THE VENEZUELAN HYDROCARBON HABITAT, PART 1: TECTONICS, STRUCTURE, PALAEOGEOGRAPHY AND SOURCE ROCKS

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Venezuela forms part of an important hydrocarbon province, defined by the presence of prolific Cretaceous source rocks, which extends across northern South America. By early 1997, the country had produced 53 billion barrels of oil. Reserves are estimated to total 73 billion barrels of oil and 146 TCF of gas with 250 billion barrels recoverable in the Heavy Oil Belt. Most reserves are located within the intermontane Maracaibo and foreland Barinas-Apure and Eastern Venezuela Basins.They correspond to more than 1.5 trillion BOE originally in place.

The province's hydrocarbon history began with a broad passive margin over which the sea transgressed throughout much of the Cretaceous. Limestones and shales followed basal sands and included rich source rocks. Convergence between the distal part of the area and the Caribbean Plate created an active margin that migrated southwards, so that flysch and wildflysch followed the transgressive facies. The process culminated in Late Cretaceous to Middle Eocene orogeny with the emplacement of southward-vergent nappes and the development of northward-deepening foredeeps. Flysch and wildflysch formed in the north while important deltaic – paralic reservoir sands accumulated in the south. Major phases of hydrocarbon generation from Jurassic-Cretaceous source rocks occurred across the entire margin of northern South America during the orogeny. They are recorded by Jurassic - Middle Cretaceous graphitic marbles, schists and quartzites (metamorphosed, organic limestones and shales and oil-bearing sandstones) in the Coastal and Northern Ranges of Venezuela and Trinidad. They probably charged giant fault and stratigraphic traps analogous to today's Oficina-Temblador and Heavy Oil Belt accumulations.

From Late Eocene to Recent times, transpressive interaction between northern South America and neighbouring parts of the Caribbean and the Pacific inverted Mesozoic extensional systems below the remaining passive margin. The area became subdivided into a series of intermontane, foreland and pull-apart basins bounded by transpressional uplifts, the latter suffering considerable shortening and strike-slip displacement. Sedimentation progressed from deep marine to deltaic and molassic facies, providing reservoir sands and local source rocks.

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Inverted faults and foreland flexuring and interplay between structuration and sedimentation produced abundant structural and stratigraphic traps. Hydrocarbons from earlier accumulations suffered further maturation in place, remigrated to younger traps or escaped to the surface. Further hydrocarbon generation, involving Upper Cretaceous source rocks, occurred in local foredeep kitchens. Minor contributions also came from Tertiary source rocks.

INTRODUCTION

Continuing synthesis and significant advances in the last ten years prompt an update of an earlier version of this paper (James, 1990). Studies by Venezuelan industrial and academic institutions, by international oil companies re-entering the country and by Venezuelan students working on Venezuelan data in overseas universities have all contributed to an improved understanding of the country's petroleum geology.The advances have involved the increased application of sequence stratigraphy (best where calibrated by palaeontology), detailed sedimentology and biostratigraphy, improved structural interpretation allowed by better seismic data, documentation of neotectonic activity and improved geochemical understanding. Yet debate continues over issues such as the depositional environments of the La Luna and Misoa Formations of the Maracaibo Basin – issues which were under discussion half a century ago and which were as "resolved" then as they are today. Indeed, a curiosity is that many recent publications fail to access the considerable data and understanding resident in the earlier literature. Greater access to data, following the example of countries such as Norway, the United Kingdom and Australia, would probably result in yet more rapid growth of knowledge.

The exploitation of abundant oil seeps in Venezuela occurred long before the hydrocarbon industry developed. In the early part of the twentieth century exploration focussed on locations close to seeps. It progressed to tests of anticlinal traps, which were detected by surface geology, by potential methods and eventually by seismic data. Advances in drilling and seismic techniques, together with growing geological understanding, led to continuing discoveries in better-defined, deeper and more complex traps. Advances in seismic quality and in sedimentology allowed the definition of stratigraphic traps. Exploration potential now lies in the deeper section in the Amacuro Delta area and below the fold and thrust belts bounding the basins and in the offshore areas. Further reserves will come from enhanced recovery, directional drilling and identification of additional reservoirs within and adjacent to known accumulations.

Talukdar and Marcano (1994) discussed two Total Petroleum Systems in the Maracaibo Basin, and Daly *et al.* (1998) described two similar systems in Eastern Venezuela. They involve Late Cretaceous and Tertiary source rocks, the former by far the more important. Both relate to late Palaeogene–Recent basins. Anka *et al.* (1998) discussed two systems involving Cretaceous source rocks in the Barinas-Apure Basin. These studies all conclude that only the La Luna system was capable of generating the huge volumes found in the country.

The above paragraph apart, this paper does not discuss petroleum systems. This, in part, is because the location, extent and timing of kitchens in Andean foredeeps are not well understood. In this light, it does not make sense to discuss subjects such as "pods of source rock" and "critical moments". Moreover, most papers discussing Venezuelan petroleum systems appear to rephrase what is already known and do not add further value. The lack of precise areal definition and timing of kitchens, in such a well-explored and prolific petroleum province, provides a caution for studies claiming to clarify understanding and quantification of exploration targets via petroleum systems analysis.

The "Hydrocarbon Habitat" referred to in this paper is defined as the total geological context of generated and trapped hydrocarbons. It considers the tectonic setting and evolution of the entire host region as these relate to the palaeogeography of source, reservoir and seal units, the evolution of intermediate and existing basins and traps, the maturation of source rocks and the migration of products. It includes the signal of basement and uplift geology. It is the holistic framework within which existing and earlier hydrocarbons developed. While Neogene

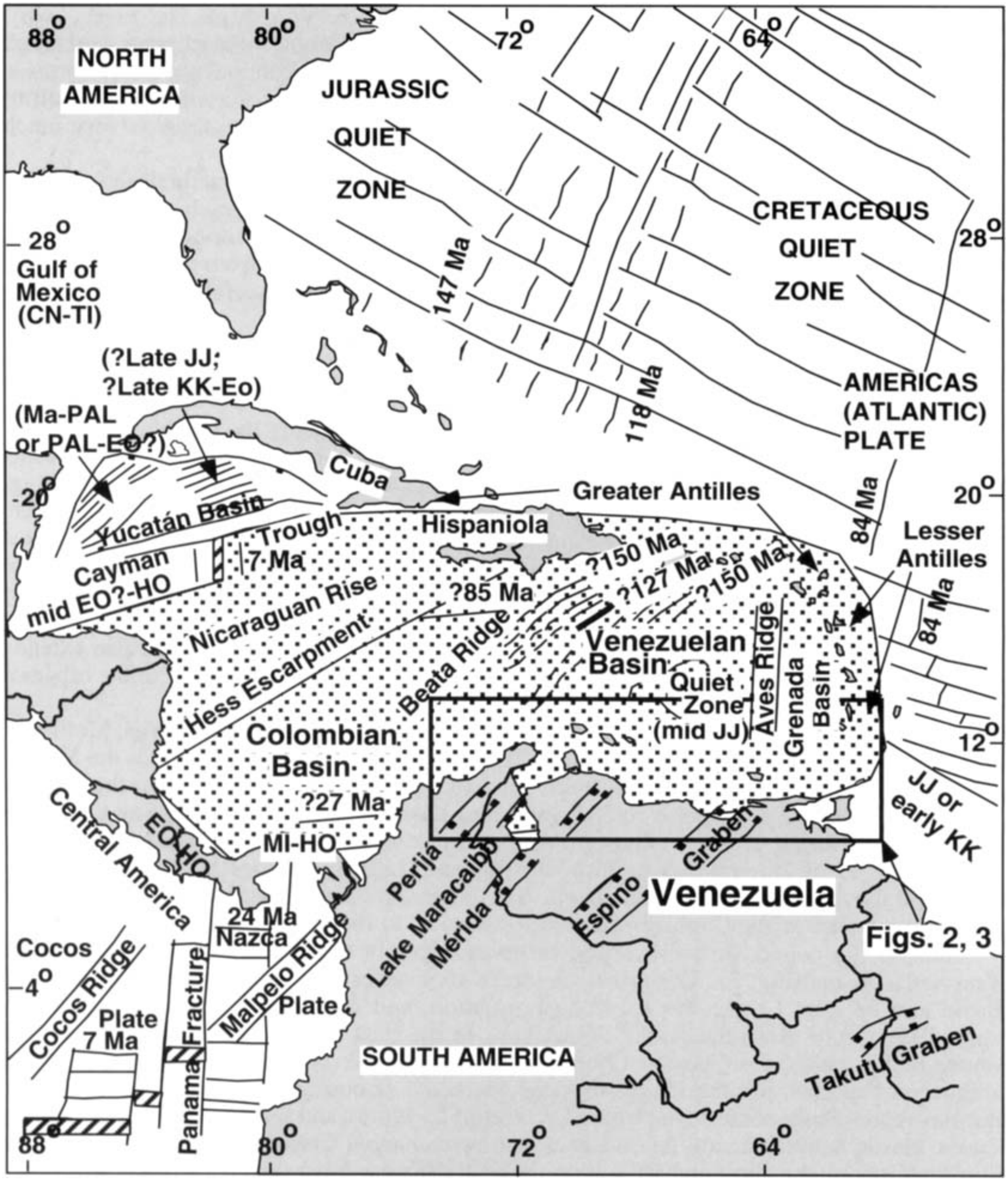

Fig. 1. Tectonic setting of Venezuela on the northern margin of South America. The Caribbean Plate (stippled) to the north includes the Colombian and Venezuelan Basins. It is bounded to the north, east and south by the Americas Plate, comprising continental North and South America and the oceanic Atlantic. To the west lie the Pacific Cocos and Nazca Plates. Named Jurassic grabens are shown onshore; fractures, and the orientation and ages of magnetic anomalies and crust are shown offshore. Abbreviations are as follows: HO: Holocene; MI: Miocene; EO: Eocene; JJ: Jurassic; CN: Callovian; TI:Tithonian.

generation from Upper Cretaceous source rocks in Venezuela is fairly well understood, the literature only patchily considers Late Cretaceous – Palaeogene generation and rarely considers any contribution from possible older sources. Volumes generated by these former systems were likely to be very large, but how much, if any, survived is difficult to estimate. I consider that their possible contribution to today's vast reserves is very much unrecognized and undervalued.

This paper is divided into two Parts. Part 1 concentrates on the structural and regional development of the Venezuelan oil provinces, and on the palaeogeography of source-rock deposition. Part 2 will consider the main Venezuelan plays and the volumes of hydrocarbons involved; some of the classic fields are also illustrated. However, apart from recent discoveries, the literature generally does not provide up-to-date field illustrations. Hopefully, this shortcoming will be addressed in future publications.

Regional Setting

Venezuela lies on the northern margin of South America, facing the Caribbean Sea (Fig. 1). The Precambrian Guayana Shield of Venezuela is rimmed by a series of foreland basins that deepen towards the uplifts of the Mérida Andes and the Coastal and Interior Ranges (Fig. 2). These basins contain Cretaceous and younger sediments above local rifts with Jurassic and Palaeozoic sedimentary rocks. The outcropping El Baúl Uplift or basement arch separates the Barinas-Apure Basin in the west from the Eastern Venezuela Basin the east. Close to the Venezuelan-Colombian border the subsurface Arauca Arch separates the Barinas-Apure Basin from the Llanos Basin. The Anaco Fault divides the Eastern Venezuela Basin into the Guárico Sub-basin in the west and the Maturín Sub-basin in the east. The Maturín Sub-basin extends eastward across the Gulf of Paria to the Southern Basin of Trinidad and thence to the offshore Columbus Basin.

The Maracaibo Basin, in the NW, is an intermontane basin bounded by the Perijá, Motilones (Santander) and Mérida transpressional uplifts. It deepens southeastward towards the Mérida Andes. A subsurface transpressional uplift separates the Maracaibo Basin from the Gulf of Venezuela. The Falcón area, NE of the Maracaibo Basin, is usually referred to as a separate basin. It is an inverted Eocene – Oligocene depocentre now having the form of an anticlinorium.

Offshore lie the Tertiary basins of La Vela Bay and Golfo Triste, together with the Cariaco Basin and the Carúpano (Margarita) Basin. These contain local Tertiary source rocks. Major gas accumulations in the Carúpano Basin are said to be of biogenic origin.

Most of the country's hydrocarbon reserves occur in the Maracaibo and the Eastern Venezuela Basins (Fig. 3). The principal source rock and reservoir units of the Maracaibo Basin are the Late Cretaceous La Luna Formation, and the Eocene Misoa and Miocene Lagunillas and La Rosa Sandstone Formations. In the Eastern Venezuela Basin, the coeval source rock is called the Querecual Formation; the main reservoirs are the sandstones of the Oligocene Naricual and the Oligo-Miocene Merecure Group and Oficina Formation. The Barinas-Apure Basin contains the Upper Cretaceous La Morita and Quevedo Formation marine shales, clastic equivalents of the La Luna, that have charged Cretaceous (Escandalosa Fm.), Eocene (Gobernador Fm.) and Oligocene (basal Carbonera Fm.) sandstone reservoirs.

THE GEOLOGICAL HISTORY OF VENEZUELA – A SUMMARY

Late Precambrian — Early Palaeozoic accretion/orogeny resulted in the SE thrusting of metasediments and sediments (Iglesias Complex of the Mérida Andes; 1400–600Ma). Granites intruded the complex at around 600 Ma and regional metamorphism to greenschist-amphibolite grade occurred in the Early Palaeozoic (Burkley, 1976). The angularity of the unconformity between metamorphosed Carboniferous rocks and the overlying Permian sediments indicates a Hercynian phase of folding and thrusting (Christ, 1927).

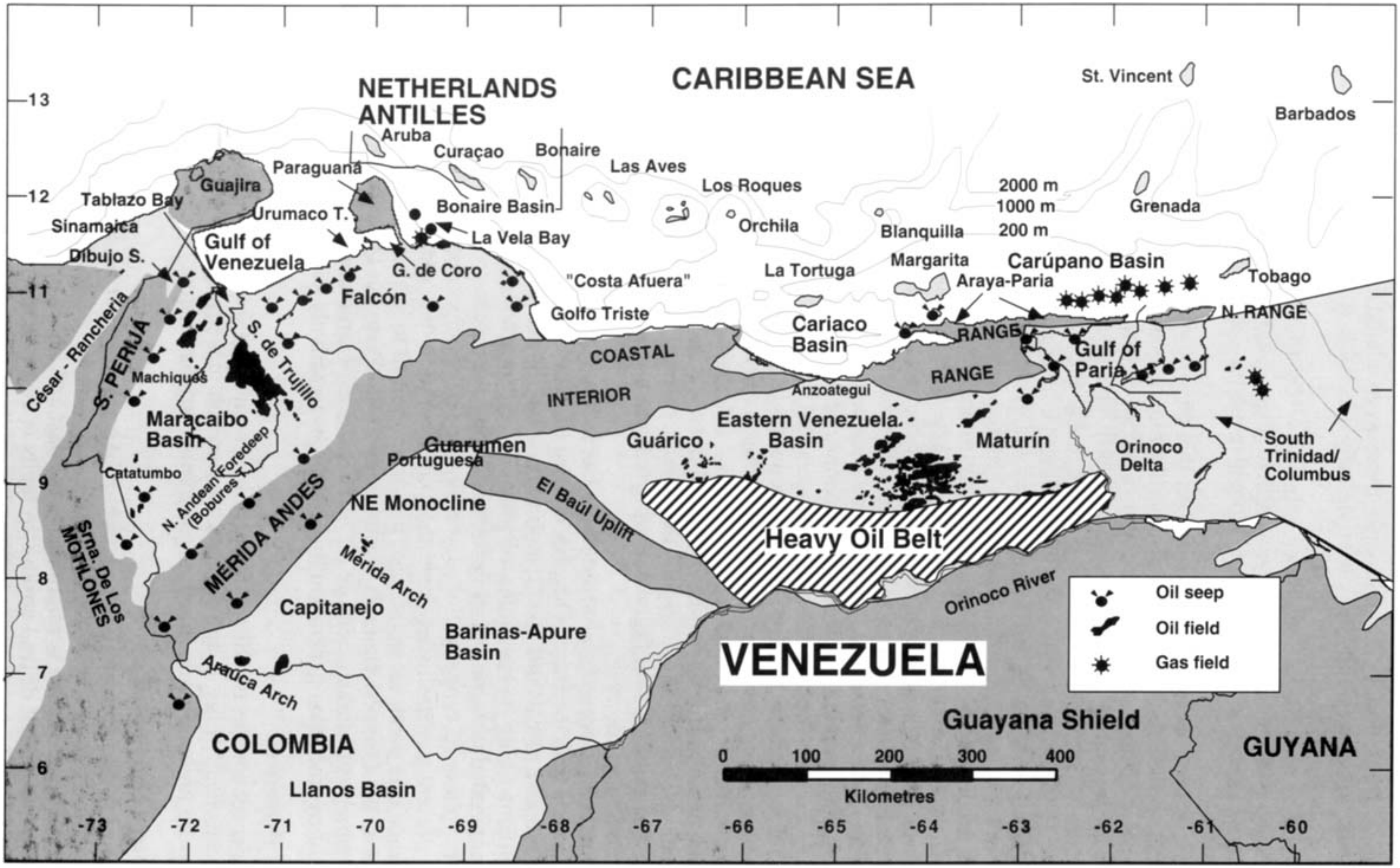

Fig. 2. The main basins, arches and uplifts of Venezuela, along with the distribution of the main oilfields and the locations of seeps. Bathymetric contours at 200, 1,000 and 2,000 m indicate the form of the continental shelf.

A system of NE-trending grabens formed in northern South America during the Late Triassic - Early Jurassic (Figs. 1 and 9). In the north, these were related to the opening of the southern North Atlantic. In the west they have been described as back-arc rifts related to subduction of the Pacific Plate (Jaillard *et al.*, 1990).

From Early to Late Cretaceous times, a broad, NNW-tilted passive margin existed along the northern and NW flanks of the Guayana Shield (Figs. 2 and 10). It accommodated fluviatile/paralic sandy sediments in the south, and lagoonal to marine carbonates and shales transgressing from the north.

Important source rocks were deposited on this passive margin as a southward-younging and -thinning section. Associated cherts and volcanic rocks are more abundant in the northern and upper parts of the section, reflecting a distal and approaching arc that may have been responsible for restricted circulation (James, 1990). The arc probably became active from the time when the Equatorial Atlantic began to open in the Late Jurassic – Early Cretaceous (Ladd *et al.*, 1985; Uchupi, 1989). As the continent converged with the Caribbean, the active margin migrated southwards. Erosion products and olistolithic materials from the advancing uplifts entered the associated foreland basins. Mesozoic sediments flooring the troughs and some of the deeply-buried flysch became metamorphosed and were later exhumed in northern uplifts such as the Coastal Ranges. Metasediments in the Venezuelan Coastal Ranges, on nearby islands and in the Northern Range of Trinidad, record the nature of this margin. Their abundant graphite content suggests that hydrocarbons may have been involved in this history.

During the Late Cretaceous convergence between the Caribbean and South American Plates culminated with the emplacement of nappes of metamorphosed Upper Jurassic island-arc material, Lower - middle Cretaceous metasediments and Upper Cretaceous sediments (Bellizia, 1985). Related foreland basins accommodated flysch/wildflysch (Fig. 11). This phase of Andean orogenesis corresponds with Barr's (1974) "mid-Laramide" phase and with the Peruvian episode of western South America (Mégard, 1987; Aleman and Marksteiner, 1993). This paper terms the episode "Caribbean" in northern South America. Again, hydrocarbons probably formed within the deeper parts of these basins. It is possible that some resided in traps that later failed, allowing remigration into younger traps and contributing to today's enormous reserves.

A further tectonic episode occurred in the late Eocene and is marked by a regional hiatus. This corresponds with the Incaic Orogeny of Peru (Mégard, *op. cit.*; Aleman and Marksteiner, *op. cit.*). I propose to call this the "Guajiro Orogeny" in northern South America, after the group of Indians living on the Guajira Peninsula. Hydrocarbons generated in the Caribbean Orogeny remigrated or were lost or destroyed during this event.

The latest phase of orogeny commenced in the Early Oligocene (Fig. 12) and continues today. The present-day basins assumed their configuration only during the latter part of this orogeny. Since it is youngest in the east, it is here referred to as the "Guarao Orogeny", after the Indians of the Orinoco Delta. It corresponds to the Peruvian Quechua phases (Mégard, *op. cit.;* Aleman and Marksteiner, *op. cit.*). This phase of structuration is responsible for the larger part of hydrocarbon generation that continues in actively subsiding areas.

Structural Provinces

This paper recognizes two distinct structural provinces in Venezuela — to the east and west of the Boconó Fault (Figs. 4 and 5); later sections on palaeogeography show that this fault (zone) plays an important role in palaeogeographic reconstruction.

(i) The Eastern Structural Province

To the east of the Boconó Fault, dextral relative movement between the Caribbean and South American Plates controls the northern parts of onshore Central and Eastern Venezuela (Fig. 4). Strain-development is migrating to the east and SE. A regional system of east-west trending, transpressional dextral strike-slip faults is associated with the uplift of the Coastal Ranges. NW-SE trending synthetic faults splay southwards, forming lateral ramps to N 70°E

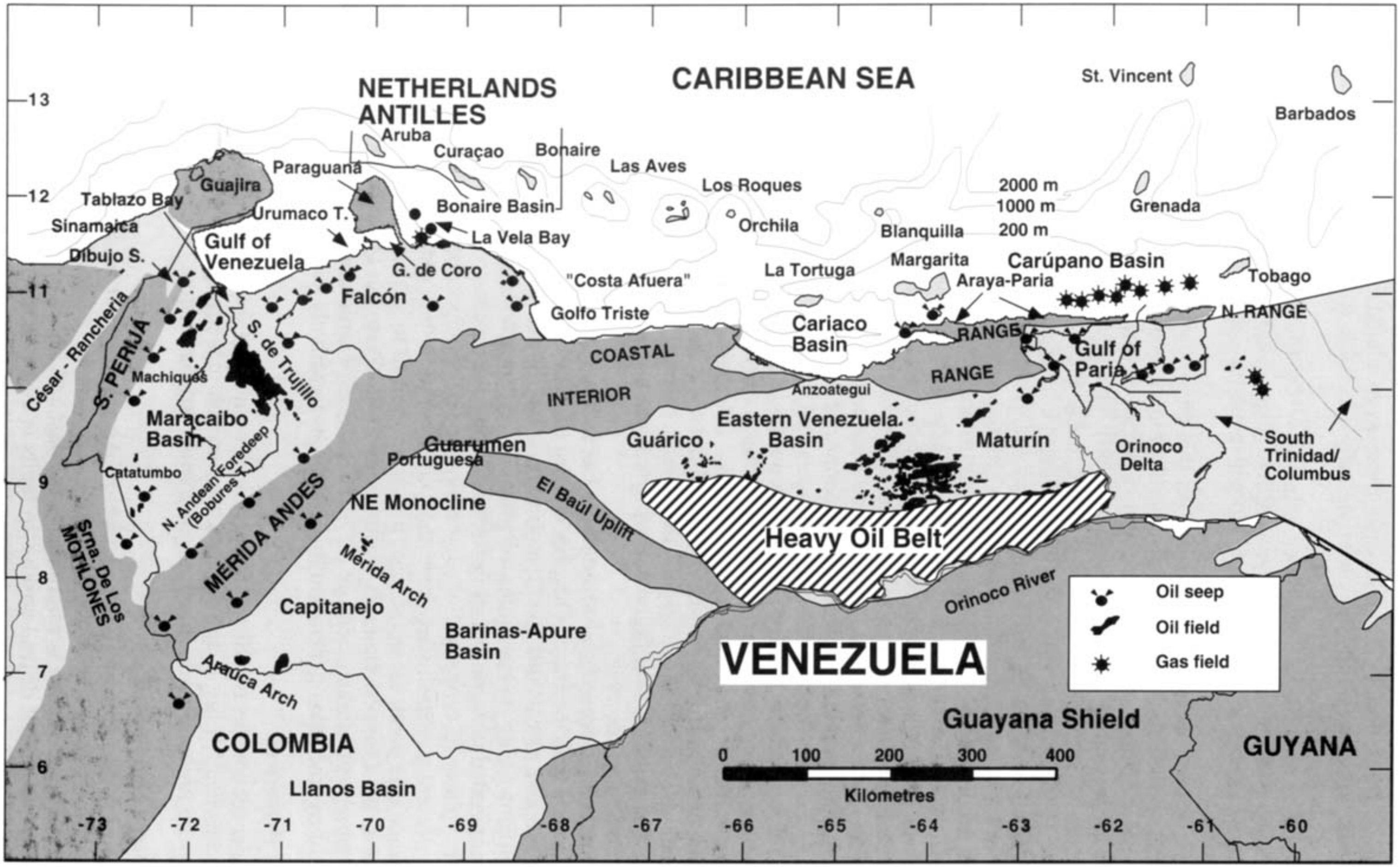

Fig. 3. The main oil- and gasfields of Venezuela.

trending thrusts and folds in the Interior Range and in the northern part of the adjacent foreland basin. Related contractional structures and facies changes form important hydrocarbon traps. Compression in the adjacent foreland basin has created pore-pressure increases that triggered mud diapirism with hydrocarbon seeps. A chain of diapirs runs from the Maturín Sub-basin (Fig. 7) across the Gulf of Paria to Trinidad's Southern Range and provides structural/ stratigraphic traps (Daly *et al.*, 1998). Extensional basins ranging from small grabens to major embayments (Cariaco Trough and the Gulf of Paria, Fig. 2) occur at the northern limits of the synthetic faults. Of these, only the Gulf of Paria, floored in part by Upper Cretaceous source rocks, has yielded commercial discoveries but drilling in the Cariaco Trough encountered significant shows of Tertiary-sourced hydrocarbons (Talukdar and de Bolivar, 1982).

South of the Interior Range lies a system of ENE-plunging foreland basins (Eastern Venezuelan Basin – Columbus/South Trinidad Basins:Fig. 2), filled with a succession of deep-marine, shallow-marine, deltaic and molassic sediments. The uplifts and basins formed first in the west, during the Oligocene, and progressively migrated eastward to the present locus of thrust activity east of Trinidad. As deformation progressed, uplift and erosion followed from the west. Oligocene to Recent sedimentation thus followed a general pattern of regression towards the east. Craton-derived paralic or continental, sandy deposits accumulated in the south and west, while marine to continental shales formed in the basin axes. Sands and conglomerates flanked the rising, east-west oriented, transpressional uplifts of the Coastal/ Interior Ranges that cut across the earlier ENE-WSW grain.

Load-related flexuring of the foreland basin ramp activated conjugate, NW-SE and NE-SW, synsedimentary, synthetic and antithetic normal faults that influenced the distribution of channel and paralic sandstone reservoirs and formed important traps. Listric faults, usually down-to-the-NE and soling-out in Miocene shales, become increasingly abundant in the Orinoco Delta and Gulf of Paria.

(ii) The Western Structural Province

West of the Boconó Fault, oblique convergence between the Pacific Plates (the Farallon and later the Nazca Plates: Figs. 1 and 4) resulted in accretion of Colombia's Western Cordillera (Middle Eocene) and Baudo Sierra (Miocene). Strain is partitioned into strike-slip and contraction within the "Bolivar Block", which is defined here as that part of NW South America moving NE along major strike-slip systems of the Eastern Cordillera and Mérida Andes (Fig. 4). Transpression resulted in shortening of the passive margin and uplift of the Central Cordillera (Late Cretaceous), the Eastern Cordillera, the Sierra Nevada de Santa Marta, the Mérida Andes, the Santander Massif and the Sierra de Perijá (Late Eocene-Pleistocene). These define the present-day Atrato, San Jorge, Plato, Magdalena Valley and Maracaibo intermontane basins and the Barinas-Apure-Llanos foreland basins. The latter three basins are underlain by Upper Cretaceous source rocks which are mature in depocentres adjacent to the Andean uplifts and are important hydrocarbon provinces. Most oil occurs in Tertiary sandstones involved in structural and stratigraphic traps. Significant quantities also occur in fractured Cretaceous carbonates and metamorphic and igneous basement rocks.

Dextral strike-slip along the Eastern Cordillera of Colombia and the Mérida Andes of Venezuela, and sinistral strike-slip along the western margin of the Santander Massif and the Sierra Nevada act as lateral ramps to a delaminated microplate referred to here as the Maracaibo-Bonaire Block (Fig. 5). This has been moving northwards to override the Caribbean Plate since the Late Eocene, creating the compressional South Caribbean Deformed Zone (Curaçao Ridge) ahead of it (Fig. 1). The northern part of the microplate is characterized by a strike-slip fault/thrust/pull-apart assemblage similar to that already described in the eastern onshore: the Netherland and Venezuelan Antillean islands are the subaerial tips of thrust sheets and are separated by NW-trending, submarine extensional basins dominated by shales. The basins contain local source and reservoir facies in their Tertiary sections. Hydrocarbons occur above a basement high in La Vela Bay (Fig. 3). Further south, major pull-apart basins formed in the

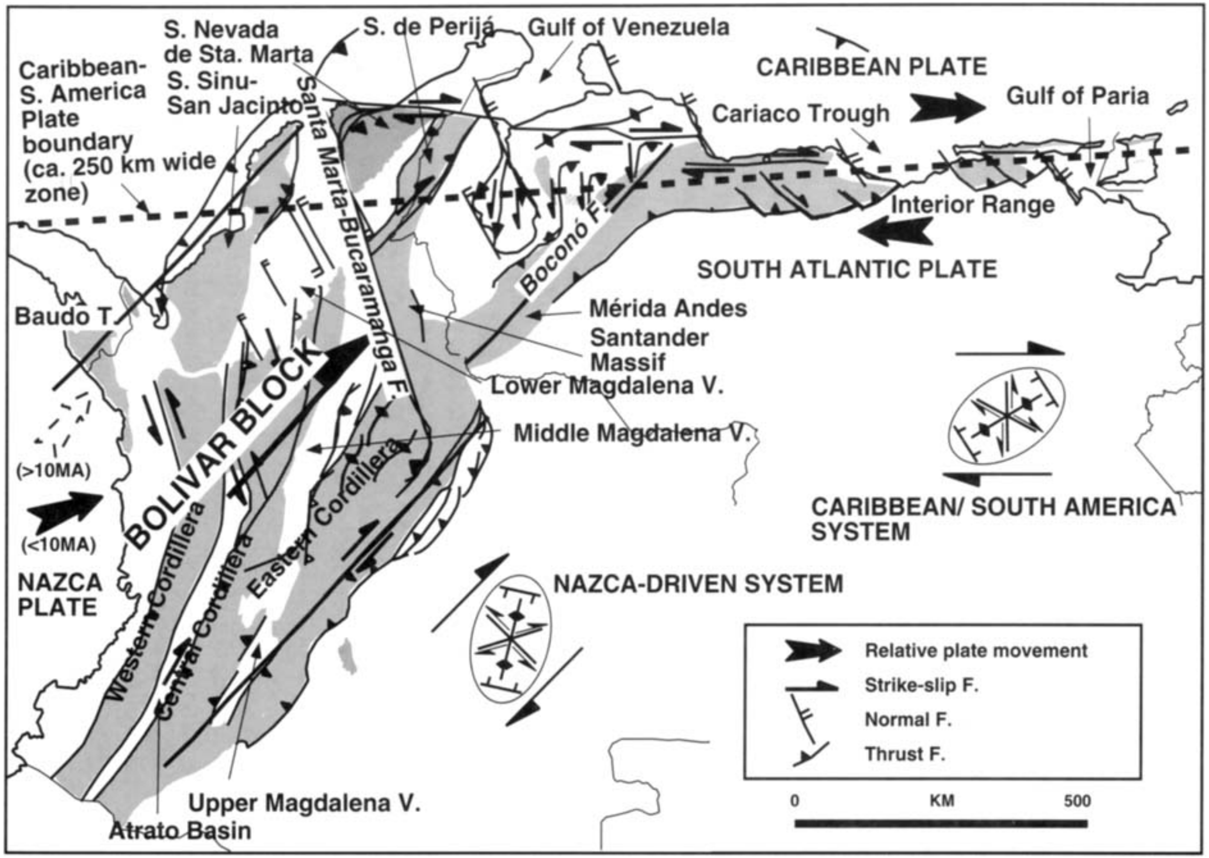

Fig. 4. Tectonic interpretation of NW South America. Dextral transpression between the Caribbean Plate and South America governs the eastern part of Venezuela, creating folds and thrusts of the Interior Range and pull-apart basins such as the Cariaco Trough and the Gulf of Paria. Northeastward movement of the Bolivar Block in the west, driven by plate push from the Pacific, results in the extrusion of triangular elements such as the Maracaibo-Bonaire Block, bounded by sinistral (Santa Marta – Bucaramanga) and dextral (Boconó) faults. As the Block crosses the Caribbean-South America Plate boundary, it suffers major pull-apart extension, seen in the Gulf of Venezuela, Lake Maracaibo, and the basins between the Netherland and Venezuelan Antillean islands (Fig. 2).

Gulf of Venezuela, the Falcón Basin (inverted in the Late Miocene) and, latterly, Lake Maracaibo. These basins hosted lagoonal to marine, mainly clastic deposition, with local carbonates laid down on highs.

PLATE-TECTONIC SETTING OF VENEZUELA AND THE CARIBBEAN

Venezuela lies on the northern margin of the South American continent that forms part of the Americas Plate (Fig. 1). The latter is moving westward relative to the Caribbean Plate and dextral transpression currently governs the roughly east - west trending plate boundary across the north of the country. Northward escape of NW South America (the Bolivar Block, Fig. 4) complicates the situation west of longitude 65°.

Geological complexity, an insufficiency of definitive data and an abundance of preferred models has resulted in a bewildering mixture of literature describing the origin of the Caribbean Plate and on the form and dimension of the plate boundaries. Many studies have set out to test models and unsurprisingly have found supporting data.

The popular model is that the Caribbean Plate entered its inter-American location from the Pacific (Wilson, 1965; Malfait and Dinkleman, 1972; Pindell and Dewey, 1982; Pindell *et al*, 1988, and many others). Though not proven, the concept forms the foundation for complex models of the Venezuelan margin. In contrast, other authors (e.g. Ball *et al.*, 1969, 1971; James, 1990; Meschede, 1998; Meschede and Frisch, 1998) contend that the plate most probably formed as part of the North Atlantic Plate when North America drifted from Gondwana in the Jurassic. It subsequently interacted in contractional and strike-slip tectonics with the surrounding Americas Plate. Until definitive data are at hand, these alternative models deserve equal consideration.

If it is entirely oceanic, the Caribbean Plate is unusually thick (12 km) near the Beata Ridge (Fig. 1) (Diebold, 1995). In contrast, it is only 3km thick in the SE part of the Venezuela Basin. Note that granite occurs on the southern part of the Aves Ridge (Fox *et al.*, 1970). According to Donnelly (1973) Donnelly *et al.* (1990) and Driscoll and Diebold (1998), the Caribbean comprises a (Jurassic) dominantly Early to mid-Late Cretaceous oceanic basalt province. It formed firstly by spreading as North America drifted away from South America, and secondly by a widespread flood basalt event in the Early to middle Cretaceous. A coeval, primitive to calc-alkaline island-arc formed on the periphery of the flood basalt province. More recently, mid-Tertiary to Holocene alkalic basaltic suites formed in Central America and in the Lesser Antilles in response to subduction of the Cocos and Americas Plates, respectively. Intriguingly, satellite altimetry data, converted to gravity and thence to bathymetry, reveal a circular depression, tentatively named the Beata Crater, close to the SE part of the Beata Ridge (James *et al.*, 1998a, b, c). This feature, 180 km in diameter, might be linked to the formation of the basalt province; alternatively, it may be related to an Eocene tektite field known from the Caribbean and the SE United States.

Perhaps because of the Late Cretaceous overthickening, magnetic data in the Caribbean area do not show a well-defined ocean-floor signature. Ghosh *et al* (1984) reported NE-trending magnetic anomalies of possible Jurassic age in the Venezuela Basin (Fig. 1). These parallel Jurassic onshore grabens that formed as a consequence of sinistral movement of North America away from Gondwana (and South America), and suggest the formation of oceanic crust in the area as the mid-Atlantic and proto-Caribbean oceans formed. In contrast, Christofferson (1976) observed E-W trending anomalies in the Colombian Basin. These parallel anomalies in the nearby Nazca Plate, suggesting that the two areas were contiguous before the (Eocene) birth of the Central American Isthmus.

Subduction of the oceanic Americas Plate below the eastern part of the Caribbean Plate generated the Lesser Antilles volcanic arc (Fig. 5). Depression of the Americas Plate is registered by gravity minima (Hess, 1938). This is expressed bathymetrically by an oceanic trench in the north; but from Barbados southwards the sediments of the Palaeocene-Pleistocene Barbados

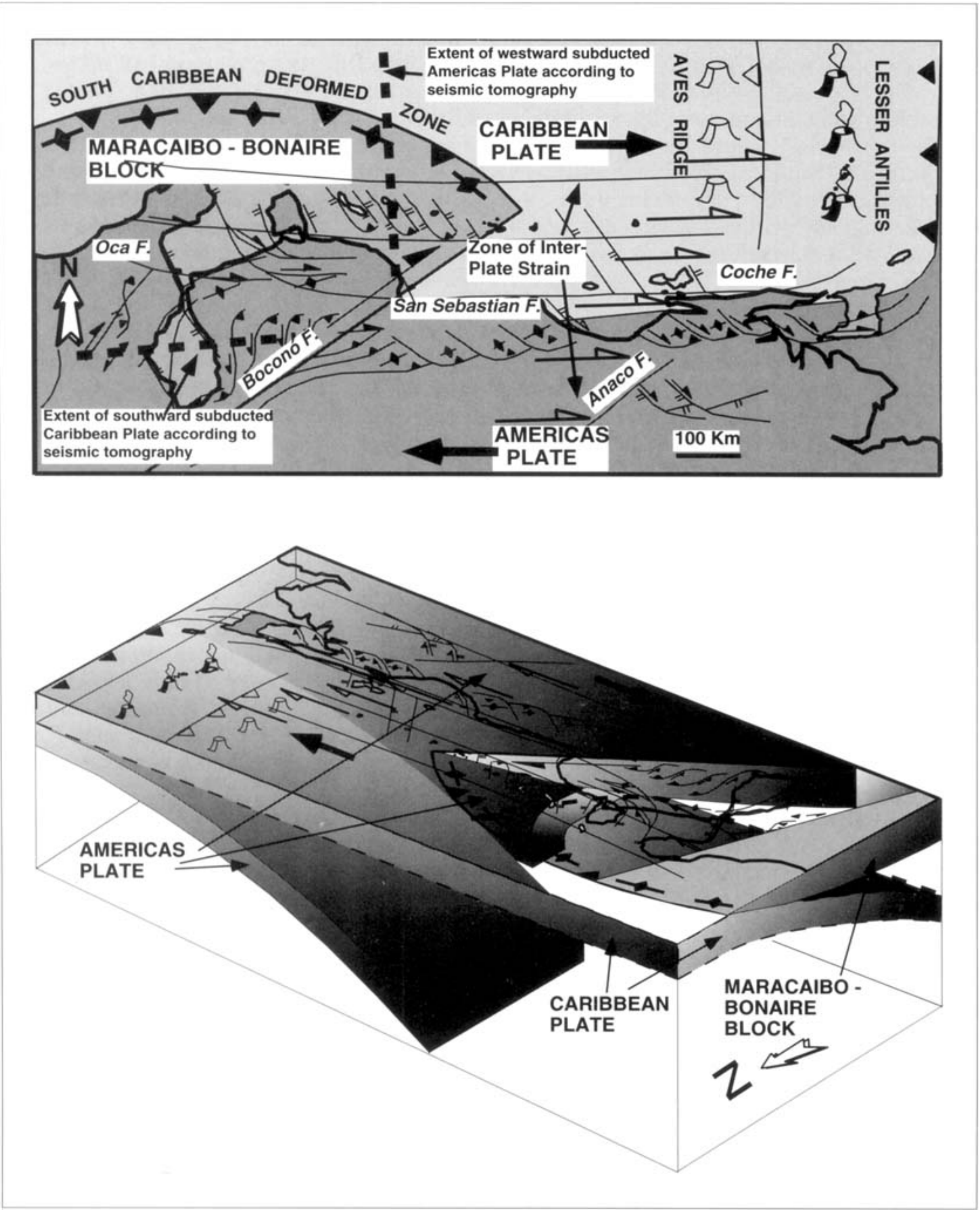

Fig. 5. Tectonic synthesis of the interaction between the Caribbean and northern South America. The plan view shows the Lesser Antillean Island Arc in the east, where the Americas Plate is being thrust below the Caribbean Plate. Dextral transpression between the Caribbean Plate and South America is distributed over a zone of strike-slip faults some 250-km wide. In the west, the delaminated Maracaibo Block overrides the Caribbean Plate, which plunges to the south. The block diagram attempts to illustrate these relationships in three dimensions. Its top surface shows the same features as the plan view.

Ridge and the modern Orinoco fan mask the trench's expression. Gravity data indicate that the depression extends via Trinidad into eastern Venezuela as far as longitude 65°W. Here, a thickness of up to 40,000 ft of sediments is reflected by a Bouguer gravity low of up to -200 mgal (Fig. 6) centered over the Amacuro Delta - southern Gulf of Paria area. This is the largest known continental negative gravity anomaly at sea level in the World.

The Caribbean — South America boundary is generally interpreted as a broad zone, up to 250 km wide (Jordan, 1975; Mann *et al.*, 1990). Defined by northern and southern limits of associated deformation, the boundary has two main elements for the purposes of this paper. East of long. 65°W, the straight, east-west trending northern margin of the continental shelf lies close to lat. 12°N (Figs. 2 and 5). To the south, plate-related deformation extends to around 9° 30'N. West of long. 65°W, the northward-convex margin extends as far as 13.5°N, while the southern limit of deformation continues at around 9° 30'N.

Bosch and Rodriguez (1992) estimated the relative motion between the Caribbean and South America to involve 1.5 cm/y of dextral displacement and 0.7 cm/y of convergence. Seismicity is focussed below the Caribbean Mountains (Coastal and Interior Ranges: Fig.2) in a 100-km wide zone from roughly 10km north of the coastline to the southern boundary of the mountains. It is distributed across the entire crust and is associated with modern active faults. These authors interpret relative plate movements to be accommodated by an east-west, flower-like triangular zone. The continental margin is one of accretion, in which Caribbean crust and/or volcanic arc remnants, similar to the onshore Loma de Hierro and Villa de Cura nappes, are interspersed with continental crust.

In the west, the Pacific Ocean Nazca Plate (Figs. 1 and 4) is moving N70°E relative to NW South America at a rate of around 10 cm/y (N30°E up to 10 Ma) (Daly, 1989). Oblique plate convergence consequently governs this part of the continent. The resultant stress is partitioned into compression and shear, generating transpression, inversion and strike-slip strain. This complex area here termed the Bolivar Block (Fig. 4) is moving NE along dextral fault systems distributed through the Eastern and Central Cordillera of Ecuador and Colombia and the Venezuelan Andes. Conjugate sinistral faults, such as the Santa Marta - Bucaramanga Fault, combine with the dextral faults to result in northward extrusion of triangular elements within the area.

This has important consequences for western Venezuela. West of long. 65°W, the northern part of the Bolivar Block (the Maracaibo-Bonaire Block, Fig. 5) is delaminating (Coney, 1989) from underlying crust and transgressing the plate boundary, driving the South Caribbean Deformed Zone/Curaçao Ridge compressional front to the north and suffering major internal pull-apart further south (Gulf of Venezuela and Lake Maracaibo Basins, Fig. 2). The dynamic movement is reflected by the large positive gravity anomaly (>+150 mgal) associated with the 5,800m high Sierra Nevada de Santa Marta (Figs. 4 and 6). Ladd *et al.* (1984) observed the plunge of the Caribbean below the Curaçao Ridge on seismic reflection data. Hilst (1990) used seismic tomography to show an inclined velocity anomaly dipping at 10-15° below the Maracaibo Block to a depth of around 280 km some 700 km south of the Curaçao Trench. Note that this understanding differs significantly from the commonly held idea that the Boconó Fault marks the boundary between the Caribbean and South American Plates (e. g. Tribovillard and Stephan, 1994).

The above discussion provides a snapshot of the deformation that is progressively invading the continent. Past displacement was probably focussed on fault systems further west; in the future, it will be associated with systems further east. While the Boconó Fault seems to be the main eastern locus of this northward translation in present-day Venezuela, the strain may be in the process of migrating to a more easterly system, such as the Caño Limon Fault (28:Fig. 7). If the current stress field persists it will generate a further Andean range across the present-day Barinas-Apure Basin to the western margin of the Cariaco Trough.

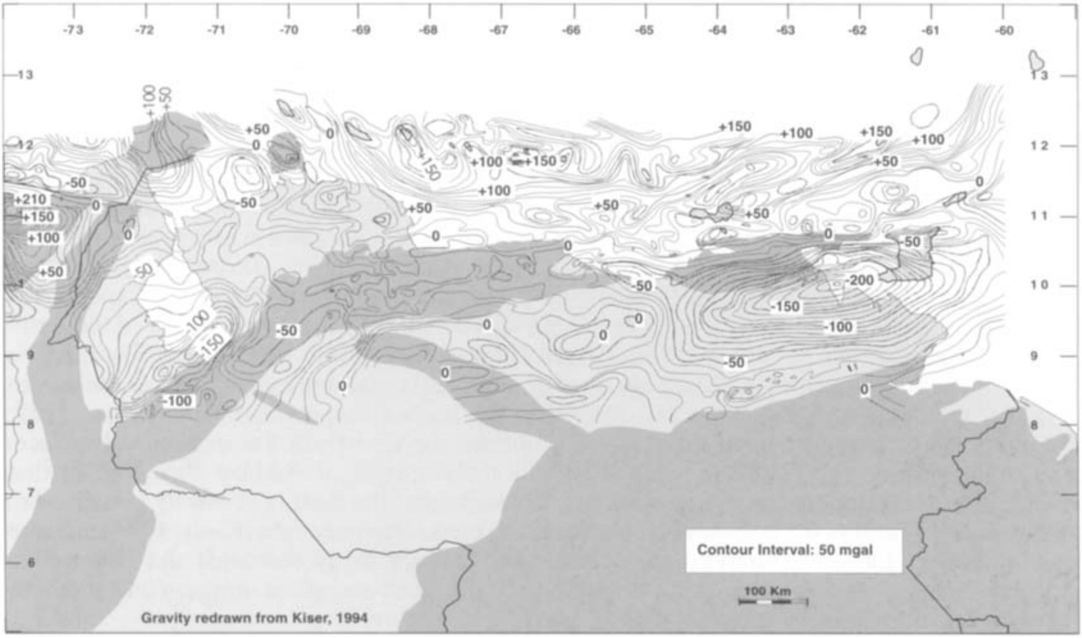

Fig. 6. Bouguer gravity anomalies over the northern part of Venezuela (redrawn from Kiser, 1994). The dynamic plate interactions are reflected by the large negative anomaly (up to –200 mgal) below the Maturín-Gulf of Paria area (Fig. 2), where more than 12 km of sediments lie below sea-level, and by the large positive anomaly (> 200 mgal) over the Sierra Nevada de Santa Marta (Fig. 4), which reaches 5,800 m above sea-level. Note also the negative anomalies associated with the North Andean Foredeep (Fig. 12) and between the Netherlands and Venezuelan Islands. East-west trends in the contours, especially in the eastern half of the figure, are interpreted to reflect major strike-slip faults (Fig. 7).

PRESENT-DAY STRUCTURES IN VENEZUELA

General structural configuration

The present-day structural configuration (Figs. 2 and 7) is of late Andean (Oligocene-Recent) or Guarao age. It reflects the interaction between the Caribbean and South American Plates in the north, and additionally, between these elements and the Nazca Plate in the NW (Fig. 4). Modern structures are increasingly recognized to be reactivated older structures which have been inverted or extended. Mora *et al.* (1993) described the importance of N50°E and N40°W lineaments in Venezuela, relating them to a Pre-Mesozoic rectangular network of crustal discontinuities. There is growing understanding of their importance in the shaping of the Jurassic-Early Cretaceous rift-drift passive margin.

The Precambrian Guayana Shield of Venezuela is rimmed by a series of foreland basins that deepen towards the limiting uplifts of the Andean system (Mérida Andes, Coastal and Interior Ranges, Fig. 2). These basins contain Cretaceous and younger sediments. The outcropping El Baúl Uplift, composed of Palaeozoic igneous-metamorphic and Triassic-

Jurassic volcanic rocks, subdivides this system into the Barinas-Apure Basin in the west and the Eastern Venezuela Basin to the east. Near the Venezuelan-Colombian border, the subsurface Arauca Arch separates the Barinas-Apure Basin from the Llanos Basin. The Eastern Venezuela Basin is subdivided by the Anaco Fault into the Guárico Sub-basin in the west and Maturín Sub-basin in the east, the latter extending eastwards across the Gulf of Paria to the Southern Basin of Trinidad, and thence to the offshore Columbus Basin.

The Maracaibo Basin, in the NW, is an intermontane basin bounded by the Perijá, Motilones and Mérida transpressional uplifts (Precambrian - Palaeozoic igneous and metamorphic and Jurassic–Cretaceous sedimentary rocks). These uplifts are associated with major strike-slip fault systems (the sinistral Santa Marta-Bucaramanga Fault and the dextral Perijá-El Tigre Fault, respectively (Figs. 4 and 7) associated with the northward tectonic escape of the Maracaibo Block. The east-west trending Oca Fault defines the northern margin of the basin which deepens to the SE towards the Mérida Andes. Here, the North Andean Foredeep is marked by a negative Bouguer anomaly of more than 150 mgal that extends below the Andes (Fig. 6), indicating that the latter are overriding the basin (Hospers and Van Wijnan, 1959; Bonini, 1978). Transpressional uplift associated with the Oca Fault has marked subsurface, but minor surface expression (e.g. Toas Island, at the mouth of Tablazo Bay, Fig. 2) that separates the Maracaibo Basin from the Gulf of Venezuela. The fault is generally perceived to step to the right across the Falcón area. However, Bouguer anomaly data (Kiser, 1994) indicate continuation of the deeper trend directly eastward, south of the Netherlands and Venezuelan Antilles, with parallel trends north of the islands, at the coast and at the northern and southern margins of the Eastern Venezuela Basin (Fig. 6).

The east-west trending, sharply defined, fault-bounded, linear Coastal and Northern Ranges of Central and Eastern Venezuela and Trinidad (Fig. 5) are an Oligocene-Recent, surface expression of transpressive dextral relative movements between the Caribbean and South America. They comprise oceanic rocks (serpentinites, amphibolites with lenses of eclogite and blueschist), metamorphosed continental margin deposits (mica and graphite schist, quartzite, marble) and Lower Palaeozoic granites. Sedimentary equivalents of the metamorphosed margin deposits also are present (e.g. Rodriguez, 1968). The metamorphic grade and age (Oligocene – Miocene) of the Coastal and Northern ranges diminish to the east (Avé Lallement and Sisson, 1992; Speed, 1992; Weber, 1995; Avé Lallement, 1997). The uplift has suffered transtensional collapse below the Cariaco and Pária Basins in the east. The northern part of the Guajira Peninsula (located to the west of the Gulf of Venezuela: Fig. 2) is a northerly offset, western continuation of the Coastal Range. It has also been likened to the three cordilleras of Colombia (Alvarez, 1968). Large volumes of detrital serpentinite occur on the Peninsula (Lockwood, 1971).

The offshore area is poorly studied relative to the onshore. In the east, a fairly continuous platform, defined by the 200 m isobath (Fig. 2), runs from east of the Falcón Basin to Tobago and is punctuated by the islands of La Tortuga, Margarita and Tobago. Further north, in the west, a series of pull-apart basins separates the emergent highs of the Netherlands and Venezuelan Antilles (Aruba, Curaçao, Bonaire, Las Aves, Los Roques, la Orchila, Blanquilla). Further offshore to the west, the Curaçao Ridge or South Caribbean Deformed Zone is an accretionary sedimentary pile forming where the Caribbean Plate descends below the overriding, delaminated northern part of the Bolivar Block (Fig. 4). Just offshore in the west, the eastward-deepening Gulf of Venezuela is bounded by the Guajira and Paraguaná Peninsulas and the Falcón area. The peninsulas are uplifts that survived the pull-apart subsidence that affected adjacent areas (Gulf of Venezuela, La Vela Bay: Fig. 2). Shallow metamorphic basement lies between them and the mainland. A sand isthmus on the Coro Platform connects Paraguaná to the mainland but much of the area remains beneath the shallow Golfete de Coro. A similar situation obtains south of Guajira; but here young sediments largely cover the Sinamaica Platform and only a remnant lake survives near Sinamaica.

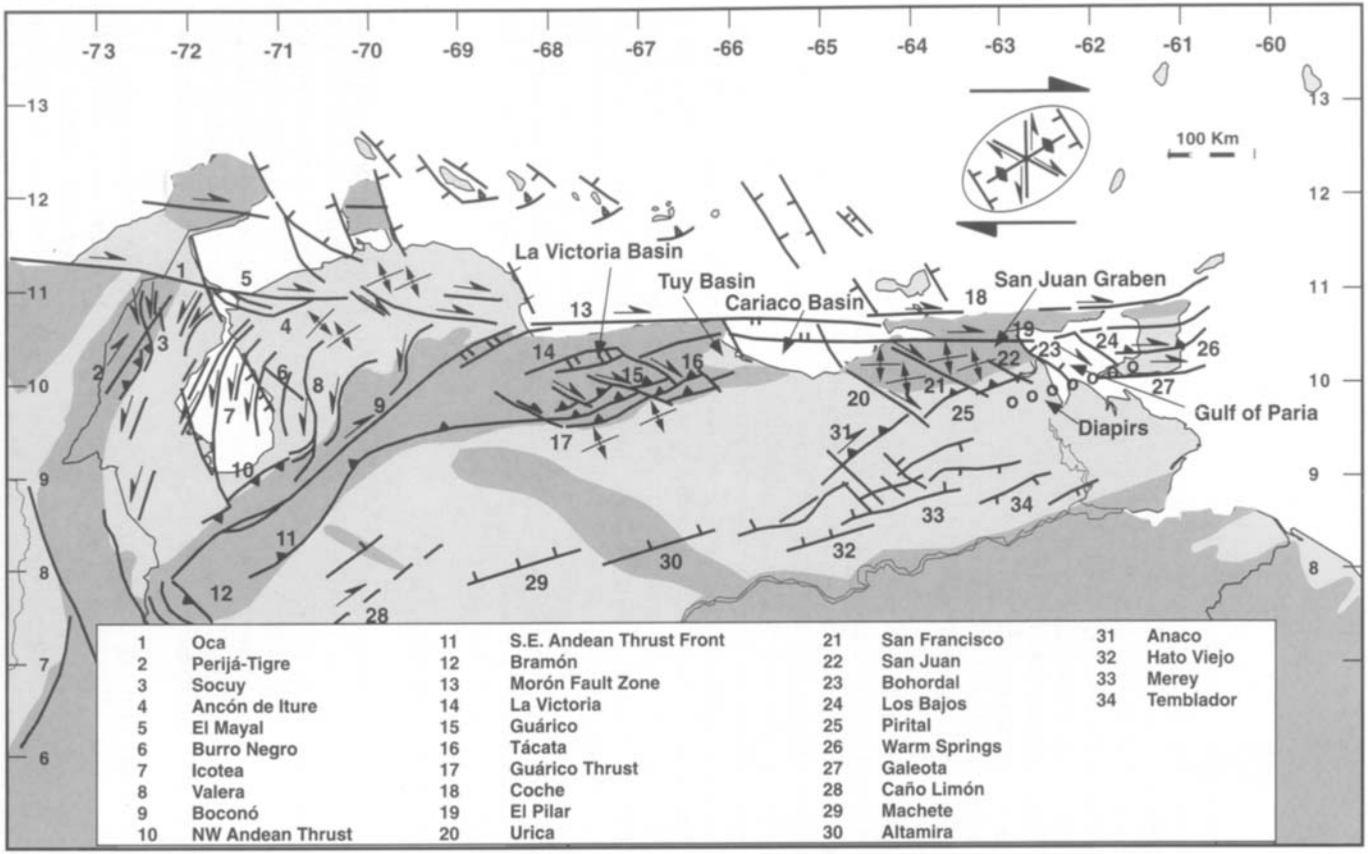

Fig. 7. The main fault systems of Venezuela. Dextral movement relative to the Caribbean Plate is reflected by the through-going, east-west Oca – Morón – El Pilar fault system (numbers 1, 13 and 19). The system steps to the right across the Falcón area (Fig. 2), the Cariaco Basin and the Gulf of Paria. Synthetic dextral faults form lateral ramps to folds and thrusts in the Interior Ranges of Eastern Venezuela (Fig. 2), providing traps in the frontal zone. In the west, the Maracaibo Block (Fig. 5) is dominated by N-S trending sinistral faults, antithetics to the Caribbean—South America interaction enhanced by northward movement of the Bolivar Block (Fig. 4). These faults control the distribution of many of the Maracaibo Basin oilfields. The foreland basins are characterized by conjugate, ENE- and WNW-trending normal faults systems, often antithetic to basement dip, activated by tectonic loading and flexuring.

The offshore pull-apart basins are of Eocene – Recent age, while the onshore Falcón Basin is an inverted Eocene-Oligocene-Miocene pull-apart; all reflect extensional stress generated by plate boundary movements. Similar pull-apart is apparent in the present-day outline of Lake Maracaibo.

Origins of structures

Many neotectonic faults in Venezuela (Fig. 7) may be explained as the strain response to dextral, east-west relative plate movements between the Caribbean and northern South America (Fig. 4). Where these movements are focussed along the Coastal Ranges, the structures include east-west trending dextral faults (Oca, Morón, La Victoria, Coche, El Pilar faults: 1, 13, 14, 19 and 18, Fig. 7). To the south of the Coastal or Northern Range, the Interior Ranges (Fig. 2) are thrust/fold belts verging to the SE, overriding and invading the Eastern Venezuela foreland basin. Palaeocene – Eocene foreland basin flysch and wildflysch and nappes of oceanic material and flysch crop out in the western (Guárico) Interior Range, while mainly Cretaceous sediments crop out in the eastern (Maturín) part. Since uplift of these ranges is progressing from west to east, James (1997) proposed that the Guárico flysch/wildflysch that crops out in the west remains buried beneath the Cretaceous units of the Interior Range north of the Maturín Sub-basin.

A series of synthetic dextral faults cross this system trending from NW to SE, forming lateral ramps to (and transforming into) ENE-trending folds and thrusts. Pull-apart basins have developed where the synthetics leave the east-west master faults. Some of these are major features (La Victoria Basin, Tuy Basin, Cariaco Basin, San Juan Graben, Gulf of Paria: Fig, 7); others are comparatively minor. The same structures are present in the offshore uplifts (peninsulas and islands, which are built of rocks similar to the Guárico Interior Range) suggesting that they also are controlled by a major, east-west dextral fault (James, 1997).

In the NW of Venezuela, this system is overprinted by strain generated by the NE movement of the Bolívar Block (Figs. 4 and 5). The main features include NE-trending dextral transpression, expressed by inverted Mesozoic/Palaeozoic elements of the Perijá and Mérida Andes (Fig. 2), and by enhanced activity of antithetic sinistral elements such as the Icotea and Valera faults (7, 8: Fig. 6). The relationship between Mesozoic metamorphic rocks in the northern, Coastal Ranges and folded and thrusted Mesozoic sedimentary rocks in the Serranía del Interior to the south is repeated on the Guajira Peninsula, indicating the offset of the Bolivar Terrane relative to central and eastern Venezuela.

Structures relating to the hydrocarbon habitat

Traps in the fold-and-thrust belt at the southern margin of the Interior Range include stratigraphic pinch-out of reservoir intervals (e.g. *Quiriquire* oilfield, Fig. 3) and thrust-related folds at shallow (*Quiamare* field) and deep (*Furrial* field) levels. A diapiric trend running from the Maturín sub-basin across the Gulf of Paria to the Southern Range of Trinidad (Fig. 7) is the result of compression and high pore pressures. At *Pedernales* and several Trinidadian fields, oil is stratigraphically trapped in sandstones pinching-out on the flanks of these structures. In the sub-surface, contraction is observed further south in inverted structures (*Las Piedritas*).

NE-SW trending normal faults are common above and parallel to the southern hinge line of the Eastern Venezuela Basin (Fig. 7). A second set of normal faults in the same area trends NW-SE, parallel to the extensional strain resulting from the regional east-west dextral stress field. These normal fault systems form a conjugate set that influenced Tertiary sedimentation and resulted in combined structural/stratigraphic traps. They form the main traps in the northern part of the Orinoco Heavy Oil Belt (Funés, 1985) and in the *Oficina* area (Figs. 3 and 7). Normal faults are also important in a similar structural setting in the *Silvestre-Sinco* fields of the Barinas-Apure Basin. Many of these normal faults are antithetic to basin depocentres. In the central part of the Colombian Llanos Basin, where similar faults provide one of the main oil plays, fault offset is commonly greater at shallower levels, indicating oblique slip (McCollough and Carver, 1992). Alternatively or additionally, they may be related to flexural extension generated by approaching thrust fronts.

The NE-trending Anaco Fault (31, Fig. 6) appears to be the inverted eastern margin of the Jurassic Espino Graben. *En-échelon* folds associated with this fault provide traps for a series of oilfields in the *Anaco* complex (Fig. 3).

The Maracaibo Basin and the southern part of the Falcón are internally deformed by a system of faults trending NE to north-south to NW, from west to east in the basin (Fig. 7). Some align with the margins of Jurassic grabens and are Mesozoic extensional faults inverted during Andean compression. These faults have played a most important role in the hydrocarbon habitat of the Maracaibo Basin, influencing sedimentation, erosion, structuration, fracture porosity and sealing. Thus, many of the basin's oilfields are associated with them (compare the pattern of oilfields in Fig. 3 with the fault pattern in Fig. 7). The faults splay to the south and deformation dies away so that the Catatumbo and Bobures areas (Fig. 2) are only subtly deformed. Deformation picks up again in the SW and SE corners of the basin.

Early studies of such faults in the *La Paz* and *Lama* oilfields determined sinistral strike-slip on the evidence of offset isopachs and facies; thus, Krause (1971) estimated some 16km of sinistral displacement on the Icotea Fault (7, Fig. 7). More recent literature denies strike-slip motion, but instead focuses upon disharmonic contraction ramping up from basement/ Cretaceous levels to the Tertiary section via Upper Cretaceous shales (e.g. Roberto *et al.*, 1990; Audemard, 1991). This disharmonic contraction is supposedly a newly-recognized feature, but in fact, company reports showed eastward- and westward-verging thrusts in the Palaeocene and younger strata above *décollements* within the Colón shales in the *Río de Oro* and *Tarra* oilfields as long ago as the 1950s and 1960s.

For this paper, the regional context of the faults strongly suggests sinistral oblique slip. The faults reflect antithetic (sinistral) strain along the Caribbean - South America plate boundary zone (Fig. 4). While they are present to a relatively minor degree in the central and eastern parts of the country, they form a major system that pervades the Bolívar Block NW of the Mérida Andes. They range from the giant, 700-km long Santa Marta-Bucaramanga Fault, through the Icotea Fault (at least 180-km long), the Valera Fault (120-km long), to faults that are around 15 km in length (Figs 4 and 7). The faults are typically S-shaped: to the north and south, they swing to ENE-contractional structures, conforming to the strain resulting from plate boundary translation. Their prevalence in the Bolívar Block is a function of the convergent interaction between this plate and the Caribbean Plate (James, 1985, 1990). While their net displacement through time is sinistral, they have acted both as normal and inverse faults during different episodes of extension and compression.

Studies of seismicity, neotectonics and strain rates

Continuing studies of tectonic activity in Venezuela, ranging from modern seismicity and neotectonics to subsurface data, are resulting in refinement of the distribution and ages of structural elements. Beltrán (1993, 1994) presented a neotectonic map of Venezuela synthesizing the work carried out since 1979. Studies of seismicity indicate rates and locations of strain, but these use data mainly collected over the last thirty years and contrast with neotectonic estimates of return periods of many thousands of years. Consequently, some authors deny that significant activity occurs along some major faults. For example, the Oca Fault has remained seismically inactive during the interval 1910-1998, leading many geologists to deny its existance (Audemard, *pers. comm.*). Likewise, the El Pilar Fault was thought by some geologists to be inactive; yet in 1929 the town of Cumana was destroyed by an earthquake (Beltrán *et al.*, 1996), and in July, 1997, the fault suffered a magnitude 6.7 earthquake, resulting in the deaths of more than 80 people and generating 25 cm dextral offset along an initial scar of 25 km (Funvisis, 1997).

Estimates of dextral displacement on the Oca Fault (1: Fig. 7) range from 25 km (Aleman, Lugo, *pers. comm.*) to 50 km (Erlich and Barrett, 1990) or 90 km (Kellogg and Bonini, 1982). T. Villamil (*pers. comm.*) determined a minimum offset of 65–70 km between schists of the Santa Marta massif and similar rocks encountered by well *Perico-1* on the Sinamaica Platform. Where the fault crosses the Falcón area, Audemard (1991) estimated 100km of dextral displacement.

Estimates of dextral displacement on the east-west El Pilar Fault (19: Fig. 7) range from 10-15 km (Metz, 1968) to 475 km (Alberding, 1957). Some authors favour normal displacement (Ball *et al.*, 1971); others reverse movement (Vignali, 1979; Gonzalez de Juana, 1980). Vierbuchan (1984) proposed 150-300km of possible dextral displacement and interpreted a steep gravity gradient across the fault to indicate a steeply-dipping fault plane to a depth of around 5-10km and the presence of dense mafic crust north of the fault. Giraldo (1996) deduced that dextral displacement of some 150 km had occurred in the last 10-15 Ma, while Audemard and Giraldo (1997) concluded that this would be a maximum, and that a more likely figure is around 60 km.

Rosales (1972) estimated displacement along the San Francisco Fault (21: Fig. 7) at 18 to 25 km, based on offsets of correlated folds, and up to 30 km, based upon offset of facies and isopachs of the Cretaceous San Juan Formation.

The Pirital system (25, Fig. 7) is one of a family of thrust faults. Parnaud *et al.* (1992) proposed that the thrusting is out-of-sequence. The degree to which the Pirital thrust complex overrides the foreland basin remains uncalibrated despite concerted efforts to determine it by the application of seismic, magnetotelluric and potential field methods. Roure *et al.* (1994) reported good seismic reflections to 2–3 seconds and again at 6 seconds, north of the fault. Daal (1992) estimated 40 km of overthrusting on this fault. More interestingly, the amount of shortening estimated for the Serranía del Interior ranges from 50 km (Chevalier and Spano, 1996) to as much as 250 km (Bally *et al.*, 1995).

Rates of displacement along the Boconó Fault (9: Fig. 7), determined from the offset of Pleistocene moraines, are 0.3-1.4 cm/y (Schubert, 1983, Soulas, 1985). If these rates and amounts of displacement have been sustained since the Eocene, major offset must have occurred. Bellizia and Graterol (*pers. comm.*) determined 30-40 km of Plio-Quaternary displacement on this fault. Estimates of the amount of displacement range from a few kilometres (Sánchez *et al.*, 1994) to 300 km (James, 1990). Displacement along the fault becomes distributed over a system of faults south of Mérida (Singer *et al.*, 1993).

A fascinating aspect of Venezuela is the periodicity and diachroneity of structural deformation. Periodicity must reflect the interplay of the stress field with inherent structural weaknesses of the area (e. g., Mora *et al.*, 1993). Note, for example, that thrust sheets, bounded by dextral lateral ramps, in the Interior Ranges of the central and eastern parts of the country show an almost perfect amplitude consistency. The pattern is repeated in the Netherlands and Venezuelan Antillean Islands (Figs. 2 and 5), leading James (1997) to suggest that the latter are submarine equivalents of the Interior Ranges, rather than the island remains of an arc.

Diachroneity allows comparison between areas of early/advanced and late/incipient structural development and helps in the understanding of structural evolution. The Oligocene Guárico depocentre is inverting in the west while the Maturín–Columbus area is subsiding at the present day in the east. Thrusts and pull-apart basins currently forming east of Trinidad are indications of how similar features formed in the Guárico area during the Oligocene and in the Maturín area in the Miocene. They illustrate the interplay between structural growth and patterns of sedimentation.

PALAEOGEOGRAPHICAL AND SEDIMENTOLOGICAL DEVELOPMENT

Introduction

Figs. 8a, b, and c illustrate the stratigraphy of the Maracaibo, Maturín and Barinas-Apure Basins, respectively. The section of interest to the hydrocarbon geologist in Venezuela ranges in age from the Late Jurassic to the Late Tertiary. It rests upon Precambrian to Mesozoic, igneous or metamorphic basement. Where fractured, basement may also provide reservoirs (e.g. at the *La Paz* and *Mara* oilfields, Fig. 3). Venezuela's main source rocks, the Upper Cretaceous La Luna and Querecual Formations are discussed below; the main reservoirs (the Eocene Misoa and Miocene La Rosa sandstones in the Maracaibo Basin, and Oligo-Miocene Oficina and Oligocene Naricual Sandstone Formations in the Eastern Venezuela Basin) will be described in Part 2.

Figs. 9 to 13 are updated palaeogeographic maps originally presented by James and Rigby (1993). They involve two major elements of palinspastic reconstruction following models discussed by Krause and James (1990) and James (1985, 1990). The first restores the northward tectonic escape of the Maracaibo-Bonaire Block along the dextral Boconó Fault of the Mérida Andes and the sinistral Santa Marta-Bucaramanga Fault of Colombia (Fig. 4). This restoration assigns the dextral offset entirely to the Boconó Fault (note the offset grid values in the western part of the maps), although displacement probably involved other faults such as the Perijá-Tigre fault (2, Fig. 7). Restoration of around 300 km is based on an extrapolation of neotectonic rates of displacement back to the Eocene. It results in a simplified, roughly east-west distribution of metamorphosed Mesozoic rocks, Palaeocene-Eocene flysch basins and the arc material these contain, and hydrocarbon basins sourced by the La Luna Formation. Uplift of the Mérida Andes probably began in the Late Eocene, so Boconó Fault displacement appears in maps from the Oligocene onwards and is added at a constant rate.

The second element recognizes shortening resulting from the Late Cretaceous - Early Palaeogene convergence of the Caribbean and South American Plates, which probably totalled several hundreds of kilometres. Olistostromes within Paleocene-Eocene flysch basins and protoliths to metasediments (Figs. 11 and 14) in the Coastal and Northern ranges of Venezuela and Trinidad allow reconstruction of the Late Jurassic - middle Cretaceous passive margin lithologies that existed further north. In the following discussion and on the palaeogeographic maps, these allochthonous units are distinguished from the autochthonous elements to the south.

Four main tectono-sedimentary sequences provide a record of the four major phases of evolution of Venezuela from Mesozoic to Recent times: Triassic–Jurassic rifting; Early Cretaceous to Palaeocene transgression; Late Cretaceous–Early Tertiary convergence and foreland basin development; and Oligocene-Recent transpression, pull-apart basin development and deltaic progradation. These sequences are described in turn below:

The Triassic — Jurassic Syn-Rift Sequence

A series of NE-trending grabens developed within the Precambrian-Palaeozoic basement in response to NW-SE oriented extension (Figs. 1 and 9) generated by the separation of North America from Gondwana. They contain continental red beds and associated basalts, known as the La Quinta Formation (La Gé Group) in western Venezuela (Fig. 8a) and the Ipire and Espino Fms. in eastern Venezuela (Fig. 8b). Volcanic rocks are present in the Perijá and El Baúl Uplifts and are known from the subsurface (Altamira Basalt) in the Espino Graben. Thicknesses exceeding 2,000m and rapid facies variations reflect strong tectonic control on sedimentation (Gonzales de Juana, 1980). To date, only Jurassic rocks are known; the Trias seems to be unrecorded.

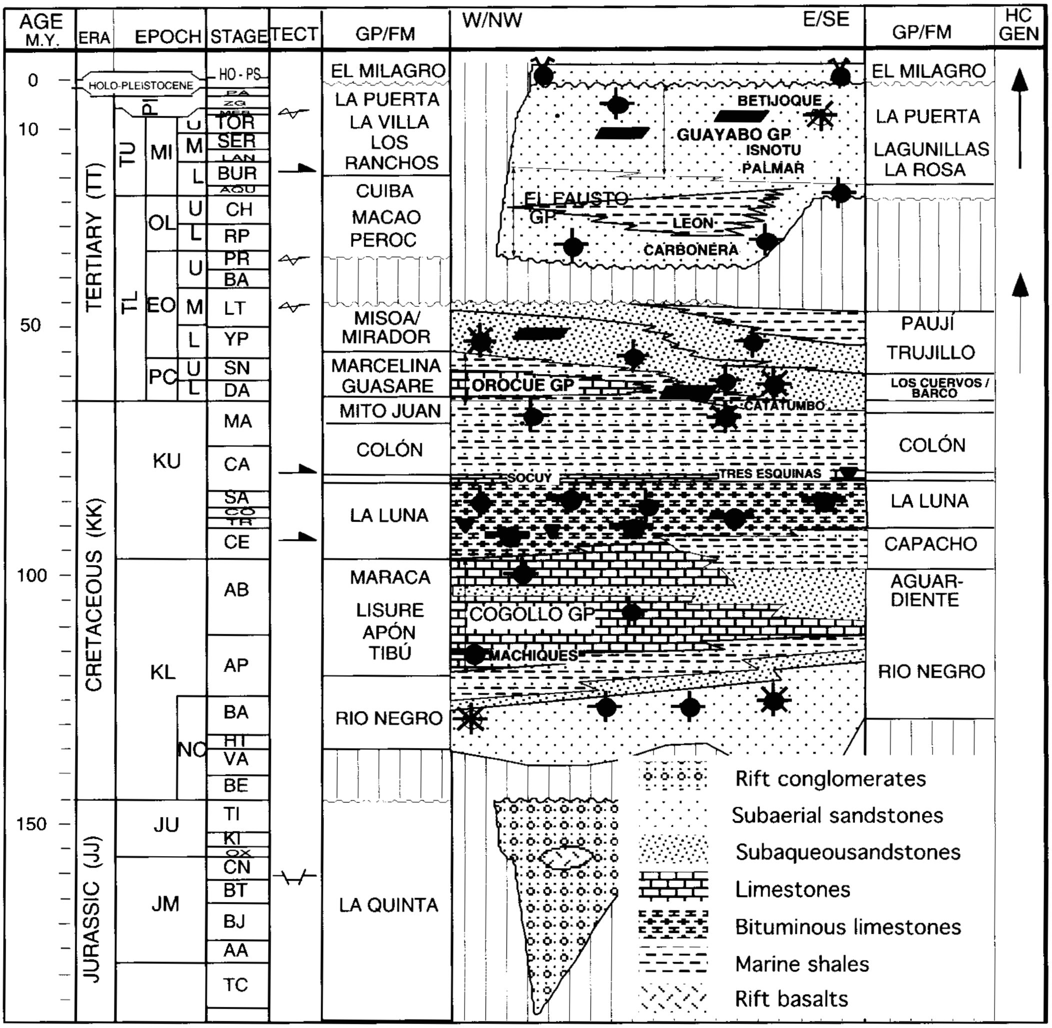

Fig. 8a. General stratigraphy of the Maracaibo Basin.

Three main grabens are known from the Maracaibo Platform: the Machiques Trough, the Urdaneta Trough and the Central Lake Trough (Fig. 9) (although Sutton (1946) assigned the Machiques Trough to the Perijá area). The Mérida Andes (Uribante-Barquisimento Trough) and the Perijá Range represent inverted troughs (Renz, 1977; Pümpin, 1978; Audemard, 1991). Other Triassic-Jurassic grabens are known from the subsurface of the Barinas-Apure and Eastern Venezuela Basins. These also contain Cambrian and Carboniferous sediments. The Apure-Mantecal and San Fernando grabens (Portilla and Osuna, 1991) lie below the SE flank of the Barinas-Apure Basin. The latter appears to step eastwards to link with the Espino Graben of the Eastern Venezuela Basin. Here, the graben trends NE towards the western end

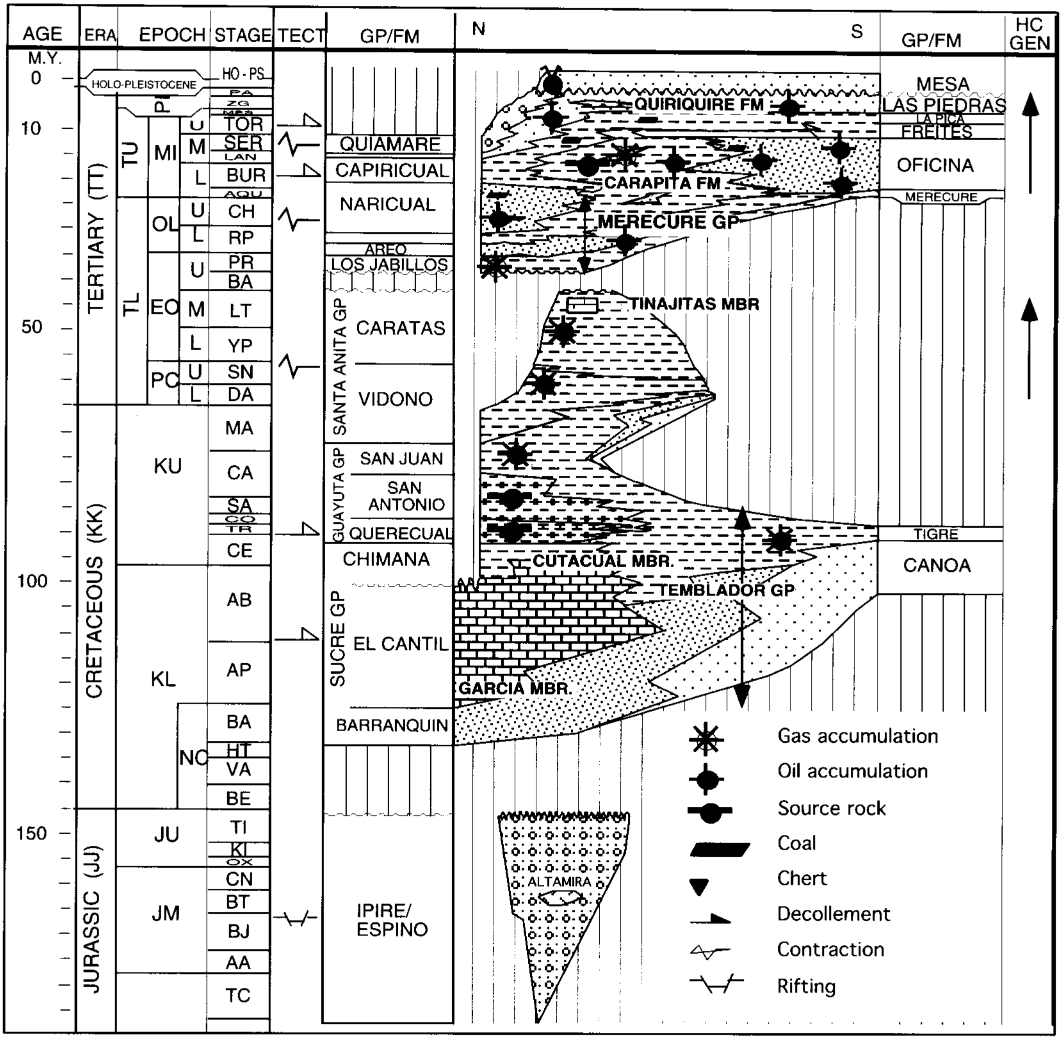

Fig. 8b. General stratigraphy of the Maturín Basin.

of the Serranía del Interior where some authors postulate its continuation. A branch of the graben continues northwards through northern Anzoategui towards the southern shore of the Cariaco Trough (El Hatillo area, Fig. 9) (Fernández and Passalacqua, 1990).

Allochthonous and shortened, mainly metamorphosed Jurassic rocks indicate that a passive margin existed along the northern edge of South America in the Triassic-Jurassic (Fig. 9). The Uquire and Tunapui Formations of the Araya-Paria Peninsula and equivalent units in the northern ranges in Trinidad are characterized by graphitic slates and schists and black marbles that suggest protoliths consisting of organic-rich shales and limestones that originally lay further north. Graphitic quartzites may be the remains of palaeo-accumulations.

The Early Cretaceous to Palaeocene Trangressive Sequence, and Early–Middle Eocene deltaic progradation

From the Early to the early-Late Cretaceous (Turonian-Coniacian), a marine transgression driven by Cretaceous eustatic sea-level rise progressed southwards across the passive margin, culminating in the Cenomanian-Turonian highstand (Fig. 10). The passive margin trended roughly east-west across eastern Venezuela while in the west its trend was SW-NE. The change in orientation occurred along a zone later activated as the dextral Boconó Fault system, a zone that influenced sedimentation through much of the Late Mesozoic-Tertiary. The platform seems to have been controlled by a conjugate system of NE- and NW-trending faults that played major roles in determining later sedimentary facies, thicknesses and consequent structuration.

Barremian

Sedimentation over the Maracaibo Platform area commenced in the Barremian with deposition of regional thin, red, continental sandstones of the Río Negro Formation (Fig. 8a) while continued fault activity in the Machiques, Uribante and Barquisimento Troughs accommodated several thousand metres of Neocomian to Barremian arkosic continental sandstones and minor marine shales. The thicker Rio Negro and Aguardiente Fms. of the Mérida Andes (Fig. 8a) indicate more active subsidence in this area also. Bucher (1952) noted that the (allochthonous) metamorphic Las Brisas Formation of the Coastal Range, which includes marbles and limestones with Jurassic-Cretaceous marine fossils, can be correlated with the Tomón Formation (an obsolete term for Rio Negro Formation). This basal unit rests upon the gneissic Sebastopol complex. Its metamorphic grade increases to the north, where it becomes graphitic. Its Upper (Zenda) limestone member compares with the "Upper Tomón" where the latter grades into the Cogollo limestones. The Peña de Mora Formation, further north, grades to a garnet-muscovite schist, with marble lenses in the upper part, that may correlate with the Las Brisas (Dengo, 1953). Further west in the same range, the correlative Los Cristales Group includes the Nirgua, Aroa and Mamay Fms. composed of low-grade crystalline limestones, marble, schists and amphibolites with an upward increasing graphitic content.

Aptian-Albian

In Aptian times, continued subsidence in the Machiques area of the Maracaibo region (Fig. 2) resulted in dysoxic conditions and the accumulation of bituminous shales and limestones. This potential source rock, the Machiques Member (Fig. 8a), also known as the 'false La Luna', is lithologically similar to the younger La Luna Formation. Limestones of the overlying Cogollo Group record open-marine conditions that followed. Albian bituminous limestones and shales also occur in the García Member and Chimana (Cutacual) Formation of the NE-most part of the Serranía del Interior in Eastern Venezuela (Fig. 8b) (Metz, 1968). They interfinger with the El Cantil Formation and appear to be transitional to the overlying Querecual Formation (Gonzalez de Juana *et al.*, 1980).

In eastern Venezuela (Fig. 8b), sedimentary rocks in the Interior Range show that the margin accommodated mainly continental and coastal clastics, with local limestones, of the Barranquín Formation throughout the Early Cretaceous. The overlying El Cantil limestones record the advent of open-marine conditions. Allochthonous units in the north indicate a mixed clastic/carbonate shelf with occasional rudist reefs and *Orbitolina* bioherms and include graphitic schists and marbles indicating the intermittent accumulation of organic-rich sediments along the Early Cretaceous Venezuelan passive margin (*see the section below on the original extent of Cretaceous source rocks).*

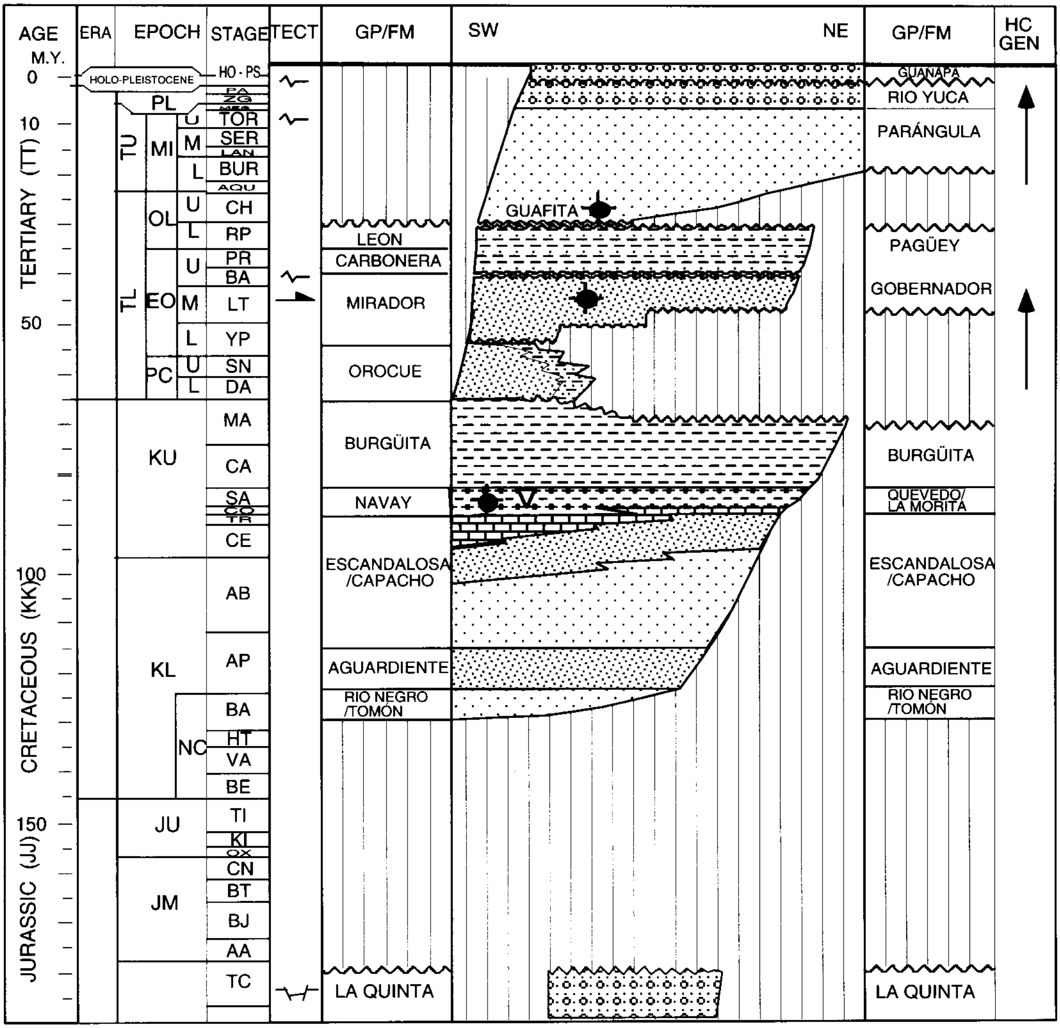

Fig. 8c. General stratigraphy of the Barinas-Apure Basin.

Cenomanian-Coniacian

During Cenomanian, Turonian and Coniacian times, the transgression reworked nutrients and resulted in low rates of clastic supply to the shelf during high sea level. Combined with the probable presence of an island-arc barrier to the north, this resulted in the accumulation of finely laminated, organic-rich limestones and shales across the entire Venezuelan margin and beyond (Fig. 10). The resulting La Luna, Querecual and Naparima Hill Formations of the Maracaibo Basin, Eastern Venezuela Basin and Trinidad, respectively, source the great majority of hydrocarbons in this province.

The dysoxic environment migrated southwards with the Cretaceous transgression. The oldest sediments assigned to the La Luna Formation in the Maracaibo Basin were deposited in the northern and central parts during Late Albian to Early Cenomanian times. Tribovillard and Stephan (1989) reported that in the Mérida Andes, the La Luna Fm. on the northern side of the Boconó Fault is Cenomanian-Santonian, while on the southern side it is Coniacian-Santonian. The equivalent unit in the Barinas-Apure Basin — the Navay Formation (shales and sandstones of the La Morita and Quevedo members: Fig. 8c) — is also Coniacian-Santonian in age. T. Villamil (*pers. comm.*, 1999) however, has recovered Turonian ammonites from the Navay Fm. and believes the base of the La Luna to be Turonian in the Mérida Andes. Craton-margin units, known from the sub-surface, are the thin, clastic rich Escandalosa–La Morita–Burgüita Fms. of western Venezuela, and the Canoa and Tigre Fms. of the Temblador Group in the east (Figs. 8c and 10).

Campanian - Maastrichtian

In Campanian and Maastrichtian times, an extensive, low energy but oxic, shallow-marine shelf characterized the Western Venezuela platform, on which the shales and occasional limestones and sandstones of the Colón Formation accumulated (Figs. 8a and c). This unit acts as a regional seal to the underlying Cretaceous and older reservoir intervals. It is followed by the Late Maastrichtian, shallow-marine, sandy and silty Mito Juan Formation. For these intervals, Van Andel (1958) postulated a western, Santa Marta source of greywackes and a SE, shield source of quartz.

In eastern Venezuela (Fig. 8b), the Querecual Formation is followed by the Coniacian to Maastrichtian San Antonio Formation (bituminous limestones, shales, cherts and sandstones), and the sandstones of the San Juan Formation. In the Maturín Sub-basin, the deep-marine, shaly Vidoño Formation and the overlying, deep- to shallow-marine Caratas Formations of the Santa Anita Group record Campanian-Maastrichtian regression, followed by a Palaeocene marine transgression (Fig. 8b). The Tinajitas Member is a reefal deposit locally developed in the upper part of the Caratas Formation, which has significance in signaling sand deposition in Eastern Venezuela during the Eocene. It has implications, discussed in Part 2 of this paper, for the early trapping of oil.

Latest Cretaceous - Palaeogene

From the latest Cretaceous – Palaeogene onwards, the western and eastern parts of Venezuela became more differentiated. The eastern area was strongly affected by convergence with the Caribbean, while the western area, still in its more southern location prior to translation along the Boconó Fault, remained somewhat protected.

In the Maracaibo area during the Palaeocene, the southward transgressive, shallow-marine, carbonate platform deposits of the Guasare Formation overstepped the Mito Juan Formation (Figs. 8a and 11). Subsequent reactivation of a hinterland to the SW resulted in NE-ward progradation of deltaic deposits of the Orocué Group across the Maracaibo area by the close of the Palaeocene. This influx continued until the Middle Eocene, resulting in the extensive continental deposits of the Mirador Formation in the SW and estuarine-paralic deposits of the Misoa Formation in the NE. Time-equivalent deltaic deposits of the Gobernador and Paguey Formations accumulated in the Barinas-Apure area (Fig. 8c).

A fault-controlled hingeline, roughly corresponding to the NE shoreline of Lake Maracaibo, bounded the platform in the NE (Fig. 11). Beyond this, deepwater sediments of the Trujillo and Pauji Formations accumulated in the area now inverted as the Sierra de Trujillo (Fig. 2). Deep burial of the La Luna Formation probably made this an early area of oil generation. The northernmost sections (seismic) of the Pauji Formation show progradation from the north

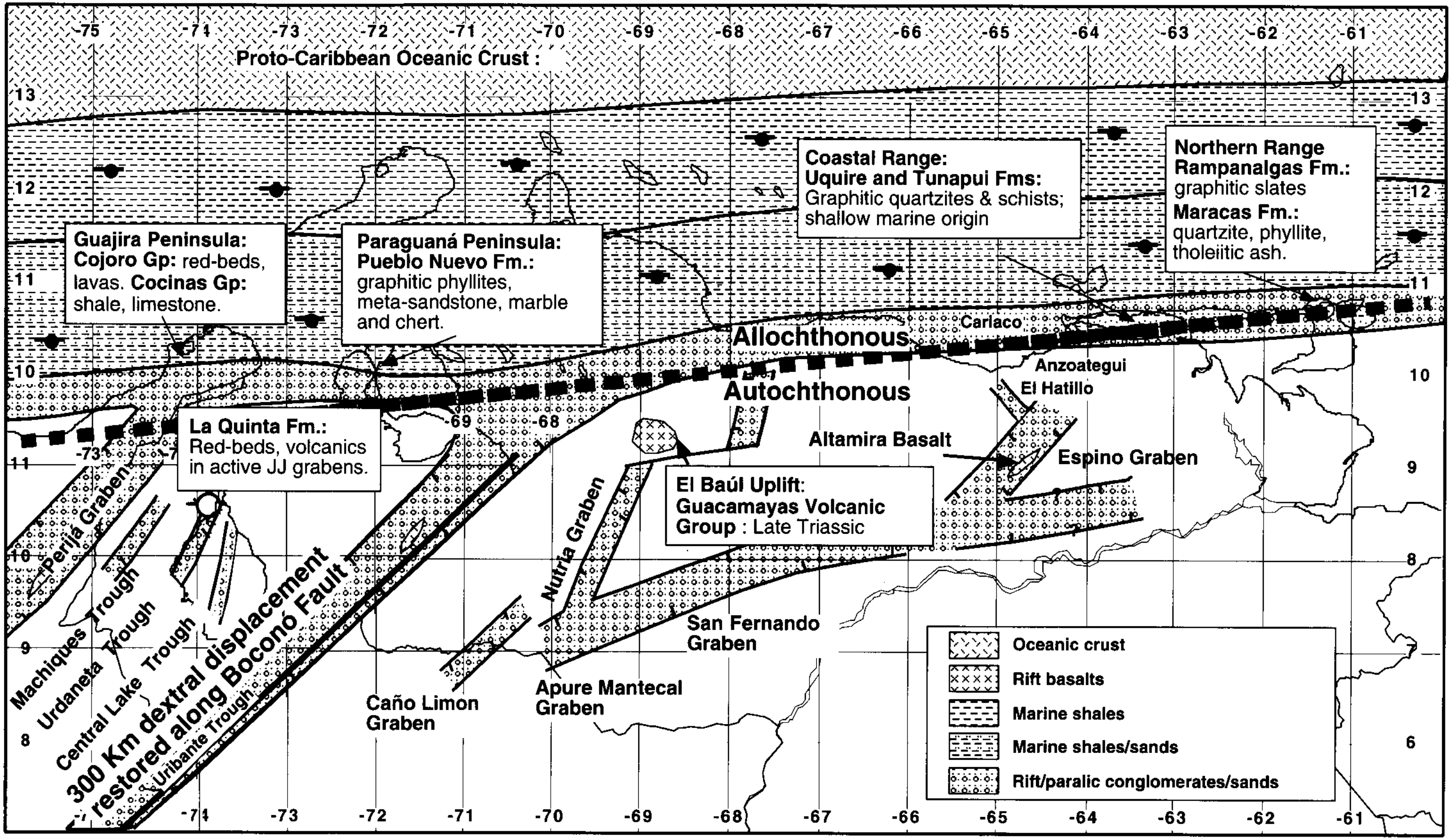

Fig. 9. Restored Jurassic palaeogeography of Venezuela. The restoration takes account of (i) 300 km of displacement of the Maracaibo Block (Fig. 5) along the Boconó Fault in the west; (ii) the recreation of protoliths to graphitic metamorphic rocks found today in the Coastal and Northern Ranges of Venezuela and Trinidad (Fig. 2); and (iii) the NW restoration of these rocks to their original, unshortened sites. Onshore, the NE- trending grabens formed in response to sinistral stresses generated by the NW drift of Northern America away from Gondwana; this area is dominated by continental sediments. The offshore region is dominated by bituminous sediments, from which the graphitic metamorphic rocks mentioned above are interpreted to be derived (see Fig. 14).

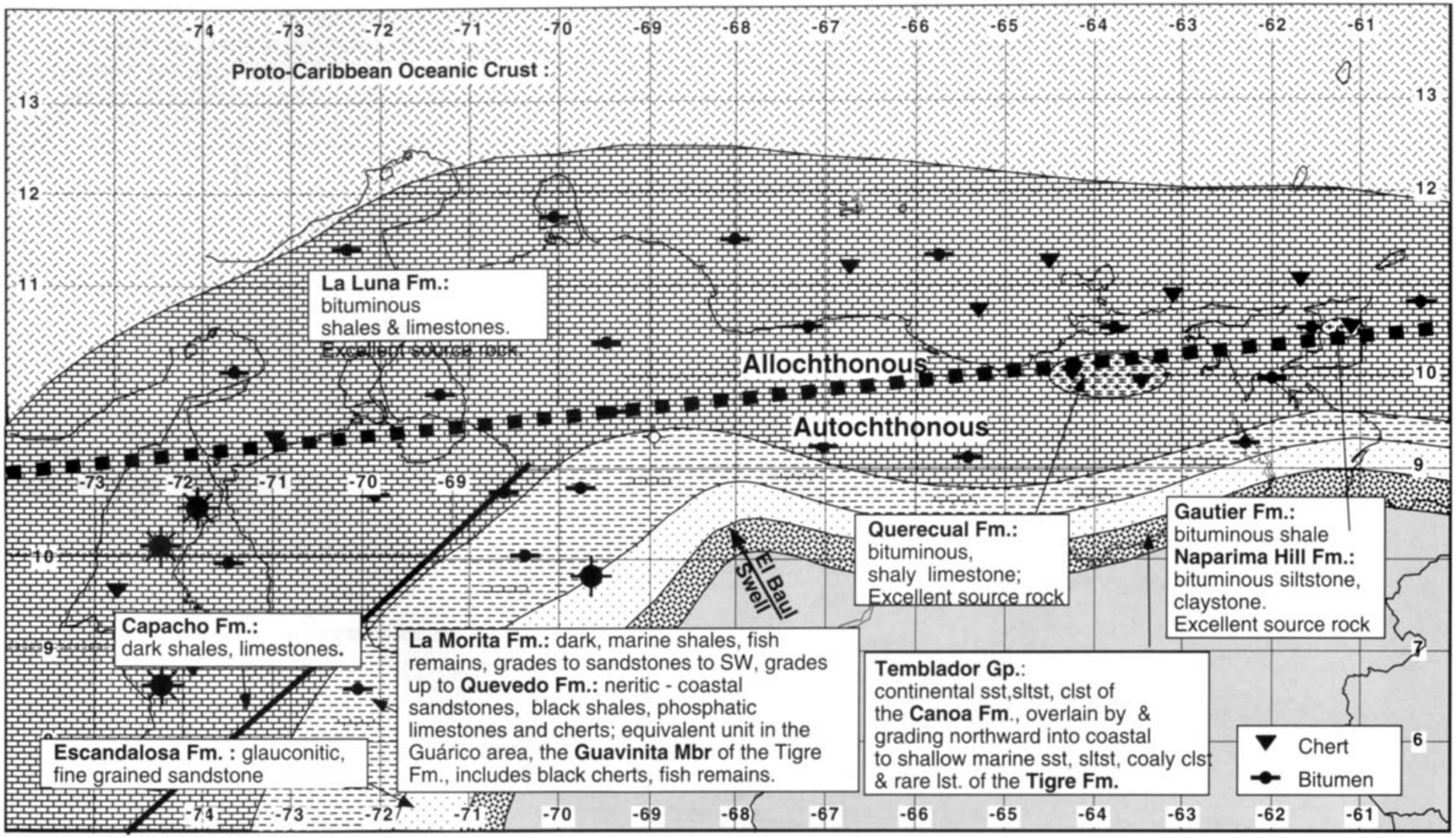

Fig. 10. Restored Late Cretaceous palaeogeography of Venezuela (see caption to Fig. 9 for details of restoration). Marine transgression leading to a Turonian high-stand resulted in the widespread deposition of source rocks which grade to clastic equivalents rimming the Guayana Shield. The wide distribution of bituminous sediments in the north is interpreted from the abundance of large olistoliths of such material, derived from the north, in regionally-developed flysch/wildflysch deposits (Fig. 11).

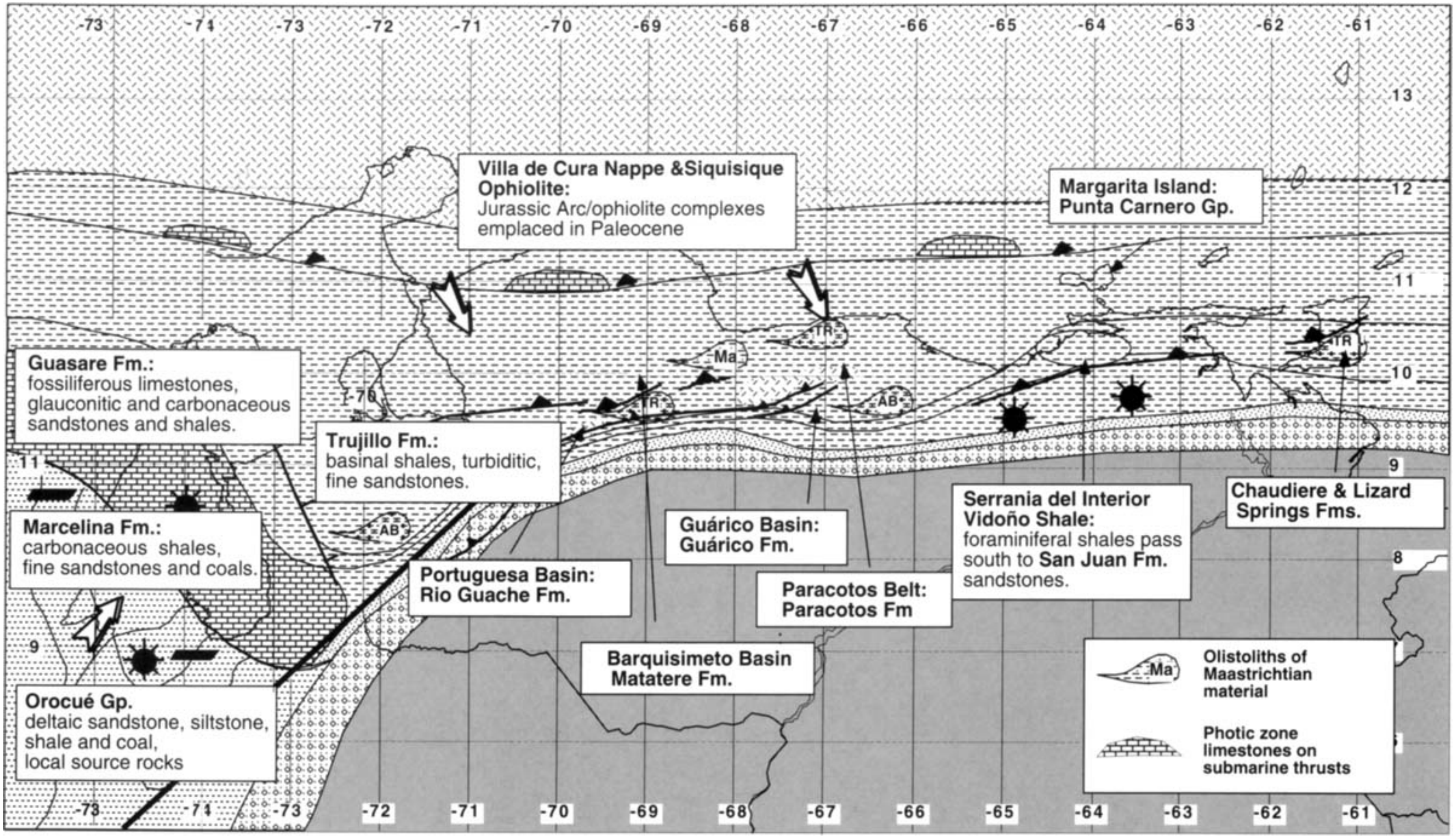

Fig. 11. Restored Palaeocene-Eocene palaeogeography of Venezuela (see caption to Fig. 9 for details of restoration). Culmination of the Late Cretaceous – Palaeogene Caribbean Orogeny resulted in regionally developed foredeeps filled with flysch/wildflsych in the north and important reservoir sandstones in the south. The foredeeps were overthrust by regional-scale nappes from the north.

(Lugo and Mann, 1995), indicating linkage to events affecting eastern Venezuela at this time. To the SE, these deposits grade to the calcareous Humocaro Formation of the Barbacoas Platform, located at the northern end of the Mérida Andes.

Late Cretaceous—Early Tertiary Convergent Margin and Foreland Basin Sequence

Convergence between South America and the Caribbean probably commenced as early as the Aptian-Albian in the far north. Throughout the Cretaceous, a southward-migrating active margin progressively consumed the passive margin. The resulting orogenesis culminated in the Late Eocene, which is marked by a regional unconformity. The Campanian-Maastrichtian to Paleocene-Middle Eocene sedimentary record of its later stages accumulated in a roughly east-west trending foreland basin along the entire Venezuela — Trinidad margin. This was bounded to the north by a zone of inversion and was characterized to the south by marine to continental clastic deposition in regressive sequence (Fig. 11). Palaeocene-Middle Eocene limestones formed on folded and thrusted structures that rose to the photic zone (Hunter, 1995). Erosion and gravity collapse in the north provided olistoliths and olistostromes to the adjacent foredeep basins in a southward recycling system that locally includes older units; thus the partially-metamorphosed Maastrichtian Barquisimeto Formation was reworked into the Palaeocene-Eocene Matatere flysch.

The detritus included Upper Jurassic limestones, Jurassic ophiolites (Villa de Cura Nappe Siquisique, Río Tocuyo and San Quintin), and Lower to Upper Cretaceous limestones and shales. The latter indicate the previously wider and more northerly extent of the La Luna/ Querecual facies *(this is discussed further below in the section on the original extent of Cretaceous source rocks).* The deposits occur (Fig.11) in the Portuguesa Basin (Río Guache Fm.), Barquisimeto Basin (Matatere Fm.), Guárico Basin (Guárico Fm.), on Margarita Island (Punta Carnero Group) and in the Central Ranges of Trinidad (the Chaudière and Lizard Springs Fms.). The interpretation of such disparate deposits remained problematic until their allochthonous origins were recognized around 1955 (see James, 1997, for a synopsis of this discussion). These deposits are not recorded from the Maturín Sub-basin although James *(op. cit.)* reasoned that they may be present beneath nappes of the Interior Range. Their regional distribution indicates the relatively synchronous culmination of the Late Cretaceous-Palaeogene orogeny across the whole of northern South America, and clearly differentiates this event from the subsequent, diachronous deformation associated with the Andean Orogeny.

It is interesting to speculate that deep burial of source rocks below these flysch basins probably caused an important early pulse of hydrocarbon generation (James, 1996).

Oligocene—Recent Transpressive Margin, Pull-Apart Basins and Progradation

A regional unconformity marks the climax of the convergent Guajiro Orogeny of the Late Eocene. After this, relative movements between the Caribbean and South American Plates became roughly east-west oriented and were characterized by transpressive, dextral strike-slip (Fig. 4).

Transpression along the Venezuelan margin generated the approximately east-west trending Coastal and Interior Ranges (see Avé Lallement, 1997, for a summary of the radiometric ages of rocks involved in the Guajiro and Guarao Orogenies). These ranges have migrated eastward through time from the Guárico area to a submarine setting east of Trinidad where they are forming at the present day (Figs. 12 and 13). They form the northern flank of a succession of N70°E-trending foreland basins (Fig. 2) that similarly migrated eastwards. The westernmost Guárico Sub-basin is now inverted along its western flank, while the youngest (the Columbus Basin) continues to subside, east of Trinidad. The foreland basins are invaded from the north by contraction associated with the Interior Ranges, generating subsurface thrusts, folds and diapirs.

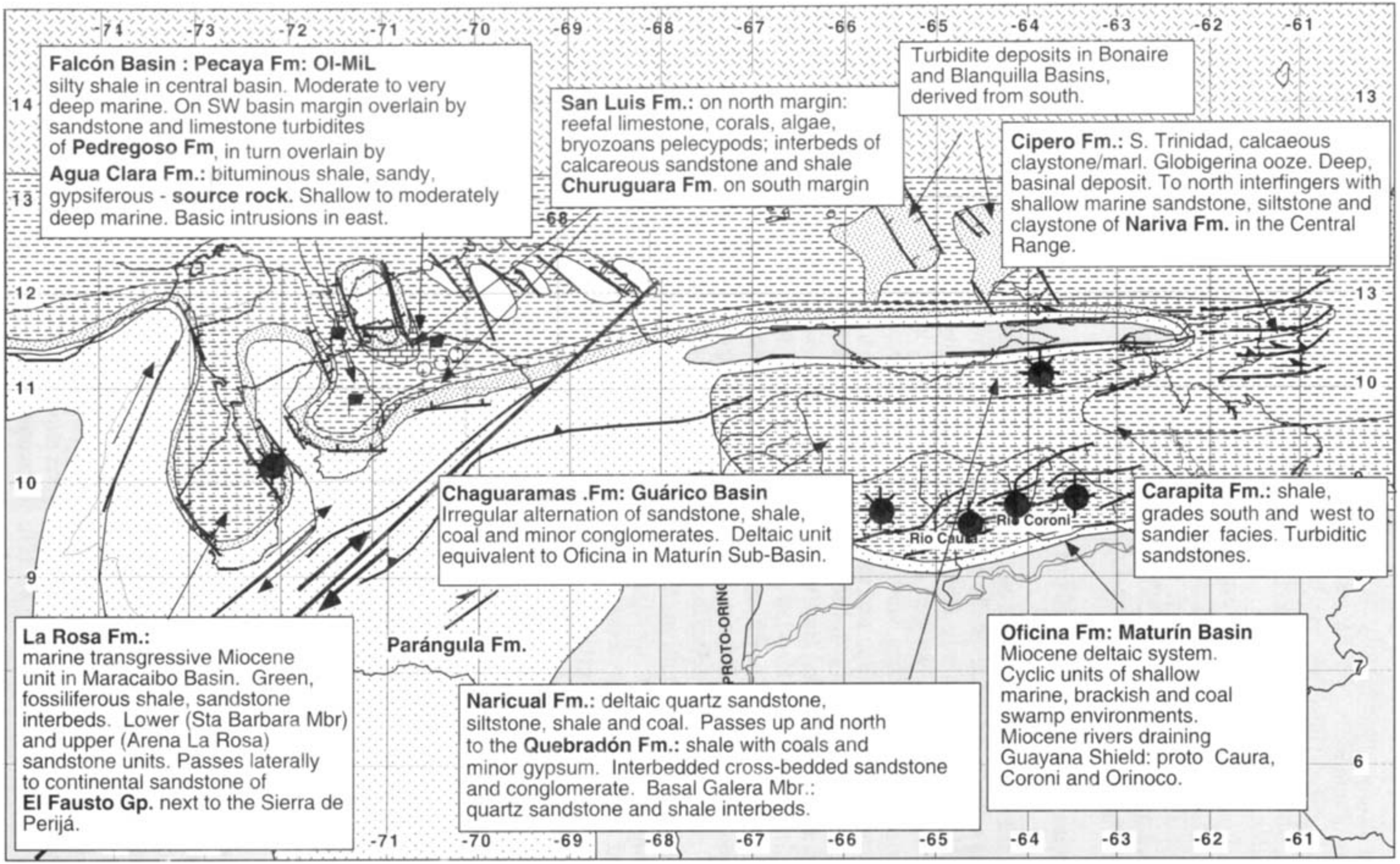

Fig. 12. Restored Oligo-Miocene palaeogeography of Venezuela. Restoration as in Fig. 9; but movement has commenced along the Boconó Fault (beginning in the Eocene), the rate being extrapolated from neotectonic studies. The Maracaibo Block (Fig. 5) in the west suffered major pull-apart deformation, accommodating a marine incursion. Eastward-migrating transpression in the east caused progressive uplift of the Northern and Interior Ranges (Fig. 2) and subsidence of the rapidly-subsiding foreland basin. Important reservoir sands of the Heavy Oil Belt (Fig. 3) accumulated along the northern flank of the Guayana Shield.

West of the Boconó Fault, the northward movement of the Maracaibo-Bonaire Block, driven by compression between the Nazca and South American Plates (Fig. 4) has complicated the tectonic and stratigraphic history. Where the Block rides above the Caribbean Plate major pull-apart basins bounded by NW-SE trending oblique-slip faults result from the dextral shear of the plate boundary. These are the Oligocene Falcón Basin (now inverted) the Gulf of Venezuela, La Vela Bay, Golfo Triste and the depressions that separate the Netherlands and Venezuela Antilles (Fig. 2).

Transpression along the fault systems that bound and cross the Block (the Santa Marta-Bucaramanga and Boconó faults, and the Perijá-El Tigre, Icotea, Valera faults, respectfully) caused inversion of the Mesozoic rifts. The resulting uplifts separate and internally structure the Cesar Ranchería, Dibujo, Maracaibo and Barinas-Apure depressions. From this time onwards, these basins assumed their present-day identities.

The Maracaibo and Barinas-Apure Basins

Throughout the early part of the Oligocene, the Maracaibo and Barinas-Apure areas formed a contiguous depression bounded by the Perijá uplift to the NW and the Guyana Shield to the SE (Fig. 2). In the west, the mainly coarse continental clastics of the La Sierra and Ceibote Formations accumulated (Figs. 8a and c; Fig. 12). In the central-western Maracaibo area, these units interfinger with the silts, shales, sandstones and coals of the Carbonera Formation, followed by fluvio-lacustrine siltstones and claystones of the León and Peroc Formations.

The Mérida Andes began to be uplifted by the Late Oligocene, and by the Middle Miocene they separated the Maracaibo and Barinas-Apure Basins (for AFTA data relating to the age of uplift, see Daly *et al.*, 1995, and Kendall *et al.*, 1997). Adjacent depocentres (and latest kitchens) in these basins, known as the North and South Andean foredeeps, received coarse molasse deposits assigned to the Isnotu, Palmar, Betijoque and Parángula Formations (Figs 8a and 13). Thereafter, the relatively stable Barinas-Apure Basin continued to accumulate continental sediments of the Parángula Formation (Fig. 8c). In contrast, from Oligo-Miocene time onwards (Fig. 12) the mobile Maracaibo Basin suffered pull-apart subsidence along a series of NNW-trending normal faults as it crossed the plate boundary. This allowed invasion by an Early Miocene sea in which the transgressive Santa Barbara sands, followed by marine shales, and finally the regressive Santa Rosa sands of the La Rosa Formation (Fig. 8a) accumulated. Coeval continental sandstones of the El Fausto Group formed adjacent to the Sierra de Perijá. By Middle Miocene times, the La Rosa Formation became covered by deltaic deposits of the Lagunillas Formation, recording increased clastic sediment supply generated by the rising Mérida Andes and the reactivated Perijá Mountains. Major delta progradation ended in the Late Miocene and continental sedimentation prevailed through the Plio-Pleistocene. On-going, pull-apart induced, fault-controlled subsidence is evidenced by the linear, NNW-trending margins of present-day Lake Maracaibo (Fig. 2) that continues to receive clastics from the Andes in the SE and from the Catatumbo Delta in its SW corner.

Falcón Area

During the Oligo-Miocene, the Falcón area (Figs. 2, 12 and 13) developed as an ENE-oriented pull-apart basin, bounded to the west and east by NNW-trending normal faults and to the north and south by right-stepping, E-W trending strike-slip faults associated with the Oca-San Sebastian fault system. Subsidence was rapid. Narrow belts of coastal to shallow-marine sandstones of the El Paraiso and Castillo Formations and reefal limestones of the San Luis and Churuguara Formations rapidly interfinger with deep-marine, moderately organic-rich shales of the Pecaya and Agua Clara Formations and turbidite sandstones of the Pedregoso Formation. Strong inversion in the Middle Miocene created a sinuous N70°E trending anticlinorium exposing Oligo-Miocene sediments.

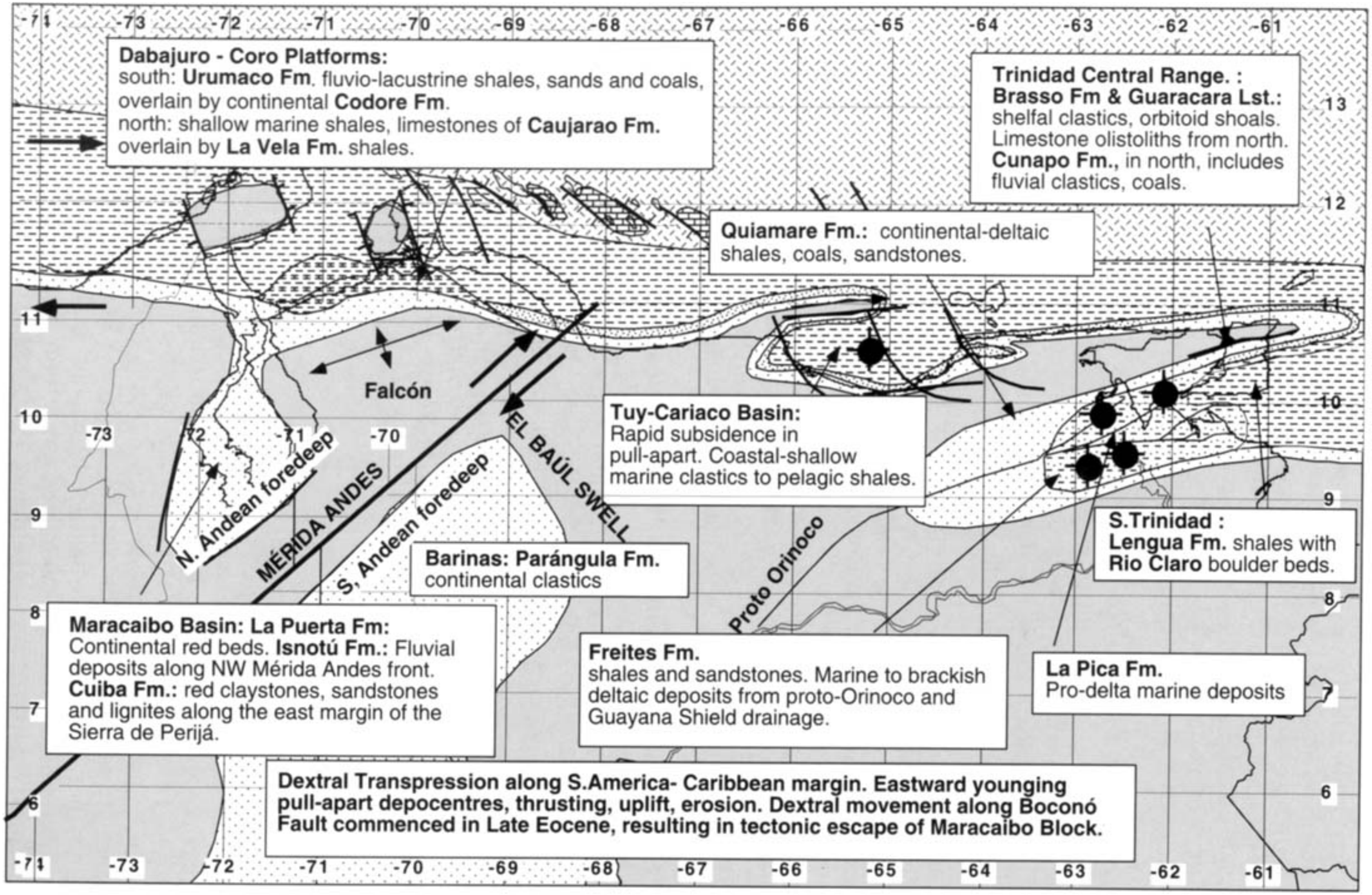

Fig. 13. Late Miocene palaeogeography. Transpression along the Boconó Fault system (Fig. 7) resulted in northeastward, progressive uplift of the Merida Andes, separating the Maracaibo and Barinas-Apure basins that filled with continental clastic sediments, including important reservoir sands. Transpressive uplift of the Coastal and Interior Ranges progressed to Trinidad. The associated foreland basin migrated to the eastern Maturín-Colombus Basin area (Fig. 2) and was filled with deltaic deposits of the proto-Orinoco River.

North of the inverted Falcón Basin, the NW-trending Urumaco Trough that plunges below the Gulf of Venezuela separates two relatively stable areas, the Dabajuro Platform to the west and the Coro Platform to the east (Fig. 13). In the south these areas accommodated Middle Miocene coastal and fluvio-deltaic sediments assigned to the Cerro Pelado, Querales and Socorro Formations, and the Late Miocene fluvio-lacustrine gypsiferous shales, sandstones and coals of the Urumaco and Codore Formations. Further north lie the shallow-marine shales, sandstones and limestones of the Caujarao and La Vela Formations. During the Plio-Pleistocene, alluvial conglomerates and sandstones of the Coro Formation formed on the Dabajuro and Coro Platforms, near the present-day coastline. Steep, local dips in these sections indicate on-going tectonic activity.

Eastern Venezuela: the Guárico and Maturín Sub-basins

Culmination of the Late Cretaceous-Palaeogene orogeny resulted in deep erosion of the Palaeocene-Eocene in southern Eastern Venezuela. Thereafter, the Oligocene and younger setting was controlled by eastward migrating, transpressive interaction between the Caribbean and South American Plates, producing eastward-younging, N70°E trending downwarps. The River Orinoco progressively changed its course eastwards and the youngest sedimentary fill evolved to molasse and alluvial plain deposits.

Transgression in the Early Oligocene established shallow to deeper marine conditions where marine shales and turbidites of the Roblecito and Areo Formations accumulated (Fig. 8b). Rivers draining northwards from the Guayana Shield deposited continental, deltaic and paralic sands and shales of the La Pascua and Los Jabillos Formations (Merecure Group) along the southern margin of the basin (Fig. 8b). Northern uplifts developed, firstly in the west, supplying lower Oligocene coastal clastics to the Guárico Sub-basin where barrier bar sands shale out to the south, and later in the east, where deltaic/paralic sands of the Naricual Fm. were deposited.

Delta/prodelta progradation towards the east dominated the Eastern Venezuela Basin throughout the Miocene and Plio-Pleistocene (Figs.12 and 13). Chaguaramas and Oficina Formation sands prograded from the south and SW into the basin centre Carapita and Capiricual Fm. shales that contain turbidite sandstones. By the Late Miocene, the Guárico Sub-Basin had been largely filled by deltaic to continental clastics and the area became emergent at the end of the Miocene. Deltas prograded through the Maturín Sub-basin, to the Gulf of Paria and the Amacuro Delta in Late Miocene times, forming the pro-deltaic/deltaic Freites and La Pica Formations. The Plio-Pleistocene proto-Orinoco delta occupied a central position over the depocentre of the Eastern Venezuela Basin, while in Recent times, the Orinoco River has migrated southward towards the Guayana Shield in response to uplift in the north.

The offshore basins

Venezuelan offshore basins (Fig. 2) include the Gulf of Venezuela, La Vela Bay, the Gulf of Triste and the Cariaco and Carúpano Basins, together with the basins separating the Netherlands and Venezuelan Antilles. These formed as pull-aparts in the tectonic setting of the dextral plate boundary. Oligocene to Recent sediments overlie metamorphosed Mesozoic or Early Tertiary basement. A continental, coastal and shallow-marine section that includes local source rocks formed during the early subsidence history of these basins, and limestones developed over slowly subsiding fault blocks (e.g. in La Vela Bay). During rapid Mio-Plio-Pleistocene subsidence, mainly deeper-marine shales and marls accumulated. Turbidite sandstones, probably derived from the south, are known from deeper marine deposits in the Cariaco and Carúpano Basins (Blanco and Giraldo, 1992; Ysaccis, 1997).

SOURCE ROCKS

Cretaceous and Tertiary source rocks are known in Venezuela. The former are mainly marine; the latter are marine or terrestrial. The source potential of older sections is unknown, though GeoMark (1993) related oils with a hypersaline signature in eastern Venezuela to a possible Jurassic - Lower Cretaceous source. Palaeozoic sediments are preserved in grabens below the Barinas-Apure and Eastern Venezuela Basins; their source potential is not known. Devonian coals occur in the Sierra de Perijá.

In general, lateral migration probably dominated Venezuela's onshore foreland basins, following laterally continuous reservoirs beneath regional seals. Oil in southern areas such as the Orinoco Heavy Oil Belt and the *Temblador, Oficina* and *Las Mercedes* fields may have migrated over 150 kilometres. The common presence of hydrocarbons in reservoirs above regional seals is evidence for vertical migration, probably via faults (particularly inverted strike-slip and thrust faults) at varying times and at varying locations. Vertical migration is important in the fold-and-thrust belts, via faults and across unconformities.

1. CRETACEOUS SOURCE ROCKS

The Maracaibo Basin

Hedberg (1931) recognized that the Upper Cretaceous La Luna Formation was the probable source of Maracaibo Basin oils. Talukdar and Marcano (1993) attributed 98% of the basin's reserves to this unit.

Talukdar *et al.* (1985a) compiled a comprehensive study of all possible source rocks from Cretaceous and Tertiary sections, analyzed for organic richness, type of organic matter and thermal maturity. Important earlier work includes that by Brenneman (1960) and Blaser and White (1984). Talukdar and Marcano (1994) analyzed the petroleum systems of the basin.

Three known Cretaceous oil source rocks are the La Luna, Capacho and Apon Formations (Fig. 8a). The Aptian-Albian Apon Formation (Aptian Machiques Member) is considered to be an active source in the NW (Alturitas, Rosario, Sol, Ambrosio and Urdaneta areas, Fig. 3). The Albian Lisure Formation locally has high organic content in the western and SW parts of the basin where it may have generated oil. The Late Albian –Cenomanian Capacho Fm.(La Grita Member) occurs only in the SW part of the basin where it is mainly mature to overmature. Gallango *et al.* (1985) reported the identification of small amounts of crude oils derived from both the Capacho and Cogollo units. The Campanian-Maastrichtian Colón Formation is mainly gas prone.

The principal source, the Cenomanian - Campanian La Luna Formation is an organic-rich limestone or calcareous shale, which is dark grey to black in colour and finely laminated. The dark laminae are composed of a brown matrix of clay minerals and organic matter; the light laminae include planktonic foraminifera tests, phosphatized fish remains and embryonic to adult ammonites (Tribovillard and Stephan, 1989; Truskowski and Galea-Alvarez, 1998). Nodules, nucleated by pelecypods or cephalopods, are common. Planktonic (often dwarfed) and pelagic fossils are abundant, benthonics are rare. Radiolaria occur in some horizons. Chert is common and increases upwards and northwards. The unit becomes sandy towards the south. Amorphous marine and algal organic matter is dominant; vitrinite is rare. The organic matter is Type II in the Maracaibo Basin, but includes Type III material south of the Boconó Fault.

Debate on the origin of the La Luna Formation continues. Blaser and White (1984) noted that formation is rich in vanadyl porphyrins and organically-bound sulphur, indications of a reducing environment with dominant carbonate deposition. The high Type II kerogen content, the absence of benthonic fossils and the abundance of planktonics are usually taken to indicate a deep, restricted-marine origin. The underlying Cogollo Group, however, is a shallow carbonate platform deposit (Chacartegui, 1985), with grainstone and ooid bar deposits. It includes lagoonal, organic-rich sediments (with oysters) which are geochemically similar to the La Luna Formation deposits. According to Tribovillard *et al.* (1991), the overlying Colón Formation has mangrove origins and the La Luna accumulated in shallow waters (near storm wave base) with near constant anoxic bottom conditions and stressed surface conditions. Méndez (1989) and Perez-Infante *et al.* (1996) attributed the unit to a rise of sea level, to the expansion of an oxygen-minimum zone and to upwelling, all affecting a platform area where surface waters remained oxygenated, supporting abundant planktonic productivity.

Macellari and De Vries (1987) attributed the high organic content of Upper Cretaceous units in NW South America to upwelling of nutrient-rich waters. In an earlier version of this paper, James (1990) argued that the deposits are too widespread to result from upwelling, and that increased nutrient supply generated by regional transgression, coupled with restriction provided by an island arc, was a more likely explanation for the organic abundance (see also Jenkyns, 1980; and Erbacher *et al.*, 1996). Talukdar *et al.* (1993) deduced from paleogeographic reconstruction that the source rocks formed in open marine, outer shelf-inner slope environments. Furrer (*pers. comm.*) notes that the Turonian part of the La Luna Fm. is incomplete and that no Coniacian section is present, indications that the environment of deposition was shallow and involved non-deposition. An excellent review of the La Luna Formation in western Venezuela by Erlich *et al.* (1997) concluded that the ancestral Maracaibo Basin was restricted by incipient highs in the Santa Marta, Santander, Cordillera Central and Mérida Andes (*see also Renz, 1977*).

In recent years, detailed work on the La Luna Formation has recognized that areal and vertical facies variations from carbonate to shale probably result in variations of times of maturity and in the local generation of sulphur (Boesi *et al.*, 1993; Escandon and Vallejos, 1993). Organic facies vary from outer shelf-slope, pelagic, organic-rich, oil-prone Type II kerogen in the north and NW, to outer neritic, less organic-rich, oil- and gas-prone kerogen (Types II and III) in the south and SE (Talukdar *et al.*, 1993). Talukdar *et al.* (1985a, b) reported TOC values ranging from 1.5 to 9.6 %, average 3.8% (calculated original values 2.5 to 10.8%) with the highest values occurring in the west. They noted that the unit is strongly oil prone, with a generation capacity of 290 million brls/km^3 (358 brls/acre foot).

The La Luna Formation has an average thickness of 110 m in the Maracaibo Basin. Core and electric log studies indicate a net source rock thickness of between one and two thirds of the gross (Blaser and White, 1984). Since the kitchen area below the present-day basin covers some 50,000 km^2, the La Luna Formation may have generated about one trillion barrels of oil. The hydrocarbon generating potentials of the Cogollo, Mito Juan and La Grita units have not been determined. In one well located in the Machiques Trough (Fig. 9), geochemical logs indicated Cogollo Group source-rock quality to be comparable with that of the La Luna over a 130-m interval. Llerena and Marcano (1997) estimated original TOC values of 2.9–7.6 and HI values of 300–500 mg HC/gm TOC for the Machiques Member. Differences between the Machiques Member and the La Luna Formation were described by Ford and Houbolt (1963) and by Escandon and Vallejos (1993). Ford and Houbolt noted that the two units may be confused in the field because of their close similarity. In thin section, the Machiques Member is seen to contain fine carbonate detritus within a bituminous, calcilutitic matrix with rare benthic particles; radiolaria are abundant. The La Luna Formation contains abundant pelagic foraminifera in a calcilutitic or lutitic groundmass with fragments of *Inoceramus*.

While the above source properties of the La Luna Fm. emphasize its rich hydrocarbon potential, it is important to note that its present-day distribution is probably a fraction of its original extent. This is indicated in later discussion and in Fig. 10. *(The generative capacity of Cretaceous source units is discussed in Part 2).*

Eastern Venezuela Basin – Guárico and Maturín Sub-basins

The Upper Cretaceous Guavinita Member of the Tigre Formation (Fig. 8b) includes marine shales and limestones with Type II, mainly marine amorphous kerogen. TOC ranges from 1-2.5% (Talukdar, 1992). Daal and Lander (1993) suggested that this unit sourced the gas in this sub-basin. Gonzalez de Juana *et al.* (1980) noted that the age of the Tigre Formation is uncertain, but that it is likely to be coeval with the Querecual Formation.

The Guayuta Group of the Eastern Venezuela Basin (Fig. 8b) includes the Querecual Formation (Fig. 10), equivalent to the La Luna, which also consists of black limestones and shales rich in planktonic foraminifera and with common nodules. Chert is present and increases in abundance upwards and northwards. It is overlain by the San Antonio Formation, a largely carbonaceous-bituminous, shaly and cherty limestone in the western part of the Serranía del Interior. Alberdi and Lafargue (1993) report that the Querecual Fm. is Cenomanian-Turonian in age, while the San Antonio is Santonian-Maastrichtian. However, T. Villamil (*pers. comm.*) has recovered Albian ammonites from the lower part of the Querecual Fm. Alberdi and Lafargue (1993) noted an overall decrease in TOC from bottom to top in the unit. Campos *et al.* (1985) interpreted the environment of deposition of the Querecual Fm. as deep-marine in the north and shallow-marine in the south. The formation overlies coastal limestones and sandstones of the El Cantil and Chimana Formations, and reef limestones of the Borracha Formation (cf. the Cogollo Group of the Maracaibo Basin). In the San Juan Graben, in the eastern part of the Serranía, the Chimana (Cutacual) Formation bituminous limestones and shales interfinger with the El Cantil deposits (Metz, 1968). At around the same longitude, the Querecual Fm's lithology changes to the dark, bituminous, siltstone and chert facies of the Naparima Hill Formation, better known in Trinidad.

The Querecual Formation is known primarily from outcrops and from shallow well penetrations in the Serranía del Interior fold-and-thrust belt. It is important to note that this range has suffered large amounts of shortening and probably long distance transport. It is significant that there is no deep penetration of the Upper Cretaceous in the autochthonous adjacent foreland. Wells testing age-equivalent rocks further south found the sandy sediments of the Temblador Group, a more proximal and clastic rich unit. Daal and Lander (1993) quoted an unpublished INTEVEP (PDVSA research group) study that detected source-rock quality intervals with marine, amorphous kerogen in the La Cruz, Infante and Guanita Formations of this group. The naphthenic oils of the Greater Mercedes area of central Guárico (Fig. 3), occurring mainly in Cretaceous and Oligocene reservoirs, may be derived from such units.

Talukdar *et al.* (1985b, 1987) determined that the Querecual Fm., containing Type II kerogen, has TOC values ranging from 0.80 to 6.6% and a generative capacity of 166 x 10^6 brls/km^3 (204 brls/acre foot). The San Antonio Formation, with TOC values of 0.67 to 4.52%, has a generating capacity of 68 x 10^6 brls/km^3 (84 brls/acre foot). The thickness of the entire Guayuta Group ranges from 610 to 1,021 m. The average net thickness, determined from GR and SP logs, is about 50-55% of the gross. Marine organic matter forms more than 85% of the organic content in the north, while to the south, the organic matter is less than 60% marine and more than 30% woody material. Alberdi and Lafargue (1993) observed that the organic content of the Guayuta Group in the Serranía del Interior remains high (2-6%) despite its elevated thermal maturity (Ro 1.7–2.2%), and so estimated that its original TOC may have been as high as 12%. Arnstein *et al.* (1982) indicated a present-day kitchen covering an area of about 28,000km^2, capable, therefore, of yielding around 2.7 x 10^{12} brls. However, there are several models purporting to identify kitchens capable of generating the huge reserves in this basin.

The Barinas-Apure Basin

The Upper Cretaceous Quevedo and La Morita Members of the Navay Fm have been identified as source-rock bearing units in the Barinas-Apure Basin (Figs. 8c and 10) (Chigne, 1985; Chigne and Hernandez, 1990). These are sandy equivalents of the La Luna Fm., deposited in coastal settings in the south and in more open-marine conditions in the north. The organic material can be classified as Type II kerogen in the north, but Type III kerogen becomes important in the south and over the Mérida and Arauca Arches (Chigne and Hernandez, *op. cit.*). Lopez *et al.* (1998) reported that at *La Victoria* and *Guafita*, the oils are paraffini-naphthenic, derived from a siliciclastic source; while at *Caipe, Silvestre, Sinco, Silvan,* and *Palmita*, the oils are aromatic-naphthenic, derived from a calcareous source.

There are no published data on the net source rock thicknesses of these units. The generative capacity has been estimated to be between 70 and 180 x 10^6 brls/km^3 (86–222 brls/acre foot) (Talukdar and De Toni, 1988). Chigne's map (*op. cit.*) indicates a kitchen area covering some 40,000 km^2.

MATURATION OF CRETACEOUS SOURCE ROCKS

The following sections summarize previously published reports on this subject. The timing and magnitude of generation in Venezuela are important considerations, discussed in Part 2 of this paper.

The Maracaibo Basin

Studies on the generation of hydrocarbons in the Maracaibo Basin have been published by Habicht (1972); Bockmeulen *et al.*, (1983); Blaser and White (1984); and Talukdar *et al.* (1985a). Habicht concluded that there were two periods of oil generation — Middle Eocene and Middle Pliocene— with similar amounts of oil being generated in each. He thought it likely that oil in place was derived mainly from the second episode.

Blaser and White and Talukdar used restored isopachs to model the generation history. They concluded that most of the La Luna Fm. to the NE of the present-day eastern limit of Lake Maracaibo and in the northern areas of Tablazo Bay (Fig. 2) passed through oil and gas maturity during the Eocene. A narrow NW-trending zone of oil maturity paralleled this limit, while to the west and SW, the La Luna Formation remained immature. In addition, Arminio *et al.* (1994) recognized that transtensional grabens associated with the Icotea Fault system (Fig. 7) formed local kitchens where the La Luna Formation matured in the latest Eocene-Oligocene. Llerena and Marcano (1997) suggested that both the Machiques and La Luna source rocks entered the oil window in the Late Cretaceous in the north of the Colón area (SW Maracaibo Basin). Oil migrated east and SE towards structures already growing during the Cretaceous.

Inversion of the Eocene kitchens in the Oligocene rendered them inactive. A very narrow zone of oil maturity developed just west of the inactive kitchens. By the late Middle Miocene, early oil generation occurred in the west and SW of the Maracaibo Basin (*Machiques, Rosario, W. Tarra, Rio Santa Ana*: Fig. 3). By the Late Miocene, main-phase oil generation occurred in the west and southwest (*Alturitas, Rosario, West Tarra, La Concepción, south Lake Maracaibo, Urdaneta*). In the San Carlos de Zulia and Borbures area, condensate and wet gas formed. At present, the La Luna Formation in the south and west is in the active dry gas window, with large oil and wet gas generating areas further north. It is immature in a narrow belt adjacent to the Sierra de Perijá.

Concretions at the type locality on the Sierra de Perijá contain oil (Hedberg, 1931) but further to the south, the La Luna Fm. at outcrop is post-mature for oil generation, as it is also at outcrop in the Mérida Andes. The La Grita Member of the Capacho Fm, a lateral equivalent of the La Luna in the south of the Maracaibo Basin, is mature for oil generation. These outcrop maturities show that the areas of Andean uplift are inverted kitchens of Palaeogene age. Since the mountains have suffered significant shortening, these kitchens must have played a major role in the supply of hydrocarbons to early traps.

The Eastern Venezuela Basin

Despite the vast oil reserves known in this basin, the timing and location of kitchens is still debated. In general, maturity studies in the western part of the Eastern Venezuela Basin indicate immaturity in the Portuguesa Basin (Fig. 2), and maturity migrating eastwards in the Guárico Sub-basin, from Guárico to Anzoategui, from Early Miocene to Recent (Blanco and Sanchez, 1990). Maturities are higher in the north of the area.

Guarumen area

Talukdar (1992) noted that this area carries autochthonous units of Cretaceous to Eocene age overlain by nappes of Palaeocene–Eocene flysch, in turn covered by molasse. Kitchen development in this area remains very uncertain, both because of the questionable presence of a Cretaceous source rock and because of the uncalibrated timing of thrusting. Talukdar and de Toni (1988) modelled the maturation of autochthonous Cretaceous source rocks below thrusts formed at 38 Ma and/or at 10 Ma, depending upon the obtaining thermal gradient.

Guárico Sub-basin

Talukdar (1992) noted that the Cretaceous Guavinita carbonates of the Guárico Sub-basin are overmature in the north and are in the early generation phase in the south. This unit sourced the marine oils of the *Las Mercedes* area and of the deep reservoirs of the *Oficina* area (Fig. 3). The Querecual Fm. is mature in the *La Vieja* area of north Anzoategui, and overmature in the Guárico mountain front. These sources could be present below the thrusts and could have generated oil that migrated, before the Middle Miocene, to the Heavy Oil Belt.

Maturín Sub-Basin

According to Talukdar *et al.* (1987), the Querecual and San Antonio Formations of the Maturín Sub-basin of Eastern Venezuela generated oil below successive thrusts of the Serrania del Interior from Late Miocene to Recent times, charging Cretaceous to Pliocene reservoirs in structural and stratigraphic traps of the northern fields. Highly altered oil residues in some of these fields may be the remains of early-migrated oils. Source rocks now in the hanging walls of the thrusts generated oil in the Early-Middle Miocene. This "Guayuta Kitchen" oil migrated upwards and southwards through the San Juan Formation sandstones to the Los Jabillos Formation sandstones, then through basal Merecure-Oficina Formation sandstones, above the Oligocene and Miocene unconformities to the Oficina Formation pinch-out. Some oil became trapped against ENE, down-to-the-south normal faults in the *Temblador* area (Fig. 3). Probably light to medium originally, it has suffered biodegradation since the Middle Miocene to produce heavy and extra heavy crudes.

Chigne *et al.* (1993) modelled oil generation to occur first in the Late Eocene-Early Oligocene, with oil migrating some 150km south to the Heavy Oil Belt. Oil formed again in kitchens that migrated southwards in the Early Miocene-Recent. Fault traps caught this later oil. According to these authors, oils in Upper Miocene and Pliocene reservoirs of northern Maturín suggest Late Miocene-Recent expulsion/remigration. Structural traps in pre-Upper Miocene sediments formed in the Middle and Early Late Miocene. The oils are genetically related and migrated after structural development. Source rocks on the hanging walls of the principal thrust are not generating, but generation may be occurring below the thrusts. Modelling by Chigne *et al.* suggests that maturity and migration occurred below successive thrusts in the Pirital system (Frontal, Pirital and El Hueso thrusts) from 12 Ma to the present-day, 5 Ma to the present-day and 3 Ma to the present-day, respectively. Migration is thought to occur along the thrusts in the *Furrial* area.

Chigne *et al.* (*op. cit.*) noted that because the principal reservoir (the Upper Middle Miocene Oficina Formation) of the Heavy Oil Belt was still being deposited at the time when thrusting interrupted the migration pathway and froze generation, alternative kitchen areas must be considered for these reserves. One such area might have been the Guárico Sub-basin, but access to the south Maturín Basin would have been blocked by the Carrizal-Tigre Depression (associated with the Espino Graben, Fig. 9). George and Socas (1994) suggested another possibility — that hydrocarbons in the Orinoco Oil Belt might have come from the *Paria/ Trinidad* area where they reported that Late Cretaceous units, with an original mean TOC of 4.7%, occur in an an area covering 160 x 75km.

Finally, Talukdar *et al.* (1990) noted the probable extension of the Late Miocene-Recent kitchen involving Upper Cretaceous source rocks far to the east of Trinidad.

The Barinas-Apure Basin

Oils are light in the western foredeep areas and heavy towards the eastern basin margins. In the context of the following debated issues of kitchen definition and age of generation, it is worth noting that structures in the basin are grouped into pre-Oligocene and Mio-Pleistocene. Important oil is found only in the former (Portilla, 1993).

The literature is inconsistent with respect to the definition of kitchen areas. For some the Barinas Kitchen is the effective area, located west and south of the Mérida Arch (Fig. 2) (see Young, 1988). Portilla and Osuna (1991) referred to this area as the Capitanejo Depression. However, Loaiza *et al.* (1990) named the foredeep north of the Mérida Arch the Barinas Kitchen, and they regarded the Arch as a barrier to migration from this area to the Capitanejo area where all wells have been dry.

Opinion is also divided on the timing of oil generation. According to Chigne (1985), Chigne and Hernández (1990) and Chigne *et al.* (1997), generation began in the depocentre adjacent to the Andes in the Apure Basin (south of the Arauca Arch) during the mid-Miocene. An estimated volume of 66 B brls of oil was formed. The source rocks here are now gas mature. A much smaller kitchen (800 million brls generated) lies north of the Arauca Arch. These authors note that Barinas crudes are more mature than Apure oils. Chigne *et al.* (1997) quoted an internal company report that observed less mature oil in the *La Victoria* oilfield(Fig. 3), from Early Miocene generation, and more mature oils in *Caño Limon-Guafita* and *Arauca,* from Middle – Late Miocene generation.

Loaiza *et al.* (1990) and Loaiza and Hernandez (1991) also maintained that oil was formed in the NE of the area (the NE Monocline area, between the Mérida and El Baúl arches) in the Eocene. Bitumen in the Pagüey Formation (Fig. 8c) supports this model. Figueroa (1997) further developed this model, but showed the Eocene kitchen located around Trujillo-Carora, an area now uplifted in the northern part of the Mérida Andes (Fig. 2). This author emphasizes the importance of pre-Oligocene structures, noting that only a small area, WSW of Barinas in the foredeep (the "Barinas kitchen") is active today.

From section-balancing studies, Findlay (1988) concluded that Middle Miocene generation occurred in the Andean region prior to the Andean Orogeny. Chigne and Hernandez (1990) argued against this model, stating that the migration path was too long, that the oils in *Guafita* and *La Victoria* (Fig. 3) are too light to have survived, and that the Mérida Andes in fact began to rise in the Middle Eocene. Galea-Alvarez *et al.* (1995) concluded that the La Luna Fm. in the SW of the basin, close to the Colombian border, entered the oil window about 4 million years ago and has not yet reached maximum generation. To the SE, the source rocks are still immature.

According to Talukdar (1992), a Pliocene-Recent kitchen is located in the Capitanejo Trough in the Barinas Basin (Fig. 2), but this is very limited in size. Migration occurred via the Burgüita Formation overlying the Cretaceous source rock and thence vertically in the Barinas fields into the Cretaceous and Eocene Gobernador Formation reservoirs. Another kitchen in the west of the Apure Basin, which also extends into Colombia, commenced generation in the Middle Miocene and peaked in the Pliocene-Recent. Pérez-Téllez (1995) discussed Eocene generation from a La Luna equivalent in the area of Colombia's Eastern Cordillera.This also may have supplied hydrocarbons to the southern part of the Barinas-Apure Basin.

FORMER EXTENT OF CRETACEOUS SOURCE ROCKS

Palaeocene-Eocene flysch deposits (Fig. 11) of the Interior Ranges of north central Venezuela (Guárico Fm., Paracotos Fm.), of the Barquisimeto Basin (Matatere Fm.), and of the Portuguesa Basin (Rio Guaché Fm.) contain allochthonous elements derived from the La Luna and Querecual Formations (Pierce, 1960; Peirson *et al.*, 1966; Gonzales Silva and Picard, 1972). Gonzalez de Juana *et al.* (1980) gave details of these and other derived material, all of which are considered to have had a northern provenance. Olistostromes range up to several kilometres in length and have been given formation names. The north-derived allochthonous material demonstrates that La Luna and Querecual Fm. source rocks originally extended further north than they do at the present day.

No such deposits are known in the Maturín Sub-basin of the Eastern Venezuela Basin; but they do occur on Margarita Island and in Trinidad. Cretaceous limestones are intercalated within the Eocene near Sabana de Uchire, on the south coast of the Cariaco embayment (Fig. 2). The Palaeocene Chaudier Formation of Trindad's Central Range is a wildflysch unit containing limestone blocks of varying size and age (Maastrichtian, Turonian, Albian and Barremian) which have been described as "Remnant Formations" (Suter, 1951). James (1997) summarized previous discussions of these flysch units, and suggested that they also occur below the Serranía del Interior of the Maturín Sub-basin and also underpin the Netherlands and Venezuelan Antilles.

Further evidence of an original, more northerly extent of the Cretaceous source rocks comes from the metamorphic units of northern and offshore Venezuela. These include graphitic black marbles, graphitic schists and graphitic quartzites that are probably derived from bituminous limestones, organic-rich shales and oil-charged sands; in short, they represent a metamorphosed hydrocarbon system. Fig. 14 illustrates the stratigraphic relationship between these units.

The Lower Cretaceous Las Brisas Formation of the Caracas area is a thick succession of schists, graphitic towards the top, with interbedded conglomerates, gneisses and limestones. The latter occur at the top of the section (Dengo, 1953; Smith, 1953). Dengo (*ibid.*) suggested that the isolated and irregular masses of limestones in the Zenda Member, and the lenticular Antimano Formation, were originally biohermal reefs. Gonzalez de Juana *et al.* (1980) noted that the Antimano marbles are grey to black, depending on the graphite content, and that their occurrences as lenses with amphibolites and eclogitic amphibolites represents a tectonic juxtaposition of lithologies as proposed by Laubscher (1955). An alternative explanation, suggested here, is that this unit is a metamorphosed wildflysch, precursor to units such as the Matatere and Guárico Formations.

The overlying Las Mercedes Formation is a 500-m (minimum) thick, graphitic calcareous schist. Graphite is more abundant toward the top of the unit, with layers of black limestone (Dengo, 1953), and the formation has a northward-increasing silica content. Lenses of volcanic ash are present in the northernmost outcrops (Wehrmann, 1972). Wehrmann remarked that some of these units are only lightly metamorphosed and contain concretions identical to those found in the La Luna and Querecual Formations. Incidentally, this report of low metamorphic grade does not support models of great regional burial of these Coastal Range deposits. No age-diagnostic fossils have been reported, but Furrer and Urbani (1973) have identified specimens of *Ophthalmidiidae* (shallow-water foraminifera). The conformably-overlying Chuspita Formation, which contains meta-conglomerates and quartzites, is interpreted as a shallow-water deposit. Calcareous graphitic phyllites and graphitic marbles similar to those of the Las Mercedes Formation form 50%of this unit (Gonzales de Juana, 1982), which contains uncoiled ammonites identified as Upper Albian genera by Macsotay (1972).

The Jurassic Uquire Formation of the Paria Peninsula (Figs. 2 and 13) includes graphitic quartzites and schists of shallow-marine origins according to Seijas (1972). The Tunapui Formation includes graphitic schists and phyllites of ?Late Jurassic-Early Cretaceous age (Seijas, *op. cit.*). The Cariaquito Fm. (overlying the Uquire Fm.) includes black, graphitic phyllites and slates, thick marbles with Valanginian calpionellids and anhydrite, while the overlying Guinimita Fm., of Barremian-Aptian age, contains graphitic phyllites and recrystallised limestones with gastropods, pelecypods, rudists, forams and algae (Gonzalez de Juana *et al.*, 1980). On the Araya Peninsula the graphitic marbles and phyllites of the Carupano Fm. (and the Yacua Member of the Cariaquito Fm.) are considered to be lithostratigraphic equivalents of the Cariaquito, Guinimita and Las Mercedes Formations (Vignali, 1979). Like the latter, the northernmost outcrops of the Carúpano contain volcanic rocks (the El Copey Member).

In Trinidad (Fig. 14), the Jurassic-Lower Cretaceous Rampanalgas Formation, the Barremian Guayamara Formation and the Coniacian Galera Formation form an apparently conformable succession composed of dark brown to black, commonly graphitic slates (phyllites) with upward increasing grit content, interpreted as submarine fan deposits (Algar and Pindell, 1990).

In the offshore Carúpano Basin (Figs. 2 and 14), the Barremian-Santonian Mejillones Group consists of cherty brown, euxinic limestones with interbedded radiolarites and basalts (Castro and Mederos, 1985). The unit is at least 1,100-m thick. The Cenomanian metasedimentary Los Robles Group of Margarita Island contains thin lenses of black limestones, black marbles, and graphitic schists (Gonzalez de Juana and Vignali, 1972), and there graphitic schists are intercalated with marbles in the upper part of the pre-Cenomanian Juan Griego Group (Vignali, 1979). The Washikemba Fm. of Bonaire, which ranges in age from Late Albian to Coniacian (Beets *et al.*, 1984), is a 5,000-m thick sequence of mainly submarine volcanics with intercalations of black shales, cherts, radiolarites and cherty limestones. Wells in La Vela Bay have penetrated black phyllites described as metamorphosed Cretaceous by Kiser *et al.* (1984, *internal company report*).

The above data point to the original, northerly existence of coeval or older, thicker equivalents of the La Luna-Querecual facies, in the vicinity of volcanic activity. It makes sense to link all the above-mentioned units into a single, large palaeogeographic province, probably in a back-arc setting, that extended right across the northern flank of South America in the Cretaceous. The areal extent of this province must have been considerably larger (more than 500,000 sq. km.) than that of its present-day remnants, for northern Venezuela has suffered much metamorphism, inversion, erosion and crustal shortening.

REGIONAL SUMMARY - CRETACEOUS SOURCE ROCKS

Upper Cretaceous source rocks are immature near the craton and mature below localized Tertiary-Recent depocentres adjacent to or below fold-and-thrust belts. The oldest reported Tertiary basin lay NE of the Maracaibo Basin and it may have extended below much of the Falcón Basin. Besides this, maturation must have occurred in foredeeps associated with regional compression during the Late Cretaceous - Palaeogene orogeny (James, 1996). Further outboard, Aptian graphitic metasediments in mountainous regions suggest an earlier phase of maturation below basins whose strata reached the metamorphic grade and which subsequently became

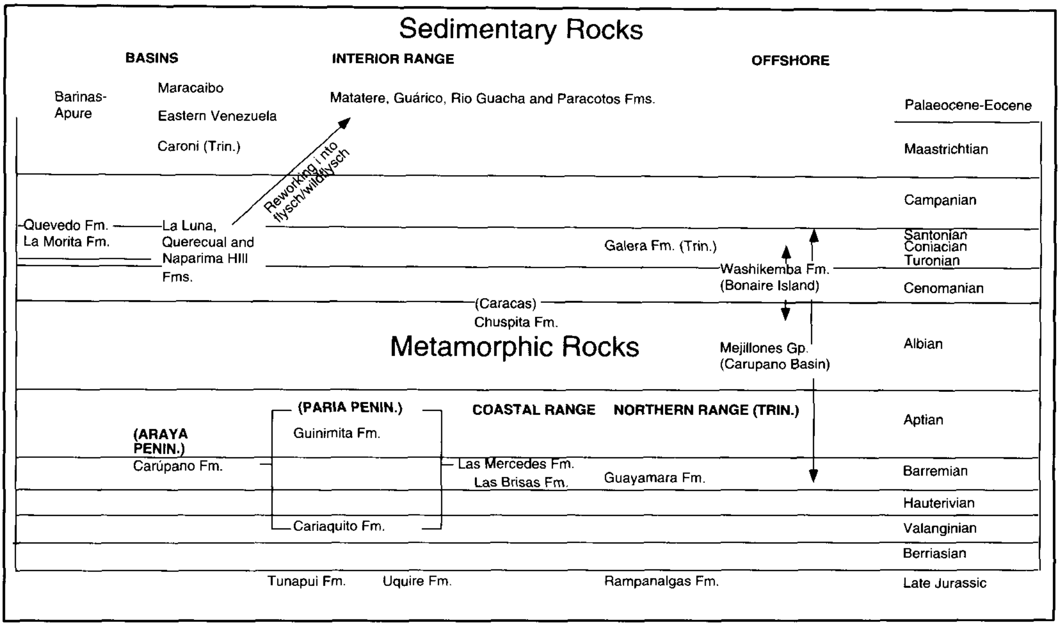

Fig. 14. Stratigraphic relationships between Jurassic and Cretaceous units. Bituminous source rocks are known to occur *in-situ* in the Barinas-Apure and Maracaibo areas, in the Interior Ranges of Eastern Venezuela, and also from olistoliths within Maastrichtian to Middle Eocene wildflysch deposits. Graphitic, metamorphic units in the Araya-Paria Peninsula and the Coastal and Northern Ranges of Eastern Venezuela and Trinidad (Fig. 2) are interpreted to be transgressive progenitors of the Upper Cretaceous source rocks.

inverted. The presence of mature/overmature La Luna Fm.in the Perijá Mountains and Mérida Andes is also important, showing that these areas too, used to be part of the kitchen areas before Late Tertiary mountain building. Cretaceous source rocks originally extended over a very wide area. They probably were diachronous, younging southwards. They matured below southward-migrating, Late Cretaceous to Tertiary depocentres. The present-day basins are remnants of a much broader petroliferous province.

2. TERTIARY SOURCE ROCKS

Tertiary source rocks are less well studied than Cretaceous source rocks, especially by quantitative investigation. This is partly because no major source sections are recognized at outcrop and also because most produced oils have been linked geochemically to Cretaceous source rocks. Such rocks do exist, however, and play their most important role in the offshore areas. One might also expect them to be important in the thick Tertiary section of the Maturín Basin.

Maracaibo Basin

Source rocks characterized by land-plant derived material are present in the south and west of the Maracaibo Basin in the Palaeocene Orocué Group and Marcelina Formation, the Eocene Mirador and Carbonera Formations, and the Miocene Lagunillas and La Rosa Formations (Fig. 8a) (Blaser and White, 1984; Talukdar *et al.*, 1985a; Cassani *et al.*, 1989). The Carbonera Formation at outcrop in the Mérida Andes is mature for oil generation. All these units should be mature in the north Andean foredeep, in the south of the Maracaibo Basin, where rather little exploration has been carried out. Talukdar *et al.* (1985a) reported that three fields *(Los Manueles, West Tarra, Las Cruces,* Fig. 3) in the SW of the basin produce some crudes derived from terrestrial sources, and seeps along the SW half of the north Andean flank type to Tertiary sources. Boesi and Goddard (1991) reported source rocks from cuttings and cores of the Eocene–Miocene units of the Misoa, Jarillal, Cerro Pelado and Agua Clara Formations in the Falcón area. They note that oil in fields in the west came from Eocene source rocks, while an Oligocene-Lower Miocene source rock is mature in the Urumaco Trough and in La Vela Bay (Fig. 2).

Falcón area

In the Falcón area, well data show that the Cretaceous is overmature and there is geochemical evidence for terrestrial source rocks (Ollo *et al.*, 1994) for a string of smallish oil fields (*El Mene – Hombre Pintado,* Fig. 3). Probable source rock sections occur in the Eocene-Oligocene sequence and generation probably occurred in the Pliocene-Recent.

Eastern Venezuela Basin

In the Eastern Venezuela Basin, there are source rocks in the Oligocene Merecure Group and La Pascua and Roblecito Formations, and in the Miocene Oficina and Chaguaramos Fms. (Fig. 8b). Arnstein *et al.* (1982) reported that these are capable of generating 1.7 to 7 kg hydrocarbons per ton. The organic material is mainly terrestrial and some waxy crudes in the *Las Mercedes* and *Oficina* areas (Fig. 3) are probably derived from these units. Paraffinic oils in the Chaguaramas and Roblecito Fms. of the Greater Saban Area of Guárico and Oficina, and Merecure Fm. reservoirs of the Greater Anaco and western Greater Oficina areas (Fig. 3), were sourced by non-marine organic matter in these formations according to Janezic *et al.* (1983). Short-distance migration occurred after formation of the Late Miocene trapping faults. Geochemical correlation of source rocks and crudes indicate, however, that most of the oil comes from Cretaceous source rocks. Aymard *et al.* (1985) reported overmature Tertiary source rocks in the 8 TCF *Yucal-Placer* gasfield in the north of the Eastern Venezuela Basin, but higher TOCs occur in the overmature Cretaceous of the same area.

George and Socas (1994) reported that the *Amarilis* well (Fig. 3) produced terrestrial oil from turbidites within the Carapita Formation, thought to contain source rock material.

Offshore Basins

Talukdar and Bolivar (1982) described Eocene and Oligocene, marine and terrestrial source rocks in the marine shales of the Cariaco Basin (Fig. 2) where oil, gas and condensate, of mainly marine origins, have been discovered. Their calculations estimate recoverable reserves of 52-157 MM brls in this area. The Patao High, a 40-km long basement uplift in the Carúpano Basin (Pereira, 1985), is the site of six large accumulations of dry gas and condensate-associated gas in Mio-Pliocene sandstones and calcarenites (Kiser, 1981; Bellizia *et al.*, 1981, Fig. 3). Source rock descriptions have not been published, but the sedimentary section ranges from Eocene to Recent (Pereira, *op. cit.),* as in the neighbouring Cariaco Trough. The Bonaire Basin (Fig. 2) likewise contains an Eocene to Recent section. One well encountered minor gas shows in this area. The sequence in La Vela Bay ranges only from (local Eocene) Oligocene to

Recent. Source rocks of terrestrial origin have been identified in the Oligocene. The Gulf of Venezuela remains undrilled at this time. The Urumaco Trough, in the east, may be analogous to La Vela Bay.

The general picture to emerge from the foregoing is that the Tertiary section locally includes mixed or terrestrial source rocks. None is as important as the Cretaceous source rocks in terms of generative capacity. However, such rocks may play an important role in offshore basins and in the deeper parts of the Maturín Basin.

CONCLUSIONS

The present-day structural configuration of Venezuela and the distribution and content of its basins and uplifts reflect the country's location at the boundary between the Caribbean and the (South) American Plates. A broad, rifted passive margin formed along the north of South America when North America drifted away during the Jurassic, allowing the formation of the Caribbean Plate. The passive margin was progressively shortened throughout the Cretaceous and Early Tertiary by convergence between the Caribbean and South American Plates resulting in a southward-progressing series of flysch/wildflysch basins.

From the Middle Eocene to Recent times, Caribbean - South America Plate interaction has been governed by east-west, dextral, transpressive strike-slip generating NW-trending pull-apart basins and ENE-trending folds and thrusts. In addition, in the west, compression resulting from ocean spreading in the Pacific is driving NW South America northwards to over-ride the Caribbean-South American Plate boundary. Consequently, this NW area is characterized by intermontane and foreland basins, bounded NE trending transpressional uplifts (inverted Jurassic rifts) and is pervaded by north-south trending sinistral faults.

The several episodes of orogeny progressively resulted in the development of distinct basins that contain the remnants of the broad passive margin sediments together with younger sands and shales that now form reservoir/seal pairs in many trapping configurations

Venezuela's large hydrocarbon reserves are derived mainly from Cretaceous, marine source rocks that accumulated over large areas of the Jurassic-Cretaceous passive margin. In the west, Upper Cretaceous source rocks occur below and on the flanks of the Maracaibo and Barinas-Apure Basins. In the east, they are known from outcrops and shallow wells in the Interior Range, north of the Eastern Venezuela Basin. They are hypothesized to occur below the northern foredeep of the Eastern Venezuela basin and possibly also beneath the Interior Range itself. Most of hydrocarbon generation is thought to have occurred during the latter part of the Tertiary, but earlier orogenesis probably brought source rocks to maturity as well. Abundant graphite in Lower Cretaceous metamorphic rocks in the Coastal Ranges of Venezuela, north of the Interior Range, suggests protoliths of organic-rich, limestone and shale source rocks and oil-charged sandstones, all recording earlier phases of hydrocarbon generation, migration and entrapment.

Compared to the well-known Maracaibo, Barinas-Apure and Eastern Venezuela Basins, the Venezuelan offshore is poorly explored. Several basins that formed during the Tertiary Period contain local source rocks. Tertiary source rocks are also known from the onshore Falcón area and from the Eastern Venezuela Basin. In the former area, Tertiary source rocks supplied hydrocarbons to a belt of small oilfields. Thick deltaic and prodelta deposits in the latter basin may contain significant accumulations of Tertiary-derived hydrocarbons.

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