Cenozoic Tectonic History of the Sierra de Perija, Venezuela-Colombia, and Adjacent Basins

James N. Kellogg
University of South Carolina - Columbia, kellogg@geol.sc.edu

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Cenozoic tectonic history of the Sierra de Perijá, Venezuela-Colombia, and adjacent basins

James N. Kellogg
Hawaii Institute of Geophysics
University of Hawaii
Honolulu, Hawaii 96822

ABSTRACT

The four major Cenozoic tectonic phases in the Sierra de Perijá and adjacent basins are the early Eocene tectonic phase, the middle Eocene Caribbean orogeny, the late Oligocene phase, and the late Miocene to present Andean orogeny. Ages of unconformities associated with particularly rapid regional uplift during these phases are early Eocene (53 m.y.), middle Eocene (45 m.y.), late Oligocene (25 m.y.), and Pliocene (3 m.y.). Northwest-southeast compression may have commenced in the Perijá and the Maracaibo Basin as early as the early Eocene. By the middle Eocene the Macoa-Totumo arch had begun to form during intense alpine-type folding and thrusting to the east in Falcón and Lara. During the late Oligocene phase, the Palmar area was uplifted and the most important structural features for hydrocarbon accumulation in the Maracaibo Basin developed. The late Oligocene phase initiated a basement block tectonic style that culminated during the Pliocene in the northwest thrusting of the Santa Marta massif, Sierra de Perijá, and Venezuelan Andes over the adjacent basins. The main uplift of the Sierra de Perijá occurred during the late Miocene-Pliocene Andean orogeny. Right-lateral oblique-slip movement of 90 to 100 km on the Oca fault and left-lateral oblique-slip movement of 100 km on the Santa Marta fault were caused by late Tertiary overthrusting in the Sierra de Perijá and Santa Marta massif. The northwest-southeast shortening that uplifted the Santa Marta massif, Sierra de Perijá, and Venezuelan Andes is related to Caribbean–North Andean convergence along the South Caribbean marginal fault.

During the Pliocene the Panama volcanic arc collided with South America. The North Andean block became detached from the South American plate and is being wedged slowly to the north between the rapidly converging Nazca, Caribbean, and South American plates. The convergence of the three plates has produced rapid subduction at the Colombia trench (6.4 ± 0.7 cm/yr; 088° ± 7°), slow subduction at the South Caribbean marginal fault (1.7 ± 0.7 cm/yr; 128° ± 24°), and right-lateral shear (1.0 ± 0.2 cm/yr; 235° ± 5°) on the Boconó and East Andean fault systems.

INTRODUCTION

Along its entire length of over 200 km, the crest of the Sierra de Perijá is the International Boundary between Venezuela and Colombia and the divide between the Maracaibo Basin of Venezuela and the César Valley of Colombia. The crest of the range is capped by mesas and benches formed of Cretaceous limestones and conglomerates dipping gently to the southeast (6°–8°). A peak 8 km south of Cerro Pintado has the highest elevation (3,650 m) in the range (Figs. 1, 2). At the mountain front on the east side of the Sierra, steeply dipping limestones form prominent flatirons. Well-developed boulder terraces on both sides of the range, but especially near Manaure, attest to rapid uplift and erosion.

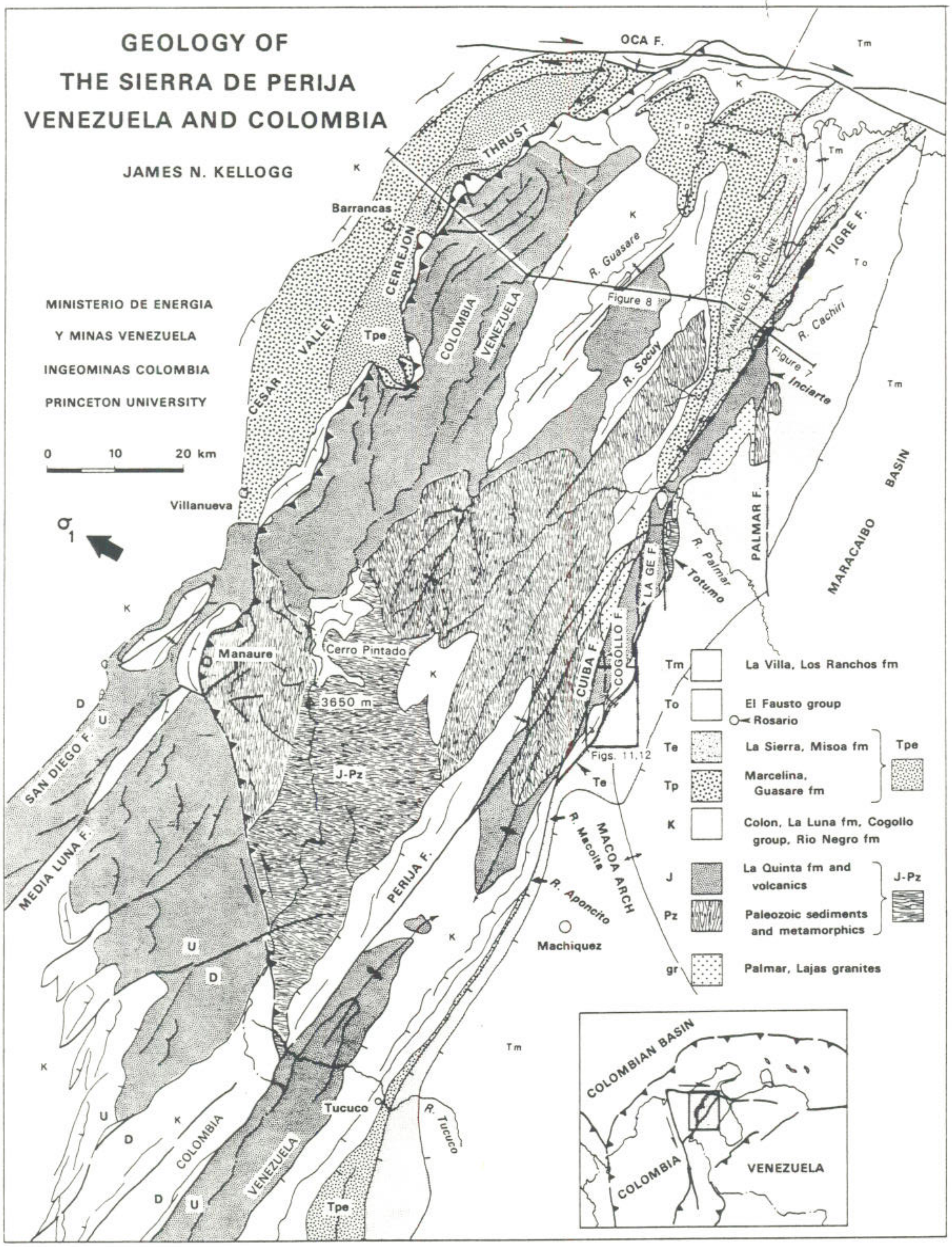
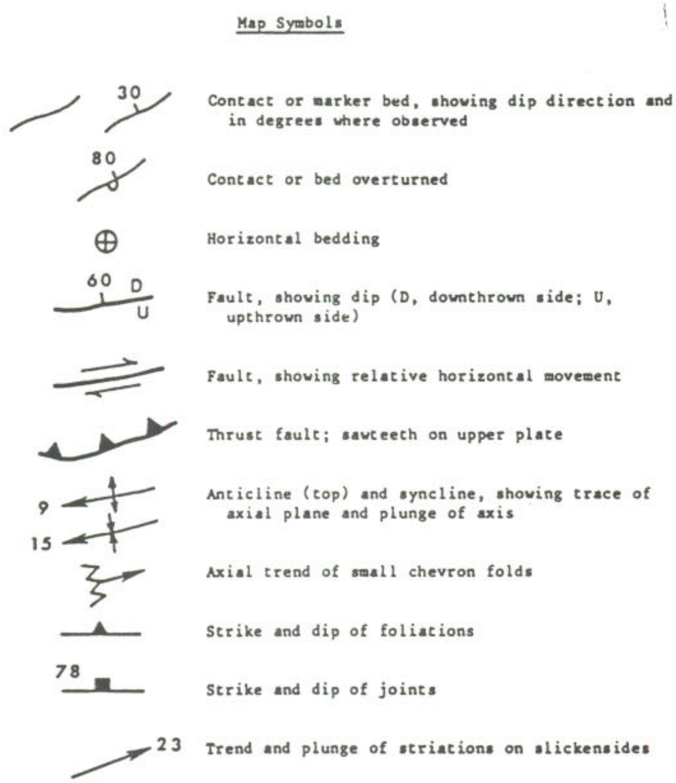


Figure 1. Geologic location map of the Sierra de Perijá. Map symbols on facing page. A radar mosaic (Fig. 2) was used as the base.



The tectonic history of the Sierra de Perijá was discussed by Miller in 1962. In the present paper a tectonic history of the Sierra is presented that incorporates the author's geologic field mapping and paleontological, radiometric, and stratigraphic data published by others in the two decades after Miller's work.

Before the beginning of Cenozoic tectonic history, at least four major tectonic episodes can be identified in the Sierra de Perijá (Kellogg, 1981): Silurian–Early Devonian; Late Devonian; Late Permian–Triassic; and Jurassic–Early Cretaceous rifting and volcanism. The four episodes all produced unconformities in the stratigraphic column (Fig. 3). All four are also associated with thermal events, unlike the upper Cenozoic block thrusting that produced the present mountain range. In this Memoir, Perijá fission-track ages are discussed by Shagam and Kohn (1984).

The two most important of the pre-Cenozoic tectonic episodes were the Silurian–Early Devonian orogeny and the Jurassic–Early Cretaceous rifting and volcanism. The only regional metamorphism in the Sierra de Perijá occurred prior to deposition of unmetamorphosed Early Devonian (390 m.y.) shales (Caño Grande Formation). Silurian–Early Devonian folding, uplift, and plutonic granitic activity may have been associated with the regional metamorphism.

During Jurassic time, thick arkosic red beds, basaltic andesite flows, ash layers, and welded tuffs were deposited in rift valleys (Maze, 1980, 1984). Geophysical evidence for a Jurassic graben 300 km wide and 5 km deep is found in seismic line PV-D in west Lake Maracaibo 30 to 40 km east of Guamo (Pumpin, 1979). This northeast-southwest-trending graben in west Lake Maracaibo and one in the Totumo area east of the Tigre-Perijá fault are also indicated by wells that have penetrated the La Quinta volcanics (Pumpin, 1979). In the upper Río Cachirí area, crinoidal limestones of the Permian Palmarito Formation are in direct contact with Lower Cretaceous Río Negro conglomerates (discordance of dip = 30°), suggesting a Jurassic–Early Cretaceous horst west of the Tigre-Perijá fault. On the northwest flank of the Sierra near Cerrejón, more than 5 km of red beds were deposited in a deep basin. The angular unconformity at the top of the La Quinta near Cerrejón is about 30°.

By Cenozoic time, igneous activity in the Sierra de Perijá had ceased, and low-angle block thrusting culminated in the Pliocene uplift of the present mountain range.

EARLY EOCENE UNCONFORMITY

The first significant Cenozoic angular unconformity in the Sierra de Perijá is in the early Eocene (53 m.y.). No significant tectonic activity marked the Cretaceous-Tertiary boundary or the Paleocene. Jurassic–Early Cretaceous rift valleys, red beds, and intermediate volcanics (Pumpin, 1979; Maze, 1980) had been covered by Early Cretaceous conglomerates, sandstones, and massive limestones. By Late Cretaceous time, limestones and shales (La Luna and Colón formations) were being uniformly deposited in a stable marine environment. Southwest of Lake Maracaibo on the eastern flank of the Sierra de Perijá, the Colón Shale is conformably overlain by Cretaceous marine to brackish water shales and thin sandstones and limestones (Río de Oro limestones) of the Mito Juan Formation, passing conformably upward into sandstones, shales, and coals of the Orocue Group of uppermost Cretaceous-Paleocene age. Farther north along the east flank of the Sierra, the Colón and Mito Juan formations are succeeded upward by the Guasare Formation of Paleocene limestones and calcareous sandstones. The Guasare Limestone is well developed in the oil fields of Lake Maracaibo (Hedberg and Sass, 1937).

Rather uniform deposition of shallow marine limestones throughout the Paleocene in the Perijá and the western part of the Maracaibo Basin suggests continued tectonic stability in these areas. The gradients in the Paleocene isopachs shown in Figure 4 are interpreted by Zambrano and others (1971) to be the result of post-Paleocene erosion. In the early Eocene record, however, are the first indications of the coming orogenies. An unconformity is found in the oil fields of Lake Maracaibo, and in the Boscan field northwest of the lake (Zambrano and others, 1971). The unconformity is located between the Guasare Formation and the Misoa Formation Unit "C." The age of the Guasare Formation is well established by molluscs, foraminifera, and pollen as Paleocene (Léxico Estratigráfico de Venezuela, 1970). The Misoa Formation is early to middle Eocene, on the basis of orbitoidforam and pollen evidence (Léxico Estratigráfico de Venezuela, 1970). Post-Paleocene, pre–middle Eocene erosion occurred on the crests of all of the present anticlines in the western Maracaibo Basin (Young and others, 1956). As the axial trend of these anticlines is

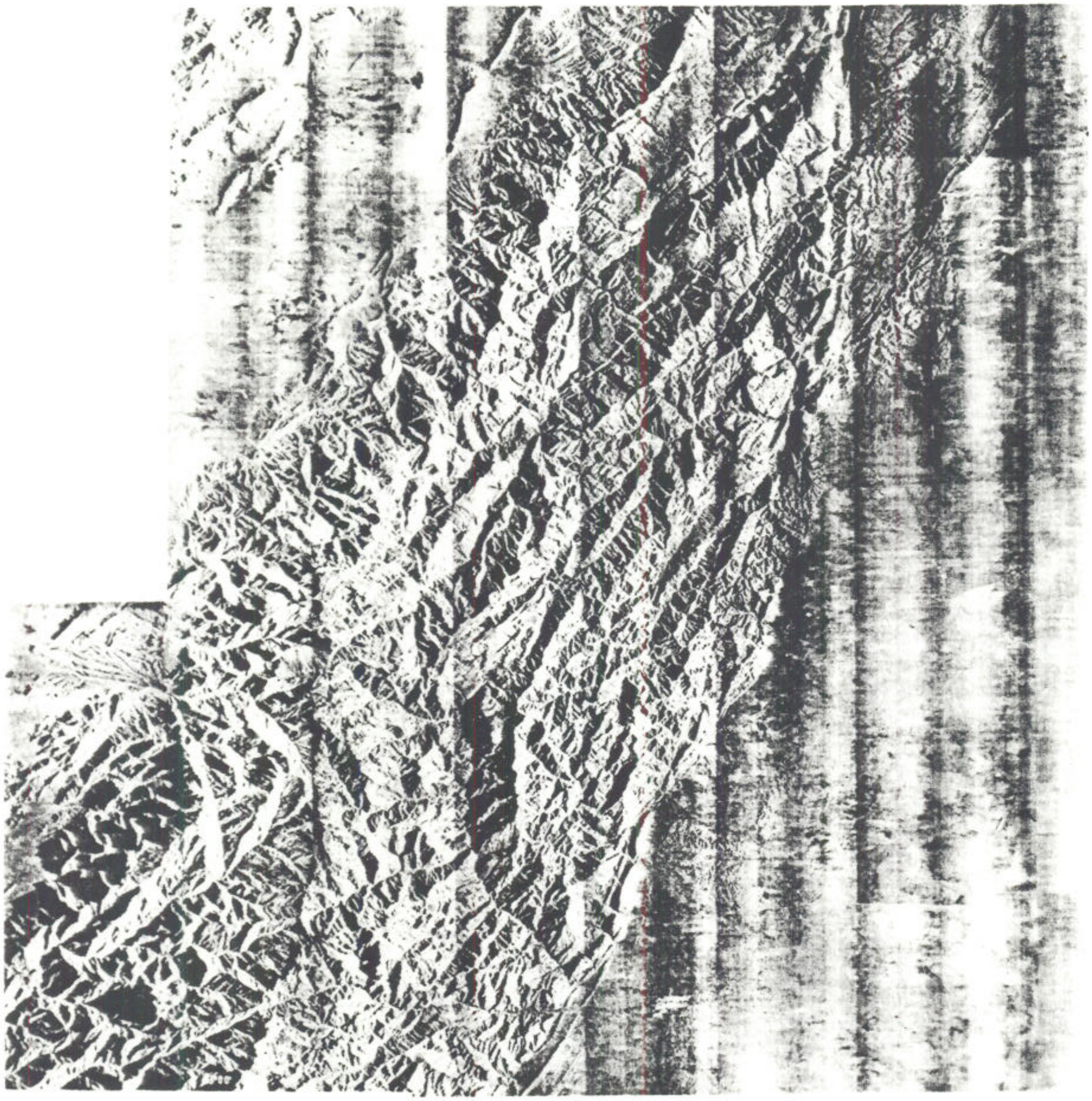


Figure 2. A 1:250,000 radar (SLAR) mosaic (Aero-Service Corporation and Goodyear Aerospace, 1971) of the Sierra de Perijá.

northeast-southwest, northwest-southeast compression might have commenced in early Eocene time.

About 250 km northwest of the Sierra de Perijá, the paleotrench on the west side of the Romeral fault had become active by Paleocene time (Fig. 4). The Romeral fault initially bordered a deep trench filled with abyssal Late Cretaceous and early Tertiary pelagic sediments and turbidites (Duque-Caro, 1979). These sediments are said to be completely absent on the continental platform immediately to the east of the fault. K-Ar ages from the Santa Marta metamorphic belt (MacDonald and others, 1971; Tschanz and others, 1974) indicate Paleocene metamorphism and intrusion of the continental margin. In the Venezuelan Coast Ranges to the east, Paleocene flysch-molasse deposition marked the initiation of the overthrusting that culminated in the middle Eocene alpine-type orogenesis of the Villa de Cura and Lara nappes.

MIDDLE EOCENE CARIBBEAN OROGENY (45 M.Y.)

A pronounced unconformity and a truncation of the Marcelina, Guasare, and Cretaceous rocks occur across the Macoa-Totumo arch (Fig. 5). This truncation beneath the La Sierra Formation is seen in the subsurface on the Macoa arch (V. D. Winkler and C Key, S. A. Lagoven, Caracas, Venezuela, personal

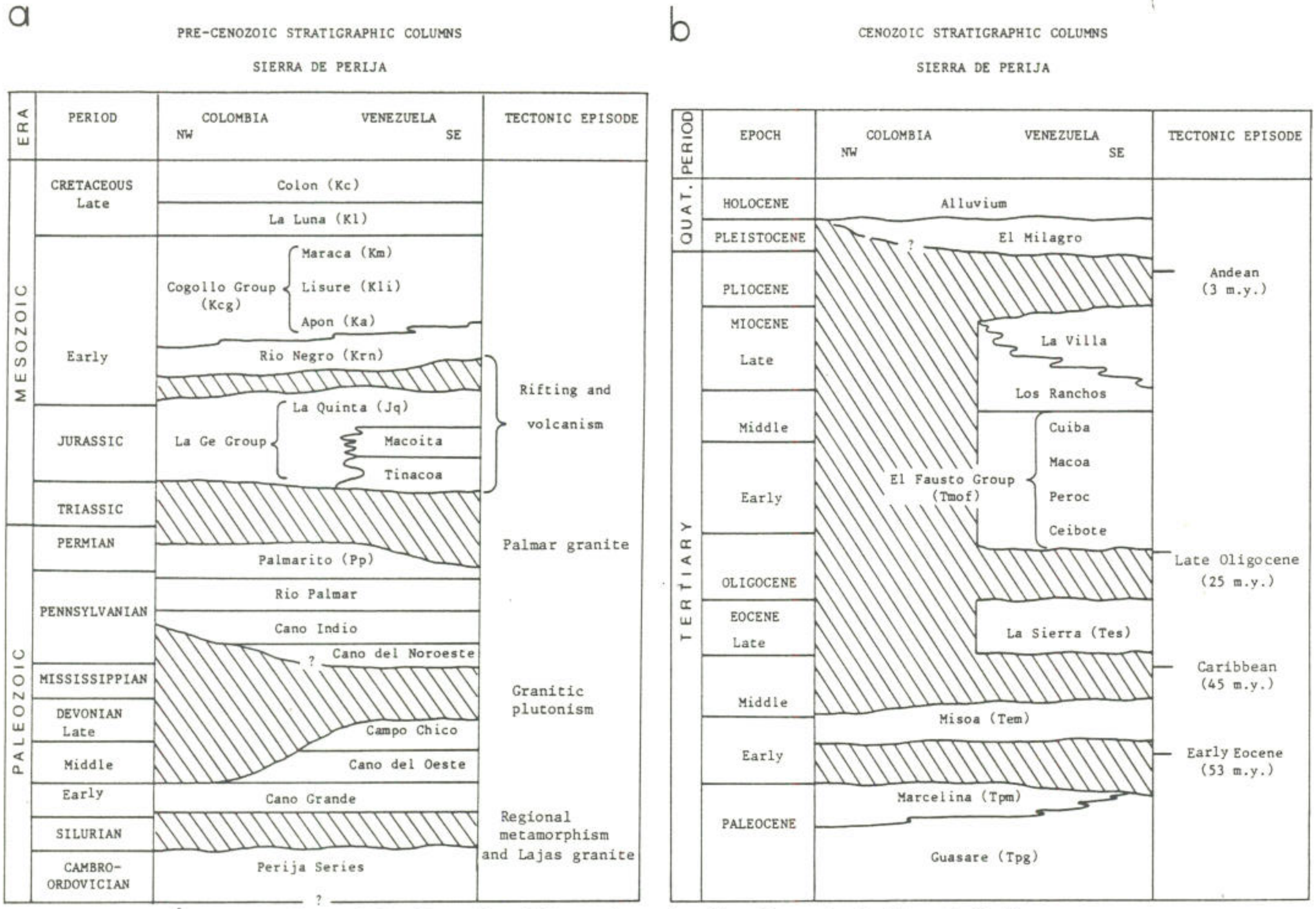


Figure 3. Pre-Cenozoic and Cenozoic stratigraphic columns for the Sierra de Perijá.

commun., 1980) and in outcrop sections southward to the Río Yasa (Miller, 1962). The La Sierra Formation contains the molluscs *Calorhadia (Litorhadia)* sp. and *Carolia.* From these and unspecified fossil evidence Kuyl and others (1955) gave the formation a late Eocene age. The La Sierra Formation can be correlated with the Carbonera Formation in the southern Sierra de Perijá, which contains diagnostic late Eocene molluscs, including *Hannatoma emendorferi, Crommium palmerae, Turritella* sp. of the groups *chira* and *samanensis* and *Raetomya* sp. (Léxico Estratigráfico de Venezuela, 1970). The truncated Marcelina Formation contains no diagnostic fossils, but from its wide association with the Guasare Formation it is assumed to be Paleocene or early Eocene. In the southwestern part of the Maracaibo Basin a pollen zone is missing near the top of the Mirador Formation, indicating a possible early middle Eocene unconformity prior to deposition of the overlying Carbonera Formation (Léxico Estratigráfico de Venezuela, 1970). In Falcón a major unconformity separates the middle Eocene Paují and the late Eocene Santa Rita formations (Zambrano and others, 1971).

In the Sierra de Perijá, the most obvious result of the middle Eocene deformation was the formation of the Macoa-Totumo arch or nose (Fig. 5). A number of faults have approximately the same north-south trend as the Macoa arch where it meets the Perijá mountain front. These include the Cogollo, La Gé, and Totumo faults (Fig. 1). Prior to late Eocene La Sierra sedimentation, the west side of each fault was downdropped slightly (contrary to the Neogene east side down displacement) (Miller, 1962). The middle Eocene displacements on the Cogollo, La Gé, and Totumo faults may have been related to the uplift of the Macoa arch. These faults are roughly orthogonal to the major middle Eocene thrust faults to the east (075°) but parallel to the thrust faults to the west in Colombia (Fig. 5).

During Eocene time, the Sierra de Perijá north of Machiques (Fig. 1) was in a sandy platform depositional environment (Zambrano and others, 1971). Deltas were forming in the southwest part of the Maracaibo Basin. Northeast of the present lake, 7 km of flysch and shales were deposited in a marginal basin (Fig. 6). The long axis of the basin is aligned northwest-southeast (325–145°). Farther east the motion of the Lara nappe was southeast (140°–170°). The basin may have formed along a marginal tear fault in response to crustal loading by the Lara nappe. In Lara a flysch and molasse with exotic blocks (Matatere Formation) containing early Paleocene to middle Eocene foraminifera was deposited in front of the southeastward thrusting Lara nappe.

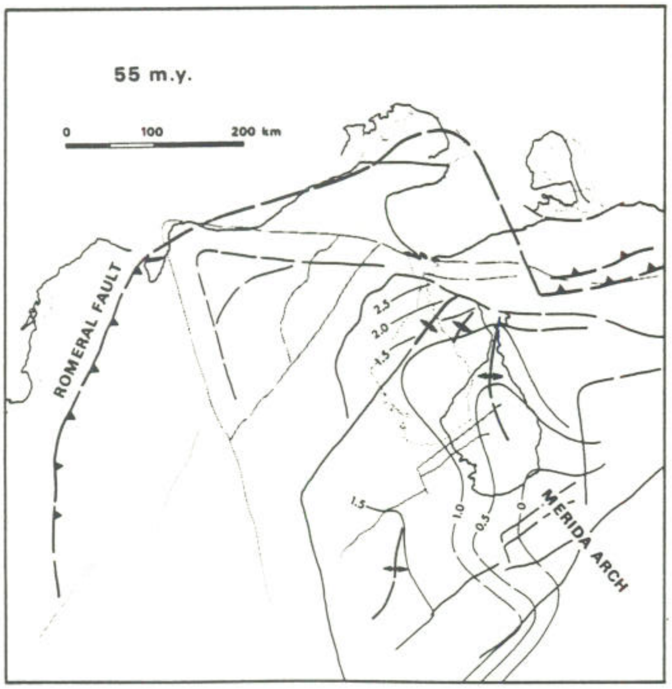


Figure 4. Tectonic reconstruction of the Maracaibo–Santa Marta block in the early Eocene (55 m.y.). Units for the restored Paleocene isopachs are thousands of feet; the contour interval is 500 ft (152 m) (after Zambrano and others, 1971). The present-day coastline is given for reference.

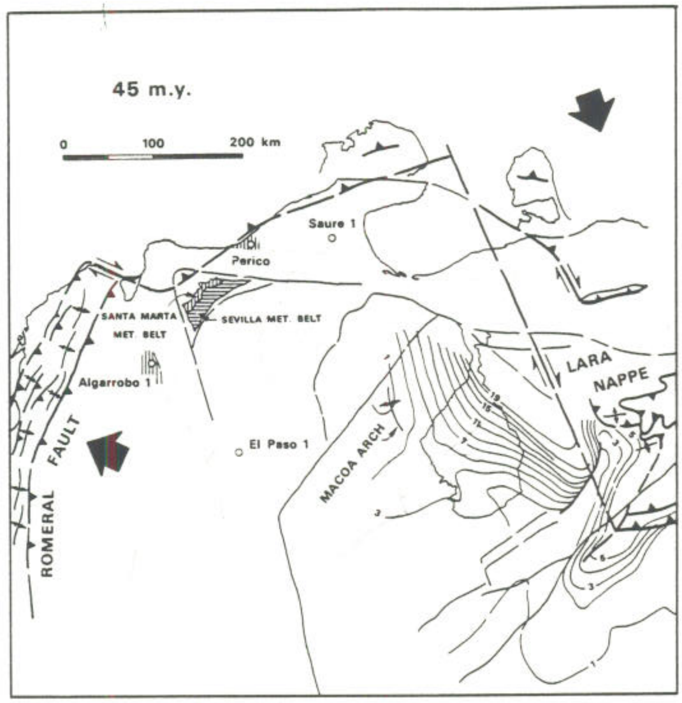


Figure 5. Tectonic reconstruction of the Maracaibo–Santa Marta block in the middle Eocene (45 m.y.). Units for the restored Eocene isopachs are thousands of feet; contour interval is 1,000 or 2,000 ft (305 or 610 m) (after Zambrano and others, 1971). The large arrows indicate the directions of maximum compressive stress for Romeral fault and the Lara nappe. The present-day coastline is shown for reference.

Fold axes that formed during overthrusting were northeast-southwest (050°–080°) (Stephan, 1977b). South-southeastward vergence is indicated by isoclinal microfolds. The nappe fronts were displaced about 250 km. Farther east in the Interior Range, the Piemontine Zone was overthrust by the Villa de Cura nappe in the early middle Eocene (Beck, 1977). The orogeny was characterized by subisoclinal folding (axial trend; 065°–075°), axial plane fracture cleavage, and thrust faults. In northeastern Venezuela and Trinidad, the middle Eocene folding and overthrusting to the south were relatively rapid (Bell, 1972; Vierbuchen, 1978).

In northern Colombia during the middle Eocene orogeny, lateral northwest-southeast compression was at a peak. Caribbean crust was being subducted beneath South America on the newly formed Sinú trench (Duque-Caro, 1979). In the San Jacinto belt to the east of the Sinú trench, steep northeast-trending (015°–025°) fold limbs, tight anticlines and synclines, and thrust faults predominate. The San Jacinto belt and the Western Cordillera were also uplifted about 5 km vertically. This estimate is based on calcium carbonate compensation depth calculations (Duque-Caro, 1972). Tonalitic (quartz diorite) plutonism occurred along the western edge of the platform near the Romeral fault and in the Santa Marta metamorphic belt. K-Ar ages from Santa Marta schists and tonalites collected in six localities (including the Santa Marta batholith) range from 43 to 48 m.y. (Tschanz and others, 1974).

Eocene convergence was occurring on the northern margin of the Caribbean plate as well as on the southern margin. Volcanism in the Greater Antilles accompanied thrusting to the northeast in Cuba and the Puerto Rico trench (Monroe, 1968; Malfait and Dinkelman, 1972; Mattson, 1973).

In summary, the Caribbean orogeny was characterized by southeast-verging alpine-type thrust faulting and tight folding in northern Colombia and northern Venezuela and northeast-verging thrust faulting in the Greater Antilles. Nappes were thrust up to 250 km south-southeastward in Lara and in the Interior Range of Venezuela. The Sierra de Perijá area was only peripherally affected by the middle Eocene folding and thrust faulting occurring to the west and east. In the Sierra the most obvious result of the middle Eocene Caribbean orogeny was the formation of the Macoa arch as an outer rise on the basin marginal to the Lara nappe.

After the Caribbean orogeny a dramatic change in Caribbean–North American relative motion occurred. By Oligocene time, thrusting to the northeast in Cuba and in the Puerto Rico trench ended (Monroe, 1968; Mattson, 1973). Volcanism ceased in the Greater Antilles and began in the Lesser Antilles on the eastern margin of the Caribbean plate (Malfait and Dinkelman, 1972). Left-lateral strike-slip motion began in the Cayman trough (Heezen and others, 1973; Holcombe and others, 1973).

LATE OLIGOCENE PHASE (25 M.Y.)

In the Sierra de Perijá a major change took place in the

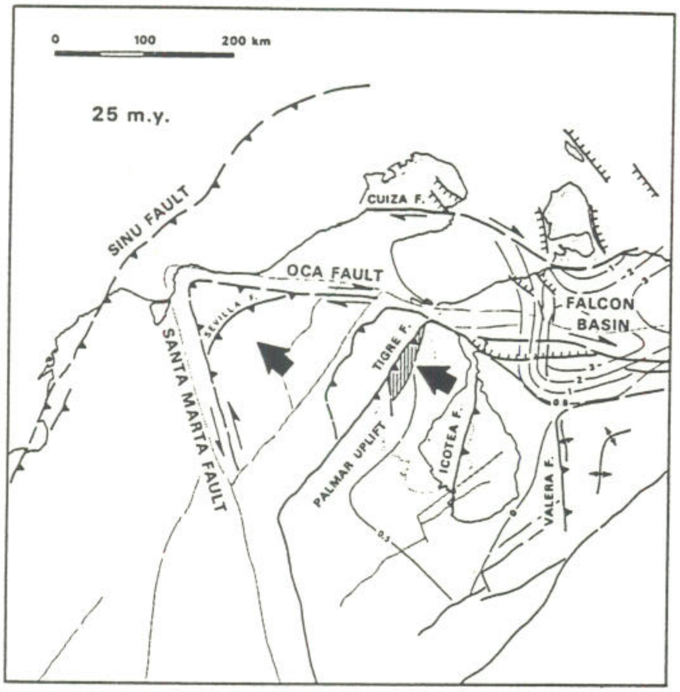


Figure 6. Tectonic reconstruction of the Maracaibo–Santa Marta block in the late Oligocene (25 m.y.). The large arrows indicate the directions of maximum compressive stress for the Santa Marta massif and the Sierra de Perijá. Units for the schematic restored lower Miocene isopachs are thousands of feet; contour interval is 500 or 1,000 ft (152 or 305 m) (after Zambrano and others, 1971). In the hachured area (Palmar uplift) pre-Cretaceous rocks were brought to the surface 25 m.y. ago. The present-day coastline is given for reference.

structural style after the Caribbean orogeny. In the late Oligocene phase, the first basement block uplifts occurred. During the late Oligocene phase the Palmar area was uplifted (Fig. 6), and the most important structural features for hydrocarbon accumulation in the Maracaibo Basin developed.

A major unconformity associated with this phase in Lake Maracaibo is generally assumed to have been caused by Eocene or early Oligocene uplift; however, a careful examination of recent published paleontological evidence as shown below reveals that the unconformity could be as young as late Oligocene. A late Oligocene age for the structural disturbance and uplift is supported by several recent apatite fission-track age determinations from the Sierra de Perijá, which will be discussed in this section.

Southeast of the Tigre fault on the Palmar or Totumo-Inciarte uplift, Eocene, Paleocene, Cretaceous, and pre-Cretaceous crystalline rocks are truncated beneath El Fausto Group shales (Dufour, 1955; Feo-Codecido, 1972). This unconformity over the late Eocene La Sierra Formation is distinctly evident on the Totumo-Inciarte arch (Miller, 1962, Zambrano and others, 1971). Zambrano also traced this unconformity to the top of the late Eocene Carbonera Formation near Alturitas in the southern Sierra. In Lake Maracaibo it overlies the shales of the Paují Formation, which contain abundant planktonic foraminifera including the uppermost middle Eocene *Porticulosphaera mexicana* zone (Léxico Estratigráfico de Venezuela, 1970). East of the Andes in Barinas the unconformity can be found at the top of the late Eocene Paguey Formation.

The El Fausto Group, which was deposited on the Oligocene unconformity on the Palmar uplift, consists of the Ceibote, Peroc, Macoa, and Cuiba formations. The Ceibote Formation, at the base of the El Fausto Group, has no diagnostic fossils. The *Léxico Estratigráfico* cites an Oligocene palynological age from Kuyl and others (1955), but they give no data for their El Fausto Group age, mention uncertainties in the position of the Oligocene boundaries, and do not refer to the Ceibote Formation specifically. The Peroc Formation has been considered Oligocene to early Miocene on the basis of its relation to units in Lake Maracaibo, but the shallow-water foraminifera found in the formation are of indeterminate age (Léxico Estratigráfico de Venezuela, 1970). The Peroc Formation thins considerably to the east under Lake Maracaibo and passes laterally into the Icotea Formation (Young, 1958). The Icotea Formation, however, contains only redeposited Eocene foraminifera. The overlying La Rosa Formation is rich in fossil foraminifera, including the *Globorotalia fohsi* zone (Dusenbury, 1956) formerly considered late Oligocene but now assigned to middle Miocene. To the south there is a lateral transition from the Peroc to the León Formation (Young, 1958). The León Formation contains molluscs of mid-Miocene age, *Tellina, Chione, Arca, Turritella, Conus,* and *Olivella,* and the early mid-Miocene planktonic foraminifera, *Globigerinatella insueta* (Kuyl and others, 1955; Léxico Estratigráfico de Venezuela, 1970). Thus, the micropaleontological evidence permits a wide range of possible ages for the unconformity, extending from earliest Oligocene through early Miocene.

Recent fission-track age determinations from the Totumo-Inciarte uplift (Kohn, *in* Shagam, 1980) are evidence for a late Oligocene age for the deformation and uplift. The fission-track ages determined from apatite in three samples varied from approximately 22 to 25 m.y. The temperature at which fission tracks in apatite become stable (the blocking temperature) is about 120 °C for rapid uplift or subsidence, but annealing may occur at 50 °C if the temperature is maintained for an extended period of time (Shagam, 1980). As the pre-Cretaceous rocks on the Totumo-Inciarte uplift were significantly eroded at the surface prior to El Fausto deposition, they must have passed through the blocking temperature for apatite at that time. Deposition in the Totumo-Inciarte area was then continuous, and there was no further uplift until Pliocene time. Thus, the only period of uplift that could possibly have been consistent with the late Oligocene (25 m.y.) fission-track ages was the pre–El Fausto phase.

By the end of the Oligocene the pre-Cretaceous crystalline rocks and the overlying Cretaceous, Paleocene, and Eocene sediments east of the Tigre fault were raised 3 to 4 km along the fault and tilted 7° to the southeast, forming the Palmar or Totumo-Inciarte uplift (Fig. 7). Gravity data suggest that near the surface the original dip on the Tigre fault was about 20° ± 10° to the southeast (Kellogg, 1981). Cretaceous limestones were folded as crystalline basement rocks were thrust to the northwest. Geomet-

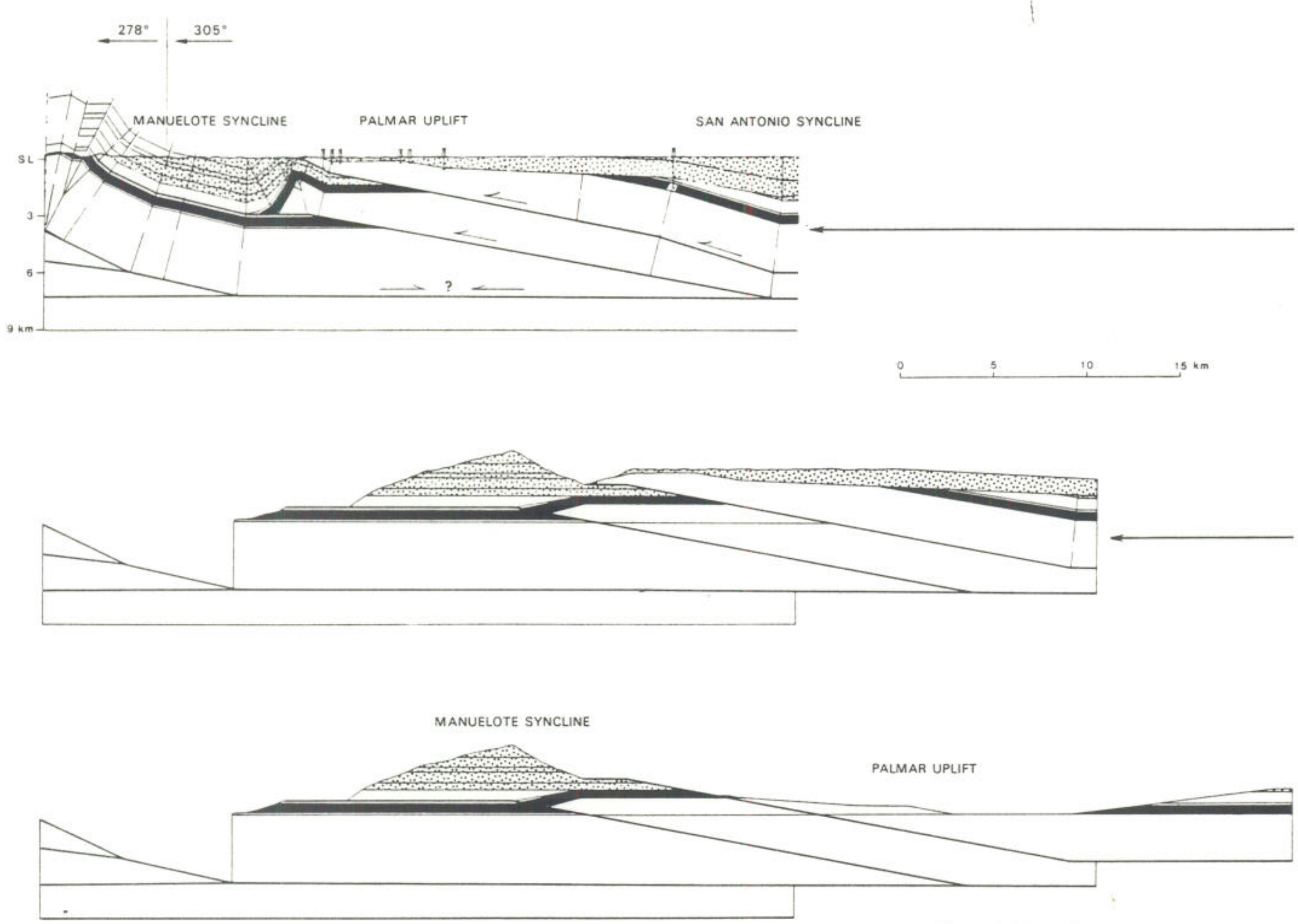


Figure 7. Restored cross sections illustrating the development of the Palmar uplift and Manuelote syncline from the Eocene (bottom) through the Miocene (middle), to the present-day (top). Tertiary rocks are shown in dot pattern and Cogollo Group in black.

ric considerations (Figs. 7, 8) are consistent with up to 11 km of lateral shortening and possible flattening of the fault at a depth of 7 or 8 km.

In Lake Maracaibo the most important structural features for hydrocarbon accumulation were developed during the late Oligocene phase. The period was characterized by folds and high-angle reverse and strike-slip faults trending north-northeast–south-southwest (Icotea trend) and by intense erosion (Zambrano and others, 1971). As a result of this epeirogenesis the massive Cretaceous limestones of the Cogollo Group and La Luna Formation were fractured enough to constitute high-quality reservoir rocks, especially in the zones most affected structurally, such as the crests of the Lamar, Concepción, and La Paz-Mara anticlines. Petroleum interest is considerably reduced to the south of these oilfields because the massive limestones pass into a shaley facies intercalated between limestone beds, which reduces the fracturing of the Cretaceous section. This is the case in the central and southern Perijá Macoa and Alturitas structures (Salvador and Hotz, 1963). The late Oligocene folds and faults in northern Lake Maracaibo, such as the Icotea or Urdaneta fault, were formed under west-northwest-verging compression (Zambrano and others, 1971; K. W. Stauffer, Corpoven, Maracaibo, personal commun., 1979). Commercial hydrocarbon accumulations were subsequently trapped on structural highs beneath the late Oligocene unconformity. When the Sierra de Perijá was uplifted in the Pliocene, oils migrated updip to the northwest along the late Oligocene unconformity beneath impermeable El Fausto shales, forming numerous oil and asphalt seeps at the surface (Dufour, 1955).

Strike-slip motion on both the Santa Marta and Oca fault systems probably commenced in the Oligocene. The interpretation presented in this paper of the Palmar uplift as a result of late Oligocene thrusting on the Tigre fault requires about 9 km of right-lateral displacement on the east-west-trending Oca fault system. On the basis of well data north of the Palmar uplift, Feo-Codecido (1972) postulated vertical movement during the Oligocene and 15 to 20 km of right-lateral post-Eocene displacement on the Oca fault. In Falcón, Muessig (1979) ascribed alkaline basaltic intrusions radiometrically dated at 23 to 28 m.y. to tension produced by dextral movement on the Oca fault sys-

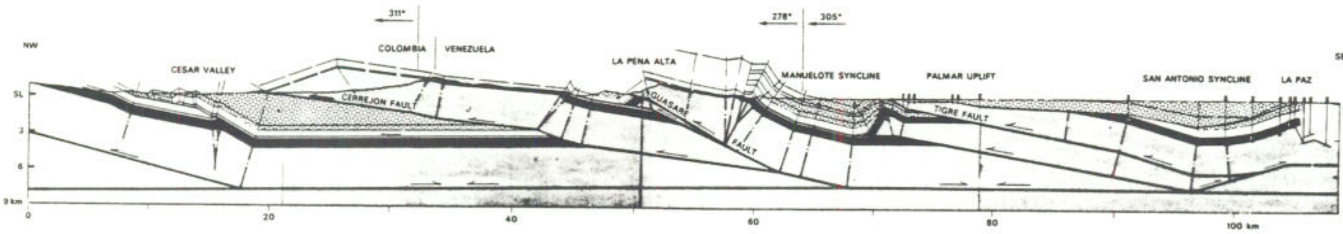


Figure 8. Deep geologic cross section of the northern Sierra de Perijá. The location of the section line is shown in Figure 1. All Tertiary units are shown in the dot pattern; the Cretaceous Cogollo Group is in black; and pre-Cretaceous units are shown in the screen pattern.

tem. Continued right-lateral movement on the east-west-trending fault systems resulted in Miocene subsidence and deposition in the Falcón and Bonaire pull-apart basins (Fig. 6).

Evidence of late Oligocene movement on the north-northwest–south-southeast-trending (343°) Santa Marta Fault system was found in the Algarrobo 1 well (Fig. 5). Drill cuttings from a depth of 8,327 ft (2,538 m) contained Santa Marta phyllite in a pre–lower Miocene boulder conglomerate (T. V. Tolleson of Superior Oil Co. of Colombia, *in* Tschanz and others, 1974). The unconformity is very pronounced in El Paso 1 (Figs. 5, 14) near the Santa Marta fault zone in the César Valley (26 km northeast of Chimichagua) where lower Miocene sediments rest directly on Jurassic La Quinta red beds (Polson and Henao, 1965). West of Santa Marta the margins of the continental platform were being compressed laterally (Duque-Caro, 1979). Upper Oligocene and Miocene pelagic sediments and turbidites were deposited in a trench west of the Sinú fault (Fig. 6) while shallow-water carbonate facies of the same age were being deposited east of the fault.

An apatite fission-track age of approximately 26 m.y. on the Valera granite (Kohn, *in* Shagam, 1980) may indicate late Oligocene uplift in the northern Andes of Venezuela. The uplift may have been the result of displacement on the north-south-trending Valera fault.

There has been no Neogene regional metamorphism or igneous activity in the Santa Marta–Maracaibo block. The late Oligocene phase initiated a basement block tectonic style that culminated in the Pliocene northwest thrusting of the Santa Marta massif, Sierra de Perijá, and Venezuelan Andes over the adjacent basins.

PLIOCENE ANDEAN OROGENY (3 m.y.)

Sierra de Perijá

The main uplift of the Sierra de Perijá occurred during the late Miocene and Pliocene Andean orogeny (Fig. 9). The Sierra was thrust as a block to the northwest over the César Valley on a low-angle thrust fault that extends down to the middle of the crust. The Sierra Nevada de Santa Marta and the Venezuelan Andes were uplifted by similar northwest-verging Pliocene overhrusting. The basement block overthrusts of the Sierra de Perijá, Venezuelan Andes, and the Santa Marta massif are Pliocene-Pleistocene analogues for Laramide orogenic structures in the middle and southern Rocky Mountains of the United States (Kellogg, 1981). As the Venezuelan Andes overrode the Maracaibo Basin, the southeastern part of the basin subsided and gradually filled with coarse sandstones and conglomerates.

Well logs and seismic data from the Maracaibo Basin indicate the gradual initiation of Andean tectonic activity in the middle Miocene. Maraven's 1978 seismic profile CMO-2 showed an apparent Miocene growth fault on the West Mara anticline. Well-log data suggest that Miocene sediments onlap the northwest flank of the La Paz anticline (Fig. 8). According to Lagoven data (C. E. Key and V. D. Winkler, Lagoven, S. A., Caracas, Venezuela, personal commun., 1979), the Icotea (Urdaneta) fault in Lake Maracaibo began to move in middle Miocene, but the greatest displacement was Pliocene-Pleistocene.

A Pliocene age for the major uplift of the Sierra de Perijá can be inferred from stratigraphic relationships and from apatite

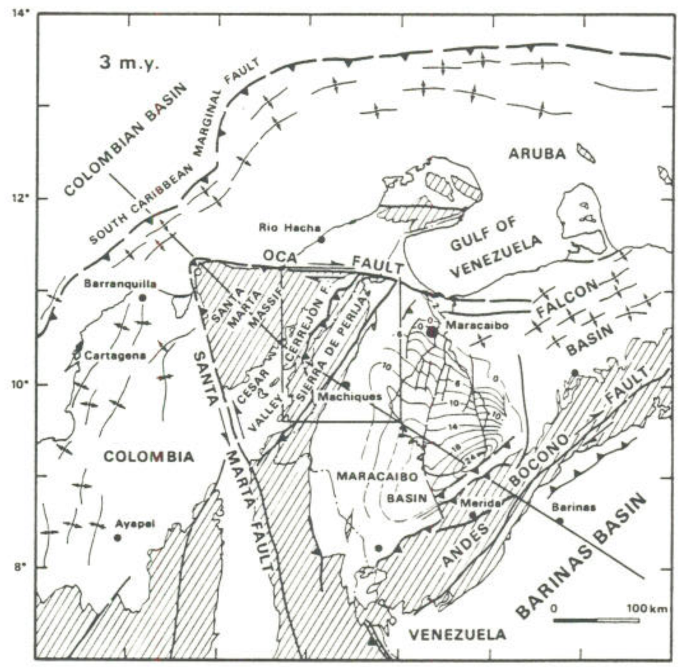


Figure 9. Tectonic reconstruction of the Maracaibo–Santa Marta block during the Pliocene (3 m.y.). Hachured areas are major uplifts with pre-Tertiary rocks exposed. Depths to the late Oligocene unconformity (25 m.y.) are given in thousands of feet; the contour interval is 2,000 ft (610 m) (Zambrano and others, 1971).

Figure 10. Flatirons at the eastern mountain front south of Río Apón (west of Machiques).

fission-track age data. (1) The frontal monocline with its Cretaceous limestone-capped flatirons bordering the Maracaibo Basin is one of the most striking structural features in the mountain range (Figs. 10, 11, and 12). The late Miocene Los Ranchos and La Villa formations are conformably folded in the frontal monocline with little apparent onlap. One kilometre east of the mountain front near Rio Macoita, La Villa Formation beds dip steeply to the southeast (015°; 55°SE) (Fig. 13), indicating a post–La Villa age for the folding of the frontal monocline. Just east of the monocline, seismic reflection profile PU-10 (Western Geophysical for Corpoven, S.A., 1977) shows displacement of the La Villa Formation on the west-dipping Macoa fault. (2) Deposition on the southeast flank of the Sierra continued without interruption through the middle and upper Miocene. An unconformity then separated the La Villa Formation and the overlying El Milagro Formation (Sutton, 1946; Young, 1958; Léxico Estratigráfico de Venezuela, 1970; Zambrano and others, 1971). The late Miocene age for the La Villa Formation is based on regional correlations. The only fossils found in the El Milagro Formation are silicified wood, but it is probably Pleistocene (Léxico Estratigráfico de Venezuela, 1970), suggesting an approximate Pliocene age for the unconformity. (3) A Pliocene age for the uplift of the Sierra de Perijá is also supported by apatite fission-track age determinations of about 3 m.y. for samples of La Quinta volcanics (Caño El Tigre) and Río Lajas granite (Kohn, *in* Shagam, 1980).

The Andean uplift of the northern Sierra de Perijá involved northwestward movement on the Cerrejón thrust fault. Field geologic and gravity data (Kellogg, 1981; Kellogg and Bonini, 1982) suggest that near the surface the Cerrejón fault dips 15° ± 10° to the southeast. To account for the total volume of rock uplifted by the Cerrejón thrusting, the fault as shown in Figure 8 must extend to a depth of at least 8 km in the crust. As interpreted in Figure 8, Jurassic La Quinta red beds were displaced 16 to 26 km horizontally and 4.5 km vertically on the thrust. The red beds were emplaced above southeast-dipping shales and sandstones of the Marcelina Formation and the lower part of the Misoa Formation. The thrusting had to at least postdate the early Eocene Misoa Formation. Although no fission-track ages are available for the Colombian side of the Sierra, the high topography (up to 3,650 m) and high Pleistocene terraces (200 to 300 m above river base level south of Manaure) on the Colombian side of the range attest to more rapid Pliocene-Pleistocene uplift there than on the Venezuelan side. In the southern César Valley on the Becerril anticline, Phillips Petroleum Company well and seismic data indicate reverse faults displacing Miocene sediments.

On the northeast flank of the Sierra, the Manuelote syncline and Mostrencos arch also were formed during the Pliocene An-

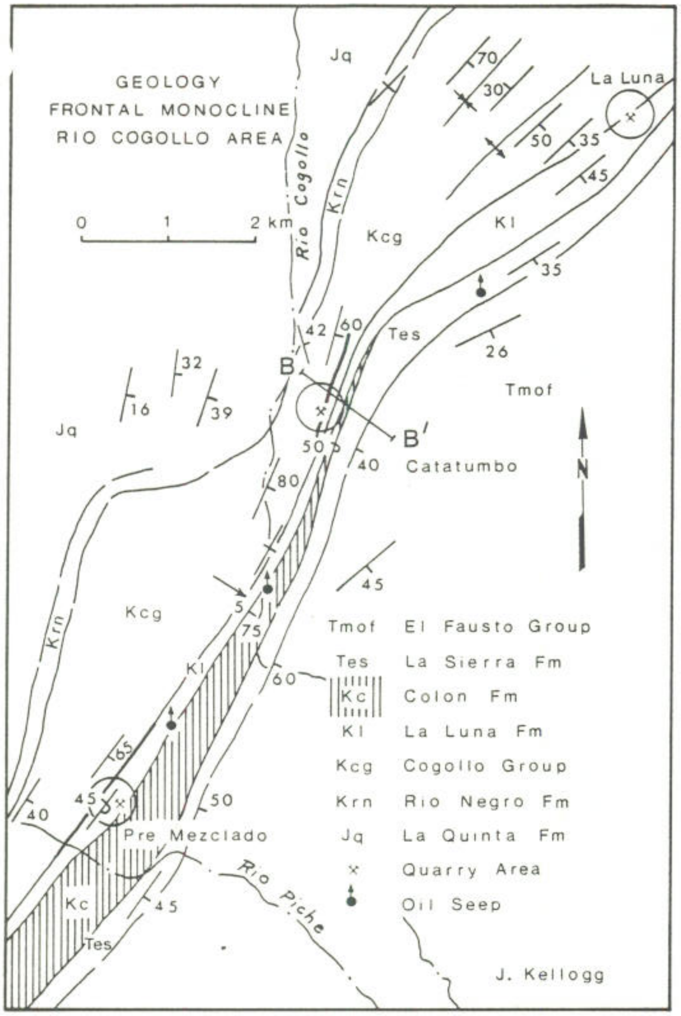


Figure 11. Geologic map of the monocline near Río Cogollo. For location see Figure 1.

dean orogeny. The age of the structures is known by the conformable folding of the late Miocene Los Ranchos Formation within the syncline (Hedberg, 1929). According to the structural interpretation presented in Kellogg (1980, 1981), the Manuelote syncline and the Mostrencos arch were results of a fault bend at a depth of about 3 km. Northwest-southeast compression resulted in 2 to 6 km of shortening and 3 km of vertical displacement on the arch.

Oca Fault Zone

The Sierra de Perijá, the Cerrejón fault, and the Tigre fault are bounded on the north by the east-west (097°) Oca fault system. The model presented in this paper of Perijá orogeny by northwest-southeast shortening (299°) requires oblique right-lateral motion on the Oca fault system. The predicted Pliocene northwest-southeast shortening in the northern Sierra (Cerrejón, Guasare, and Mostrencos arch faults) is about 25 to 35 km. The predicted Oligocene northwest-southeast shortening across the Tigre fault is 7 to 11 km. As the movement is oblique to the Oca fault system, the apparent displacement will depend on the strike of the displaced structure. Apparent displacement of northeast-southwest-trending structures will be greater than the apparent displacement of northwest-southeast-trending structures. Also, because of crustal shortening in the Sierra de Perijá and Santa Marta massif south of the Oca fault, relative right-lateral displacement will increase to the east.

Estimates of total Tertiary movement on the Oca fault are based on correlation of rock units across the fault. Pre-Cretaceous serpentinite found in the Guajira well Saure 1 (Figs. 5, 14) has been tentatively correlated with serpentinite in the Santa Marta massif 100 km to the west and south of the fault (P. Bartok, F. Jansen, V. Pumpin, Maraven, S. A., Caracas, Venezuela, personal commun., 1979). Serpentinite can be found in a few small ultramafic units in the Sevilla de Santa Marta provinces (Tschanz and others, 1974). Tschanz and others (1974) correlate schist found in the Perico well (Figs. 5, 14) north of the fault with schist from the Santa Marta metamorphic belt south of the fault. If the displacement is northwest-southeast (310°), the true total movement would be about 50 km.

There is no evidence of Paleocene or Eocene activity on the Oca fault, so the Cenozoic movement on the fault was probably associated with the late Oligocene and Andean orogenies in the Sierra de Perijá and Santa Marta massif (Coronel, 1970). Early Andean (middle to late Miocene) activity on the fault is suggested by two apatite fission-track ages of about 12 and 13 m.y. from Toas Island (Kohn, *in* Shagam, 1980).

Toas Island is a small sliver (1.5 by 6 km) in the middle of the Oca fault zone at the entrance to Lake Maracaibo (Fig. 14). The island consists principally of granites, rhyolites, basalts, and Mesozoic sediments (Pimentel, 1977) that are 3 to 4 km higher than immediately adjacent units of the same age. The lack of any significant gravity anomaly suggests that the island has been detached from the basement. The brittle deformational style, small size, and large abrupt vertical displacement are consistent with the flower-structure geometry commonly observed in small slivers along major wrench faults (Harding and Lowell, 1979). Olistostromes formed during uplift on the north side of the island contain blocks of red and white sandstone of probable Miocene age. Post-Miocene fault activity is also supported by strongly deformed Miocene sandstone (125°; 60°NE) found along the Oca fault north of the Sierra de Perijá (2 km east of Las Trojas on Route 1). Along the fault trace in Falcón, Miocene and Pliocene beds of the Coro Formation have been tilted vertically. Maraven's 1978 seismic profiles W-78-7 and W-78-12 (Figs. 15a, 15b), located 80 and 100 km east of the mouth of Lake Maracaibo, also show major vertical movement of late Tertiary sediments in horsts and grabens along the Oca fault zone, demonstrating significant late Tertiary displacement on the fault in Falcón.

Feo-Codecido (1972) estimated only 15 to 20 km of right-lateral post-Eocene displacement on the Oca fault, from the displacement of the Sinamaica depression and San Carlos uplift from the Manuelote syncline and Palmar uplift, respectively. Additional dextral movement may have occurred on the right-lateral

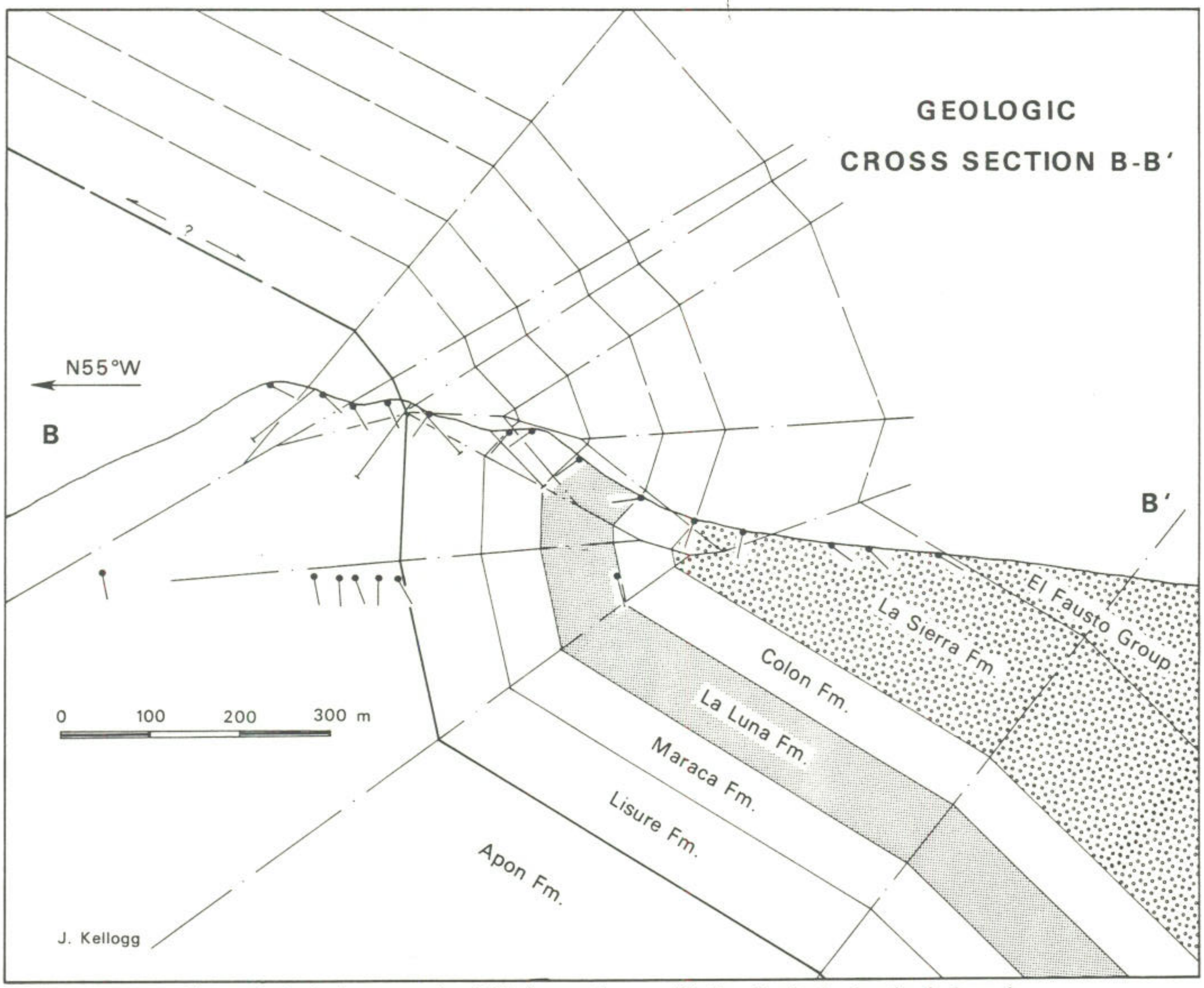


Figure 12. Geologic cross section B-B′ of monocline near Río Cogollo. Section location is shown in Figure 11.

strike-slip Matuare fault just north of the Oca, however. In Falcón, Vasquez and Dickey (1972) calculated shortening by folding in the northeast-trending (072°) Falcón anticlinorium as 50 to 60 km in the past 25 m.y. They ascribed the shortening and folding at the surface to dextral shear on the Oca fault zone in the basement. Isopachs for the Pecaya Formation, which was termed Oligocene by Zambrano and others (1971) but which contains primarily early Miocene planktonic foraminifera (Cati and others, 1968), are shown in Figure 14. If the zigzag trend of the present isopachs (Fig. 14) is the result of simple shear distributed across a wide fault zone (Oca) and the linear restored isopachs for 25 m.y. ago shown in Figure 6 are correct, then about 50 km of dextral movement occurred on the Oca fault zone in the past 25 m.y. This apparent 50-km east-west displacement of north-south-trending isopachs would be equivalent to about 60 km of northwest-southeast (298°) displacement.

If the estimated total Tertiary oblique dextral movement on the Oca fault zone in Colombia of 50 km (correlation of Perico well schist and Santa Marta schist by Tschanz and others, 1974) is added to the 40 ± 8 km estimated dextral movement on the Oca fault zone produced by northwest-southeast shortening in the northern Sierra de Perijá (Cerrejon, Guasare, Mostrencos arch, and Tigre faults; Kellogg, 1981), the predicted total Tertiary oblique dextral movement on the Oca fault zone east of the Sierra is 90 ± 8 km. If 60 km of the displacement on the Oca fault zone occurred in the past 25 m.y. (calculated shortening by folding, Vasquez and Dickey, 1972; and displaced isopachs, Fig. 14), then 30 km of oblique-dextral movement are predicted to have taken place on the fault zone in the Oligocene or early Tertiary.

Estimates of the post–middle Eocene sinistral displacement on the Caribbean–North American plate boundary are as high as 1,000 km. These estimates are based on the horizontal displace-

Figure 13. La Villa Formation sandstones dipping steeply to the southeast (015°; 55° SE) 1 km east of the Perijá mountain front near Río Macoita (Fig. 1).

ment of Mesozoic evaporites in Central America (Pinet, 1972) and the opening of the Cayman trough (Holcombe and others, 1973). These estimates of Caribbean–North American movement can be combined with the constraints on relative motion between North America and South America derived by Minster and others (1974) and Ladd (1976) to deduce the post–middle Eocene, Caribbean–South American motion as approximately 600 to 1,000 km (1.5–2.2 cm/yr) (45×10^6 yr) in a west-northwest–east-southeast direction (Jordan, 1975; Minster and Jordan, 1978; K. Burke, Department of Geological Sciences, SUNY, Albany, New York, personal commun., 1980). Post–middle Eocene displacement of this magnitude did not take place on the Oca fault system. The late Tertiary movement on the Oca and Santa Marta faults is the result of shortening in the Sierra de Perijá and Santa Marta massif. This shortening is probably related to upper Tertiary Caribbean–South American and Quaternary Caribbean–North Andean convergence.

North-South Compression

In the northern Sierra de Perijá there is evidence of north-northeast–south-southwest 014° ± 16° (α_{95}) compression from stylolites, folds, and reverse faults (Kellogg, 1981). This compression is perpendicular to the Oca fault. The faulting and folding involves the Misoa Formation, so it is post–middle Eocene. In the Manuelote syncline some of these faults are offset by northwestward thrusting (E. Moya, O. Castillo, and Figueroa, Corpozulia, personal commun., 1978). The east-west trend of folds and reverse faults on Toas Island suggests that the uplift of the island may have been caused by north-south compression along the Oca fault (Rod, 1956). A middle to late Miocene age for at least part of the uplift of Toas Island is indicated by two apatite fission-track ages (Kohn *in* Shagam, 1980). The north-south compression has continued into the Pleistocene, because east-west-trending (110°) thrust faults displace the Pliocene-Pleistocene El Milagro Formation (south of La Concepción) near Maracaibo (Bellizzia and others, 1976).

The north-south shortening may be caused by the predicted oblique movement on the Oca fault system. Because of the rigidity of the Maracaibo–Santa Marta block (Dufour, 1955), the deformation near the Oca fault zone is parallel to the fault rather than oblique to it. The shortening is also increased on left-stepping segments of the dextral fault, such as the Montes de Oca at the northern termination of the Sierra de Perijá. Well-log and

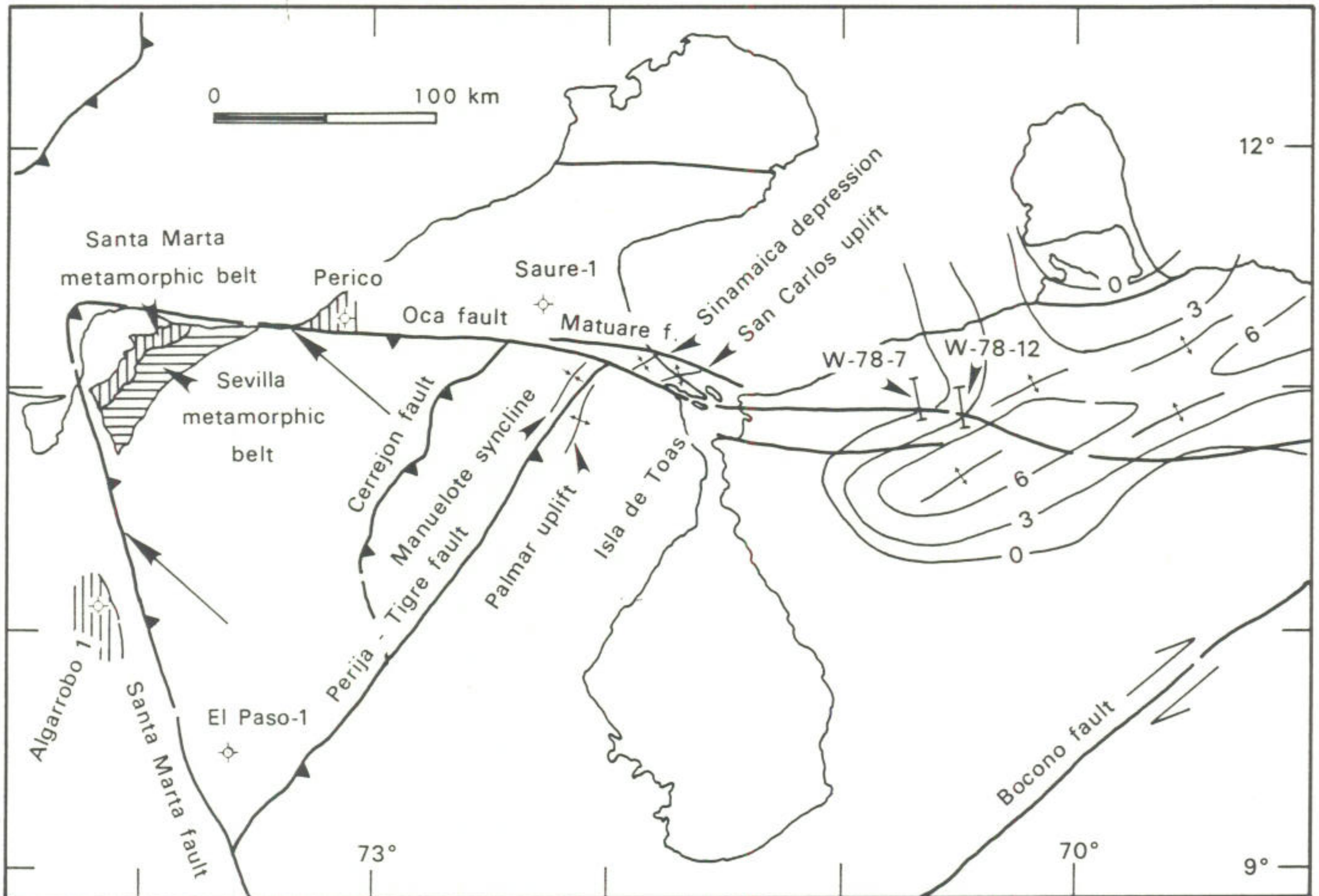


Figure 14. Map of the Oca fault zone. Unrestored lower Miocene isopachs for northwestern Venezuela (Zambrano and others, 1971). Compare with the restored isopachs (Fig. 6) in which the movement on the Oca fault system has been removed.

seismic data from north of the Palmar uplift show that the Oca fault has a reverse profile with the south side up an average of 1 km (Feo-Codecido, 1972).

Santa Marta

The Santa Marta–Bucaramanga fault is a north-northwest–south-southeast-trending (340°), left-lateral, strike-slip fault that forms the southwest margin of the Santa Marta and Santander massifs. Campbell (1968) claimed that the César and Middle Magdalena basins were contiguous until separated by 110 km of post-Miocene movement, although this is disputed by Polson and Henao (1965). Drill cuttings of phyllitic schist in a pre-Miocene boulder conglomerate from a depth of 8,327 ft (2,538 m) in the Algarrobo 1 well (Fig. 5) are correlated with Santa Marta schists (Tschanz and others, 1974). This correlation demonstrates 100 to 115 km of left-lateral Tertiary separation on the Santa Marta fault system. Subsurface evidence from the El Difícil oil wells 20 km south of Algarrobo 1 also indicates about the same sinistral separation of Precambrian granulites, gneisses, and schists from the Sevilla metamorphic belt. Late Miocene compression across the fault is suggested by the uplift of the Santander massif. The Guayabo Group sediments that accumulated as the Santander massif began to rise have been identified as late Miocene–early Pliocene (James, 1977). This uplift age is supported by a 6-m.y. apatite fission-track age determination from the massif (Kohn, *in* Shagam, 1980). Pleistocene activity on the Santa Marta–Bucaramanga fault system is shown by deformed terraces and offset stream patterns (Campbell, 1968).

The Santa Marta massif (Sierra Nevada de Santa Marta, Fig. 9) is the highest range in Colombia (about 5,800 m) and one of the highest topographic reliefs (over 9 km) of any coastal mountain in the world. The structural relief is 12 km. The tremendous gravity high (180 mgal relative to the adjacent basins) over the Santa Marta massif (Case and MacDonald, 1973; Bonini and others, 1980; Kellogg and Bonini, 1982) indicates that the crystalline massif is out of local isostatic equilibrium and may have been thrust to the northwest on the Oca and Santa Marta faults (Case and MacDonald, 1973; Bonini and others, 1980). The gravity data are consistent with a low-angle thrust fault extending to the base of the crust. The symmetry of the topography, structure, and gravity anomalies suggests that the thrust-

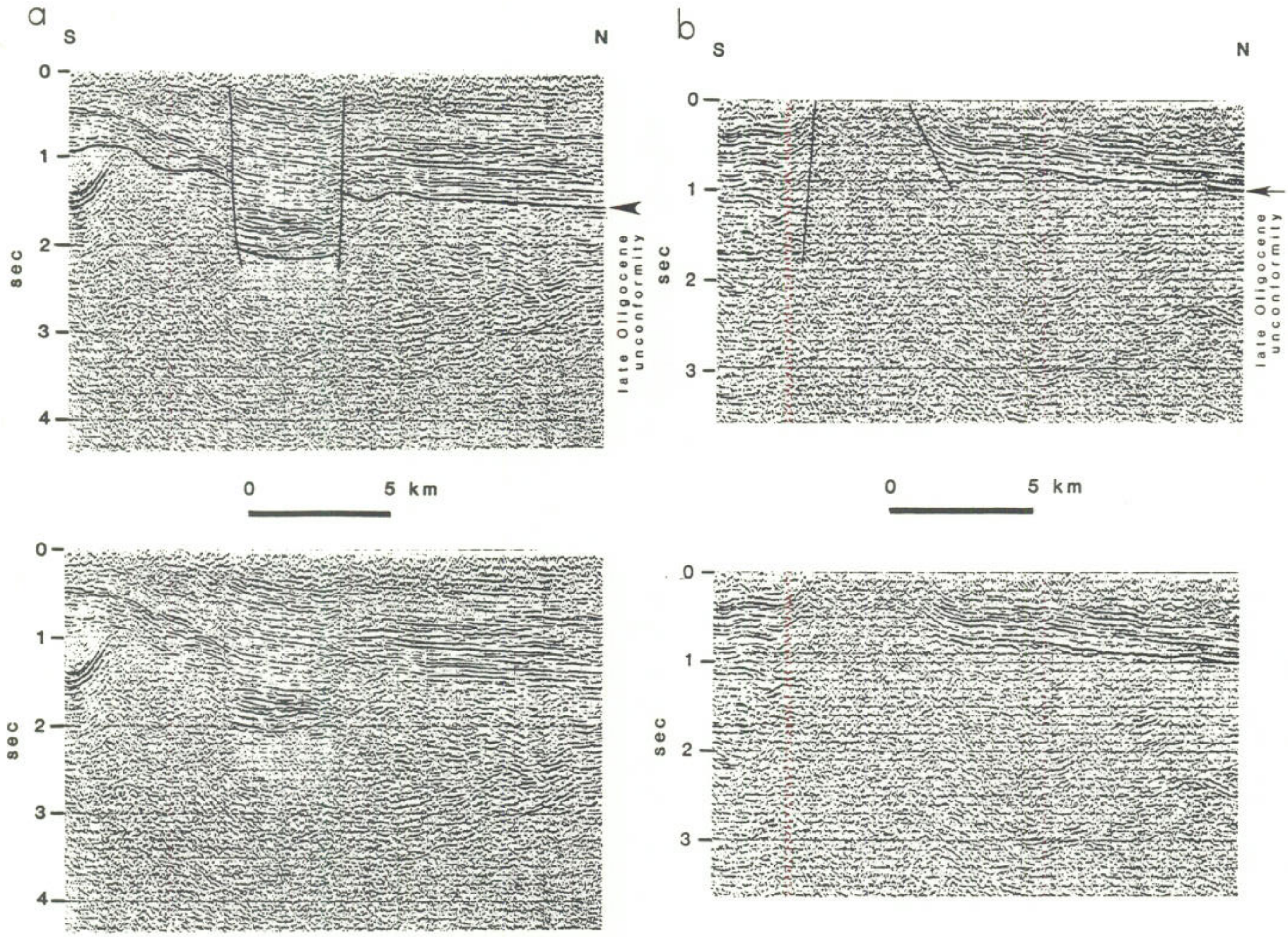


Figure 15. (a) Seismic line W-78-7 from the western Falcón area, Venezuela, showing a pull-apart graben displacing upper Tertiary sediments along the Oca fault (Western Geophysical Co. for Maraven, S.A., Venezuela). Location shown in Figure 14. (b) Seismic line W-78-12 from the western Falcón area, Venezuela, shows a horst displacing upper Tertiary sediments along the Oca fault (Western Geophysical Co. for Maraven, S.A., Venezuela). Location shown in Figure 14.

ing was to the northwest (312°), forming approximately equal angles of 30° to 35° with the Oca and Santa Marta faults. According to this interpretation, the faults accommodated late Tertiary oblique strike-slip (oblique reverse) motion, and their dips are low angle at their junction, increasing along strike to the east and southeast. Fault displacement is not predicted to have continued, at least in the late Tertiary, northwest of their junction. This model also implies that the movements on the Oca and Santa Marta faults have been contemporaneous and of similar magnitudes during the late Tertiary.

To the west of Santa Marta, uplift, folding, and faulting resulted from continued lateral compression during the Pliocene Andean orogeny (Duque-Caro, 1979). Underthrusting and turbidite deposition began on the northwest side of the newly active South Caribbean marginal fault. Mud volcanism and plutonism began in the Sinú trench sediments located west of the Sinú fault.

Venezuelan Andes

Stratigraphic and fission-track data show that the major Cenozoic uplift of the Venezuelan Andes (Fig. 9) was during the Pliocene-Pleistocene orogeny. Thick late Miocene to Pliocene conglomerates of the Betijoque Formation are found on the northwestern flank of the Andes. Rio Yuca Formation conglomerates of the same age were deposited on the southeastern flank (Léxico Estratigráfico de Venezuela, 1970). Late Tertiary oxisols formed near sea level were uplifted at least 2 km during the Pliocene-Pleistocene orogeny (Weingarten, 1977). Rapid uplift is also suggested by the extensive Pleistocene terraces high above the present river base levels (R. Giegengack, Department of Geology, University of Pennsylvania, personal commun., 1979). Further proof of Pliocene uplift of the Venezuelan Andes is supplied by apatite fission-track age determinations on 15 rock

samples ranging from 2 to 5 m.y. (Kohn, *in* Shagam, 1980). Using this radiometric age data, Shagam calculated an uplift rate for the Pliocene (5 to 1.8 m.y.) of 0.8 mm/yr.

The gravity low associated with thick deposits of low-density sediments on the northwest flank of the Venezuelan Andes (Fig. 9) can be modeled as northwestward (320°) overthrusting of the Maracaibo Basin by crystalline rocks of the Andes (Bonini and others, 1980). This model involves a low-angle thrust (22°–25°) extending into the mantle and overriding the Maracaibo Basin by 25 km. This fault is similar to the structural interpretations of the Wind River thrust fault in Wyoming based on gravity data and deep crustal reflection profiling (Smithson and others, 1979). Miocene-Pliocene northwestward folding and thrusting is also apparent in the sedimentological record of the Táchira Depression southwest of the Venezuelan Andes (Macellari, 1984).

In Falcón, late Pliocene northwest-southeast shortening produced northeast-southwest-trending (065°–075°) folds (Bucher, 1952; Wheeler, 1963). This folding may be at least partially related to dextral movement on the Oca fault system. In the Serranía del Interior of eastern Venezuela, mid-Miocene to Pliocene northwest-southeast shortening caused folding (075°) and thrusting (Hedberg, 1950; Salvador and Rosales, 1960; Lamb and Sulek, 1968; Vierbuchen, 1978).

Andean deformation is continuing in the present.

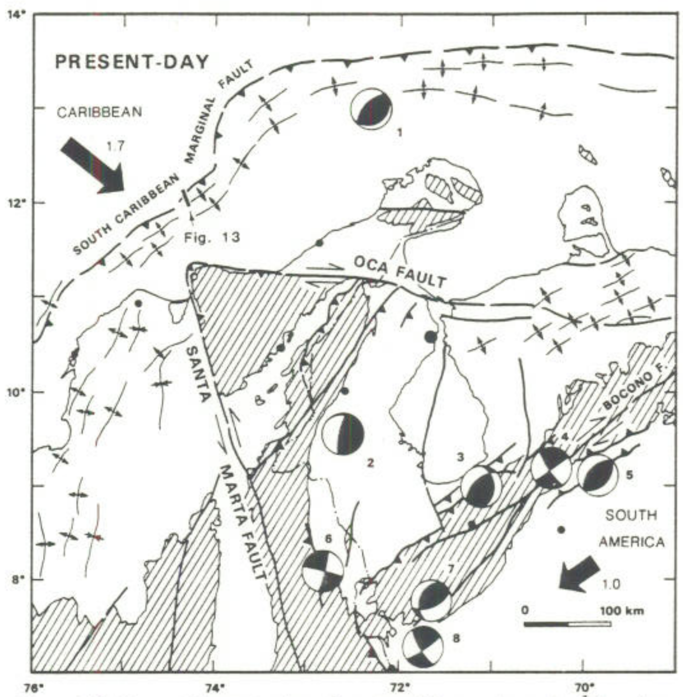


Figure 16. Present-day tectonics of western Venezuela and northeastern Colombia. Bold arrows show present plate motion vectors with respect to the North Andean block derived in this paper. Average velocities are given in centimetres per year. The eight earthquake focal mechanisms are based on P-wave first arrivals. Solution 1 was calculated by Vierbuchen (1978); 2 was by O. Perez, McCann, and A. J. Murphy (Lamont-Doherty Geological Observatory, Palisades, N.Y., unpub. data, 1978); 3, 4, 6, and 8 were by Dewey (1972); and 5 and 7 were by Perez and Aggarwal (1980). All plots are made on equal-area projections of the lower hemisphere of the focal sphere. Dark quadrants are compressional first motions. Source parameters are summarized in Table 1. Hachured areas are major uplifts with pre-Tertiary rocks exposed.

PRESENT-DAY TECTONICS

Introduction

The Caribbean–northwestern South America plate boundary has been controversial and difficult to interpret tectonically. The high seismicity and Holocene displacement on the northeast-trending Boconó fault (Fig. 16) have prompted some to interpret the Boconó fault zone as a Caribbean–South America plate boundary that accommodates east-west convergence (Molnar and Sykes, 1969; Schubert and Sifontes, 1970; Dewey, 1972; Santamaria and Schubert, 1974; Kafka and Weidner, 1981). The geologic, gravity, and seismic evidence for northwest-southeast convergence and the lack of geologic evidence for large displacements on the Boconó fault have led others to interpret the South Caribbean marginal fault (Fig. 16) as part of a diffuse Caribbean–South America plate boundary that accommodates northwest-southeast convergence (Jordan, 1975; Shagam, 1975; Case and Holcombe, 1980; Walper, 1980).

I propose that these features are simultaneous active and accommodate portions of the relative movement between the Caribbean, South America, and Nazca plates.

The Boconó and South Caribbean marginal faults form the eastern and northern boundaries, respectively, of the North Andean block. The North Andean block is bounded on the southeast by the East Andean fault and on the west by the Colombia trench. The North Andean block became detached from South America 3 or 4 m.y. ago and began to be wedged slowly to the north as the Nazca plate converged rapidly with the Caribbean and South American plates. The interpretation is based on earthquake focal mechanisms, hypocenter locations, seismic reflection profiles, and Quaternary geology.

Uplift Rates

Well-developed Pleistocene boulder terraces suggest rapid present-day uplift of the Sierra de Perijá and Venezuelan Andes (R. Giegengack, Department of Geology, University of Pennsylvania, personal commun., 1979). On the northwest margin of the Sierra de Perijá south of Manaure, terraces are 200 to 300 m above the river base level. On the southeast Perijá mountain front west of Machiques, the Pleistocene terraces contain boulders up to 2 m across (Fig. 17). A crude estimate of the late Pliocene–Pleistocene uplift rate for the Sierra de Perijá can be made from the 2.7-m.y. apatite fission-track ages of Kohn (*in* Shagam, 1980). Assuming a 100 °C closure temperature, an average crustal geothermal gradient of 25 °C/km, and an erosion rate equal to the uplift rate, the uplift rate = 100/(25) (2.7) km/m.y. = 1.5 mm/yr. In view of the low elevation (200 m above sea level) of

TABLE 1. SUMMARY OF SOURCE PARAMETERS FOR EVENTS 1 TO 8 IN FIGURE 16

Event	Date	Origin Time (UT)	m_b*	Depth† (km)	Latitude (deg)	Longitude (deg)	σ_1 (deg)
1	Mar 12, 1968	. .	. .	58	13.2 N	72.3 W	317
2	Nov 17, 1968	001610.1	5.7	175	9.55N	72.60W	280?
3	May 13, 1968	193605.8	4.8	29 5(ISC)	9.00N	71.06W	297
4	Jul 19, 1965	041321.2	5.3	20 31(ISC)	9.40N	70.28W	085
5	Mar 5, 1975	. .	5.5	shallow	9.04N	69.95W	313
6	Sep 2, 1964	181215.8	4.8	26	8.08N	72.78W	045/075
7	Composite focal mechanism solution for microearthquakes in Uribante-Caparo area						
	1979-1980	. .	. .	8-25	7.8 N	71.7 W	316
8	Dec 21, 1967	113724.5	5.4	29 8(ISC)	7.04N	72.02W	087/297

Note: The focal mechanisms in Figure 16 are based on P-wave first arrivals. Solutions 3, 4, 6, and 8 were calculated by Dewey (1972); solution 2 was calculated by O. Perez, McCann, and A. J. Murphy (Lamont-Doherty Geological Observatory, Palisades, NY, unpub. data, 1978); solutions 5 and 7 were by Perez and Aggarwal (1980); and solution 1 was calculated by Vierbuchen (1978). The estimates of the maximum principal stress direction (σ_1) are the azimuths of the axes of maximum pressure (Honda, 1962) for reverse fault solutions and 15 from the axes of maximum pressure for strike-slip fault mechanisms.

*Body wave magnitudes (m_b) are from the Earthquake Data Reports of the United States Coast and Geodetic Survey (USCGS) or the National Oceanic and Atmospheric Administration (NOAA).

†Depths are from the Earthquake Data Reports of USCGS or NOAA and the Bulletin of the International Seismological Center (ISC).

Figure 17. Photograph of one of the Pleistocene terraces on the southeastern Perijá mountain front near Río Negro (west of Machiques). The terraces contain boulders up to 2 m in diameter.

the sample locations, uplift probably did not exceed erosion by more than 200 m. On the other hand, the Pleistocene terraces suggest rapid Pleistocene uplift, so it is unlikely that Pleistocene erosion exceeded uplift by more than 1 km at the sample localities. The resulting range of predicted values for the uplift rate are 1.1 to 1.6 mm/yr. On the Cerrejón thrust fault (15° dip), this uplift rate would be equivalent to a horizontal slip rate of 1.5/tan 15° = 5.6 mm/yr. A similar Pleistocene uplift rate of about 1.1 to 1.6 mm/yr can be calculated from the Andean fission-track data. This is a slightly more rapid rate than that of 0.8 mm/yr calculated by Kohn and others (1982) for the Pliocene (3 to 6 m.y.), suggesting an increase in the Andean uplift rate during the Pleistocene.

Northwest-Southeast Compression

The northwest-southeast maximum principal stress direction that has characterized the Maracaibo–Santa Marta block and most of the Caribbean–South American margin throughout the Cenozoic continues to the present. Present-day northwest-southeast convergence across the Caribbean–South American plate boundary has been deduced from North American–South American relative plate motions (Ladd, 1976; Pindell and Dewey, 1982) combined with Caribbean–North American relative motion (Jordan, 1975; Minster and Jordan, 1978) and compressive deformation in the southern Caribbean (Krause, 1971; Shepard, 1973: Case, 1974; Bowin, 1976; Talwani and others, 1977; Ladd and Watkins, 1979; Sinton, 1982). Present-day northwest-southeast compression along the Caribbean–South American margin is also indicated by earthquake focal mechanism solutions that have been determined from P-wave first motions (Dewey, 1972; Vierbuchen, 1978; Perez and Aggarwal, 1980; Kellogg and Bonini, 1982). Five of these focal mechanisms are the thrust fault solutions for events 1, 2, 3, 5, and 7 shown in Figure 16. The source parameters for the earthquakes are listed in Table 1. The events were described in more detail by Kellogg and Bonini (1982).

The maximum principal stress direction (σ_1 in Table 1) can be estimated from the azimuths of the axes of maximum pressure (Honda, 1962) for reverse-fault focal mechanisms. The σ_1 estimates for the shallow reverse faults in Figure 16 are 297°, 313°, 316°, and 317°. These values correspond well with estimates of maximum compressive stress directions based on structural and gravity data for the Sierra de Perijá (299°), the Santa Marta massif (312°), and the Venezuelan Andes (320°).

There have been few major historic earthquakes along the Oca fault system, but north of Sinamaica the fault does displace a series of Quaternary beach strandlines (Miller, 1962) and a shell horizon with a Carbon-14 age determination of 2,500 yr (Cluff and Hansen, 1969). On May 3, 1849, an earthquake near Maracaibo with a maximum modified Mercalli scale (MM) intensity of VII damaged most large buildings and collapsed others (Cluff and Hansen, 1969). Pleistocene activity on the Santa Marta–Bucaramanga fault system is demonstrated by deformation in Pleistocene terraces and offset stream patterns (Campbell, 1968).

Fault plane solutions for earthquakes in eastern Venezuela also indicate present-day, northwest-southeast-trending compression (Rial, 1978; Kafka and Weidner, 1979; Perez and Aggarwal, 1981). The maximum principal stress direction for events in eastern Venezuela can be estimated as 320° ± 20° (Kellogg and Bonini, 1982).

East-West Compression and the Boconó Fault

Present-day east-northeast–west-southwest compression is indicated by the three focal mechanisms determined for events 4, 6, and 8 in Figure 16 (Dewey, 1972; Kafka and Weidner, 1981). It is also suggested by Quaternary displacement and major historic earthquakes on the Boconó fault.

The Boconó fault trends in a northeast-southwest direction (050°–055°) through the Venezuelan Andes. Measurements of offset stream channels, terrace deposits, alluvial fans, and glacial moraines demonstrate approximately 100 m of Holocene right-lateral displacement (Cluff and Hansen, 1969; Schubert and Sifontes, 1970. The average rate of strike-slip motion on the fault for the past 10,000 yr is approximately $100 \text{ m}/10^4 \text{ yr} = 1 \text{ cm/yr}$. Up to 800 m of postglacial south-side-up vertical displacement has also been observed on the fault (Giegengack and others, 1976). The largest estimate of right-lateral offset along the Boconó fault is 100 km (Stephan, 1977a) based on an apparent offset of the Caribbean frontal thrust. Rod and others (1958) claimed 30 to 70 km of cumulative right-lateral displacement on the fault, but most estimates are less than 50 km. Therefore, a 1 cm/yr slip rate on the Boconó could only have begun 10 m.y. ago at the earliest and may have begun only 3 or 4 m.y. ago.

Numerous large historic earthquakes have occurred on the Boconó fault system including the great earthquake of March 26, 1812 (MM intensity = XI; magnitude = 8; Cluff and Hansen, 1969). Since the advent of instrumental recordings the Boconó fault zone has been the most seismically active zone in northwestern Venezuela. Events 4, 6, and 8 (Fig. 16) are described in more detail by Kellogg and Bonini (1982).

The 60° to 65° angle between the Oca and Santa Marta fault systems suggests that Coulomb fracture criteria (ϕ = 30°) may be applicable to the major oblique wrench faults delineating the Maracaibo–Santa Marta block. If the regional stress regime that results from plate motion causes Navier-Coulomb failure, the maximum compressive stress direction (σ_1) can then be estimated as 30° from the fault plane of a strike-slip fault and 15° from the axis of maximum pressure in the focal mechanism. The predicted oblique strike-slip (oblique thrust) motion on the Oca and Santa Marta faults implies that the intermediate and least principal stresses are approximately equal in magnitude. As surface wave and geologic information specify the probable fault planes for events 4 and 8, σ_1 can be estimated as east-west (085° and 087°). Because of a lack of surface wave and geologic information, σ_1 for event 6 may be either 045° or 075°, although 075° is more

likely in view of the correlation with events 4 and 8. These compressive stress directions are close to the east-west (084°) relative convergence vector for the Nazca and South American plates (Stauder, 1975; Minster and Jordan, 1978). Focal mechanism solutions for earthquakes reveal that a zone of faults with similar dextral strike-slip motion extends along the entire eastern front of Colombia's Eastern Cordillera from Venezuela to Ecuador (Pennington, 1981).

The East Andean and Boconó fault zones mark the present eastern boundary of the tectonically active North Andean convergent zone. If we assume that the North Andean convergent zone is now moving as a semi-rigid block, we can add the South American–North Andean vector (1 ± 0.2 cm/yr; 235° ± 5°) and the Caribbean–South American vector (2.2 ± 0.5 cm/yr; 102° ± 10°) derived by Minster and Jordan (1978) to obtain the Caribbean–North Andean vector shown in Figure 16 (1.7 ± 0.7 cm/yr; 128° ± 24°). The mean direction of the Caribbean–North Andean vector (128° ± 24°) is almost identical to the mean maximum principal stress direction for the Maracaibo–Santa Marta area (130° ± 10°) inferred from earthquake focal mechanism determinations and structural and gravity data (Kellogg and Bonini, 1982).

We can also add the South American–North Andean vector and the Nazca–South American vector (Minster and Jordan, 1978) to obtain the Nazca–North Andean vector (6.4 ± 0.7 cm/yr; 088° ± 7°).

Subduction of the Caribbean beneath South America

Significant Cenozoic underthrusting of Caribbean oceanic lithosphere beneath South American continental lithosphere has been deduced from sedimentological (Duque-Caro, 1979) and gravity data (Case and MacDonald, 1973; Bonini and others, 1980). Present-day subduction along the South Caribbean marginal fault is indicated by folding and thrusting in the deformed belt and earthquake focal mechanisms and hypocenter locations.

The Colombian and Venezuelan basins are separated from the South American coast by a belt of deformed Tertiary and Quaternary sediments. Seismic reflection records from the Colombian Basin (Krause, 1971; Shepard, 1973; Case, 1974; Kellogg and Bonini, 1982) and the Venezuelan Basin (Silver and others, 1975; Talwani and others, 1977; Ladd and Watkins, 1979; Diebold and others, line 119, 1981; Sinton, 1982) show that the belt of deformed sediments is being compressed, folded, and thrust to the north and west over Caribbean oceanic crust. Mud volcanism and diapiric intrusion are presently active near Cartagena and northwest of Santa Marta, as a consequence of lateral compression in the deformed belt (Shepard, 1973; Higgins and Saunders, 1974) and/or methane genesis in the organic-rich Miocene-Pliocene sediments (H. Hedberg, Gulf Oil Exploration and Production Co., Houston, Texas, personal commun., 1983).

In Figure 18, earthquake hypocenters from Sykes and Ewing (1965) and Dewey (1972) have been projected onto a

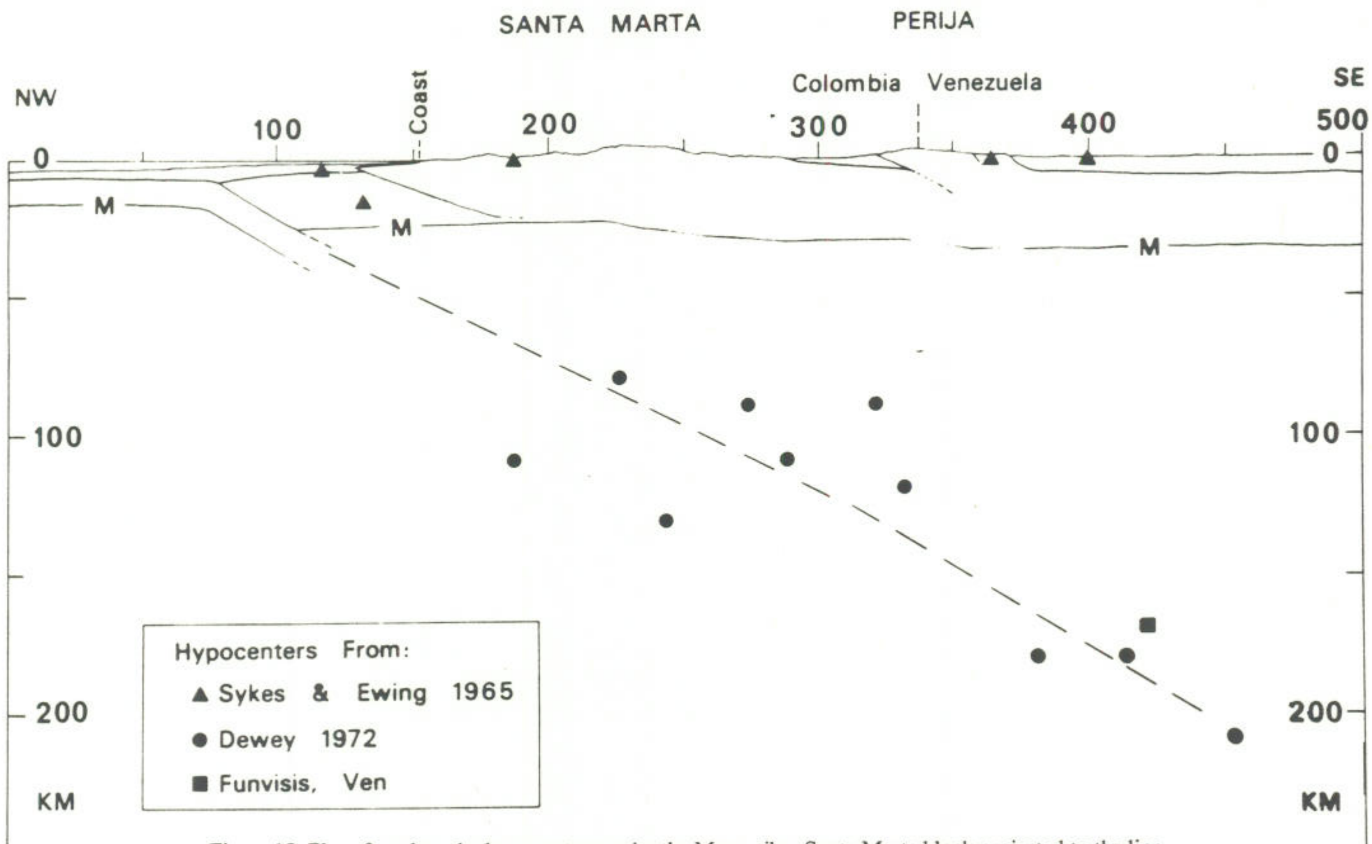


Figure 18. Plot of earthquake hypocenters under the Maracaibo–Santa Marta block projected to the line of section in Figure 9 from the Colombian Basin to the Maracaibo Basin.

northwest-southeast cross section through the Sierra de Perijá and the Santa Marta massif. The earthquakes occurred in a southeast-dipping seismic zone recognized by Dewey (1972) and Pennington (1981). The seismicity terminates 200 km below the Maracaibo Basin. The down-dip length of the Benioff Zone is about 380 to 400 km. Uplift and folding of Miocene-Pliocene pelagic sediments west of the Sinú fault suggest that subduction has moved from the Sinú trench 50 km northwest to the South Caribbean marginal fault in the past 10 m.y. (Duque-Caro, 1979). If one assumes that the thickness of the lithosphere is 100 km, that the Benioff Zone started with an initial length equivalent to the rupture of the lithosphere 100 km/sin 30° = 200 km, and that the equilibration time for a cold slab is 10 m.y. (Isacks and others, 1968), then the horizontal subduction rate is (390–200 km) $/10^7$ yr = 1.9 ± 0.3 cm/yr. This is similar to the 1.7 ± 0.7 cm/yr Caribbean–North Andean convergence rate derived in this paper.

The P-wave-derived fault plane solutions for events 1 and 2 in Figure 16 are consistent with subduction in a southeast-dipping zone. Event 1 was produced by thrust faulting at a depth of 58 km below the deformed belt southeast of the South Caribbean marginal fault (Vierbuchen, 1978). The nodal plane dipping shallowly to the southeast coincides with the predicted zone of subduction. Event 2 was a deep earthquake (175 km) located southeast of the Sierra de Perijá. The focal mechanism determination (O. Perez, McCann, and A. J. Murphy, Lamont-Doherty Geological Observatory, Palisades, N.Y., unpub. data, 1978) can be explained by east-southeast downdip tension on the down-going Caribbean lithosphere.

SUMMARY AND CONCLUSIONS

Eight major Phanerozoic tectonic phases have been identified in the Sierra de Perijá. The last four of these occurred in the Cenozoic: the lower Eocene tectonic phase, the middle Eocene Caribbean orogeny, the late Oligocene phase, and the upper Miocene to present Andean orogeny.

During the late Oligocene phase the Palmar area east of the Tigre fault was raised 3 to 4 km along this fault and tilted 7° to the southeast (Fig. 8). The structure was truncated by a major erosional unconformity that is responsible for the most important hydrocarbon trapping in the Lake Maracaibo oil fields. This unconformity had been generally assumed to be late Eocene or early Oligocene, but a reexamination in this paper of recent published paleontological evidence reveals that the unconformity could be as young as late Oligocene. It is also shown that the Oligocene phase was the only period of uplift and erosion that could have been consistent with three late Oligocene (25 m.y.) apatite fission-track ages from the Sierra de Perijá (Kohn, *in* Shagam, 1980).

During the Andean orogeny the main uplift of the Sierra de Perijá occurred, the frontal monocline folded on the southeast flank of the Sierra, and the Manuelote syncline and Mostrencos arch were formed. The predicted Pliocene age is based on stratigraphic relationships and new radiometric data. The apatite fission-track ages of Kohn (*in* Shagam, 1980) were used to estimate the uplift rate for the range: 1.5 mm/yr in the upper Pliocene-Pleistocene.

Right-lateral, oblique-slip displacement of 40 ± 8 km on the Oca fault zone is related to Cenozoic northwest-southeast shortening in the northern Sierra de Perijá. Combining this value with previous estimates of movement on the Oca fault in Colombia, a total Tertiary oblique dextral slip of 90 ± 8 km is predicted for the fault zone east of the Sierra. Published estimates of North American–South American and Caribbean–North American movements have also been used by Kellogg and Bonini (1982) to deduce 600 to 1,000 km of upper Tertiary Caribbean–South American convergence in a west-northwest–east-southeast direction. If these estimates of slip on the Oca fault and Caribbean-–South American convergence are correct, the upper Tertiary slip on the Oca fault zone was an order of magnitude too small for the fault to be the Caribbean–South American boundary.

Most of the upper Tertiary Caribbean–South American convergence occurred on the Romeral, Sinú, and South Caribbean marginal faults. The Panama volcanic arc collided with South America 3 m.y. ago, forming the land bridge between North and South America. The Northern Andes were uplifted on deep thrust faults, and the North Andean block became detached from South America and is being wedged slowly to the north as the Nazca plate converges rapidly with the Caribbean and South American plates. Slow present-day subduction of Caribbean oceanic lithosphere beneath North Andean continental lithosphere is indicated by folding and thrusting in the deformed belt and earthquake focal mechanisms and hypocenter locations. The seismic zone dips 30° to the southeast and terminates 200 km below the Maracaibo Basin (Fig. 18).

The Quaternary Caribbean–North Andean convergence (1.7 ± 0.7 cm/yr; 128° (308°) ± 24°) has produced a northwest-southeast maximum principal stress direction (σ_1) in the overriding North Andean plate. The mean σ_1 direction for the Maracaibo–Santa Marta block is 310° ± 10° based on earthquake focal mechanism determinations, structural, and gravity data (Kellogg and Bonini, 1982).

Rapid convergence of the Nazca and South American plates has produced rapid subduction at the Colombia trench on the west side of the North Andean block and right-lateral shear along the Boconó fault on the east side of the North Andean block.

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