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# *Structural Evolution of the Sinu-Lower Magdalena Area (Northern Colombia)*

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## ABSTRACT

The Lower Magdalena Valley of northern Colombia can be subdivided into two very distinct structural provinces separated by the Romeral fault system. The Sinu–San Jacinto Province, located west of the Romeral fault, is a Paleocene to Oligocene accretionary wedge floored by Cretaceous oceanic crust. The Plato–San Jorge Basin is a back-arc basin filled by Oligocene to Pliocene sediments. The basin is structured into several northwest-southeast-trending structural highs and lows controlled by transtensional and transpressional faults that evolved through geologic time. The basement of the Plato–San Jorge Basin is a Paleozoic metamorphosed oceanic crust. Paleocene-Eocene siliciclastic series including shale, sandstone, and mostly conglomerate and breccia unconformably overlie the basement close to the Romeral fault. A widespread deltaic sandy section referred to as Cienaga de Oro Formation overlies this section. The Cienaga de Oro sandstone (locally, "Cicuco Limestone") represents the main reservoir of the area and is overlain by deep-water shale with interbedded sandstone (i.e., Porquero Formation).

The Sinu–San Jacinto area is the onshore part of the northern Colombia accretionary prism, related to the subduction of the Caribbean Plate underneath the South American Plate. The onshore part of the wedge is dominated by west-vergent imbricates involving Cretaceous oceanic crust (Cretaceous ophiolitic series) and Cretaceous to Oligocene sediments. The Cretaceous sedimentary section (i.e., Cansona Formation) consists of organic-rich shale, limestone, and chert. The Paleocene-Eocene section consists of deep-water shale and turbiditic sandstone, except in the Tolú area where it is made up of shallow-water sandstone, conglomerate, and reefal limestone (La Risa Reef). The Miocene section is composed mostly of flysch-type deposits (i.e., Floresanto Flysch), which can be reservoir rock.

Seismic and geologic data suggest that the Romeral fault is a major strike-slip fault that offsets the obduction suture.

## REGIONAL SETTING

The Sinu–Lower Magdalena area is located along the intersection between the Central America (Panama) and southern Caribbean accretionary wedges (Figure 1). The offshore northern Colombia basin is floored by a 4- to 8-km-thick crust of the Caribbean Oceanic Plateau (Bowland, 1993; Van der Hilst and

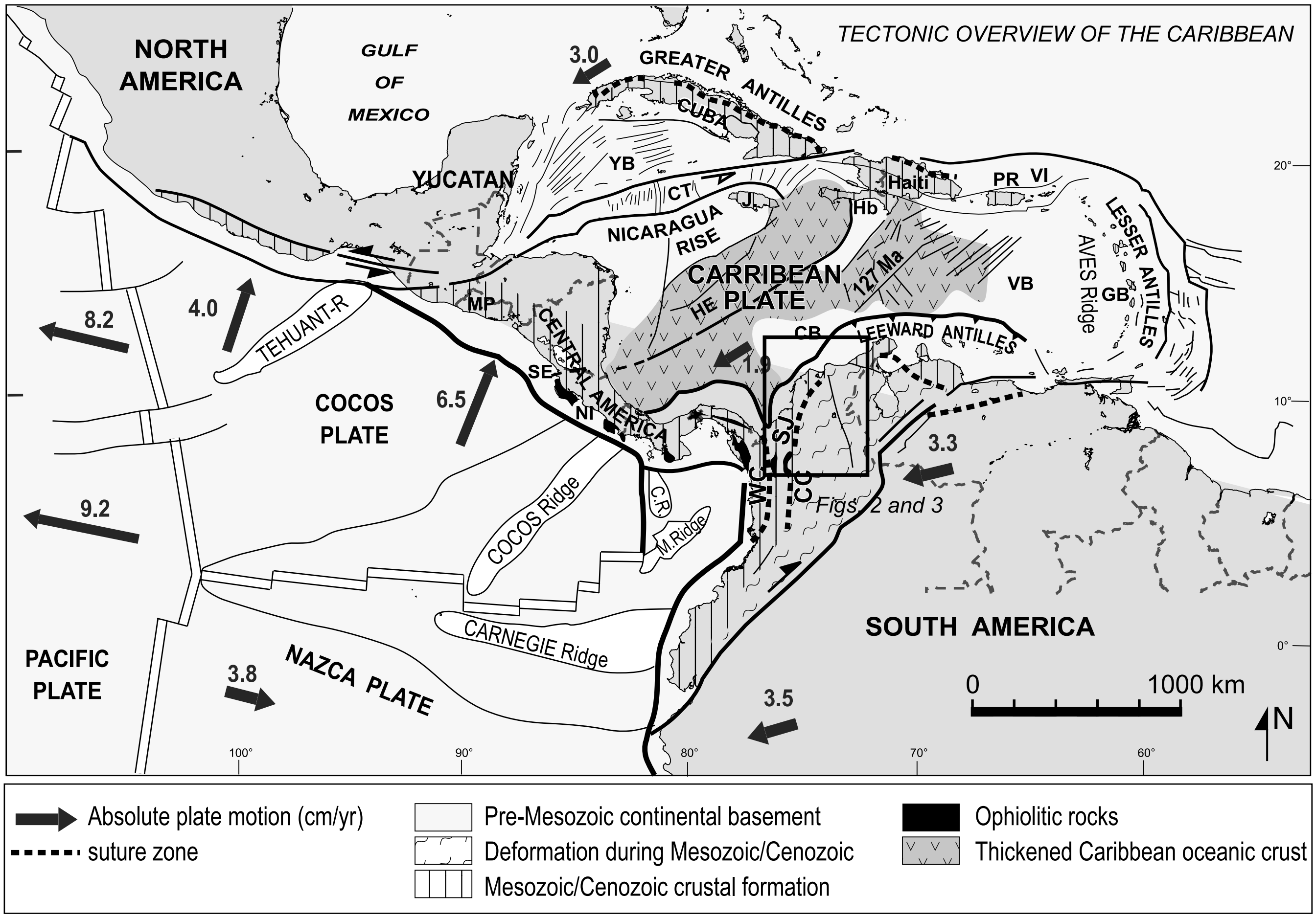


**Figure 1.** **Tectonic sketch map of the Caribbean region, location of the study area. Modified from Case et al., 1990; Pindell and Barrett, 1990; Muehlberger, 1992; Mauffret and Leroy, 1997; Meschede and Frisch, 1998. CB = Colombia Basin, CC = Central Colombia, CT = Cayman Trough, GB = Grenada Basin, HE = Hess Escarpment, SJ = San Jacinto, VB = Venezuela Basin, YB = Yucatán Basin, WC = Western Colombia.**

Mann, 1994) that consists of complex basalt flows and sills with interbedded sedimentary rocks (Driscoll and Diebold, 1999). The origin and age of the Caribbean Oceanic Plateau crust is still debatable. The radiometric age of offshore northern Colombia flood basalts (90–75 Ma according to Mauffret and Leroy, 1997, or 91–88 Ma according to Sinton et al., 1998) is used to date the age of the Oceanic Plateau. According to some authors, the Caribbean Oceanic Plateau crust originated near the Galapagos Hot Spot in the Pacific (Mauffret and Leroy, 1997) and for others has an Intra Plate *in situ* origin in Central America (Meschede and Frisch, 1998). The oceanic crust of the northern Colombian basin is thought to be of pre-Coniacian age (Case et al., 1990). The present rate of convergence between the Caribbean and South American Plates is about 1.3 ± 0.3 cm/yr (Van der Hilst and Mann, 1994) or 1.5 cm/yr (Kellogg and Vega, 1995). There are large discrepancies in the present motion between the subducting Nazca and the South American Plates; 6.8 ± 0.2 cm/yr according to Van der Hilst and Mann (1994) and 3.5 cm/yr according to Kellogg and Vega (1995).

Seismicity suggests an eastward-dipping subducting slab defined from 50- to 250-km deep that stops around the Santa Marta–Bucaramanga left-lateral strike-slip fault. A cluster of deep-focus earthquakes is associated with this fault. Earthquake first motions reflect the change from subduction below the Plato–San Jorge Basin to strike-slip along the Santa Marta–Bucaramanga fault (Kellogg and Bonini, 1982; Malavé and Suarez, 1995 ). Seismic tomography allows differentiation of two different segments of the Caribbean subducting slab. The southern Bucaramanga slab dips 50° SE, and the northern Maracaibo slab dips 17° SSE (Van der Hilst and Mann, 1994).

The Panama accretionary wedge is characterized by northward-vergent imbricates, mud volcanoes, minor directional faults, and by the presence of gas hydrates (Reed et al. 1990, Westbrook et al., 1995).

Slope tectonics, mostly characterized by active slumping, as well as active seismicity, characterize the present activity of this wedge (Vitali et al., 1985).

## GEOLOGY OF NORTHERN COLOMBIA

The tectonic map of northern Colombia (Figure 2) shows the migration of magmatic arcs (from Jurassic to Paleogene) and accreted ophiolitic terranes (i.e., Jurassic and Cretaceous ophiolitic series). The map also shows the Sinu–San Jacinto accretionary wedge with related piggyback basins separated from the Plato–San Jorge Basin by the Romeral fault. Notice that a zone of inversion structures is associated with the Romeral fault (Figure 2). Notice also the major displacement of the Santa Marta–Bucaramanga strike-slip fault that accounts for more than 100 km of left-lateral offset, if we take the edge of the Jurassic strata as a reference. In the geologic map (Figure 3), the Jurassic and Cretaceous ophiolitic units have been separated as well. The basement of the Plato–San Jorge Basin consists of Precambrian and Paleozoic metamorphic rocks. Locally, Lower Cretaceous sediments overlie the deformed basement. These strongly deformed Cretaceous strata bounded by basement faults can be attributed to the inversion of normal-fault-bounded Cretaceous basins. Jurassic sediments, obducted ophiolitic rocks, and granites occupy the eastern part of the geologic map (Figure 3). They represent the Jurassic oceanic crust and its overlying pelagic section structurally emplaced above the Paleozoic basement. Close to the Santa Marta–Bucaramanga fault, the structure of the Middle Magdalena Valley consists of a set of inverted Oligocene-Miocene basins located at the front of the Central Cordillera. Farther to the north, only Miocene and Pliocene to Pleistocene fluvial-alluvial sediments are exposed on the surface. The western part of the Plato–San Jorge area is occupied by large basement-involved inversion structures similar in age and geometry to those located west of the Santa Marta–Bucaramanga fault in the Middle Magdalena Valley. North of the Monteria area (Figures 3 and 4), the contact between the Sinu–San Jacinto fold belts and the Plato Basin is the Romeral fault system (Duque-Caro, 1979). South of Uraba, the Cretaceous ophiolitic units are involved in the deformation and are intruded by Paleogene granites. The structure of this area is characterized by thrust imbricates and related folds (Duque-Caro, 1979). In the Lower Magdalena area, the granites are younger toward the west, indicating the westward migration of the magmatic arc as the continent was growing by lateral accretion.

## STRATIGRAPHY

The stratigraphy of the study area varies laterally from west to east and is strongly controlled by the tectonic evolution of the active margin (Duque-Caro, 1979). The stratigraphy of this part of northern Colombia can be subdivided into the Plato–San Jorge Basin to the east and the Sinu–San Jacinto Province to the west (Figure 4).

### *Stratigraphy of the Plato–San Jorge Basin*

#### *Basement*

The basement of the Plato–San Jorge Basin, Ayapel, Balsamo, and Sucre areas, is quite different from the oceanic basement of the Sinu–San Jacinto area. In this eastern domain, the basement is metamorphic and older in age than in the west. The oldest rocks exposed are Precambrian granulite, migmatite, amphibolite, and biotite gneiss. Paleozoic high-grade metamorphic rocks consisting of granitic orthogneiss, hornblende- and biotite-bearing gneiss, and migmatite overlie this section. Green-schist facies metamorphic rocks consisting of amphibolite, micaceous and actinolitic schist, quartzite, and marble top the Paleozoic section (Ingeominas, 1997). Lower Jurassic granodiorites and other granitoids intrude these metamorphic terranes. In the southern part of the study area, the metamorphic and magmatic basement is overlain by Lower Cretaceous serpentinized peridotite, gabbros, pillow lava, and basalt. South of the study area, the metamorphic basement is overlain by interbedded shale, sandstone, conglomerate, and limestone of Cretaceous age.

#### *Cienaga de Oro Formation*

The Cienaga de Oro Formation is exposed along the northwestern San Jorge Basin. The base of this unit consists of conglomerate, mostly quartzite, quartz, lidite, and igneous rocks. Most of this unit is made up of well-bedded, varicolored quartz sandstone, locally conglomeratic, with interbedded limy siltstone, carbonaceous and silty shale and occasional limestone and coal beds, limy-sandstone, and limestone. The Cienaga de Oro formation was deposited in a deltaic to shallow-water sedimentary environment and is considered to be Oligocene–lower Miocene in age (Reyes-Harker et al., 2000, Reyes-Santos et al., 2000) (Figure 5a). It constitutes a wedge-shaped

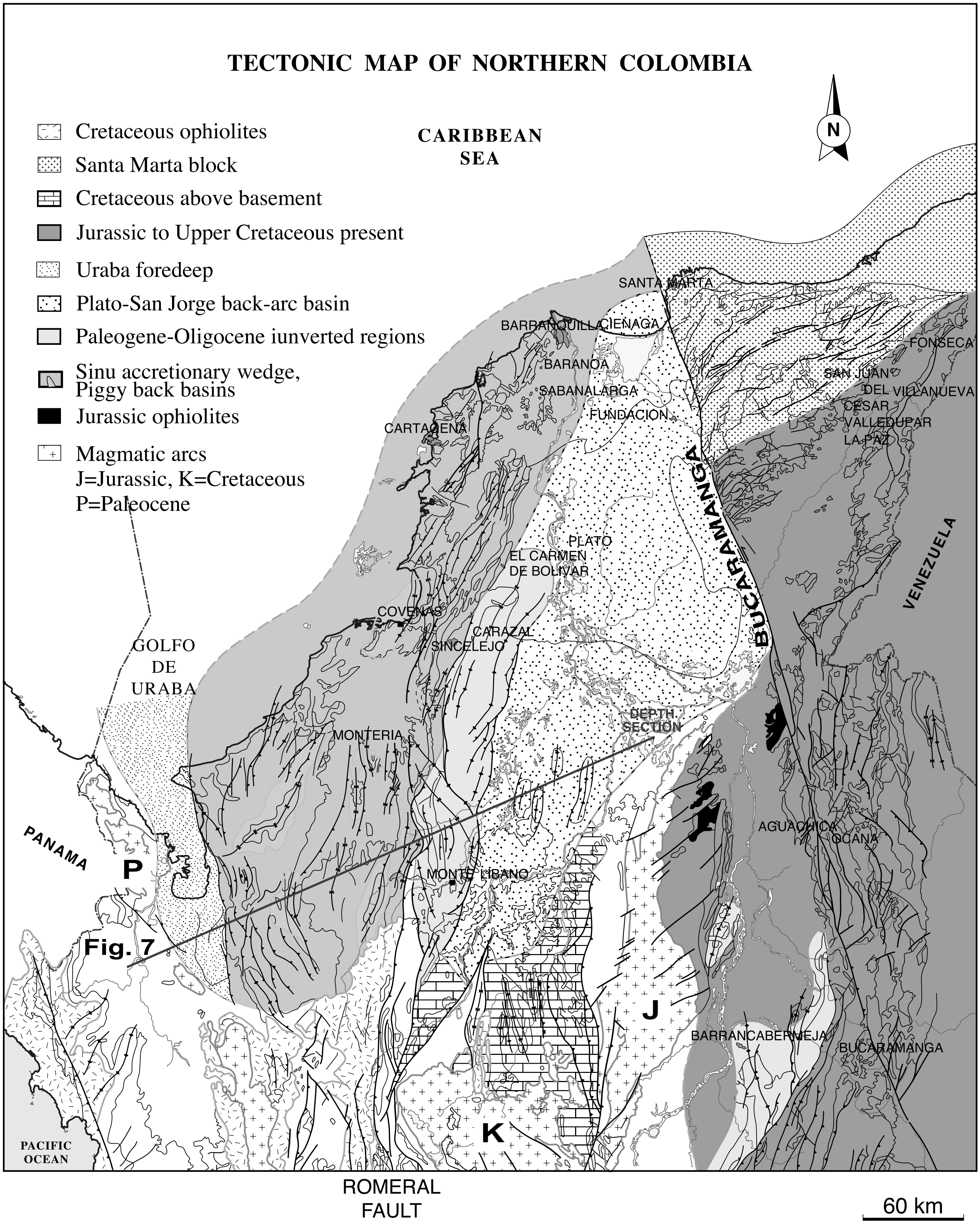


**Figure 2.** Tectonic map of northern Colombia, based on surface geological data from Ingeominas (1997) and subsurface data from this study. The location of Jurassic and Cretaceous ophiolites, magmatic arcs, and the accretionary wedge are indicated. The Santa Marta–Bucaramanga strike-slip fault and the inversion zone associated with the Romeral fault are the main structural features of the area.

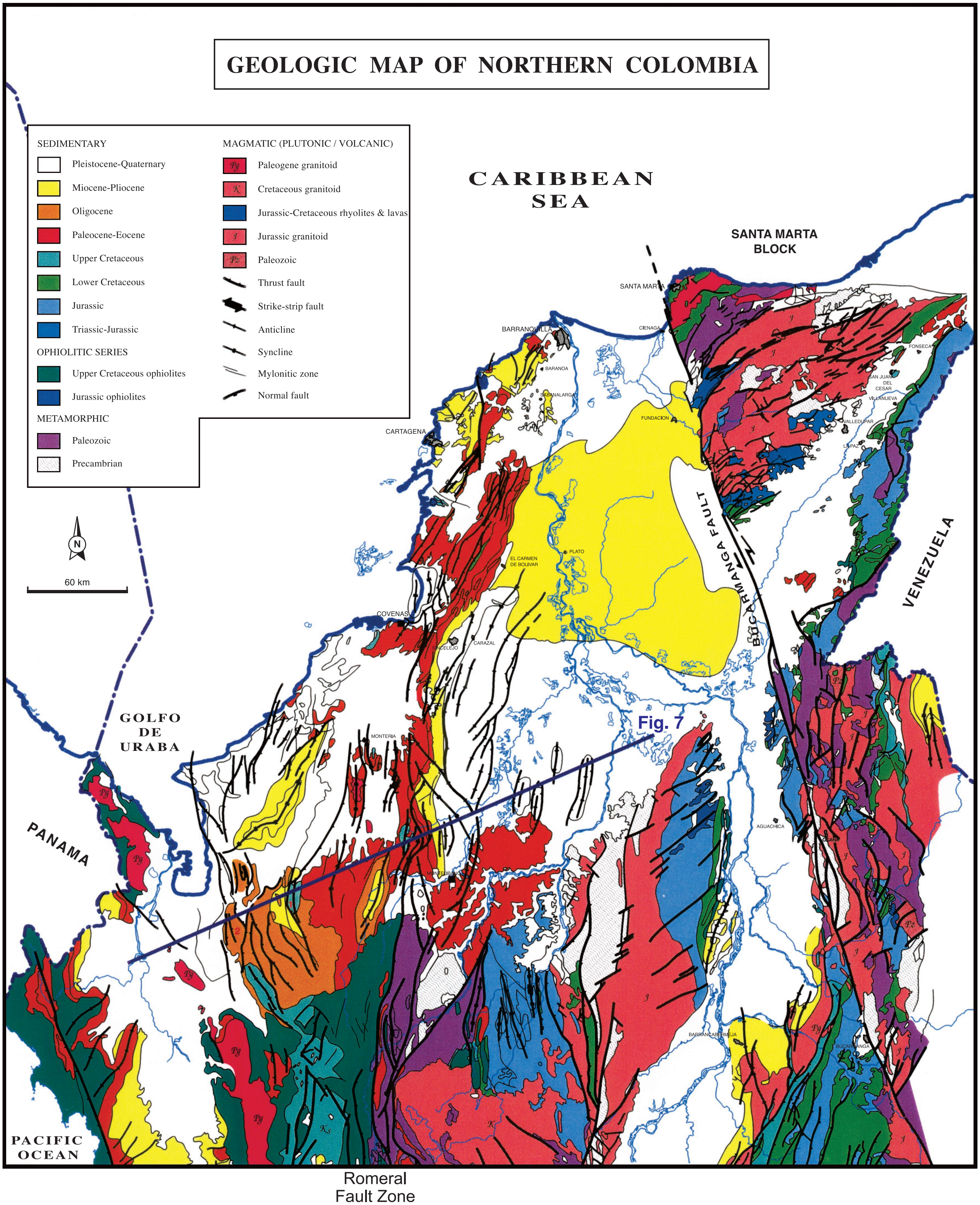


**Figure 3.** Geologic map of northern Colombia. Surface geological data were modified from Ingeominas (1997). Main thrust faults and structural highs were added to the geologic map based on seismic data from this study.

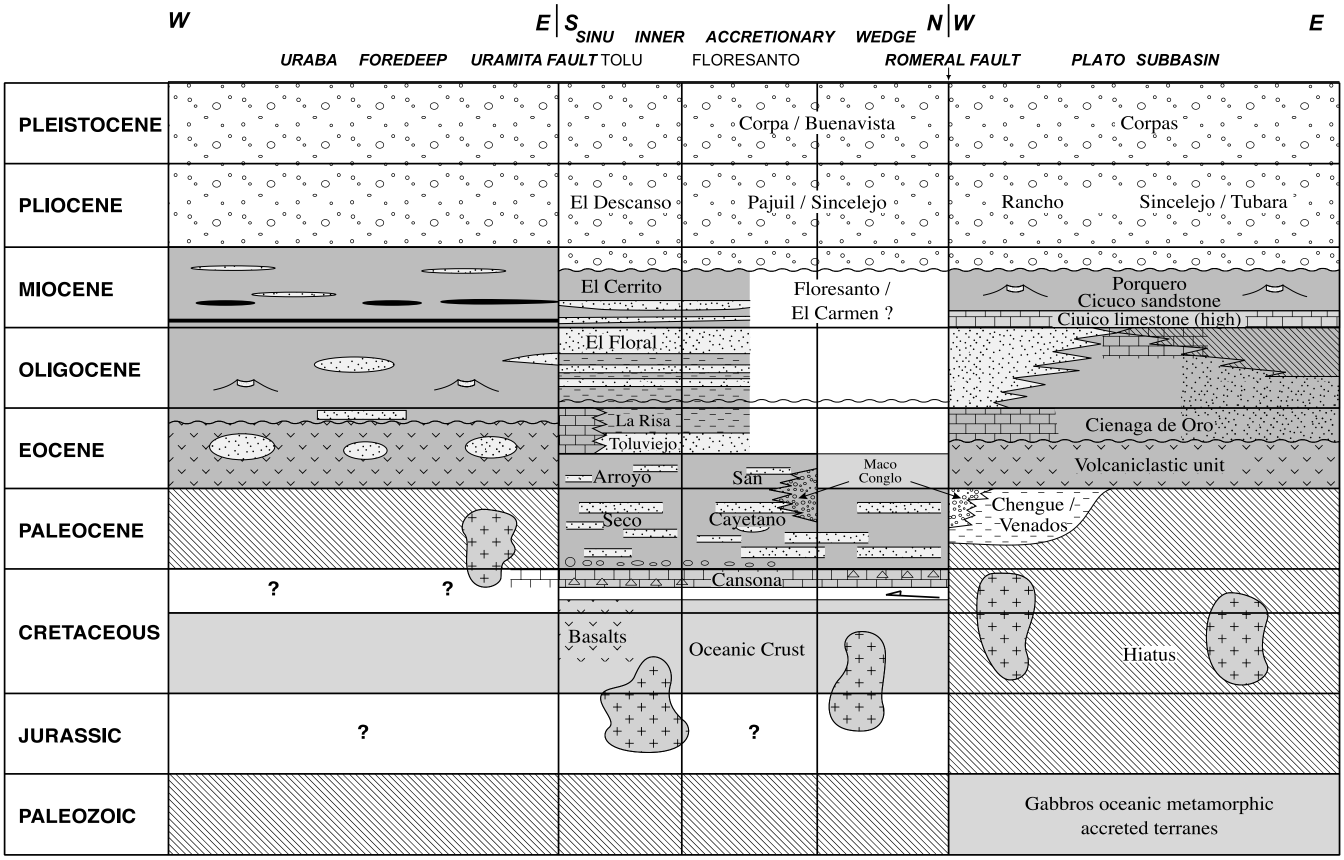


**Figure 4.** West-to-east chrono-lithostratigraphic chart from the Uraba foredeep (offshore) to the Plato subbasin (onshore). This chart is based on well-log data from Ecopetrol and surface data from numerous authors. Notice the major stratigraphic changes across the Romeral and Uranita faults.

shelf-edge unit with a thickness range of between 600 to 1000 m. Isopach maps confirm the wedge shape of this unit, which pinches out towards the east.

### *Porquero Formation*

The Porquero Formation consists of gray-greenish silty and carbonaceous shale, lutites, and siltstone with occasional interbeds of lenticular sandstone. This unit conformably overlies the Cienaga de Oro Formation and is locally referred to as the Porquero flysch. The lower part of this unit contains upper Oligocene–lower Miocene deep-water fauna, suggesting a deep-water environment (Figure 5a). The upper part of the section consists of carbonaceous shale with interbedded sandstone and coal. This upper middle Miocene unit represents mostly delta-plain sediments.

### *Sincelejo/Tubara Formation*

The Sincelejo or Tubara Formation unconformably overlies the Porquero Formation. This upper Miocene unit consists of cross-bedded, fine- to coarse-grained sandstone, conglomeratic sandstone, and conglomerate with occasional interbeds of sandy and silty gray-blue fossiliferous shale. Conglomerates are well-sorted and rounded and contain boulders of quartz and lidite. The Sincelejo unit has an average thickness of 700 m, and it is interpreted as a continental unit of upper Miocene age (Reyes-Harker et al., 2000) (Figure 5a).

### *Corpa Formation*

The Pliocene to Pleistocene Corpa Formation consists of gray shale and siltstone with occasional interbeds of sandstone and conglomerate bounded by major unconformities (Reyes-Santos et al., 2000). The Pleistocene strata consist of alluvial deposits and fluvial terraces.

## *Stratigraphy of the Sinu–San Jacinto Area*

### *Basement*

The basement of the Sinu–San Jacinto accretionary complex is exposed west of Uraba, along the Isthmus of Panama, and locally in the southern part of the Monteria region (Ingeominas, 1997) (see Figure 3). The basement consists of Upper Cretaceous gabbro,

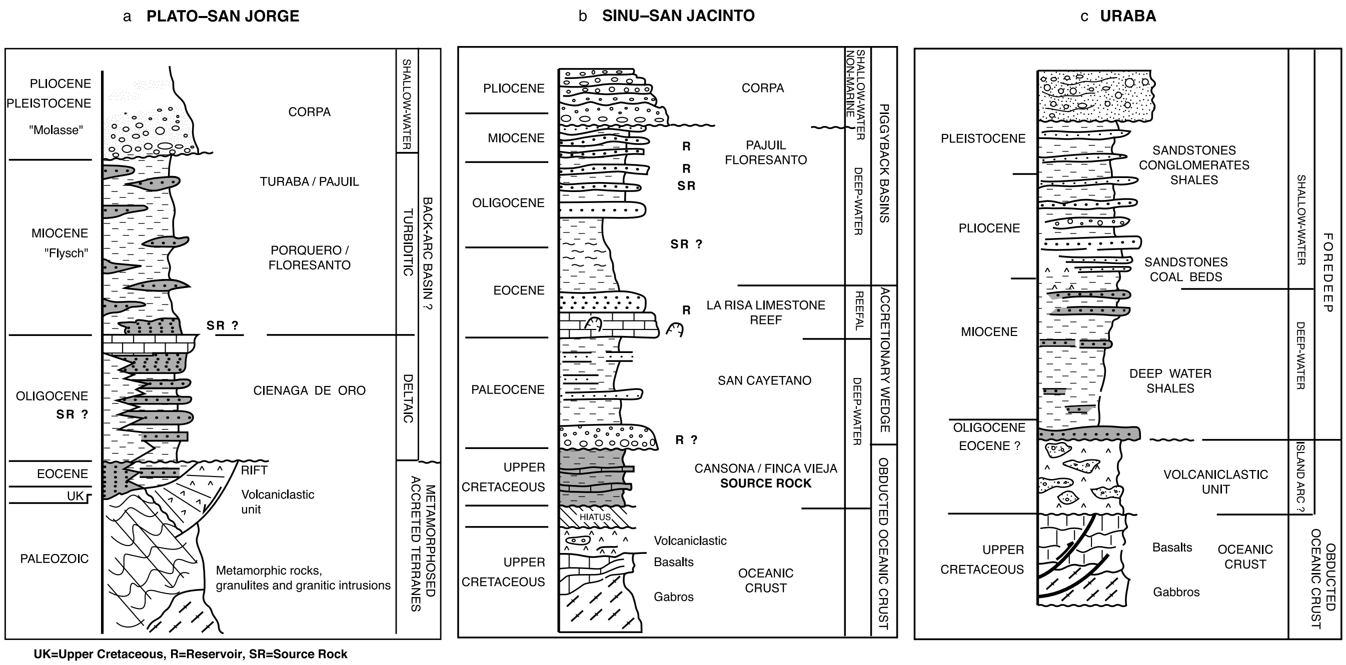


**Figure 5.** **Composite idealized stratigraphic columns of the study area. (a) Plato–San Jorge Basin. This column illustrates the main Neogene units that unconformably overlie the Paleozoic basement. (b) Sinu–San Jacinto area. This idealized section of the Sinu–San Jacinto area shows the Cenozoic turbiditic to shallow-water section that constitutes the Sinu accretionary wedge and related piggyback basins. This Cenozoic section unconformably overlies the Cretaceous oceanic basement and its deep-water cover. (c) Uraba area. This idealized column illustrates the sedimentary filling of the flexural basin that overlies the oceanic crust and a volcaniclastic unit of probable Eocene age.**

basalt, and pillow lava, intruded by Paleocene monzodiorite, monzonite, sienite, and gabbro. These oceanic crust deposits are unconformably overlain by the volcaniclastic facies of the Barroso Formation. This unit consists of basalt and diabase interbedded with sandstone and conglomerate that represent reworked volcanic rocks and volcano-sedimentary deposits.

### *Cretaceous-Paleogene*

The Cretaceous sedimentary section unconformably overlies the basalt, green-schist, gabbro, and pillow lava of the oceanic crust. The lowermost Cretaceous sedimentary unit is Coniacian in age and is locally referred to as the Cansona Formation; it is time equivalent with and has similar facies as the La Luna Formation of Venezuela. The Cansona Formation consists of lidite, chert, and limestone interbedded with pelagic organic-rich shale and siltstone. The organic-rich shaly section constitutes the Finca Vieja Member of the Cansona Formation (Figure 5b). The Cansona Formation can reach 150 m of thickness in the San Jacinto area (Duque-Caro, 1973). The Upper Cretaceous section constitutes a deepening-upward section that is overlain by Paleocene–middle Eocene hemipelagic shale with interbedded turbiditic sandstones and conglomerates of the San Cayetano/Carreto Formations. The Paleocene section is well-exposed in the Tolú area, where it consists of normally graded sequences of fine-grained sandstone, siliceous siltstone, and gray shale of the San Cayetano Formation (Duque-Caro and Guzmán, 1995) (Figure 5b). The Paleocene siliciclastic section is overlain by Eocene platform carbonates of the La Risa Formation, consisting mostly of reefal limestone. The Lorica-1 well encountered 3000 m of middle Eocene Chengue Formation, which consists of interbedded gray-to-brownish silty mudstone, marl, and fine- to coarse-grained, subangular to subrounded gray sandstone. Occasional fine-grained, quartz-rich sandstone intervals are common in the upper part of the section. Stratigraphic variations in the Eocene section between the Tolú and Lorica areas suggest strong facies changes in the Sinu area. In the Uraba region, a thick volcaniclastic unit of probable Eocene age unconformably overlies the oceanic crust (Figure 5c).

### *Oligocene-Miocene*

Neogene sediments are widespread in the Sinu–San Jacinto area (Duque-Caro, 1972). Most of the Neogene units are exposed on the surface and also were penetrated by several exploratory wells. The Oligocene section is composed mostly of shale with occasional interbeds of sandstone in the onshore area (Ingeominas, 1997). The Oligocene–lower Miocene Floresanto Formation consists of deep-water turbiditic sandstone, limestone, sandy-claystone, and pelagic shale with occasional thin-bedded conglomerate (Figure 5b). The upper Miocene Paujil Formation consists of sandstone and conglomerate interbedded with shale and occasional siltstone that represent shallow-water beach deposits.

### *Pliocene and Pleistocene*

The Pliocene Corpa Formation consists of gray shale and siltstone with occasional interbeds of sandstone and conglomerate. They represent fluvio-deltaic facies in the west and fluvial-alluvial facies in the east.

Offshore sedimentation during the Pliocene and Pleistocene was controlled by the shifting of the Magdalena River delta, the Sinu River delta, and probably another major fluvial system located along the southern Uraba region. Seismic data have provided evidence for the presence of a major Pleistocene deep-sea fan located north of Cartagena and south of the present Magdalena delta (Kolla et al., 1984). The present sea-bottom morphology of this area suggests the presence of Pleistocene to present channel-levee complexes and meandering channel systems (Pirmez, et al. 1998). The Holocene Magdalena fan developed to the north of its present mouth and is dominated by mass wasting and erosion. The most recent sea-level rise coupled with tectonic activity (Pirmez et al., 1998) apparently induced this switch of the Magdalena fan from the south to the north. Major sediment supply to the area was triggered by the uplift of the Andes mountains since the Miocene, a process that still is active today.

### *Stratigraphy of the Uraba Basin*

The Uraba Basin is a Neogene basin located east of the Panama isthmus and is made up of a thick Oligocene to Holocene siliciclastic section floored by Cretaceous oceanic crust. Upper Cretaceous basalt and gabbro of the Caribbean oceanic crust constitute the basement of the Uraba Basin. The basement is locally overlain by a volcaniclastic unit of presumed Eocene age (Figure 5c). The clastic section begins with deep-water shale and occasional interbeds of sandstone of probable turbiditic origin(?). This lower unit may be Eocene and mostly Oligocene in age and represents a shallowing-upward sedimentary cycle. The Miocene section is composed of shallow-water sandstone, shale, and occasional interbeds of coal and conglomerate (Figure 5c).

## STRUCTURE

The structure of the Sinu–Lower Magdalena area from the foreland to the hinterland can be subdivided into: the Uraba flexural basin, the Sinu–San Jacinto accretionary wedge, and the Plato–San Jorge Basin. Figure 7 is an east-west-trending sketch of a depth section showing the lateral contacts and internal structure of these units.

### *Uraba Basin*

The region of Uraba is occupied by an Oligocene to Pliocene flexural basin that unconformably overlies the deformed oceanic basement of the Panama accretionary wedge, also referred to as the Northern Panama folded belt (Reed et al., 1990; Vitali et al., 1985). A thick volcaniclastic unit encountered by several wells (i.e., Apartado-1, Uraba-1, and Chigorodo-1) unconformably overlies the acoustic basement formed by oceanic crustal rocks (Ingeominas, 1997). Seismic data suggest the presence of imbricates in the basement that are overprinted by normal faults with half-graben geometries (see Figures 7, 8, and 9). The relationship between the half-graben structures and the volcaniclastic deposits is not clear. The foredeep section grades from Oligocene deep-water facies to shallow-water siliciclastic Pleistocene sediments. Nearly north-south trending, dominantly west-vergent anticlines, with local backthusts involving the Neogene section of the Uraba Basin, represent the leading edge of the Sinu accretionary wedge. The structure of the Uraba Basin is illustrated by cross sections shown in Figures 8 and 9.

### *The Sinu–San Jacinto Accretionary Wedge*

Historically, this area has been separated into the Sinu folded belt and the San Jacinto folded belt. From a structural point of view, both areas belong to the southern Caribbean accretionary wedge that extends from Uraba to Venezuela along the Caribbean margin, but from a stratigraphic point of view, the San Jacinto area is characterized by surface exposures of Cretaceous strata (older rocks than in the Sinu area). The leading edge of the Sinu accretionary wedge is represented by the Uramita fault. The Uramita fault is interpreted here as a west-vergent thrust, but other authors (Duque-Caro, 1984, 1990; Ruiz et al., 2000) interpret this structure as a right-lateral transpressional fault. As in all accretionary wedges, the inner parts of the prism involve older rocks than the more external parts of the prism, which involve younger rocks (see Figures 7 and 10). According to this interpretation, the San Jacinto province represents the inner part of the wedge where Cretaceous and mostly Paleocene deformed strata are exposed. On the contrary, the Sinu area represents the exposed younger part of the prism that consists mostly of Eocene and Oligocene imbricates overlain by Miocene piggyback basins. Some authors (Laverde, 2000) emphasize the role of cross-cutting strike-slip faults in the Sinu San Jacinto area.

The geologic maps of the Monteria area (Figure 3) display the complex imbrication of the accretionary wedge and the geometry and age of the overlying piggyback basins.

### Plato–San Jorge Basin

A complex fault zone, referred to in the literature as the Romeral fault, separates the complex imbricated zone of the Sinu–San Jacinto area (i.e., the inner accretionary wedge) from the Plato–San Jorge Basin. This fault system has a long and complex structural history of extension and compression and, probably, strike-slip. The Ayapel, Balsamo, and Sucre areas belong to the so-called Plato–San Jorge Basin, which is a Neogene basin underlain by a structurally complex metamorphic basement of continental affinity. The San Jorge subbasin in the south is separated from the Plato subbasin in the north by the Magangue High. This structural high is characterized by northwest-southeast-trending normal faults. The basement consists of Paleozoic metamorphic rocks and is intruded by granodiorites of the so-called Antioqueño batholith, which is exposed around the Medellín region. These rocks constitute Paleozoic accreted terranes sutured since the Paleozoic to the western margin of South America (Restrepo-Pace, 1992; Duque-Caro, 1990). The structure of the Plato–San Jorge area consists of fault-bounded blocks and listric normal faults (Reyes-Santos et al., 2000). Reyes-Harker et al., (2000) interpret part of the Plato–San Jorge area between the Bucaramanga and Ariguani-Algarrobo Faults as being a pull-apart basin since the late Eocene. Oligocene transtension was, according to these authors, associated with the Romeral and Palestina Faults. The Neogene basin that overlies this basement can be interpreted as a back-arc basin that alternated between transtension and transpression and was controlled by large half-graben geometries and strike-slip faults. Basement-involved thrust structures and positive inversion structures are common in the Sucre and Ayapel regions of the Plato–San Jorge Basin. Initial basement-involved thrusting in the Plato–San Jorge subbasins was marked by a major deep-water onlap of the Porquero Formation onto the Cienaga de Oro shelfal unit. This lower Miocene subsidence event marked the beginning of a well-differentiated back-arc basin in that area.

### Regional Transects

The structure of the Lower Magdalena area can be illustrated by a series of east-to-west-trending composite seismic sections. Figure 6 shows the location of the seismic transects and the depth section (Figure 7). Two transects run through the Uraba Basin and show the relationship between this basin and the frontal part of the Sinu accretionary wedge. The other transects display the internal structure of the accretionary wedge that dominates the classical Sinu–San Jacinto area and its contact with the Plato–San Jorge Basin; that is, the Romeral fault. The transects proceed from south to north (from the Uraba area to the Santero area).

#### Uraba-Monteria Transect

This transect is a composite dip profile that illustrates the geometry of the Uraba flexural basin and its contact with the Sinu accretionary wedge (Figure 8). The transect displays half-graben features overlying the basement. In the western part of the Uraba Basin, inversion structures evolved on the faulted oceanic basement. A basal volcaniclastic unit is overlain by an Oligocene to Pliocene sedimentary wedge. This foredeep section directly overlies the deformed basement. The leading edge of the Sinu accretionary wedge is represented by a west-vergent thrust, locally referred to as the Uramita fault. The Chigorodo-1 well drilled a thrust-ramp anticline associated with the Uramita fault. The internal structure of the Sinu accretionary wedge is characterized by thin-skinned west-vergent thrusting defined by a Cretaceous décollement. Upper Eocene to Miocene piggyback basins overlie the underlying wedge imbricates.

### Uraba Transect

This transect (Figure 9) illustrates the frontal thrust of the Sinu accretionary wedge, locally referred to as the Uramita fault. The Uraba transect shows the geometry of the Uraba Basin and the contact with the Sinu accretionary wedge in the Monteria area. Large-scale folding affects the Neogene section and probably involves the oceanic basement. The well Necocli-1 was drilled on the flank of this major fold. Normal faults affect the basement and the volcaniclastic cover of the Uraba Basin. West of the Uramita fault

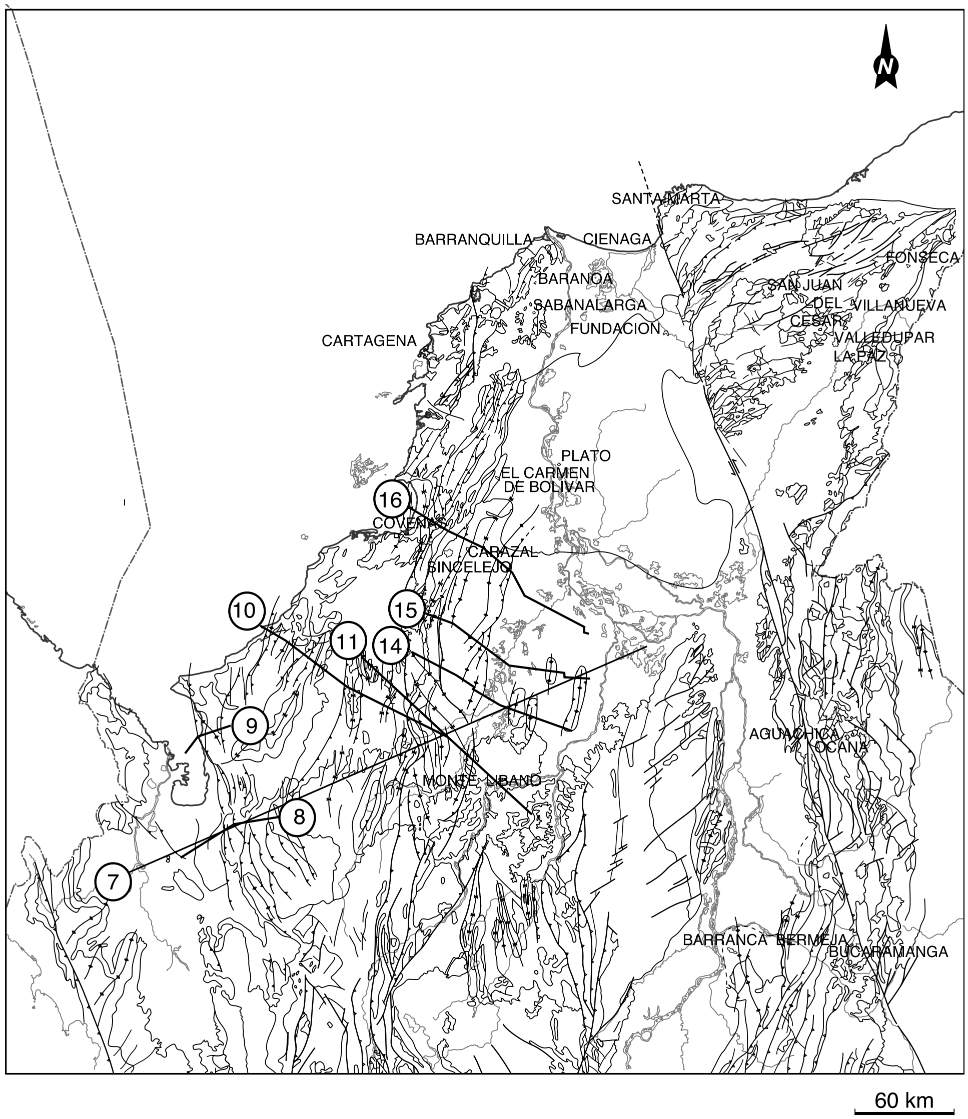


**Figure 6.** Location map of seismic transects and depth section.

(the leading edge of the Sinu accretionary wedge), the Neogene anticlinorium is overlain by Paleocene shale of the wedge. Piggyback basins of lower Miocene to Pliocene age are superimposed on the wedge imbricates of dominantly Paleocene-Oligocene age.

### *Monteria to Ayapel Transect*

Figure 10 is a seismic transect that extends from the offshore area to the Plato subbasin and illustrates the geometry of the accretionary wedge and related piggyback basins. Seismic data suggest that most of the supra-wedge basins are thrust-related piggyback basins, but some may be controlled by normal faulting and shale diapirism (El Arbi and Kellogg, 1992). The western (offshore) part of the transect consists of Oligocene imbricates overlain by a thick Miocene to Pleistocene sedimentary wedge, dominated by Pliocene-Pleistocene clastic sediments. The La Risa-1 well was drilled at the edge of a piggyback basin floored by Cretaceous and Paleocene imbricates. The internal structure of the wedge is complex and is defined by the structural stacking of several décollement levels. In the southern Monteria area, piggyback basins overlying the accretionary wedge are Oligocene and Miocene in age. The central part of this transect is occupied by thick Oligocene deposits drilled by the Arboletes-1 and South Cordoba-1 wells. The contact between the Sinu–San Jacinto accretionary wedge and the basement-involved units of the Plato subbasin (Sucre and Ayapel regions) are clearly shown on this transect. The Romeral fault is not well-imaged in this seismic section but separates zones of two very distinct structural styles: accretionary wedge imbricates from basement-involved inverted half-graben structures. East of this major contact, the structure is characterized by inverted half-grabens filled by Eocene(?) volcaniclastic rocks (recognized in the well Puerta Negra-1) and the Oligocene Cienaga de Oro Formation.

### *Monteria to Ayapel Transect through Purgatorio Quarry*

Figure 11 is a transect subparallel to the previous one that runs through the Purgatorio Quarry, where organic-rich strata of the Upper Cretaceous Cansona Formation are exposed on the surface. Figure 12 is a seismic enlargement of the Purgatorio Quarry area that illustrates basement-involved imbricates of oceanic affinity. The section shows a major angular unconformity located at the contact between the oceanic crust and the Cretaceous sedimentary section.

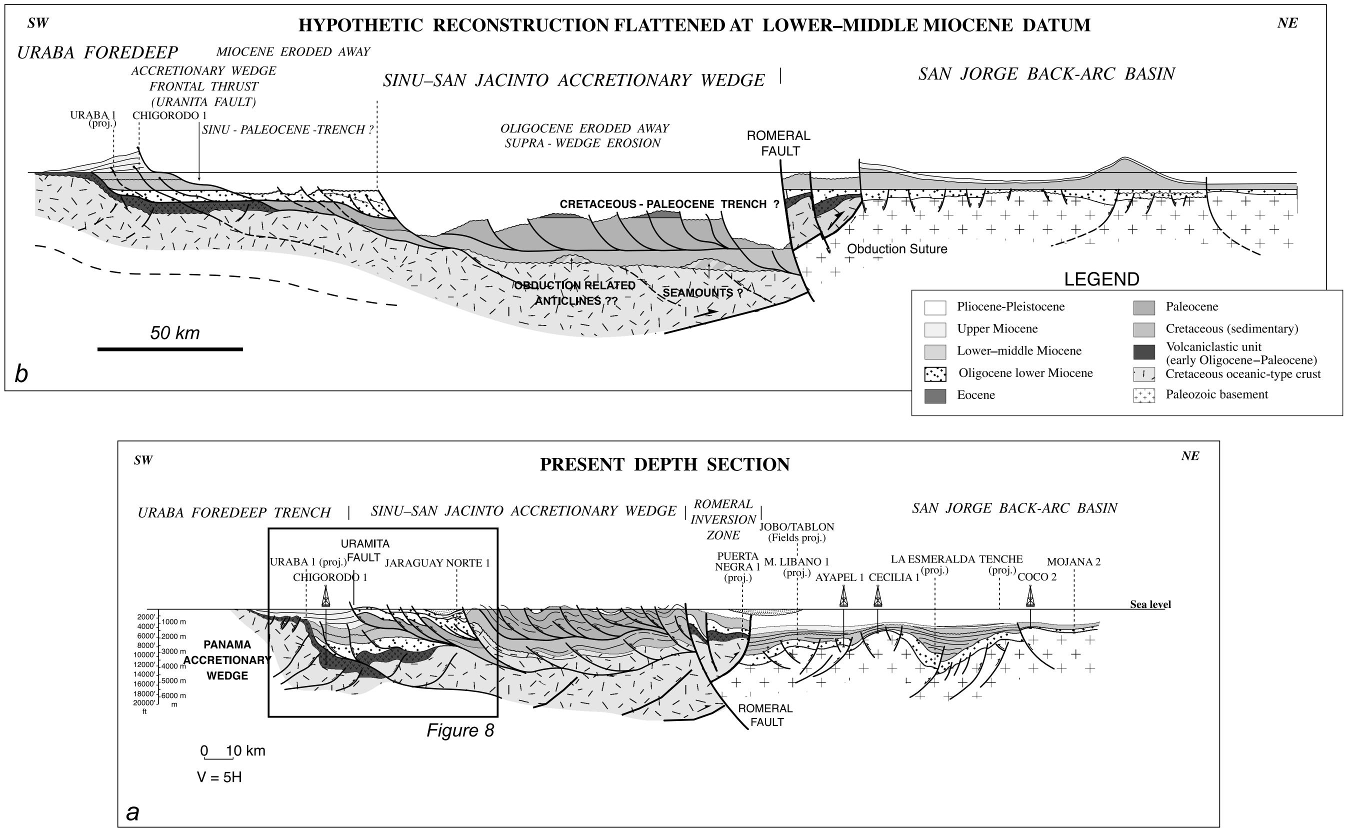


**Figure 7.** (a) Depth cross section from Uraba to Ayapel southern onshore Sinu area (present-day). (b) Hypothetical reconstruction with top Oligocene–lower Miocene datum (after Flinch et al., 2000). This cross section shows the thrust contact between the obducted oceanic crust and the continental basement offset by the Romeral fault. The contact between the Sinu–San Jacinto accretionary wedge and the Uraba foredeep also is displayed.

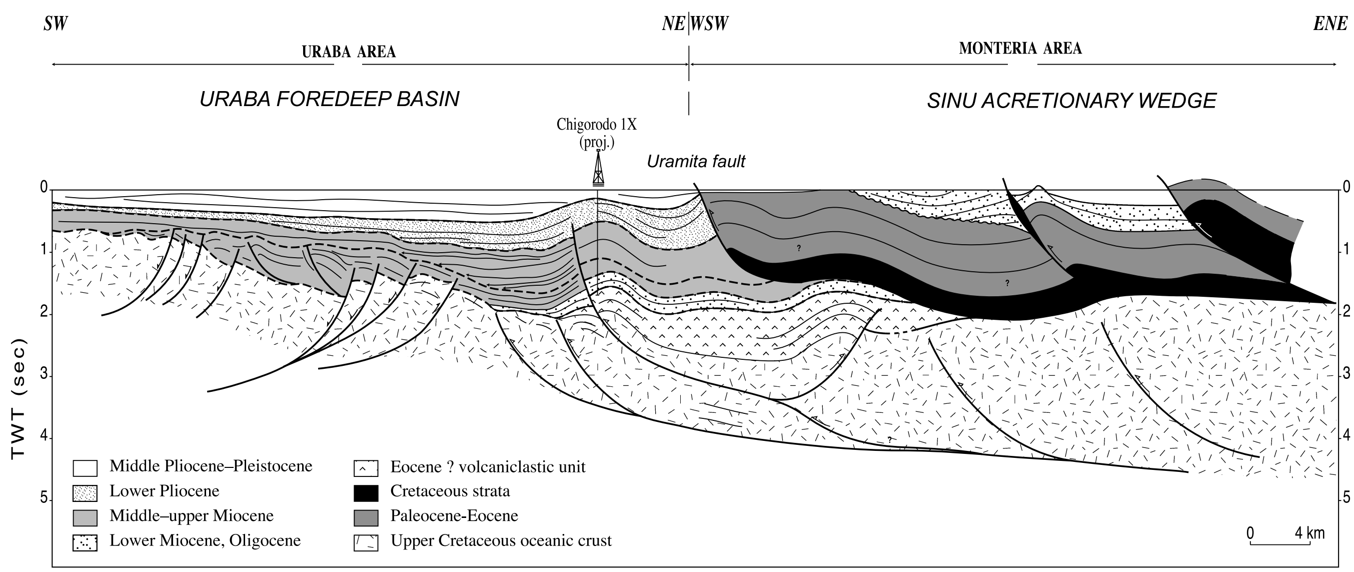


**Figure 8.** Seismic line drawing of transect from Uraba to Monteria area. This transect illustrates the contact between the Uraba Basin and the accretionary wedge at the Monteria area, represented by the Uramita fault. The Chigorodo well encountered most of the foredeep section represented by basal volcaniclastic rocks overlain by deep- to shallow-water siliciclastic Oligocene to Pleistocene sediments bounded by major onlap surfaces.

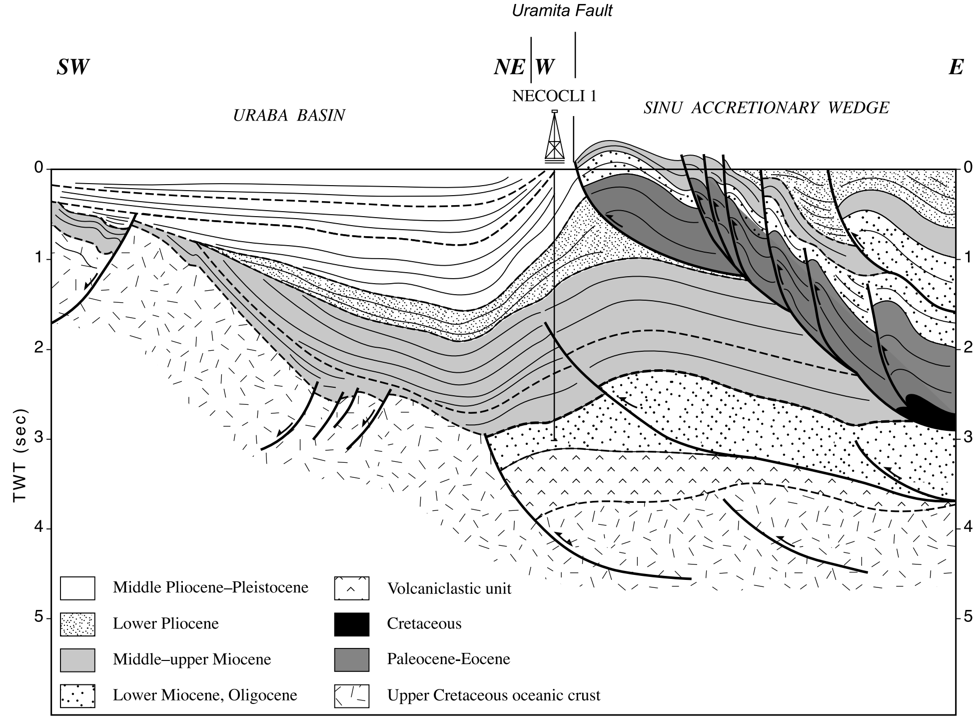


**Figure 9.** **Seismic transect through the Uraba Basin. This section shows the faulted-block geometry of the Uraba oceanic basement and the contact with the accretionary wedge. A major unconformity, characterized by truncation below and onlap above, separates the upper Miocene from the Pliocene section.**

Notice the complex geometry of the basement caused mostly by basement-involved thrusting but also by irregular topography, possibly related to seamounts, as in present oceanic basins. The transect illustrates the complex imbricated geometry of the accretionary wedge. The structure of the wedge seems to be controlled by two décollement levels, one in the oceanic crust, and the other perhaps in the Upper Cretaceous to Paleocene shale section. Surface geologic maps (Ingeominas, 1997) also support the presence of two décollement levels. Figure 13 is a seismic section that illustrates the contact between the Sinu–San Jacinto wedge and the Plato–San Jorge Basin, which are separated by the Romeral fault.

## *Ayapel Transect*

This transect (Figure 14) runs through the Jobo-Tablón field in the Ayapel area. The structure of this area is characterized by basement-involved thrusting that was succeeded by normal faulting. Inversion of Oligocene normal faults occurred adjacent to the Romeral fault system. The contact between the basement of the Plato Basin and the basement of

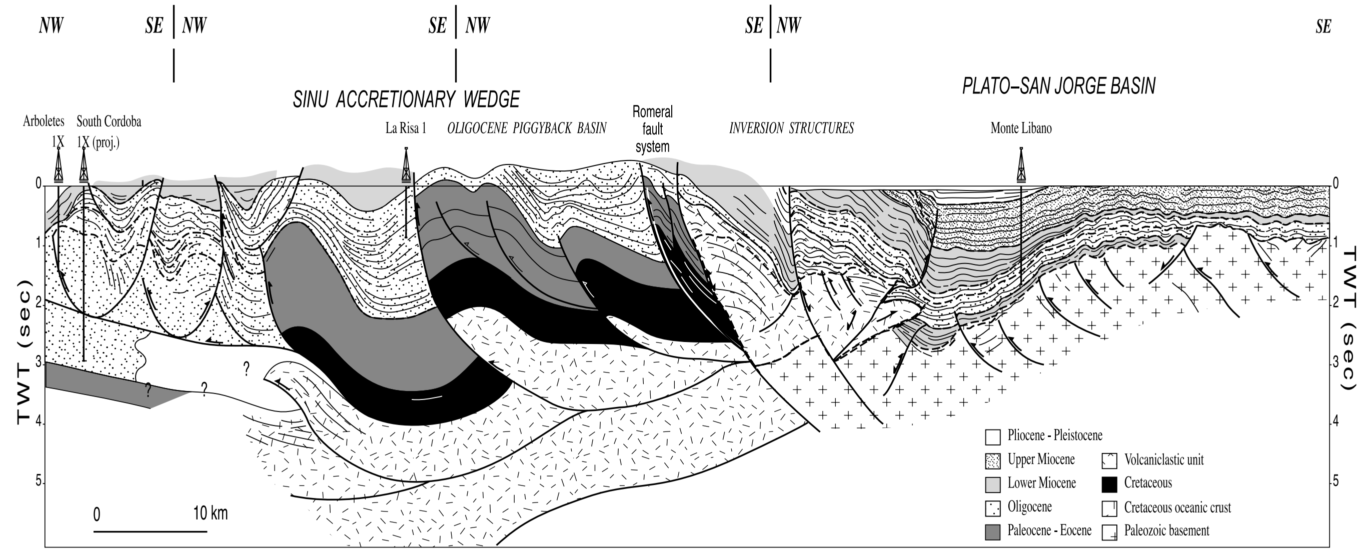


**Figure 10.** **Seismic transect from Monteria to Ayapel area. The contact between the Sinu accretionary wedge floored by oceanic crust and the Plato–San Jorge Basin is well-shown in this transect. Notice the role of the Romeral fault system that offsets the thrust of the Cretaceous oceanic crust above the Paleozoic continental basement of the San Jorge Basin (obduction contact).**

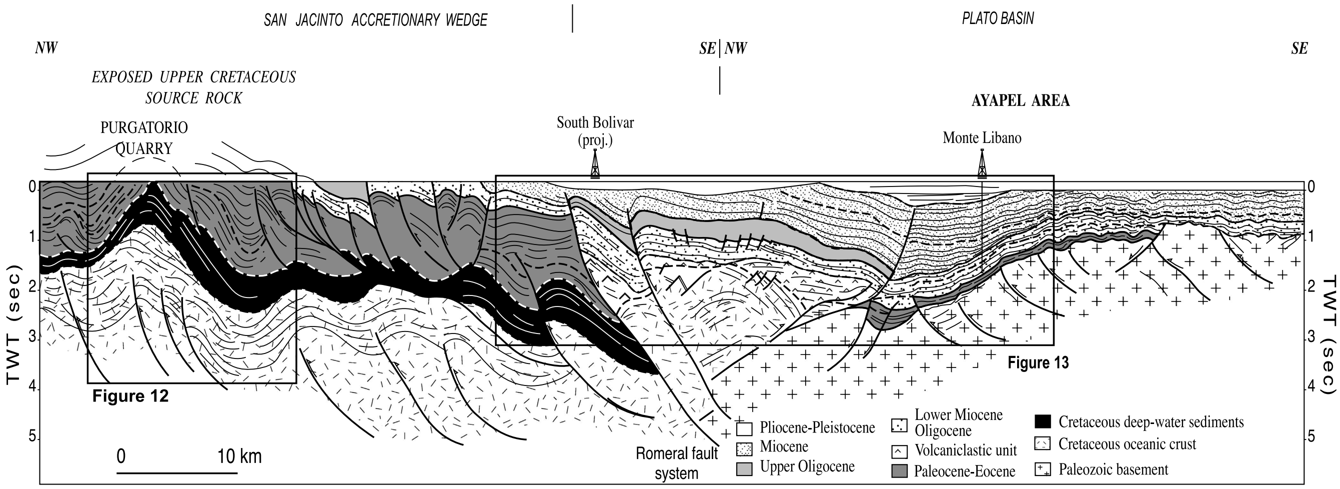


**Figure 11.** Seismic transect from Monteria to Ayapel through Purgatorio. This transect shows the inversion structures related to the Romeral fault system that cross-cut the obduction contact, and the relationship between the oceanic crust and its sedimentary cover.

the Sinu accretionary wedge is not well-imaged by the seismic data. The Sinu prism is characterized by Cretaceous to Oligocene west-vergent imbricates. A major onlap separates the Cienaga de Oro Oligocene formation from the lower Miocene Porquero Formation. Several major angular unconformities suggest that basement-involved thrusting took place intermittently from the lower Miocene to the Pliocene in the Plato–San Jorge area.

### *Sucre Transect*

The transect of Figure 15 runs through the Sucre area in the Plato Basin and illustrates the basement-involved structural style of this province. The transect

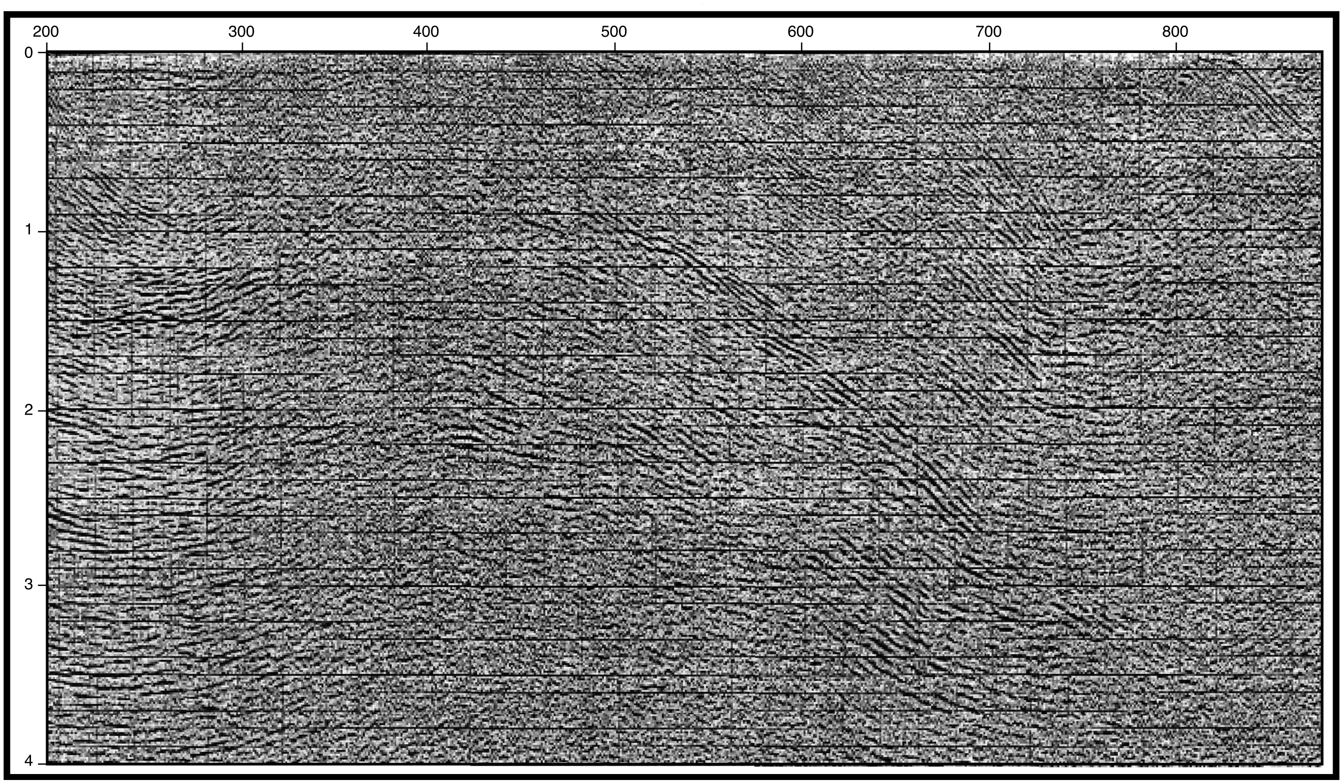


**Figure 12.** Seismic section through the Purgatorio Quarry area. The major truncation surface shown by the section is interpreted as the top of the oceanic crust, which is overlain here by the Cansona Formation (i.e., the major source rock of the area).

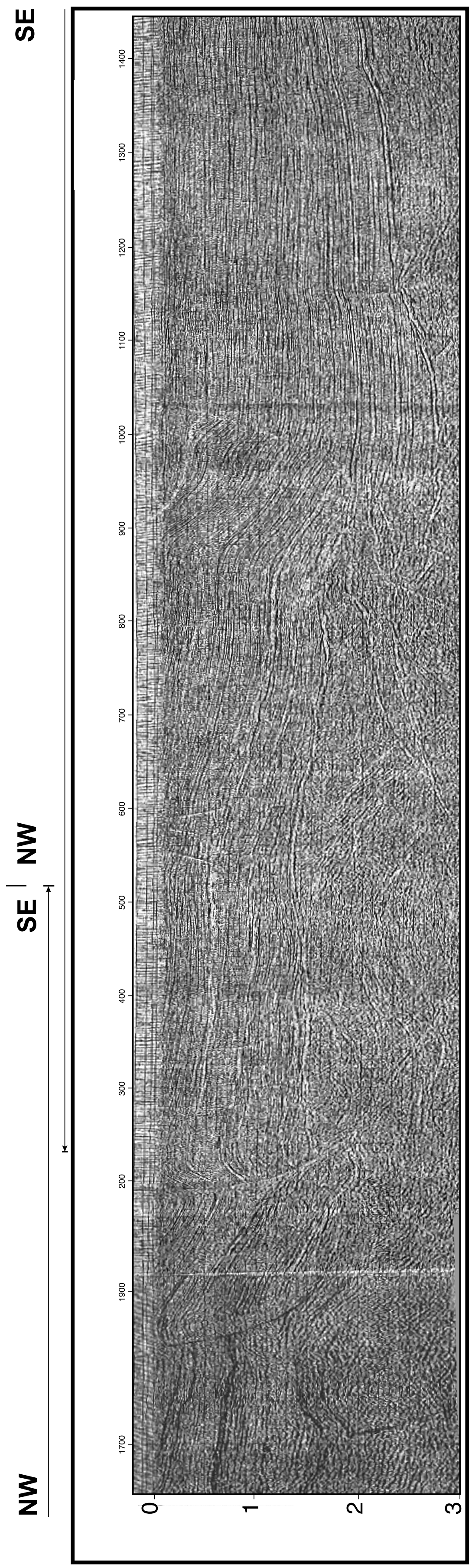


**Figure 13.** Seismic section of the contact between the Sinu–San Jacinto wedge and the Plato Basin. The seismic section shows the east-vergent thrust, interpreted here as the obduction suture. This section also illustrates inversion structures associated with the Romeral fault system.

shows prominent structural highs and normal faults in the distal part of the basin. A major onlap surface defines a major angular unconformity and suggests that major subsidence began in the lower Miocene and was defined by deep-water turbiditic facies above shallow-water sandstones and carbonates. Wells were drilled at the crests of major basement-involved anticlines. The transect suggests that Pliocene or even Pleistocene compression has affected this area.

### *Santero to Sucre Transect*

This transect (Figure 16) runs from the state border of Sucre in the San Jorge Basin to the Tolú area. The transect illustrates the structure of the Santero area, where the Tolú exploration wells are located. The southeastern part of the transect illustrates normal faults affecting the basement of the basin. The central part is affected by basement-involved compressional and inversion structures that have disrupted the apparent extensional geometry of the basin. Major inversion occurred in the Tirón–Nueva Granada area (where the Tiron oil field is located). The transect also illustrates the major unconformity between the Cienaga de Oro prekinematic unit and the overlying synkinematic Neogene strata (Porquero Formation). The contact between the Paleozoic basement and the Sinu accretionary prism, the Romeral fault, is not obvious from the seismic line. West of this zone, the structure of the prism is characterized by west-vergent thrust imbricates involving Cretaceous to Oligocene strata and related piggyback basins that are filled by Miocene to Pliocene sediments. The Tolú basin is, in fact, a piggyback basin floored by Cretaceous oceanic crust with a thin Cretaceous sedimentary cover, the Cansona Formation. Oligocene flysch and Pliocene shallow-water siliciclastic sediments overlie Eocene limestone and shallow-water sandstone.

## STRUCTURAL EVOLUTION

The Sinu–Lower Magdalena area underwent a complex tectonic evolution of obduction and accretion since the Cretaceous, in the context of B-type subduction of the Caribbean and South American Plates (Case et al., 1990; Mann, 1999). Structural styles are strongly different on either side of the Romeral fault system. Several isopach maps and the regional transects, as well as a reconstructed section in depth (Figure 7), were made in order to understand this complex tectonic evolution.

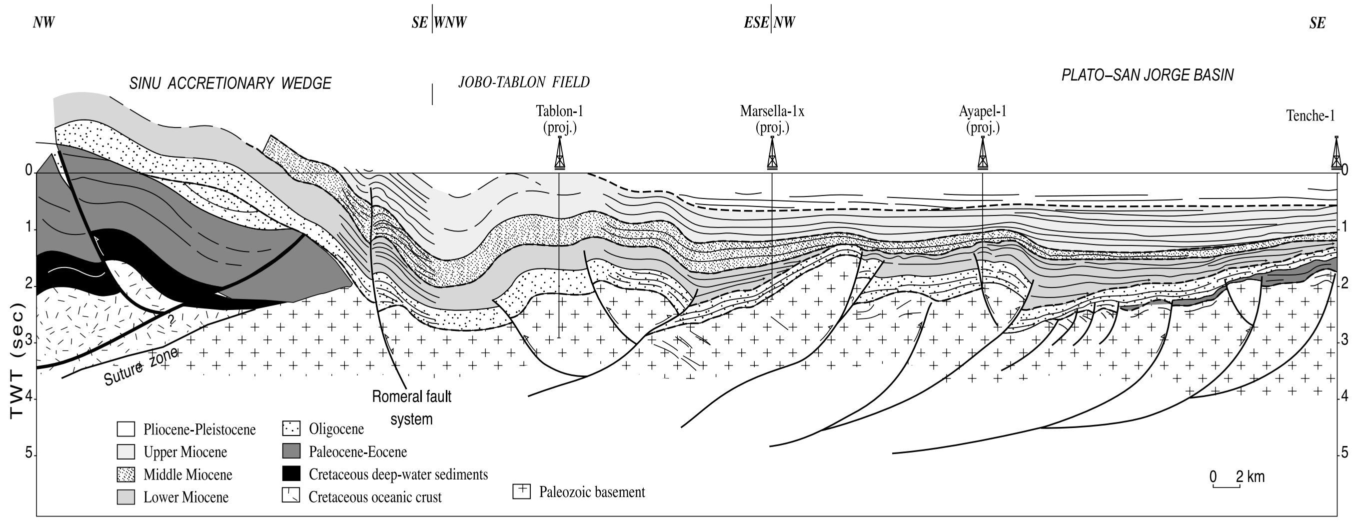


**Figure 14.** Seismic line drawing through the Ayapel area through the Jobo-Tablon field. This transect shows the east-vergent basement-involved thrust that characterizes the Plato–San Jorge area. A major onlap surface separates the Oligocene from the lower Miocene section, suggesting the beginning of thrusting. Growth strata above thrust-related anticlines extends up to the upper Miocene.

## *Upper Cretaceous–Paleocene*

During the Coniacian, deep-water, organic-rich shaly limestone and chert overlay basalt and gabbros comprising oceanic crust. Deep-water sediments, mostly shale with occasional turbiditic sandstone, were deposited during the Paleocene. This deep-water section was deposited west of the paleo-Romeral fault system. No deposition took place east of that position. By that time, basement comprised of Paleozoic gabbros, mafic crystalline rocks, basalt, and metamorphosed deep-water facies was already accreted to the South American continent (Restrepo-Pace, 1992). This Paleozoic accreted terrane was being intruded by granitic batholiths and was incorporated into the South American continent. Across most of the study area, the Romeral fault represents the contact between accreted Paleozoic basement and the Cretaceous oceanic crustal rocks with their overlying sedimentary section. South of the Uraba area, the thick Upper Cretaceous–Paleocene section pinched out against the emergent oceanic basement of the Central Cordillera. The Upper Cretaceous to Paleocene section may have been deposited in a trench setting related to the subduction of the Caribbean Plate underneath the South American Plate. The Paleocene isopach map suggests the emplacement of a north-northwest–south-southeast-trending oceanic ridge. Figure 17 is a block diagram that illustrates the Sinu–Lower Magdalena area during the Paleocene.

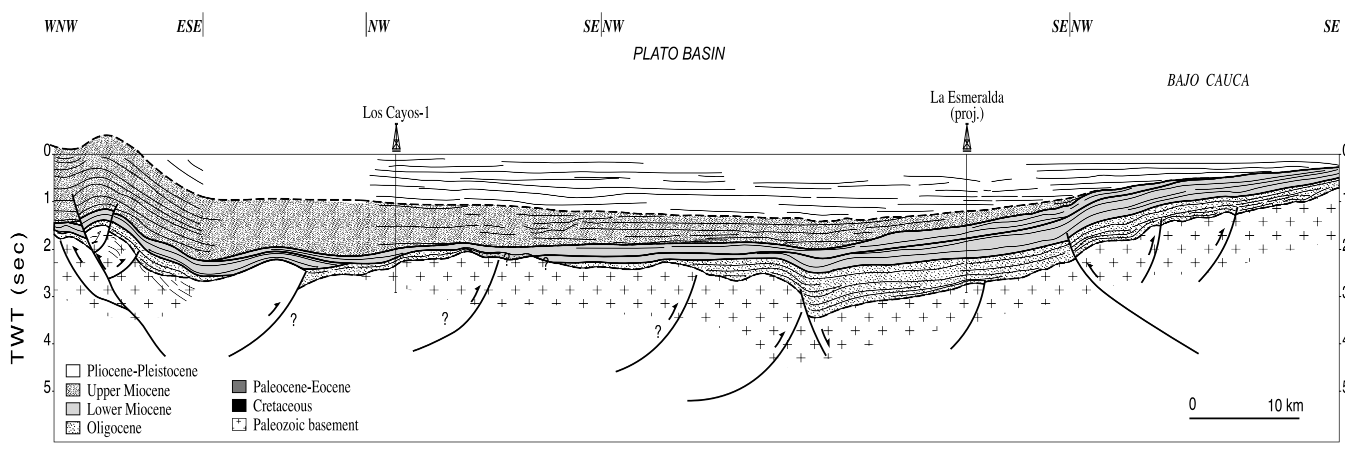


**Figure 15.** Seismic line drawing in Sucre state, Bajo Cauca area. This transect illustrates the geometry of the Plato Basin stratigraphic units. Along the eastern flank of the basin, the Pliocene-Pleistocene section onlaps above the tilted (westward-dipping) Oligocene to lower Miocene section.

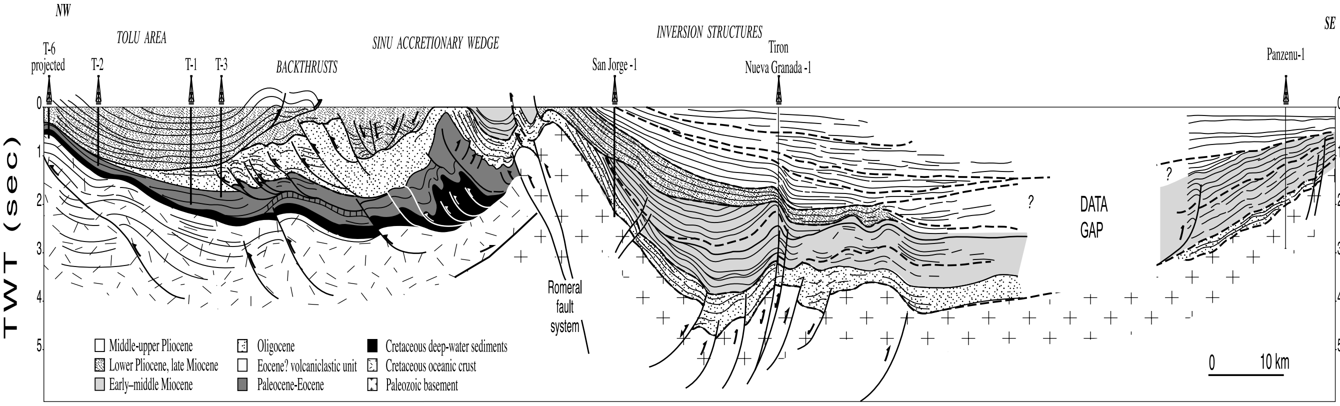


**Figure 16.** Seismic transect from the Sucre area to the Tolú Basin (Santero area). This transect shows the structure of the accretionary wedge and the oceanic basement imbricates at the Tolú area. Major inversion structures occur at the westward flank of the Plato Basin.

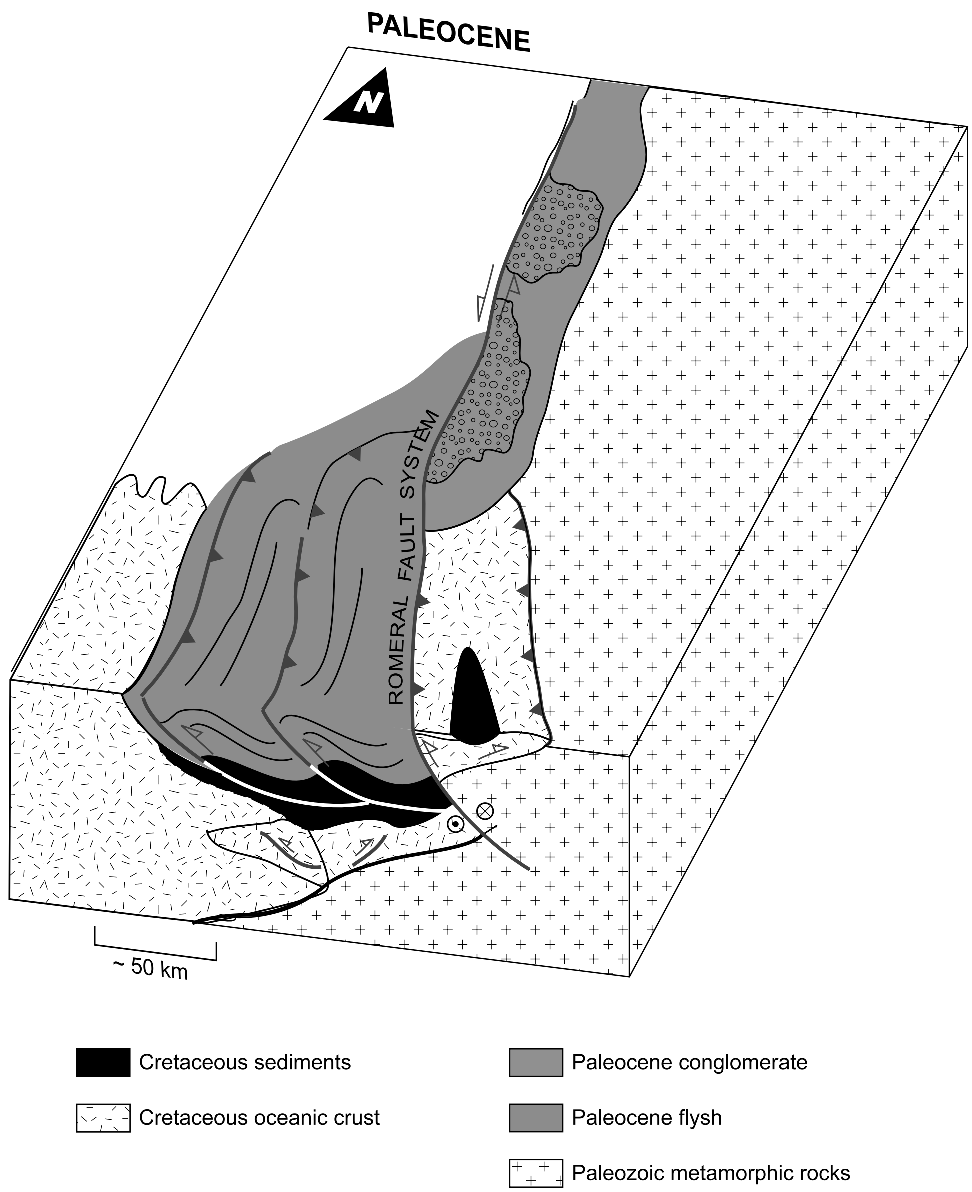


**Figure 17.** Block diagram reconstruction of the Sinu–Lower Magdalena area during the Paleocene. Transpressional activity at the Romeral fault is indicated.

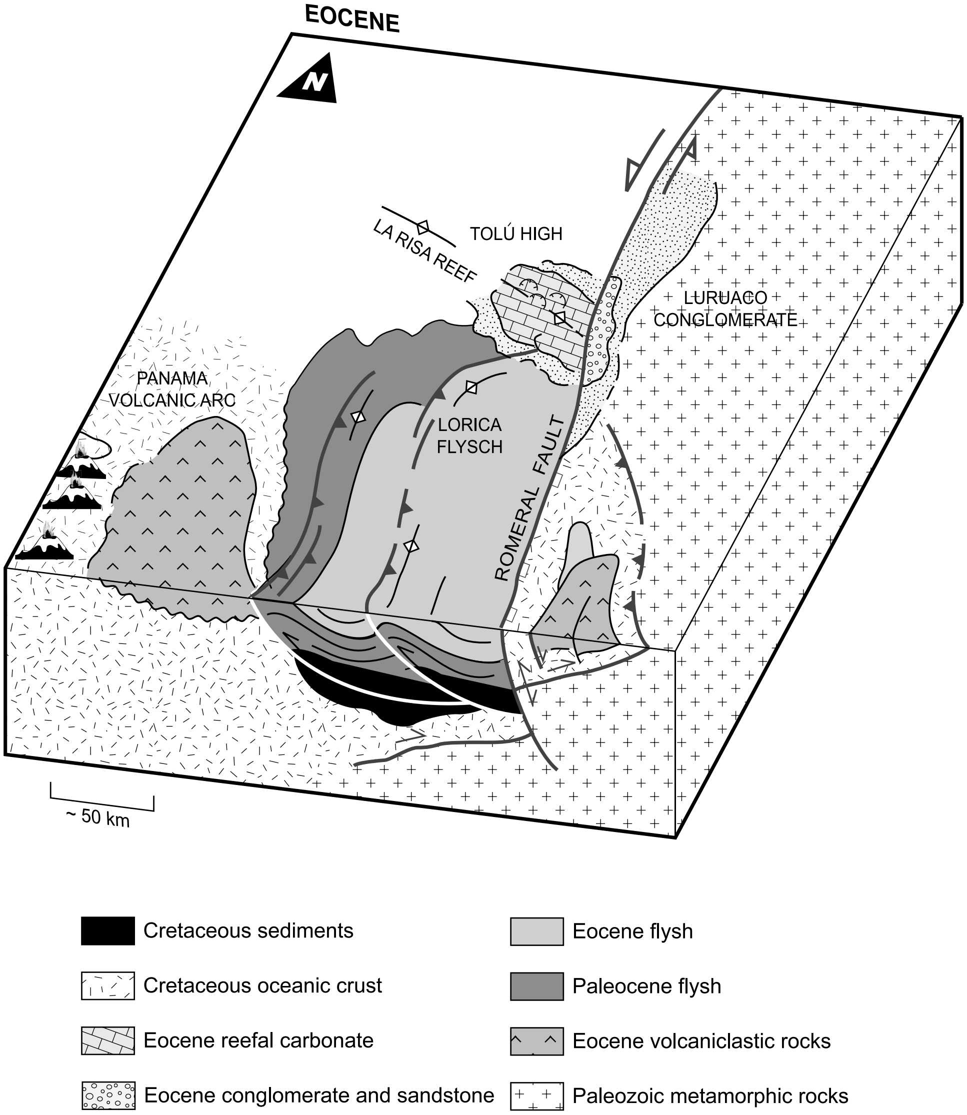


**Figure 18.** Block diagram reconstruction of the Sinu–Lower Magdalena area during the Eocene. Transtension at the Romeral fault is coeval with thrusting at the flysch dominated accretionary wedge.

## *Upper Eocene–Oligocene*

A thick volcaniclastic unit was deposited above the Cretaceous oceanic crust in the Uraba area. This thick unit may be related to the northern Panama accretionary wedge or to an island arc located between the Panama and northern Colombia prisms. Similar volcaniclastic rocks were deposited in a half-graben in the southern region. Figure 18 is a sketch-block diagram of the study area during the Eocene. According to surface geologic data, the base of the piggyback basins may be as old as upper Eocene in age (Ingeominas, 1997), and well log data suggest that the accretionary wedge is overlain by upper Eocene to Miocene piggyback basins. Deposition in these basins was mostly turbiditic as late as the middle Miocene, when it became transitional to continental. A large Oligocene flysch depocenter in excess of 3000-m-deep formed in the Arboletes–South Cordoba area (see Figure 12). Palinspastic reconstructions of seismic data suggest a wedge-type geometry in this area during the Oligocene (Figure 19). While accretion was taking place in the west (Sinu–San Jacinto area), east-west-trending normal faulting and strike-slip deformation(?) was taking place in the Sucre and Ayapel areas (Plato–San Jorge subbasin) in an overall transtensional regime. Pull-apart activity in the Plato–San Jorge Basin may have started during the Eocene (Reyes-Harker et al., 2000, Reyes-Santos et al., 2000). Oligocene transtension has been suggested, based on seismic data along the Romeral and Palestina Faults (Reyes-Harker et al., 2000).

## *Miocene*

During the Miocene, the piggyback basin fill changed from marine to transitional and finally to continental deposits. Shallow-water to continental deposition in the east was coeval with deep water deposition in the west, in the vicinity of the present shoreline of the Caribbean Sea. The uplift of the accretionary wedge resulted in a major regression or seaward shift of facies.

East of the Romeral fault system, a north-south-trending basement-involved thrust system developed along with major inversion of preexisting half-graben structures. Lower Miocene inversion has been reported along the Ariguani-Algarrobo fault system (Reyes-Harker et al., 2000). Upper Miocene compression also is interpreted from seismic data (Reyes-Santos et al., 2000). Northwest-southeast-trending

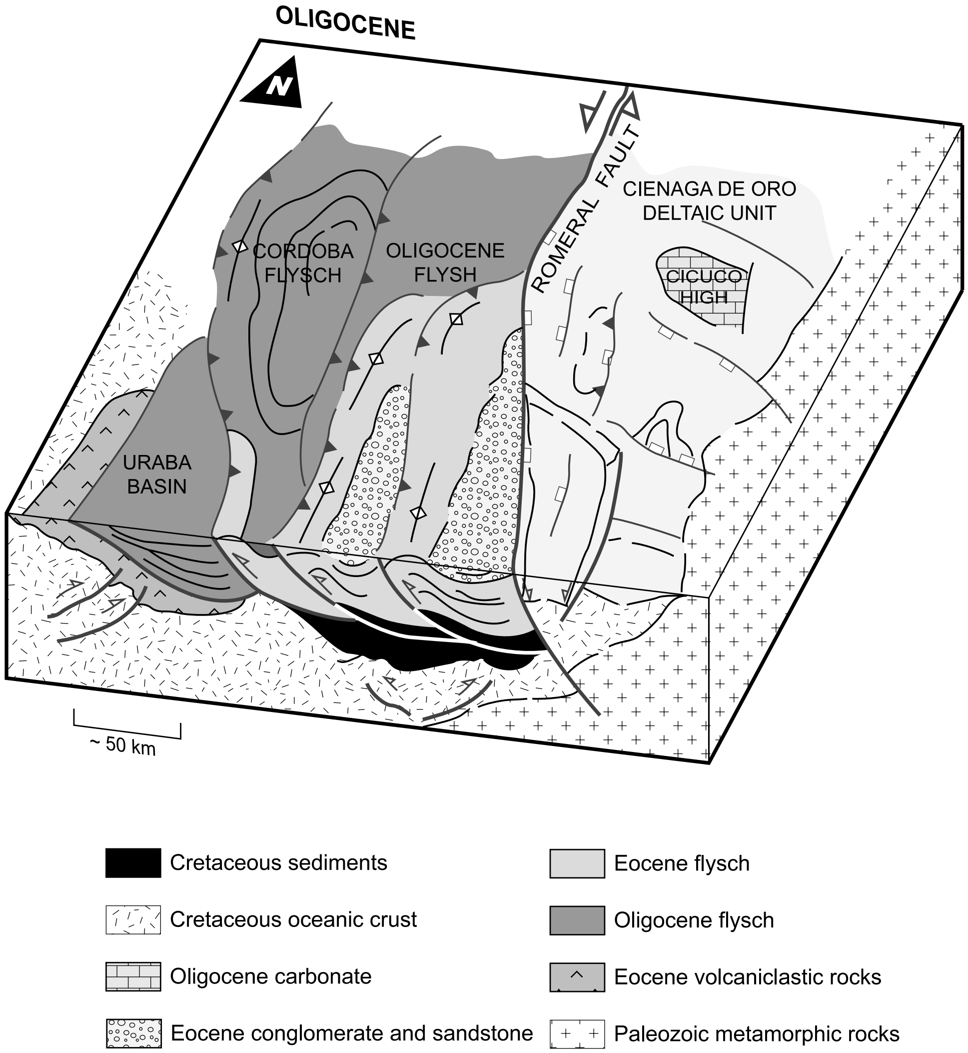


**Figure 19.** **Block diagram reconstruction of the Sinu–Lower Magdalene area during the Oligocene. Transtension along the Plato–San Jorge Basin is coeval with thrusting at the flysch-dominated accretionary wedge and the development of the Uraba flexural basin.**

Oligocene normal faults were inverted during the Miocene, so areas that were low during the Oligocene became high areas during the Miocene. Basement-involved, doubly vergent thrusting in the east was coeval with thin-skinned thrusting in the west.

### *Pliocene-present*

Since the Pliocene, sedimentary depocenters shifted toward the offshore. A major regression was responsible for a rapid facies change from coastal to marine sediments to marginal marine and eventually to continental sediments. The shallowing-upward sequences that resulted from this regression can be seen clearly along piggyback basins of the Floresanto area (see Figures 2 and 3, and transects in Figures 8–11 and 14–16). Widespread fluvial-alluvial deposition represented by the continental Corpa Formation took place along both sides of the Romeral fault. Compression and inversion took place close to the Romeral fault, as seen in the Tiron field (Reyes Santos et al., 2000).

## DISCUSSION

The seismic transects, depth sections, and tentative reconstructed section (Figure 7) illustrate the complex structure of the study area. The evolution of the Sinu–San Jacinto accretionary wedge can be traced by the shifting of sedimentary depocenters. This apparent migration toward the offshore area was disrupted by lateral ramps and by the emplacement of oceanic basement ridges oblique to the thrust transport direction (i.e., the Tolú ridge). The nature of the contact between the Plato–San Jorge Basin and the Sinu Prism also is not clear and is discussed in the next section.

### *The Accretionary Wedge and Related Piggyback Basins*

Seismic and surface data suggest that piggyback basins developed from the upper Eocene to the upper Miocene. Most of these basins initially were filled by deep-water sediments (flysch) until the middle Miocene, and then by transitional to continental (''molassic'') deposits. The presence of parallel and very widespread Oligocene turbiditic sandstones in the Floresanto area may suggest the presence of an Oligocene foreland basin that was later deformed. This hypothesis is consistent with the reconstruction shown in Figure 8, and it would imply a younger age for the piggyback basins located above the accretionary wedge. The shifting of sedimentary

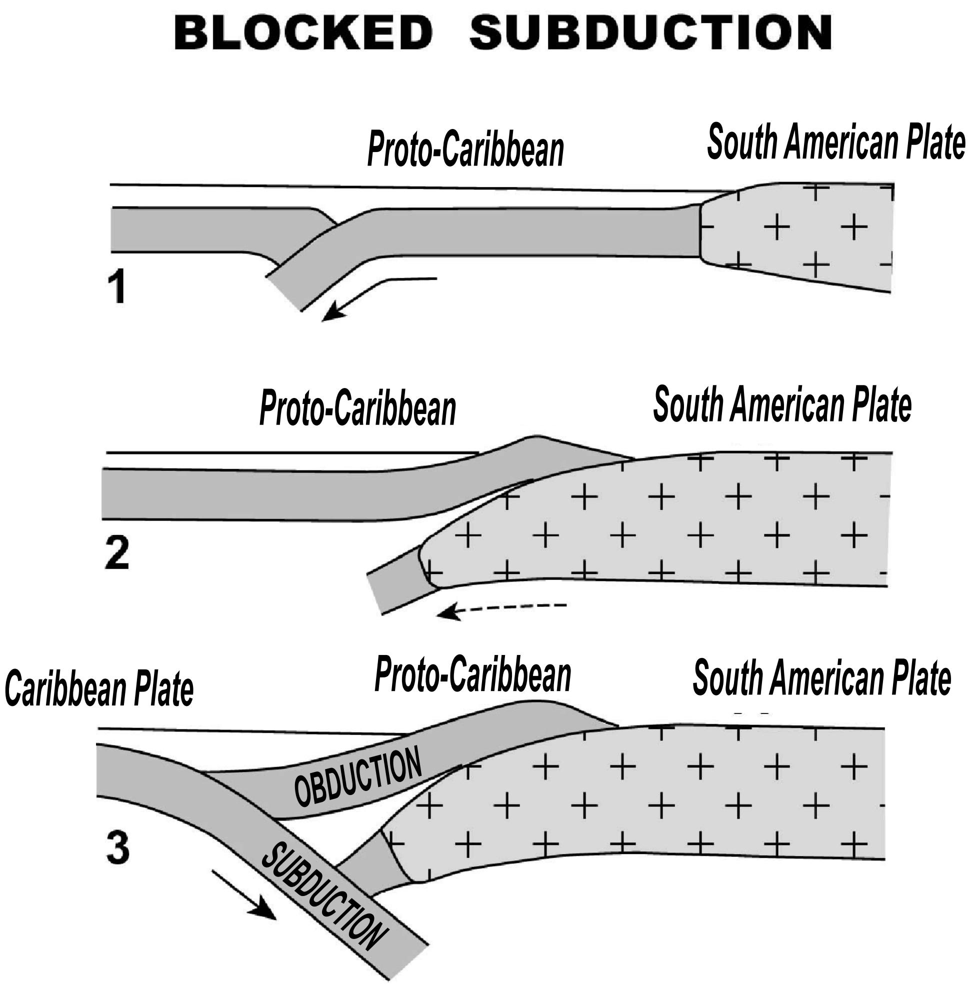


**Figure 20.** Diagram illustrating the concept of blocked subduction applied to northern Colombia. Obduction of the proto-Caribbean oceanic crust during the Upper Cretaceous is followed by Neogene subduction and accretion, which is still active today.

depocenters reflects the westward migration of the accretionary wedge through time.

### *The Romeral Fault System*

One of the most intriguing aspects of the structure of the region is the contact between the metamorphic basement that underlies the Plato–San Jorge Basin to the east and the strongly deformed Upper Cretaceous to Neogene sedimentary section of Sinu–San Jacinto to the west. This major geologic contact, poorly exposed on the surface and with a complex subsurface seismic expression, is the Romeral fault. The mapping patterns inferred from seismic data suggest a steeply eastward-dipping fault with at least three clear kinematic stages: reverse offset during the Late Cretaceous to Paleocene, normal offset during the Eocene-Oligocene, and compressional (reverse) offset during the Pliocene to Pleistocene. Inversion structures are present along the Romeral fault system. The Romeral fault system represents a sharp rheological contact that separates two very different structural styles. Thin-skinned detachment thrusting existed west of the Romeral fault (Sinu–San Jacinto accretionary wedge), consisting of deformed Upper Cretaceous–Paleocene trench deposits. This was coeval with basement-involved deformation east of the Romeral fault system (Plato–San Jorge Basin). Regardless of the major role played by the Romeral fault, seismic and surface data suggest that the Romeral fault is not the suture between obducted Cretaceous ophiolitic units with Paleozoic continental basement. Seismic data show a major westward-dipping thrust in the acoustic basement overlain by volcaniclastic sediment that was reactivated during the Neogene. This contact is crosscut by the steeply eastward-dipping Romeral fault. These observations, along with the presence of widespread ophiolitic rocks east of the Romeral fault (see Figure 1), suggest that the Romeral fault was not the obduction suture. The ophiolites thrust onto the basement of the South American Plate may represent obducted fragments of a large peri-Caribbean set of Cretaceous island arcs, the so-called Great Arc of the Caribbean of Burke (1988), or parts of the over-thickened Caribbean Plateau crust. The structural evolution of the study area can be interpreted in terms of blocked subduction (Figure 20); that is, after an obduction event ceases and is blocked (Upper Cretaceous–Paleocene in the study area), subduction takes over (from the Paleocene to Holocene), is responsible for accretion, and begins a process of exhumation of the preexisting obducted slab.

## CONCLUSIONS

The Sinu–San Jacinto area is a Paleocene to Oligocene accretionary wedge. Older rocks of this prism are exposed to the east, which is referred to as the San Jacinto Mountains. The younger imbricated part of the prism is known in the literature as the Sinu area, and it is exposed to the west.

The Sinu–San Jacinto accretionary wedge represents the older part of the northern Colombia accretionary wedge, while the younger part of the wedge is the Oligocene to Holocene offshore Sinu wedge.

The Plato–San Jorge area represents a back-arc basin that was controlled by transtension during the Oligocene and by transpression during the Miocene. Major subsidence and tilting occurred at the base of the Porquero Formation. The underlying Oligocene Cienaga de Oro represents the major reservoir unit.

The Romeral fault system is a complex fault zone that has undergone Oligocene extension/transtension and Miocene to Pliocene compression/transpression. This fault system offsets the obduction suture between the proto-Caribbean oceanic plate and the South American continental plate.

The Coniacian Finca Vieja member of the Cansona Formation represents the major source rock of the Lower Magdalena area. Younger Tertiary oil- and gas-prone source rocks also exist in the area.

The Paleocene-Oligocene Sinu–San Jacinto prism is dominated by turbiditic flysch deposits, except in the Tolú area, which is dominated by shallow-water sandstone and carbonate.

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