lebrija section; Cediel 1968). In other areas, Cretaceous sedimentary rocks rest along an angular unconformity (SB 15) on earlier Mesozoic, Paleozoic, or even Pre-Cambrian rocks. In the Tablazo sub-basin, the first facies were mainly sandstones (Los Santos, Tambor, and Arcabuco Fms.) deposited in fluvial environments (Renzoni 1985a, b, c; Clavijo 1985; Vargas et al. 1985; Laverde and Clavijo 1985; Galvis and Rubiano 1985; Etayo-Serna and Rodríguez 1985). Bürgl (1960, 1964, 1967) suggested that an initial marine incursion in the Cundinamarca sub-basin flooded a continental area with an arid climate, permitting evaporite formation during the early stages of marine transgression. McLaughlin (1972) cited paleontological evidence from the Berriasian-Valanginian for some evaporite occurrences. During the Berriasian, the sea flooded the basin from the northern part of the Central Cordillera to the west, toward the Cundinamarca sub-basin (Etayo-Serna et al. 1976). Subsequently, the sea proceeded from the Cundinamarca sub-basin northward filling two sub-basins, while the Santander-Floresta paleo-Massif remained emergent (Etayo-Serna et al. 1976; Fabre 1985, 1987; Sarmiento 1989; Cooper et al. 1995).

Early Cretaceous Sedimentation on the Tablazo Sub-Basin Latest Jurassic to Valanginian fluvial sedimentation In the Tablazo sub-basin was followed by mudstone deposition in marginal marine environments, recording a marine transgression (Cumbre Fm. of Mendoza 1985 and Renzoni 1985c, and Ritoque Fm. of Ballesteros and Nivia 1985 and Rolón and Carrero 1995). Later, tidal and shallow-water marine shelf carbonates (Rosablanca Fm. of Cardozo and Ramirez 1985) were deposited during the Valanginian-Hauterivian, followed by shallow marine shales (Paja Fm.) during the Hauterivian-Barremian (*c.f.* Etayo-Serna et al. 1976). Although transgression was progressive from the center of the basin, two periods of relative retreat occurred, during the Hauterivian (SB 13) and Aptian (SB 11A) (Rolón and Carrero 1995; Ecopetrol et al. 1994; Figs. 10.13, 10.14, 10.22, and 10.23). Near Villa de Leiva, the Paja Fm. records an abrupt change from organic-rich marine shelf facies in the lower (Barremian) part of the Paja Fm. (the Arcillolitas Negras Inferiores Member of Etayo 1968) changing to proximal tidal shabka and calcareous algal facies of the middle (Aptian) part of the unit (Forero and Sarmiento 1985; the Arcillolitas Abigarradas Member of Etayo-Serna 1968). This abrupt change represents a regression and a relative sea level drop (SB 11A).

Later, during the Aptian (Figs. 10.13, 10.14 and 10.23), a relative tectono-eustatic sea level rise (MFS 10A) is suggested by deeper marine facies in the upper part of the Paja Fm (Forero and Sarmiento, 1985; Ecopetrol et al. 1994; Rolón and Carrero, 1995). Near Curití, a condensed section compresses the entire Aptian into a thickness of 15 m (MFS 10A; Villamil and Pindell, 2012).

The Upper Aptian-Lower Albian Tablazo Fm. presents a problem. In the Middle Magdalena Valley, the lower part of the Tablazo Fm. consists of calcareous shale, while it contains massive fossiliferous limestone and marls in its upper part (Morales et al. 1956). The calcareous shales are rich in organic matter and are proven petroleum source rocks, interpreted to have been deposited along an anoxic outer marine shelf (i.e., La Luna-1 well; Sarmiento 2011, 2015). In contrast, along the western flank of the Eastern Cordillera near Barichara, the lowermost part of the Tablazo Fm. includes fine-grained limestones and sandy bioclastic limestones, while coarse fossils are found in the remainder of the unit. The Tablazo Fm. of the Middle Magdalena Valley, at least in its lower section, is a distal shaly organic-rich facies, while most of the Tablazo Fm. in the Eastern Cordillera represents a sandy, bioclastic, proximal shallow marine shelf facies. As a working hypothesis, I propose that the lower organic-rich part of the Tablazo Fm. in the Middle Magdalena Valley is a distal facies, correlatable with the lowermost fine-grained part of the Tablazo Fm. of the Eastern Cordillera or, alternatively, with the uppermost part of the Paja Fm. of the Eastern Cordillera. This distal interval was deposited during maximum marine flooding (MFS 10A). It is also possible that the lower part of the Tablazo Fm. of the Eastern Cordillera is coeval with a condensed section in the Middle Magdalena Valley. The massive, bedded fossiliferous limestone of the Tablazo Fm. in the Middle Magdalena Valley possibly correlates to the sandy bioclastic limestones of the Tablazo Fm. of the Eastern Cordillera.

Berriasian to Aptian Sedimentation on the Cocuy Sub-basin. During the latest Jurassic to earliest Cretaceous, marine transgression in the Cocuy sub-basin initiated in the south, as recorded by the Brechas de Buenavista Fm. (Dorado 1984) and the Calizas del Guavio Fm. (Ulloa and Rodríguez 1976; Fabre 1985; Mojica et al. 1996). To the north, facies changes record the transition from continental to shallow marine sedimentation (Lutitas de Macanal Fm.), during the Berriasian to Valanginian (Fabre 1985). During the Hauterivian to Barremian, wave-dominated deltaic sandy environments are recorded (Arenisca de Las Juntas Fm; Fabre 1985). In the Hauterivian, deposition of prograding sands in a rapidly subsiding basin (Fabre 1985) was probably facilitated by a fall in relative tectono-eustatic base level (SB 13). (Figs. 10.13, 10.14, 10.21, 10.22 and 10.23).

Early Cretaceous Sedimentation Over the Santander-Floresta Paleo-Massif. The Santander- Floresta paleo-Massif remained emergent until the Hauterivian, at which time deposition of continental sandstones, followed by progradation of deltaic sandstones (Rionegro Fm. and lower part of Tibasosa Fm.) and, in turn, by deposition of shallow marine carbonates, took place. The two sub-basins coalesced into a single basin during the Hauterivian flooding and base level rise over the paleo-Massif (Fabre 1985; Moreno 1990a, b, 1991). Santander-Floresta formed an intrabasinal high and significant barrier to sediment movement until the Aptian time (Cooper et al. 1995). The succession of sandstone (Tambor and Los Santos Fms.), limestone (Rosablanca Fm.), and dark shale (Paja Fm.) facies, recorded in the Tablazo sub-basin, is laterally younger toward the east over the Santander-Floresta paleo-Massif (sandstone, Rionegro Fm.; limestone and shale, Tibú and Mercedes Fms.) and in the Cocuy sub-basin (sandstone, Arenisca de Las Juntas Fm.; limestone and shale, Apón Fm; Fabre 1985). This lateral change in age of facies occurred as a result of the oscillating and progressive marine transgression toward the east during Valanginian to Aptian times. (Figs. 10.12, 10.13, 10.14, 10.21, 10.22 and 10.23).

Berriasian to Aptian Sedimentation in the Cundinamarca Sub-basin. Toward the south, both the Tablazo and Cocuy sub-basins record a gradual increase in dark shale content, deposited in poorly oxygenated, shallow marine environments (Caqueza Gp., Villeta Gp; Fabre 1985; Rubiano 1989; Sarmiento 1989). In the Cundinamarca sub-basin, Cretaceous sedimentation started in the Tithonian?-Berriasian-Valanginian, with turbidite deposits along both the eastern (lower

Caqueza Gp; Pimpirev et al., 1992) and western (lower part of Utica Sandstone, Murca Fm; Sarmiento 1989; Moreno 1990b, 1991) flanks. Turbidite deposition along the eastern border of the basin prevailed into the Hauterivian (Caqueza Gp; Pimpirev et al. 1992). (Figs. 10.14, 10.15, 10.21, 10.22 and 10.23).

During the earliest Cretaceous, basin subsidence exceeded sediment supply, resulting in retrogradation of the turbidite fan system, such that distal fan sediments covered middle fan mouth channel deposits. In post-Berriasian time, sediment supply increase overwhelmed basin subsidence, resulting in progradation of the turbidite fan system (Pimpirev et al. 1992) and locally by progradation of deltaic sands during the Hauterivian (upper part of Utica Sandstone; Sarmiento 1989; Moreno 1990b). This reflects a relative sea level drop (SB 13). Toward the south, the shallow marine sandstones and limestones of the Naveta Fm. mark the development of a shoreline during the Hauterivian-Barremian (Cáceres and Etayo-Serna 1969; Sarmiento 1989). Differential subsidence related to syn-sedimentary normal faulting generated unstable slopes on basin margins. These processes favored turbidite deposition from the Early Cretaceous to the Aptian (lower part of Utica Sandstone, Murca Fm., Socotá Fm; Polanía and Rodríguez 1978; Sarmiento 1989; Moreno 1990b, 1991; Caqueza Gp, Pimpirev et al., 1992).

Aptian Sedimentation in the Upper Magdalena Valley Cretaceous sedimentation is recorded for the Aptian (Vergara and Prössl 1994), although probably initiated in an extensional basin during the Late Jurassic. Feldspathic and lithic sandstones, conglomerates, and red mudstones (Yaví Fm.) were deposited as alluvial fans on valley slopes, while finer sandstones and mudstones (Alpujarra Fm. sensu Florez and Carillo 1994, Etayo-Serna 1994 and Etayo-Serna and Florez 1994) and/or Lower Sandstone member of the Caballos Fm. (sensu Guerrero et al. 2000) accumulated within a flowing northward fluvial system. (Figs. 10.16, 10.17, 10.22 and 10.23).

Abrupt lateral thickness changes and ubiquitous turbidite deposition throughout the Eastern Cordillera basin (Figs. 10.13, 10.14, 10.15 10.16, 10.21, 10.22 and 10.23) attest to local tectonic/differential subsidence depositional conditions in the Cretaceous. Regional correlation of relative Early Cretaceous tectono-eustatic cycles is difficult to establish due to active localized extensional tectonics. Since the Aptian, however, these relative tectono-eustatic level cycles become increasingly traceable.

An important transgression followed a relative sea level rise during the Late Aptian (MFS 10A), as the sea flooded all the area of the present Eastern Cordillera, including south of the Cundinamarca sub-basin (Etayo-Serna et al. 1976; Etayo-Serna 1994). During the Late Aptian, the sea gradually flooded the Upper Magdalena Valley, and dark mudstone and limestone (El Ocal Fm. sensu Florez and Carillo 1994, Etayo-Serna, 1994 and Etayo-Serna and Florez, 1994, or Middle mudstone and biomicrite member of the Caballos Fm. sensu Guerrero et al., 2000), were deposited in a shallow marine environment (Etayo-Serna 1994).

Dark-gray to black mudstone was deposited regionally upon a dysoxic shallow marine shelf which included the upper part of the Paja Fm. in the former Tablazo sub-basin, the Fómeque Fm. in the former Cocuy sub-basin, the Villeta Gp., the upper part Socotá Fm. in the former Cundinamarca sub-basin, and the El Ocal Fm. in Upper Magdalena Valley.

Cretaceous Post-Rift Sedimentation

Cretaceous post-rift sedimentation is illustrated in Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.25, 10.26, 10.27, 10.28, 10.29, 10.30, 10.31 and 10.32. Villamil (1994) interpreted limestone-shale or chert-shale rhythmic beds as Milankovitch cycles. Using high-resolution graphical stratigraphic correlation, he showed that distal pelagic limestone-shale cycles are coeval to proximal parasequences. Assuming these cycles all have the same duration, and that subsidence was constant through time, Villamil (1994) plotted the thickness of all cycles in a modified Fisher plot (a stacking plot for cyclic rhythmic sedimentation) to obtain a curve of changes in relative accommodation space or relative tectono-eustatic base level.

Based on facies analysis, macrofossil biostratigraphy, high-resolution event, and cycle chronostratigraphy, together with the modified Fisher plots, Villamil (1994) proposed a sequence stratigraphic interpretation and a relative tectono-eustatic level history.

During the Albian (Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.24 and 10.25), a relative base level fall (SB 11) favored progradation of deltaic and littoral sands (Caballos Fm.; Flórez and Carrillo 1994; Etayo-Serna 1994) in the area of the Upper Magdalena Valley and along the eastern border of the basin (lower part of Une Fm; Fabre 1985).

During the Middle to Late Albian (Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18 and 10.25), the transition from near-shore marine facies of the Caballos Fm. to the deepening upward, lower part of Villeta Gp. in the Upper Magdalena Valley recorded a rise in relative tectono-eustatic level (MFS 10; Villamil 1994; Etayo-Serna 1994). This tectono-eustatic level rise was also recorded by the upward deepening trend from the shallow-water San Gil Inferior Fm. to the deeper San Gil Superior Fm., the Socotá Fm. to the Hiló Fm., and within the Une Fm. (Villamil 1994). During the Middle Albian, regionally distal, organic-rich outer shelf facies were deposited over most of the basin, during a global anoxic event responsible for the petroleum generation potential of these rocks (i.e., Tetuán Fm. in the Upper Magdalena Valley). However, there are no petroleum source rocks of Middle Albian age in the Middle Magdalena Valley. A possible explanation for this anomaly is that in the Middle Magdalena Valley, the Middle Albian maximum flooding surface (MFS 10) occurs in a condensed section with a very reduced sedimentation rate, which is not favorable for the accumulation of organic matter.

During the Late Albian-Early Cenomanian (Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.25, and 10.26), a relative tectono-eustatic level fall (SB 9A) was recorded by progradation of the upper part of Une Fm., and a generalized shallowing upward facies trend is recorded. In the Late Albian-

Earliest Cenomanian, there is a sequence boundary (SB 9A) expressed as a forced regression (unnamed shale overlying the cherts of the Hiló Fm., shallow-water sandstone of Churuvita Fm. over deeper shale of the San Gil Superior Fm; Villamil 1994). In the Upper Cenomanian, Villamil (1994) interpreted the next marked sequence boundary (SB 9, including first sandstone in the shales of the Villeta Gp., upper sandstone part of Churuvita Fm., and uppermost sandstone of the Une Fm.).

During the Late Cenomanian, Turonian, and Coniacian (Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.26, 10.27 and 10.28), the tectono-eustatic base level reached its maximum level for the Mesozoic. The sea flooded the entire northwestern corner of South America, and dark-gray shale was deposited from Venezuela to northern Peru. Villamil (1994) recognized smaller relative tectono-eustatic level cycles during this time interval.

A relative tectono-eustatic base level rise during the Late Cenomanian (Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18 and 10.26) induced a slight deepening of the basin and a notorious decrease of the detrital supply. This led to basin starvation and the slow deposition of black laminated shale grading to distal micritic limestone pelagic facies. The maximum flooding surface located at the Cenomanian-Turonian boundary (MFS 8, Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17 and 10.18) is characterized by a highly fossiliferous concretion horizon within the Frontera Fm. and the lower part of San Rafael Fm. (Villamil 1994). During the Turonian-Coniacian, the present-day foothills of the Eastern Cordillera close to the Llanos Basin were flooded (Cooper et al. 1995), but not the entire Llanos Basin area. From the Middle Turonian to Late Coniacian, a gradual progradation and shallowing upward occurred during deposition of the upper part of the San Rafael Fm. and the Villeta Gp. in the Upper Magdalena Valley was related to a relative tectono-eustatic sea level fall (SB 7, Villamil 1994).

In the Upper Magdalena Valley, during the Late Coniacian to Santonian (Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.28 and 10.29), the transition from the uppermost Villeta Gp., deposited upon an inner shelf, to the Lidita Inferior unit of the Olini Gp., deposited on a deeper middle shelf (Jaramillo and Yepez 1994; Ramirez and Ramirez 1994), points to a deepening of the basin and relative tectono-eustatic level rise (MFS 6; *c.f.* Fig. 2 of Etayo-Serna 1994).

During the Santonian, Campanian, Maastrichtian, and Paleocene (Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.29, 10.30, 10.31 and 10.32), a general regression and progradation were recorded by littoral to transitional coastal plain facies (Guadalupe Gp., Guaduas Fm.). Guadalupe Gp. sands represent two cycles of westward shoreline progradation, aggradation, and retrogradation, dominated by high-energy quartz-rich shoreface sandstones derived from the Guiana Shield (Cooper et al. 1995). Regression did not occur continuously but with minor transgressive events recorded by fine-grained siliceous and phosphatic facies (Föllmi et al. 1992; Plaeners Fm., Olini Gp., upper part of La Luna Fm.).

A sequence boundary (SB 5) occurs at the base of the medium shale unit of the Olini Gp. (Aico Shale; Lower-Middle Santonian according to Villamil, 1994, or Late Santonian-Early Campanian according to palinostratigraphy by Jaramillo and

Yepez, 1994) and Etayo-Serna, 1994) and the shallow-water El Cobre Sandstones of Barrio and Coffield (1992) in the Upper Magdalena Valley (Villamil 1994). The shallow-water marine sands of the Arenisca Dura Fm. represent a lower forced regression system tract (sensu Posamentier et al. 1992; Cooper et al. 1995), caused by a relative sea level drop (SB 5).

Mudstones of the upper part of the Arenisca Dura Fm. and shales of the Plaeners Fm. represent a transgressive system tract (Cooper et al. 1995). During the Santonian-Early Campanian, a maximum flooding surface (MFS 4) and a relative tectono-eustatic level rise from the medium shale unit of the Olini Gp. to the Upper Chert unit has been interpreted by Villamil (1994). In contrast to the Eastern Cordillera, where the Cretaceous maximum flooding surface occurred at the Cenomanian-Turonian boundary (MFS 8), the maximum flooding in the Llanos Basin occurred during the Campanian (MFS 4 at the top of Gachetá Fm; Fajardo et al., 1993; Fig. 10.4 of Cooper et al. 1995).

During the Late Campanian (Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18 and 10.30), relative sea level continued to drop (SB 3), and shallow marine oxygenated environments prevailed in the Eastern Cordillera. A shale stratigraphic interval between the Labor and Tierna Fms., informally called “Upper Plaeners,” records a relative sea level rise (MFS 4). The Labor Fm. represents a sand-dominated, forced regression system tract (Cooper et al. 1995), induced by a relative sea level drop (SB 2A).

The regional regression and long-term relative tectono-eustatic level fall were interrupted by two small cycles of relative tectono-eustatic base level rise during Late Campanian (MFS 4), during deposition of the “Upper Plaeners” and Early Maastrichtian (MFS 2A), as suggested by Föllmi et al. (1992) and Villamil (1994). According to Cooper et al. (1995), the Upper Plaeners unit represents a condensed marine mudstone deposited during a relative tectono-eustatic level rise (MFS 4).

During the Early (?) Maastrichtian (Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18 and 10.31), the eastern part of the basin was filled by the littoral quartz sands of the Arenisca Tierna Fm. (Fabre 1985). According to Cooper et al. (1995), the latter represents the transgressive systems tract of the next sequence that reached a maximum flooding surface (MFS 2) at the base of Guaduas Fm. (Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.31 and 10.32). The gradual uplift of the western margin of the Upper Magdalena Valley supplied clasts of metamorphic rocks that were accumulated by fluvial systems close to the sea in a braided delta (Cimarrona Fm; Gómez and Pedraza, 1994). Sands were dispersed along a littoral belt (Monserate Fm; Ramírez and Ramírez, 1994), while in the more distal areas, carbonate silt (Díaz, 1994a, b) or mud (Umir Fm.) accumulated (Etayo-Serna 1994).

Southern Cauca Valley The Campanian basement of the southern Cauca Valley, herein termed the “Amaime Heterolithic Complex,” represents tectonic stacking of oceanic basalts and sediments, trench deposits, and slivers of dismembered ophiolites (Barrero and Laverde, 1998), accreted to the continental margin. Over this accreted basement, the Nogales Fm. was deposited during the Maastrichtian.

The lower Nogales Fm. consists of matrix-supported conglomerates, calcareous sandstones, mudstone, and claystone sourced from the emergent Central Cordillera and deposited as debris flow, most probably in the proximal part of a fan delta (fan delta-front facies). The middle part of the section consists of turbiditic sandstones, siliceous claystone, and chert beds. Maximum flooding probably occurred during deposition of the cherts and claystones (MFS 2). The upper section consists of claystone and cross-bedded sandstone. Conglomerate and claystone of red and green color dominate the upper part and suggest transition to continental deposits. This segment is interpreted to be deposited in the fan delta transition zone front to alluvial fan facies (Pardo et al. 1993; Blau et al. 1995). In the southern areas of the Cauca Valley near Vijes, Cali-Timba, and El Dinde-Chimborazo, chert has been reported (Marilopito Fm.) and marine mudstones (Aguaclara Fm.) similar to those deposited during maximum flooding (MFS 2) in the Nogales Fm. These units have been considered Maastrichtian in age. In the Patía sub-basin, the uppermost conglomerates (lower part of the Rio Guabas unit) suggest transition to continental deposits. The Paleocene is represented by a stratigraphic hiatus (SB 1). (Figs. 10.16, 10.17, 10.30 and 10.31).

Northern Sinu-San Jacinto Basin. In this basin the Cansona Fm. was deposited during the Late Cretaceous (Coniacian-Santonian-Maastrichtian; Figs. 10.12, 10.13, 10.28, 10.29, 10.30 and 10.31). Its lower part was deposited unconformably (SB 5?) over oceanic basement (Guzmán et al. 1994, 2004). The Cansona Fm. is composed of foraminifera-rich calcareous mudstone, thin limestone, chert, and locally sandstone and conglomerate, within a transgressive-regressive sequence marked by a Campanian maximum flooding surface (MFS 4). During the Late Cretaceous and Early Paleogene, a coastline developed close to the present western boundary of the Lower Magdalena Valley, a region that formed positive relief and a source area for the sediments of the Cansona Fm. Conglomerates and sandstones are interpreted to record a proximal setting close to the shore line. Environments of deposition include proximal, low energy and relatively inner to middle shelf (Alfonso et al. 2009), and middle neritic to deep bathyal pelagic, as marked by planktonic foraminifera, cocolithophorids, and radiolarian (Guzmán et al. 1994). Palinofacies indicate a sub-oxic to anoxic environment (Juliao et al. 2011). The Early Paleocene corresponds to a hiatus represented by the unconformity surface between the Cansona Fm. and overlying rocks. This unconformity (SB 1) implies that the Cansona Fm. was exposed to erosion as a result of Early Paleocene uplift, as recorded by the AFTA data analyzed by Alfonso et al. (2009).

Catatumbo Sub-basin (Colombian Portion of the Maracaibo Basin) Sedimentation started as continental fluvial facies (Rionegro Fm. in Maracaibo and sandy lower part of Tibú Fm.) unconformably deposited upon (SB 15) over a pre-Cretaceous peneplanized surface. Marine transgression during the Aptian initially deposited littoral facies followed by shallow marine shelf limestones (Tibú and Mercedes Fms.). In distal areas, inner shelf mudstones were deposited and prevailed during a sea level rise (MFS 12). During the Albian, deltaic sands prograded to the NW (Aguardiente Fm.). Progradation was favored by a relative sea level fall (SB 11). Sandstones are dominantly quartz arenites sourced from the craton (Figs. 10.12, 10.21, 10.22 and 10.23).

During the Late Cretaceous (Figs. 10.12, 10.24, 10.25, 10.26, 10.27, 10.28, 10.29, 10.30, 10.31 and 10.32), sedimentation was controlled by eustatic changes, and mudstone deposition prevailed along an inner marine shelf (mudstones of the Capacho, La Luna, Colón, and Mito-Juan Fms.). During the Middle Albian and Lower Turonian, marine flooding events (MFS 10 and MFS 8 respectively) deposited organic-rich fine-grained pelagic limestones and shales (Albian Capacho Fm. and Turonian La Luna Fm.) during maximum sea levels, coinciding with global anoxic events. Subsequently, inner shelf mudstones coarsening upward to siltstones record a gradual shallowing of the basin (Colón and Mito-Juan Fms.). By the end of Cretaceous and beginning of the Paleocene, uplift in the Central Cordillera supplied sand and silt to the basin, and a final regression occurred marked by coarsening shallowing upward units (Catatumbo, Barco, and Los Cuervos Fms.).

Perijá Range and the Cesar-Ranchería Basin In these areas, Cretaceous stratigraphy is very similar to that of the northern Maracaibo Basin (Fig. 10.11). Extensional episodes in the Perijá Range controlled sedimentation during the Berriasian to Early Aptian (Figs. 10.11, 10.21, 10.22 and 10.23), until the Early Cretaceous (pre-late Aptian), and a clastic succession (Rio Negro Fm.) was deposited unconformable over Jurassic red beds (La Quinta Fm., Maze 1984) of the Perijá rift. The Rio Negro Fm., containing sandstones and conglomerates with occasional claystone and siltstone interbeds, was deposited in a fluvial to transitional environment. In the Perijá depocenter, the Rio Negro Fm. attains thickness up to 1500 m, while in the Cesar-Rancheria Basin, thickness decreases to 200 m and to a minimum of 10 m on the NW border of the basin, along the southeastern flank of the Sierra Nevada de Santa Marta.

During the Late Aptian (Figs. 10.11 and 10.24), thick-bedded fossiliferous limestones and very thin-bedded calcareous shales of the Lagunitas Fm. were deposited upon an inner carbonate shelf. During the Albian to Cenomanian (Figs. 10.11, 10.25, and 10.26), biomicritic limestones and fossiliferous, organic-rich shales, glauconitic sandstones, mudstones, and sandy limestones of the Aguas Blancas Fm. (Colombia) and Maraca Fm. (Venezuela) were deposited on an inner to middle marine shelf. Vertical changes from carbonate inner shelf facies to argillaceous middle to outer shelf facies were controlled by relative sea level changes.

During the Cenomanian to Coniacian (Figs. 10.11, 10.26, 10.27 and 10.28), bituminous biomicrites (pelagic limestones), organic-rich calcareous shales with abundant concretions, chert, including planktonic and benthonic foraminifera and ammonites contained within the La Luna Fm., were deposited on an outer to middle shelf controlled by relative sea level changes. Similarly, in western Venezuela, the interval between the Cenomanian-Turonian boundary and the lower Turonian is a condensed section that contains the maximum flooding surface (MFS 8) of the Cretaceous. During deposition of this stratigraphic interval, relatively low rates of sedimentation favored accumulation of organic matter under global marine anoxic conditions, allowing deposition of what is considered the best petroleum source rock in northwestern South America. The Tres Esquinas glauconitic mudstone member, only a few meters thick, widely recognized in Venezuela, has been also recorded in most of the wells drilled in the Cesar-Ranchería Basin (Intera Information Technologies-Bioss 1995). This member represents a condensed section recording transgression and maximum flooding (MFS 6).

Overlying the Tres Esquinas Member, biomicrites and calcareous mudstones of the lowermost part of Colón Fm. (the Molino Fm. of the Cesar-Ranchería Basin) were deposited upon an inner to middle shelf. The rest of the Molino Fm. is comprised of calcareous and carbonaceous shales with abundant benthonic and planktonic foraminifera, also deposited upon an inner to middle marine shelf (Martínez 1989). In its uppermost segment, thin interbedded sandstones mark transition to an intertidal environment.

Central Cordillera and the Lower Magdalena Valley (Plato-San Jorge Area) In most of these areas, there is no Cretaceous sedimentary record (Figs. 10.12 and 10.13). I suggest that, although these areas were covered by the sea, the lack of subsidence, or very reduced subsidence, did not provide accommodation space for sediment accumulation (indicated in the paleo-facies maps with color for sedimentary environment). In the absence of a stratigraphic record (indicated by a pattern of "x"s in Fig. 10.7), it may be postulated that accumulated sediment would have been eroded during Maastrichtian to Paleocene and Eocene uplift of these areas, as suggested by Cediel et al. (2003a, b).

10.5.1.3 Southern Colombia (Putumayo Basin) and Ecuador (Oriente Basin)

Sedimentation in southern Colombia and Ecuador is illustrated in Figs. 10.18, 10.19, 10.23, 10.24, 10.25, 10.26, 10.27, 10.28, 10.29, 10.30, 10.31 and 10.32. A slight reactivation of Jurassic normal faults during the Early Cretaceous time is recorded. Continental sedimentation was followed by development of a coastal plain and marine transgression. Deposition of shallow marine sandstone facies in the southern Upper Magdalena Valley of Colombia and Aptian in the sub-Andean Putumayo and Oriente Basins (Caballos Fm. in Colombia, and Hollín Fm. in Ecuador) during the Albian was followed by deposition of inner shelf mudstones (lower part of Napo Fm. in Ecuador, and lower part of Villeta Fm. in Colombia). Since the Turonian, in Ecuador and possibly southernmost Colombia, regional transpression leading to tectonic inversion of the Andean Ranges converted the basin to a back-arc foreland. During this time, marine sedimentation continued, and the sea reached its maximum extension toward the craton during the Cenomanian-Turonian boundary (MFS 8; upper part of Napo Fm. in Ecuador, and middle part of Villeta Fm. in Colombia). Later, depositional environments became shallower and included a proximal marine sandstone facies (Rumiyaco Fm. in Colombia, and Tena Fm. in Ecuador). Several stratigraphic sequences generated by tectono-eustatic changes have been identified in southern Colombia and Ecuador in the Aptian to Upper Cretaceous section (Hollín, Napo and basal Tena Fms. in Ecuador, and Caballos, Villeta and basal Rumiyaco Fms. in Colombia), Barragán et al., 2004). Each stratigraphic sequence includes an erosive sequence boundary corresponding to fluvial incised valleys during a sea level drop. These valleys were filled by fluvial and estuarine deposits followed by marine mudstones during a transgressive phase and deposited organic-rich mudstones during maximum flooding events. The upper part of each cycle contains distal shallow marine limestones and mudstones and proximal prograding deltaic sandstones, and most of these cycles show a transition from fluvial to estuarine and marine shelf (Barragán et al. 2004). Such sequences include the following from base to top: (1) Aptian, dominated by sandstones (lower part of Hollín Fm. in Ecuador), deposited on a surface incised by fluvial erosion of valleys generated during a relative sea level drop (SB 11A). Later, during sea level rise, sand deposition filled these valleys, (2) Lower and Middle Albian, including the fluvial to estuarine sandstones of the Caballos Fm. in Colombia, and the upper part of the Hollín Fm. in Ecuador. This sequence is bounded at the bottom by SB 11 and contains marine mudstones (base of Napo and Villeta Fms.). This configuration represents a transgressive sequence wherein the maximum flooding surface (MFS 10) is within the outer shelf distal and organic-rich facies, (3) Upper Albian to Lower Cenomanian. The base is the SB 9A surface at the base of the "T" sand. It contains inner shelf shale facies, and its maximum flooding surface is MFS 8A, in the distal outer shelf facies, (4) Cenomanian to Turonian. The base is the SB 9 surface at the base of the "lower U" sand. The maximum flooding surface is MFS 8, with organic-rich, distal shales, (5) Coniacian to Santonian. The base is the SB 7 surface, which occurs at the base of the "M2" sand in Ecuador and the "upper U" sand in Colombia. The maximum flooding surface is MFS 6. In the upper part, a minor Santonian sequence can be recognized as a subdivision of this sequence. Sequences 3 to 5 are dominated by marine shelf facies in the Napo and Villeta Fms. (6) The Upper Campanian, SB 5, at the bottom, represents an unconformity with a hiatus spanning the lower and Middle Campanian, suggesting regional uplift of the basin. This sequence is dominated by sandstone, including the "N" sand in Colombia, and "M1" sand in Ecuador. It only occurs in the eastern segment of the basin, probably due to continued uplift in the western segment.

In Ecuador, in the Sub-Andean Zone east of the Real Cordillera and west of the Oriente Basin, between the Sub-Andean and Cosanga Faults, the Margajitas Fm. (Fig. 10.19) measures more than 1 km in thickness. Pratt et al. (2005) describe the unit as a dark-gray, pyrite-bearing, noncalcareous, strongly cleaved, silty mudstone to mudstone with occasional interbeds up to 15 m thick of massive, well-sorted quartz arenite. The arenites are dark gray due to interstitial organic material and pyrite and contain about 1% distinctive blue quartz grains. Bioturbation, including horizontal traces on bases, is widespread. The Margajitas Fm. was considered Paleozoic in age by Tschopp (1948) and was included in the Upano unit, a meta-andesite-dominated Jurassic sequence, by Litherland et al. (1994). Notwithstanding, the Margajitas mudstones include conformable, non-tectonized sequences of cleaved limestone with typical Cretaceous bivalves and echinoid fauna, which measure up to

25 m thick. The Margajitas quartz arenites are petrographically identical to Hollín arenites and contain a similar proportion of blue quartz. Based on these considerations, Pratt et al. (2005) suggest a Cretaceous age for this unit. If the Margajitas Fm. is of Cretaceous age, the dark-gray pyritiferous mudstones would have been affected by high degrees of diagenesis and hence may represent organic-rich facies deposited in a distal part of the Oriente basin. Such mudstones could represent source rocks for petroleum found in the Oriente and Putumayo basins and may help explain the volume of petroleum discovered therein.

A Campanian to lower Maastrichtian stratigraphic hiatus has been described in the western part of the basin in both Colombia and Ecuador, which was generated by basin uplift and erosion in the foreland area, followed by development of a ravinement surface formed by flooding due to the subsequent sea level rise (Barragan et al. 2004). The Campanian to lower Maastrichtian hiatus is related to early phases of compressional tectonism in the sub-Andean zone (Baby et al. 2004).

During the Late Maastrichtian to Early Paleocene, shallow marine and fluvial sandstones were deposited (Tena Fm. in Ecuador and Rumiyaco Fm. in Colombia).

10.5.1.4 Southernmost Ecuador, Northern Peru, and Northwestern Brazil

In southern Ecuador and Peru, the following paleogeographical zones are recognized from east to west (Jaillard, 1993, Jaillard et al.,1990, 1995, 2000; Fig. 10.1):

1. The pre-Cambrian Guiana and Brazilian Shields.
2. The East Peruvian Trough, an eastern, westward sloping, moderately subsiding, marine shelf in along which sedimentation initiated during the Aptian. The eastern continuation constitutes the eastern basins of Ecuador (Oriente Basin) and Peru (Santiago, Huallaga, Marañón, and Ucayali Basins), containing marine and continental fill. This zone corresponds to the easternmost Cordillera Real-Eastern Cordillera (Ecuador and Peru, respectively), the sub-Andean Zone, and the eastern basins.
3. The Marañón High, an axial swell which constitutes a positive (lesser subsiding) horst block with a thin Cretaceous section, deposited during the Aptian. It is contained within the Eastern Cordillera of northern Peru (Marañón geanticline) and the southwestern Altiplano of Southern Peru.
4. The West Peruvian Trough, which formed a deep, rapidly subsiding rift basin, filled with a thick, dominantly marine section, during Mesozoic. It contains a complete section representing the whole of the Cretaceous. The Western Peruvian Trough became an incipient Western Cordillera during the Senonian. Northward its sedimentary fill thins and continues north into the southern part of the Cordillera Real and sub-Andean Zone of Ecuador. The West Peruvian Trough, the Marañon High, and the East Peruvian Trough constitute part of a back-arc basin complex.
5. The Coastal Trough, or intra-arc basin, is filled with very thick sections of latest Jurassic and mid-Cretaceous volcanic and volcanoclastic rocks which outcrop

along the present-day coast. In northwestern Peru and southwestern Ecuador, the Celica intra-arc basin is the northward equivalent of the coastal trough of Peru. In northwestern Peru, the Lancones and Talará Basins are fore-arc marginal basins, comparmentalized during the Albian and Campanian, respectively.

6. The Coastal Cordillera contains mainly Paleozoic and older rocks, because uplift and erosion during the Cenozoic removed most of the Mesozoic section. It outcrops in southern Peru. In northern Peru and southern Ecuador, the Amotape Massif is regarded as an allochthonous terrane accreted during the latest Jurassic (Mourier et al. 1988). During the Cretaceous, it was a morphological equivalent of the Coastal Cordillera in southern Peru.

Cretaceous Sedimentation in Northern Peru and Northwestern Brazil

In Peru, Cretaceous sedimentation spanning the latest Jurassic to Early Aptian is characterized by mainly deltaic siliciclastic deposits, followed by carbonate platform sedimentation up to the Campanian, and subsequently by deposition of continental red beds. Cretaceous sedimentation in northern Peru and northwestern Brazil is illustrated in Figs. 10.20, 10.21, 10.22, 10.23, 10.24, 10.25, 10.26, 10.27, 10.28, 10.29, 10.30, 10.31 and 10.32.

Latest Jurassic to Early Aptian Sedimentation

West Peruvian Trough Well-documented earliest Cretaceous rocks are restricted to the West Peruvian Trough (Dalmayrac et al. 1980, Figs. 10.20 and 10.21). To the north, lagoon deposits of probable Early Tithonian age (Simbal Fm.) are overlain, in sharp contact, by a Late Tithonian to Berriasian aggradational section of proximal turbidites, slope deposits, and basinal black shales (Chicama Gp; Jaillard and Sempere 1989), measuring up to 1500 m thick. In the West Peruvian Trough, subsequent deposition of the Oyón Fm., comprised of continental mudstones and sandstones containing some coal beds (Wilson 1963), is recorded. Rapid subsidence of the basin permitted deposition of various hundreds of meters of sediment. The abrupt vertical upward change, from deep marine sediments of the Chicama Gp. to continental facies of the Oyón Fm., is interpreted to represent a sequence boundary (SB 15) at the base of Oyón Fm. Although the Oyón Fm. is mostly continental in nature, it contains shallow marine interbeds with Berriasian ammonites. This marine interval contains a maximum flooding surface (MFS 14A). To the southwest, in Lima province, Berriasian deposits include thick andesite flows with limestone and shale interbeds (Rivera 1979; Macellari 1988).

During the Valanginian (Figs. 10.20 and 10.21), sedimentation was also restricted to the West Peruvian Trough, albeit covering a larger area than area during the Berriasian. Valanginian sedimentation extended to the north of the trough into the northern Cajamarca area, where quartz sandstones and minor interbeds of carbonaceous shales containing plant remnants and minor coal beds (Chimú Fm. Benavides 1956; Wilson 1963) record a fluvio-deltaic transitional environment (Scherrenberg et al. 2012). Over the Chimú Fm., brackish to shallow marine limestones and shales of the Santa Fm. (Benavides 1956) record Valanginian transgression, with a maximum flooding surface (MFS 14; Scherrenberg et al. 2012). Deeper water environments occurred to the southwest. This transgression was followed by deposition of regressive, varicolored nonmarine mudstones, siltstones, and quartz-sandstones of the Carhuáz Fm. during the Hauterivian-Barremian(?) (Figs. 10.20 and 10.22). A brackish interval within the Carhuáz Fm. probably contains a maximum flooding surface (MFS 12). In central Peru, Scherrenberg et al. (2012) report gypsum and oolitiic and bioclastic limestones, interpreted as shallow marine incursions (MFS 12). Overlying the Carhuáz Fm., the quartz sandstones of the Aptian(?) Farrat Fm. are recorded (Figs. 10.20 and 10.23; Wilson 1963). In central Peru, the Farrat Fm. contains plant remains, ripple marks, and other evidence of a fluvial-deltaic depositional environment (Scherrenberg et al. 2012). During deposition of Farrat Fm., progradation and maximum regression, were probably associated with a drop in sea level (SB 11 A). In conclusion, during the Berriasian to Early Aptian, several cycles of continental to shallow marine sedimentation are interpreted to be associated with the development of deltaic systems, controlled by relative tectono-eustatic changes.

Late Aptian to Campanian Sedimentation

During the Aptian, sedimentation continued in the West Peruvian Trough but also extended to the Marañón high and the Eastern Peruvian Trough (Figs. 10.20 and 10.23).

A Late Aptian to Early Albian transgression is documented over most of Peru (Figs. 10.20, 10.24, and 10.25). The basal transgressive unit in the West Peruvian Trough is the Inca Fm., which consists of interbedded brownish-gray oolitic, sandy, and ferruginous limestone, green fossiliferous shale, minor quartz-sandstone, and ferruginous siltstone (Benavides 1956). To the east, in the Marañón High, this unit is possibly replaced by the Goyllaarisquizga Fm. (Macellari 1988). To the south, the unit becomes less ferruginous and more calcareous, and it passes into the Pariahuaca Fm. (Wilson 1963). The base of the Inca Fm. and the Pariahuaca Fm. represents a transgressive surface. To the southwest in the Lima province, widespread volcanic activity is recorded at this time and extended into the Cenomanian in the western intra-arc basin (Casma Gp; Atherton et al. 1983).

Over the Marañón High, quartz sandstones of the Goyllarisquisga Fm. were deposited unconformably (SB 11A?) over metamorphic basement. It is possible that this formation is also coeval with older units of the West Peruvian Trough, but a reduced thickness accumulated over the less subsiding Marañón horst block.

In the northern part of the East Peruvian Trough, overlying the Inca Fm., Early to Middle to Albian open marine shelf fossiliferous calcareous shales and limestones of the Chulec Fm. were recorded by Benavides (1956). During the Middle Albian (Figs. 10.20, 10.24, and 10.25), maximum flooding of the West Peruvian

Trough resulted in the deposition of black bituminous shales interbedded with fetid limestones and cherts of the Pariatambo Fm. (Cobbing et al. 1981). This unit was deposited upon an outer marine shelf at a time of global anoxic conditions and contains an important maximum flooding surface (MFS 10).

In the northern part of the Marañón High, the lateral equivalents of the Chulec and Pariatambo Fms. are represented by the Crisnejas Fm., consisting of calcareous shale and sandstone with limestone interbeds (Benavides 1956). This unit probably represents a more proximal facies of the marine shelf.

In the West Peruvian Trough, during the Late Albian to Cenomanian (Figs. 10.20, 10.25, and 10.26), a normal oxygenated environment was re-established, and regressive massive limestones (Yumagual Fm. lower part of Pulluicana Gp.), followed by wavy-bedded, nodular argillaceous limestone with interbedded sandstone and shale (Mujarrun Fm. upper part of Pulluicana Gp.), were deposited upon a shallow marine shelf (Benavides, 1956). During the Cenomanian, the margins of the trough emerged (Cobbing et al. 1981), possibly due to a relative drop in sea level. The Mujarrun Fm. is a shallowing upward carbonate shelf (Jaillard and Sempere 1989); near its top there is a sequence boundary (SB 9; Macellari 1988).

In the East Peruvian Trough (Figs. 10.20, 10.24, and 10.25), sedimentation initiated on a basal unconformity (SB 11A), with cross-bedded white quartz sandstones, micaceous mudstones, and siltstones comprising the Aptian-Albian Cushabatay Fm. (Kummel, 1984). The lower part of the unit was deposited in fluvial environments, but the upper part represents deltaic or coastal barrier sands (Huerta-Kohler 1982). The Esperanza Fm. overlies the Cushabatay Fm. It is comprised of black fossiliferous shale, with occasionally glauconitic sandstone and limestone interbeds. The shales contain ostracods, foraminifera, bivalves, and gastropods, indicative of a shallow marine environment (Soto 1979). The Albian Esperanza Fm. contains a maximum flooding surface (MFS 10). To the east, in the Marañón Basin, the lateral equivalent of the Esperanza Fm. is recorded in the sandstones and shales of the Raya Fm., deposited in a more proximal shallow marine environment. Renewed regression and progradation of a delta system is recorded by coarse-grained (conglomeratic), massive to cross-bedded quartz sandstones containing minor black shale interbeds and plant remains, comprising the Agua Caliente Fm. (Soto 1979). It may be possible to interpret a sequence boundary at the top of the unit (SB 9A?).

During the Late Cenomanian and Early Turonian (Figs. 10.20, 10.26, and 10.27), transgression is recorded by the deposition of brown shales and marls interbedded with limestones (Quillquiñan Gp; Benavides 1956). This unit was deposited in a neritic environment and recorded a deepening-upward trend between the shallower deposits of the Pulluicana Gp. and the deeper sediments of the overlying Cajamarca Fm. The Cajamarca Fm. consists of fine-grained limestones, well-stratified marls, and very thin shales deposited upon an outer marine shelf during the Middle to Late Turonian (Benavides 1956). Deepening of the basin is related to a relative sea level rise (MFS 8). Over the Marańon High, the Pulluicana and Quillquiñan Gps. were replaced by the Jumasha Fm. This unit is composed of bioclastic and pelletal limestone and dolomite, with interbeds of very fine-grained limestone and siltstone

(Wilson, 1963), deposited in a shallow marine environment. In central Peru Scherrenberg et al. (2012) interpreted the depositional environment of the Jumasha Fm. in terms of a shallow, open marine epicontinental carbonate platform, with associated bars of oolite sand, distinct layers of ammonites, and moderate to strong bioturbation, containing intercalations of hydrocarbon source rocks. They interpreted these features to indicate eustatic sea levels ranging to maximum sea level stands (MFS 8). Ammonite assemblages indicate Middle-Late Albian to Late Turonian age (Scherrenberg et al. 2012).

In the West Peruvian Trough, during the Coniacian to Santonian (Figs. 10.20, 10.28, and 10.29), calcareous shale and siltstone with interbeds of nodular limestone of the Celedín Fm. were deposited in a shallow marine environment, shallower than that of the Cajamarca Fm. (Benavides 1956). In central Peru, the unit consists of limestone, marl, and gypsum, interpreted locally as a sabkha depositional environment, possibly representing basin shallowing due to a drop in sea level (SB 7). Subsequently, slightly deeper water environments to the west were possibly related to a rise in sea level (MFS 6; *c.f.* Scherrenberg et al. 2012).

In the East Peruvian Trough (Figs. 10.20, 10.25, 10.26, 10.27, 10.28 and 10.29), above the sequence boundary at the top of the Agua Caliente Fm., a new transgression was recorded by deposition of dark-gray marine shales with interbeds of sandstone, siltstone, and limestone (Chonta Fm.). This unit varies from a thin (100 m), predominantly sandy proximal in the southeast to a thick (1600 m), more distal, predominantly shale and limestone unit to the northwest. It is interpreted as a deltaic unit in its proximal area (Soto 1979). The lower part of the Chonta Fm. is basal sandstone followed by a shale interval, while the middle section starts with sandstone followed by an organic-rich micritic limestone. The upper part is gray shale with micritic limestone interbeds. The lower dark-gray shales possibly records a sea level rise (MFS 8A), while the sandstone at the base of the middle part may represent a proximal influx of sand during a drop in sea (SB 9). According to Jaillard and Sempere (1989), the organic-rich micritic limestone is Early Turonian in age, interpreted to record outer shelf deposition during times of maximum sea level and global anoxic conditions (MFS 8). The upper part of the unit was deposited on a shallow marine shelf. The Chonta Fm. contains micro- and macrofauna indicative of an Albian to Santonian age (Knechtel et al. 1947; Huerta-Kohler 1982).

Late Campanian to Paleocene Sedimentation

During the Campanian (Figs. 10.20, 10.30, 10.31 and 10.32), in the West Peruvian Trough and Marañón High, the appearance of widespread red beds marks the transition to completely continental sedimentation resulting from uplift of detrital source areas marking initiation of the Andean Orogeny. By the end of the Santonian, the western part of the West Peruvian Trough had been uplifted and provided the source for continental red beds of the Chota Fm. (northern Peru) and the Casapalca Fm. (central Peru; Benavides 1956). In central Peru, the upper part of this continental sequence contains sporadic floodplain and abundant alluvial fan deposits, including thick fluvial intervals demarcating braided channels. The Casapalca Fm. unconformably overlies the Celedín Fm. (SB 5). It is only preserved in the cores of synclines adjacent to thrust faults. The map pattern indicates foreland depocenters located east of the parallel fault traces (Scherrenberg et al. 2012).

In the East Peruvian Trough (Figs. 10.20, 10.30, 10.31 and 10.32), the Vivian Fm. was deposited during Campanian. It is the most important petroleum reservoir of the Marañón Basin. The unit consists of cross-bedded sandstone with minor interbeds of black shale containing plant remains. The lower section represents an extensive braided fluvial channel system (Del Solar 1982). Vertical change in depositional environment from a marine shelf in the underlying Chonta Fm. to the fluvial system of the Vivian Fm. was the result of a relative sea level drop. The base of the unit represents a sequence boundary (SB 5). The upper part of the unit represents coastal barriers (Del Solar 1982), overlain by Maastrichtian to Early Paleocene (?) black shales, claystone, and siltstones of the Cachiyacu Fm., which contains brackish to marine fauna (Kohl and Blissenchach 1962). The Cachiyacu Fm. represents the next transgression resulting from a relative sea level rise (MFS 2A). It is overlain by continental red beds of the Huchpayacu Fm., representing the first clastic input resulting from Andean uplift (Huerta-Kohler 1982).

In the western part of the Solimoes Basin of northwestern Brazil, Triassic and Jurassic red beds are observed (IHS 2008a, b). The Alter do Chao Fm. crops out in the basin and overlies the red bed deposits. Alter do Chao Fm. consists of cross-bedded sandstone, conglomerate, and mudstone, deposited in a meandering fluvial system flowing to the SW as indicated by paleocurrent data (Mendes et al. 2012; Franzinelli and Igreja 2011). The formation contains few fossils. Some authors (Price 1960; Daemon 1975; Dino et al. 1999; Mendes et al. 2012) consider it Late Cretaceous, but Caputo (2009, 2011a, b) considers it Cenozoic in age. A Late Cretaceous age for the formation is more consistent than a Cenozoic age, based on the fact that the Alter do Chao SW flowing fluvial system drained toward during low elevation basins during Cretaceous, which were completely inverted and uplifted during Cenozoic to form the Andes mountains, which began to supply detrital sediments towards the east into the Amazonas basin. In the present work, I assume an uppermost Cretaceous to Paleocene age to the Alter do Chao Fm. (Figs. 10.20, 10.31, and 10.32).

Cretaceous Sedimentation in the Fore-Arc Region of Southern Ecuador and Northwestern Peru

In southern Ecuador and northwestern Peru, the fore-arc Talara and Lancones Basins and the intra-arc Celica Basin contain an incomplete Cretaceous sedimentary and volcanic record, due to uplift during some Cretaceous time intervals (Fig. 10.20). In all of these basins, Cretaceous rocks rest unconformably upon Paleozoic Amotape Terrane basement, and pre-Albian stratigraphy is not recorded. In the intra-arc Celica Basin, volcanic rocks of the Albian Celica Fm. inter-finger with turbidites and deep marine shales of the Alamor Fm. These sediments were deposited up to Early Cenomanian. In the Talara Basin, an initial transgression during Albian times, with deposition of basal sandstone followed by shallow marine limestone and shale of the Pananga Fm., was followed by deposition of organic-rich marine shales of the Muerto Fm., which is the petroleum source rock of the Talara Basin. This unit was likely deposited during a time of relative high sea level (MFS 10), under global anoxic conditions.

During the Late Cenomanian to Santonian (Fig. 10.20), Albian to Lower Cenomanian rocks were deformed and possibly partly eroded during uplift, which corresponds to a major sequence boundary resulting from lumping other sequence boundaries (SB 5 and 7) in the Lancones and Celica Basins. In the Talara Basin and western part of the Lancones Basin, this Late Cenomanian to Santonian hiatus is also recorded but interrupted during Late Turonian-Early Coniacian times, when the Copa-Sombrero Fm. was deposited. This formation consists of deep marine turbidites and shales. According to Jaillard et al. (2005), the Copa-Sombrero Fm. represents a transgression resulting from a relative sea level rise (MFS 8). The event is also recognized in the Peruvian back-arc basins and correlatable with the lower part of Celendín Fm. in the Rentema area, the upper part of Chonta Fm. in the Marañón Basin, and the upper part of the Napo Fm. in the Oriente Basin of Ecuador. The maximum flooding surface in southern Ecuador and northern Peru: Late Turonian-Early Coniacian in age (MFS 8) is slightly different from Colombia and Venezuela. This observation is attributed to tectonic activity in southern Ecuador and Peru which has yet to be recognized in Colombia and Venezuela. In the Talara Basin and the western part of Lancones Basin, the Copa-Sombrero Fm. is bound by sequence boundaries (SB 9 and SB 7, respectively) at both the base and the top.

During the Campanian and Maastrichtian (Fig. 10.20), sedimentation in the Talara, Lancones, and Celica Basins was controlled by compartmentalized basin segments, separated by local highs. Rapid lateral changes in facies and thickness suggest sedimentation coeval with deformation and uplift, which provided detrital sources. In all the stratigraphic columns described by Jaillard et al. (2005), sedimentation apparently initiated upon unconformities, at different times in different areas, with sandstones followed by marine shale deposits.

During the Early Campanian (Fig. 10.20) in the Rio Playas area of the Celica basin, the El Naranjo Fm. records a transgression, which reached maximum flooding (MFS 4 and 4A). In the Lancones Basin, sedimentation started during the Late Campanian, with deposition of a sandstone and shale unit (Mesa Fm.). Marine transgression reached maximum flooding (MFS 4) during deposition of a middle marine limestone interval in the middle part of the Mesa Fm. In the same basin, in the La Tortuga area, Late Campanian deposits of alluvial fan breccias suggest sedimentation near an uplifted detrital source. During the Campanian in the Talara Basin, a marine transgression was recorded by the Sandino Fm. This transgression reached maximum flooding (MFS 10)when the anoxic marine shales of the Muerto Fm. were deposited.

During the Maastrichtian, in the northern Peru fore-arc basins, several marine shale units were deposited (Fig. 10.20), which according to Jaillard et al. (2005), represent marine transgressions that reached maximum flooding events during the

Early Maastrichtian (MFS 2A) and Late Maastrichtian (MFS 2). Interlayered with these shale units are coarse detrital fluvial or alluvial fan deposits and littoral sandstones; detrital fluvial or alluvial fan deposits include the Maastrichtian Casanga Fm. in the Rio Playas area of the Celica Basin, the Maastrichtian upper part of the La Tortuga Fm., in the La Tortuga area of the Lancones Basin, and the Petacas Fm. in the Talara Basin; littoral sandstones include the Maastrichtian Cenizo Fm. in the Tortuga area of the Lancones Basin and within the Cazaderos Fm. in the western part of Lancones Basin. Some of these coarse detrital units are associated with unconformities related to tectonic uplift and possible sea level drops.

10.5.2 Accreted Oceanic Terranes of the Pacific Domain

The oceanic basement of the Colombian Western Cordillera and the Cauca-Patía Valley includes the Calima Terrane (sensu Toussaint and Restrepo 1989, 1994 and Toussaint 1995a, b) or Cañas Gordas, Dagua-Piñón, Sinú and San Jacinto Terranes (sensu Cediel et al. 2003b, 2011), and the Baudó coastal range (Cuna Terrane sensu Toussaint and Restrepo 1989, 1994 and Toussaint 1995a, b, or Baudó Terrane sensu Cediel et al. 2003b, 2011). The Western Cordillera of Ecuador has been referred to as the Dagua-Piñón Terrane (Cediel et al. 2003b, 2011). The mafic to ultramafic igneous components of these composite terrane assemblages have been interpreted to have formed above an oceanic hotspot or mantle plume (Kerr et al. 1997a, b; Sinton et al. 1998). Recent studies suggest the Galapagos hotspot represents the point of origin for this magmatic activity (Nerlich et al. 2014). According to prevailing tectonic models, flair-up of the Galapagos hotspot during the mid-Cretaceous led to extrusion of large volumes of oceanic plateau lavas, which were emplaced within/upon an oceanic substrate provided by N-MORB basalts +/− deep ocean sediments comprising the Farallon Plate.

The composite assemblage of Farallon crust + mantle plume-derived volcanics has been referred to as the Caribbean-Colombian Oceanic Province (CCOP) or Caribbean large igneous province (CLIP; see summary and discussion in Nerlich et al. (2014) and Leal-Mejía et al. 2018). It is generally accepted that the ultramafic and mafic basement rocks of the Calima and Cuna Terranes (after Toussaint and Restrepo, 1989, 1994, ; Toussaint 1995a, b) or Cańas Gordas, Dagua-Piñón, Baudó, Sinú, and San Jacinto Terranes (after Cediel et al. 2003b, 2011), exposed in western Colombia and Ecuador, form part of the CCOP/CLIP assemblage. Several authors have provided lithochemical, radiometric, and biostratigraphic evidence to show that the plateau rocks exposed in the Caribbean, Colombia, and Ecuador (and elsewhere) are geochemically and temporally equivalent and range in age from ca. 100 to 88 Ma with a lesser pulse between 76 and 72 Ma (e.g., Kerr et al. 1997a, b, 1998, 1999, 2003, 2004); Sinton 1997; Sinton et al. 1998; Spikings et al., 2001; Luzieux et al. 2006; Vallejo et al. 2009; Nerlich et al. 2014).

Thus, several oceanic terranes containing mafic/ultramafic assemblages have been accreted to the continental margin north of Peru. Tectonic models presented by numerous authors (*e.g.*, Kerr et al. 1997a, b, 1998, 1999, 2002a, b, 2003, 2004; Kerr and Tarney, 2005; Pindell 1990, 1993; Cediel et al. 2003b; Pindell and Kennan 2009, among others) depict the accretion of fragments of the CCOP/CLIP assemblage (Caribbean Plate) to the continental margin, during its northward and eastward migration from the Galapagos hotspot toward its present position, beginning in the mid-Cretaceous. Interstratified with, and on top of, the CCOP/CLIP volcanic rocks, deep marine sediments also accumulated. These volcanic and sedimentary rocks are also shown in the stratigraphic sections presented in Figs. 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18 and 10.19. However, because these rocks are highly deformed and locally metamorphosed, it is difficult to distinguish and separate conventional stratigraphic units or sequences. Except for local detailed studies (mainly in Ecuador), only generic or regional lithostratigraphic assemblages have been defined, and the level of stratigraphic knowledge of these rocks is much lower than the sedimentary rocks deposited upon/within the continental margin. No attempt to identify or correlate stratigraphic sequences in this domain has been made herein. In northern Venezuela, Caribbean oceanic terranes accreted to the continental margin have also been identified (*e.g.*, Caribbean Mountain Terrane of Cediel et al. 2003b). This accretion, however, occurred later during the Cenozoic and is not included in this paper.

10.6 Discussion and Conclusions

The present work attempts to decipher, integrate, and graphically depict the Cretaceous sedimentary record, basin development, and the dynamic interaction of paleo-facies, within the context of global eustacy and the geological and tectonic history of northwestern South America during the Late Mesozoic. One of the underpinning factors behind the complex, compartmentalized basin evolution in the region is the observation that, from the latest Jurassic to Paleocene, tectonic models record kinematic interplay involving no less than four distinct tectonic plates, including (1) South America, (2) Pacific/Farallon, (3) Proto-Caribbean, and (4) Caribbean (CCOP/CLIP), resulting in varied configurations of a triple-junction, and generating numerous tectono-sedimentary environments along extensional-transtensional, compressive-transpressive, and transcurrent margins, in marine, continental, and transitional settings. Due to this complex tectonic configuration, penecontemporaneous, active vs. passive margin and marine vs. continental sedimentation is recorded in separate basin-filling events during the Cretaceous, over the region spanning northern Peru through Ecuador, Colombia, and Venezuela.

Notwithstanding, Cenozoic reactivation of Mesozoic structure and tectonic inversion of many of the Late Mesozoic basins during Paleogene and Neogene orogenesis have provided abundant natural outcrop for the field-based study of sedimentation and paleo-facies development at the regional level, throughout the Northern Andes. This information is supported by abundant borehole and geophysical data generated during over a half-century of fossil fuel exploration and development in the region, a process which has delineated world-class petroleum and coal resources, and created a detailed and functional database for ongoing exploration and study.

The exercise of stratigraphic correlation is a preliminary step in any attempt to build paleogeographic maps. In northwestern South America, there are many names for lithostratigraphic units, and in "too many" cases, the same unit has been given different local names, or the same name has been applied to different or heterochronous stratigraphical units. As a result, and until such inconsistencies in stratigraphic nomenclature are sorted out, any attempt to build truly accurate paleogeographic maps is rendered next to impossible. Regardless, in such a case, the well-founded application of the concepts and methods of sequence stratigraphy, as applied herein, provides an essential tool for regional and local stratigraphic correlation and paleofacies interpretation.

During Jurassic rifting throughout northwestern South America, a passive continental margin developed along the northern and northwestern edge of the continental block (Guiana Shield, Venezuela), while active subduction with a continuous and well-developed magmatic arc and craton-ward back-arc extensional basins developed along the western margin of the continent (Colombia, Ecuador, and Peru). The localization of many of these basins was controlled by normal faulting related to Jurassic and earlier rifting. Continental clastic sedimentation dominated in most of these rapidly subsiding basins, while in those undergoing extreme subsidence (*e.g.*, the West Peruvian Trough, the northern Venezuela rift basin, the Cundinamarca sub-basin), marine sediments also accumulated during the Late Jurassic.

Cretaceous sedimentary rocks, including locally, uppermost Jurassic and Paleocene deposits, form a mega-sequence bounded by regional unconformities that are at least locally angular. On a broad scale, Cretaceous sedimentary rocks represent a major transgressive-regressive cycle with the maximum flooding surface close to the Cenomanian-Turonian boundary (MFS 8), corresponding to the maximum Cretaceous, and even Mesozoic, eustatic level. Superimposed on this large-scale trend, several smaller transgressive-regressive cycles are present, suggesting an oscillating relative tectono-eustatic level. These minor cycles correspond to the several stratigraphic sequences defined herein. I have attempted to correlate these stratigraphic sequences throughout the whole of the Northern Andean study area. Most of these stratigraphic sequences have been defined by earlier workers at specific locations, but not over the region as a whole. Within the Cretaceous, I propose 10 stratigraphic sequences and correlate 21 surfaces, including sequence boundaries (SB) and maximum flooding surfaces (MFS), throughout the studied area, based upon the critical assumption that they represent time surfaces. Most of the proposed surfaces appear to be correct; however, others remain speculative and in need of better biostratigraphic data to test their validity. In this sense, I have not attempted to use new biostratigraphic data for this purpose but have integrated ages proposed in the cited literature. However, it remains clear that, in places where sedimentation occurred coeval with structural deformation and uplift, we cannot expect to correlate stratigraphic sequences over distances greater than the wavelength of the structures being generated at that time. For example, in the area of the northern

Peruvian Andes, the end of the Cretaceous (Campanian-Maastrichtian), it has been observed that syntectonic sedimentation occurred only in synclinal troughs, while structural uplift at the crest of related anticlines reduced local subsidence or even generated exhumation and erosion. Thus, correlation of stratigraphic sequences over great distances in this region is inhibited.

In theory, eustacy and tectonics are responsible for relative tectono-eustatic changes of relative sea level or base level changes. Therefore, differential vertical movements of the earth's surface generated by active tectonics will generate differential vertical changes of relative sea level or base level, controlling the development of stratigraphic sequences. In addition, at a regional scale, the wavelength of structures generated by tectonism reflects the thermal age of the lithosphere. In general, at the scale of northwestern South America, during the Cretaceous, the wavelength of structural folding seems to decrease toward the border of the continent. As a conclusion then, we may say that the validity of the proposed stratigraphic correlations may only be applied to distances equal to or shorter than the wavelength of syn-tectonic structures, which seem to decrease toward the continent margin.

Cretaceous sedimentary history can be summarized in four episodes: (1) Berriasian to Aptian, (2) Aptian to Cenomanian, (3) Cenomanian to Santonian, and (4) Campanian to Early Paleocene.

During the Berriasian to Early (?) Aptian, sedimentation was restricted to rapidly subsiding extensional basins inherited from Jurassic rifts. Because of differential tectonic subsidence between graben and horst blocks, it is difficult to recognize the eustatic signal and correlate stratigraphic sequences. Notwithstanding, great thicknesses of sediment accumulated. Sedimentation initiated in continental environments (alluvial fan and fluvial), followed by marine transgression. An exception to this occurred in the Cundinamarca sub-basin presently exposed in the Colombian Eastern Cordillera, where Berriasian sedimentation occurred in marine environments. Important lateral changes of facies and thickness, due to differential tectonic subsidence of tectonic blocks, are recorded. In Venezuela and northeastern Colombia, shallow shelf carbonate platforms developed. During times of maximum marine flooding (MFS) in some stratigraphic sequences, carbonates were replaced by shales deposited upon inner marine shelves. In Central Colombia, mud-dominated sedimentation occurred. A great thickness of inner to outer marine shales accumulated, initially with some turbidites, probably resulting from tectonically induced sea bottom instability. In Peru, a great thickness of alternating, littoral deltaic to shallow marine sandstones and shales accumulated. The marine shales were preferentially deposited during times of maximum marine flooding.

During the Late (?) Aptian to Cenomanian, regional thermal subsidence (following earlier active rifting) resulted in a regional increase in the area of marine sedimentation, and previously isolated basins coalesced into a major regional basin extending along the margin of the continent from Venezuela to Peru. During this time, marine incursion into new areas such as the Barinas-Apure basin in Venezuela, the Llanos, Upper Magdalena Valley, Putumayo basins in Colombia, the Oriente basin in Ecuador, and the Marañón and East Peruvian Trough basins in Peru is well documented. Regional thermal subsidence permitted the sedimentary record to become more sensitive to eustatic changes, and therefore, it is easier to recognize the eustatic signal and correlate stratigraphic sequences at the regional level. In Venezuela and northwestern Colombia, carbonate-dominated platforms were replaced by marine shale sedimentation, interrupted in western Venezuela by a progradation of deltaic sandstones (Aguardiente Fm.). In Colombia, mud-dominated sedimentation prevailed in the marine shelf, also interrupted by progradation of deltaic sands (Aguardiente and Une Fms.). In Peru, earlier siliciclastic deltaic sedimentation restricted to the West Peruvian Trough was replaced by regional carbonate platform sedimentation upon a shallow shelf. Regionally, from Venezuela to Peru, sea level rise coinciding with an oceanic anoxic event during the Middle Albian favored accumulation of petroleum source rocks.

During the latest Cenomanian to Santonian, regional subsidence continued, and, due to a global rise in sea level, craton-ward marine incursion into previously unaffected areas is recorded. During the latest Cenomanian to Early Turonian, the sea reached its maximum Cretaceous level, representing the sea level high for the entire Phanerozoic. Sedimentation was controlled by eustatic changes. Coincident with maximum Cretaceous flooding, oceanic anoxic events favored accumulation of organic matter at the sea bottom, resulting in deposition of the best petroleum source rocks in northern South America (La Luna Fm. and equivalents). From Venezuela to Ecuador, pelagic shale and pelagic fine-grained limestone sedimentation prevailed. During this time interval, but specifically during the Coniacian-Santonian in Venezuela and Colombia, marine upwelling conditions favored development of siliceous plankton and chert deposition. In Peru, shallow marine carbonate shelves were replaced by mud-dominated marine shelves. Due to the somewhat earlier initiation of tectonic activity (deformation, uplift) in Peru when compared to the rest of the Northern Andes from Venezuela to Ecuador, some sequence boundaries and maximum flooding surfaces of the stratigraphic sequences recognized in Peru are slightly temporally shifted, with respect to the corresponding stratigraphic equivalents in the northern Andes.

Beginning in the Santonian, and into the Campanian to Paleocene, marine regression, a general shallowing of sedimentary environments, and penecontemporaneous compressional deformation are recorded throughout northwestern South America. As noted, these processes initiated somewhat earlier in Peru. In Venezuela, at the end of the Cretaceous (Maastrichtian) and Paleocene, passive margin conditions shifted to an active margin, with obduction of oceanic terranes of Caribbean affinity, and to the west, uplift in the Sierra Nevada de Santa Marta. Along the Pacific margin of Colombia-Ecuador, during the Campanian and Maastrichtian, the collision and accretion of fragments of the Caribbean Plate (CCOP/CLIP assemblage) to the continental margin generated uplift in the Central Cordillera and its northern prolongation into the Lower Magdalena Valley (Plato-San Jorge area), the Cordillera Real, and the sub-Andean zone, including the western part of the Oriente basin. Regional Late Maastrichtian and Paleocene regression led to a transition from marine to dominantly continental environments extending from Venezuela to Ecuador. In Peru, Andean uplift beginning on the Campanian provided a source of detrital sediments, accumulated in active synforms as continental and alluvial fan deposits. By the

Paleocene, continental sedimentation dominated throughout the Northern Andean region, and basins began to compartmentalize due to active regional transpressive-transtensional deformation within the context of the South American-Pacific-Caribbean plate triple junction.

In southernmost Ecuador and northwestern Peru, sedimentation within fore-arc basins, active since the Albian, is characterized by strong lateral changes of facies and thickness, marked by periods of uplift and localized sedimentation during the entire Late Cretaceous. Enhanced tectonic activity during this time in Peru resulted in punctual time shifts with respect to the sequence boundaries and maximum flooding surfaces recognized in Venezuela, Colombia, and Ecuador.

I have herein compiled a Cretaceous sedimentary and tectonic history for the northwestern corner of South America, attempting to define and correlate a framework for several stratigraphic sequences across the entire Northern Andean region, as permitted by their sequence boundaries and maximum flooding surfaces. This methodology has proven useful in the correlation of the Cretaceous sedimentary record of basins located upon/within the continental margin.

However, I have not attempted to define and correlate similar sequences in the Cretaceous record which was deposited over the oceanic crust, and associated with accreted terranes incorporated into the Northern Andean mosaic to the north of Peru, because these units are highly deformed, and much less precisely known. Regardless, some of the proposed sequence boundaries discussed herein are certainly the result of active tectonism in the region, and many of these sequences are related to tectonic events in Peru, as proposed by several workers (*e.g.*, Jaillard, 1993; Jaillard et al., 1990, 1995, 2000). In Ecuador, Colombia, and Venezuela, Cretaceous tectonic activity affecting the stratigraphic record deposited on the continent seems to have been less intense than that recorded in Peru.

Notwithstanding, some unconformities can be correlated in time and location with known or proposed tectonic events. An example of this is the unconformity at the beginning of the Aptian, recognized in southern and central Colombia. This unconformity correlates in time and location with the closure of the Quebradagrande oceanic margin basin and the accretion of the Quebradagrande arc to southern Colombia and Ecuador. Although it is likely that this Lower Aptian unconformity is related to some degree of structural deformation, the driving mechanisms behind the unconformity remain uncertain. An alternative explanation for this unconformity may involve changes in the stress regime due to the chage from active syn-rift to thermal flexural subsidence, recognized in other parts of the world as a breakup unconformity.

In several seismic lines in south central Colombia (Upper Magdalena Valley and southern part of the Eastern Cordillera), Jaimes and De Freitas (2006) recognized an unconformity associated to some degree of structural deformation in rocks of middle Cretaceous age. It is possible that this unconformity corresponds to the aforementioned Lower Aptian unconformity, associated with the Quebradagrande closure event. Based upon biostratigraphic data from petroleum wells, however, these authors proposed an Albian-Cenomanian age for the unconformity and correlated it with changes in subduction/deformation along the Colombian and Peruvian segments of the Andes. Jaimes and De Freitas (2006) suggest that such changes may be related to the opening of the South Atlantic Ocean at equatorial latitudes.

Another example of a tectonic-related unconformity has been documented, based upon biostratigraphic and seismic data in western Venezuela, by Cooney and Lorente (2009). These authors demonstrated the absence of several Campanian foraminiferal biozones and illustrate unconformable relationships in some seismic lines, mainly within the Maracaibo Basin. When horizontalized to a seismic reflector near the top of the Cretaceous, the seismic lines reveal compressional structures developed below the unconformity. This Upper Campanian unconformity correlates temporally and spatially with the the initial collision of the Antilles magmatic arc with northern Colombia. Following collision, during the Paleocene, continental sedimentation became dominant in most of the basins of Colombia and Venezuela, as they became progressively compartmentalized during active Northern Andean deformation and uplift.

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