Basin Development and Tectonic History of the Llanos Basin, Eastern Cordillera, and Middle Magdalena Valley, Colombia[1]

M. A. Cooper,[2] F. T. Addison,[3] R. Alvarez,[3] M. Coral,[3] R. H. Graham,[3] A. B. Hayward,[3] S. Howe,[3] J. Martinez,[3] J. Naar,[3] R. Peñas,[3] A. J. Pulham,[3] and A. Taborda[3]

ABSTRACT

The Middle Magdalena Valley, Eastern Cordillera, and Llanos basin constituted a major regional sedimentary basin from the Triassic to the middle Miocene. Basin development began during the Triassic to the earliest Cretaceous with a synrift megasequence related to the separation of North and South America in the proto-Caribbean. The synrift megasequence began with deposition in a continental environment that became paralic and shallow marine in the Early Cretaceous. Basin development continued into the Cretaceous in a back-arc setting east of the Andean subduction zone. The back-arc megasequence was dominated by shallow-marine sedimentation and produced an excellent regional source rock during the Turonian–Coniacian. Marine deposition was abruptly terminated during the early Maastrichtian due to the final accretion of the Western Cordillera.

Accretion of the Western Cordillera created the early pre-Andean foreland basin megasequence of late Maastrichtian to early Eocene age. This depositional episode consists of coal-rich alluvial plain, coastal plain, and estuarine deposits throughout the Middle Magdalena Valley, Eastern Cordillera, and eastern Llanos basin. The megasequence was terminated by middle Eocene deformation in the Magdalena Valley, which ended sediment deposition throughout Colombia. Loading effects of this deformation reestablished the basin, in which the late pre-Andean foreland basin megasequence was deposited, until the early Miocene. This megasequence also consists of alluvial plain, coastal plain, and estuarine deposits, including the primary reservoir in the Llanos Foothills—the upper Eocene Mirador Formation. The megasequence also includes a series of four major grossly coarsening-upward cycles in the Llanos basin; these cycles correspond to changes in sea level, sediment supply, and foreland basin loading. The mudstone in the lowermost of these cycles is the regional seal in the Llanos basin and Foothills.

The middle Miocene onset of Andean deformation in the Eastern Cordillera isolated the Middle Magdalena Valley from the Llanos basin. The deformation was dominated by inversion of the basin-controlling faults; the resultant loading of the lithosphere created the accommodation space for the Andean foreland basin megasequence. A major transgression into the Llanos basin coeval with this deformation caused deposition of marine mudstones in the lower part of the megasequence. However, the majority of the Andean foreland basin megasequence consists of the Guayabo Formation, a classic molasse sequence, deposited in a high-energy, coarse-grained, bed-load–dominated fluvial system that was supplied by the developing mountains of the Eastern Cordillera.

INTRODUCTION

The physiography of Colombia is dominated by the Andes mountains in the west and the Amazon/Orinoco basin in the east. The Colombian Andes form three separate ranges, the Western, Central, and Eastern Cordilleras, which merge southward into a single range. The Cauca valley separates

---

[1] Manuscript received June 10, 1994; revised manuscript received March 14, 1995; final acceptance June 6, 1995.

[2] PanCanadian Petroleum, 150 9th Ave. SW, Calgary, Alberta, Canada T2P 2S5.

[3] BP Exploration (Colombia) Ltd., Carrera 9A no. 99-02, Piso 9, A.A. 59824, Bogotá, Colombia.

We wish to thank BP Exploration (Colombia) Ltd. for permission to publish this paper and Olga Lucia Daza for drafting the figures. We are also grateful to Jaime Buitrago and Kevin Biddle for constructive and helpful reviews and to John Weissenberger for reading numerous drafts of the revised manuscript.

💾 An extended bibliography is available on diskette (Macintosh or Windows). Send your check, made out to AAPG, for $3.00 to Publications Manager, P.O. Box 979, Tulsa, Oklahoma 74101-0979.

AAPG Bulletin, V. 79, No. 10 (October 1995), P. 1421–1443.

the Western and Central Cordilleras, and the Magdalena Valley separates the Central and Eastern Cordilleras. East of the Eastern Cordillera is the Llanos, a savanna that is part of the catchment area for the Orinoco River.

Early workers made detailed age determinations using ammonites from Cretaceous beds around the Sierra Nevada del Cocuy and Villa de Leiva (von Buch, 1839; Lea, 1840; Orbigny, 1842). The first detailed maps of the Eastern Cordillera were produced by Hettner (1892), and maps of the Llanos Foothills were produced by Hubach (1957). Advances in Colombian geological knowledge have been closely linked to mineral exploration and exploitation. Emeralds are in the Lower Cretaceous and coal is in the Upper Cretaceous and Lower Tertiary of the Eastern Cordillera and Guajira (Figure 1). Oil and gas exploration has been concentrated in the Llanos, Putumayo, and Magdalena basins.

Bürgl (1961) produced a reconstruction of Cretaceous and Tertiary paleogeography and related sedimentation to tectonics, establishing a chronological correlation of the Cretaceous and Tertiary nomenclature. He compiled Cretaceous thicknesses (Ramirez, 1953; Morales and the Colombian Petroleum Industry, 1956; Renz, 1956; Bürgl, 1960) and observed considerable variability in thickness in the Sabana de Bogotá. He interpreted these differences in thickness as being due to four stages of marine transgression during the Upper Jurassic and Cretaceous. These stages progressively onlapped the Guyana shield. Since the work of Bürgl (1961), the stratigraphic interpretation of the Eastern Cordillera has developed slowly. Etayo (1964, 1979), Etayo et al. (1969), and Fabre (1987) refined the understanding of Cretaceous shoreline changes, and numerous authors have identified continental sediments in the Jurassic and Lower Cretaceous prior to the marine transgressions (Cediel, 1968; Mojica and Dorado, 1987). The majority of recent literature that integrates stratigraphy and tectonics has been focused on the Magdalena Valley (Butler and Schamel, 1988, 1989; Schamel, 1991; Montgomery, 1992). Significant papers on the tectonics of the Eastern Cordillera are Campbell (1974), Colletta et al. (1990), and Dengo and Covey (1993).

In this paper, we present a sequence stratigraphy for the Middle Magdalena Valley, Eastern Cordillera, and Llanos basin. The sequence stratigraphy is related to the deformation that has affected Colombia since the Triassic and provides a framework for interpreting basin evolution. The paper is also intended to provide the regional context for the companion paper by Cazier et al. (1995), which discusses the petroleum geology of the Cusiana field.

REGIONAL TECTONIC FRAMEWORK AND BASIN DEVELOPMENT

Major tectonic events that influenced development of the Colombian basins are all closely tied to the evolution of the active margin of western South America. In this paper, we concentrate on basin development from the Cretaceous onward in the Middle Magdalena Valley, Eastern Cordillera, and the Llanos basin (Figure 1). Models of tectonic evolution prior to the Late Cretaceous are unconstrained by ocean floor magnetic anomaly data (Pardo-Casas and Molnar, 1987) and thus are speculative.

The basement of Colombia is divisible into three zones separated by major sutures (Suarez, 1990): (1) the Precambrian Guyana shield in the east; (2) the Central Province of Precambrian–early Paleozoic metamorphic rocks, which underlies the Central and Eastern Cordilleras; and (3) accreted oceanic crustal fragments and subduction-related sediments and volcanics, which form the Western Cordillera (Barrero, 1979; Alvarez, 1983; Duque-Caro, 1990). Megard (1987) interpreted accretion of the western terrane along the Romeral suture (Figure 1) as a series of discrete collisions commencing in the Early Cretaceous and ending in the Eocene. The suture between the Guyana shield and Central Province is the Borde Llanero, which approximately coincides with the Llanos Foothills thrust front (Suarez, 1990). Following the work of Butler and Schamel (1988, 1989), Montgomery (1992) suggested that the distribution of Cretaceous and Tertiary basins in central Colombia was possibly controlled by reactivation of old faults.

During the Triassic, Jurassic, and earliest Cretaceous, Colombia was peripherally affected by rifting related to eventual separation of North and South America in the proto-Caribbean (Jaillard et al., 1990). Maze (1984) proposed an alternative mechanism for the extension in a back-arc setting, which, given the oblique nature of the subduction zone, may have had a transtensional component. Both mechanisms probably contributed to the extension. Exact timing of rifting onset is difficult to determine because the synrift continental clastics are difficult to date. The depocenters were established throughout the Eastern Cordillera and Upper Magdalena with marginal basins in the Llanos and Putumayo basins (Figures 1, 2). In the Eastern Cordillera, two rift basins developed (Figure 2), the Cocuy basin in the east and the Tablazo-Magdalena basin in the west (Etayo et al., 1969). Between the two depocenters is the intrabasinal Santander high (Figure 2), which includes the Santander and Floresta massifs and persists south of Tunja as a zone of thinned Lower

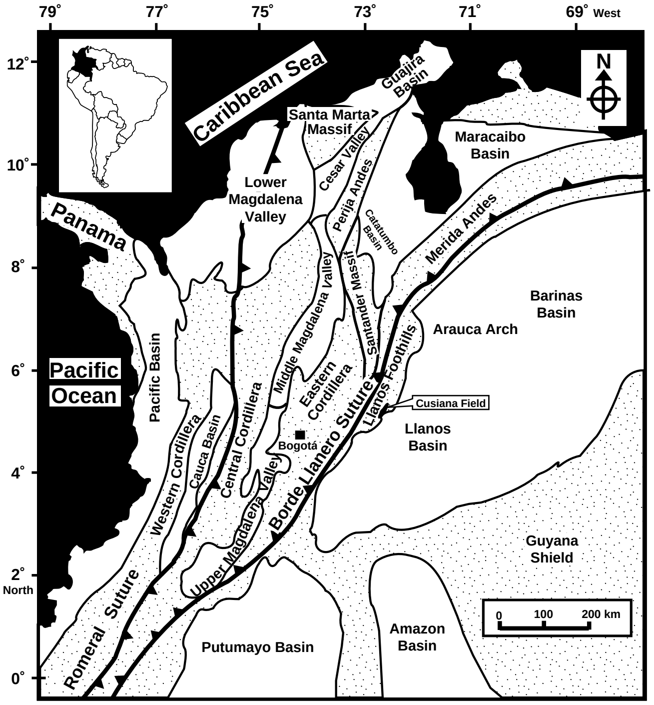


Figure 1—Map of major tectonic provinces of Colombia, with present-day sedimentary basins shown in white.

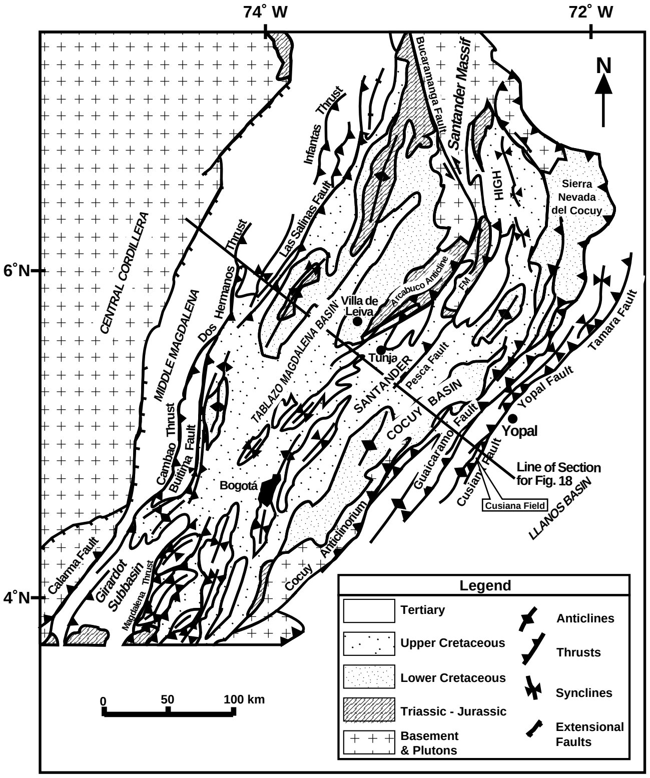


Figure 2—Map of major tectonic elements and stratigraphic units within the Eastern Cordillera, Middle Magdalena Valley, and the Llanos basin. Location of the regional cross section in Figure 18 is also shown. FM = Floresta massif.

Cretaceous stratigraphy (Etayo et al., 1969). This system of basins was active into the Early Cretaceous, when considerable accommodation space was created in the Eastern Cordillera (Hebrard, 1985; Fabre, 1987) allowing thick Lower Cretaceous deposition. Shallow-water sedimentation through much of the Cretaceous suggests that deposition approximately kept pace with subsidence. Early Cretaceous extension and subsidence may have been due to back-arc stretching behind the subduction zone off the western coast of South America. Subduction is believed to have intensified in the Late Jurassic and Berriasian based on the presence of calc-alkaline plutons of this age in the eastern part of the Central Cordillera (McCourt et al., 1984).

A Valanginian–Barremian hiatus in igneous activity is interpreted to have resulted from accretion of the Amaime terrane, composed of Upper Jurassic to Lower Cretaceous oceanic crust along the Romeral suture (Aspden and McCourt, 1986). Megard (1987) suggested that subduction shifted westward following the accretion, as did plutonic activity, which peaked in the Campanian and Santonian (Aspden and McCourt, 1986). The subsidence rate in the back-arc basin decreased in the post-Cenomanian. Magmatic arcs produced during subduction do not appear to have created emergent landmasses west of the back-arc basin, except in the Upper Magdalena Valley where immature, continental clastics were deposited until marine conditions were established in the Aptian. The implication is that an emergent barrier related to subduction developed in southern Colombia, but did not persist northward into the Tablazo-Magdalena basin. The Central Cordillera remained submerged until the Maastrichtian, although Bürgl (1961) believed there was a submarine barrier between the Western Andes (his eugeosyncline) and the nonvolcanic Eastern Andes (his miogeosyncline). First indications of western sediment provenance (granitic and volcanic pebbles derived from the Central Cordillera) are in the early Maastrichtian Cimarrona Formation on the eastern margin of the southern Middle Magdalena Valley.

Four major occurrences of deformation have been recognized in the Tertiary of central Colombia: Late Cretaceous–early Paleocene, middle Eocene, late Oligocene–early Miocene, and late Miocene–Pliocene (Bürgl, 1961; Ben Avraham and Nur, 1987).

Late Cretaceous–early Paleocene deformation resulted from the final accretion of the Western Cordillera (McCourt et al., 1984) (Figure 3). This

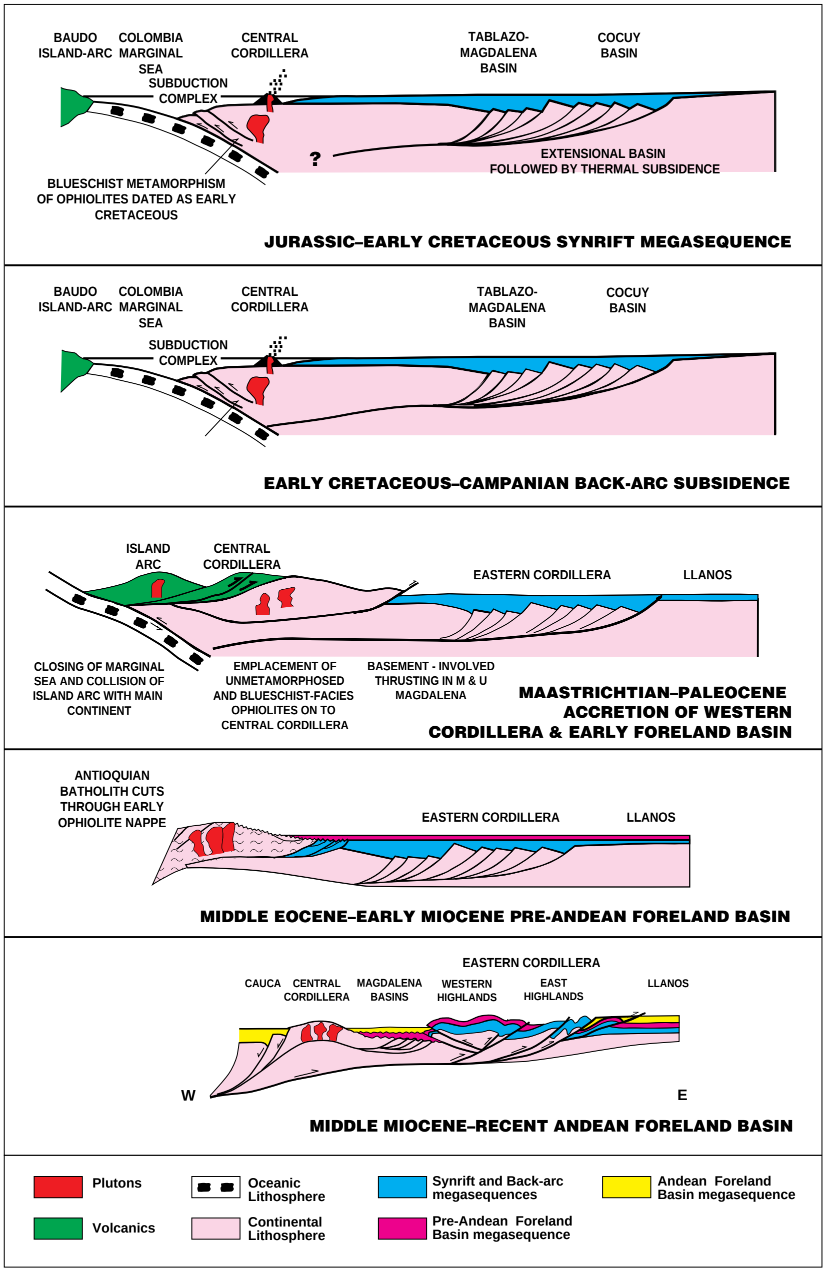


Figure 3—Sequential model of regional tectonic development for the Eastern Cordillera, Middle Magdalena Valley, and the Llanos basin.

deformation marks a significant change in depositional environments throughout the Eastern Cordillera, Magdalena basin, and Llanos basin (Figures 4, 5) from marine to continental in the incipient foreland basin (Van der Hammen, 1961). Prior to this deformation, deposition since the Early Cretaceous was entirely marine except for the shoreline facies on the Guyana shield margin and some fluvial sedimentation in the Upper Magdalena. Late Cretaceous–early Paleocene deformation was restricted to the Western and Central Cordilleras except for some deformation and uplift in the Sierra Nevada del Cocuy (Figure 2) (Fabre, 1987). The amount of compressional deformation generated during the accretion may have been limited by the oblique convergence of the Nazca and South American plates until 49 Ma (Pardo-Casas and Molnar, 1987).

Middle Eocene deformation created folds and thrusts in the Middle Magdalena Valley. These folds are truncated and unconformably overlain by upper Eocene clastics (Morales and the Colombian Petroleum Industry, 1956). This deformation may be related to an increase in convergence rate between 49 and 42 Ma (Daly, 1989).

Changes in plate tectonic motions documented in the late Oligocene to early Miocene (Pilger, 1984;

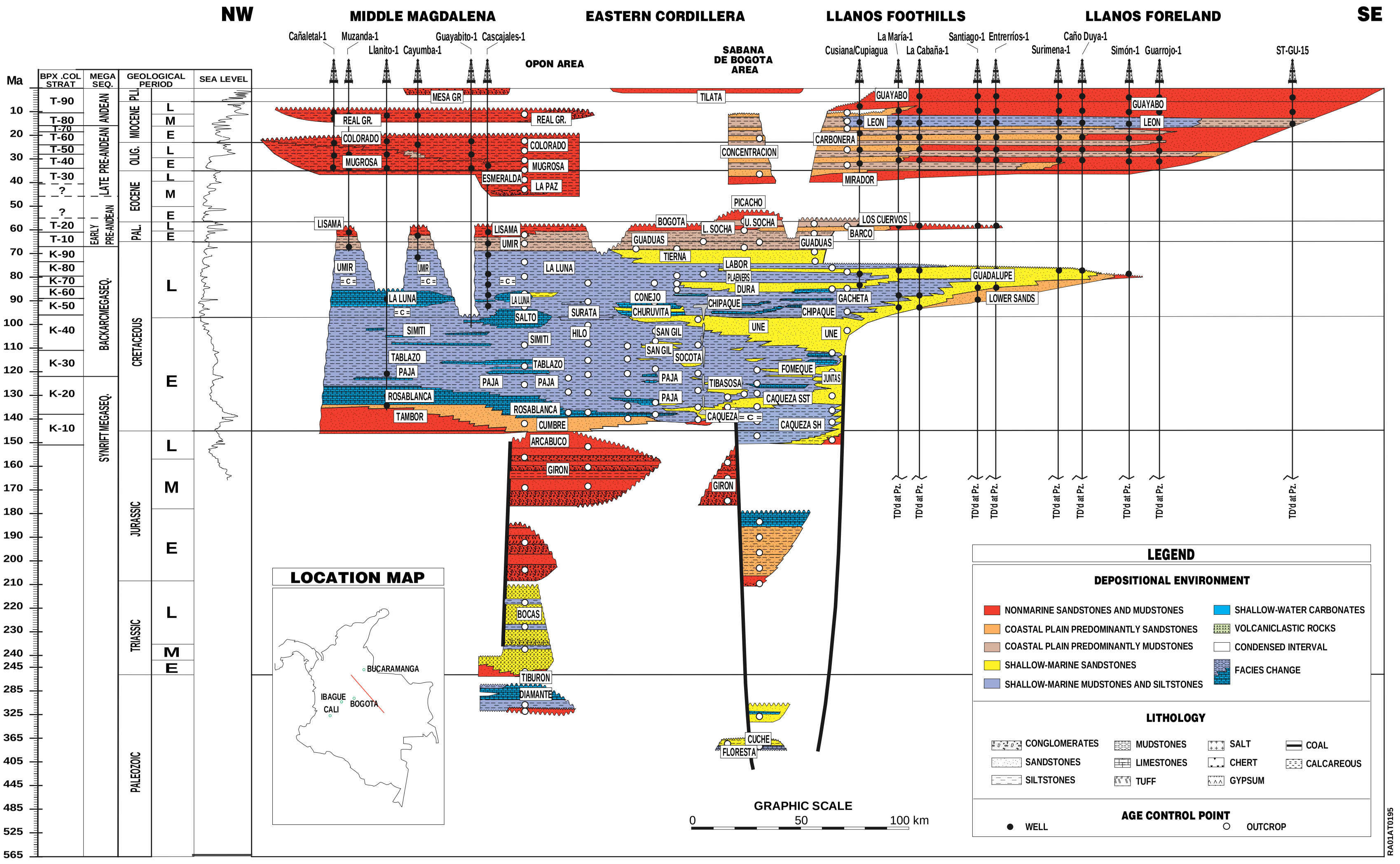
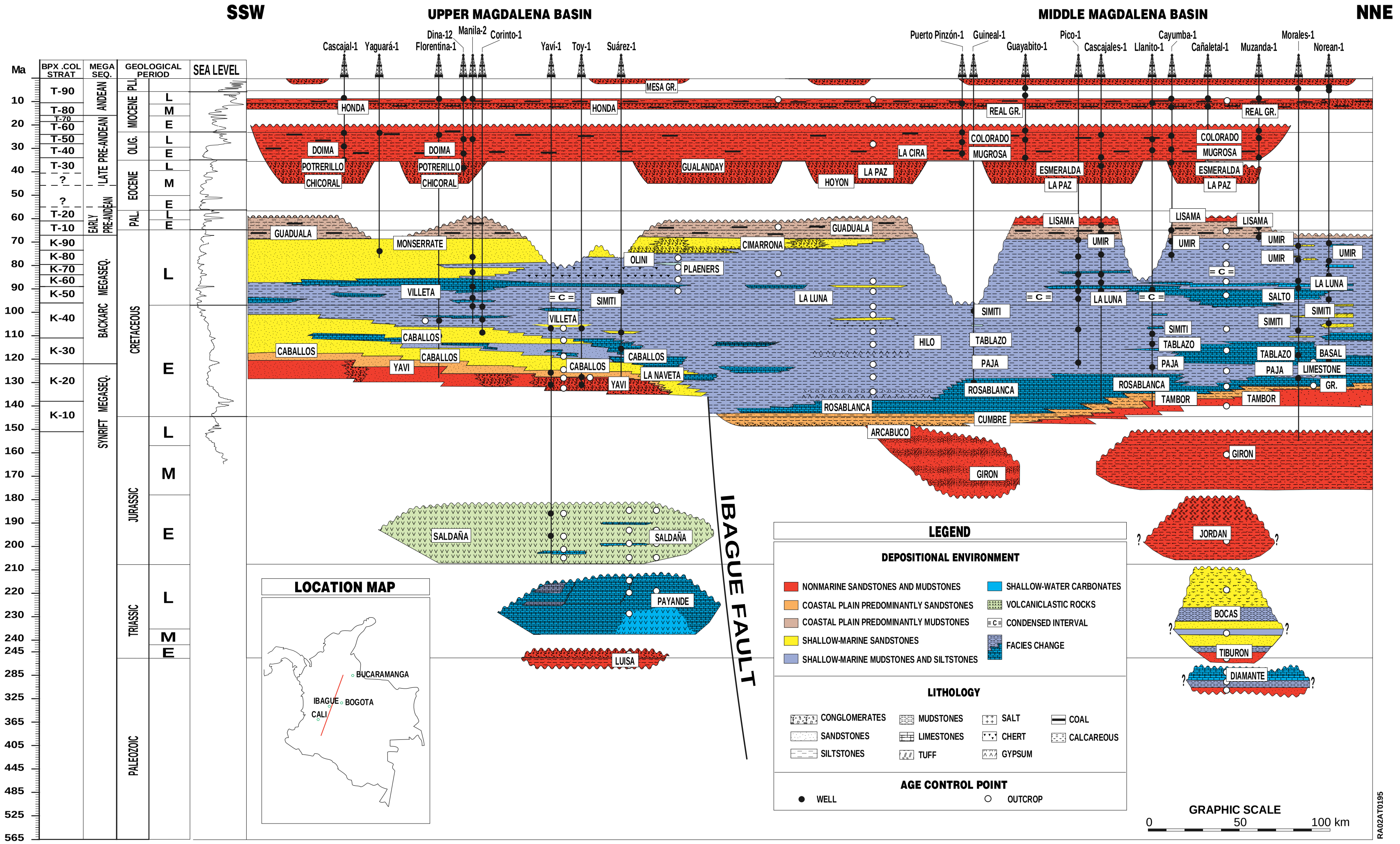


Figure 4—Chronostratigraphic summary diagram for the Middle Magdalena Valley and the Llanos basin with key lithostratigraphic formation names indicated in their correct spatial and temporal locations. Note the change in the time scale at 245 Ma. The controlling data points for the interpretation are shown on the diagram, and the references are available on the supplementary data diskette available from AAPG.



LEGEND

DEPOSITIONAL ENVIRONMENT

- 🟥 NONMARINE SANDSTONES AND MUDSTONES
- 🟧 COASTAL PLAIN PREDOMINANTLY SANDSTONES
- 🟫 COASTAL PLAIN PREDOMINANTLY MUDSTONES
- 🟨 SHALLOW-MARINE SANDSTONES
- 🟪 SHALLOW-MARINE MUDSTONES AND SILTSTONES
- 🟦 SHALLOW-WATER CARBONATES
- ▨ VOLCANICLASTIC ROCKS
- =C= CONDENSED INTERVAL
- ▨ FACIES CHANGE

LITHOLOGY

- ▨ CONGLOMERATES
- ▨ SANDSTONES
- ▨ SILTSTONES
- ▨ MUDSTONES
- ▨ LIMESTONES
- ▨ TUFF
- ▨ SALT
- ▨ CHERT
- ▨ GYPSUM
- ▬ COAL
- ▨ CALCAREOUS

AGE CONTROL POINT

- ● WELL
- ○ OUTCROP

Figure 5—Chronostratigraphic summary diagram for the Middle and Upper Magdalena Valleys with key lithostratigraphic formation names indicated in their correct spatial and temporal locations. Note the change in the time scale at 245 Ma. The controlling data points for the interpretation are shown on the diagram, and the references are available on the supplementary data diskette available from AAPG.

Ben-Avraham and Nur, 1987) did not cause any deformation in the Eastern Cordillera or the Llanos. Deformation of this age has been described in the Cauca Valley (Alfonso et al., 1989) and in the Magdalena Valley where the reactivation of the middle Eocene structures created an upper Oligocene unconformity (Schamel, 1991). Collision of the Choco terrain with the northwestern margin of South America also occurred during the middle Miocene (Duque-Caro, 1990), which may have contributed to loading and initiated deformation in the Eastern Cordillera.

Major deformation of the Eastern Cordillera and Llanos Foothills began at approximately 10.5 Ma and resulted from Panama's collision with South America. During this deformation phase, the Eastern Cordillera was uplifted and eroded. Old extensional faults were inverted and new compressional structures developed. On the western flank of the Eastern Cordillera and in the Magdalena Valley, middle Eocene folds were reactivated (Butler and Schamel, 1989).

Erosional deposits from the Eastern Cordillera are preserved in the Guayabo Formation in the Llanos basin. Deformation and uplift are still active, periodically causing earthquakes in the Llanos Foothills. Studies of the Pliocene Tilata Formation suggest that 1000–2000 m of the uplift occurred at approximately 3.5 Ma (Van der Hammen, 1957; Hooghiemstra, 1984). These data were used by Dengo and Covey (1993) to time basement-involved deformation in the Eastern Cordillera; however, the Tilata rests with a pronounced angular unconformity on a variety of older strata, indicating that some deformation preceded deposition of the Tilata.

REGIONAL STRATIGRAPHIC FRAMEWORK AND BASIN EVOLUTION

Our basin stratigraphic model is based on published well-log, core, seismic, and outcrop data acquired by BP during exploration of the Llanos Foothills, combined with regional studies of the Llanos basin and Eastern Cordillera. The regional database includes logs from over 170 exploration and development wells; 25,000 km of seismic data; 40 biostratigraphic analyses from individual wells; regional outcrop and mapping studies in the Eastern Cordillera and Llanos basin; and numerous published papers. Schamel (1991) published a stratigraphic correlation for the Upper and Middle Magdalena Valley with a number of transgressive/regressive cycles after Macellari (1988). Dengo and Covey (1993) produced a lithostratigraphic correlation from the Middle Magdalena to the Llanos along the line of their regional cross section. Our model considers a larger area and subdivides the Cretaceous and Tertiary into more sequences.

Bürgl (1961) proposed that gentle, vertical Cretaceous movements caused cycles of sedimentation, beginning with shallow-water deposits followed by bathyal and littoral sediments. He did not recognize angular unconformities within the Cretaceous in the Andean zones, but did describe stratigraphic gaps, condensed sequences, and isopach changes that he interpreted as the consequence of syndepositional folding. This deformation was considered to have initiated the present-day mountain ranges and five synclinoria basins in which Tertiary and Quaternary sediments were deposited.

In this paper, we have synthesized the confusing lithostratigraphic nomenclature in Colombian geological literature to produce chronostratigraphic summaries of the Llanos basin, Eastern Cordillera, and the Magdalena Valley (Figures 4, 5). These summaries are based on a sequence stratigraphy developed for the Cusiana field (Figures 1, 2) and adjacent areas of the Llanos basin (Figure 6). We then applied the sequence stratigraphy throughout the Llanos basin, Eastern Cordillera, and Middle Magdalena Valley by combining selective field work, biostratigraphic analyses, and interpretation of published and publicly available data. The chronostratigraphy was correlated over such a wide area to develop a regional model of basin evolution. This methodology is justified because subbasins existed only after the 10.5-Ma deformation in the Eastern Cordillera. Cretaceous sequences are prefaced with a "K" and Tertiary sequences with a "T" (Figure 6). The data diskette for this paper, available from AAPG, contains the raw data used to construct the chronostratigraphic correlations and the gross depositional environment maps.

Synrift Megasequence (Triassic to Sequence K20) and Older Sequences

Upper Cretaceous sediments normally rest directly on a Paleozoic sedimentary and metamorphic basement in the Llanos. Triassic–Lower Cretaceous rocks are absent in the Llanos except for small, localized (synrift?) packages in isolated wells (Numpaque, 1986). In the Eastern Cordillera, thick sequences of Lower Cretaceous and Jurassic rocks are exposed (Figure 2), although thicknesses are variable due to extension on faults controlling deposition (Cediel, 1968; Mojica and Dorado, 1987). Two depocenters can be recognized in the Eastern Cordillera (Figure 2), the Cocuy basin in the east and the Tablazo-Magdalena basin in the west, separated by the Santander high (Etayo et al., 1969)

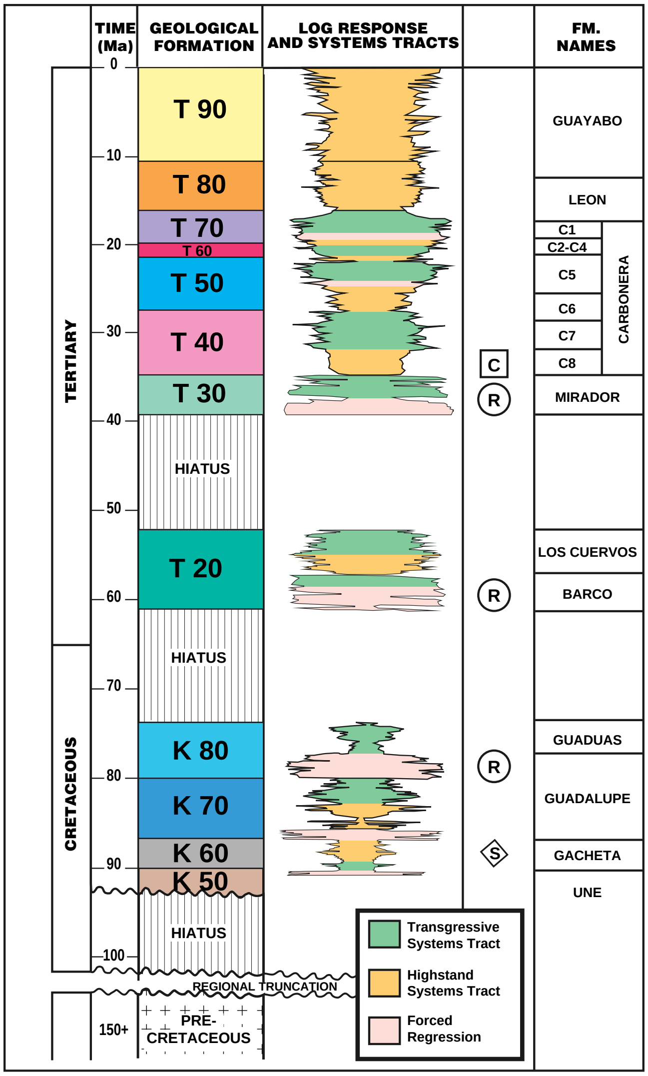


Figure 6—Cusiana field area stratigraphy showing typical gamma-ray log response. The gamma-ray log has been displayed twice by reversing the scaling for the right curve and, hence, low gamma-ray intervals are where the two curves are widely separated. The reservoir (R), cap rock (C), and source (S) intervals are indicated. The log signature is color-filled based on the systems tract interpretation. The correlation of the sequence nomenclature proposed here with conventional, industry stratigraphic terminology for the Llanos basin is illustrated in the column at the right of the figure.

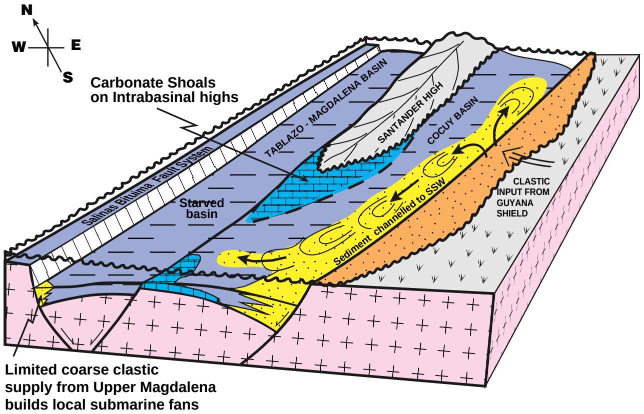


Figure 7—Block diagram illustrating the separation of the Cocuy and Tablazo-Magdalena basins during the Lower Cretaceous (sequences K20–K40) and the influence of the Santander high on facies distribution.

(Figure 7). The K10 sequence is dominated by continental red beds in the Tablazo-Magdalena basin and by shallow-marine sediments in the Cocuy basin. The sequence is not present in the Upper Magdalena Valley. The base of the K20 sequence marks a change from continental sediments of K10 to shallow-marine sedimentation in the Tablazo-Magdalena basin (Figure 4). In the Upper Magdalena Valley, the continental sandstones of the Yavi Formation were deposited during deposition of K20 following a hiatus in the Middle and Late Jurassic and K10. The Ibague fault, an ancestral Triassic–Jurassic strike-slip fault, controlled facies distribution during the Berriasian and Valanginian (Geotec, 1992). The Ibague fault may have continued to control facies during deposition of K20. Clastics eroded from the Guyana shield were efficiently ponded in the sediment sink of the Cocuy basin and gradually shale out to the southwest, suggesting a sediment entry point near the northern end of the rift (Figures 7, 8). On the Santander high, which appears to lose elevation to the south, shallow-marine carbonates were deposited (Figures 7, 8). Shallow water depths, combined with starvation of coarse clastics, caused restricted marginal marine mudstones to accumulate on the western margin of the Santander high (Paja Formation; Morales and the Colombian Petroleum Industry, 1956) (Figures 7, 8). In the Tablazo-Magdalena basin, the sequence is represented by organic-rich marine mudstones (Villeta and La Luna formations). The map of gross depositional environments (GDE) for the K20 sequence is very similar to that of the K30 sequence, which has been designated using sea level curve data (Haq et al., 1987) and regional facies patterns (Figures 4, 5). The boundary between K20 and K30 is considered to be the boundary between the synrift and backarc megasequences, coinciding with the westward jump in the subduction zone after accretion of the Amaime terrane (Aspden and McCourt, 1986; Megard, 1987). The megasequence boundary could be placed at the base of K20, but this was rejected because there are substantial thickness changes across the basin-controlling faults within the K20 sequence.

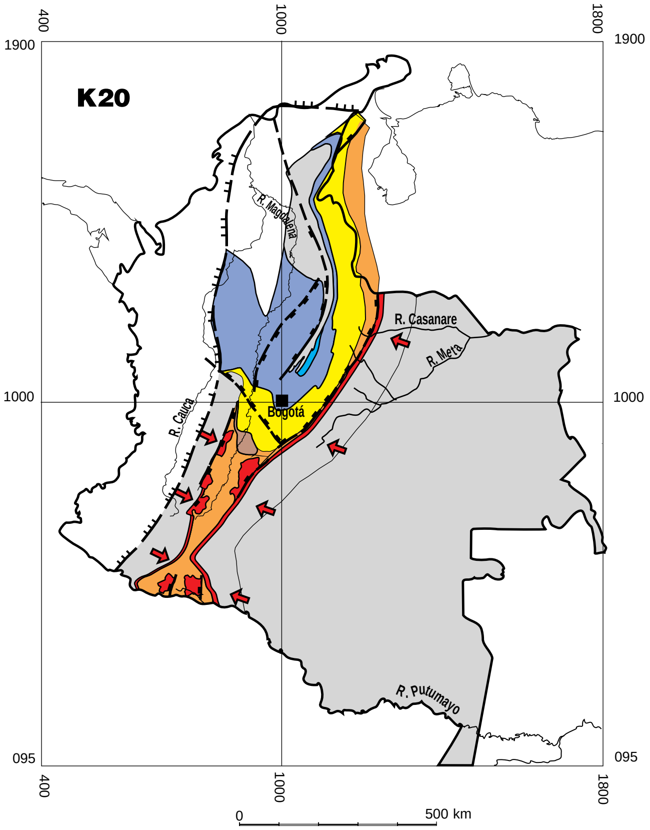


Figure 8—K20 (138–122 Ma) gross depositional environment (GDE) map drawn within the highstand systems tract at approximately 125 Ma. This map and all subsequent GDE maps have been drawn using present-day geographical positions; the key for the color scheme is the same as in Figures 4 and 5. The red arrows indicate the interpreted direction of sediment supply into the basin for this and all subsequent gross depositional environment maps.

Back-Arc Megasequence (Sequences K30–K90)

In the southern part of the Tablazo-Magdalena basin the K30 and K40 sequences are dominated by organic-rich marine mudstones and occasional thin limestones and sandstones (Villeta, Tablazo, San Gil, Simiti, and Salto formations). Most workers assume that these sediments were deposited in a deep-marine basin. However, an alternative model is that the basin became restricted and anoxic due to continued starvation from coarse clastic input. The other potential source of coarse clastics for the Tablazo-Magdalena basin during deposition of K30 and K40 was the Upper Magdalena Valley, which has thick sequences of Valanginian–Barremian fluvial and coastal plain sands (Yavi Formation). The depositional environment of the sands became marine in the Aptian (Caballos Formation, Figure 5) and intermittently supplied submarine fans to the Tablazo-Magdalena basin (Gallo, 1979). This pattern of shallow-marine sedimentation continued throughout the Cretaceous, with accommodation space being produced continually by extension in the back-arc basin.

In the Cocuy basin, deposition of K30 was characterized by minor pulses of shallow-marine sands derived from the Guyana shield, as in the Fomeque Formation (Figure 4). During K40 deposition, a gradual rise in sea level, combined with continued subsidence, caused a regional transgression. This transgression established a shallow-marine siliciclastic shelf over a wide area, including the Santander high (Une Formation; Hubach, 1931; Herngreen et al., 1990). These sandstones progressively onlapped farther eastward onto the Guyana shield during K50 deposition. The K50 sands have also been referred to as the Une Formation, but are significantly younger (Figure 4). In the Eastern Cordillera and westward, the sequence becomes increasingly muddy and eventually passes into marine mudstones with subordinate thin carbonates (Simiti and San Gil formations) (Figure 4). This transition reflects the increasingly distal nature of the primary source for the clastic sediments, which, throughout K30–K50 deposition, was the Guyana shield (Figure 4). The K40 sequence marks the end of the intrabasinal Santander high as a significant barrier to sediment movement.

In the Turonian–early Coniacian (91–88 Ma), sequence K60 was initiated by global sea level rise (Haq et al., 1987) that, combined with anoxic upwelling (Villamil and Kauffman, 1993), deposited marine mudstones, cherts, and phosphates (Figures 4, 9). K60 contains prolific source rocks; for example, the Villeta Shale in the Upper Magdalena Valley (Beltrán and Gallo, 1968) (Figure 5) and the La Luna Formation of the Middle Magdalena Valley and western Venezuela (Garner, 1925; Talukdar et al., 1986) (Figure 4). The K60 sequence has been penetrated only by the Medina 1 well in the Llanos Foothills, but field work done in the Eastern Cordillera and well data to the east in the Llanos basin indicate that it is almost certainly present throughout the Foothills area (Gachetá Formation; Miller, 1979). The K60 mudstones are oil prone and are the main petroleum source rock for the Llanos Foothills and basin (Fabre, 1987; Palmer and Russell, 1988; Droszd and Piggott, in press) and the Magdalena Valley (Zumberge, 1984). The K60 onlapped the Guyana shield and overstepped the basal Cretaceous sands to establish a more easterly littoral facies belt (Figure 9).

Anoxic conditions during K60 were terminated by a fall in relative sea level in the Coniacian–early Santonian (88–85 Ma). The fall in relative sea level shifted deposition into a northeast-trending basin

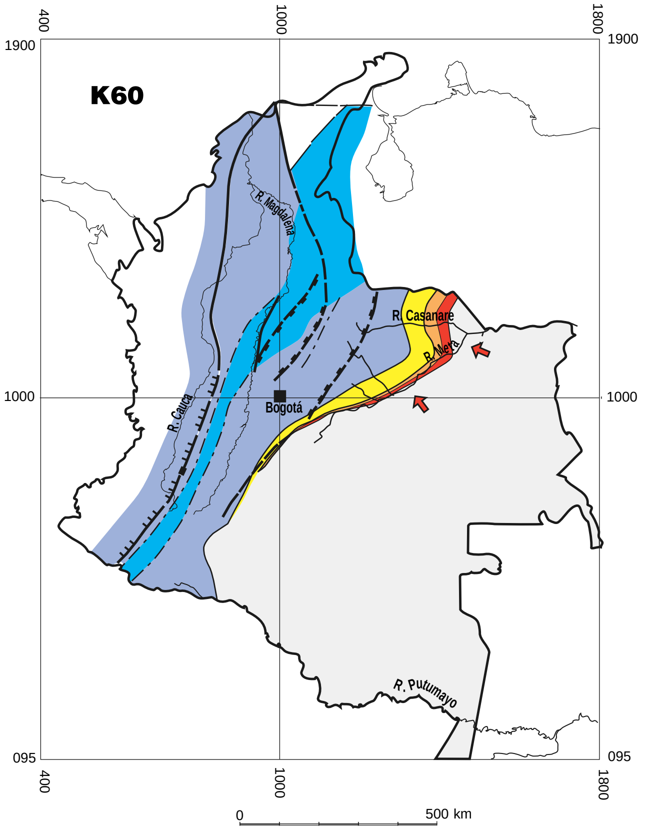


Figure 9—K60 (89–84 Ma) gross depositional environment map drawn within the transgressive systems tract at approximately 88.5 Ma. Key for the color scheme is the same as in Figures 4 and 5.

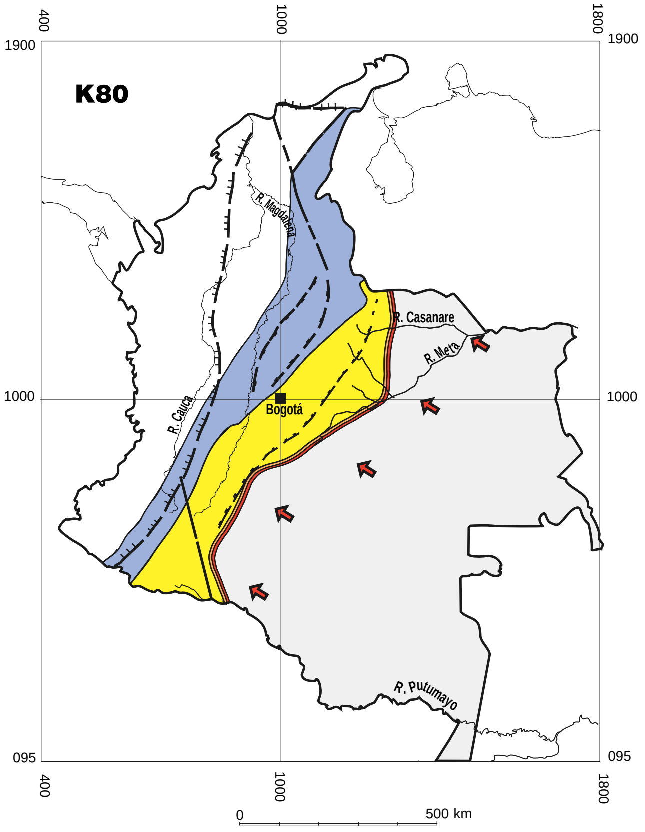


Figure 10—K80 (79.5–73.5 Ma) gross depositional environment map drawn within the highstand systems tract at approximately 76 Ma. Key for the color scheme is the same as in Figures 4 and 5.

system in the Eastern Cordillera, which extended northward to the Maracaibo basin. The Llanos basin was on the eastern margin of this basinal system. The K70 and K80 sequences were deposited on the shallow-marine shelf created by the fall in sea level (Figures 4, 5, 10). K70 and K80 equate approximately with the Guadalupe Group (Hettner, 1892; Hubach, 1931; Pérez and Salazar, 1978). Sequences K70 and K80 represent two major cycles of westward shoreline progradation, aggradation, and retrogradation dominated by high-energy, quartz-rich, shoreface sandstones derived from the Guyana shield. Sequence K70 began with a lower forced regression systems tract (sensu Posamentier et al., 1992) of shallow-marine sands (lower Guadalupe Sandstone and Dura formations) and ended with a transgressive systems tract (Guadalupe Shale and lower Plaeners). Sand progradation into the basin began again as sea level began to drop. The upper and lower Plaeners of the Guadalupe Group in the Eastern Cordillera are siliceous, locally phosphatic, silts, mudstones, and porcellanites interpreted to be the result of upwelling at the shelf edge (Föllmi et al., 1992). In the western highlands of the Eastern Cordillera the K70 is represented by distal mudstones of the La Luna Formation (Figure 4).

The K80 is divided into a sand-dominated, forced regression systems tract (Santonian–early Campanian Upper Guadalupe Sandstone Formation) overlain by shale-dominated highstand and transgressive systems tracts. The shales have been mistakenly identified as the Maastrichtian–Paleocene Guaduas Formation (Figure 3) (Sarmiento, 1992) in some of the earlier wells in the Llanos Foothills; e.g., the Medina 1. Recently acquired data by BP has conclusively dated these youngest Cretaceous rocks in the Llanos Foothills as Campanian in age (Pulham, 1994). The sands at the base of K80 extend west beyond Tunja, but in the western highlands of the Eastern Cordillera are represented by marine shales (La Luna Formation). In the Eastern Cordillera, the K80 sand is the middle sand unit of the Guadalupe Group (Labor Formation). K80 sandstones form the oldest proven commercial

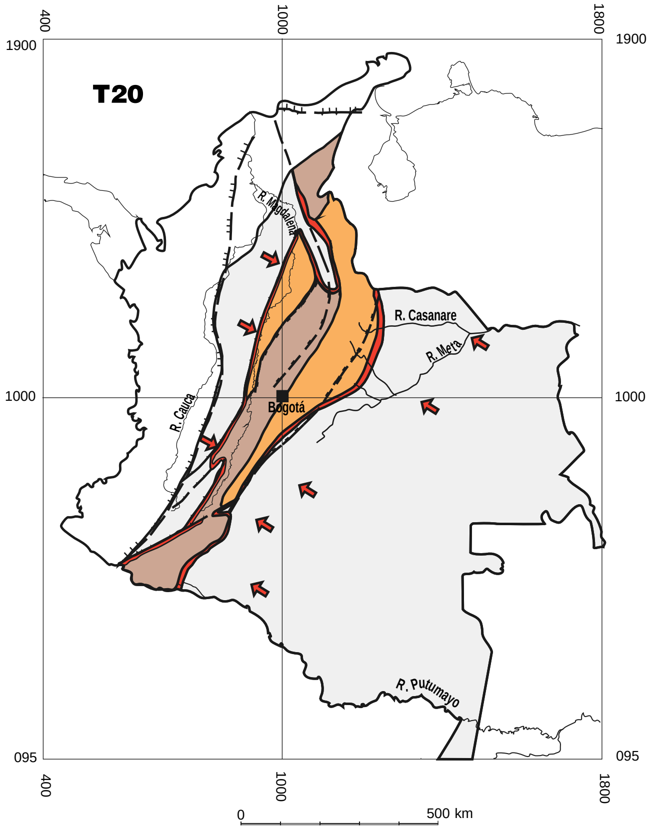


Figure 11—T20 (61–55 Ma) gross depositional environment map drawn within the highstand systems tract at approximately 58 Ma. Key for the color scheme is the same as in Figures 4 and 5.

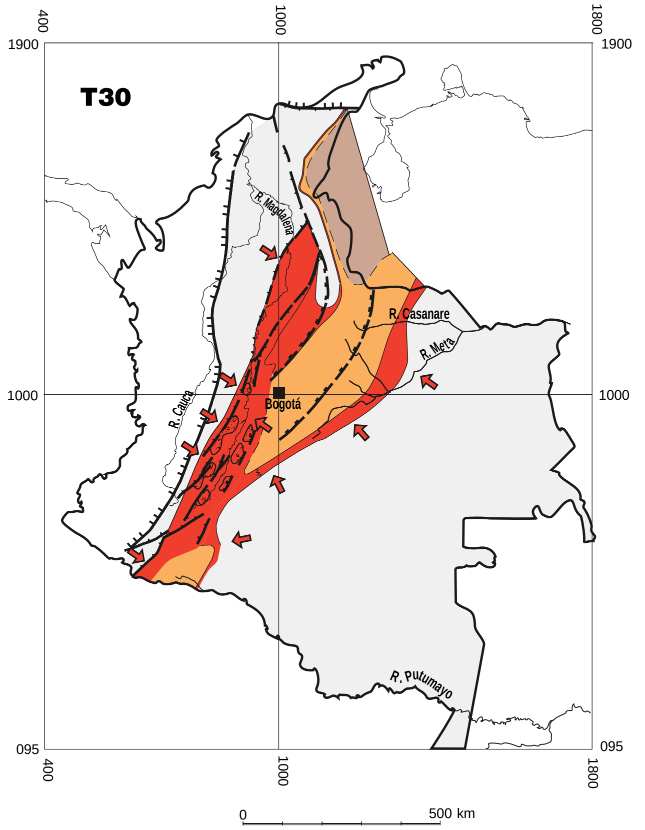


Figure 12—T30 (40.5–34 Ma) gross depositional environment map drawn within the transgressive systems tract at approximately 35 Ma. Key for the color scheme is the same as in Figures 4 and 5.

reservoir unit in the Llanos Foothills. The highly mature quartzarenites were deposited as a relatively uniform sheet over a shallow shelf that extended from the Llanos into the Eastern Cordillera. A rise in relative sea level in the early Campanian effectively starved the K80 shelf of sand and capped the sequence with a condensed marine mudstone in the Eastern Cordillera (upper Plaeners Formation; Figures 4, 5, 10).

The K90 sequence is early Maastrichtian and is composed of a sand-dominated transgressive systems tract (Tierna Formation) overlain by a poorly developed, shale-dominated highstand systems tract. K90 is present throughout the Eastern Cordillera, but as in the sequences below, the sands shale out and are represented by the Umir Formation in the Middle Magdalena Valley (Figure 4). The sequence is not present in wells in the Llanos Foothills, where few reliable Maastrichtian deposits have been reported (G. Eaton, 1992, personal communication). The K90 correlates with the hiatus above K80 in the Llanos Foothills.

Early Pre-Andean Foreland Basin Megasequence (Sequences T10–T20)

The final episode of accretion in the Western Cordillera began near the end of the early Maastrichtian and resulted in a fundamental change to the nonmarine deposition of the pre-Andean foreland basin megasequence (Figures 4, 5). The T10 sequence is dominated in the Eastern Cordillera by the coastal and alluvial-plain mudstones and coals of the Guaduas Formation (Hettner, 1892). These rocks were dated by Sarmiento (1992) as late Maastrichtian and early Paleocene. This sequence is not present in the Llanos basin and Foothills, but is correlative with a hiatus of approximately 14 m.y., spanning the Cretaceous–Tertiary boundary. Dengo and Covey (1993) considered this sequence to persist to the east of the Guaicaramo fault, but this does not agree with the available biostratigraphic data (Pulham, 1994). The T10 sequence shows a systematic northward and eastward thinning; sudden thickness changes occurring across major faults in

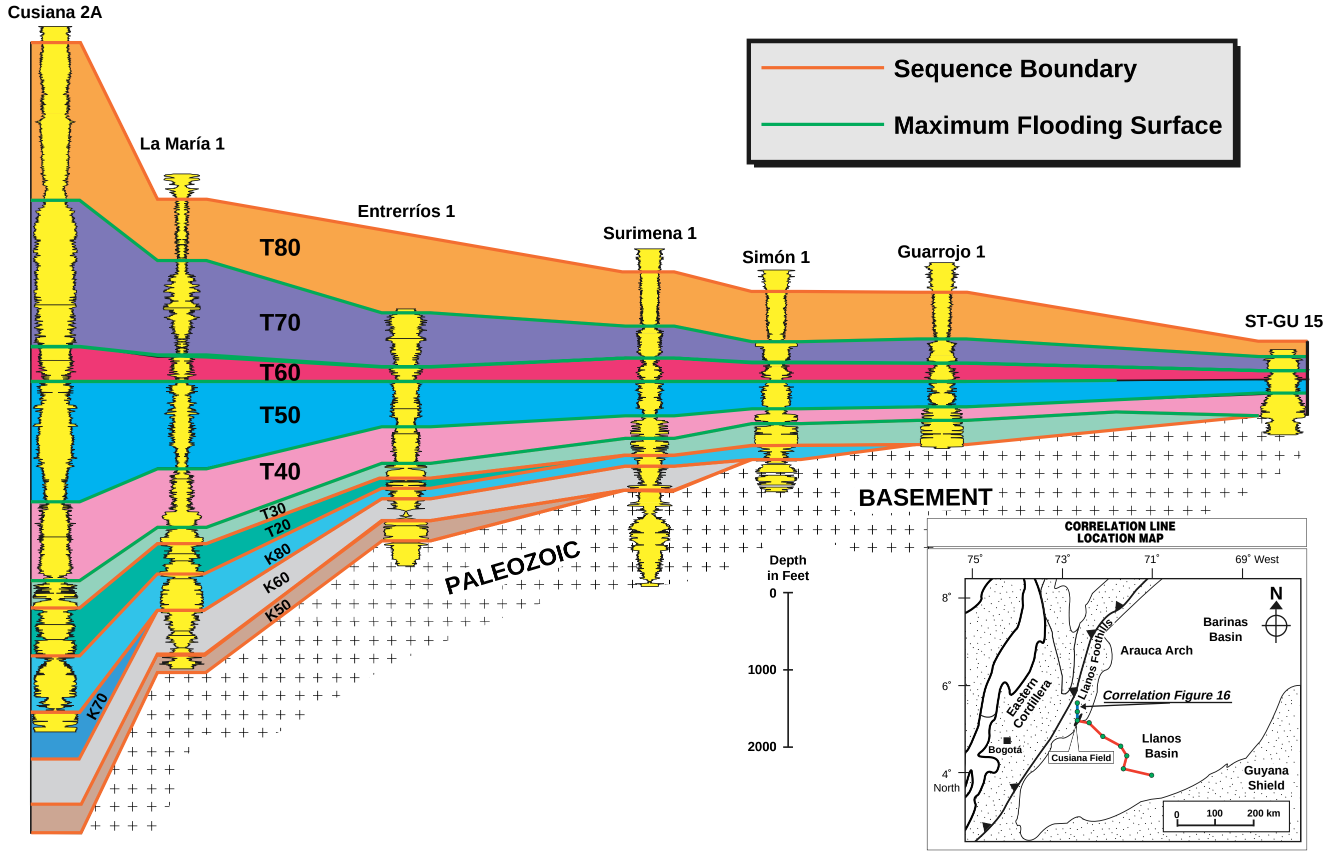


Figure 13—Correlation of stratigraphic units K50–T70 in the Llanos basin based on seven representative wells. The log signatures are gamma ray in API units; the gamma-ray curve has been plotted twice by reversing the scale for the right curve. Wide separation of the two curves indicates a low gamma-ray response of the formation, which is correlative with sands in the cuttings. The locations of this correlation section and of the correlation section of Figure 16 are shown on the inset map.

the Eastern Cordillera are considered to result from later erosional truncation (Sarmiento, 1992). However, the thinning may represent progressive onlap onto the eastern hinterland. The T10 is present in the eastern highlands of the Eastern Cordillera immediately west of the Guaicaramo fault system, but is absent in the Foothills. This placement suggests some degree of fault control on T10 deposition, possibly due to differential subsidence across the fault. In the Magdalena Valley the T10 is represented by a series of shales and occasional sands (Lisama Formation, Figure 4).

Deposition began again in the Llanos Foothills in the late Paleocene at approximately 60 Ma in response to a transgression that extended foreland basin deposition across the Llanos basin. The T20 sequence extends farther east than the underlying T10, possibly due to a combination of transgression and early loading of the protoforeland basin due to deformation in the Central and Western Cordilleras (Figures 4, 5, 11). The Barco Formation reservoir (Notestein et al., 1944) forms the basal transgressive systems tract of T20. It is predominantly a highly mature, sandstone-rich, estuarine deposit derived from the Guyana shield. Marine influence is strong throughout the Barco Formation in the area of the Cusiana field with a relatively abrupt upward transition into more heterolithic coastal and alluvial-plain deposits. Basal T20 sandstones are developed throughout the Llanos Foothills, Eastern Cordillera (Soacha Formation in part), and Magdalena Valley (Figures 4, 11). Conformity exists between T10 and T20 in the Eastern Cordillera and the Middle Magdalena Valley. T20 sandstone deposition ended as the late Paleocene transgression weakened and a relative sea level highstand was established (~59 Ma). Subsequent regression shifted the regional shoreline gradually westward. Coarse clastics appear to have bypassed the Llanos Foothills and Eastern

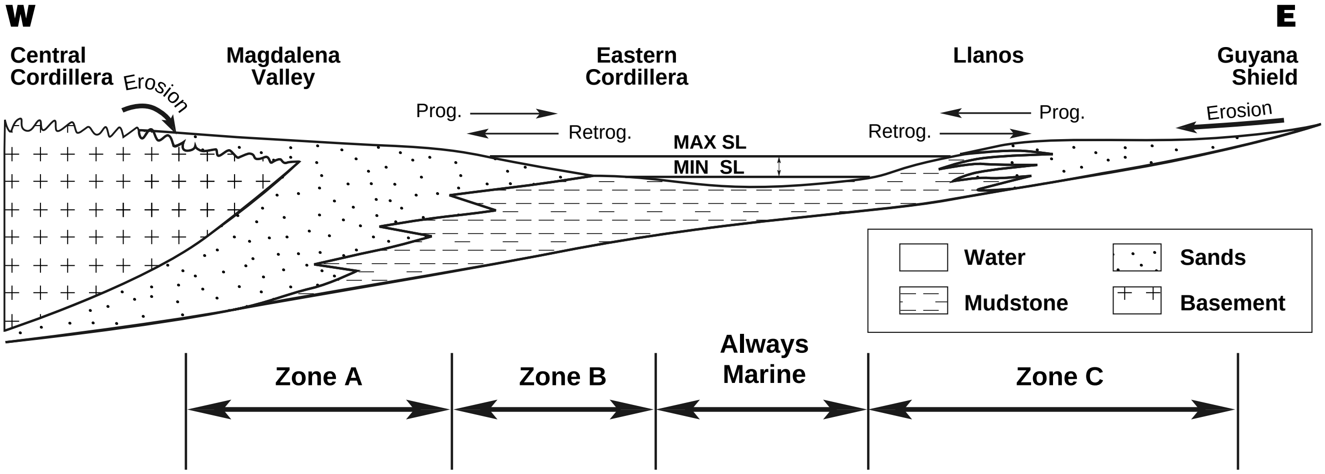


Figure 14—Zonation of the Llanos foreland basin modified from the generic model of Posamentier and Allen (1993) with the addition of zone C where parasequence patterns resemble those in zone B, but with opposite polarity. Zone A is located where the maximum rate of eustatic fall is less then the rate of subsidence and zone B is located where subsidence rates are less than the maximum rate of eustatic fall. In zone C the relationship between subsidence and eustatic change will be the same as in zone B, but the sediment supply will be from the opposite direction.

Cordillera in the middle of T20 deposition, where a regressive, mud-dominated coastal plain system was established (lower Los Cuervos Formation) (Notestein et al., 1944). These mudstones may have some source potential in the Llanos Foothills (Droszd and Piggott, in press).

A major drop in relative sea level at about 54 Ma (the top of T20) resulted in a shift in deposition to the west and north (Catlin et al., 1994). In the Llanos the depositional hiatus lasted almost 16 m.y. and resulted in a disconformity with no apparent angular component (cf. Dengo and Covey, 1993) (Figure 4). The fluvial systems in the upper T20 lay in the Eastern Cordillera (Picacho and Bogota formations). These bypass systems are in the same cycle of deposition in which the Misoa "C" delta in Venezuela was deposited (Catlin et al., 1994). Thickness variations within T20 (Naar and Coral, 1993) imply continued extension on the Cusiana-Tamara fault system in the Llanos Foothills. Earliest middle Eocene sediments are not present throughout Colombia (Figures 4, 5) due to deformation in the Magdalena related to change in the direction or rate of subduction (Daly, 1989). The deformation produced thrust and fold structures in the Magdalena Valley. The hiatus corresponds to the unconformity at the base of the Gualanday Formation in the Magdalena Valley and separates two pre-Andean megasequences (Figures 4, 5) (Corrigan, 1967). Although some uncertainty exists regarding the exact length of the hiatus, the regional plate tectonic data have been used to time the deformation (Daly, 1989).

Late Pre-Andean Foreland Basin Megasequence (Sequences T30–T70)

Deposition in the Llanos was renewed in the latest middle Eocene (~40.5 Ma) in response to a transgression that spread southward and eastward from the foreland basin (Figures 4, 12). The T30 transgression was significantly more extensive than the earlier T20 flooding and caused the T30 to onlap much farther to the east onto the Guyana shield (Figure 13). Initial T30 deposition consisted of marine-influenced, sandstone-rich, fluvial and estuarine valley-fill deposits contained in muddier coastal plain sediments (Pulham, 1994). Coarse and often pebbly, fluvial and alluvial fan sandstones are the dominant component of T30 deposited over a wide area of the Llanos basin and Foothills (Mirador Formation; Notestein et al., 1944). The T30 sequence contains the most important reservoir units in the Cusiana, Cupiagua, and Volcanera fields (Cazier et al., 1995). The middle T30 in the Cusiana field contains a distinctive, muddy alluvial-plain unit that is at least subregionally extensive in the Llanos Foothills and western Llanos basin (McCollough, 1991; Pulham, 1994). Continued transgression eventually submerged the alluvial plain and established a shallow-marine shelf across the Cusiana area. The upper T30 comprises heavily bioturbated estuarine parasequences punctuated by sandstone-rich, estuarine valley-fill deposits. In the Cusiana field, major flooding (~34 Ma) effectively ended sand deposition (Figure 13). All of the coarser grained T30 sandstones in the Llanos

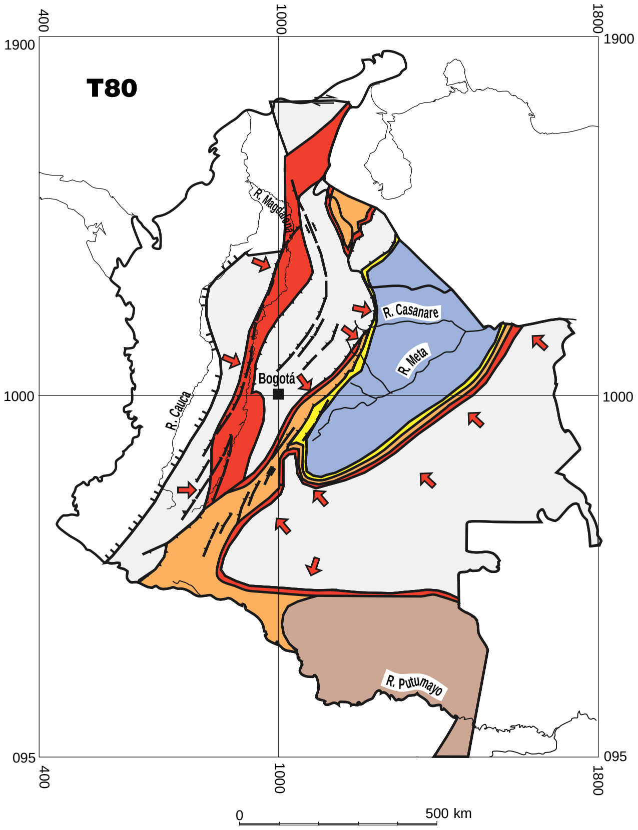


Figure 15—T80 (16–10.5 Ma) gross depositional environment map drawn within the highstand systems tract at approximately 15 Ma. Key for the color scheme is the same as in Figures 4 and 5.

Foothills are extremely mature quartzarenites similar in composition to those of the underlying T20. Locally, fine-grained litharenites occur in highstand coastal and alluvial-plain deposits that overlie transgressive, estuarine, and valley-fill sediments. Fabre (1987) concluded that the Santander massif was already being eroded at this time and may be the source for the lithic component in the sediments. Significant thickness variations in T30 (Moreno and Velazquez, 1993; Naar and Coral, 1993) (Figure 13), may be a result of fault control or may be due to the westward thickening into the foreland basin. In the Magdalena Valley, T30 sediments are termed (in part) the Gualanday, Esmeraldas, and La Paz formations that range from late Eocene to middle Oligocene in age (Figures 4, 5) and occur above a dramatic angular unconformity (Corrigan, 1967). The Gualanday and La Paz formations contain feldspathic and lithic material and local conglomerates in contrast to the mature quartzarenites of the Mirador Formation to the east. This compositional change is interpreted to be the result of sediment supply from the volcanics and intrusives of the Central Cordillera into the Magdalena Valley (Figure 12).

After T30, four major cycles of marine-influenced, lower coastal-plain deposition accumulated in the Llanos basin and Foothills (T40–T70), traditionally termed the Carbonera Formation (Notestein et al., 1944). However, due to erosion, only sparse outcrops of these sequences occur in the Eastern Cordillera (Concentracion Formation). In the Middle Magdalena, these sequences are represented (in part) by the Esmeraldas, Mugrosa, Colorado, and La Cira formations. Sequences T40–T70 (~34–16.5 Ma) correlate to industry usage in the Llanos basin as shown in Figure 6. These sequences are separated at maximum flooding surfaces, which are more correlative through the basin than sequence boundaries. Thus, the sequences are not true sequences in the sense of Mitchum et al. (1977), but are genetic stratigraphic units in the sense of Galloway (1989). The sequences record easterly migration of foreland basin subsidence, which culminated with the onset of Eastern Cordillera deformation. T40–T70 are correlatable throughout the Llanos basin (Figure 13), displaying a gradual increase in sand percentage and becoming increasingly continental with proximity to the Guyana shield. The sequences all thicken gradually westward due to increasing accommodation space in the foreland basin axis. Well and seismic data also indicate continued episodic normal displacement on the Cusiana fault system during T40–T70 deposition (Figure 13). The extension results from lithospheric loading that reactivated preexisting faults.

Each sequence consists of a mud-dominated highstand systems tract, followed by a thin, forced regression systems tract, and ends with a sand-prone transgressive systems tract that culminates in a maximum flooding surface. Droszd and Piggott (in press) suggested that the mudstones in the highstand systems tract of T40 may be the source rock for one of the component oils in the Volcanera and Cupiagua fields, which they typed to a Tertiary source. During T30–T70 the major source of sediment for the Llanos basin was the Guyana shield and, as a result, parasequences prograde westward into the basin. The gross pattern that results is of onlap onto the Guyana shield. An exception is T50, which does not onlap as far east as either T40 or T60 (Figure 13). Protracted peneplanation since at least the Jurassic created low relief in the Llanos basin; this relief was susceptible to shifts in gross depositional environments caused by changes in sediment supply, accommodation space resulting from loading, and global eustatic sea level changes.

The coarse clastics of the Gualanday, Mugrosa, and Doima formations in the Magdalena Valley indicate that the depocenter in the Magdalena and the

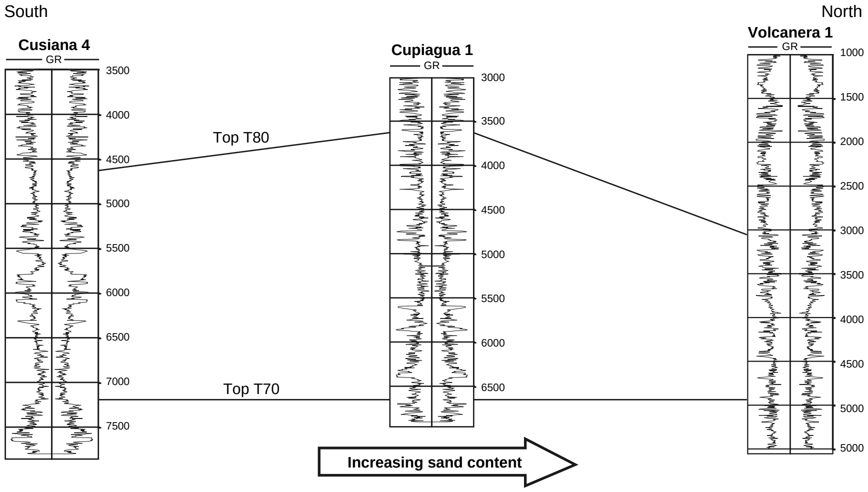


Figure 16—Correlation of T80 in the Cusiana 4, Cupiagua 1, and Volcanera 1 wells in the Llanos Foothills using the top of T70 as the datum. The log signatures are gamma ray in API units; the gamma-ray curve has been plotted twice by reversing the scale for the right curve. Wide separation of the two curves indicates a low gamma-ray response of the formation, which is correlative with sands in the cuttings. Location of the section line is shown on the inset map of Figure 13.

western part of the Eastern Cordillera was an efficient sink for the sediments being derived from the west. Posamentier and Allen (1993) recently presented a model that divided a foreland basin into two depositional zones. This model has been modified to account for sediment supply from the Guyana shield into the foreland basin (Figure 14).

Andean Foreland Basin Megasequence (Sequences T80–T90)

During the middle Miocene, the global rise in sea level (Haq et al., 1987) coincided with the first significant deformation and uplift in the Eastern Cordillera. This deformation isolated the Middle Magdalena Valley from the Llanos basin. The resultant loading tectonically enhanced the highstand systems tract, causing deposition of the T80 mudstones (Léon Formation of Notestein et al., 1944). Evidence for at least partial emergence of the Eastern Cordillera is more sand in the T80 in the western Foothills than in the east (Figures 15, 16). The T80 marine mudstones extend farther eastward than any of the older sequences. The eastern onlapping edge of the T80 onto the Guyana shield is marked by a change in facies to shoreface sands and marginal-marine facies dominated by coarse clastics (Figure 15). Additional evidence for deformation, uplift, and erosion of the Eastern Cordillera during T80 deposition is a correlative unconformity between the Honda and Real formations in the Middle Magdalena Valley (Figure 4).

The Léon Formation illustrates the problems of the lithostratigraphic correlation schemes. The Léon in the Llanos falls within T80, whereas the Léon Formation in Venezuela is Oligocene (Boesi et al., 1988) and is correlative with the T50 mudstones of the Llanos basin. Bürgl (1955) suggested that a widespread transgression occurred during the late Oligocene based on marine shales of the Léon and La Cira formations, an erroneous conclusion driven by miscorrelation of the Llanos and Venezuelan Léons. In the absence of definitive biostratigraphic data, the top of the T80 is defined by a color change of the mudstones from gray to red, which reflects the last vestige of marine influence in the system.

In the Llanos basin, approximately 3000–3500 m of T90 coarse continental clastics were deposited from about 10 to 2 Ma (Guayabo Formation; Hubach, 1957). This phase of deposition records uplift of the Eastern Cordillera (Van der Hammen et al., 1973) immediately west of the Foothills and the end of migration of the foreland basin axis (Figure 17). The Guyana shield is no longer the provenance of the sediment because Cretaceous clasts eroded from the Eastern Cordillera occur within T90 (Moreno and Velazquez, 1993). In the Magdalena basin, T90 is represented by the Honda and Real groups. Deposition of the T90 molasse caused rapid late-stage burial of the Late Cretaceous–early Tertiary stratigraphic section in the Magdalena Valley and in the Llanos. The deposition of T90 placed the K60 and Tertiary source rocks in the oil window at approximately 5 Ma when generation began in the Llanos Foothills (Cazier et al., 1995).

STRUCTURAL EVOLUTION AND STYLE OF THE ANDEAN DEFORMATION

In the Eastern Cordillera and Llanos basin, major tectonic elements are the Las Salinas-Bituima fault system and the Guaicaramo fault system that bound the Eastern Cordillera, the faults bounding the Santander massif, and the Cusiana-Tamara fault system that separates the Llanos Foothills from the Llanos basin (Figure 18).

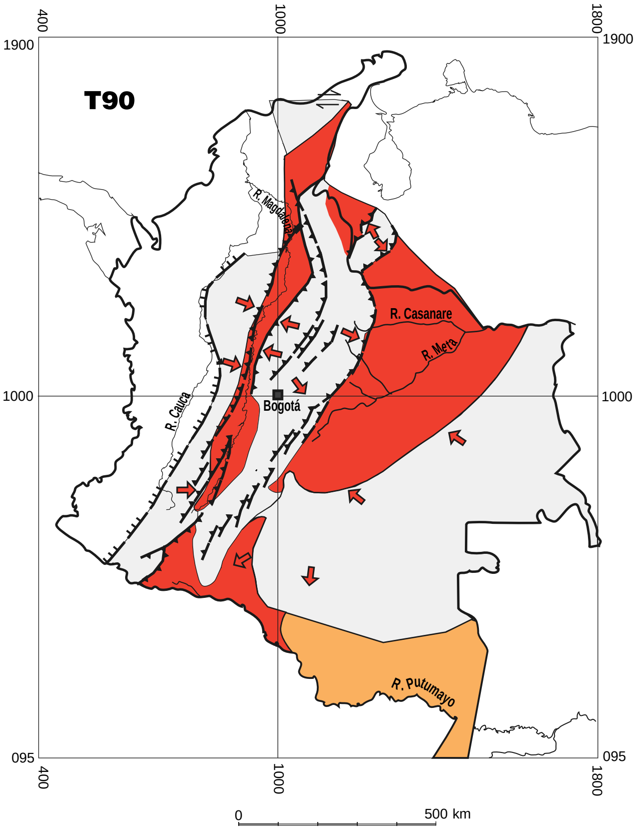


Figure 17—T90 (10.5 Ma–present) gross depositional environment map drawn at approximately 10 Ma. Key for the color scheme is the same as in Figures 4 and 5.

Structural geometry of the orogene is illustrated by a regional cross section from the Middle Magdalena Valley, through the towns of Villa de Leiva and Tunja, and the Cusiana field (Figures 2, 18), which includes a Middle Miocene restoration prior to the main Andean deformation. The cross section is constrained by published geological maps, field traverses, and well and seismic data. The section was bed length and area balanced using the GEOSEC software package. Total shortening is approximately 68 km, significantly less than the estimate of shortening published by Dengo and Covey (1993). The section is similar to that of Colletta et al. (1990). The most important geometric observation is dramatic thickening of Jurassic (and older sediments?) and the Lower Cretaceous in the hanging walls of some of the faults. The Guaicaramo, Arcabuco, and Las Salinas-Bituima fault systems show thickening in their hanging walls. Thickening of the Lower Cretaceous is the result of continued oblique extension in the back-arc on these faults and creation of accommodation space in the Cocuy and Tablazo-Magdalena basins. The location of the faults can be inferred by examining geologic maps of the region and comparing the published stratigraphic thicknesses from the hanging walls and footwalls. Inversion of these faults (Cooper and Williams, 1989) during the main deformation phase (beginning at ~10.5 Ma) controlled style and distribution of compressional structures, uplift, and erosion of the Eastern Cordillera. Figure 18 also illustrates the truncation of the Paleocene and older strata by the middle Eocene unconformity due to middle Eocene deformation in the Middle Magdalena Valley. This relationship is not shown on the cross section published by Colletta et al. (1990).

The earliest thickening across the Cusiana-Tamara fault system occurred in the Late Cretaceous K80 sequence. The thickening is shown by differences in thickness between Cusiana field wells and the wells in the immediate foreland (Figures 13, 19). The Guaicaramo fault system that bounded the Cocuy basin controlled the dramatic thickening of Lower Cretaceous sediments from the foreland into the Eastern Cordillera (Ulloa and Rodríguez, 1981; Hebrard, 1985). The Cusiana-Tamara fault system may have had an earlier extensional history as an extensional footwall collapse of the Guaicaramo fault system during the Early Cretaceous rifting and back-arc subsidence. This interpretation differs from that of Colletta et al. (1990), who did not recognize an early extensional history of the Cusiana-Tamara fault system. Movement continued episodically from the Late Cretaceous until deposition of the T80 sequence. This phase of normal displacement on the Cusiana-Tamara fault system accommodates lithospheric flexure in response to loading by accretion of the Western Cordillera and deformation of the Central and Eastern Cordilleras. Similar faults have been described in other foreland basins (Kittler and Neumayer, 1983).

Other inversion structures can be recognized in the Eastern Cordillera (Figure 18). For example, the footwall of the Pesca fault carries folds with a wavelength of 1–2 km whose limbs are locally cut by both fore- and backthrusts. In the hanging wall, a homoclinal dip panel extends 10 km to the west, suggesting deep detachment of the Pesca fault. Between Tunja and Villa de Leiva, tight, faulted folds once again developed, ending on the southeastern limb of the Arcabuco anticline. West of the Arcabuco anticline the structure is dominated by folds that have a wavelength of 10 km, implying a deep detachment. The area from the Arcabuco anticline to the Las Salinas fault is substantially above regional elevation, even in the syncline cores, and is interpreted as the inverted hanging wall of the Arcabuco fault. The Arcabuco fault controls the western margin of the Santander high. The Pesca fault is interpreted as a footwall shortcut of the inverted

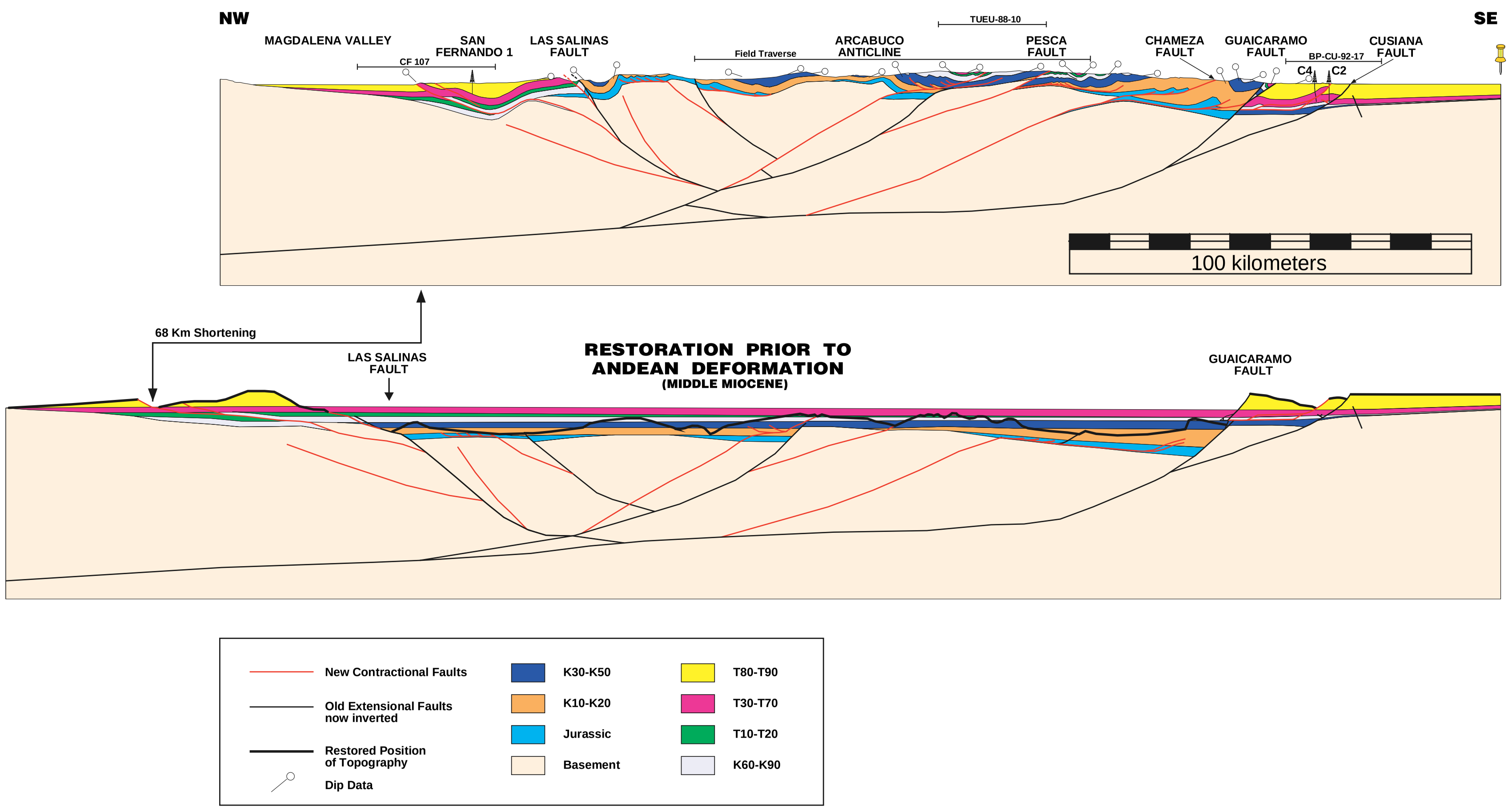


Figure 18—Regional cross section from the Middle Magdalena Valley through the Eastern Cordillera to the Llanos basin. Location of the section is on Figure 2. Constraining seismic, dip, well, and surface geological data are indicated on the section. Stratigraphic units shown in the section are based on the sequence stratigraphy. The restoration at the top of T70 suggests that Andean deformation caused shortening of 68 km. Data from the following 1:100,000 geological map sheets was also used; J-12 Tunja, J-11 Chiquinquira, 211 Tauramena, and 193 Yopal. (For references, see the supplementary data diskette available from AAPG.)

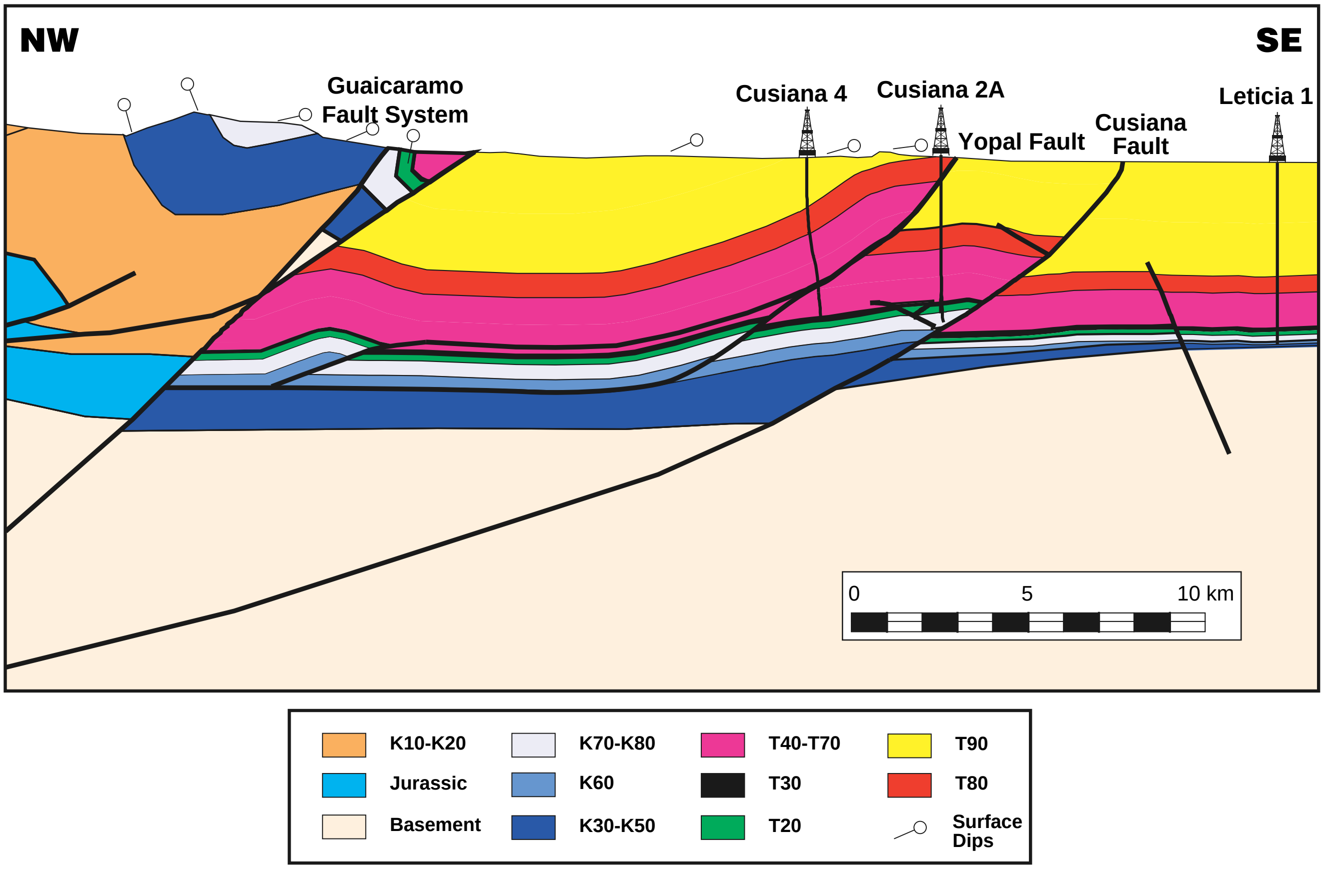


Figure 19—Cross section through the Cusiana field in the Llanos Foothills showing the typical structural style of the Llanos Foothills. Constraining, dip, well, and surface geological data are indicated on the section, which is based on seismic line BP-CU-92-17 (see Figure 20 for location). Stratigraphic units shown in the section are based on the sequence stratigraphy.

Arcabuco fault, which implies that the Santander high is allochthonous (cf. Colletta et al., 1990). The smaller wavelength folds and their associated faults developed to accommodate slip where deeper detaching faults splay into shale-prone Lower Cretaceous sequences. The Cusiana-Tamara fault system may have originated as a system of extensional footwall-collapse faults based on thickness changes of the Cretaceous and Tertiary sequences across the fault. The alternative is to interpret the faults as footwall shortcuts to the inversion of the Guaicaramo fault. Colletta et al. (1990) also recognized the significant role of these inverted extensional faults in the deformation history of the Eastern Cordillera; however, these workers did not describe the footwall shortcuts and their relationship to intense, locally observed deformation. Dengo and Covey (1993) interpreted much of the structural elevation as being due to thin-skinned deformation detaching within the K60 and K30; as a result, their estimate of shortening is significantly higher than that of the section presented here. On the western margin of the Eastern Cordillera, the Las Salinas-Buituima fault system that forms the boundary with the Middle Magdalena Valley is also characterized by footwall shortcuts involving basement (Schamel, 1991).

In the Llanos Foothills west-northwest–east-southeast compression caused inversion along the Cusiana-Tamara fault system (Figure 19). The thin-skinned Yopal fault, which detaches within T40, overrides the Cusiana fault to the north and buries the branch line with the latter fault (Figure 20). West of the frontal inversion structures is a system of major regional synclines including the Nunchia and Zamaricote synclines (Figure 20). The western limbs of the synclines are elevated by a series of structures that involve the Late Cretaceous and early Tertiary sedimentary sequences. These structures can be modeled as a series of basement-involved or thin-skinned duplex horses detaching in the K60 shale. The duplex model is based on repetition of T30 in the El Morro well (Naar and Coral, 1993) and the short wavelength and geometry of the upper horse, which outcrops to the

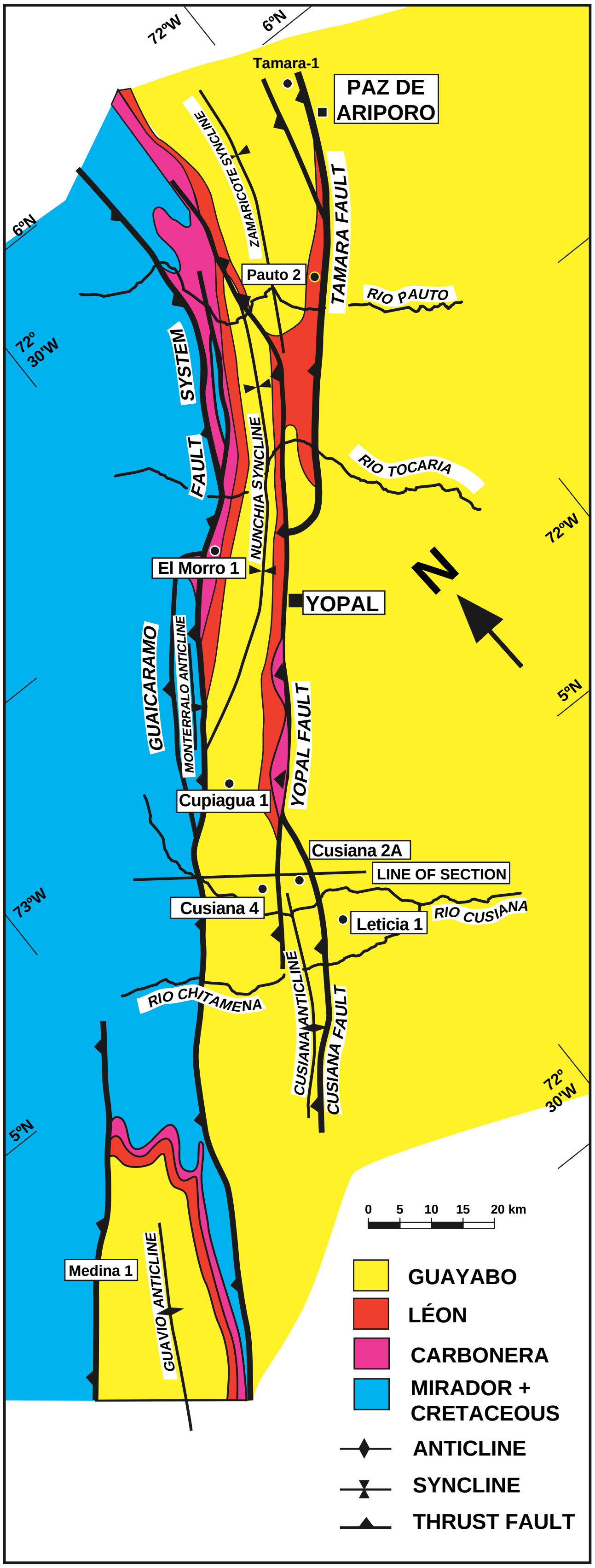


Figure 20—Summary surface geology map of the Llanos Foothills showing key wells and line of cross section for Figure 19. The map is based on the 1:100,000 map sheets 211 Tauramena and 193 Yopal, proprietary data collected for BP by Geotec Ltda., and mapping by Moreno and Velazquez (1993), Naar and Coral (1993), and Arango and Venegas (1994).

north (Moreno and Velazquez, 1993). The duplex is truncated to the west by the out-of-sequence Guaicaramo fault. The Guaicaramo fault is defined in this paper as the inverted extensional fault that originally controlled the Cocuy basin. The fault is complicated in outcrop by a number of faults within the hanging wall that detach toward the base of the Cretaceous. One of these detached faults is folded by the Monterallo anticline to the west of the El Morro 1 well (Figure 20).

The Foothills contain both deep-detaching basement-involved faults, which have inverted and developed footwall shortcut faults, and thin-skinned thrusts detaching within the Cretaceous and Tertiary. This pattern of deformation is also characteristic of the Eastern Cordillera and the Middle Magdalena Valley (Figures 2, 18).

CONCLUSIONS

Mesozoic and Tertiary evolution of the Middle Magdalena Valley, Eastern Cordillera, and Llanos basin is closely tied to the tectonics of the margin of western South America. Conventional stratigraphic analyses of the basin have been based on lithostratigraphic correlations with limited biostratigraphic control. The chronostratigraphy presented here is based on an extensive database of compiled biostratigraphic and lithological data from wells and outcrops. The sedimentary succession is divided into five megasequences, each related to a discrete period of deformation.

The Triassic–Barremian synrift megasequence was dominated by continental clastic sediments until an Early Cretaceous transgression established marine conditions. The synrift megasequence includes two Cretaceous sequences, K10 and K20, which thicken dramatically into the hanging walls of major basin-controlling faults. Shallow-marine clastics, derived from the Guyana shield, were ponded in the Cocuy basin by the intrabasinal Santander high. The western Tablazo-Magdalena basin was dominated by fine-grained marine mudstones with minor submarine fan deposition.

The Cretaceous back-arc megasequence was deposited in a basin behind the Andean subduction zone. In the middle Cretaceous a marine transgression established a shallow-marine siliciclastic shelf over a wide area (K40), including the intrabasinal Santander high. Continued relative sea level rise, combined with anoxic upwelling, resulted in the deposition of a succession of marine mudstones, cherts, and phosphates (K60), which are prolific source rocks in the Llanos basin and Middle Magdalena Valley. The overlying Santonian–early Maastrichtian sequences (K70–K90) comprise a series of high-energy quartz-rich sandstones derived from the Guyana shield. The sequences are widespread, comprising a series of major cycles of shoreline progradation, aggradation, and retrogradation. K80 sandstones are the oldest significant reservoir units in the Llanos basin and Foothills.

Accretion of the Western Cordillera at the end of the Cretaceous resulted in a fundamental change from marine to nonmarine deposition (the K90/T10 boundary) and development of the pre-Andean foreland basin. The pre-Andean foreland basin is divided into two megasequences by middle Eocene deformation in the Magdalena Valley, a result of changes in direction and rate of subduction (Daly, 1989).

In the Llanos basin, both pre-Andean foreland basin megasequences contain mature quartz-rich fluvial sands derived from the Guyana shield (e.g., T30, Mirador Formation). In contrast, in the Middle Magdalena Valley feldspathic and lithic fluvial sands derived from the Central Cordillera dominate. In the Llanos basin and Eastern Cordillera the younger sequences form a series of major grossly coarsening-upward cycles separated by maximum flooding surfaces (T40–T70). In this distal foreland basin setting, the sediment supply was from the east, not from the orogenic hinterland to the west.

In the middle Miocene, a global rise in sea level coincided with the first significant deformation and uplift in the Eastern Cordillera and initiated the Andean foreland basin megasequence. The marine mudstone (T80) deposited onlapped far to the east across the Guyana shield. Increasing sand content within T80 to the west documents the initial partial emergence of the Eastern Cordillera and the resultant isolation of the Llanos and Middle Magdalena Valley. The final depositional episode is the deposition of a thick, coarse, continental clastic sequence (T90) derived from the Eastern Cordillera during deformation and uplift, which caused the source rocks to generate hydrocarbons.

Andean deformation within the Eastern Cordillera is dominated by the inversion of the earlier Cretaceous extensional faults, resulting in major folds, with wavelengths of 10 km, that developed above deep, detaching planar faults. Only where the deep detaching faults splay into the overlying cover did short-wavelength folds develop.

REFERENCES CITED

Alfonso, C. A., P. E. Sacks, and D. T. Secor, Jr., 1989, Late Tertiary northwestward-vergent thrusting in Valle del Cauca, Colombian Andes (abs.): AAPG Bulletin, v. 73, p. 327.

Alvarez, J. A., 1983, Geología de la Cordillera Central y el Occidente Colombiano y petroquímica de los intrusivos granitoides Mesocenozoicos: Colombia Instituto Nacional de Investigaciones Geológico-Mineras Boletín de Geología, v. 26, 175 p.

Arango, F., and D. Venegas, 1994, Analisis estratigrafico de una region la Occidente de la Población de Paz de Ariporo (Casanare): Tesis de pregrado, Universidad Nacional de Colombia, Bogotá, p. 1–70.

Aspden, J. A., and W. J. McCourt, 1986, Mesozoic Oceanic terrane in the Central Andes of Colombia: Geology, v. 14, p. 415–418.

Barrero, D., 1979, Geology of the central Western Cordillera west of Buga and Roldanillo, Colombia: Colombia Instituto Nacional de Investigaciones Geológico-Mineras Publicación Geológicas Especiales de Ingeominas, no. 4, 75 p.

Beltrán, N., and J. Gallo, 1968, The geology of the Neiva subbasin, Upper Magdalena basin (southern portion): 9th Annual Field Conference Guidebook, Colombian Association of Petroleum Geologists and Geophysicists, p. 253–274.

Ben-Avraham, Z., and A. Nur, 1987, Effects of collisions at trenches on oceanic ridges and passive margins, *in* J. W. H. Monger and J. Francheteau, eds., Circum-Pacific orogenic belts and evolution of the Pacific Ocean basin: American Geophysical Union, Geodynamics Series, v. 18, p. 9–18.

Boesi, T., F. Galea, G. Rojas, M. A. Lorente, I. Duran, and M. Velazquez, 1988, Estudio estratigrafico del flanco Norandino en el sector Lobatera-El Vigia, III: Simposio Bolivariano de Exploracion Petrolera de las Cuencas Subandinas, p. 2–24.

Bürgl, H., 1955, Globorotalia Fohsi en la Formación Usme: Boletín Geológico, v. 3, p. 56–65.

Bürgl, H., 1960, El Jurásico e Infracretáceo del río Batá, Boyacá: Boletín Servicio Geológico Nacional, Informe 1319, v. 1–3, p. 169–211.

Bürgl, H., 1961, Sedimentación cíclica en el geosinclinal Cretáceo de la Cordillera Oriental de Colombia: Servicio Geológico Nacional, Informe 1347, 60 p.

Butler, K., and S. Schamel, 1988, Structure along the eastern margin of the Central Cordillera, Upper Magdalena Valley, Colombia: Journal of South American Sciences, v. 1, p. 109–120.

Butler, K., and S. Schamel, 1989, Upper Crustal control of deformation and hydrocarbon traps along the Upper Magdalena Valley, Colombia (abs.): AAPG Bulletin, v. 73, p. 339.

Campbell, C. J., 1974, Colombian Andes, *in* A. M. Spencer, ed., Mesozoic–Cenozoic orogenic belts: data for orogenic studies: Edinburgh, Scottish Academic Press, p. 705–724.

Catlin, T. J., E. G. Guzmán, and M. Stredel, 1994, Stratigraphic framework for the Eocene, southwest of Lake Maracaibo, Venezuela: Fifth Simposio Bolivariano de Exploracion Petrolera de las Cuencas Subandinas, p. 43–61.

Cazier, E. C., A. B. Hayward, G. Espinosa, J. Velandia, J-F. Mugniot, and W. G. Leel, Jr., 1995, Petroleum geology of the Cusiana field, Llanos basin Foothills, Colombia: AAPG Bulletin, v. 79, no. 10, p. 1444–1463.

Cediel, F., 1968, El Grupo Girón, una molasa Mesozoica de la Cordillera Oriental: Boletín Servicio Geológico Nacional, v. 16, no. 1–3, p. 5–96.

Colletta, B., F. Hebrard, J. Letouzey, P. Werner, and J-L. Rudkiewicz, 1990, Tectonic style and crustal structure of the Eastern Cordillera (Colombia) from a balanced cross-section, *in* J. Letouzey, ed., Petroleum and tectonics in mobile belts: Paris, Editions Technip, p. 81–100.

Cooper, M. A., and G. D. Williams, 1989, Inversion tectonics: Geological Society of London, Special Publication 44, 376 p.

Corrigan, H. T., 1967, The geology of the Upper Magdalena basin, *in* Geological fieldtrips, Colombia 1959–1978: Colombian Society of Petroleum Geologists and Geophysicists: (reprinted 1992 by Geotec Ltda., Bogotá, Colombia), p. 221–251.

Daly, M. C., 1989, Correlations between Nazca/Farallon plate kinematics and forearc basin evolution in Ecuador: Tectonics, v. 8, p. 769–790.

Dengo, C. A., and M. C. Covey, 1993, Structure of the Eastern Cordillera of Colombia: implications for trap styles and regional tectonics: AAPG Bulletin, v. 77, p. 1315–1337.

Droszd, R. J., and N. Piggott, in press, The geochemistry of the Cusiana field oils: Memórias del IV Congreso de Geoquímica Orgánica Latinoaméricana, Bucaramanga, Colombia: Rio de Janeiro, Brazil, Petrobras, 8 p.

Duque-Caro, H., 1990, The Chocó block in the northwestern corner of South America; structural, tectonostratigraphic and paleogeographic implications: Journal of South American Earth Science, v. 3, p. 1–14.

Etayo, F., 1964, Posición de las Faunas en los depósitos Cretácicos Colombianos y su valor en la subdivisión cronológica de las mismas, Bucaramanga: Universidad Industrial de Santander, Boletín, no. 16-17, p. 5–142.

Etayo, F., 1979, Zonation of the Cretaceous of central Colombia by ammonites: Publicacion Especial Ingeominas, no. 2, p. 1–186.

Etayo, F., G. Renzoni, and D. Barrero, 1969, Contornos sucesivos del mar Cretáceo en Colombia: Primero Congreso Colombiano de Geología, Memorias, p. 217–252.

Fabre, A., 1987, Tectonique et génération d'hydrocarbures: un modèle de évolution de la Cordillère Orientale de Colombie et du bassin des Llanos pendant le Crétacé et le Tertiaire: Archive Science Genève, v. 40, p. 145–190.

Föllmi, K. B., R. E. Garrison, P. C. Ramírez, F. O. Zambrano, W. J. Kennedy, and L. L. Benedikt, 1992, Cyclic phosphate-rich successions in the Upper Cretaceous of Colombia: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 93, p. 151–182.

Gallo, J., 1979, The environmental facies analysis of selected Tertiary and Cretaceous outcrops along the Villeta–Honda Road, *in* Geological fieldtrips, Colombia 1959–1978: Colombian Society of Petroleum Geologists and Geophysicists: (reprinted 1992 by Geotec Ltda., Bogotá, Colombia), p. 471–487.

Galloway, W. E., 1989, Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface-bounded depositional units: AAPG Bulletin, v. 73, p. 125–142.

Garner, H., 1925, Suggested nomenclature of the geological formations in Venezuela: New York, Petroleum Development Technology, AIME, 677 p.

Geotec, 1992, Facies distribution and tectonic setting through the Phanerozoic of Colombia: a regional synthesis combining outcrop and subsurface data presented in 17 consecutive rock-time slices: Bogotá, Colombia, Geotec Ltda., 17 maps, 17 tables.

Haq, B. U., J. Hardenbol, and P. R. Vail, 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1166.

Hebrard, F., 1985, Les foothills de la Cordillère Orientale de Colombie entre les rios Casanare et Cusiana. Evolution géodynamique depuis l'Eo Crétacé: Ph.D. thesis, Université Pierre et Marie Curie, Paris, 162 p.

Herngreen, G. F., W. Jiménez, and H. Dueñas, 1990, Dating of the Cretaceous Une Formation, Colombia, and the relationship with the Albian–Cenomanian African–South American microfloral province, *in* B. Owens and H. Visscher, eds., Circum-Mediterranean Palynology: Keyworth, British Geological Survey, Review of Palaeobotany and Palynology, v. 66, p. 345–359.

Hettner, A., 1892, Die kordillere von Bogotá: Ergzh zu Petermanns Mitteilungen Bd. 22, Erganzungsheft 104, p. 1–131.

Hooghiemstra, H., 1984, Vegetational and climatic history of the high plain of Bogotá, Colombia: a continuous record of the last 3.5 million years: Disertaciones Botanicae, v. 79, 368 p.

Hubach, E., 1931, Geología petrolífera del departamento de norte de Santander: Servicio Geológico Nacional, Informe No. 176, part A, p. 1–218; part B, p. 219–416; part C, 26 láminas.

Hubach, E., 1957, Contribución a las unidades estratigráficas de Colombia (enumeración regional, de mas reciente a mas antiguas): Servicio Geológico Nacional, Informe No. 1212, 165 p.

Jaillard, E., P. Solar, G. Carlier, and T. Mourier, 1990, Geodynamic evolution of the northern and central Andes during early to middle Mesozoic times: a Tethyan model: Journal of the Geological Society of London, v. 147, p. 1009–1022.

Kittler, G., and R. Neumayer, 1983, Austria molasse basin, *in* A. W. Bally, ed., Seismic expression of structural styles: AAPG Studies in Geology 15, v. 3, p. 3.4.1-33 to 3.4.1-34.

Lea, I., 1840, Notice of the oolitic formation in America, with descriptions of some of its organic remains: Transactions of the American Philosophical Society, 2nd series, v. 7, p. 1–10.

Macellari, C., 1988, Cretaceous paleogeography and depositional cycles of western South America: Journal of South American Earth Sciences, v. 1, p. 373–418.

Maze, W. B., 1984, Jurassic La Quinta Formation in the Sierra de Perija, northwestern Venezuela: geology and tectonic environment of red beds and volcanic rocks, *in* W. E. Bonini, R. B. Hargraves, and R. Shagam, eds., The Caribbean–South American plate boundary and regional tectonics: Geological Society of America Memoir 162, p. 263–282.

McCollough, C. N., 1991, Cano Limon field, Llanos basin, Colombia, *in* E. A. Beaumont and N. H. Foster, eds., Structural traps II: AAPG treatise of petroleum geology: Atlas of Oil and Gas Fields, p. 65–93.

McCourt, W. J., J. A. Aspden, and M. Brook, 1984, New geological and geochronological data from the Colombian Andes: continental growth by multiple accretion: Journal of the Geological Society of London, v. 141, p. 831–845.

Megard, F., 1987, Cordillera Andes and marginal Andes: a review of Andean geology north of the Arica elbow (18 deg. S), *in* J. W. H. Monger and J. Francheteau, eds., Circum-Pacific orogenic belts and evolution of the Pacific Ocean basin: American Geophysical Union, Geodynamics Series, v. 18, p. 71–95.

Miller, T., 1979, The geology of the Eastern Cordillera between Aguazul–Sogamoso–Villa de Leiva, part I, *in* Geological fieldtrips, Colombia 1959–1978: Colombian Society of Petroleum Geologists and Geophysicists: (reprinted 1992 by Geotec Ltda., Bogotá, Colombia), p. 349–396.

Mitchum, R. M., P. R. Vail, and S. Thompson III, 1977, Seismic stratigraphy and global changes of sea level; part 2: the depositional sequence as a basic unit for stratigraphic analysis, *in* C. E. Payton, ed., Seismic stratigraphy—applications to hydrocarbon exploration: AAPG Memoir 26, p. 53–62.

Mojica, J., and J. Dorado, 1987, El Jurasico anterior a los movimientos intermalmicos en las Andes Colombianos: Bioestratigrafía de los Sistemas Regionales del Jurasico y Cretácico de América del Sur, Mendoza, Argentina, p. 49–110.

Montgomery, S., 1992, Petroleum potential of Upper and Middle Magdalena basins, Colombia. Part 2: plate tectonics, reservoirs, source rocks and field histories: Petroleum Frontiers, v. 9, part 3, p. 1–57.

Morales, L. G., and the Colombian Petroleum Industry, 1956, General geology and oil occurrences of Middle Magdalena Valley, Colombia, *in* L. G. Weeks, ed., Habitat of Middle and Upper Magdalena basins, Colombia. Oil—a symposium: AAPG, p. 641–695.

Moreno, J., and M. Velazquez, 1993, Estratigrafía y tectónica en los alrededores de Nunchia Departamento de Casanare, Colombia: Tesis de pregrado, Universidad Nacional de Colombia, Bogotá, p. 1–60.

Naar, J., and M. Coral, 1993, Modelo tectónico de un area al NW de Yopal Casanare, Colombia: Tesis de pregrado, Universidad Nacional de Colombia, Bogotá, p. 1–32.

Notestein, F. B., C. W. Hubman, and J. W. Bowler, 1944, Geology of the Barco concession, Republic of Colombia: Geological Society of America Bulletin, v. 55, p. 1155–1218.

Numpaque, L. E., 1986, Geologia regional del sector norte cuenca Llanos Orientales de Colombia: Memorias Segundo Congreso Colombiano del Petroleo, Tomo II, v. 1, p. 73–102.

Orbigny, A. D., 1842, Coquilles et echinodermes fossiles de Colombie, recueillis par M. Boussingault, Paris, Bertrand, 64 p.

Palmer, S. E., and J. A. Russell, 1988, The five oil families of the Llanos basin, III: Simposio Bolivariano de Exploracion Petrolera

de las Cuencas Subandinas, p. 724–754.
Pardo-Casas, F., and P. Molnar, 1987, Relative motion of the Nazca (Farallon) and South American plates since Late Cretaceous time: Tectonics, v. 6, p. 233–248.
Pérez, G., and A. Salazar, 1978, Estratigrafía y facies del Grupo Guadalupe: Geología Colombiana, v. 10, p. 7–87.
Pilger, R. H., Jr., 1984, Cenozoic plate kinematics subduction and magmatism: South American Andes: Journal of the Geological Society of London, v. 141, p. 793–802.
Posamentier, H. W., and G. P. Allen, 1993, Siliciclastic sequence stratigraphic patterns in foreland ramp-type basins: Geology, v. 21, p. 455–458.
Posamentier, H. W., G. P. Allen, D. P. James, and M. Tesson, 1992, Forced regressions in a sequence stratigraphic framework: concepts, examples, and exploration significance: AAPG Bulletin, v. 76, p. 1687–1709.
Pulham, A. J., 1994, The Cusiana field, Llanos basin, eastern Colombia: high resolution sequence stratigraphy applied to late Paleocene–early Oligocene estuarine, coastal plain and alluvial clastic reservoirs, *in* S. D. Johnson, ed., High resolution sequence stratigraphy: innovation and applications: University of Liverpool, Abstract Volume, p. 63–68.
Ramirez, J. E., 1953, Excursión a la Cueva de los Guácharos, Corregimiento de Palestina, Municipio de Pitalito, Departamento del Huila: Revista Javeriana, v. 40, p. 197–208.
Renz, O., 1956, Cretaceous in western Venezuela and the Guajira (Colombia): 20th International Geological Congress, Mexico City, 13 p.
Sarmiento, G., 1992, Estratigrafía y medios de depósito de la Formación Guaduas: Boletín Geológico, no. 32-1, p. 3–44.
Schamel, S., 1991, Middle and Upper Magdalena basins, Colombia, *in* K. T. Biddle, ed., Active margin basins: AAPG Memoir 52, p. 283–301.
Suarez, A. F., 1990, The basement of the Eastern Cordillera, Colombia: an allochthonous terrane in northwestern South America: Journal of South American Earth Sciences. v. 3, p. 141–151.
Talukdar, S., O. Gallango, and M. Chin-a-lien, 1986, Generation and Migration of hydrocarbons in the Maracaibo basin, Venezuela: an integrated basin study: Organic Geochemistry, v. 10, p. 261–279.
Ulloa, C., and E. Rodríguez, 1981, Geología del cuadrángulo K-13, Tauramena: Boletín Geológico, no. 24, p. 3–30.
Van der Hammen, T., 1957, Estratigrafía palinológica de la Sabana de Bogotá: Boletín Geológico, v. 5, p. 187–203.
Van der Hammen, T., 1961, Late Cretaceous and Tertiary stratigraphy and tectonogenesis of the Colombian Andes: Geologie en Mijnbouw, v. 40, p. 181–188.
Van der Hammen, T., J. H. Werner, and H. van Dommelen, 1973, Palynological record of the upheaval of the northern Andes: a study of Pliocene and lower Quaternary of the Colombian Eastern Cordillera and the early evolution of its high-Andean biota: Paleobotany and Palynology, v. 16, p. 1–122.
Villamil, T., and E. G. Kauffman, 1993, Milankovitch climate cyclicity and its effect on relative sea level changes and organic carbon storage, Late Cretaceous black shales of Colombia and Venezuela (abs.): AAPG Bulletin, v. 77, p. 354.
von Buch, L., 1839, Petrifications recueillis en Amerique par M. A. de Humboldt et par Charles Degenhardt: Reprinted, 1885, in Ewald, Roth and Dames, Leopold von Buch Gesammelte Schriften, 4, Band, 2, Halfte, p. 519–542.
Zumberge, J. E., 1984, Source rocks of the La Luna Formation (Upper Cretaceous) in the Middle Magdalena Valley, Colombia, *in* J. G. Palacas, ed., Petroleum geochemistry and source rock potential of carbonate rocks: AAPG Studies in Geology 18, p. 127–133.

ABOUT THE AUTHORS

Mark Cooper

Mark Cooper has a B.Sc. degree in geology from Imperial College and a Ph.D. from Bristol University. He taught at University College Cork prior to joining BP in 1985. He has worked on many basins worldwide, has published over 35 papers, and is an advisory editor for the *Journal of the Geological Society*. He is now with Pan-Canadian Petroleum in Calgary.

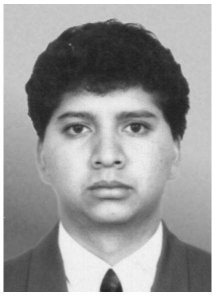
Fergus Addison

Fergus Addison received a B.Sc. degree in geology from the University of Aston in Birmingham and a Ph.D. in geophysics from the University of Newcastle upon Tyne, England. He joined BP in 1982 and is currently manager of Llanos Foothills exploration for BP Exploration Colombia.

Ricardo Alvarez

Ricardo Alvarez received a B.Sc. degree in geology from the Colombian National University in Bogotá in 1986. He joined BP Exploration in 1987 and is currently business planning team leader for BP Exploration Colombia.

Mario Coral



Mario Coral received a B.Sc. degree in geology from the Colombian National University in Bogotá in 1993. He joined BP in the same year and is currently working as a geophysicist on the development of the Cupiagua oil field in Colombia.

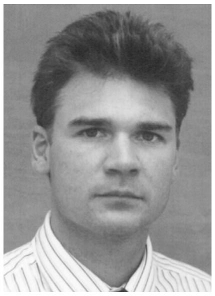
R. H. Graham

Rod Graham graduated from the University of Wales in 1966, obtained a Ph.D. from Imperial College in 1969, and taught at University College Swansea for thirteen years before joining BP in 1984 as a structural geologist. He has published many papers on structural geology.

Anthony B. Hayward

Tony Hayward received a B.Sc. degree and a Ph.D. in geology from the University of Edinburgh. He joined BP Exploration in 1982 and is currently exploration manager for BP Exploration Colombia.

S. Howe

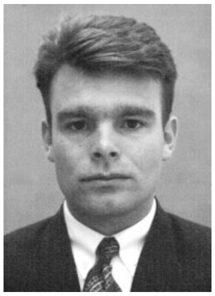


Spencer Howe received a B.Sc. degree in applied physics and chemistry and an M.Sc. degree in geophysics from the University of Durham, England. He joined BP Exploration in 1984 and is currently working on Llanos Foothills exploration in Colombia.

Jaime Martinez

Jaime Martinez received a B.Sc. degree in geology from the Colombian National University in Bogotá in 1991. He joined BP Exploration in 1992 and is currently working on Llanos Foothills exploration.

Joaquín Naar

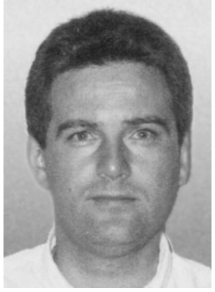


Joaquín Naar received a B.Sc. degree in geology from the Colombian National University in Bogotá in 1993. He joined BP in the same year and is currently working as a development geologist on the Cusiana oil field in Colombia.

Ricardo Peñas

Ricardo Peñas received a B.Sc. degree in geology from the Colombian National University in Bogotá in 1990. He joined BP in 1992 and is currently working as an exploration geologist in the business planning team for BP Exploration Colombia.

Andy Pulham



Andy Pulham received a B.Sc. degree in physical geography and geology at Liverpool University and a Ph.D. in geology at Swansea University. He has worked for BP Exploration in Aberdeen, London, Houston, and Bogotá. He is currently working as a sedimentologist with responsibility for reservoir description in the Cusiana field.

Adriana Taborda

Adriana Taborda received a B.Sc. degree in geology from the Colombian National University in Bogotá in 1984. She has worked in the Colombian oil industry as a geophysicist since then, and joined BP in 1989. She is currently working as a development geophysicist on the Cusiana oil field in Colombia.