
Regional Hydrocarbon Systems of Colombia and Western Venezuela: Their Origin, Potential, and Exploration

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ABSTRACT

This paper synthesizes technical, commercial, and strategic issues regarding the petroleum systems and exploration of the northwest corner of South America in three parts: a technical analysis of the presence and distribution of the hydrocarbon systems; analysis of the areas with the largest remaining potential; and Colombia's exploration strategy in relation to its geology and potential.

The technical portion outlines, with the use of countrywide paleogeographic maps, the main reasons for the presence and distribution of hydrocarbons in the region. Regional petroleum systems are described using a process and genesis methodology. The proposed hypothesis for source-rock quality and distribution combines regional plate tectonics with the formation of a large igneous province, global warming, increased upwelling, widespread anoxia-dysoxia, and sea-level rise. The hypothesis for reservoir distribution and quality comprises details of a regional orogenic event that affected the northwest margin of South America. The distribution of different reservoir qualities is determined by the erosion of an elongated mountain belt formed by this orogeny, the associated synorogenic sedimentation, and the evolution of a closing foreland basin that received sediments from the west from a mountain chain with varied basement stratigraphy, and from the east, sediments from the Guyana Shield. The explanation for regional seal deposition lies in the tectonic extension and foundering of large portions of Colombia and western Venezuela, the regional subsidence associated with diminished plate-tectonic convergence, and the associated increase of accommodation space. The inversion of the Eastern Cordillera and the development of doubly verging thrust belts bounding the mountain belt explain the formation of most traps. Adjacent forelands and foredeeps to the mountain belt and thick molasse packages combined with tectonic burial of the source rock explain

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generation and migration patterns. This paper also considers where the largest volumes of hydrocarbons will be found in the future, based on technical issues, and on the exploration history of different play areas in Colombia.

WHY IS THERE OIL AND GAS IN COLOMBIA AND WESTERN VENEZUELA?

Introduction

To address the question of why there is oil and gas in northwestern South America, a large-scale petroleum systems approach will be used (Figure 1). This active and highly prolific Cretaceous-Tertiary petroleum system accounts for more than 96% of hydrocarbons discovered and yet to be found in Colombia and western Venezuela. The remaining 4% of encountered and expected reserves are attributed to other minor petroleum systems. The Cretaceous-Tertiary petroleum system consists of the following combination of elements: (1) The La Luna source rock and equivalent units. These source rocks have generated more than 2.3 trillion barrels of oil (James, 2000a, b, plus budgets for Colombia, Trinidad, and Ecuador), more hydrocarbons than any other source rock in the world. Most of these hydrocarbons, however, are trapped as heavy oil in the Orinoco Tar Belt of eastern Venezuela. (2) A very broadly distributed reservoir interval primarily of Eocene age. These Eocene reservoirs contain proven reserves on the order of 24 billion barrels of oil in western Venezuela and along the foothills of the Eastern Cordillera of Colombia. A highly prolific reservoir unit of Miocene age, restricted to the Maracaibo Basin of western Venezuela, holds approximately 23 billion barrels of oil. This reservoir system is not present in Colombia and represents one of the main reasons why the Maracaibo Basin contains significantly more reserves than adjacent Colombian basins with the same source-rock unit. (3) A widespread but discontinuous seal interval of Oligocene age that seals approximately 23 billion barrels of oil encountered in Colombia and western Venezuela. (4) Trap formation, maturation, and migration of Miocene to Pleistocene ages. These traps and their filling history account for approximately 40–50 billion barrels of oil in northwest South America. In analyzing the La Luna-Tertiary petroleum system, this paper addresses the following issues: the deposition, distribution, and quality of the La Luna source rock and equivalents; the widespread deposition, distribution, and differences in quality of the Eocene reservoir; the regional change in facies that allowed the deposition of sealing strata over reser-

voirs during the Oligocene; and the formation of traps and maturation of the source rock. The rationale for this approach is that, by establishing the origins of regional petroleum systems, as opposed to

		SOURCE	RES.	SEAL	TRAP
T E R T I A R Y	Pliocene			23 billion	40 billion
	Miocene	3100 MMBO	23 billion		
	Oligocene	2400 MMBO	105 MMBO	23.5 billion	3060 MMBO
	Eocene		23.5 billion		13.7 billion
	Paleocene		2.5 billion	2.5 billion	940 MMBO
	Maastrich	<2 billion	1.5 billion		
C R E T A C E O U S	Campanian				
	Santonian				
	Coniacian	300 billion aprox.	194 MMBO		
	Turonian				
	Cenoman	225 billion aprox.		4 billion	
	Albian		4 billion		

Figure 1. Large-scale petroleum systems of Colombia and western Venezuela. Numbers represent barrels of oil equivalent generated and expelled from the source rock, accumulated within the reservoirs, retained by the seal, and trapped by the structures. Timing and critical events are not shown; they are highly variable from basin to basin and within basins closest to mountain-front areas.

providing a purely descriptive account of them, there is a significant enhancement to the power of interpretation and prediction in studying the petroleum geology of the northern margin of South America.

Setting the Stage: General Features and Rifting of the Eastern Cordillera Graben

Because most of the regional petroleum systems of Colombia and western Venezuela (Figures 1, 2) are related to the opening, fill, and inversion of a Jurassic to Early Cretaceous graben system, the grabens and associated processes will be reviewed briefly.

During the Triassic, Jurassic, and earliest Cretaceous, the northern margin of South America was subject to significant extension. Precise values of crustal extension have not been calculated, but a gross estimate suggests that the value of extension of the Eastern Cordillera graben was about 60% of most accepted values for subsequent shortening, i.e., approximately

60–70 km (e.g., Villamil, 1999; Linares, 1999). This estimation is derived from a calculation of the mass deposited inside the graben, the mass presently elevated above sea level, and changes in paleo water depth through time. The present topographic expression of the Eastern Cordillera of Colombia, the *Serranía de Perijá* of Colombia and Venezuela, and the *Mérida Andes* of Venezuela mimics in a gross sense the main distribution of Jurassic grabens. Mojica (1982) and Mojica and Macias (1982) summarize the distribution of synorogenic graben-fill deposits. Because of the separation of the South American Plate from the North American Plate, and the slow convergence between ancestral Pacific oceanic plates and the South American Plate, a significant region along the western margin of South America was subject to extension, ultimately controlled by slab roll processes. As will be seen later in this paper, the main graben-bounding faults currently are inverted and are located

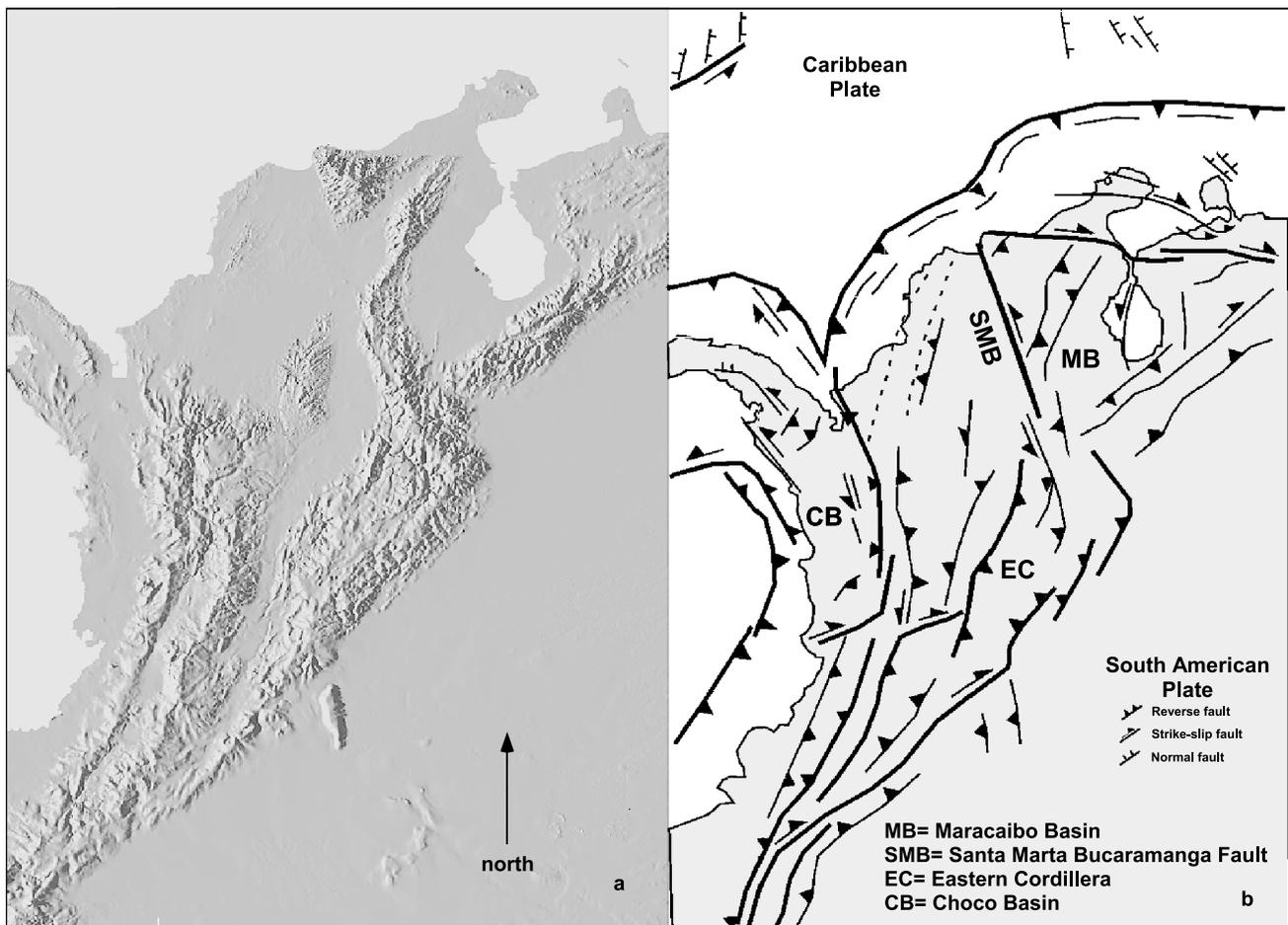


Figure 2. Location map of Colombia and western Venezuela showing major tectonic elements mentioned in the text. (a) Radar image of northwest South America, including most of the Eastern Cordillera (EC); the *Perijá* range and the *Mérida Andes* are inverted positive topographic expressions of Jurassic–Early Cretaceous extensional systems. (b) Schematic representation of principal faults of the region.

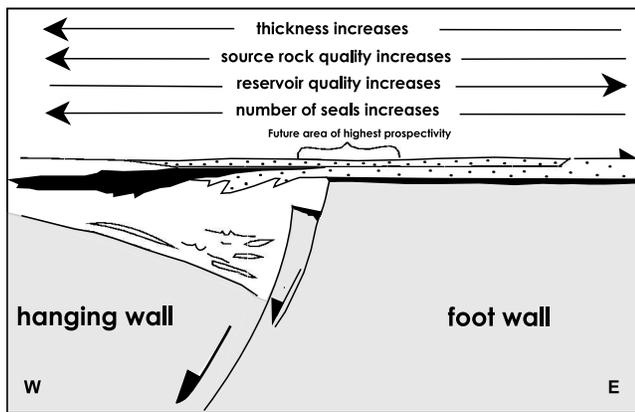


Figure 3. Simple model showing relationships across a major extensional fault that will later be reactivated. Sediment supply is mostly from the east.

at the eastern and western margins of the Eastern Cordillera of Colombia, the Perijá Range, and the southern flank of the Mérida Andes. The western continuation of the Espino Graben of Venezuela was not reactivated and inverted during the pre-Andean and Andean orogenic events because the strike of the graben was, and still is, oblique to the direction of convergence caused by subduction. Graben systems perpendicular to the direction of convergence remain buried in the plains of the Barinas Basin of Venezuela and the Llanos Basin of Colombia.

The Eastern Cordillera of Colombia, the Serranía de Perijá, parts of the Mérida Andes (Figure 2), and

the Serranía del Interior Oriental in eastern Venezuela contain thick wedges of early Mesozoic sediments in the ancestral downthrown hanging-wall sides of graben systems and along central portions of the grabens (Figures 3 and 4). The margins of middle Mesozoic grabens are currently inverted faults or fault systems that clearly and abruptly separate thick and more distal Cretaceous sediments that are generally mud-dominated sections in present hanging walls from sand-dominated, thin, and more proximal facies of generally younger ages in the footwalls (Figure 4). The best example and better-known inverted fault system is located along the eastern foothills of the Eastern Cordillera of Colombia (Dengo and Covey, 1993; Cooper et al., 1996a, b). At the latitude of Bogotá and to the north, the Guaicaramo fault system separates a 2–3-km-thick sequence of Berriasian to Aptian age strata that consists primarily of shales, turbidites, and scattered shallow-water sandstones from a region to the east that was exposed to erosion during those times. The thick shale-dominated package is currently observable in the hanging wall of inverted fault-related anticlines west of the Guaicaramo Fault (Figures 3 and 4); similar mirrored relationships also are observable in hanging-wall rocks east of the La Salinas Fault system and similar fault systems that bound the Eastern Cordillera mountain range to the west. Similarly, the footwall stratigraphies are sand-dominated. Figure 3 is a schematic diagram of the

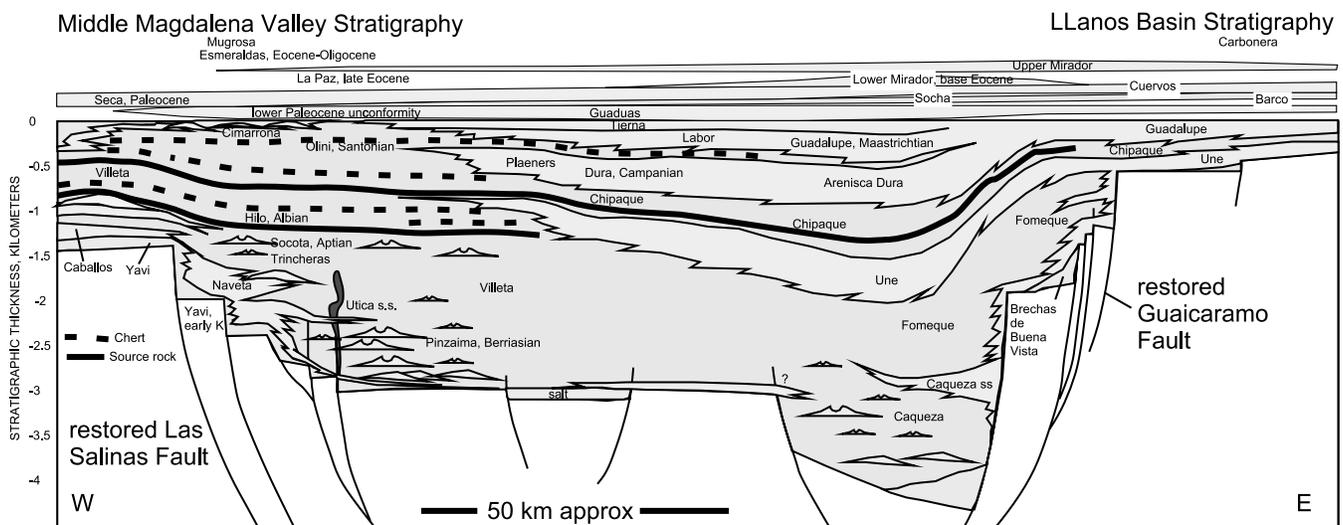


Figure 4. Cross section of the Eastern Cordillera of Colombia at the latitude of Bogotá. The datum for this section is the base of the Guaduas Formation and approximately coincides with the Cretaceous-Tertiary boundary. Note significant changes in stratigraphic thickness, age, and facies across the main extensional faults bounding the Jurassic to Cretaceous graben. The Eastern Cordillera can be grossly interpreted as a large and partly broken inverted half graben; this half graben had its principal fault system along its eastern margin; i.e., the present-day inverted Guaicaramo fault.

Cretaceous paleo Guaicaramo Fault system; it shows the stratigraphic relationships outlined above and suggests the area where, after Miocene-Pliocene inversion, most of the prospectivity is concentrated. Because a significant part of the Cretaceous system of Colombia and western Venezuela was influenced in terms of accommodation space (primarily facies and thickness) by synextensional growth and differential compaction (Figure 4), some general relationships can be proposed. The Albian Une Formation reservoir is of significantly better quality in footwall areas of the extensional faults. The thickness and quality of the Chipaque (La Luna equivalent) source rock was influenced by differential compaction across old extensional faults, and it is of much better quality within the graben itself. The source rock in the Llanos foothills and Llanos Basin, having been deposited outside of the graben, is of lower quality; it also is generally immature. Active rifting had ceased during the deposition of the Late Cretaceous source rock; however, the ancestral Guaicaramo Fault Zone and similar boundaries remained significant inasmuch as they represented the transition zone between areas of high and low compaction and subsidence: the hanging-wall and footwall zones, respectively. The latest Cretaceous Guadalupe Formation reservoir and equivalent units is cleaner and of better quality in the footwall zone of old extensional faults.

The La Luna Source Rock and Equivalent Units: Distribution, Origin, and Yield

The La Luna source rock and its equivalent units, such as the Villeta Formation in Colombia, the Quecual Formation in eastern Venezuela, and the Naparima Hill Formation in Trinidad, is the most prolific source rock in the world. The La Luna and equivalents have generated more than 2.3 trillion barrels of oil. Most of this oil is trapped in the heavy-oil belt of eastern Venezuela, and a significant volume has escaped from open systems like the Magdalena Valley and other producing basins. A significant volume of source rock has been destroyed in northern Colombia, central northern Venezuela, and offshore eastern Venezuela by the diachronous transpression and accretion of Caribbean Plate terranes.

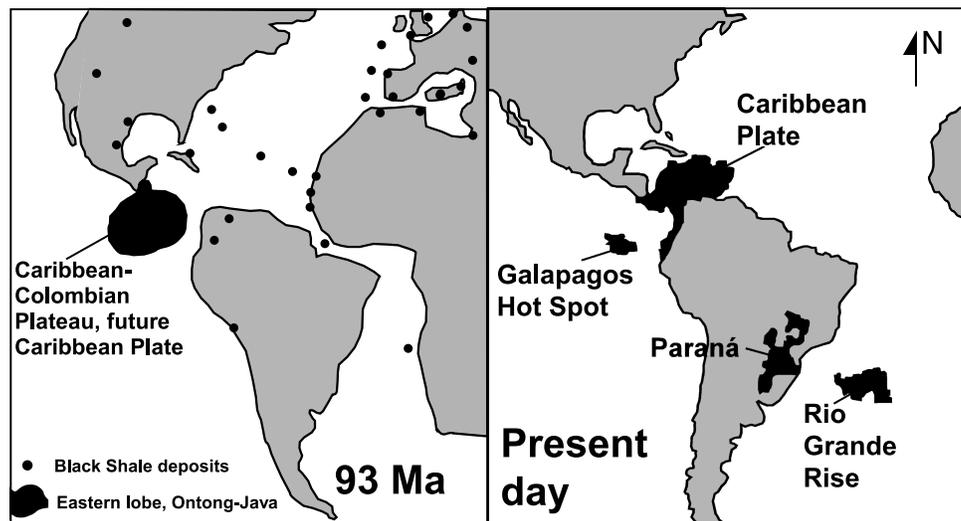
The occurrence, quality, and distribution of the La Luna and equivalent source rocks were controlled and determined by a combination of tectonic and paleoceanographic events that ultimately allowed the deposition of this extraordinary facies. The events that caused the deposition of this prolific unit are reviewed in relative detail. These events can be sum-

marized as follows: (1) A plate tectonic thermal event that generated the Caribbean Oceanic Plateau, a large igneous province (LIP) of four million cubic kilometers of lava (Kerr, 1998) that were extruded to the sea bottom. This event caused a rise in eustatic sea level, widespread flooding, and transgression. It also injected a significant volume of CO₂ into the atmosphere, thus warming an already warm world (Kerr, 1998). (2) A tectonic drift of the South American Plate towards the north, relative to the mantle reference frame. This event placed the northern margin of South America in regions north of the paleoequator, changing in a marked manner the paleoceanographic regime that affected epicontinental waters during those times (Villamil et al., 1999). (3) Because of global plate tectonics and changes in climate, the paleoceanographic regime that took place during the early Turonian (times of maximum transgression and highest source-rock quality) is considered to be a worldwide oceanic anoxic event. The low oceanic oxygen content combined with relatively high paleobioproductivity allowed anomalous organic carbon preservation by preventing oxidation of organic matter that fell through the water mass to the sea bottom. These three major factors affected the pre-source rock sea bottom. This sea bottom was of very low topographic relief; the epicontinental area of Colombia, Venezuela, and Trinidad was a gently inclined shallow surface (sea bottom and coastal areas). This continental margin was passive in Venezuela and Trinidad, and a postextensional or postdrift passive sag that behaved as a passive margin in Colombia. The effect of even a minor rise in sea level across this almost flat surface was a rapid transgression and widespread flooding. In addition to the tectonic and oceanographic conditions and the paleotopography of the basin, the epicontinental sea received a relatively constant rain of fine-grained, clay-dominated sediments that facilitated trapping of large quantities of organic matter.

A 90 Ma Large Igneous Province (Lip, Caribbean Plate): The Ultimate Economic Effect of Superplume Activity

Approximately 93 Ma, a vast volume of extra oceanic crust of approximately 4 million km³, occupying an area of approximately 1 million km², was generated over the Galapagos Hotspot (Figure 5; Kerr, 1998). This igneous event was in addition to anomalous volumes generated globally by rapidly expanding oceans. The Galapagos Hotspot formed a discrete oceanic plate, or LIP, and displaced seawater producing a rise in eustatic sea level. This LIP is the present

Figure 5. Turonian (93 Ma) and present position of the Caribbean Plate–Caribbean Colombian plateau large igneous province. This large igneous province consists of the Caribbean Plate, its subducted slabs, and the Caribbean fragments that have been accreted to the northwest corner of South America. Figure is synthesized from Kerr (1998).



Caribbean Plate, subducted slabs, and accreted fragments. The plate was located west of and, through time, between the North America–South America oceanic passage and was later locked by west and east subduction zones in the mantle reference frame. Because of westward drift of the South American and North American Plates, the LIP had a relative movement to the east and entered the space between them (Figure 5). The volcanic activity associated with the formation of the LIP injected a very large volume of CO₂ into the atmosphere (Kerr, 1998). The combination of extra lava in the oceans and extra CO₂ in the atmosphere caused marine flooding and global warming and contributed to widespread dysoxic-to-anoxic oceanic conditions. This intense volcanic event also expelled significant quantities of silica into the ocean, favoring in an indirect manner the supply of nutrients to increase paleoproductivity. Flooding and dysoxia, combined with exceptional paleoceanographic conditions, allowed the deposition of a very widespread and rich source rock throughout northern South America in the Cretaceous. The La Luna Formation was deposited over a very broad, large marine epicontinental seaway (Figure 6) that extended from northern Peru to Trinidad during a time when sea levels already were superior to Phanerozoic averages. Whereas rocks of this age are not the only Cretaceous source rock, the La Luna has generated more oil than any other source rock and has produced the largest accumulation of hydrocarbons on the planet, as evidenced by the Orinoco heavy-oil belt. In Colombia, the La Luna Formation is distributed throughout most of the main basins and along the eastern and western foothills of the Eastern Cordillera. The La Luna source rock and equivalent units is a crucial formation for oil exploration because of its widespread nature, its richness (as much as 16% TOC; Figure 7), and its thickness. The

presence of this super source rock has a major impact on reducing exploration risk.

Warming

As mentioned above, the submarine extrusion of vast volumes of lava injected significant volumes of CO₂ into the atmosphere. CO₂ is a greenhouse gas; it is transparent to short-wave visible radiation coming from the sun, and it is semiopaque to outgoing, longer-wave, infrared radiation reflected by the earth (see Wells, 1986, and primary references therein). Warming caused by extra CO₂ in the atmosphere has a significant impact on source-rock development. Seawater holds dissolved oxygen in an inverse relationship to temperature; i.e., cold water can hold much more oxygen than warm water. The content of oxygen determines the capacity of the water as an oxidizing agent, and thus the capacity to destroy organic matter that falls through the water column and finally reaches the sea floor. Apart from a decrease in the rate of destruction by oxidation of organic matter, warming of seawater causes modifications in the circulation of water masses. Warm waters circulate in a slower, sluggish manner, and this allows mixing of the water column, which, in turn, favors productivity.

Sea-level Rise

The eustatic rise in sea level caused by the formation of the Caribbean Plate resulted in a worldwide transgression. The effects of this transgression were especially marked along the Cretaceous passive margin of Venezuela and Trinidad and along the post-extensional sag margin of Colombia. The very low topographic relief of the northern South America epicontinental basin permitted the shoreline to

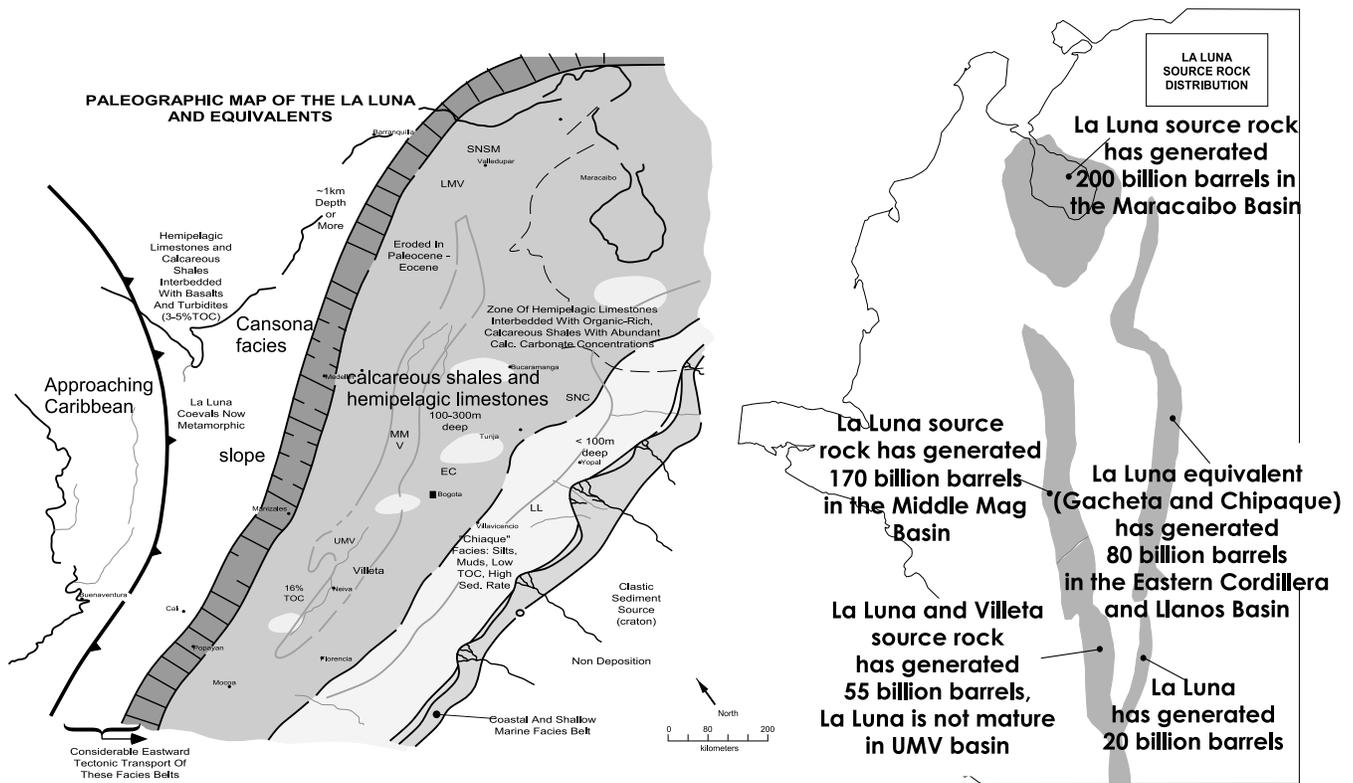


Figure 6. Paleogeographic map of the La Luna Formation and equivalent units (left) and regions where the La Luna is preserved and in maturation kitchen (right) with hydrocarbon values, in barrels of oil equivalent that have been expulped from the source rock. The paleogeographic map is palinspastically restored and shows the original distribution of the La Luna Formation and equivalent units in northwest South America.

rapidly transgress significant distances with a relatively modest rise in sea level. Based on facies associations dated with high-resolution stratigraphy, it was determined by Villamil and Arango (1998) that the shoreline transgressed about 65 km to the east and southeast over a period of only approximately half a million years, from the late Cenomanian to the early Turonian. The rise in sea level caused by the tectonothermal event that produced the LIP, combined with the low angle of the epicontinental basin in northern South America, explains the widespread regional distribution of the La Luna Formation and coeval units. Transgression peaked regionally (and globally) during the early Turonian (Haq et al., 1987; Villamil, 1998, for Colombia and Venezuela) with the deposition of a major and widely distributed condensed section that spans the Cenomanian-Turonian boundary interval into the early Turonian. The base of this condensed section is the base of the La Luna Formation in its type locality (Quebrada La Luna in western Venezuela), in the Middle Magdalena, Catatumbo, and western Venezuelan Basins (Villamil and Arango, 1998), and the base of the Navay Formation of the Barinas Basin of Venezuela (Figure 6).

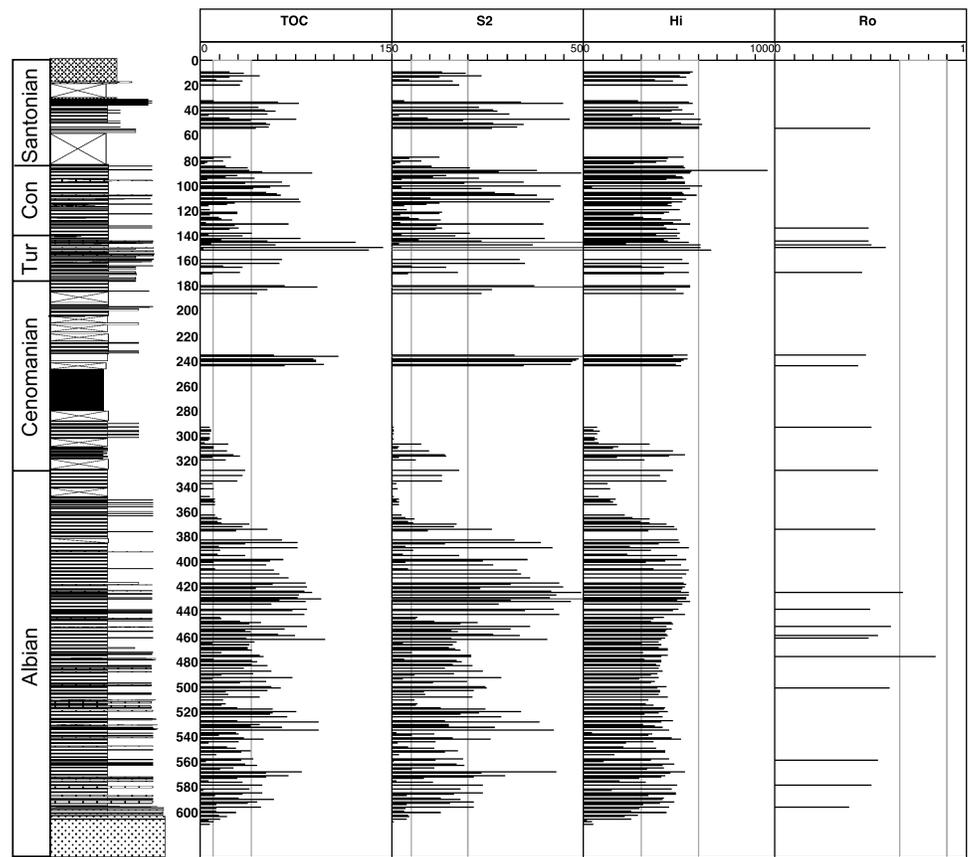
Dysoxia

The fine-grained Cretaceous stratigraphic record in Colombia and Venezuela records three widely recognized oceanic anoxic events. These oceanic anoxic events (OAEs) are major elements in understanding the La Luna and equivalent source rocks in northern South America. The first OAE began in Colombia and Venezuela during the early Albian and comprises most of the Albian stage. Rocks of this age are the main hydrocarbon source rock of the Upper Magdalena Valley in Colombia; they overlie the Aptian Caballos Formation reservoir. The contribution of this portion of the Villeta Formation and equivalents in the total hydrocarbon budget generated in Colombia and Venezuela is currently being investigated by geoscientists. Judging from the total organic carbon richness and other geochemical indicators measured from these fine-grained facies (Figure 7), it is easy to predict that a significant amount of oil and gas will be generated from these rocks.

The second and most dramatic oceanic anoxic event is the Cenomanian-Turonian OAE II of Schlanger and Jenkyns (1976), Arthur et al. (1987), and many other sources. The Cenomanian-Turonian (C-T)

Figure 7. Source rock geochemistry of the La Luna Formation equivalent in the Upper Magdalena Valley of southern Colombia (the Villeta Group). The figure shows the oil generating potential of this middle-Late Cretaceous interval.

boundary OEA has been interpreted as a global phenomenon. In Colombia and western Venezuela, the strata that contain the evidence for OAE coincides with the base of the La Luna Formation *sensu stricto* and represents the richest and most prolific source rock of the region. At outcrop scale, the C-T interval is seen as a resistant calcareous unit in a sequence composed primarily of poorly resistant shales; thus, it can be easily traced and mapped in the field. The color of C-T outcrop surface exposures in distal portions of the basin in Colombia is generally of a characteristic reddish-brown color as a result of the alteration, oxidation, and leaching of pyrite. Geochemical anomalies across the C-T boundary have been used by Schlanger and Jenkyns (1976), Pratt (1985), and Arthur et al. (1987) to interpret Cretaceous global oceanic and atmospheric conditions and paleoclimate. In Colombia and western Venezuela, the $\delta^{13}\text{C}$ and TOC anomalies corroborate this hypothesis. These anomalies represent the geochemical expression of the OAE and correspond to lithological and paleobiological evidence of O_2 depletion. The $\delta^{13}\text{C}$ anomaly has been found in many basins worldwide and can be considered as a chemostratigraphic synchronous marker (Kauffman, 1988; Hart and Leary, 1991; Gale et al., 1993). The anomaly has been interpreted as reflecting increase in burial of $\delta^{13}\text{C}$ -depleted organic carbon (Arthur et al., 1987). In facies around the C-T boundary of Colombia, the $\delta^{13}\text{C}$ anomaly coincides with a TOC anomaly that reaches very high values (Figure 7). The C-T boundary is found within a condensed section caused by the rapid rise in sea level discussed above and resulted in coastal encroachment and sediment trapping shoreward (Villamil and Arango, 1998). As accommodation space in-



creased in proximal regions, clastic sediments filled this space and were trapped in nearshore and estuarine environments.

The third Cretaceous oceanic anoxic event, OAE III, is interpreted from late Coniacian to early Santonian facies in western Venezuela and Colombia. Strata of this age might have generated a large volume of hydrocarbons encountered along the Llanos foothills and the Barinas-Apure Basin. Facies with significant source-rock quality (Figure 7) representing the OAE III are shales, calcareous shales, and hemipelagic limestones of the upper portions of the La Luna Formation in the Middle Magdalena Valley and Maracaibo Basin and of the upper portions of the Villeta Group in the Upper Magdalena Valley.

Migration to the North of the South American Plate: Upwelling and Paleoproductivity

In addition to the events and controlling factors outlined previously, the quality of the La Luna source rock and equivalent units in Colombia and Venezuela was controlled by a general increase in upwelling and associated paleoproductivity. This increase in upwelling and paleoproductivity affected only regions

in the northern margin of the South American continent; it explains why the exceptional quality of the La Luna and equivalent units is restricted to regions north of central Ecuador.

In general terms, the Cretaceous stratigraphic record changes from Jurassic-Valanginian red beds and coarse clastics to widespread, well-developed Hauterivian–early Albian carbonate platforms and coarse-grained clastics. These stratigraphies are followed by early Albian–Coniacian organic rich shales (the principal petroleum source rock) and hemipelagic foraminiferal limestones with minor chert beds representing short-lived events of vigorous upwelling conditions. The paleoceanographic event climaxed in terms of paleoproductivity during the Santonian and Campanian with the deposition of widespread bedded cherts representing regional and long-term upwelling conditions. Two explanations of this long-term facies change have been proposed (Villamil et al., 1999). The first explanation is that a change in paleoceanographic regime from southward-directed Ekman transport to northward-directed Ekman transport, caused by northern migration of the South American Plate with respect to the paleoequator, resulted in the deposition of upwelling-related facies. The second explanation is a migration of the northern margin of South America into the equatorial upwelling region caused by the position of the Cretaceous Intertropical Convergence Zone.

The increase in upwelling is evidenced by lithology, paleobiology, and geochemistry. This increase in paleoproductivity was superimposed on a changing stratigraphic record composed of several sequences resulting from transgressive-regressive “cycles” deposited in dynamically changing basins and subbasins. The early Albian–late Coniacian stratigraphic record depicts the deposition of organic-rich shales cyclically interbedded with hemipelagic marls and limestones; i.e., the La Luna and equivalents. Facies representing vigorous upwelling conditions generally increase in volume and frequency through the Cretaceous of northern South America, with variations that depend on local conditions. Widespread chert deposition suggests that a superproductive regime reached a peak during the Santonian–early Campanian. The very high paleoproductivity regime established at the beginning of the Santonian persisted through the Maastrichtian, but it was obscured locally by high input of sediment from regressive systems from the east and west.

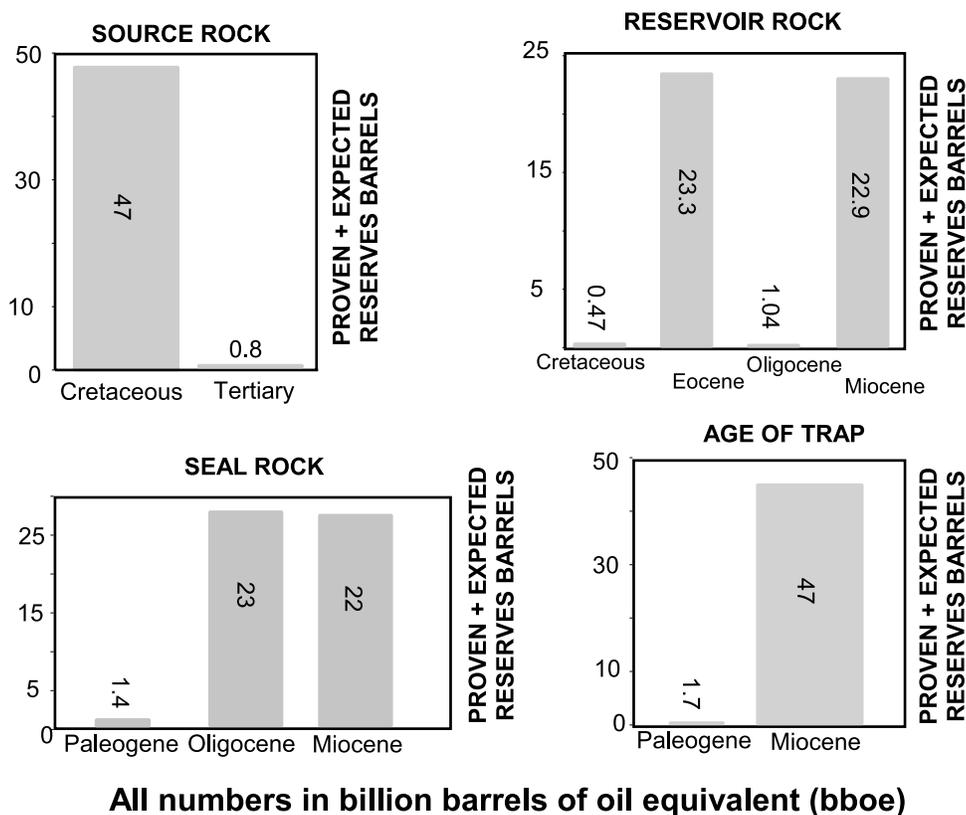
The early Albian records the demise of Hauterivian to Aptian carbonate platforms and the initiation of

widespread black shale deposition. The demise of carbonate platforms was possibly caused by a marked transgression combined with increased paleoproductivity drowning and the poisoning of carbonate-producing organisms. Above the transgressive surface overlying carbonate platforms, glauconite-rich calcareous and, in some cases, siliceous shales and even cherts were deposited. Transgression and increased paleoproductivity are represented regionally by widespread deposition of calcareous shales very rich in organic carbon (Figure 7) interbedded with hemipelagic planktic foraminiferal limestones.

Evidence of vigorous upwelling and paleoproductivity continues to increase upsection with more chert and phosphorites being deposited regionally through the late Turonian and Coniacian. The increase in paleoproductivity reached its peak during the Santonian with widespread deposition of relatively shallow-water bedded cherts in proximal regions of the basin and relatively deep-water shales in distal offshore settings. These cherts represent replacement of calcareous, foraminifer-dominated planktic communities by siliceous, radiolarian-dominated planktic communities. Chert deposition occurred regionally in a slowly regressing system, or early highstand systems tract. Units represented by chert-dominated facies are the Oliní Group of the Upper Magdalena Valley of Colombia, the La Luna Formation of the Middle Magdalena Valley, the Táchira Chert, and the cherts of the upper La Luna Formation of western Venezuela. Chert-dominated units have been recognized in northern South America (Bürgl and Dumit, 1954; Hubach, 1957; Morales et al., 1958; Gonzalez de Juana et al., 1980; Etayo, 1985; Macellari and De Vries, 1987; Macellari, 1988; Tribovillard et al., 1991; Martinez and Hernandez, 1992; Perez-Infante et al., 1996; Villamil et al., 1999).

Chert units, despite having been deposited during vigorous upwelling and high-productivity regimes, do not contain as much total organic carbon (TOC) as fine-grained, shale-dominated facies. The microstructure of chert is rounded and cannot trap organic matter in the efficient manner of the microstructure of flat and layered shale (see Johnson, 1982, for additional details).

Geochemically, TOC values reaches a peak in lower Turonian strata (Figure 7) just above the Cenomanian-Turonian boundary interval. This peak in TOC correlates precisely to the Cretaceous maximum-flooding surface. Total organic carbon values decrease upsection from their lower Turonian peak because of the increase in chert and because the strong regression



All numbers in billion barrels of oil equivalent (bboe)

Figure 8. Graphs showing volumes and budgets of hydrocarbons generated and encountered in northern South America versus age. Note that most of the hydrocarbons, in barrels of oil equivalent, have been generated by the Cretaceous La Luna and equivalent units. The volume expelled from Albian and Turonian to Santonian strata exceeds 800 billion barrels, and this Cretaceous source rock explains most of the hydrocarbons encountered in the region; i.e., see different size of bars, upper left. The two main ages for reservoir deposition are Eocene and Miocene, upper right. This graph is highly biased by the vast volumes of hydrocarbons encountered and potential of the Maracaibo Basin and eastern foothills of the Eastern Cordillera. Eocene reservoirs were deposited during and as a consequence of the pre-Andean orogeny, whereas Miocene reservoir deposition took place as a consequence of the early phases of the Andean orogeny. Most of the strata that retain hydrocarbons are seals (lower left) of Oligocene and late Miocene ages. In Colombia, the vast majority of retaining lithologies are Oligocene shales and other fine-grained strata; in the Maracaibo Basin, Miocene fine-grained deposits seal significant quantities of hydrocarbons. Oligocene and late Miocene seal deposition was the consequence of tectonic foundering of large portions of the northern South America continental crust. Andean Miocene structures trap most of the hydrocarbons found in northern South America (lower right); Eocene or pre-Andean structures also are important traps, but most of those were destroyed by exhumation during the Andean orogenic event.

and resulting increasing sediment supply dilutes the organic matter. Figure 8 shows budgets for reserves encountered that have been tied to the La Luna and equivalent units.

The Pre-Andean Orogeny, 30 Million Years of Diachronous Reservoir Deposition

As described previously, the formation of the Caribbean Plate large igneous province (LIP) influenced

directly the source-rock quality and distribution. The relative plate tectonic movement of this LIP eastward with respect to South America was of special significance in the genesis of most of the reservoirs in Colombia and western Venezuela. Convergence and collision between the Caribbean and South American Plates began in the Maastrichtian and uplifted vast regions of Colombia. Synorogenic erosion of this diachronous and progressive uplift, which climaxed in the middle Eocene, produced large volumes of sediments that were transported to adjacent depocenters; these sediments are the main reservoirs of northwest South America.

During the Maastrichtian to Eocene, the present Central Cordillera had its major episode of uplift and erosion; sediment products of this erosion were transported toward the east by major river systems. During those same times, the Guyana Shield underwent uplift and delivered vast amounts of sediment to the west and north. Rivers flowing to the east converged with those flowing to the west along a northward-draining central river system. The marginal-marine basin regressed at the end of the Cretaceous to a Paleogene fluvial envi-

ronment that produced the main megafacies of the principal reservoirs of Colombia and western Venezuela, particularly the Misoa and Mirador formations of the Maracaibo Basin and of the Llanos and eastern foothills of the Eastern Cordillera. The coeval La Paz and Esmeraldas Formations of the Middle Magdalena Valley were derived solely from the Central Cordillera mixed terrane and show a poorer reservoir quality than facies derived from the Guyana Shield to the east.

The line that separates sediments delivered from the east and southeast from sediments delivered from the west will be referred to from now on as the central axis of deposition. This line is determined as follows: (1) the line that separates westward from eastward sediment-transport direction; (2) the line that separates sediment composition indicating provenance in the Central Cordillera and/or allochthonous nappes from sediments very rich in quartz with provenance in the Guyana Shield; (3) the axis of the basin with the greatest accommodation space or subsidence; and (4) the central axis of the basin with thicker or more distal facies of coeval strata. For a detailed description of the methodology, refer to Villamil (1999). The concept of a central axis of deposition is critical for understanding the petroleum geology and for prediction of the exploration potential of this region. The central axis of deposition separates, at any particular time, sediments derived from the Guyana Shield from sediments derived from the uplifting ancestral Central Cordillera. Coarse-grained stratigraphies derived from the Guyana Shield consist of almost pure multicycle quartzarenites that are very well-sorted and rounded. These rocks, when they are fine-grained sandstones, have significant permeabilities that allow economic deliverability despite relatively low porosities. In the Cusiana and Cupiagua fields of the Llanos foothills of Colombia, the Mirador reservoir maintains these high-quality characteristics even at considerable depths of burial (5486 m [18,000 ft]; see Cazier et al., 1995, 1997). In the Caño Limon field, similar facies derived from the Guyana Shield, but of a younger age, present excellent reservoir quality, deliverability, and recovery factors. In contrast, reservoirs derived from the Central Cordillera are of lower quality because the sediments were not as quartz-rich as those derived from the Guyana Shield. Sediments derived from the Central Cordillera are poorly sorted, and contain lithics, chert, feldspars, and some volcanic and metamorphic grains. These impurities affect the reservoir quality of units such as the La Paz, Esmeraldas, and Murgosa Formations (e.g., Figures 9 and 10).

The position of the central axis of deposition has changed dramatically as a consequence of tectonic uplift of large regions, primarily the ancestral Central Cordillera, differential subsidence, and of changes in sediment input and accommodation space (Figure 10).

The central axis of Campanian deposition was located a few kilometers east of the present Central Cordillera and shifted eastward through time, reach-

ing the easternmost portions of the Eastern Cordillera in the Eocene-Oligocene. The shift was not continuous or gradual, and because of several isolated uplift events, restricted and short-lived drainage divides were established. In the late Oligocene, the initial inversion of the Eastern Cordillera created a drainage divide, and the dominant axis of Late Cretaceous–Eocene deposition was divided permanently into two main drainage basins: the ancestral Orinoco and the ancestral Magdalena River systems. As the Eastern Cordillera and Mérida Andes grew, they forced the proto-Orinoco drainage system to move east and the proto-Magdalena drainage system to move west (Figure 10). Oligocene base-level rise allowed sporadic marine floods into parts of the Eastern Cordillera, Middle Magdalena Valley, and Llanos Basin.

Changes in accommodation space were caused by a combination of tectonic uplift or loading of the basin (e.g., Villamil et al., 1995) and eustatic changes in sea level. These changes in base level were superimposed onto the general migration of the central axis of deposition toward the east.

The main events that controlled the origin of most reservoirs in Colombia and western Venezuela are: (1) Campanian to Maastrichtian uplift of the ancestral Central Cordillera, evidenced by westerly-derived coarse-clastic sediments (see Villamil, 1999). The ancestral Central Cordillera was much longer than it is presently, and it included the present basement of the Lower Magdalena Valley and the Sierra Nevada de Santa Marta. (2) Cretaceous-Tertiary boundary minor uplift of the easternmost regions of the Eastern Cordillera and portions of the western foothills of the Eastern Cordillera. (3) Late Paleocene–early Eocene subsidence event that allowed deposition of coarse-grained facies in the Llanos foothills and deposition of fine-grained units in the central portions of the Eastern Cordillera. (4) Middle Eocene pre-Andean orogeny evidenced by a widespread regional unconformity and by vast amounts of syn-orogenic sediments deposited in the Maracaibo Basin and in the Trujillo Range (e.g., the Trujillo, Misoa, and Mirador Formations). This uplift event affected primarily the Central Cordillera and produced a dominantly east-verging fold belt that propagated to regions in the Eastern Cordillera. (5) Late Eocene minor subsidence and relaxation event that allowed the deposition of fluvial to marginal marine sediments in the Magdalena Valley, the Llanos Basin, and the Maracaibo Lake area (e.g., La Paz, Cacho, Mirador, Pauji, and Paguey Formations).

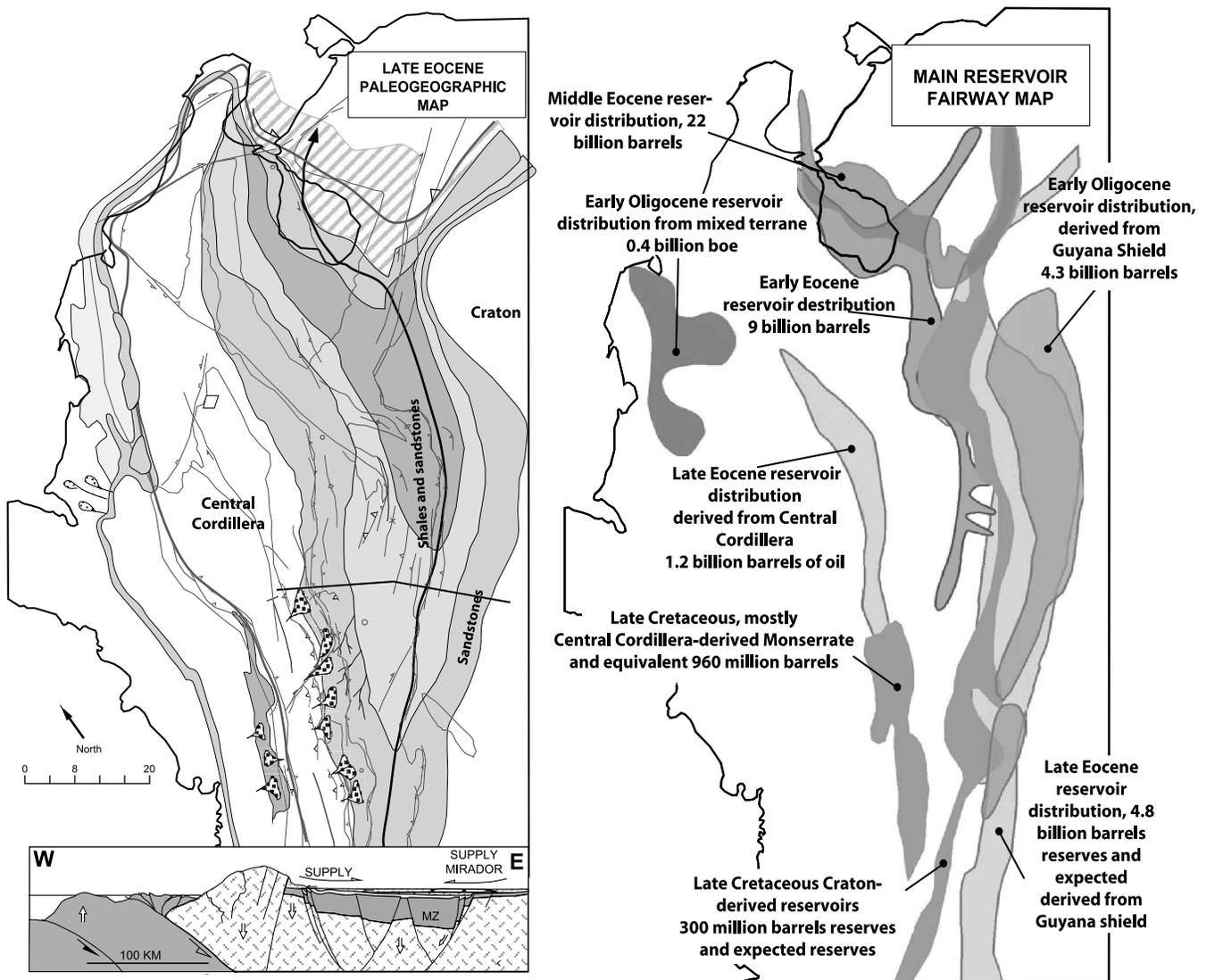


Figure 9. Late Eocene paleogeographic map with the position of the central axis of deposition. The map shows an increase in accommodation space related to relaxation of the crust following the climax of the pre-Andean orogenesis. Deposition during these times took place in large areas of Colombia and western Venezuela, and onlap onto regions previously exposed to erosion is evident in seismic data and the diachroneity of units. The figure on the right shows a reservoir fairway map with the major ages that produce hydrocarbons in the region. The late Eocene paleogeographic map is an example of the evolving foreland basin that received sediments derived from a mixed terrane west of the axis of the basin and sediments from the west that represent an almost pure quartz multicycle cratonic origin. The axis of the basin has evolved through time and has, at any give time, separated regions with good reservoir quality from regions with excellent reservoir qualities. Miocene hydrocarbon budgets are highly biased by accumulations in the Maracaibo Basin. In Colombia, most of the reservoir is Eocene in age.

Maastrichtian Reservoirs

The Maastrichtian stage marks the time of terminal Cretaceous regional regression in northwestern South America and the time of initial strong tectonic control on sedimentation from the accelerated uplift of the ancestral Central Cordillera and uplift of portions of the eastern margin of the Cretaceous rift. The uplift of a very continuous ancestral Central Cordillera determined the configuration of

the restricted Maastrichtian epicontinental basin and shifted the position of the central axis of deposition from a Campanian location at or west of the Magdalena Valley to a location along the present western foothills of the Eastern Cordillera (Figure 10). The central axis of deposition continued to shift eastward through the Maastrichtian stage, moving gradually to a location along the main center of the Eastern Cordillera, where it remained until the Paleocene.

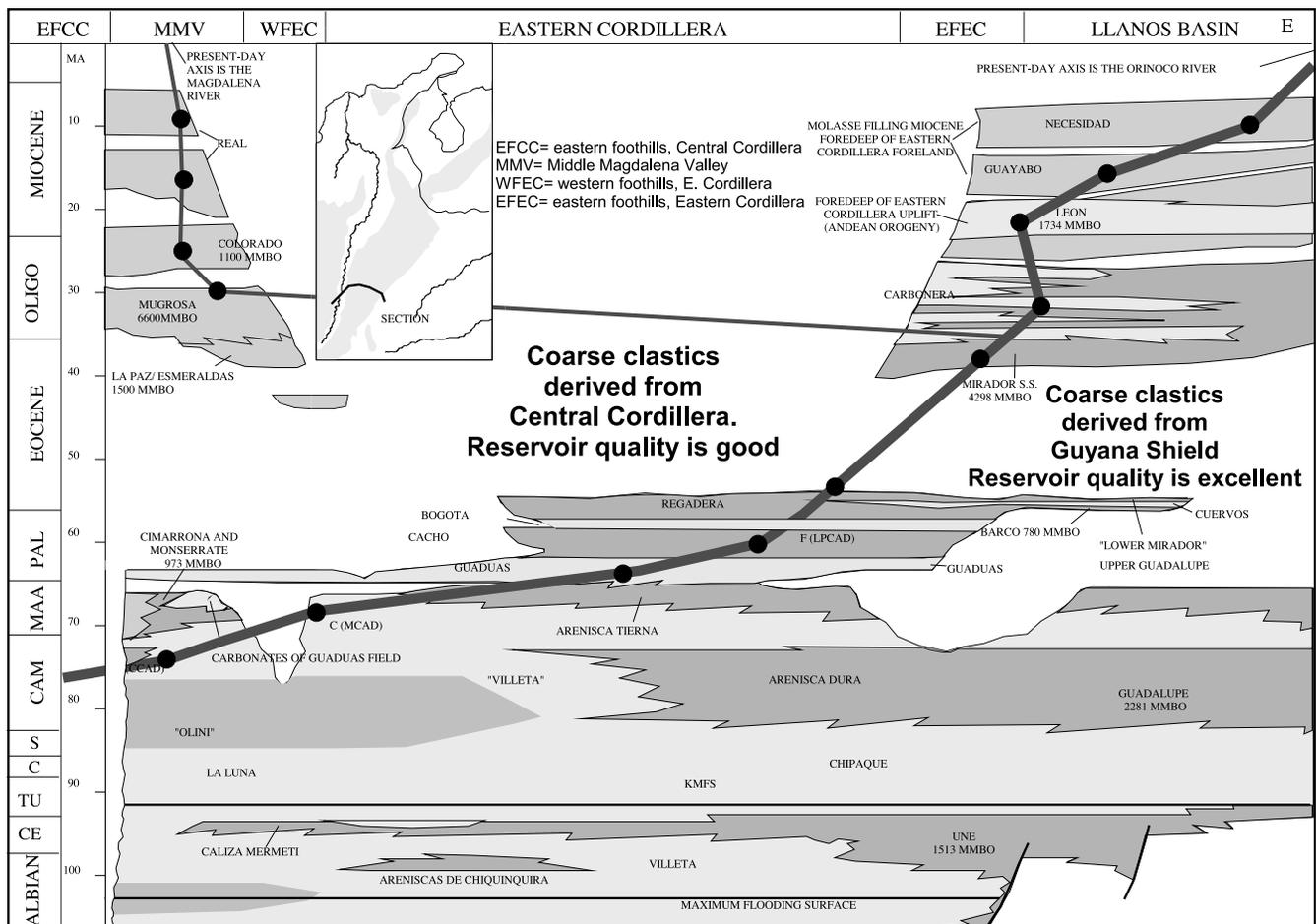


Figure 10. West-east chronostratigraphic section of the Eastern Cordillera of Colombia at the approximate latitude of Bogotá (see inset for location of section). Dark dots and the line connecting them represent the west-to-east migration of the central axis of deposition and its evolution into two main axes in the Oligocene. The central axis of deposition separates, at any given time, areas that received sediment delivered from the west, and that are adequate to good reservoir qualities, from areas that received sediment delivered from the east. Sediments derived from the Guyana Shield are excellent in quality; even at great depths (18,000 ft [5486 m]) they allow high deliverability rates with very low porosity.

Depositional systems delivered sediments into an asymmetric, north-northeast–south-southwest-elongated marine seaway that opened and became wider to the north (Villamil, 1999). As evidenced by facies associations, the Maastrichtian marine seaway had a generally steep western flank and an eastern flank with a relatively gentle slope. The axis of lower Maastrichtian deposition was located at approximately the present geographic position of the western foothills of the Eastern Cordillera. Facies near the central axis of Maastrichtian deposition are calcareous banks and mounds (micrite-dominated) of the El Tobo and similar calcareous units in the Upper Magdalena Valley of southern Colombia. Coeval fine-grained clastics (shales and claystones) of the Umir and Buscavidas shale are present in the west-

ern part of the Eastern Cordillera and the Middle Magdalena Valley. Fine-grained clastics of the Colón and lower portions of the Mito Juan Formations are found in western Venezuela and northeastern Colombia. Reservoir qualities of these units are limited; they are mostly fine-grained and relatively thin calcareous packages. Coarse clastic-dominated systems fringed fine-grained facies belts in a landward direction east and west of the central axis of deposition. These coarse-grained clastics were supplied by approximately east-west oriented clastic delivery systems. Coarse-grained systems derived from the east belong to the Guadalupe Formation in eastern regions of the Upper Magdalena Valley of Colombia and the coarse-grained Tierna Formation of the Guadalupe Group in the Eastern Cordillera and Llanos Basin (termed

upper Guadalupe in the Llanos; e.g., Guerrero and Sarmiento, 1996). Coarse-grained facies of this age present adequate to very good reservoir qualities. In the Llanos Basin and foothills, these facies are derived from the Guyana Shield and represent the third most important reservoir package of the region. In the Upper Magdalena Valley, these units and the Aptian Caballos Formation are the main reservoirs.

Coarse-grained clastics derived from the ancestral Central Cordillera vary markedly in facies, and their distribution is discontinuous. Facies variations were caused by differential topography and different sediment source areas of the ancestral Central Cordillera. Coarse-grained systems derived from the west belong to the La Tabla and Monserrate Formations in the Upper Magdalena Valley of Colombia and the Cimarona Formation of southern regions of the Middle Magdalena Valley (Villamil et al., 1999), and they present adequate reservoir qualities. Infilling the elongated seaway from the southwest and southeast is the Monserrate Formation of the Upper Magdalena Valley.

Early Eocene Reservoirs

Following a Cretaceous-Tertiary boundary uplift event, there was a period of crustal relaxation that generated accommodation space and allowed deposition of coarse-grained fluvial units above the unconformity. The basal sandstones of this tectonically driven transgression belong to the Barco Formation of the Llanos foothills. At the top of the Los Cuervos Formation is an unconformity representing an initial pulse of the pre-Andean orogeny. The lower "Mirador" of the Llanos foothills is an incised valley-fill deposit above this unconformity (Figure 10). The lower Mirador fills in minor paleotopography created by the unconformity, and its distribution is limited (Figure 9). The top of the lower Mirador (see Pulham et al., 1997) is the unconformity that represents regionally in Colombia the pre-Andean orogeny. Figure 9 is a simplified Eocene map with the known and proposed distribution of reservoirs of early Eocene age. The map shows incised valley-fill deposits perpendicular to the central axis of deposition. For details on the construction of the map and information utilized for this synthesis, refer to Villamil (1999).

Middle Eocene Reservoirs

Regional accommodation space in northwestern South America decreased dramatically during the

middle Eocene. This decrease in accommodation space was caused by the climax of the pre-Andean orogenic event (Duque-Caro, 1980; Casero et al., 1997; Villamil, 1999) that propagated from the west toward the east and caused a regional and pronounced angular unconformity. The west-to-east propagation of the deformation front affected western regions of Colombia in a more abrupt manner than eastern regions. The middle Eocene orogenic event accelerated the uplift of the Central Cordillera. This continuous mountain chain supplied sediment eastward toward the northeast-flowing central axis of lower Eocene deposition.

The angular unconformity produced by this uplift has been recognized in the published literature of Colombia for many years (e.g., Hubach, 1957; Forero, 1974; Duque-Caro, 1980; Villamil et al., 1995). This unconformity is also well known to oil companies working in the Magdalena Valley because of its clear angular expression in seismic data (e.g., Suarez, 1997); in very general terms, the unconformity separates underlying source rocks from reservoirs. The middle Eocene orogenic event resulted in irregular uplift in Colombia, causing differential erosion of the pre-Eocene section (Villamil et al., 1995). This uplift event also controlled the position of several fluvial trunk systems that flowed through the valleys between paleo-highs. These fluvial systems probably joined a major river that drained large portions of Colombia and western Venezuela and delivered large amounts of sediments into the present position of the Maracaibo Lake area. The delta to marginal-marine facies of the Eocene Misoa and Trujillo Formations is evidence of such a large fluvial-marine system; it is this system that makes the Maracaibo basin such a rich hydrocarbon province (see Muller, 1993; Parnaud et al., 1995).

Caribbean nappes were loading a foredeep basin and allowed thick sections to accumulate (Villamil, 1999, and references therein). The Maracaibo Basin and Trujillo area were depocenters for the detritus derived from South America during the middle Eocene pre-Andean orogeny. Most parts of the Misoa and Trujillo Formations do not have coeval equivalents in other regions of northwestern South America because most areas were exposed to erosion. For details on the stratigraphy for this age of northwest Venezuela, see Pinto (1991), Maguregui and Tyler (1991), Muller (1993), Parnaud et al. (1995), and references therein.

The pre-Andean orogeny uplifted the ancestral Central Cordillera in a diachronous manner from

west to east; it began in southern Colombia and propagated through time toward western Venezuela. The middle Eocene climax of the orogeny in Colombia had remarkable implications for the petroleum systems of western Venezuela, resulting in Maracaibo Lake and the Bolivar coast oil fields in the eastern portion of the lake. Most of the eroded material of the large uplifted areas of Colombia was delivered to western Venezuela. Accommodation space in western Venezuela was being created rapidly by foredeep loading by the Caribbean plate. The combination of these two tectonic events, uplift with erosion in Colombia and loading with deposition in western Venezuela, allowed a thick, sand-rich section to accumulate. This thick clastic succession, represented by the Misoa Formation and other units of the same genesis, produced the reservoirs that store the vast quantities of hydrocarbons generated by the underlying La Luna Formation.

The central axis of middle Eocene deposition migrated to the east, but base level dropped toward the north with the uplift of large portions of Colombia (Figures 9 and 10). The central axis of deposition probably was located in eastern regions of the Eastern Cordillera of Colombia. Only in regions close to the central axis of deposition in Colombia and in the Maracaibo Lake area are facies of middle Eocene age present. Other regions of Colombia may contain isolated pockets of molasse units associated with the pre-Andean orogeny.

Late Eocene Reservoirs

After the loss in accommodation space and marked base-level drop associated with the onset and accelerated uplift of the ancestral Central Cordillera and other regions of Colombia during the pre-Andean orogeny, subsidence and transgression began to take place. Subsidence caused the base level to rise regionally and allowed progressive preservation of depositional belts to the east, west, and south of the central axis of middle to upper Eocene deposition; these depositional belts constitute very important reservoirs in Colombia. Depositional units in the subsurface of the Magdalena Valley onlap to the west and south, whereas those of the Llanos Basin onlap to the east and south. The rise in base level and increase in accommodation space allowed sporadic marine flooding of regions of lowest paleotopographic expression. The resulting intraformational fine-grained facies are, in some cases, critical seals for significant volumes of hydrocarbons. The late Eocene central axis of deposition was located approximately along the present po-

sition of the eastern foothills of the Eastern Cordillera of Colombia and extended north into a diffuse location east of Maracaibo Lake (Villamil, 1999). The Maracaibo Lake region was filled by sediments derived mostly from the Central Cordillera of Colombia intermixed with quartz-rich sand from the Guyana Craton. Sediments were deposited in the Barco Concession of northeastern Colombia and in the Maracaibo Basin in braid-plain, meander-plain, and deltaic systems (see Van Andel, 1958, Van Veen, 1969, for examples of depositional environments and sediment source areas; Notestein et al., 1944, for the Catatumbo area). The marine-influenced late Eocene upper Mirador Formation of the Cusiana and Cupiagua fields areas has been studied by Pulham (1994) and Cazier et al. (1995, 1997). Pulham's (1994) and Cazier et al.'s (1995) finding on the tidal to marginal marine nature of the Mirador Formation has been reinforced with more evidence presented by Cazier et al. (1997).

The late Eocene stratigraphy records an increase in accommodation space upsection, as well as progressive onlap away from the central axis of deposition (Villamil, 1999). This vertical and lateral change in facies has significant reservoir implications, as reservoir quality decreases upsection. Facies association changes vertically from amalgamated fluvial channel sands with low content of fines to distal fluvial channel sands "floating" within a fine-grained package. This is the main reason why fields such as Provincia-Payoa produce only from the basal portions of the late Eocene stratigraphy. Regions west of the central axis of late Eocene deposition received sediments from the Central Cordillera and from isolated regions that had been uplifted during the middle Eocene orogenic event or were actively being uplifted in the late Eocene. This explains the differences in reservoir quality between the excellent reservoirs in the fluvial to marginal-marine sands of the Mirador Formation of the Llanos foothills compared to the poor reservoirs of the fluvial channel sands of the La Paz and Esmeraldas Formations in the Middle Magdalena Valley.

The central axis of late Eocene deposition was located approximately along the Llanos foothills. The Eocene Mirador Formation is among the best-studied units in this region because it is the primary hydrocarbon reservoir in the Cusiana giant oil field and adjacent fields of the region. Pulham (1994), Cooper et al. (1996a, b), Cazier et al. (1997), and Pulham et al. (1997) have used well data, outcrop information, and a revised and improved biostratigraphy to generate

solid depositional models for the late Eocene portions of the Mirador Formation. The late Eocene upper Mirador Formation of the Cusiana field was deposited east but very close to the central axis of deposition. The main drainage region that delivered sediments to the Cusiana area, therefore, was the Guyana Craton that was exposed to erosion during the Neogene. The Mirador system is marine-influenced along the Llanos foothills (Cazier et al., 1997; Pulham et al., 1997). A narrow and elongated marine seaway opened to the northern Maracaibo Lake area and partially flooded western Venezuela and Colombia. This seaway represents the continuous increase in accommodation space after the pre-Andean orogeny. Late Eocene facies to the east in the Llanos Basin are represented by dominantly fluvial depositional systems. Sediments that comprise this basin fill primarily were easterly derived from the Guyana shield and present excellent reservoir quality. The reservoirs of Caño Limón field were deposited later, as onlap progressed diachronously toward the east; however, they belong to the same depositional system.

Eocene and Miocene series accumulate most of the hydrocarbons in the region (Figure 8). The Eocene reservoir system was a consequence of the pre-Andean orogeny, whereas the Miocene reservoir system was deposited as a consequence of the Andean orogeny. Adequate and widely distributed thick Miocene reservoir facies are found in the Maracaibo Lake area, but this reservoir play concept is not encountered in Colombia. In Colombia, most of the Miocene syntectonic sequences are coarse-grained and of poor reservoir quality.

Oligocene Extension and Subsidence of Northwest South America: The Regional Seal

During the Oligocene, most of northwestern South America underwent a period of extension and subsidence that allowed the deposition of fine-grained strata above the principal reservoirs. These strata form a regional and widespread package of seals. Units that form part of this megasequence are the Carbonera Formation of the Llanos foothills and Basin, the Murgosa and Colorado Formations of the Middle Magdalena Valley, and the Potrerillo Formation of the Upper Magdalena Valley. Subsidence was sufficiently rapid to allow sporadic marine incursions into vast regions of western Venezuela and Colombia and allowed the ancestral Orinoco delta (Carbonera delta) to backstep southward from the Maracaibo Basin area into the Llanos Basin of southeastern Colombia

(Figure 11). Subsidence rates increased in the late Oligocene in the Lower Magdalena Valley and in the Falcón Basin of northwestern Venezuela, where the crust foundered.

In the Oligocene, a large region of the Central Cordillera foundered (Figure 11). This collapsed fragment of the Central Cordillera is located in present Lower Magdalena Valley (Plato and San Jorge Basins) and currently is buried by late Oligocene to Pliocene sediments. Most of the basement of the Lower Magdalena Valley was uplifted and subject to erosion prior to the Oligocene. Because of the tectonic events outlined previously, the Oligocene epoch marks a time of major changes in the paleogeography of northern South America. Facies associated with these times are generally fine-grained and constitute the main seals that retain the hydrocarbons contained in Eocene reservoirs. West and east of the main Oligocene seal sections, the stratigraphy onlaps onto the unconformity surface. Facies change toward the onlap, becoming coarser-grained with channels tending to amalgamate. Facies of the early Oligocene, coeval to the main seals of the foothills and central Middle Magdalena Valley, lose seal quality but gain reservoir properties. The main reservoirs in the giant Caño Limon and Guafita fields in the Llanos Basin to the east and the Velasquez field of the Middle Magdalena Valley to the west are coeval to the seals of the Llanos foothills.

Figure 8 shows a graph that represents total reserves against age of seal. The main conclusion is that the subsidence event of the Oligocene explains significant quantities of hydrocarbons (i.e., >25 billion barrels of oil equivalent). The next most important seal interval is above the Miocene reservoirs of the Maracaibo Basin area; these shales retain approximately 23 billion barrels of oil equivalent.

Miocene Inversion of the Eastern Cordillera and Reactivated Uplift of the Central Cordillera: The Main Timing of Trap Formation, Generation, and Migration

The Eastern Cordillera of Colombia is a large inverted graben (Figures 2, 4, and 12). As mentioned previously, during the Late Jurassic to Early Cretaceous, the Eastern Cordillera was a major site of subsidence and deposition of marine sediments. Graben subsidence was marked throughout the Early Cretaceous, rifting ceased during the Barremian, and subsidence across extensional faults decreased during the Cenomanian. The graben systems were inverted

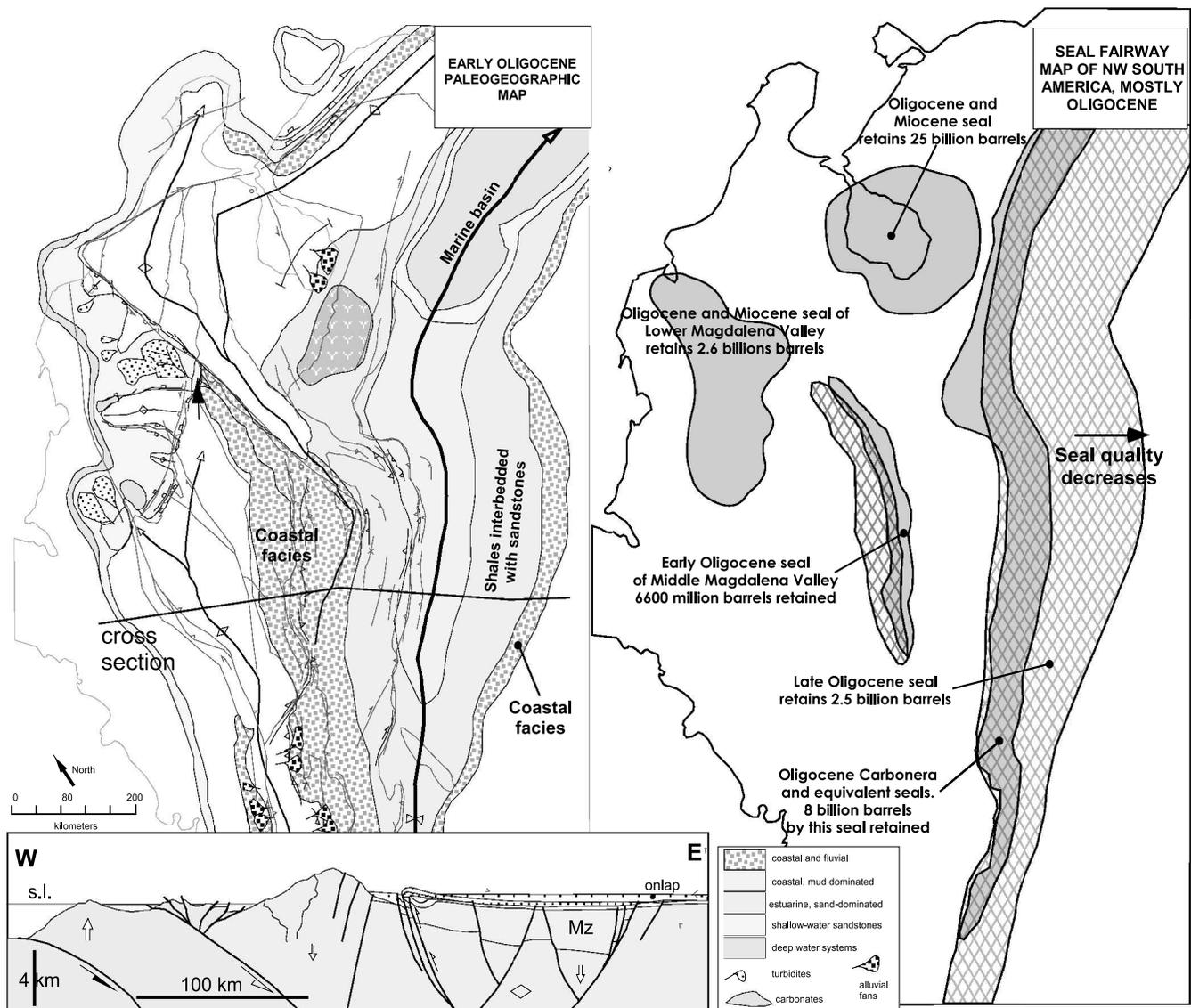


Figure 11. Early Oligocene paleogeographic map and a simplified seal fairway map for northwest South America. Note the volumes of hydrocarbons retained by the Oligocene seal, a consequence of increased subsidence and tectonic foundering of large areas of the northwest South American continental crust. During the Oligocene, the ancestral Central Cordillera was separated from the Sierra Nevada de Santa Marta, and the proto-Magdalena River flowed between the topographic highs into a collapsing Lower Magdalena Valley. The map shows how accommodation space increased regionally and the Carbonera delta backstepped southward from the Maracaibo Basin to the Llanos Basin of Colombia, sealing most of the reservoirs of Eocene age.

gently during the latest Cretaceous and middle Eocene (Villamil, 1999), but the main inversion happened during the Miocene to late Miocene. During the late Miocene, convergence increased between the oceanic plates to the west of Colombia and the northern corner of the South American Plate, producing inversion and shortening of the Eastern Cordillera and thrusting the Central Cordillera over the valleys. Convergence, inversion, and thrusting generated most of the traps that have been drilled

to date in the northwestern corner of South America. Molasse deposits from the uplift of the mountain belts and burial by overthrusting matured the source rock on both sides of the Eastern Cordillera, and migrated oil filled many traps. Most of the oil that has been found in Colombia is trapped in structures flanking the inverted Eastern Cordillera (Figures 8 and 12).

The Miocene epoch was a time of rapid mountain uplift and buildup in Colombia and in other regions

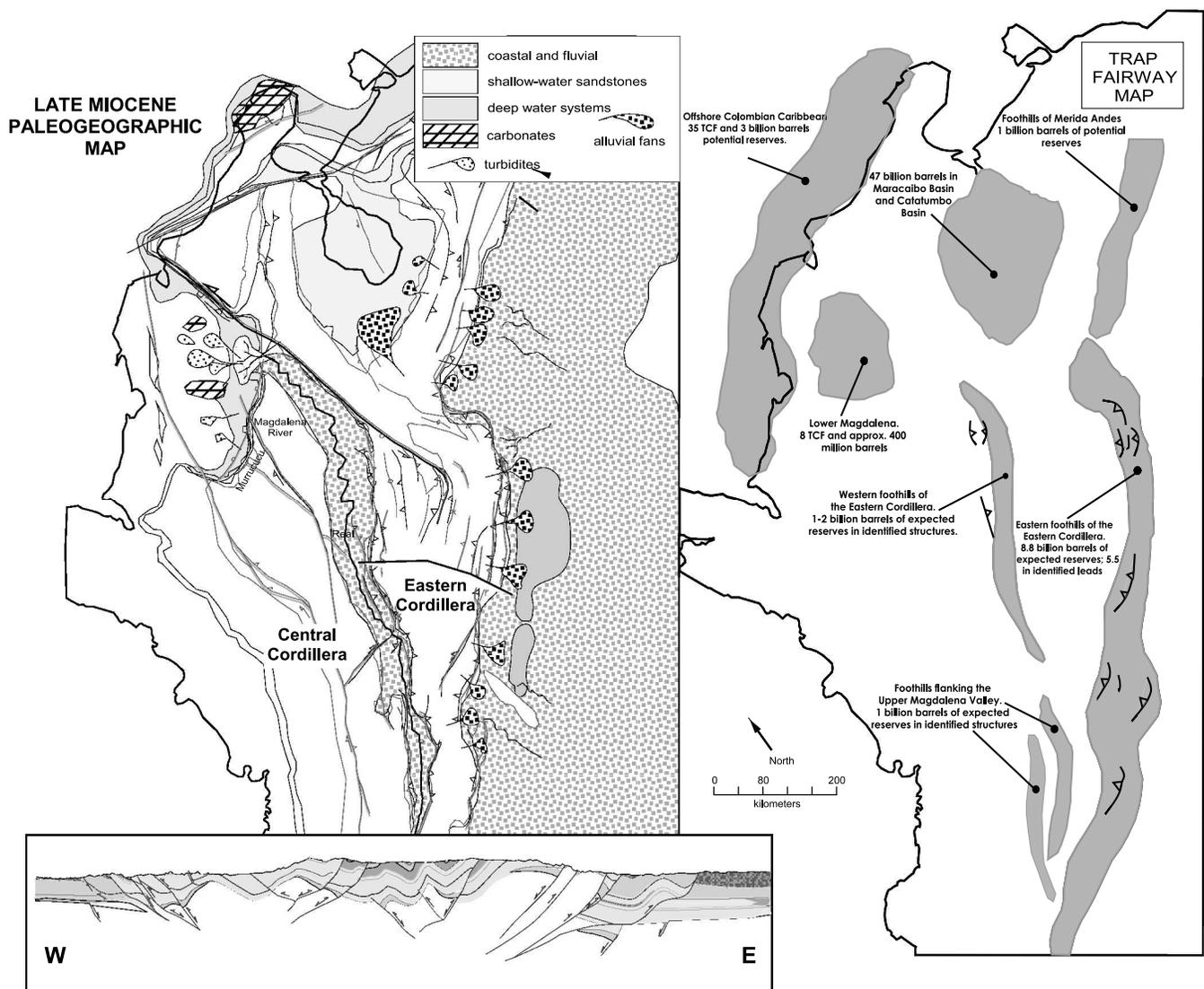


Figure 12. Simplified Middle Miocene paleogeographic map with the position of elevated mountain belts. The newly born Eastern Cordillera had a clearly defined topographic expression at this time. The bounding fault belts contain most of the large structures identified as leads and prospects along the Llanos foothills and along the western foothills of the Eastern Cordillera. The fairway map represents a high-potential structural trend; this trend contains most of the hydrocarbons found, as well as most of the remaining potential of Colombia and a significant amount of hydrocarbons encountered in the Maracaibo Basin. Inserted cross section from Restrepo et al., 1999.

of South America. Rapid uplift favored increased rates of erosion and deposition of molasse units at the base of the flanks of the Eastern and Central Cordilleras. These molasse sequences, combined with tectonic stacking by structural repetition, are the main reason why the underlying source rock enters the maturation window. The development of foredeep and foreland basins also happened during the Miocene, as a result of loading by mountain mass. Sediment delivery generally was rapid during these times, causing infill and aggradation of the Magdalena and Orinoco drainage basins.

While the Eastern and the Central Cordillera were being uplifted, the eastern part of the Lower Magdalena Valley still was subsiding rapidly, and the Magdalena delta continued to aggrade. This is why there is a transgressive Oligocene section above Central Cordillera basement in the Lower Magdalena Valley. The reservoirs above the transgressive sandstones in the Lower Magdalena Valley are distal, deep-water turbidites, Miocene in age. The Miocene stratigraphy of the Middle Magdalena Valley records the uplift of the Eastern and Central Cordilleras and initiation of volcanic activity in the Central Cordillera. The Miocene

stratigraphy is poorly recorded in the Eastern Cordillera because of non-deposition and erosion. As mentioned previously, structural shortening of the Eastern and Central Cordillera began in the Paleogene, compression accelerated, relaxed, then reinitiated during the Miocene. Structural shortening of the Eastern Cordillera was linked to the sinistral strike-slip component of the Santa Marta–Bucaramanga Fault and the movement to the east of the Central Cordillera tectonic block with respect to the Guyana Shield.

Despite the discovery of the La Cira–Infantas field (900 mmbo) in the level, slightly-deformed region in the west of the Middle Magdalena Valley and the Caño Limon field (1200 mmbo) in a similar region in the north-central area of the Llanos foothills, traps generally diminish in size away from the Eastern Cordillera foothills as deformation decreases across the Llanos plains and the Magdalena Valley. Seismic data quality improves away from the Eastern Cordillera foothills, and depth to target also decreases.

Stacking Geometry along the Llanos Foothills

The structural development of the eastern foothills of the Eastern Cordillera is complex. In general, in the foothills themselves, shortening values increase from south to north toward the Eastern Cordillera bend near the Colombia-Venezuela border. The southern foothills structural regime consists of inverted ancestral graben-bounding faults that thrust hanging-wall rocks over a deformed foredeep. In contrast, the structural configuration of the northern Llanos foothills consists of vertically stacked horses. The stacking of as many as four horses in northern areas of the Llanos foothills produce multiple traps that belong to the same or a similar hydrocarbon system. In the Cusiana region, horses are stacked vertically west of Cusiana and laterally east of the Paleogene outcrop belt (the trap for Cusiana field). North of the Eastern Cordillera bend, the structural configuration beneath the foothills is poorly known. Seismic data quantity and quality is poor, and exploratory drilling activity north of the bend has not been sufficient to unravel the structural stacking patterns of this region. Current exploration activities in this area, including drilling of the high-profile Gibraltar well and planned future exploration and development of the region, will clarify the configuration. It is likely that vertically stacked structures will be encountered in regions in and immediately north of the Eastern Cordillera bend. Shortening values in the foothills increase toward the north; however, this

does not necessarily imply that net shortening follows the same relationship as the Central Cordillera versus the Guyana Shield.

Break-back Sequences along the Western Foothills of the Eastern Cordillera

The western foothills of the Eastern Cordillera present different stratigraphy and different types of structural configuration; however, they contain similar exploration plays in the subthrust environment. Some of the western foothills of the Eastern Cordillera structures are break-back in sequence. The evolution of this portion of the mountain belt also was more complex than the evolution of the eastern foothills. This region was affected markedly by the pre-Andean orogeny, whereas the Llanos foothills suffered only minor deformation. Several traps of significant size have been identified along the western foothills of the Eastern Cordillera northwest of Bogotá, but not a single one has been drilled in a proper manner. A large and evident trap was drilled in 1998, but the well did not reach the reservoir section. The well, Agata-1, spudded in Cretaceous rocks of the hanging wall and penetrated Miocene to Oligocene rock in the footwall. The main reservoirs in this area are of Eocene age and belong to the La Paz Formation, but they were not evaluated by the well. Because the area contains several traps at the prospect and lead stages and the hydrocarbon system of the basin is functioning, it is likely that exploration activities in the next few years will focus on this area in order to unravel, in an optimal technical manner, the potential of the subthrust environment.

Continuation of the Upper Magdalena Valley underneath the Eastern and Central Cordilleras

Recent long-line seismic acquisition south of the Upper Magdalena Valley has shown that the faults that bring the Central and Eastern Cordilleras over the Upper Magdalena Valley are low-angle and relatively flat. Because of this, it can be determined that the basin actually continues underneath the mountain belts south of the point where the valley ends; that is to say, south of the region of traditional and mature exploration. It is in this area that the oil industry is now unearthing new exploration plays. TotalFina-Elf and Hocol recently drilled through more than 2743 m [9,000 ft] of Precambrian granulites and found oil in the Cretaceous of the footwall. Talisman Energy has acquired and interpreted seismic data

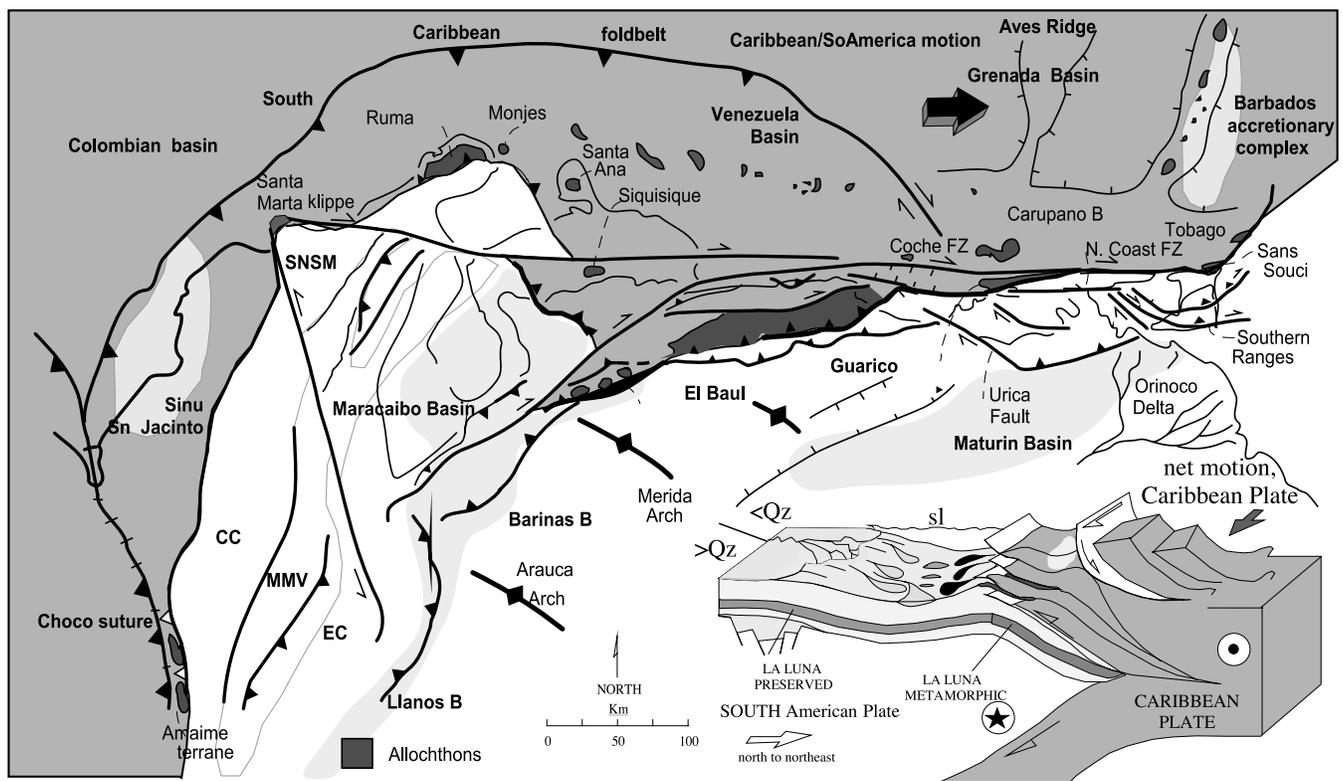


Figure 13. Tectonic model with a schematic representation of the line or region that separates the autochthonous South American crust from the allochthonous Caribbean terranes. This line is defined as the southern limit of allochthons. These allochthons metamorphosed large regions as accretion progressed from the Late Cretaceous to the Miocene. Because accretion happened after the La Luna Formation and equivalents were deposited, it obliterated the petroleum system of the area. Currently, this line separates an oil-prone hydrocarbon system dominated by the La Luna source rock from a gas-prone hydrocarbon system dominated by source rocks primarily of Tertiary age. Even though the system north and west of the allochthons is gas-prone, there is evidence derived from sea-bottom cores, fingerprinted hydrocarbons, and outcropping source rocks that shows that the area has potential for encountering approximately 3 billion barrels of oil in the Colombian offshore Caribbean. Figure modified from Pindell et al. (1998).

searching for Cretaceous reservoirs underneath faults that bring economic basement to the surface.

Offshore Hydrocarbon Systems: The Northwest Side of a Terrane Boundary

As mentioned previously, the origin of the Caribbean Plate and accreted Caribbean terranes caused the deposition of the hydrocarbon-rich Cretaceous La Luna Formation and equivalent units. The later translation of this discrete plate to the east, relative to South America, caused trap formation in vast regions of the margin and the destruction of most of the La Luna source rock along the convergence zone; i.e., the northern margin of South America. The tectonic history of northeastern Colombia and western Venezuela comprises a long-lasting (Maastrichtian-Miocene) transpressive collision between the Caribbean Plate and northern South America. The Caribbean Plate moved east and south with respect to

South America. This transpressive event affected the sedimentary basins adjacent to the boundary of the two plates:

- 1) The upper portions of the large buoyant and anomalously thick (more than 10 km) igneous province of the Caribbean Plate (Figure 5) were scraped as collision started; the scraped material was thrust southward and eastward as the plate progressively moved east (Figure 13). This oceanic material is known as the Amajime Formation, the Lara Nappes, Villa de Cura Klippe, and other names in Colombia and western Venezuela and continues to the east into Trinidad.
- 2) Loading of the Caribbean nappes formed an eastward-migrating foredeep basin (e.g., Lugo and Mann, 1995; Pindell et al., 1998; Villamil, 1999). The foredeep axis had a northeast to north-northeast direction.

3) As the oceanic material was tectonically transported in a transpressive manner toward South America, it matured by loading the underlying, and older, Cretaceous source rocks. As compression and tectonic transport continued, the La Luna and equivalent units were metamorphosed to grades varying from schist in some regions (e.g., the Caracas Group and the metamorphic Cretaceous of the Guajira Peninsula) to mature source rocks incorporated in an accretionary prism (e.g., the Cansona and Finca Vieja units in the Sinu foldbelt). The Colombian Caribbean offshore also may contain Cretaceous source rocks incorporated in an accretionary prism that were deformed but not metamorphosed by plate interaction (Figure 13).

The line that separates regions affected by the scraping and thrusting of Caribbean Plate terranes (Figure 13) generally separates a region where the La Luna Formation was subject to average depositional and tectonic burial from a region where the La Luna was over-ridden by Caribbean oceanic terranes. This line, therefore, separates a region with the La Luna preserved from a region where the La Luna and equivalents were either metamorphosed or complexly involved in an accretionary prism. Most of the Cretaceous source-rock component of the petroleum system was destroyed north of this line. Tertiary deposition occurred over the metamorphosed or complexly folded Cretaceous rocks, and these Tertiary facies are generally gas-prone. This line, representing the southeastern extent of Caribbean allochthonous terranes, separates in a gross manner a gas-prone system to the north (Tertiary source rocks) and west of the line, from an oil-prone system south and east of the line (Cretaceous oil-prone source rocks). All of the Caribbean offshore of Colombia and the adjacent Sinu and San Jacinto onshore basins in northwest Colombia are located north or west of the southern limit of allochthonous Caribbean terranes and, therefore, can be considered as a gas-prone region. Because of this, the ultimate potential gas resources of Colombia are concentrated in the offshore Caribbean with approximately 35 TCF and 3 billion barrels of oil unrisks recoverable reserves. Additional thermogenic gas reserves are present in the Llanos foothills (8 TCF) and the Lower Magdalena Valley (7 TCF), with approximately 20 TCF of additional ultimate potential reserves scattered throughout the rest of Colombia. Because oil-prone source rocks are present, exploration for liquid hydrocarbons cannot be

ruled out for the Colombian offshore Caribbean, especially off the city of Cartagena to the west and immediately offshore of the Sierra Nevada de Santa Marta; but oil exploration is of higher risk than south and east of the line.

Offshore exploration in Colombia is in its earliest stages; however, it is safe to predict that most of the future significant gas resources of Colombia will be encountered in the Caribbean Sea. Oligocene gas-prone source rocks overlie an accretionary prism along the northwestern Caribbean coast and a slightly metamorphosed basement. Reservoirs in this area are interbedded with Eocene and Oligocene fluvio-deltaic sediments rich in terrestrial organic material, carbonates, and shallow-marine deposits, and change facies to well-developed turbidite systems in deeper waters.

The exploration history of the offshore gas-prone area can be summarized as follows. Southwestern regions between the Gulf of Uraba and the tip of the Sierra Nevada de Santa Marta comprise an area of approximately 12 million acres. The last wells were drilled in 1980 and 1984, prior to acquisition of large seismic programs and before the "explosive" development of modern offshore exploration concepts and technology. Four thousand kilometers of 2-D seismic were acquired in 1983 and an additional 11,000 km after drilling the last well. This area remains underexplored, and the exploration that has taken place has not benefited from recent technological advances. Proprietary studies have calculated an unrisks potential of about 13 billion BOE, with the possibility of encountering 30% liquids and 70% thermogenic and biogenic gas. The northeastern region between the tip of the Santa Marta massif and the Guajira peninsula comprises an area of approximately 12.5 million acres, on which 30,000 km of 2-D seismic data have been acquired. Figure 14 is a dip seismic line of the Caribbean offshore accretionary prism. None of the structures observable in the line have been tested, despite their size and potential. For location of this seismic line, refer to Figure 15. Mapping using recently acquired seismic data is a powerful tool for postmortem evaluation of some of the dry holes in the area. In conclusion, most dry wells were drilled on crests of shale or mud diapirs and did not test valid plays. New seismic data allows mapping of new plays and traps of significant size. Some of the traps are simple in geometry and vary in size from 400 BCF to 15 TCF potential (e.g., the Mac-1 prospect has a closure area of approximately 100,000 acres). Water depths comprise a complete spectrum; some traps are located in water depths of less than 300 ft [91 m],

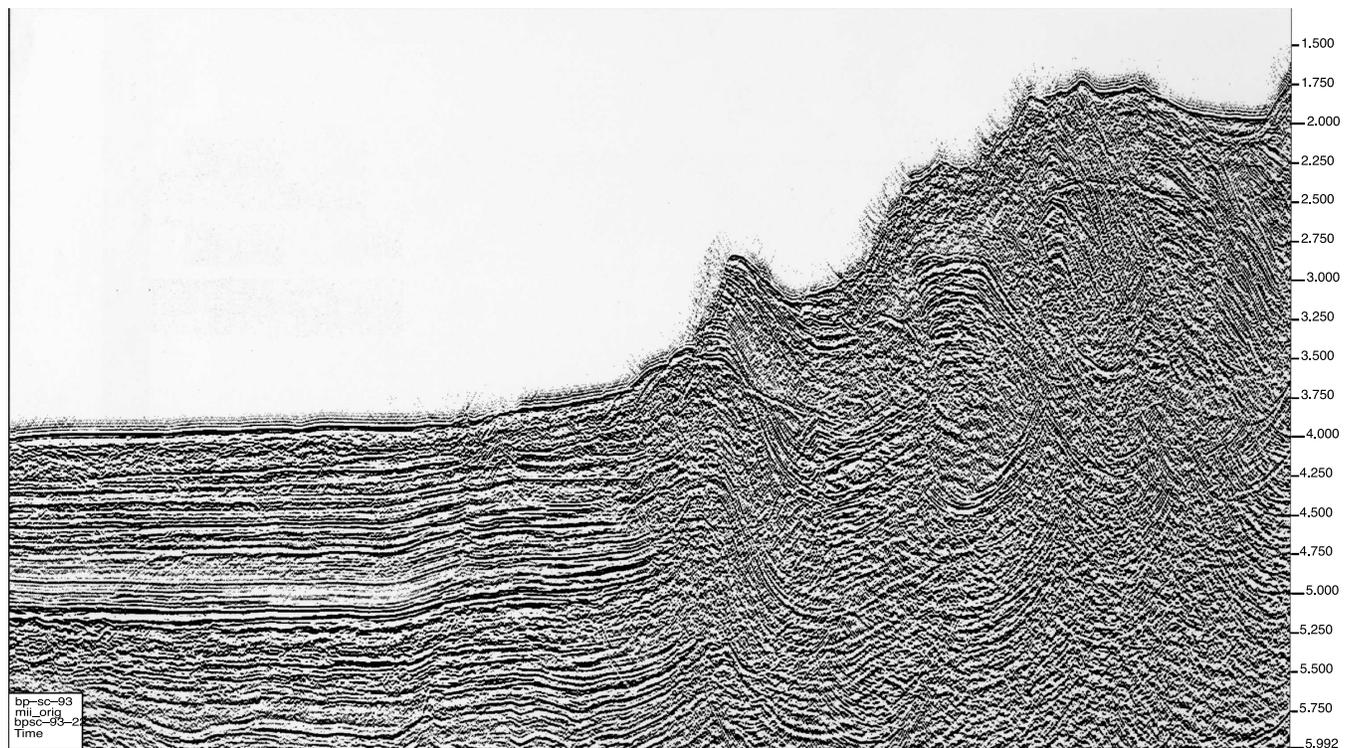


Figure 14. Offshore seismic line over the accretionary prism in the Colombian Caribbean. Note stacked north-verging structures with relatively high-amplitudes on their crests. Structures such as these contain significant hydrocarbon potential. Exploration in this type of play is in the very early stages of development. For location of seismic lines, see Figure 15.

while the Mac-1 trap is in 2,000 ft [609 m] of water. To fully unravel the offshore Caribbean potential it is necessary to acquire large 3D surveys (>1,000 km²) and to study them with industry-standard methodology; i.e., geophysical analysis of amplitudes, AVO, etc. Following seismic acquisition and study, several well-positioned exploration wells are necessary to verify seismic prospects and find commercial hydrocarbons.

WHERE IS THE OIL OF THE FUTURE IN COLOMBIA AND WESTERN VENEZUELA?

Despite significant oil and gas potential in Colombia, prospective basins and foothills remain relatively unexplored to underexplored. Evidence of this is provided by the discovery in 2000 of Guando Field (~100 mmbo recoverable, 31° API, Petrobras-Nexen) along the western foothills of the Eastern Cordillera. There is an evident surface expression of the trap with the reservoir lying at a depth of 3,000 ft (914 m). Guando is an obvious feature in a new and not-so-obvious place; explorers have traditionally focused on

adjacent basins rather than the foothills, but this is changing largely thanks to the Guando discovery. It is here predicted that significant oil reserves (several billions BOE) will be found along Colombia's underexplored foothills. Only a few valid exploratory wells have tested valid traps along the eastern foothills of the Eastern Cordillera, despite the fact that Cusiana and Cupiagua (900 and 600 mm BOE, respectively) are among the largest fields in Latin America and that there are analogous structures along trend. Less than five true exploratory wells have tested valid traps along the western foothills of the Eastern Cordillera. This contrasts markedly with the state of exploration maturity of, for example, the foothills of the Canadian Rockies or other fold belts.

Following this discussion of the regional geology of northwest South America and associated petroleum systems, a summary of the areas most likely to be the focus of near- to long-term exploration will be presented. The Maracaibo Basin of western Venezuela is a mature and hydrocarbon-rich basin. Because this paper centers on exploration, the significant potential of low-technical-risk incremental production in the Maracaibo Basin will not be discussed.

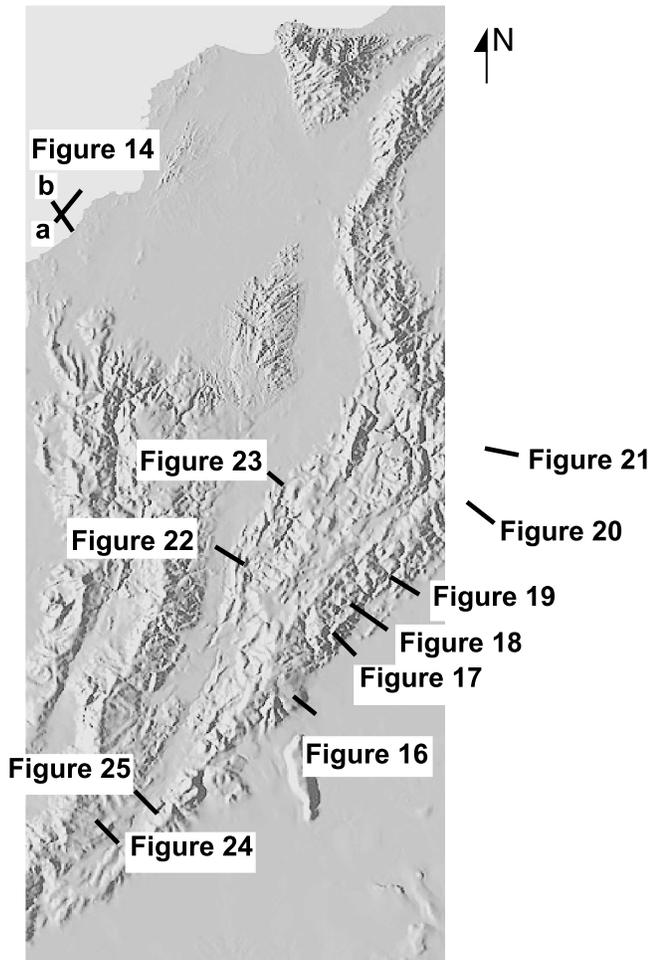


Figure 15. Regional map of Colombia with approximate position of all seismic lines presented in this paper.

Eastern Foothills of the Eastern Cordillera

The eastern foothills of the Eastern Cordillera is a very long structural trend that has all the necessary components of a world-class prospective play area. The trend has few true exploratory wells, significant light hydrocarbon discoveries, and an immature exploration history. It will be the focus of significant near-term exploration endeavors by large integrated oil companies and consortia. Prospects that will be drilled in the years 2003 and 2004 target recoverable reserves on the order of 3,500–4,000 million barrels of oil, as well as significant reserves of associated gas. Figures 16–20 show leads or prospects that will be explored in the near future.

From south to north, these leads comprise sub-thrust structures underneath hanging walls with early Cretaceous stratigraphy; i.e., structures adjacent to inverted Jurassic and Cretaceous normal faults. Figure 16 shows a seismic line across one of these leads located south of the town of Villavicencio. The play

concept consists of early Cretaceous to Eocene reservoirs underneath the frontal and relatively steep thrust of the Eastern Cordillera (Figure 16). Because this fault is a reactivated extensional feature, wells may penetrate Paleozoic or even Precambrian basement before reaching Neogene stratigraphy in the footwall. The main risks of these plays are trap imaging, adequate geophysical determination of the velocity model for the hanging-wall stratigraphy, and adequate drainage from kitchens to traps. Structures, however, are large—on the order of 500 mmbo—and offer the upside required to cover risk when exploring the trend. The line is over the Rio Guape lead that was drilled originally by Chevron with the Anaconda well. The well, however, was drilled downdip on the structure, as confirmed by a postwell strike-seismic line, almost at regional level.

In regions north of the Rio Guape prospect lie the Medina-Palomas trend (Figure 17). The play in this area consists of Eocene and secondary Paleocene and Cretaceous reservoirs sourced from the La Luna Formation (here called Gacheta) in the Eastern Cordillera kitchens. Traps are three-way closures with frontal thrusts closing the eastern portions of the structures. This play is similar to the Cusiana and Cupiagua fields. The main risks of this play are trap imaging and assuring that the detachment of frontal thrusts is not above the Mirador Formation, the main reservoir of the area. Technical risks when drilling also need to be taken into account; the key is not to drill against natural deviation. Structures are large and of significant potential, on the order of 300–400 mmbo. Figure 17 shows a seismic line over the Palomas prospect, located south of the Cusiana field. This prospect was drilled in 2000, but the well did not reach the target because of operational drilling problems; the well was sidetracked five times, and one of those sidetracks reached but did not penetrate the Mirador reservoir. Close to the Palomas play is another play that will be tested in the near future. The west Medina play concept consists of late Cretaceous to Eocene reservoirs involved in hanging-wall anticlines sourced from the La Luna or equivalents in the Eastern Cordillera kitchens (Figure 18). The main risks of this play are seismic imaging, trap definition, and migration history. Seismic acquisition is complicated by the abrupt topography of the area, which hinders trap imaging and adds risk to exploration in this terrain. However, reserve potential is high and justifies investment in this type of play.

Exploration west of Cusiana, toward the hinterland, is in its very early stages. Only one well has been

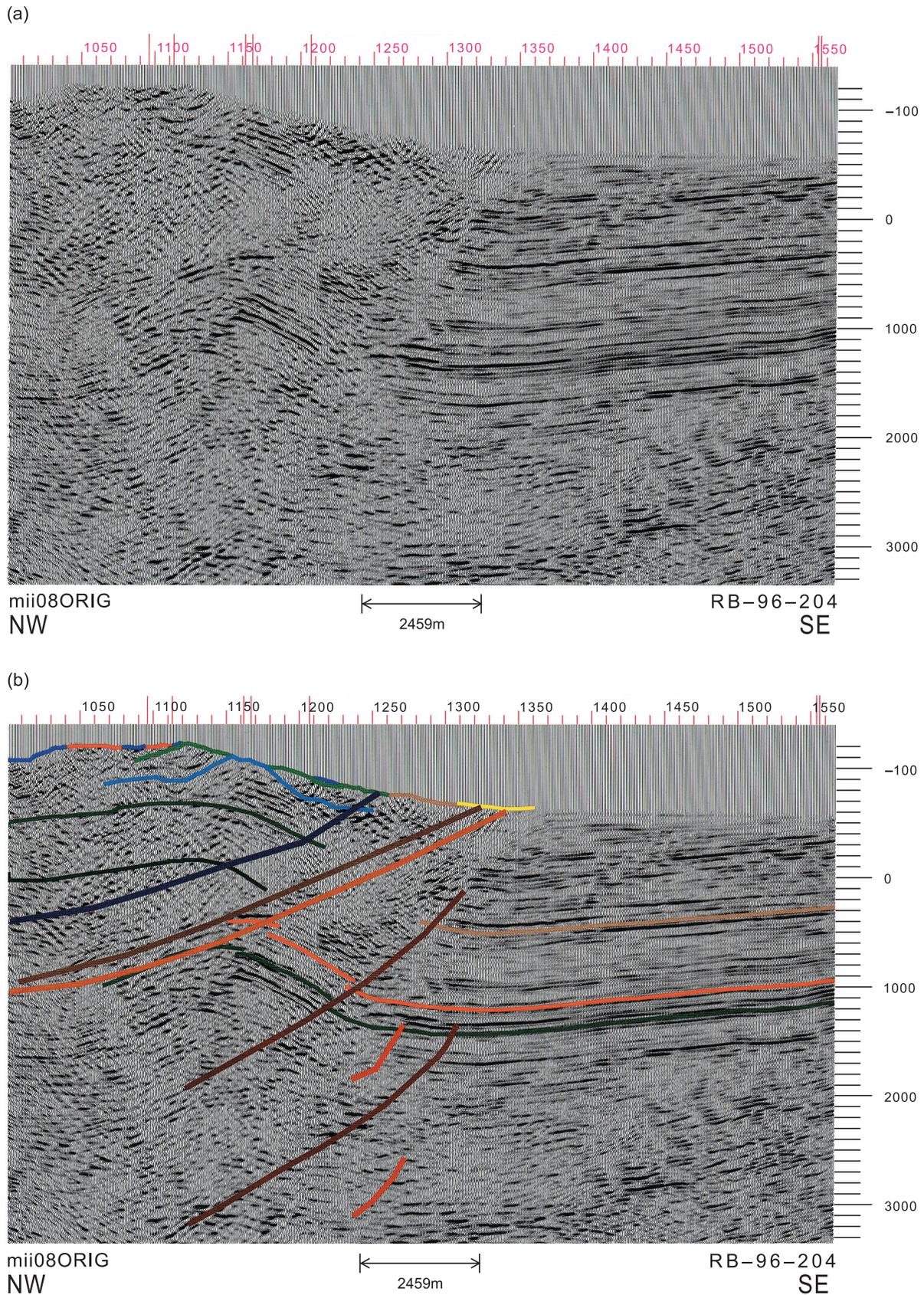


Figure 16. Seismic line over the Rio Guape lead. This line shows a subthrust lead underneath a basement-involved hanging-wall wedge. The fault overlying the lead is an inverted Mesozoic extensional feature and represents the ancestral rift shoulder of the Eastern Cordillera graben. For location of seismic lines, see Figure 15.

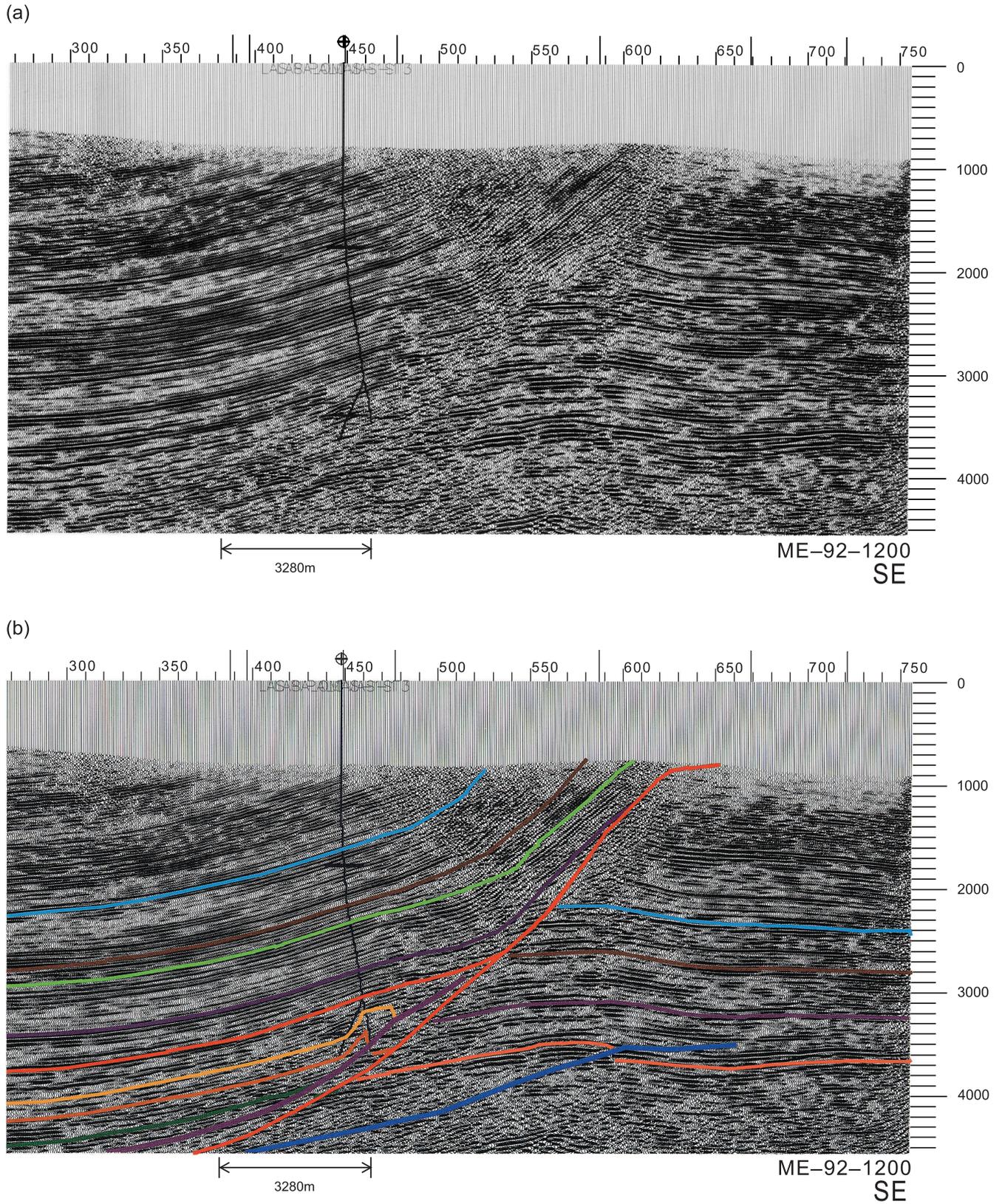


Figure 17. Seismic line over the Palomas prospect south of Villavicencio. The structure is a fault propagation fold sealed by the Carbonera Formation above and closes against a fault that brings the late Cretaceous to Eocene reservoir section over the Oligocene fine-grained Carbonera Formation. For location of seismic lines, see Figure 15.

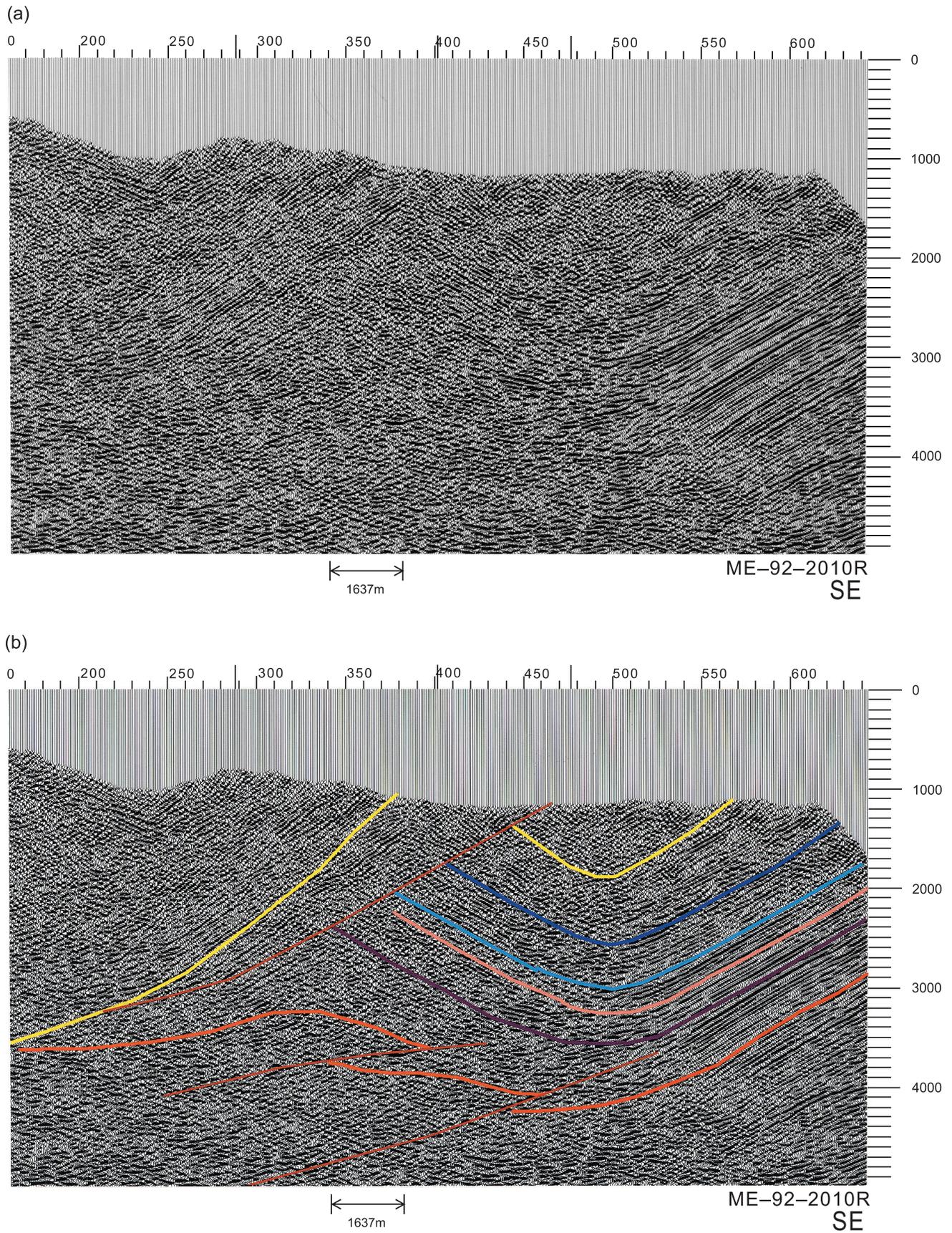


Figure 18. Seismic line over the Medina lead. This is a hanging wall anticline with late Cretaceous to Eocene reservoirs sealed by the Oligocene Carbonera Formation. For location of seismic lines, see Figure 15.

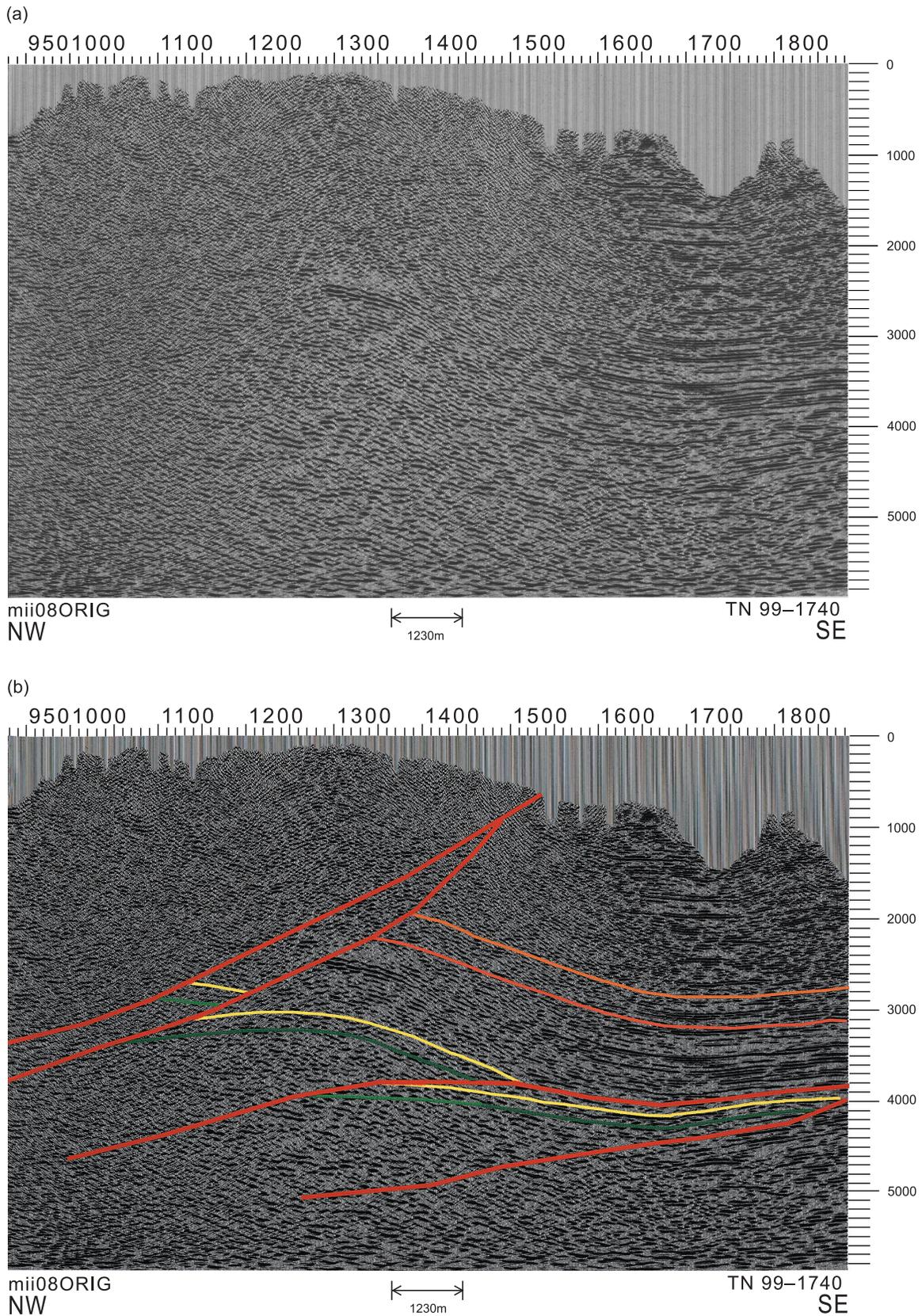
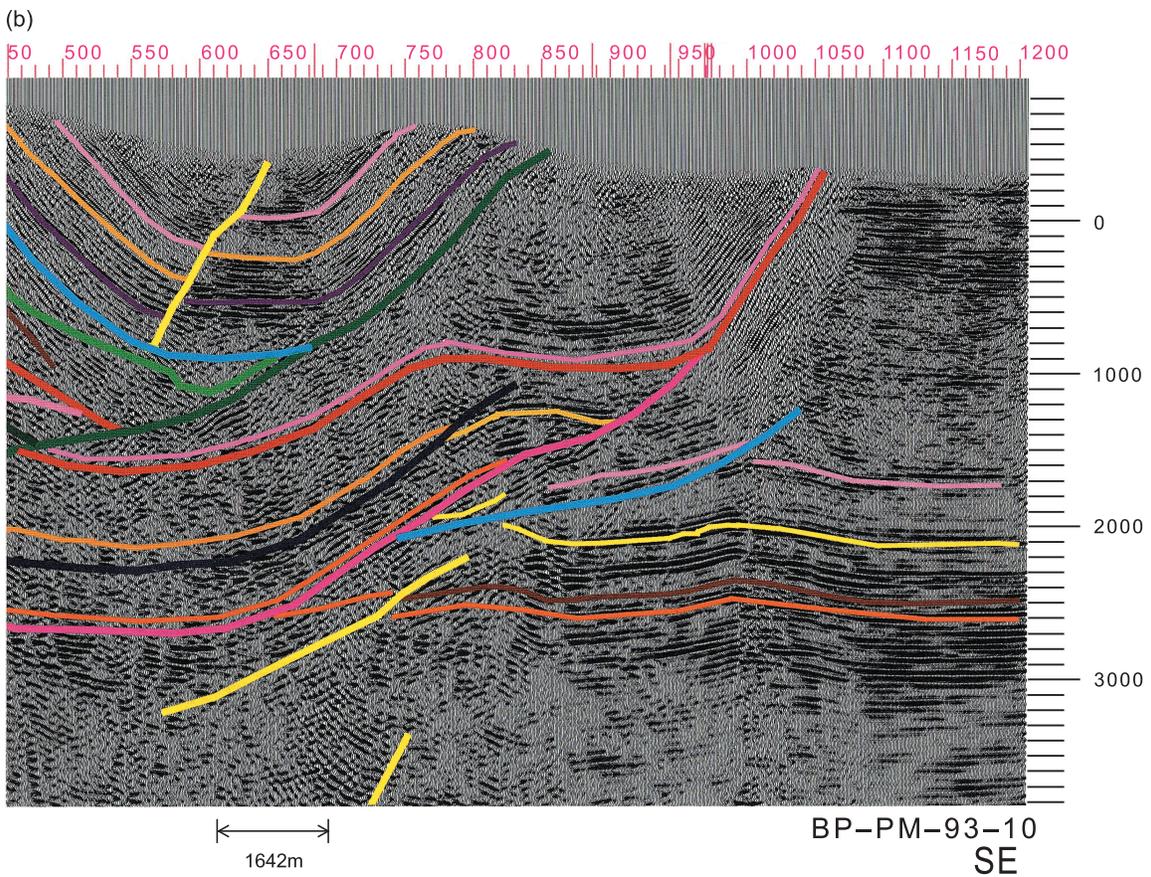
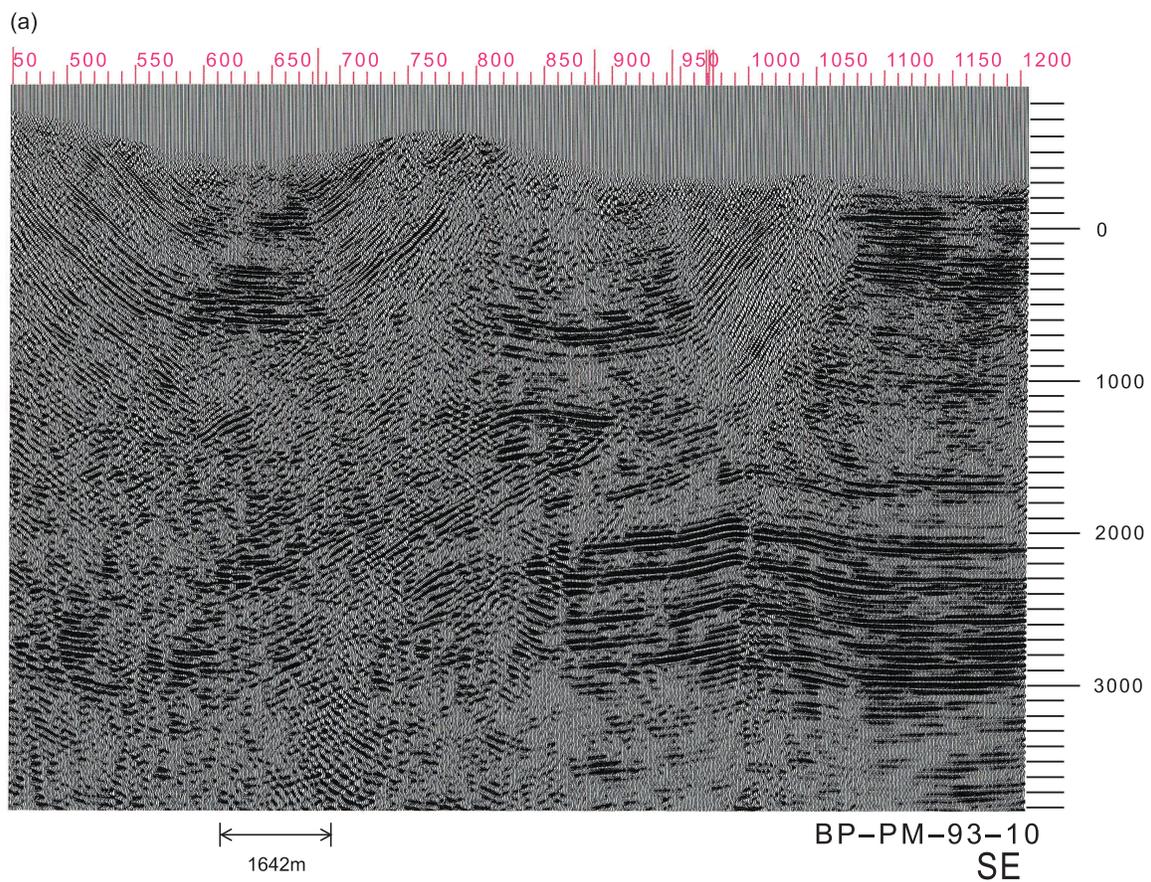


Figure 19. Dip seismic line over the Tierra Negra area immediately west of the Cusiana field. The Tierra Negra lead consists of two to three vertically stacked duplexes that involve Late Cretaceous to Eocene reservoirs sealed by the Oligocene Carbonera Formation. Horses are sourced from the Eastern Cordillera kitchen to the west; this kitchen contains the La Luna equivalent Gacheta and Chipaque Formations. For location of seismic lines, see Figure 15.



drilled in this trend, but it did not reach the reservoir. Figure 19 shows the Tierra Negra play immediately west of Cusiana field. This play consists of vertically stacked anticlines that involve the Late Cretaceous to Eocene reservoir section. The vertical stacks here also are three-way closures with a frontal thrust. Trap imaging with seismic data recorded in difficult terrain, detailed structural analyses, and multiple working models are essential for success in this type of play. Surface topography is abrupt, imposing complications that hinder both seismic acquisition and drilling operations. The play, however, contains several structures on the order of 600-million to one-billion-barrel potential. The learning curve for this type of play has been very steep in the recent past. Beginning in 2003 and 2004, two structures in this play area will be explored: Niscota and Tierra Negra.

Exploration north of Cusiana and Cupiagua resumed in 2001 after being inactive for more than ten years. Features external to the foldbelt, such as the Tame anticline, part of a deformed foredeep, have been explored and drilled, whereas internal features along the vertically stacked horses north of the producing fields are scheduled to be explored with wildcat drilling in 2002–2004. The Tame anticline was drilled in late 2001 and early 2002 and tested at 4,500 barrels per day of 37.5° API crude oil from the late Cretaceous Guadalupe Formation. It is interesting to note that this large anticline was originally drilled by Shell in 1965, but Shell's well did not reach the reservoir; it was then drilled by Esso in 1986, but the reservoir was not tested despite the oil shows encountered. Details of these leads and prospects currently are confidential, but structures are of significant size with recoverable reserve potential ranging from 100 mmbbl to 1 billion barrels. Despite exploration success in this trend, the play remains underexplored. Figure 20 shows an example of one of the structures that will be drilled in 2003–2004. There are two plays in Figure 20. The most obvious one consists of structures in the deformed foredeep similar to those of Cusiana and Cupiagua. This play concept consists of three-way closing features and a thrust fault that places Late Cretaceous to Eocene reservoirs

(Guadalupe, Barco, and Mirador Formations) adjacent to overpressured shales of Oligocene age (Carbonera Formation). Structures such as this one have produced in regions south of the line presented here. The second play concept consists of vertically stacked duplexes in a hinterland position with respect to the frontal thrusts. This play concept is new, and it is in the early stages of development; initial drilling on this concept will be conducted by BP in mid 2003.

The Gibraltar structure was drilled in 2001–early 2002 (Figure 21a and b). The Gibraltar structure is formed by at least four vertically stacked horses that verge to the eastern foreland basin with a passive-roof detachment. This passive-roof, a faulted unconformity, confines the stacks within a triangle zone underneath a passively deformed dip panel tilted to the east and verging to the west. The Gibraltar well penetrated the reservoirs of an intermediate stack at approximately 6,000 ft (1829 m), and the well's total depth was within reservoir section at 12,000 ft (3658 m); the well encountered significant potential pay in the Mirador and Cuervos Formations. Seismic quality is poor, and there are uncertainties related to reservoir quality, well productivity, and type of fluids in the reservoirs. However, it is here predicted, based on available information, that the Gibraltar structure will be an oil field of significant reserves in the near future. The Gibraltar-1 well reentry initiated in late 2002, and it has recently been announced as a discovery. The Gibraltar-1 well tested at 550 barrels per day of colorless high-quality oil of 57°API and 44 million cubic feet per day of rich gas. Test results were constrained by gas separation capacity and storage.

Current numbers of Gibraltar reserves are on the order of 200 million barrels oil equivalent, but analog and very similar structures (leads) exist north of the well itself. Since the test results have been positive, additional seismic acquisition will take place and structural uncertainties will diminish.

The Gibraltar play cannot be treated as an exploration play like the examples previously mentioned herein and to follow. Gibraltar already had a well through the main reservoir section, and that well

Figure 20. Dip seismic line over a lead north of Cusiana. This line shows vertically stacked horses in western regions and a frontal thrust that involves late Cretaceous to Eocene reservoirs sealed by the Oligocene fine-grained Carbonera Formation. The structure closes in three ways and against the frontal thrust. This type of trap style is proven along the foothills, and this lead shares significant similarities with Cusiana and Cupiagua fields. Western regions of the line show the vertically stacked duplexes; this structural band is a new play in Colombia. One of the largest structures in this play area will be drilled in early 2004. For location of seismic lines, see Figure 15.

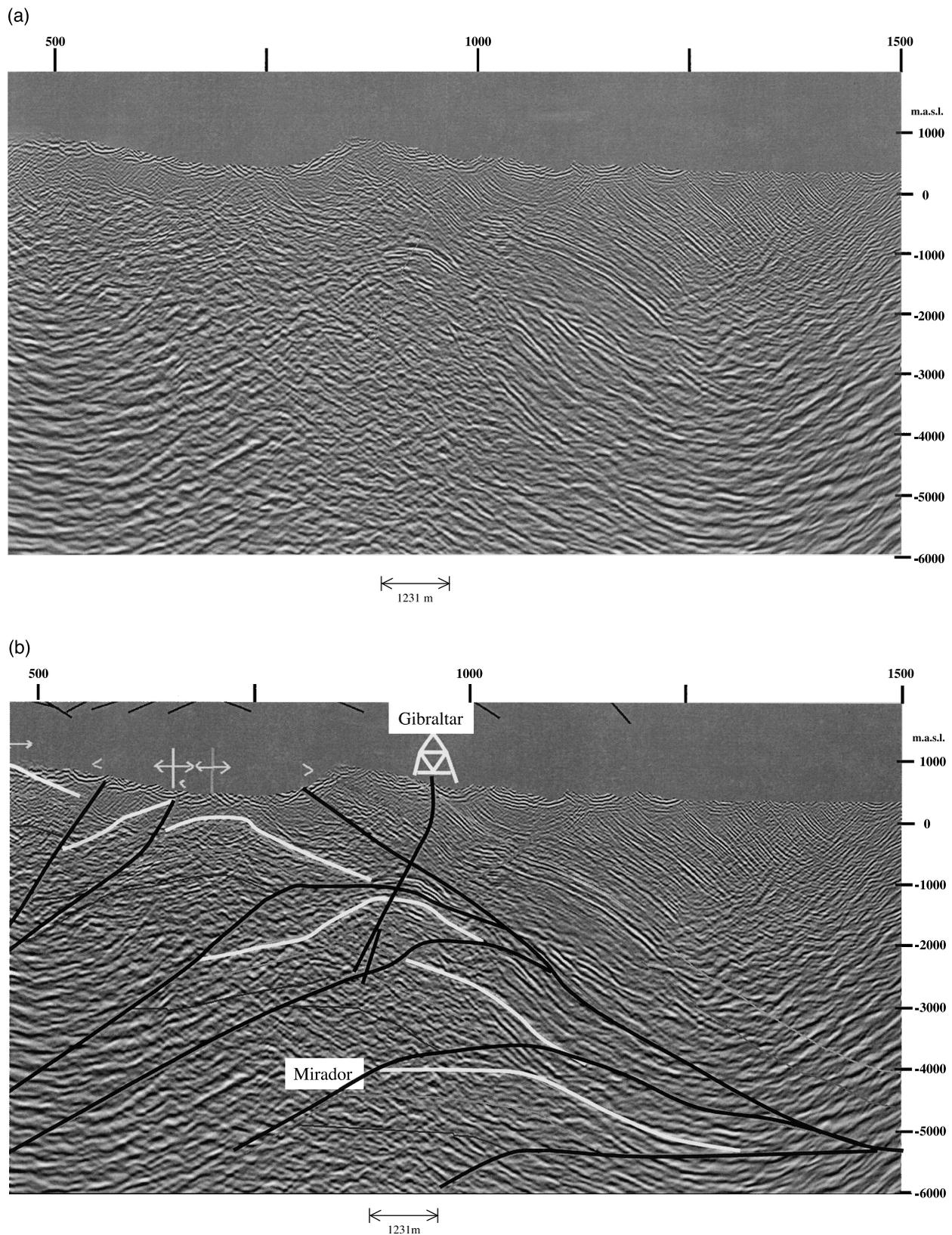


Figure 21. (a) Uninterpreted dip seismic line over the Gibraltar structure in the northern part of the Llanos Foothills area. (b) Interpreted seismic line over the Gibraltar structure. Note that the broad structure is comprised of a series of vertically stacked horses with a passive-roof detachment confining the stacks to a frontal triangle zone. The Gibraltar well (Figure 22) penetrated the reservoirs of an intermediate stack at approximately 6,000 ft (1830 m) and the well's total depth was within reservoir section at 12,000 ft (3658 m). The line shows the approximate position of the Gibraltar well.

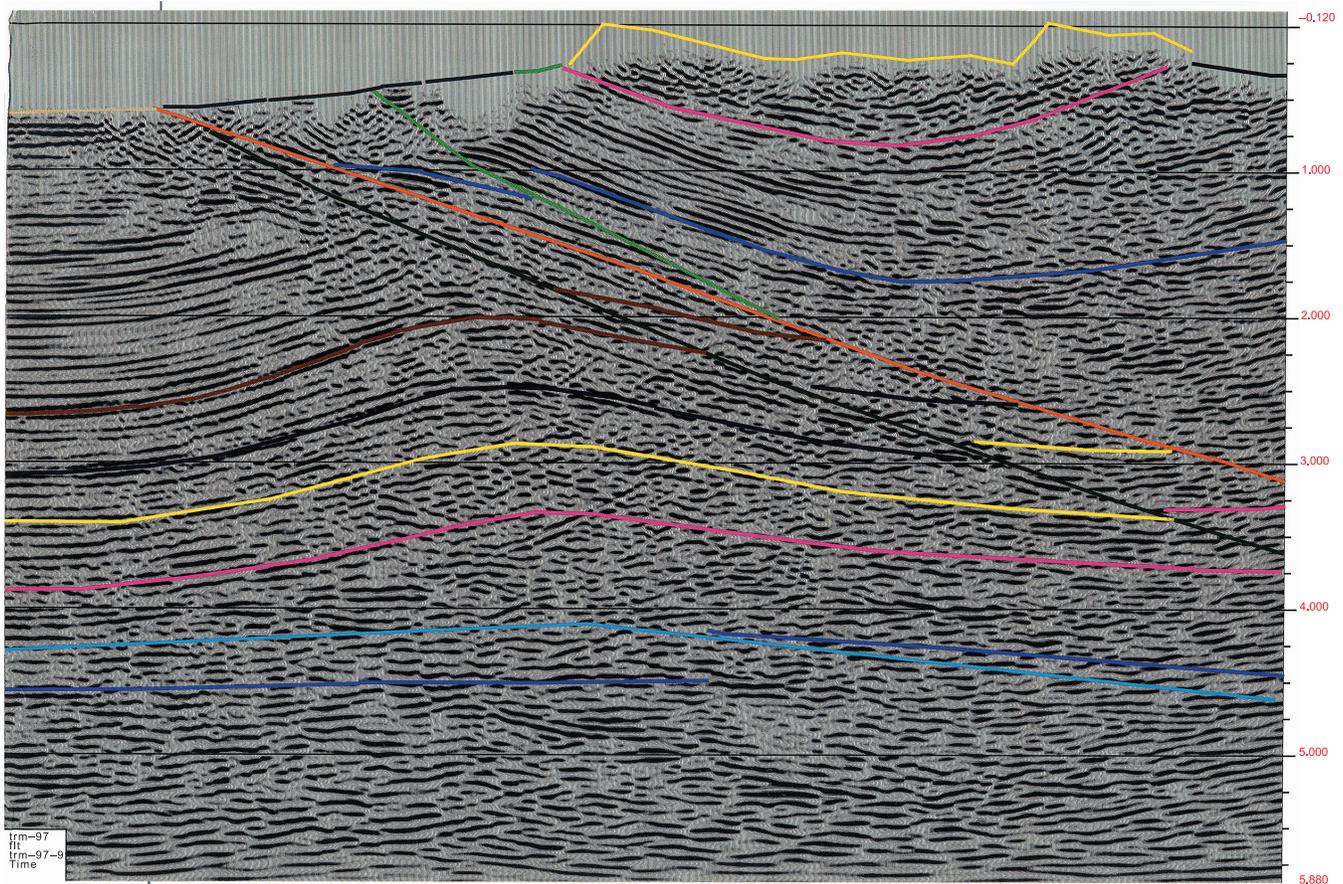


Figure 22. Dip seismic line illustrating the Zeus prospect. This prospect exemplifies the western foothills of the Eastern Cordillera play. The play consists of a fining-upward clastic sequence of Eocene reservoirs that have been proven in flat areas of the basin. The target is underneath a thrust that brings the La Luna Formation over a previously deformed region. Timing of the structure can be determined by onlapping reflections observable just west of where the thrust reaches surface. The western foothills region of the Eastern Cordillera contains the richest source rock of Colombia; this source rock is shared with the Maracaibo Basin. For location of seismic lines, see Figure 15.

showed interesting results: significant pay, e-log curves that showed mobile hydrocarbons, and abundant gas and oil shows. The pressure analysis showed oil and gas gradients and fluid-inclusion data that supported the presence of hydrocarbons.

Western Foothills of the Eastern Cordillera

The western foothills of the Eastern Cordillera are a largely unexplored structural province. The play area has clastic reservoirs that are proven in the flat regions of the basin, overlying a world-class super source rock. The western foothills of the Eastern Cordillera contain an estimated reserve potential of approximately 1,600 mmbo recoverable reserves, when adding identified prospects and leads in advanced stages of evaluation. At least two of these prospects will be drilled from 2003 to 2005. Figures 22 and 23 show examples of seismic sections across leads and

prospects located along the western foothills of the Eastern Cordillera. The play concept is unexplored and consists of Eocene clastic reservoirs in the subthrust environment, beneath Cretaceous source rocks brought to surface by shallow-dipping, west-verging faults. The main risks in the area are related to lack of exploration data, as this is a new play in Colombia. The reservoirs have not been proven (although they are proven outside the subthrust environment). The western foothills of the Eastern Cordillera play is illustrated by two examples. Figure 22 shows a seismic line over the Zeus prospect west of the Velasquez field (1 billion barrels in place). Zeus is a large subthrust structure with potential reserves on the order of 300 mmbo. The Eocene reservoir overlies a very rich La Luna source rock and is sealed by Oligocene fine-grained facies. The structure is back-breaking, and the thin-skinned fault brings the Cretaceous La

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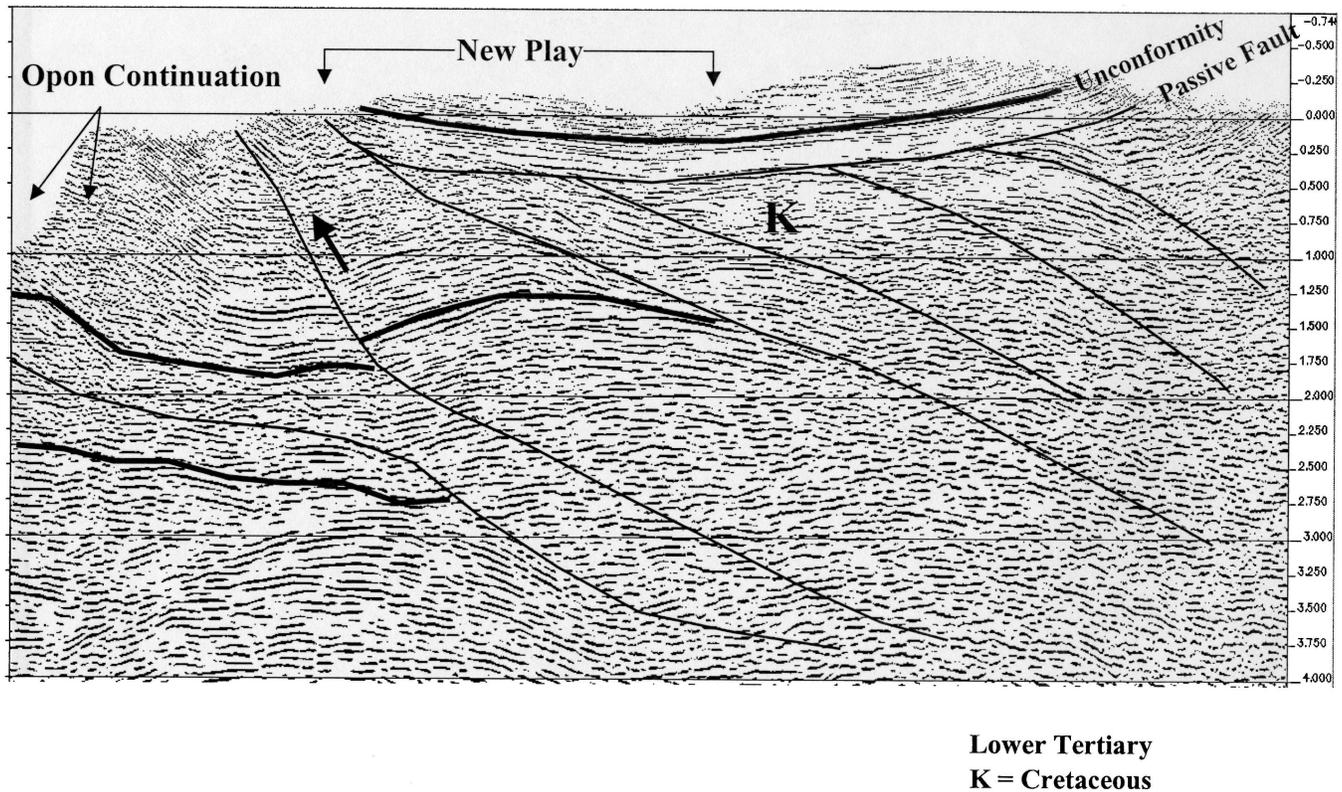


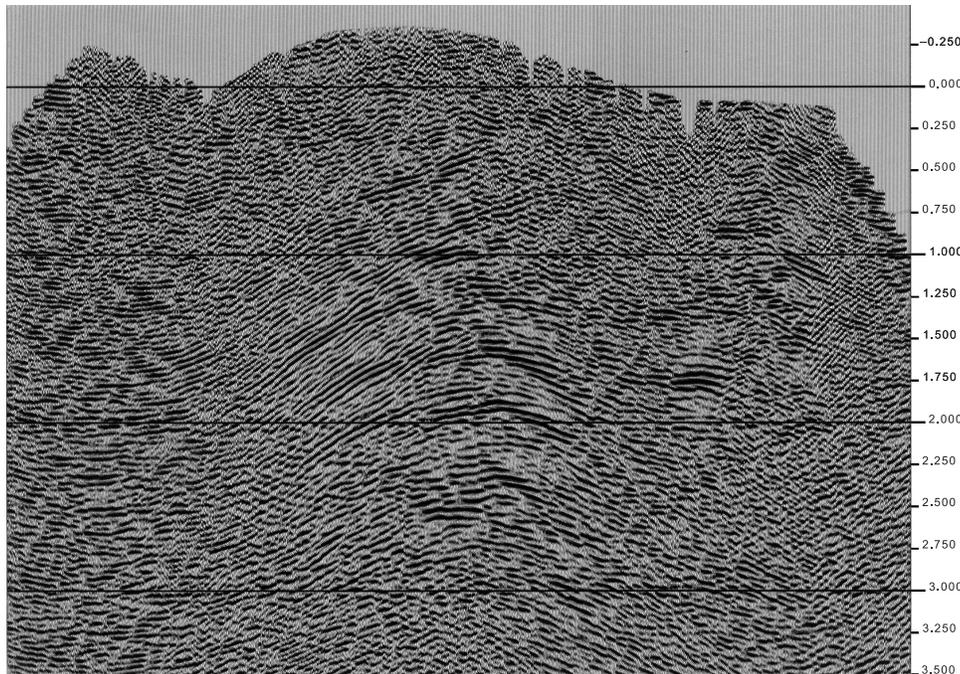
Figure 23. Dip seismic line over the Quebradalarza lead. This lead is part of the western foothills of the Eastern Cordillera play area. Structures involving the Eocene La Paz and Esmeraldas Formations are located underneath frontal synclines of the Eastern Cordillera. This trend is in its earliest stages of exploration, but significant potential is envisioned once success is attained. For location of seismic lines, see Figure 15.

Luna Formation over the subthrust feature, literally sandwiching the reservoir between the La Luna and a tectonically transported La Luna. The La Paz and Esmeraldas reservoirs crop out in the hanging wall, where they seep oil. The main risk of the play is reservoir quality and trap imaging; Eocene reservoirs have not been penetrated in the subthrust environment along the western foothills of the Eastern Cordillera, and this uncertainty has a strong influence on the risk. The main advantage of this play is that it is located in a proven oil-rich province sourced by the prolific La Luna Formation in an area with a well-developed infrastructure. There are some wells in the play, but none of them have penetrated the Eocene basal Tertiary sandstones. Reservoir qualities encountered by some of the wells drilled in the region are not indicative of quality in the basal Eocene section because the sequence is fining-upward and fluvial-dominated. The base of the section is formed of amalgamated channels, whereas the upper part of

the Eocene is composed of distinct fluvial channels, poorly connected and floating in overbank deposits. Fields such as Provincia produce only from the basal Tertiary sandstones rather than from the entire clastic sequence.

Figure 23 is a dip line over the Quebradalarza lead, another new high-potential play along the western foothills of the Eastern Cordillera, with a potential of approximately 200 mmbo. This play is similar to the one outlined previously (Zeus), but the structural configuration is somewhat different. In this play, the Eocene reservoir lies in structures located underneath frontal synclines of the Eastern Cordillera foothills. Seismic imaging is critical in this emerging play, and drilling will have to take place in axial regions of the syncline. Companies are currently acquiring seismic data to evaluate this play concept. Structures are relatively shallow and of significant potential (several hundred millions of barrels), but reservoir quality remains problematic because of the

(a)



(b)

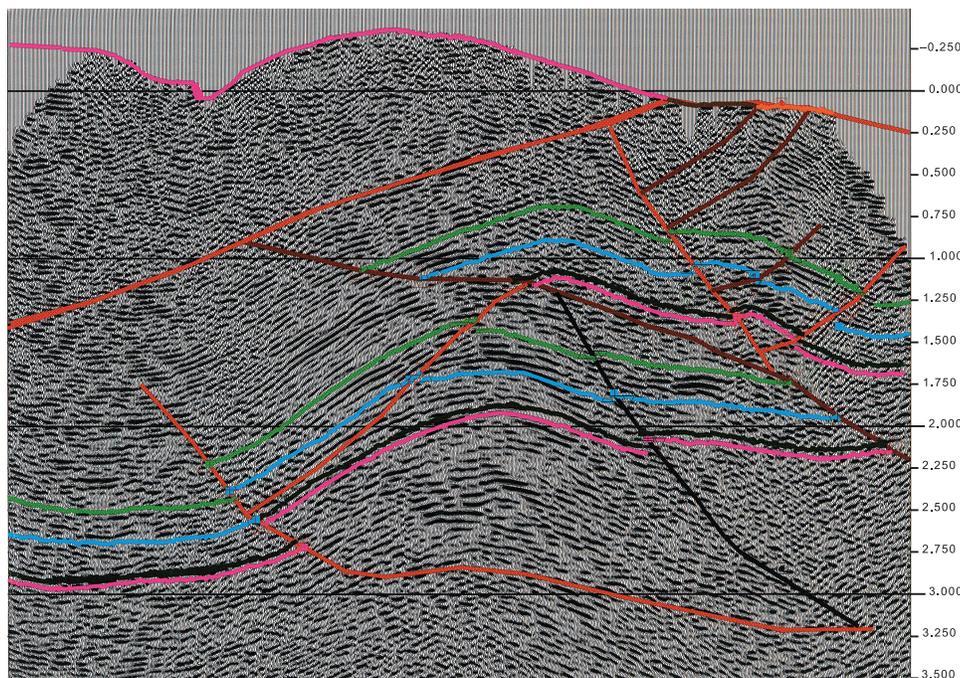


Figure 24. Dip seismic line over the Compadre structure in southernmost regions of the Upper Magdalena Valley. In this area, the Upper Magdalena Basin continues underneath flat thrust faults that bring economic basement to surface. The main target in this area is the Aptian Caballos Formation, which is sourced and sealed by the overlying Villeta Group (La Luna equivalent). For location of seismic lines, see Figure 15.

ery made by Petrobras and Nexen Petroleum extended the boundaries of this basin, and the concept of the play area changed completely after the discovery. Recently, Hocol and Total Fina-Elf have drilled a subbasement trap that significantly modifies the views of this region. Prospects and leads of this play area that are currently being drilled or are committed to drilling add up to approximately 900 mmbo recoverable reserves. Figures 24 and 25 are dip seismic lines that illustrate the play concept. The play targets Aptian and Maastrichtian reservoirs underneath a thrust fault system that brings economic basement over identified structures. The reservoirs are stratigraphically sandwiched between La Luna source rocks in the subthrust environment. The main risks of this play are trap imaging and

lack of exploration data and the absence of analogs along trend.

Extending the Boundaries of a Prospective Basin

The Upper Magdalena Valley is a somewhat narrow basin bound by thrust faults to the east and west. These thrusts are low angle, and the basin extends underneath the foothills area. The Guando discov-

erage of source rock in the kitchen area, but some targets are relatively shallow and of significant size.

Figure 24 is a dip seismic line across the Compadre prospect in the southernmost part of the Upper Magdalena Valley. Low-angle thrust faults bring Jurassic economic basement (the Saldaña Formation) over a preexisting deformed Cretaceous-Tertiary stratigraphy. The main target of this structure is the Early Cretaceous

Figure 25. Dip seismic line over a lead underneath the frontal thrust of the Eastern Cordillera in the southeastern margin of the Upper Magdalena Basin. The seismic line images rising reflections underneath the fault. For location of seismic lines, see Figure 15.

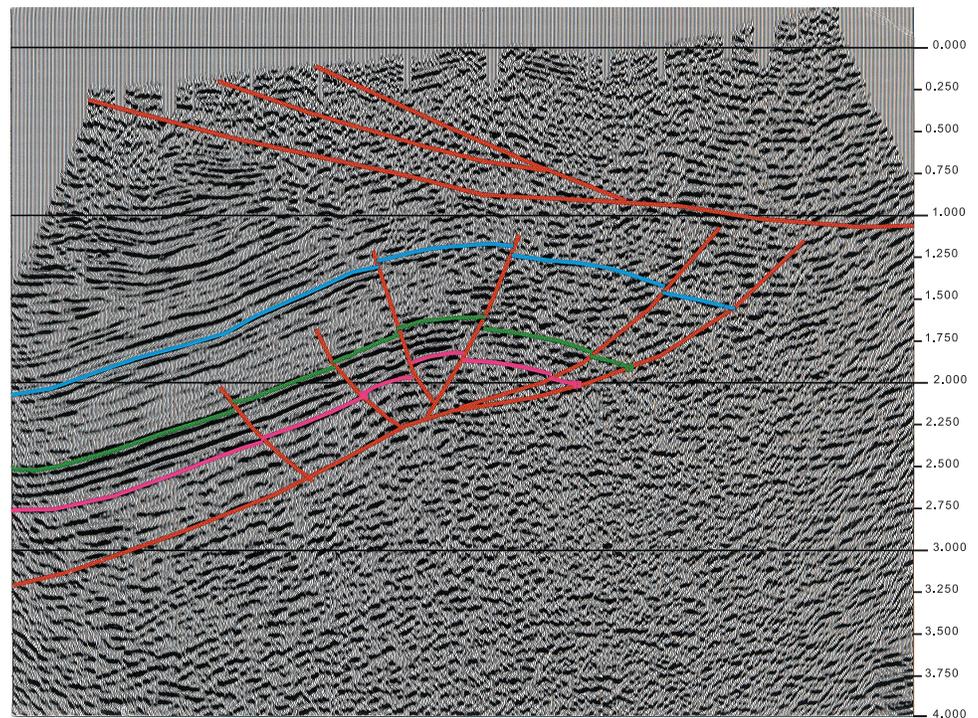
Caballos Formation, a prolific reservoir of this region. The Caballos is sourced and sealed by the overlying La Luna Formation (here called the Villeta Group). A secondary target is the Late Cretaceous Monserrate Formation, but it is possible that this unit has been structurally decapitated. The Compadre structure has a potential of approximately 200 mm BOE and the reservoir is at a depth of approximately 9,000 ft (2743 m).

Figure 25 is a seismic line over one of the prospects beneath the Eastern Cordillera frontal thrust belt. The main difference between this lead and the Compadre prospect is that this particular feature has an identified limb underneath the flat part of the Upper Magdalena Valley basin. The Compadre is entirely in the subthrust environment. The play, however, is similar; the target is the Cretaceous Caballos Formation, and the well most probably will penetrate the basement wedge over the sedimentary section.

Underexplored Offshore Potential

Approximately 50% of the gas reserves in Colombia are located in the Caribbean offshore. The un-risked recoverable reserve potential of this area is currently estimated to be approximately 35 TCF and 3 billion barrels of oil. The area barely has been explored in terms of drilling, but seismic has been acquired. It is here predicted that a significant volume of 3-D seismic data will be shot within the next few years, and exploratory drilling in this area may resume in approximately two–four years (the last exploratory well was drilled in the early 1980s).

Several large structures have been mapped in the Colombian offshore Caribbean; two of the largest and simplest are discussed here. Offshore, 50 km north of the western tip of the Santa Marta Massif, is a large basement-involved structure, very simple in nature,



with an area closure of approximately 70,000 acres. Reservoir depth has been estimated at 20,000 ft (6096 m) and is located in approximately 3,400 ft (1036 m) of water depth. Reserves estimates are between 400 and 600 mm BOE. Northeast of the northernmost tip of the Guajira Peninsula is a very large and simple basement-involved structure (Figure 26). This structure has 99,000 acres in P50 closure and has potential reserves on the order of more than 10 TCF. The structure is located in approximately 2,000 ft (610 m) of water depth, and depth to reservoir is approximately 12,000 ft (3658 m). These structures eventually will be drilled in the Colombian Caribbean; short-term drilling, however, is not foreseen because of risks associated with the gas market and lack of 3-D seismic surveys in the area.

CONCLUSIONS

- 1) The La Luna Formation super source rock and equivalent units generated most of the hydrocarbons in northwestern South America. This source rock is exceptional by world standards and was the product of a distinct combination of geological events. The genesis of the La Luna and equivalent units is closely related to the formation of a large igneous province (LIP) that formed

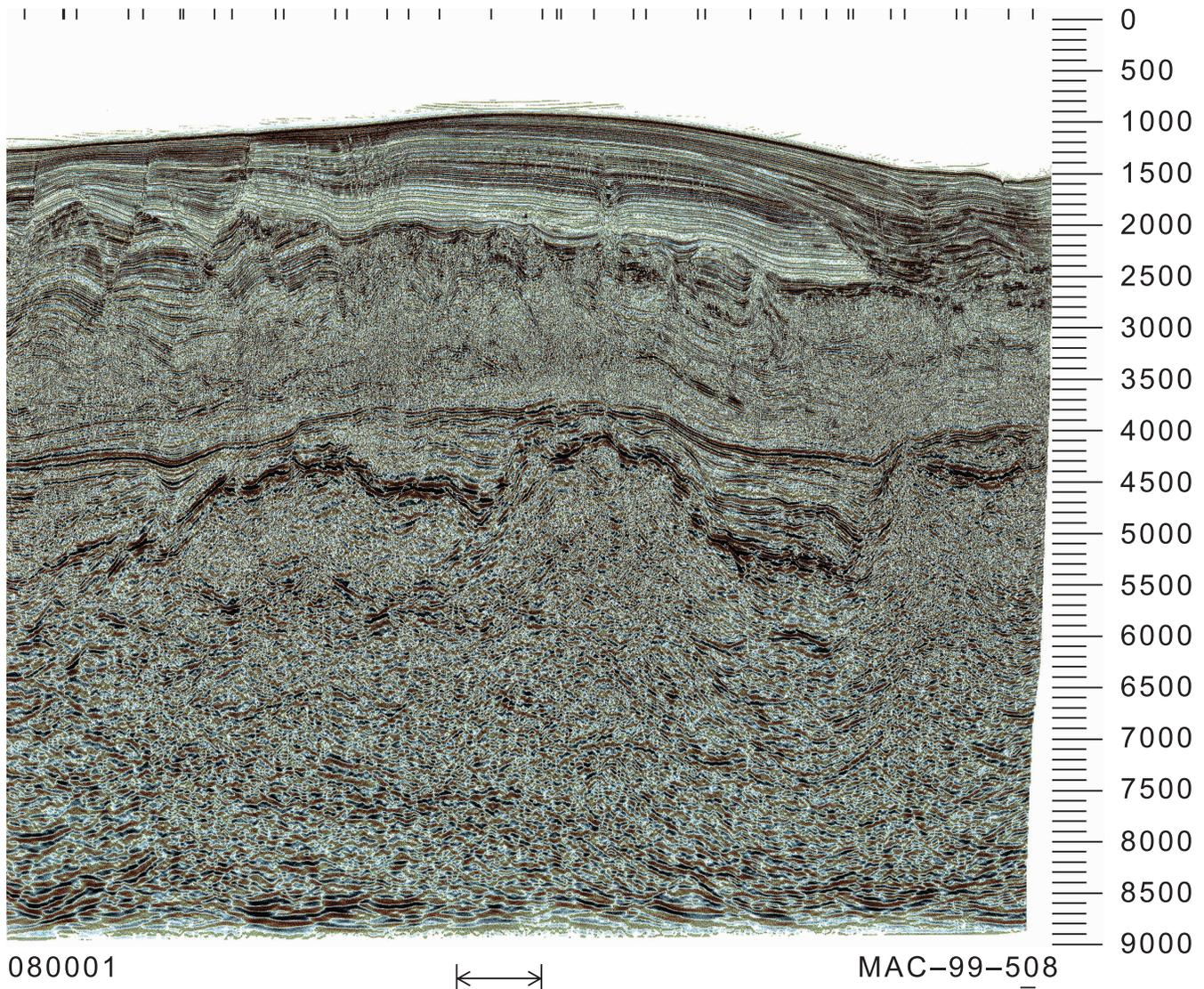


Figure 26. Seismic line across the crest of a large, relatively deep-water structure in the Guajira basin off northern Colombia. The structure is a simple, basement-involved, four-way-dipping anticline with predicted Oligocene reservoirs sealed by a thick section of Miocene shales. The line is east-to-west. Top of reservoir is located at approximately 3.5 sec TWT in the center of the seismic example; the Miocene section seems to be detached at a position that coincides approximately with the base seal (relatively transparent zone just above high amplitudes representing top-reservoir section); the scale bar is 4.1 km long.

a discrete oceanic plate and, at a later time, converged with North and South America. This convergence severely altered portions of the La Luna source rock. The formation of the LIP displaced the sea, causing levels to rise during times of already high sea level; it also injected CO_2 into the atmosphere and warmed an already warm earth. The La Luna is very rich north of the equator because the northern margin of South America was tectonically emplaced in an upwelling zone that favored organic productivity. Organic carbon was deposited in a dysoxic to anoxic sea bottom, and dysoxia prevented destruction

of organic matter. The La Luna Formation and equivalents generated volumes on the order of 2.5 trillion barrels of oil in northern South America and account for 95% of the reserves encountered in the region.

- 2) Beginning in the Maastrichtian and climaxing during the middle Eocene, the pre-Andean orogeny uplifted vast areas that were the sediment source for most of the reservoirs in northern South America. Sediments that were delivered from the Guyana Shield make excellent reservoirs in the Llanos Basin, Llanos foothills, and Maracaibo Lake areas. Sediments derived from the

actively rising ancestral Central Cordillera were deposited over the present Middle Magdalena Valley and Eastern Cordillera. The source area was and still is a mixed terrane; reservoirs derived from this are good but not of the same excellent quality as those derived from the shield. Synorogenic sediments from the pre-Andean and Andean orogenies contain more than 80% of the discovered and potential reserves in the north-west corner of South America.

- 3) During the Oligocene most of Colombia and Venezuela suffered subsidence and tectonic collapse; these were times of widespread seal deposition. Graben systems were strongly inverted during the Miocene. This process explains most of the traps encountered in the region. Stratigraphic stacking by multiple structural repetitions, inversion of Jurassic–Early Cretaceous faults, and molasse deposition in foredeeps adjacent to mountain belts caused maturation and migration of hydrocarbons into traps.
- 4) It is likely that most of the future oil discoveries in Colombia and western Venezuela will be made in complex foothills areas that contain a proven petroleum system, large traps, and are underexplored to unexplored. Most of the gas will be discovered in regions north and west of the southern and eastern limit of Caribbean terranes, mainly in offshore Caribbean regions. These areas have many structures, adequate reservoirs, and a proven gas system.

Whereas source rock and seal risks are less significant regionally, exploration risk for future large discoveries will be dependent on improved imaging and better structural understanding of a complex and challenging geology along the eastern and western foothills of the Eastern Cordillera of Colombia.

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