Structural Evolution of the Northernmost Andes, Colombia

GEOLOGICAL SURVEY PROFESSIONAL PAPER 846

Prepared in cooperation with the Instituto Nacional de Investigaciones Geológico-Mineras under the auspices of the Government of Colombia and the Agency for International Development, United States Department of State

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By EARL M. IRVING

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An interpretation of the geologic history of a complex mountain system

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STRUCTURAL EVOLUTION OF THE NORTHERNMOST ANDES, COLOMBIA

By Earl M. Irving

ABSTRACT

The primeval Guayana shield of northern South America is older than the metamorphism of the eugeosynclinal Imataca Complex of southeastern Venezuela which took place at least 3,000 m.y. ago. Metamorphism and two granitic magma cycles welded the shield area into a stable craton between 2,250 and 1,850 m.y. (Guyanese). To the west and probably to the north the shield rocks are younger; in Colombia the oldest known rocks are about 1,350 m.y. old (Orinocan). This Precambrian crust extends well into the Andean Cordillera and appears to have provided a platform for ensialic miogeosynclinal sedimentation during much of Phanerozoic time.

During the Paleozoic Era a pericontinental eugeosyncline developed along and around the western and northern margin of the platform. In late Paleozoic time, miogeosynclinal sediments near the edge of the platform and sediments and volcanic material in the adjoining eugeosyncline were regionally metamorphosed along an arcuate fold belt (late Paleozoic orogen) that included the areas of the present Central Cordillera, the central part of the Sierra Nevada de Santa Marta, and the Guajira Peninsula; the uplift and deformation at this time produced the central northeast-trending arcuate crystalline spinal column of the present Colombian Andes. During the Mesozoic Era a second eugeosyncline formed outside the late Paleozoic orogenic arc; at the close of the Cretaceous the eugeosynclinal deposits were strongly folded but only locally metamorphosed. This orogeny formed the Western Cordillera and coeval fold belts (Late Cretaceous orogen) along the northeastern Caribbean coast of Colombia. The immense Antioquian batholith and several satellitic intrusions were emplaced along the inner side of the Late Cretaceous orogenic arc. In the middle Eocene and again in the Oligocene-early Miocene, small posttectonic granitic plutons were emplaced along the late Cretaceous orogenic axis. During the middle Tertiary Andean orogeny, the intracratonic Eastern Cordillera rose along sharp marginal flexures, high-angle reverse faults that dip toward the cordillera, and locally along wrench faults.

The present trident Andean Cordilleras of northernmost Colombia therefore are distinctive geologically and came into being at different times. High positive Bouguer anomalies in westernmost Colombia and abyssal to bathyal lower Tertiary sedimentary rocks overlying mafic volcanic rocks in easternmost Panama suggest that the Isthmus of Panama probably is of oceanic crustal origin and became connected to and associated with the Andes during the Andean orogeny.

Little attrition is recognized along the western edge of the continent at the latitude of Colombia (0°–9° N.). To the contrary, accretion by an unknown amount is probable during the late Paleozoic orogeny, and more than 100 miles was added to the continental margin during the Late Cretaceous orogeny. In northernmost Colombia, east-trending Caribbean structures intercept Andean structures and are therefore younger. Late Tertiary epeirogenic uplift accompanied by faulting produced much of the present relief.

INTRODUCTION

The Cretaceous and Tertiary sedimentary basins of Colombia have been studied in detail for more than half a century by geologists searching for petroleum. However, the pre-Cretaceous formations have hardly received their deserved attention except for the monumental work of Grosse (1926) in western Antioquia and reconnaissance studies by Hubach and Alvarado (1934), Hubach (1957a, b), Trumpy (1943), Gansser (1954, 1955), Bürgl (1961), Radelli (1967), and Stibane (1967).

In the decade of the 1960's, several intensive studies of pre-Cretaceous formations were undertaken in connection with regional mapping programs. Beginning in 1962, Princeton University students (MacDonald, 1964; Lockwood, 1965; Alvarez, 1967) undertook field studies for doctoral dissertations on the basement rocks of the Guajira Peninsula in extreme northeastern Colombia. Prof. Gerardo Botero Arango in 1963 published the results of his studies of the western half of the Antioquian batholith and its encasing rocks. In 1964, under a cooperative program financed by the Ministry of Mines and Petroleum of the Government of Colombia and the Agency for International Development, U.S. Department of State, the U.S. Geological Survey in collaboration with the Colombia Instituto Nacional de Investigaciones Geológico-Mineras (formerly Inventario Minero Nacional) undertook systematic investigations of selected areas in northern Colombia. More than 60 Colombian geologists participated for various periods of time during the 6-year program. Geologists of the U.S. Geological Survey who were associated with the program were Charles M. Tschanz (in the Sierra Nevada de Santa Marta);

Richard Goldsmith, Dwight E. Ward, and Donald H. McLaughlin, Jr. (in the Eastern Cordillera); and Tomas Feininger, Robert B. Hall, and Laurence V. Blade (in the Central Cordillera).

This paper endeavors to synthesize the history and origin of the northernmost Andes on the basis of the results of this work and much recent data gathered by others in the region. The extensive use of my Colombian and American colleagues' data is fully and gratefully acknowledged, although I alone am responsible for the tectonic concepts herein outlined.

Special appreciation is extended to Drs. Aurelio Lara A. (deceased), Dario Suescún G., and Andrés Jimeno V., respective Directors of the Instituto Nacional de Investigaciones Geológico-Mineras (hereinafter referred to as Ingeominas) and its predecessor agencies, who provided unqualified support for the program. Richard Marvin and his associates, U.S. Geological Survey, very kindly supplied many new radiogenic age determinations, without which important tectonic events in the area could not have been dated satisfactorily.

PRINCIPAL GEOMORPHIC-STRUCTURAL PROVINCES OF COLOMBIA

The Republic of Colombia borders on the Isthmus of Panama and occupies the "turn of the corner" of the northwestern part of the South American Continent. South of Colombia the basement rocks of the Andean Cordillera, along a belt some 5,000 miles long, apparently constitute a single, though complex, orogen. In Colombia, the Andes mountains divide into three subcordilleras known as the Eastern, Central, and Western Cordilleras (fig. 1). The Central Cordillera appears to be the northerly extension of the basement rocks underlying the Cordillera Real of the Ecuadorian Andes. Approximately at the equator the Eastern and Western Cordilleras branch off from this Central Cordillera. In northern Colombia, the Western and Central Cordilleras are overlapped and concealed by a Tertiary sedimentary wedge that adjoins the Caribbean Basin. At lat 70° 30′ N., the Eastern Cordillera bifurcates, and the main branch of that range passes northeasterly into Venezuela, where it is known as the Merida Andes; a somewhat smaller prong, the Serranía de Perijá, extends northward until it terminates against the Oca fault (pl. 1). The triangular mountain block of the Sierra Nevada de Santa Marta, 19,000 feet in altitude at its highest point, is set off to one side from the Serranía de Perijá and lies on the rim of the Caribbean Basin.

Where the southeast-trending Isthmus of Panama joins the South American Continent, its hills veer southward to become the coastal Serranía Baudó, or Pacific Coast Hills, and its central syncline continues as the Atrato synclinorium (fig. 1). The Atrato synclinorium merges southward with the Pacific Coastal Basin of southwestern Colombia. The thick Tertiary strata of the lengthy north-trending Atrato synclinorium separate the basement rocks of the Isthmus and the Pacific Coast Hills from those of the Western Cordillera.

Of particular interest is the multiple bifurcation and the general "fleur de lis" pattern of the trident Colombian Andes.

PRECAMBRIAN ROCKS IN RELATION TO THE GUAYANA SHIELD

The northern Andean orogen borders the Guayana shield on the west in Colombia and on the north in Venezuela (fig. 2). The history of the shield is reviewed briefly here to demonstrate how far the shield extends westward and northward into the cordilleran system and to establish the part that these rocks have played in the geologic and structural history of the Colombian Andes.

The oldest rocks of the Guayana shield appear to be gneissose migmatites in the Haut Sinnamary district of French Guiana. Choubert (1964) reported that four radiogenic age determinations on alluvial zircon derived from these rocks range from 4,100 to 3,770 m.y. These extreme ages appear to be suspect.

At least one and possibly several narrow east-trending eugeosynclinal belts developed upon the primitive shield. The eugeosynclinal rock groups are referred to as the Ile de Cayenne in French Guiana (Choubert, 1964), the Adampada-Fallawatra in Surinam (Holtrop, 1968), the Kanukú in Guyana (Williams and others, 1967), and the Imataca Gneiss Complex in Venezuela (Kalliokoski, 1965; Martin-Bellizzia, 1968). Metamorphism of the Imataca Complex in eastern Venezuela is now well established at more than 3,000 m.y. (Posadas and Kalliokoski, 1967; Hurley, Kalliokoski, and others, 1968). Williams, Cannon, and McConnell and others (1967, p. 42), regarded the younger Barama-Mazaruni assemblage in Guyana, on the basis of radiogenic dating by Snelling, to have a minimum age of 2,500 m.y. The subjacent migmatites are rarely distinguishable from the highly metamorphosed eugeosynclinal rock groups deposited upon them. The eugeosynclinal rocks are commonly in the high amphibolite to gran-

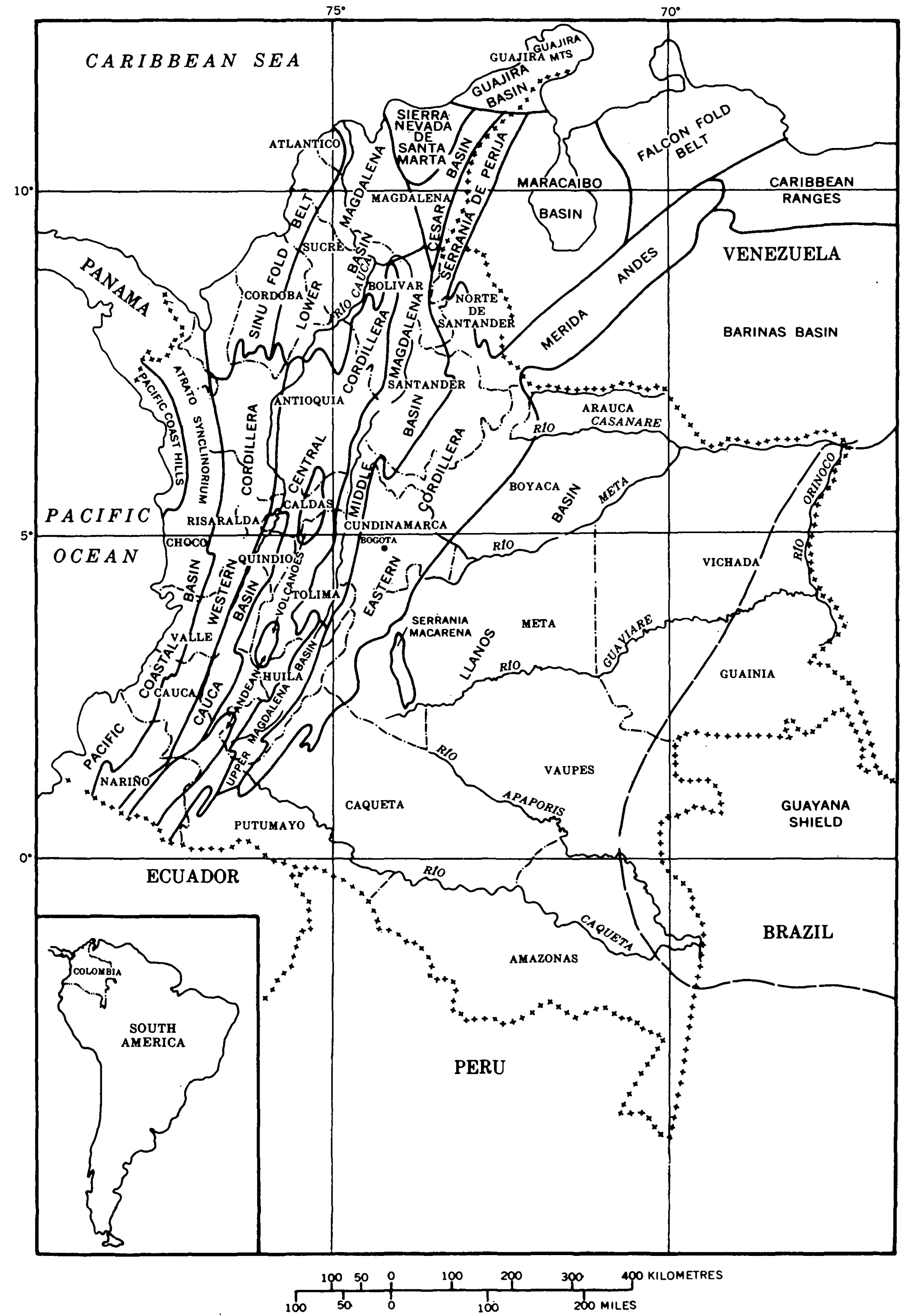

FIGURE 1.—Principal structural provinces of Colombia.

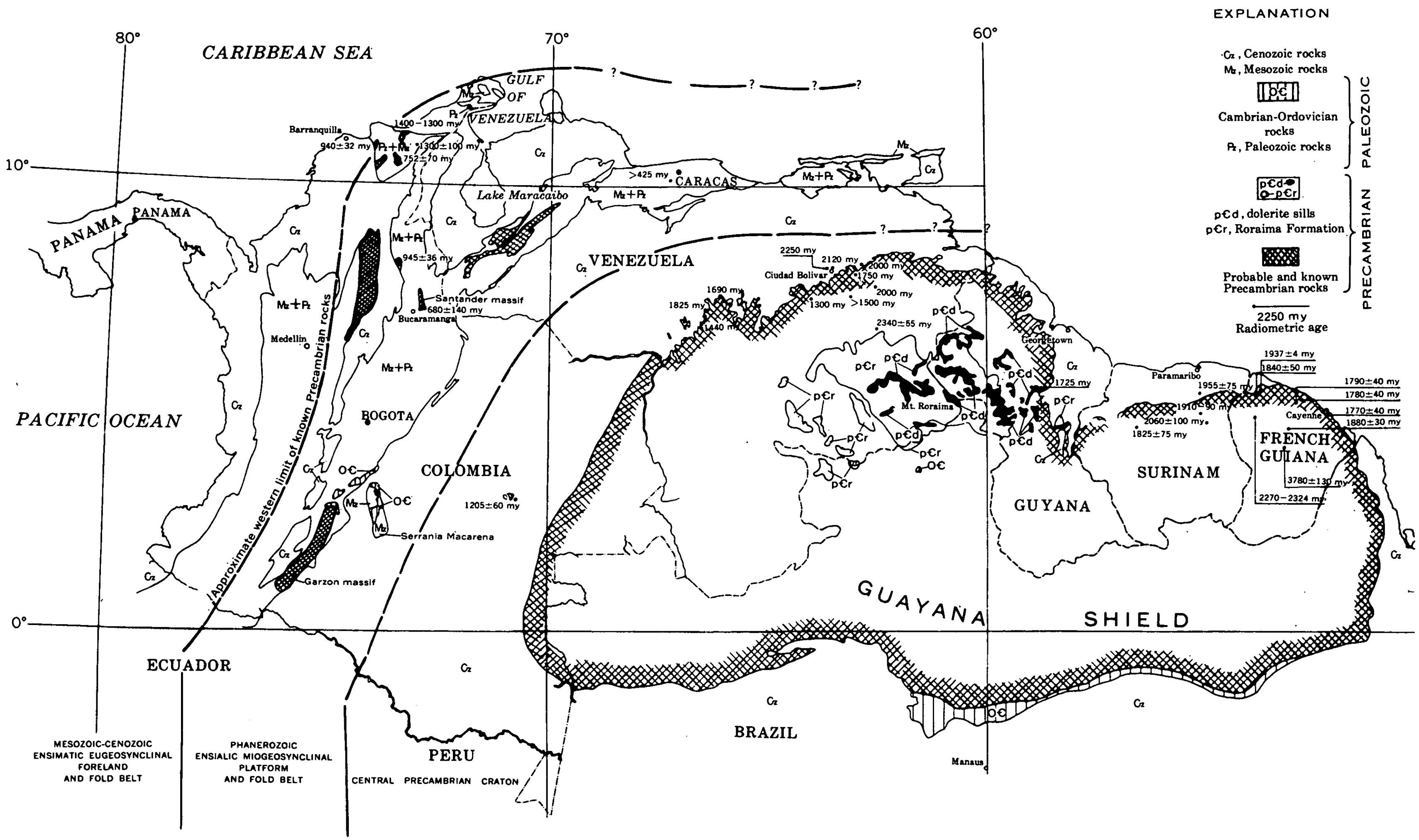

FIGURE 2.—Sketch map of northern South America showing major tectonic subdivisions, the distribution of Precambrian and Cambrian-Ordovician rocks, and radiogenic ages.

ulite facies of regional metamorphism. Their high grade of metamorphism suggests steep geothermal gradients and probably active flow of fluids from the mantle into the crust, most especially during orogenies. The early eugeosynclinal belts may have formed as depositories upon a relatively thin granitic crust, in the manner suggested by Anhaeusser, Mason, Viljoen, and Viljoen (1969) for the greenstone belts of the South African shield.

These high-grade metamorphic rocks are overlain unconformably by younger sedimentary and volcanic formations—for example, the Carichapo and Pastora Series of Venezuela—which are also metamorphosed and are widely intruded by granitic batholiths and plutons of the Akawaian episode (Snelling and McConnell, 1969), also known as the Guyanese or Transamazonas igneous cycle. Radiometric ages on these plutons range from 2,250 to 1,850 m.y. (fig. 2). At least two magmatic cycles can be distinguished during this time span; in the Guayanas they are referred to as "younger" and "older" granites (Choubert, 1964; Williams and others, 1967; Holtrop, 1968).

In southern Surinam and Guyana, and in southeastern Venezuela, the above-mentioned metamorphic and intrusive rocks are beveled by a major unconformity and are overlain by the widespread, relatively flat lying Roraima Formation (fig. 2), which is composed of conglomerate, red orthoquartzite, and minor shale and jasper (Sellier de Civieux, 1956, p. 509). These sedimentary rocks are extensively intruded by mafic sills, some of which are enormous in size and in outcrop area, and are locally as much as 1,200 feet thick.

Snelling (1963) analyzed a hornblende-pyroxene mixture from one of these sills, the Kopinang Valley dolerite, and obtained a K/Ar age of 1,665 ± 130 m.y. On muscovite from a mica hornfels taken 5 feet above the upper contact of the same dolerite sill, he obtained an age of 1,735 ± 70 m.y. These ages, averaging about 1,700 m.y., are now confirmed by many K/Ar analyses and by Rb/Sr whole-rock determinations. Of course the sedimentary rocks are older than the sills that cut them. The lack of later orogenic and igneous activity in the region of the Roraima Formation clearly establishes that the central part of the Guayana shield was converted into a craton upon intrusion of the granites about 2,000 m.y. ago and that it has been a stable cratonic mass throughout subsequent geologic time.

The Guayana shield passes out to sea to the east, descends sharply southward beneath a Cambrian-Ordovician and younger sedimentary cover of the Amazon River Valley, but descends very gently northward beneath Cenozoic strata of the Barinas Basin, sensu lato, of Venezuela, and westward beneath similar strata of the Llanos Basin (fig. 1) in Colombia. Examination of structure-contour (Smith, 1962) and geologic maps of Venezuela and Colombia suggests in fact that the Andean Cordilleras wrap around the Guayana shield on its north and west sides.

In northern Surinam, gneiss and biotitic granite were emplaced in almandine-diopside-hornblende metamorphic rocks, from which Holtrop (1968, p. 505) reported a whole-rock Rb/Sr age of 1,250 ± 40 m.y. In northern Guyana a disturbance locally called the Nickerian episode produced mylonitization and caused resetting of K/Ar ratios in many rocks 1,300–1,100 m.y. ago (Williams and others, 1967). At several points along the periphery of the exposed shield in southern Venezuela, radiogenic ages of about 1,300 m.y. have been measured on intrusive rocks that are referred to the Orinoco igneous cycle (Martin-Bellizzia, 1968).

Rocks of similar radiogenic ages are represented in Colombia by a suite of granitic rocks collected by Manuel Carvajal from exposures along the Guaviare River (lat 3°00′ N., long 70°43′ W.). Radiogenic analyses of these rocks by Pinson, Hurley, Mencher, and Fairbairn (1962) gave ages of 1,205±60 m.y. (fig. 2). Banded granulitic quartz-feldspar and mafic paragneiss collected by C. M. Tschanz (written commun., 1969) in the Sierra Nevada de Santa Marta gave radiometric ages of 1,300±100 m.y. MacDonald and Hurley (1969) obtained Rb/Sr whole-rock ages between 1,400 and 1,300 m.y. on four specimens of similar granulite collected by MacDonald from the northeastern Sierra Nevada de Santa Marta. Very recently MacDonald (written commun., 1972) collected specimens of granite near Jojoncito, Guajira Peninsula, whose contained zircon gave an age of 1,250 m.y. The granite is believed to be late Paleozoic in age. The great age indicated by the zircon suggests that the granite traverses, and probably has assimilated, underlying Precambrian rocks.

Tomas Feininger (written commun., 1969) mapped granulite west of the Middle Magdalena Basin that is overlain by graptolite-bearing Ordovician strata, and Darío Barrero L. reported (written commun., 1970) similar granulites near Payandé and Rovira in the Department of Tolima (fig. 1) and in the Garzón massif in southern Colombia (fig. 2). No radiogenic age determinations, however, have been made for these probable Precambrian rocks. These data establish that Precambrian rocks do extend well into the cordilleran region and generally have younger radiogenic ages than do rocks of the central shield. These outer shield rocks may be older rocks whose radiogenic clocks have been reset by more recent tectonic events. This interpretation indeed is indicated by retrograde metamorphism in many outer shield rocks.

In westernmost Sierra Nevada de Santa Marta (lat 10°40′ N., long 74°08′ W., fig. 1), hornblende from a garnet-hornblende-pyroxene-feldspar granulite collected by C. M. Tschanz gave an apparent age of 940±32 m.y. (fig. 2). In the Eastern Cordillera, hornblende from an amphibolite in the Bucaramanga Gneiss, collected by Richard Goldsmith west of the Santa Marta-Bucaramanga fault (pl. 1; lat 8°17′ N., long 73°25′ W.), gave a K/Ar age of 945±36 m.y. Both could be minimum ages. The approximate correspondence in age could be interpreted as follows: (1) the Santa Marta granulite sample is an older deep-seated metamorphic rock whose radiogenic clock has been reset and (2) the amphibolite, which is interbedded with paraschist and paragneiss of the Bucaramanga Gneiss possibly represents a younger Precambrian stratigraphic unit that never achieved the depth of burial nor as high a temperature as that of the granulite facies. H. N. A. Priem and others (1966) reported K/Ar ages on biotite from the tin-bearing granites of Rondonia (northwest Brazil) to be 960 to 930 m.y. This clustering of the dates suggests that a regional disturbance may have involved the western edge of the continent at this time.

On the southeast side of the Sierra Nevada de Santa Marta, Tschanz collected quartz-perthite gneiss samples from the Los Mangos Granulite Series that yielded ages of 752±70 m.y. Goldsmith collected a sample of paragneiss (lat 7°16′ N., long 72°54′ W.) in the Santander massif (fig. 2) of the Eastern Cordillera from which whole-rock Rb/Sr analysis gave an apparent age of 680±140 m.y. Although the negative deviation could throw the Santander sample into the Cambrian Period, regional considerations indicate a Precambrian age.

The westernmost outcrops of Precambrian rocks in Colombia are along the west side of the Sierra Nevada de Santa Marta, along the eastern side of the Central Cordillera, and in the Garzón massif of the southern Eastern Cordillera. Because these westernmost Precambrian rocks are commonly bounded by major faults at the surface, rocks of this age presumably extend at least some additional distance westward in the subsurface.

To summarize, the oldest Precambrian rocks of northern South America are in the east-central part of the Guayana shield, and radiogenic ages decrease irregularly by large increments northward and westward. Thus, the peripheral rocks of the shield, even though of similar metamorphic rank to those of the interior, appear to have been involved in younger tectonic events. The sequential relations might be interpreted as a growth pattern, but it is more likely that the outer edges of the shield experienced late Precambrian orogenies that reset the isotopic clocks of older rocks. The outer edge of the shield, of course, is in the zone of interaction between the continent and oceanic crust, where many adjustments can be expected to have taken place. The shield rocks, nevertheless, provided a comparatively stable platform for epicontinental and miogeosynclinal sedimentation during Phanerozoic time.

PHANEROZOIC SEDIMENTATION AND OROGENY

LOWER PALEOZOIC ROCKS AND OROGENY

Fossiliferous Cambrian and Ordovician sedimentary rocks have been identified at several localities in Colombia (Trumpy, 1943; Olsson, 1956; and Bürgl, 1961).

In the central part of the Serranía Macarena of south-central Colombia (figs. 1–3), trilobites, brachiopods, and graptolites collected by Otto Renz of the Shell Oil Company from a 500-foot section of thin-bedded shale and minor limestone of the Güejar Series, were identified by Marshall Kay (Harrington and Kay, 1951) as ranging from Middle Cambrian to Early Ordovician in age. Enrique Hubach (in Hans Bürgl, unpub. data, 1967) collected fossils of similar age from the Güejar Series in the southern part of the Serranía Macarena (southeast of mapped area). Trilobites and graptolites collected by Renz northeast of the town of Uribe in the Eastern Cordillera were identified by Kay (Harrington and Kay, 1951) as probably Cambrian (St. Croixian); these rocks appear to be the westerly extension of the Güejar Series. Just west of the crest of the Eastern Cordillera along the trail on Cueva Creek, a tributary to the Ambica River, soft micaceous shale yielded graptolites of probable Ordovician age, according to Kay (Harrington and Kay, 1951). These rocks are overlain by about 3,200 feet of barren quartzite.

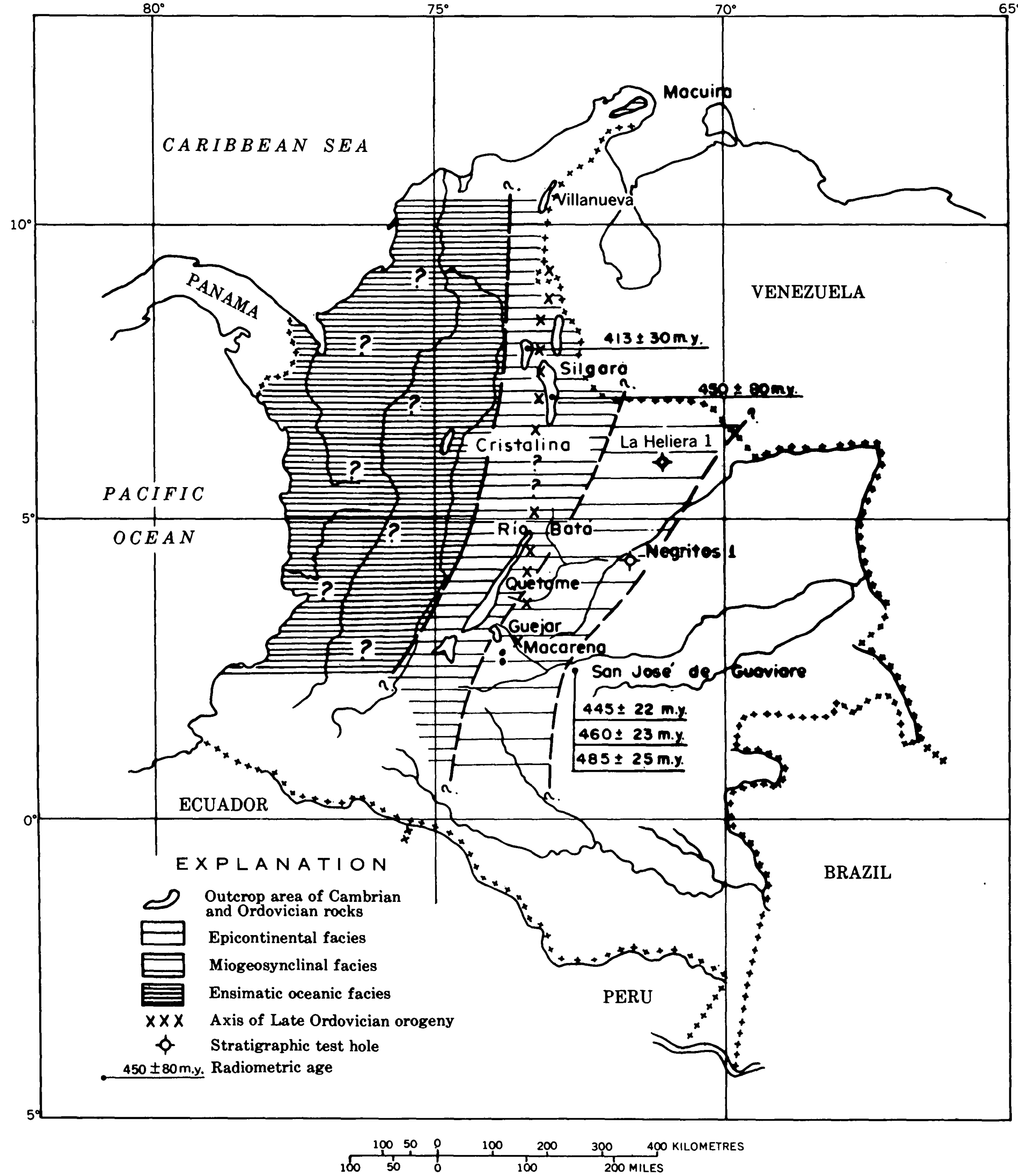

FIGURE 3.—Sketch map showing the paleogeography, facies, and location of outcrops of Cambrian and Ordovician age (from Bürgl, 1967), the axis of Late Ordovician orogeny, and radiogenic ages.

Hans Bürgl (unpub. data, 1967) reported that cores of dark-gray shale from the Negritos No. 1 well (fig. 3) in the eastern great plains area (Llanos Basin, fig. 1) contain graptolites of probable Ordovician age. Similar rocks cored in the La Heliera No. 1 well (160 km (100 miles) NNE; fig. 3) may also be of Cambrian and Ordovician age.

At Cristalina (fig. 3) west of the Middle Magdalena Basin, Harrison (1930) discovered dark-gray shaly rocks containing graptolites of Early Ordovician age. Tomas Feininger (Feininger, Barrero, Castro, and Hall, 1973) found that the slightly metamorphosed shale overlies highly metamorphosed granulitic paragneiss of probable Precambrian age. That graptolites are still preserved in the shale at Cristalina appears to indicate a low temperature-pressure regime for metamorphism. Feininger inferred that the Ordovician rocks and the underlying Precambrian paragneiss were transported into the area from the southeast by movement on the Otú strike-slip fault (pl. 1). This interpretation probably explains the presence of fossils in an area that is otherwise characterized by medium- to high-rank metamorphism. Metamorphic rocks that constitute the bulk of the Central Cordillera are probably Paleozoic in age (Nelson, 1957).

In several areas, unfossiliferous, weakly metamorphosed beds are overlain unconformably by Devonian rocks. Some of these pre-Devonian rocks may be of Cambrian and Ordovician age. The Quetame Series, named originally by Hettner (1892), crops out prominently along the Bogotá-Villavicencio road and extends as a belt along the east side of the Eastern Cordillera at least from Gutierrez (Olsson, 1956) in the Department of Cundinamarca to the Río Batá gorge (fig. 3) in the Department of Boyacá (Bürgl, 1960b). The Quetame Series consists of highly folded green chloritic and gray sericitic phyllite, interlayered quartzitic sandstone and siltstone, and some quartz conglomerate. According to D. H. McLaughlin, Jr. (McLaughlin and Arce H., 1972), the series, although intensely folded, is little metamorphosed as compared with all known Precambrian rocks. Because of its proximity to the Güejar Series of the Serranía Macarena, the Quetame is thought to be the equivalent of the Güejar Series.

At the western base of the Serranía de Perijá near Villanueva (fig. 3), Forero S. (1967) mapped as Cambrian and Ordovician a thin sequence of little-metamorphosed clastic sedimentary rocks that lie beneath fossiliferous Devonian beds.

The Silgará Schist (Ward, Goldsmith, Cruz, and Restrepo, unpub. data, 1973) overlies the high-amphibolite-grade Bucaramanga Gneiss (Precambrian) in the Santander and Norte de Santander Departments (fig. 1). The Silgará is composed of siliceous rocks of low to medium metamorphic grade and appears to represent sediments deposited under miogeosynclinal conditions. The Silgará Schist and the Bucaramanga Gneiss are invaded by syntectonic granitic orthogneiss. All these rocks are overlain by unintruded and unmetamorphosed fossiliferous Devonian strata. This evidence indicates, therefore, a profound pre-Devonian orogenic disturbance in the area.

A hornblende metadiorite collected by Goldsmith from a roadcut (lat 8°18′ N., long 73°24′ W.) between Río de Oro and Puerto Nuevo yielded a K/Ar age on hornblende of 413±30 m.y. (fig. 3; pl. 1). A paragneiss of granitic composition on the road from Berlin to Pamplona (lat 7°15′ N., long 72°48′ W.) gave a whole-rock Rb/Sr age of 450±80 m.y. (fig. 3; pl. 1). Both metadiorite and paragneiss probably formed during the same orogenic disturbance.

Five samples of peralkalic syenitic rocks collected in the low hills south of San José de Guaviare (about 75 miles east of the Serranía Macarena, fig. 3) by petroleum geologists yield K/Ar ages (biotite) ranging from 485±25 m.y. to 445±22 m.y. (Pinson and others, 1962). The mean age of the five samples is 460± 23 m.y.

Stratigraphic and structural data clearly establish the presence of an early Paleozoic miogeosynclinal sea that extended through the general area of the present Eastern Cordillera and the Serranía de Perijá (fig. 3). Although difficult to prove, an associated eugeosyncline very likely existed west of the miogeosyncline because (1) the graptolitic shale at Cristalina indicates increasing depth of water as compared with the original sand and sandy shale of the Silgará Schist; (2) the metasedimentary rocks of the Central Cordillera are more graphitic than the Silgará Schist and (3) farther to the west, the metamorphic rocks of the Central Cordillera contain increasing amounts of mafic volcanic material.

Radiometric age data from metamorphic and igneous rocks establish that a strong orogeny took place near the end of the Ordovician in the Santander Department, and probably extended southward. The fold axes and schistosity of this orogeny trend north. Meager structural data indicate that fold axes within the Quetame and Macarena areas also trend north. The northeasterly trend of the present Quetame outcrop area (fig. 3) does not reflect internal structure and results from comparatively recent Andean deformation.

Radelli (1967) and others referred to the Late Ordovician orogeny as Caledonian. Radiogenic age data indicate that it corresponds closely to the Taconic orogenic phase of the northeastern United States.

Absence of Silurian faunas from all of Colombia probably indicates that much of the area was elevated and undergoing erosion during the Silurian.

MIDDLE AND UPPER PALEOZOIC ROCKS AND OROGENY

DEVONIAN

Devonian rocks crop out in comparatively small windows along the Eastern Cordillera, from the Serranía de Perijá in the north to Jagua in the Garzón massif in the south (fig. 4). Fossiliferous reddish-gray shale and gray sandstone are exposed along the foothills of the Serranía de Perijá east of Villanueva (Forero S., 1967). To the east in Venezuela, rocks probably of equivalent age are referred to as the Cachirí Group (Liddle, 1946). The two lower formations of the Cachirí Group are fossiliferous and are Early to Middle Devonian in age. The Cachirí rocks consist of dark-gray to black shale containing many intercalations of gray siltstone and quartzite.

In Boyacá Department, the Floresta Formation consists of a basal breccia overlain successively by 1,900 feet of fine-grained black slaty fossiliferous shale, and 150 feet of gray sandstone (Botero R., 1959). An extensive fauna collected by A. A. Olsson from the lower part was studied by Castor (1939, 1942), and another was studied by Royo y Gómez (1942). The Floresta fauna appears to be similar and is probably approximately equivalent to the fauna of the Cachirí Group in Venezuela.

Bürgl (1960b) reported a thin sequence of Devonian beds at Río Batá in the Quetame area.

In the Garzón area in the Department of Huila, thin Devonian strata crop out beneath Carboniferous rocks (Stibane, 1966, 1968). Thick nonfossiliferous sandstone (orthoquartzite in many places) in the Quetame, Macarena, and Huila areas overlies dated Cambrian and Ordovician rocks and is thought (Trumpy, 1943; Bürgl, 1961; Olsson, 1956) to be of Devonian age.

In all areas the basal Devonian sediments consist of conglomerate or other coarse clastic rocks that rest with strong angular discordance upon older rocks. Apparently these sediments were deposited in a transgressive seaway that extended at least over much of the area of the present Eastern Cordillera. In Santander Department, recent geologic mapping by Ingeominas has established that the Floresta Formation is increasingly metamorphosed northward from the type locality. Because Permian and Triassic beds in the same area are little or unmetamorphosed, the Devonian beds must have experienced a sharp, but probably local, disturbance in Late Devonian or Carboniferous time. The north-trending foliation and axes of folding of the Devonian metamorphic rocks generally coincide with those of the Cambrian-Ordovician and Precambrian metamorphic rocks beneath them. No igneous rocks associated with this Late Devonian or Carboniferous disturbance have yet been recognized.

Uplift resulting from this disturbance apparently produced a regressive coarse clastic facies upon retreat of the seas from the region. Shoaling of the sea floor is evinced by the conspicuous sandstone and orthoquartzite in upper parts of many of the Devonian sequences.

MISSISSIPPIAN THROUGH PERMIAN

In Colombia, rocks of early Carboniferous (Mississippian) age seem to be generally absent, perhaps because of uplift produced by the Late Devonian disturbance. Hans Bürgl (unpub. data, 1967) stated that in latest Mississippian time a marine transgression began with deposition of a basal conglomerate and that the later deposits of this sea consisted of reddish sandstone, variegated shale and mudstone, and reddish marine limestone.

In the Serranía de Perijá, Forero S. (1967) and Radelli (1967) reported thick sections of dark-gray to black phyllitic shale that contains fossils of late Carboniferous (Pennsylvanian) age. The upper limestone member of the Chandua Group (Gansser, 1955) of the Sierra Nevada de Santa Marta (fig. 4) may represent a nearshore facies of these rocks.

In the Santander Department, Pennsylvanian and Permian rocks include the Diamante Formation and the Labateca Formation. Farther south in the Floresta area of the Department of Boyacá, beds of similar age are referred to as the Cuché Formation (Botero R., 1959), and in the Quetame area of Cundinamarca Department as the Gachalá Formation (Stibane, 1966).

The Diamante Formation in the Bucaramanga region crops out in several small areas. It appears to be separated from the underlying Floresta Formation (Devonian) by a pronounced unconformity

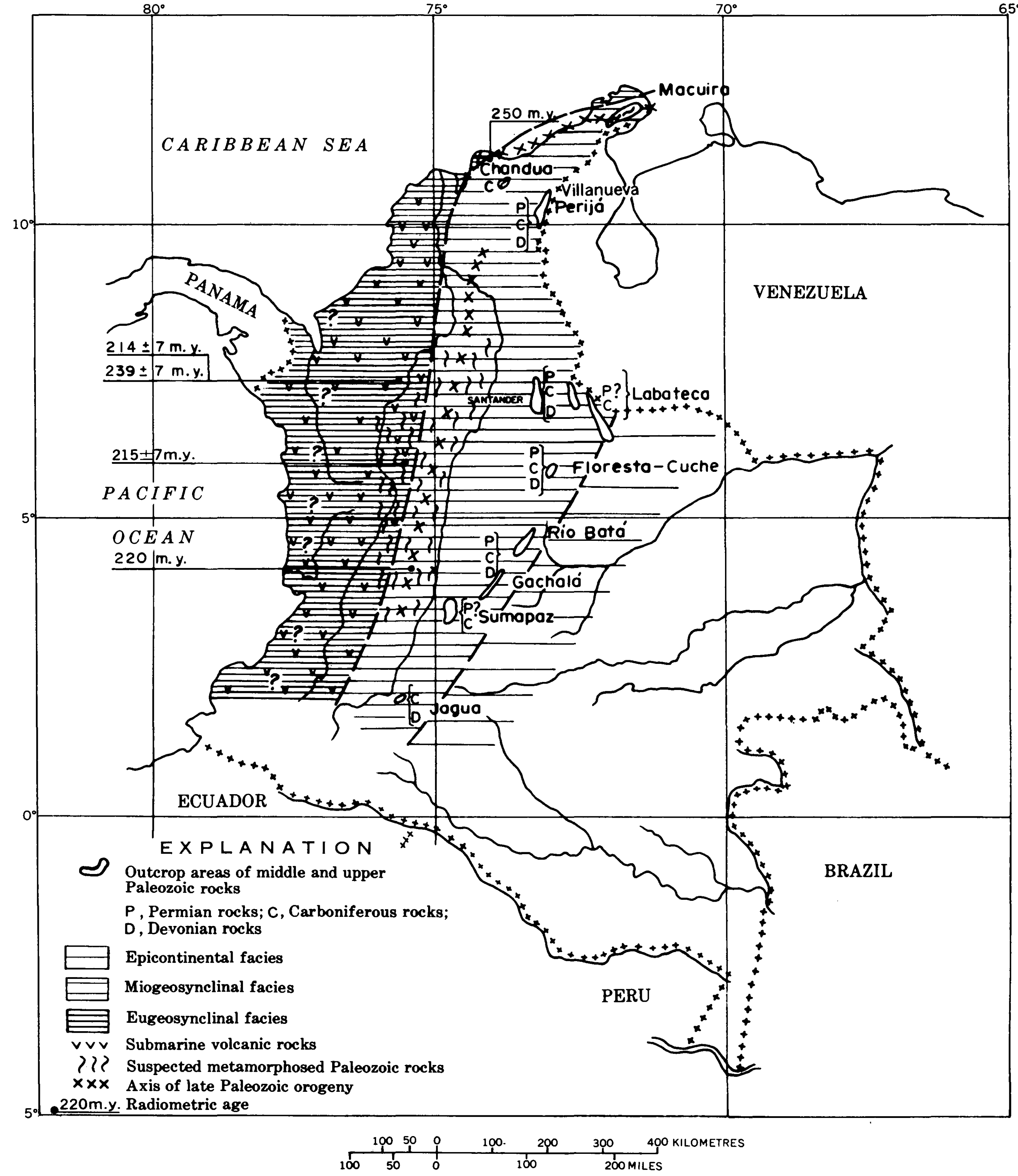

FIGURE 4.—Sketch map showing the paleogeography, facies, and location of outcrops of middle and late Paleozoic age (from Bürgl, 1967), the axis of the late Paleozoic orogeny, and radiogenic ages.

and from the overlying Tiburón Formation by a somewhat less pronounced unconformity (D. E. Ward, Richard Goldsmith, Jaime Cruz B., and H. Restrepo, unpub. data, 1973). The lower 450 feet of the Diamante consists of purple sandstone containing intercalated limestone; the upper 750 feet is dark-gray argillaceous limestone. Fossils collected by Ward indicate a Middle Pennsylvanian to Middle Permian age for the Diamante Formation.

In the Bucaramanga region, the Tiburón Formation is overlain by the Bocas Formation (Triassic). The Tiburón consists largely of massive beds of conglomerate whose pebbles are derived mainly from the Diamante Formation.

The thick predominantly Carboniferous Labateca Formation in Santander Department and beds of the Sumapáz section in Cundinamarca Department may include some strata of Permian age in their uppermost parts.

LATE PALEOZOIC OROGENY

Upper Paleozoic rocks of the Eastern Cordillera are little metamorphosed and, except in the Serranía de Perijá area, are little disturbed; most dip at low to moderate angles, which led Stibane (1967) to ascribe their deformation principally to vertical movements. The composition of the rocks indicates deposition under miogeosynclinal conditions, and their structural attitudes indicate deformation over a cratonic platform. In the Guajira Peninsula, the Sierra Nevada de Santa Marta, and the Central Cordillera, however, the Paleozoic rocks are represented by low- to high-rank paraschist and paragneiss that were certainly metamorphosed before the Late Triassic. These metamorphic rocks are very distinct from the little-metamorphosed Paleozoic formations of the Eastern Cordillera (fig. 4).

In the Guajira Peninsula, the Uray Gneiss Member and paraschist of the Macuira Formation underlie red beds of the La Quinta Formation of Triassic age and Middle Jurassic marine strata (MacDonald, 1964; Lockwood, 1965; Alvarez, 1967) (fig. 4). The Macuira Formation is intruded by granitic rocks. Muscovite from an associated pegmatite gave a K/Ar radiogenic age of 195 ± 8 m.y.; metamorphism of the Macuira and plutonic intrusion thus predate this Triassic pegmatite and of course the Triassic red beds that overlie the basement rocks.

In the Sierra Nevada de Santa Marta, paraschist, orthoschist, metadiorite, and amphibolite form an arcuate belt (Sevilla arc) northwest of the Precambrian platform area (pl. 1). Tschanz (written commun., 1969) regarded these rocks as probably correlative with the Macuira Formation. A sample of amphibolitic and biotitic gneiss from the Sevilla Complex gave a K/Ar age of 250 m.y. (MacDonald and Hurley, 1969); metamorphism here thus appears to be of Late Permian age.

Rocks in the eastern part of the Central Cordillera consist of metamorphosed carbonaceous pelite, wacke, graywacke, and sandstone, and include a prominent belt of marbleized limestone. Metamorphism has destroyed all vestiges of fossils in the rocks. On the basis of lithology these rocks appear to have been deposited under miogeosynclinal conditions.

In the central and western parts of the Central Cordillera, volcanic tuffs and lava flows, now metamorphosed to greenstone, greenschist, and amphibolite, are progressively more abundant westward; they clearly belong to an eugeosynclinal facies.

At the latitude of Ibagué (4°25′ N., south of the area of pl. 1), paraschist and orthoschist of the Central Cordillera were defined by Nelson (1957) as the Cajamarca Group. At Payandé 10 miles southeast of Ibagué, these rocks are overlain by the fossiliferous Payandé Formation of Late Triassic age. In the Medellín area (pl. 1), Botero A. (1963) referred to similar metamorphic paraschist as the Ayurá-Montebello Formation. North of Yarumal in the Department of Antioquia, R. B. Hall (Hall and others, 1972) referred to similar rocks and interbedded volcanic rocks as the Valdivia Group, and to migmatitic rocks of higher metamorphic rank as the Puquí Metatonalite. Two samples interpreted by Hall as syntectonic orthogneiss of the Puquí Metatonalite, gave a K/Ar age on biotite of 239 ± 7 m.y. and on muscovite of 214 ± 7 m.y. (fig. 4; pl. 1), indicating a minimum Late Permian to Early Triassic age for the metamorphism. A sample from the Amagá stock southwest of Medellín gave a K/Ar age on biotite of 215 ± 7 m.y. (fig. 4).

Thus far no rocks from the Central Cordillera have yielded radiogenic ages older than Permian. Had regional metamorphism in the Central Cordillera taken place in early Paleozoic time, one could reasonably expect to find there some fossiliferous upper Paleozoic strata, equivalent in age to the unmetamorphosed or little metamorphosed miogeosynclinal strata of the Eastern Cordillera, but such rocks have not been found. The existence of Ordovician graptolites near Cristalina (Harrison, 1930) may indicate that these rocks are not in their true palinspastic position because of structural dislocation as suggested by Feininger (written commun., 1969). Regional metamorphism of the rocks in the Central Cordillera is thus considered to be of late Paleozoic age.

The apparent near simultaneity of comparable events in the Guajira Peninsula, Sierra Nevada de Santa Marta, and in the Central Cordillera along strike, continuity in trends of structural grain and in geographic distribution, suggest that miogeosynclinal deposition extended from the sialic continental platform westward and northward to its outer edge and that eugeosynclinal sediments accumulated in a trough along the foreland of the continent during the Paleozoic Era (fig. 4). The outer edge of the sialic platform probably is some tens of kilometers beyond the present outermost exposures of Precambrian granulites. At the close of the Paleozoic Era, this natural mobile zone in the outer crust appears to have been subjected to the most intense orogeny recorded in Phanerozoic rocks of Colombia. This orogeny gave rise to the ancestral Colombian Andes. Intense regional metamorphism, local anatexis, and sporadic igneous intrusion converted the zone into an area of cratonic attributes which has characterized the Central Cordillera, central Sierra Nevada de Santa Marta (Sevilla arc), and Guajira Peninsula (Guajira arc) throughout much of subsequent geologic time.

The late Paleozoic orogeny clearly resulted in some continental accretion, which is represented by the belt of metamorphosed eugeosynclinal sedimentary rocks now exposed along the western side of the Central Cordillera in the Department of Antioquia. This belt is covered by younger rocks westward (fig. 9) and northward passes beneath younger rocks and the Caribbean Sea. The total width of the belt of metamorphism is unknown; for only the inner side of the belt is now exposed.

MESOZOIC ROCKS AND OROGENY

TRIASSIC

The first incursion of seas after the Central Cordillera-Sevilla arc-Guajira arc orogeny in late Paleozoic time is represented by the Los Indios Formation along the southwest flank of the Sierra Nevada de Santa Marta (fig. 5). The Los Indios Formation overlies Precambrian rocks and consists of a lower 600-foot-thick fossiliferous black shale and an upper 1,000-foot-thick green arenaceous member containing some conglomerate and tuff beds. Ostracodes in the formation are tentatively regarded as Late Permian(?) or Early Triassic. The Corual Formation of the north and southeast sides of the mountain block may be correlative in part with the Los Indios Formation, although its variable lithology is more variable than that of the Los Indios Formation. The Corual Formation consists of a basal conglomerate overlain by siltstone, graywacke, shale, chert, and abundant mafic to silicic lava and volcanic tuff; some of the lava and tuff is keratophyric to spilitic (Tschanz, written commun., 1969). The Guatapurí Formation on the southeast flank of the Sierra Nevada de Santa Marta overlies the Corual Formation and consists of 10,000 to 14,000 feet of well-bedded crystal and lithic tuffs that are reddish and can easily be confused with other Colombian red-bed formations. This formation appears to have been deposited in a narrow northeast-trending trough (Tschanz, unpub. data, 1969), as it is poorly represented along the southeast side of the Cesar Basin (fig. 1), where similar red beds are younger and contain less volcanic rocks. In the Sierra Nevada de Santa Marta, volcanism increased in intensity through the Triassic and extended through much of the Jurassic and locally continued into Early Cretaceous time. During the Triassic, the area of volcanism extended southward into the Central and Western Cordilleras.

In the Santander region of the Eastern Cordillera, the Bocas Formation was deposited under paralic to nonmarine conditions, nearly conformable with the underlying Suratá Group of late Paleozoic age. The Bocas is composed of sandstone and shale that weather buff; it appears to have been deposited marginal to a Triassic seaway that transgressed southward from the Sierra Nevada de Santa Marta area into the Santander Department, through the Department of Boyacá, and into the Payandé area (fig. 5) of the Department of Tolima. In the Department of Boyacá, a black shale sequence containing *Estheria* and small gastropods is called (Hubach, 1957a) the Montebel Formation. At Payandé, a prominent basal conglomerate overlain according to Nelson (1957), by 500 feet of barren sandy shale (Prepayandé Formation of Renz, 1960), is in turn overlain by 500 feet of fossiliferous limestone and associated calcareous rocks (Payandé Formation) of Late Triassic age. The Payandé is overlain by 1,600 feet of mafic lava flows, agglomerate, and tuff (Postpayandé Formation). Hubach (1957a) tentatively correlated the Payandé Formation with the Los Indios and the Montebel Formations. The fossils in each of the formations differ, however, and a restudy of them is needed to arrive at firmer correlations.

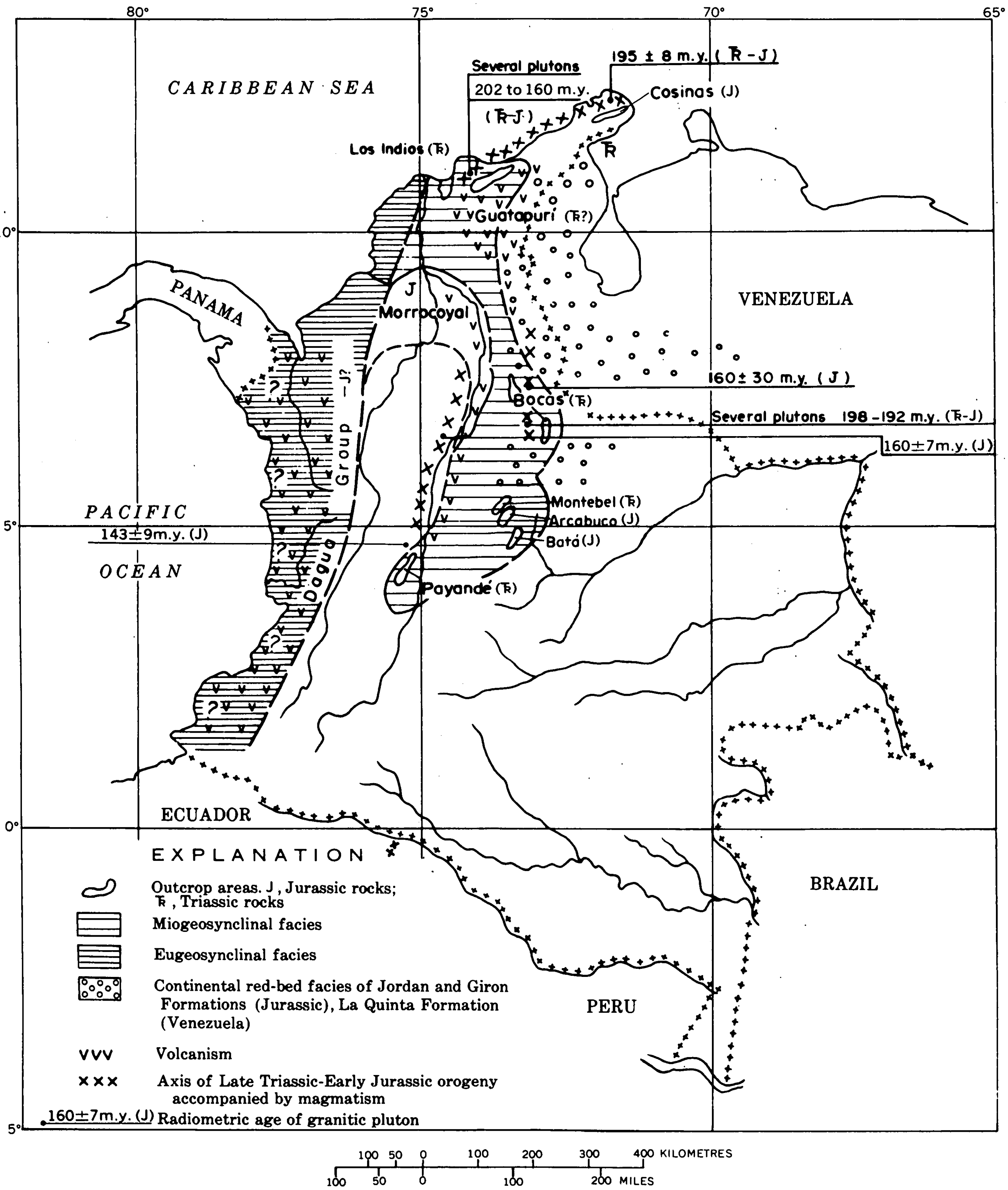

FIGURE 5.—Sketch map showing the paleogeography, facies, and location of outcrops of Triassic and Jurassic age (from Bürgl, 1967), the axes of Upper Triassic to Lower Jurassic plutons, and radiogenic ages.

The Triassic Period closed with the initiation of intrusion of several large batholiths in the Sierra Nevada de Santa Marta and in the Santander Departments in the Eastern Cordillera. The age of the earliest batholiths is older than 202±13 m.y., determined on a diorite on the west side of the Sierra Nevada de Santa Marta (pl. 1). Other early ages range from 195±8 m.y. (fig. 5) for a pegmatite associated with a granite that cuts the Macuira Formation in the Guajira Peninsula, to 193±6 and 194±6 m.y. (pl. 1) (K/Ar, biotite) for the Santa Barbara and Pescadero batholiths southeast of Bucaramanga. Emplacement of batholithic masses began slightly before the close of the Triassic. Some were emplaced during an interval that spanned the Triassic-Jurassic time boundary; others, as indicated by radiogenic ages of 170 to 160 m.y. (fig. 5; pl. 1), were emplaced during the Jurassic. The intrusions are mesozonal to epizonal and discordant, but their form is influenced by the gross structures of the encasing Precambrian and Paleozoic rocks.

JURASSIC

The marine Cosinas Group (fig. 5), 5,000 feet thick and ranging from Middle to Late Jurassic age, was deposited in a trough on the Guajira Peninsula (Rollins, 1960). The Cosinas trough in which this group was deposited must have been exceedingly narrow.

On the southeast slope of the Sierra Nevada de Santa Marta, Jurassic rocks of various formational names are represented by a thick section of subaerial volcanic breccias, flows, and welded tuffs that range in composition from andesite to rhyolite. Volcanism (Triassic and Early Jurassic) apparently preceded emplacement of most of the batholiths. Tschanz (unpub. data, 1969), however, observed that in some areas keratophyric and spilitic Triassic volcanism antedates batholithic intrusion. In other areas, dacitic to rhyolitic volcanism and Jurassic plutonism are essentially penecontemporaneous. In still other areas, Cretaceous rhyolitic ignimbrites rest unconformably upon Jurassic batholiths.

At Morrocoyal (fig. 5), Trumpy (1943) described the Morrocoyal Formation as consisting of a lower unit of fossiliferous black shale and thin limestone interbedded with red beds, shale, and sandstone, and an upper unit of mafic volcanic rocks. On the basis of rich faunas, the lower Morrocoyal beds are considered to be Liassic. The thick volcanic sequence overlying them thus may be Middle Jurassic, corresponding approximately in age with the volcanic rocks in the Sierra Nevada de Santa Marta.

In the Department of Boyacá, the Jurassic (Hubach, 1957a) is represented by the Arcabuco Formation (fig. 5), which consists of massive, light-colored sandstone containing thin intercalations of red shale. On the lower Batá River, Bürgl (1960b) identified fossiliferous littoral quartzose sandstone of late Liassic (Early Jurassic) age, 4,250 feet thick, separated by a stratigraphic hiatus from 2,600 feet of overlying dark-gray shale of Tithonian (latest Jurassic) Age. Russell Travis (written commun., 1970) reported that the shale may be as much as 8,500 feet thick.

The most distinctive sedimentary beds of Jurassic age in Colombia are continental red beds of the Girón Group that extend from Serranía de Perijá southward along the Eastern Cordillera at least as far as Floresta in the Department of Boyacá, and may extend as far south as the Department of Huila (figs.1, 5). The Girón Group is correlated in part with the La Quinta Formation of western Venezuela and possibly with the Chapiza Formation in Ecuador. In Colombia, some confusion has resulted from the practice of assigning all red beds of this approximate position in the stratigraphic column to the Girón, whereas in fact red beds in Colombia range in age from Carboniferous (parts of the Gachalá Formation), through Triassic (Guatapurí Formation of the Sierra Nevada de Santa Marta) and Jurassic, to and including the Río Negro Formation of Early Cretaceous age in the Serranía de Perijá. The Girón Group, in past literature, for lack of satisfactory fossil evidence, therefore, has been assigned ages ranging from Pennsylvanian (Langenheim, 1961) to Jurassic.

At the type locality and vicinity, Cediel (1968) was able to separate two red-bed sequences in the Girón Group. He defined the older, finer, and more uniform grained sequence in the canyon of the Sogamoso River, where it contains interstratified volcanic material (ignimbrites), as the Jordán Formation. Overlying these beds are the normal quartzose Girón-type beds that are relatively free of volcanic materials. Cediel considered the Jordán Formation as late Paleozoic and retained the oft-used "Juratriassic" age designation for the Girón Group in the belief that the age of plutonism in the nearby Eastern Cordillera was probably late Paleozoic; he concluded that the Girón red beds were a molassic offwash from that area after uplift. D. E. Ward (in D. E. Ward, Richard Goldsmith, Jaime Cruz B., and

H. Restrepo, unpub. data, 1973), however, collected granite cobbles out of the base of the Jordán Formation, which Richard Goldsmith identified as probably having been derived from the nearby Los Clavos Granite, radiometrically dated as Early Jurassic in age. Thus, both the Jordán and Girón beds near their type localities should probably be regarded as Middle to Late Jurassic age; the uppermost beds indeed may extend into the Early Cretaceous.

Volcanic material is prominent in the belt of Jurassic rocks along the east side of the Central Cordillera, overlying the Lower Jurassic (Liassic) marine beds of the Morrocoyal Formation of the Middle Magdalena Basin. On the Anacué River southwest of Barrancabermeja (pl. 1), these strata are intruded by a large granitic pluton. Farther south, near Virginias on the Puerto Berrío-Medellín railroad, a catazonal to mesozonal diorite that intrudes volcanic rocks gave a K/Ar age on hornblende of 160 ± 7 m.y. (fig. 5; Feininger and others, 1973). A very recent sample, collected by Darío Barrero L. from the Ibagué batholith, near Ibagué, gave a K/Ar radiogenic age, on hornblende, of 143 ± 9 m.y. (fig. 5).

Sedimentary rocks of eugeosynclinal aspect are represented by the Dagua Group (fig. 5) in the Western Cordillera. The lower part of the Dagua Group, as described by Nelson (1957), consists of dark-gray graphitic pelite—which has some sericite and chlorite along bedding planes—interbedded with abundant basaltic volcanic rocks. The middle part of the Dagua is characterized by arenaceous rocks and some limestone, and the uppermost beds of the middle part are black commonly siliceous shale. Included within these sedimentary rocks are greenish to dark-violet schistose rocks that are interpreted by Nelson to be triturated and mylonitized doleritic rocks. The upper part of the Dagua is composed of black graphitic shale, dark-gray to black chert, and dark-gray siliceous shale. Bürgl (1961) reported Callovian ammonites from similar beds near Popayán. Overlying the Dagua Group is a thick section of diabasic lava flows, including intrusive sills and dikes, which were referred to by Grosse (1926) as "Porphyrites" and by Nelson (1957) as "Diabases." These "Diabases" are considered by most authors as clearly Cretaceous in age.

The widespread evidence of Jurassic magmatism, plutonic as well as volcanic, indicates that the region of the Sierra Nevada de Santa Marta, northern part of the Eastern Cordillera, and the eastern side of the Central Cordillera, were involved in a tectonic paroxysm. Jurassic volcanic rocks seem to reflect a continuation of the volcanism that began in the Triassic. Little metamorphism appears to be associated with the intrusions, and their relations to the country rocks suggest that most were intruded at comparatively low temperatures and shallow depths. The batholiths are situated on the eastern or inner side of the late Paleozoic orogenic arc and do not seem to be associated with a tectogene in the normal sense.

CRETACEOUS

As the detailed stratigraphy of the Cretaceous has been amply described in several outstanding publications by Notestein, Hubman, and Bowler (1944), Olsson (1956), Morales and Colombian Petroleum Industry (1958), and Bürgl (1961), the stratigraphy of the Cretaceous will only be briefly reviewed.

The Cretaceous sea transgressed from the Pacific and appears to have encroached from the southwest (fig. 6), bringing with it faunas of Peruvian and Argentinian affinities (Olsson, 1956). The sea gradually spread northward along the area of the present Eastern Cordillera; in Early Cretaceous (Hauterivian) time it connected with waters of the present Caribbean area. The merging of the seaways introduced into Colombia faunas of European affinities that characterize the younger marine Cretaceous rocks (Olsson, 1956). In Aptian-Albian time another seaway connection (fig. 6) formed briefly, from the Pacific across the area of the Department of Antioquia. The miogeosynclinal seaway reached its maximum extension in early Late Cretaceous (Turonian and Coniacian) time when phosphorites were deposited in association with chert; afterwards the seas shallowed and eventually withdrew during the Maestrichtian Stage. At the close of the period, the marine facies gave way to an upper Maestrichtian and Paleocene paralic coal-bearing facies.

Detailed studies of several sedimentary basins by petroleum geologists show that the miogeosyncline was not a simple trough or embayment of sedimentation. In places it was separated into smaller basins by islands, ridges, or by emerged positive areas. Two major northeast-trending axes of subsidence formed, one that passed through Bogotá, where the more complete Cretaceous section is as much as 40,000 feet thick, and another along the Cesar Basin (fig. 6) south of the Sierra Nevada de Santa Marta and the Guajira Peninsula. The positive relief feature known as the Santander arch (fig. 6) separated

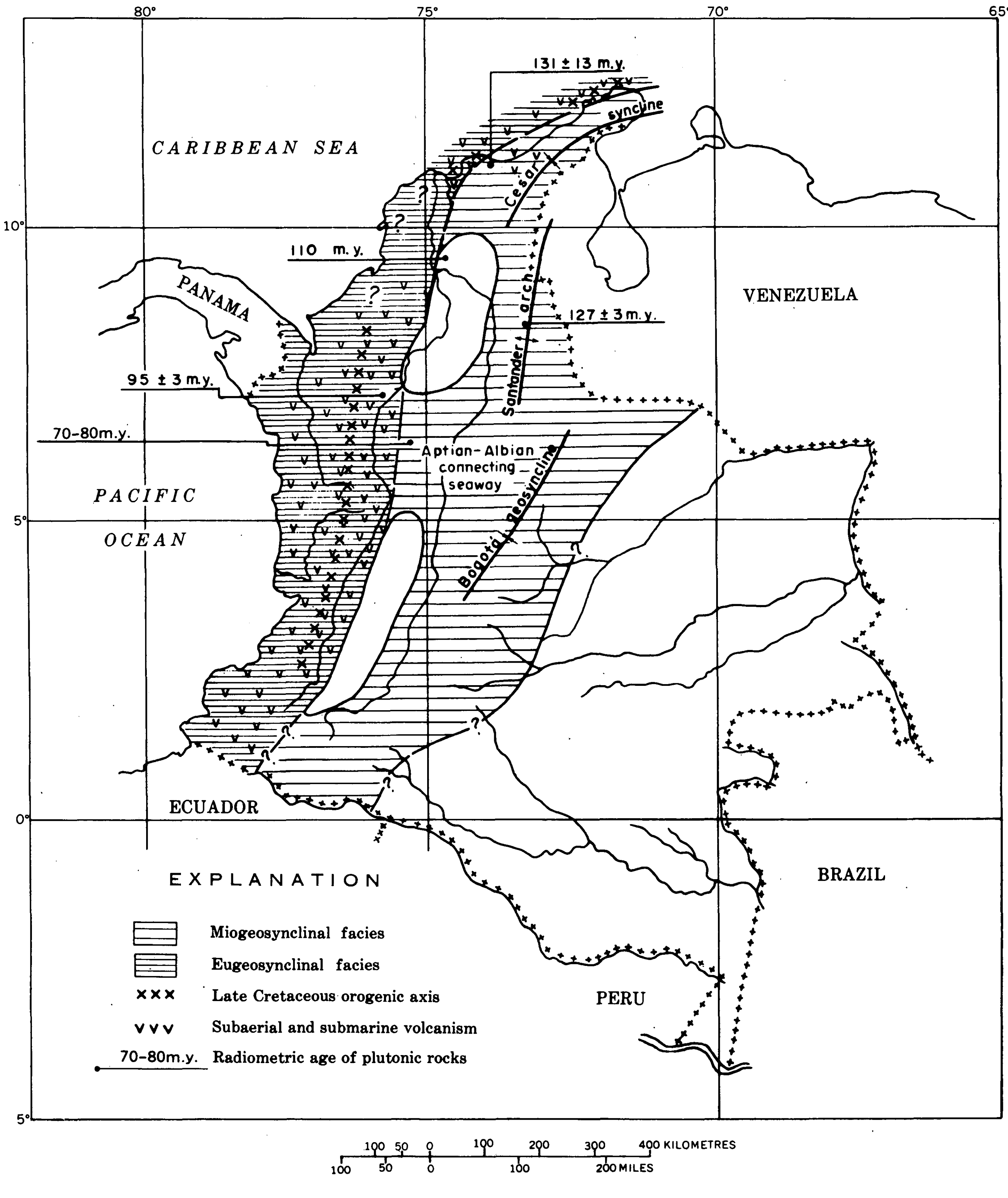

FIGURE 6.—Sketch map showing the paleogeography and facies of Cretaceous age, the axis of Upper Cretaceous plutons, and radiogenic ages.

these two predominantly negative areas. The axis of the Santander arch coincides approximately with the axes of the Late Ordovician orogeny, Late Devonian or Carboniferous disturbance, and the Late Triassic-Middle Jurassic orogeny.

The western margin of the Cretaceous miogeosyncline was the ancestral Central Cordillera that formed at the end of the Paleozoic. During the Cretaceous the range was emergent but low, except for a brief interval in Aptian-Albian time when its central part was submerged (fig. 6). The miogeosyncline extended far east of the present Eastern Cordillera, for exploratory drilling by oil companies shows that Cretaceous sedimentary rocks subcrop beneath the present Tertiary sedimentary mantle east of that cordillera. High-level aeromagnetic surveys east of the Eastern Cordillera front, in fact, show that the depth to crystalline basement in certain areas may be as much as 30,000 feet. These depths are a composite thickness of Tertiary and Cretaceous rocks and locally may include Paleozoic strata.

The enormous volume of clastic sediments in the miogeosyncline must have been derived in the main from the Guayana shield to the east and southeast. Some material was derived from the Central Cordillera, because Cretaceous strata along the eastern flank of that cordillera contain clasts of chert and metamorphic rocks that differ from clasts in Cretaceous sedimentary rocks elsewhere in Colombia.

In the Western Cordillera a thick sequence of submarine mafic volcanic rocks and beds of gray to black shale, graywacke, and dark chert, as much as 30,000 feet thick and perhaps much thicker, continued to be deposited in the eugeosyncline that began to form during the Jurassic. According to Hubach (1957a), Tulio Ospina first described these rocks in 1914. The sequence was later named the "Porphyritic Formation" (Grosse, 1926), and still later the "Diabase Group" (Nelson, 1957). In the northern part of the Western Cordillera, sedimentary beds locally predominate over volcanic material, and these strata are referred to as the Quebrada Grande Formation and the Cañasgordas Group. Fossils collected at various localities along the length of the Western Cordillera indicate that these rocks represent most of Cretaceous time (Hans Bürgl, unpub. data, 1967).

Petrographic study (Philipa Black, written commun., 1969) of samples of the Cañasgordas Group showed abundant detrital biotite, muscovite, quartz, feldspar, and lithic fragments of quartz-mica schist, indicating a metamorphic provenance for these flysch-type sedimentary rocks, doubtless from the adjacent Central Cordillera. Some recrystallization to albite, epidote, chlorite, actinolite, sericite, and a little pumpellyite indicates that the Cañasgordas rocks have undergone a very low grade, probably lithostatic, metamorphism in strong contrast, for instance, to the high-pressure metamorphism characteristic of Mesozoic eugeosynclinal rocks in many parts of the circum-Pacific folded mountain belts.

Cretaceous rocks constitute the bulk of the Western Cordillera. They extend from Ecuador in the south almost to the Gulf of Urabá (pl. 1) in the north. Judging from the presence of mafic igneous rocks and their derivatives along the Bolivar fault (pl. 1) of the Caribbean Coastal Plain (Zimmerle, 1968), the mafic composition of amphibole schist in the northwestern Sierra Nevada de Santa Marta (Tschanz, written commun., 1969), and the volcanic rocks and serpentinite in parts of the Jarara and Etpana Formations of northwest Guajira Peninsula (Lockwood, 1965), the eugeosyncline in which these rocks were deposited extended to the northeast and possibly into northern Venezuela to the east. Lockwood (1965) and Alvarez (1967) found identifiable Cretaceous Bryozoa in the Jarara and equivalent rocks, despite the low-grade metamorphism to which these rocks have been subjected.

LATE MESOZOIC OROGENY

Along this arcuate western eugeosynclinal belt the Cretaceous Period closed with an orogeny that began with strong folding and emplacement of many small masses of Alpine-type ultramafic rocks and serpentinite. The orogeny ended with emplacement of the large discordant Antioquian batholith and several satellite stocks along the inner side of the arc. The Antioquian and Sonsón batholiths in the Central Cordillera are well dated radiogenically at 70–80 m.y. (Maestrichtian). Cretaceous sedimentary and volcanic rocks are affected only by low-grade, mainly contact, metamorphism, in contrast to the low- to high-rank regional metamorphism of pre-Mesozoic rocks. This Late Cretaceous orogenic event is significant in the structural evolution of the northernmost Andes, because it gave rise to the Western Cordillera alongside and oceanward from the Central Cordillera (pl. 1, fig. 9) and to the coeval fold belt along the Caribbean coast; it also gave rise to the second clear case of continental accretion in Colombia. Little folding is found in and only minor disconformities are noted between Cretaceous and lower Tertiary rocks in the miogeosynclinal area to the east and southeast of the Late Cretaceous fold belt.

CENOZOIC ROCKS AND OROGENY

The stratigraphy of the Tertiary in Colombia is summarized in the comparatively few but significant works by Notestein, Hubman, and Bowler (1944), Anderson (1945), Morales and Colombia Petroleum Industry (1958), van der Hammen (1958), Bürgl (1961), and Van Houten and Travis (1968). Texts accompanying geologic quadrangle sheets published by the Colombian Instituto Nacional de Investigaciones Geológico-Mineras provide additional generalized information.

In general, marine Cenozoic deposits are confined to coastal zones; almost all the deposits in the interior are nonmarine. Strata ranging mainly from Paleocene to Oligocene are widely distributed; Miocene, Pliocene, and Pleistocene strata, except in the coastal deposits, are more localized and appear to have been deposited as coarse clastic fills in intermontane basins. In the coastal plains, Cenozoic sections, from Paleocene to Holocene, are complete. Most Pliocene and all Pleistocene deposits overlie older Tertiary formations with notable angular discordance.

PALEOCENE

In the Eastern Cordillera, Cesar Basin, southwest Maracaibo Basin, and the Magdalena Basin (fig. 1), uppermost Cretaceous marine formations are generally conformable with the overlying dominantly clastic nonmarine Tertiary formations. The Paleocene beds are generally molassic in nature—such as the Limbo Shale and sandstone along the eastern foothills of the Eastern Cordillera, the Barco Formation of the western Maracaibo Basin, the Lisama Formation of the Middle Magdalena Basin, and the Guaduas Formation of the Eastern Cordillera and the Upper Magdalena Basin.

Paleocene strata are chiefly clay, mudstone, fine-grained poorly sorted sandstone, and local coal deposits. Sedimentation apparently took place upon extensive, slowly subsiding flood plains that stretched outward from the Central Cordillera which was rejuvenated by Late Cretaceous orogeny (fig. 7). Besides debris deposited along the flood plains at the base of the Central Cordillera, much detritus was probably brought in from the south and southeast by north-flowing streams that drained the central continental area beyond the borders of Colombia.

EOCENE

Sandstone and conglomerate appear in middle and upper Eocene rocks over a wide area and are the result of regional diastrophism during late early to middle Eocene time. This diastrophism reflects a strong orogeny that took place along the outer (northwest) Sierra Nevada de Santa Marta and on the northwest side of the Guajira Peninsula. The orogenic belt extends southward along the Central Cordillera. During this orogeny, Cretaceous sedimentary rocks of the Guajira Peninsula and the Sierra Nevada de Santa Marta in the orogenic belt were metamorphosed to greenschist. The orogeny culminated with the emplacement, respectively, of the Santa Marta, Parashi, El Bosque, and other plutons. Radiogenic ages indicate that metamorphism possibly began as early as Late Cretaceous (Tschanz, written commun., 1970) and ended before the emplacement of the plutons between 50 and 48 m.y. ago (late early to early middle Eocene time; fig. 7). H. Duque (written commun., 1970) reported a notable stratigraphic hiatus throughout Colombia in the middle Eocene. This hiatus represents an orogeny that may correspond with deposition of the San Jacinto and Maco Conglomerates in the Lower Magdalena Basin, with the unconformity at the base of the thick and massive La Paz Sandstone that transgresses the eroded edges of the gently folded Lisama Formation (Taborda, 1965), and with deposition of the Gualanday Conglomerate of the Middle Magdalena Basin, the Mirador Sandstone of the western Maracaibo Basin, the Limbo (Mirador?) Shale and sandstone along the eastern flank of the Eastern Cordillera, and the Jamundí Conglomerate of the Cauca Basin. The coal-bearing Cerrejón Formation and other Eocene rocks of the Cesar Basin area immediately southeast of the orogen seem to have been deposited contemporaneously with the orogeny and without interruption.

Van der Hammen (1958) referred to this Eocene orogeny as a "pre-Andean" orogenic phase.

In late Eocene time, quiescence was restored, and deposition of fine-grained clastic sediments resumed. Marine tongues apparently penetrated far inland for brief intervals, as indicated by marine and brackish-water horizons that are found at widely spaced localities in the Llanos Basin and in the Eastern and Western Cordilleras. Van der Hammen (1958) reported marine Foraminifera in the Usme Formation of late Eocene to early Oligocene age in the Eastern Cordillera. Because the Central Cordillera was a land area of considerable relief after the Late Cre-

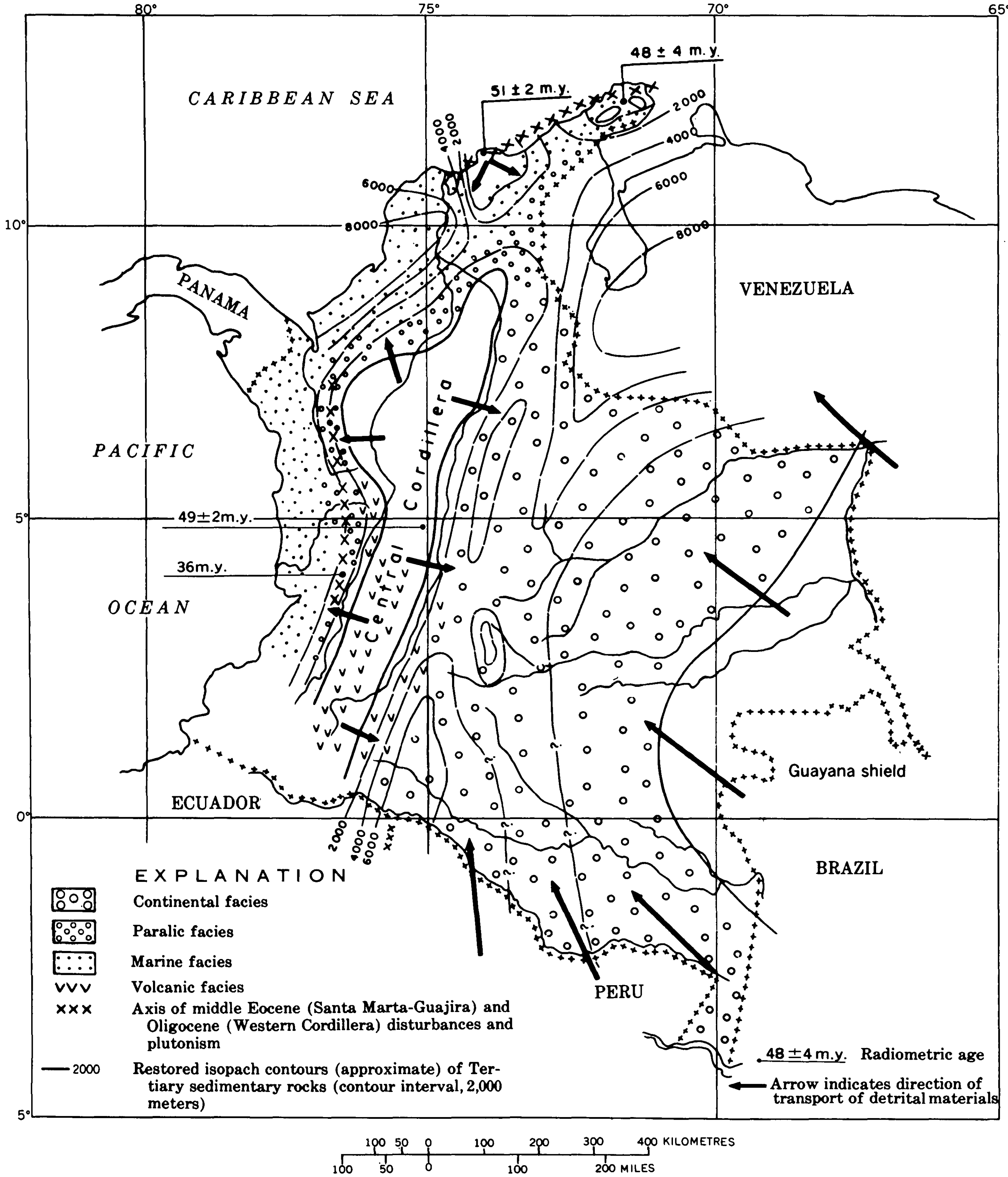

FIGURE 7.—Sketch map showing facies, thickness, and direction of transport of Tertiary deposits before the Andean orogeny (Miocene), location of axes of Eocene and Oligocene-Miocene plutons, and radiogenic ages of the plutons.

taceous orogeny, the brief marine incursions to its east were probably from the Caribbean; in contrast, those invading the area of the present Cauca Basin to its west were from the Pacific. Brief marine transgressions into a dominantly nonmarine environment have also been noted along the southern margin of the Maracaibo Basin (Miller and others, 1958).

OLIGOCENE

Material deposited during the early and middle Oligocene consisted mainly of nonmarine sandstone and shale. Occasional fingers of the sea penetrated inland to form key marker units, such as the upper Mugrosa Formation of middle Oligocene age and the La Cira Formation of late Oligocene[1] to early Miocene age. Renz (1938, in van der Hammen, 1958) stated that the upper San Fernando Formation of the western Llanos Basin and northern Serranía Macarena contains marine and brackish-water Foraminifera.

In the upper Oligocene sections, the beds containing conglomeratic horizons become coarser, indicating that transporting agents were acquiring greater competence. Within the present area of the Eastern Cordillera, deposition seems to have stopped toward the close of Oligocene time, because Miocene beds, so far as we know, are absent along its axial area.

Many stress adjustments have been recorded in the lower Tertiary sedimentary rocks in the Upper Magdalena Basin, as is well documented by Van Houten and Travis (1968). Van der Hammen (1958) referred to these earliest movements as "proto-Andean."

Concurrent with the initiation of Andean folding, granitic plutons were emplaced along the Western Cordillera (pl. 1). Specimens collected by Gerardo Botero A. (written commun. to Tomas Feininger, 1969) from batholiths east of Quibdó, between Buenaventura and Cali, and near Pasto were analyzed radiometrically by Prof. Andrew Vistelius of the Institute of Mathematical Geology, Leningrad, U.S.S.R. They range in age from early Oligocene to early Miocene (36 m.y. to 24 m.y.). This period of granitic intrusion could well have been an early manifestation of the Andean orogeny.

MIOCENE AND THE ANDEAN OROGENY

Miocene strata of the interior consist mainly of many thick conglomerate beds, pebbly sandstone, and some shale. Volcanism in the Central Cordillera is expressed by abundant volcanic material within the Miocene sedimentary rocks along the flanks of the cordillera. Nonmarine Miocene sections, many having an unconformity at their base, are as much as 10,000 feet thick (for example, the Real Formation (Morales and Colombian Petroleum Industry, 1958)) and are distributed along the intermontane Magdalena and Cauca Basins, beneath the eastern plains (Llanos Basin), and in the southwestern reentrant of the Maracaibo Basin near Cucuta (pl. 1). The predominantly nonmarine formations of the interior interfinger and pass into marine strata along the Caribbean and Pacific Coastal Plains. These lithologies, together with the cessation of deposition in late Oligocene time over the Eastern Cordillera, suggest that the Colombian Andes began to take their present form and that deposition became localized in the present basins during Miocene time, where it has continued to the present.

The deep Cenozoic intermontane basins now separated by the branches of the Colombian Andes have been thought to represent sedimentary accumulations in elongated downwarps, in half grabens, or in grabens; such reasoning implies that most sedimentary strata in these basins were derived primarily from the Andean Cordillera. A recent description of the history and structural development of the Upper Magdalena Basin by Van Houten and Travis (1968) has provided information on the origin of these basins.

The deepest parts of the interior basins contain extraordinarily thick, predominantly nonmarine, sedimentary beds of early Tertiary age that are overlain by coarse clastic upper Tertiary sedimentary beds. Most present topographic surfaces of the basins are less than 2,000 feet above sea level. The base of the Tertiary in the deepest parts of the basins, therefore, extends to depths of thousands of meters below sea level, as may be noted from the isopachs on plate 1. However, the reconstructed upper surface of the Cretaceous in the adjoining cordilleras, particularly in the Eastern Cordillera, ascends to as much as 15,000 feet or more above sea level. The structural relief of the Cretaceous-Tertiary interface therefore may be as much as 10 miles within remarkably short distances (pl. 2). Examples of such structural relief are evident in sections through the Sierra Nevada del Cocuy (northern Boyacá Department) to the deep Tertiary Llanos Basin immediately to the east (lat 7° N.;

[1] Van der Hammen (written commun., 1969) has informed me that, as a result of subsequent regional paleontological studies of the Caribbean Basin area, the upper Oligocene as used in his correlations (1958) must now be revised to Aquitanian, or basal Miocene.

section, pl. 2), and through the Sierra de Farallones east of Bogota eastward to the Llanos Basin (lat 5° N.; section, pl. 2). Miller and others (1958) described similar structural relief for the sections through the Mérida Andes of western Venezuela.

The relation of the margins of the basins to adjoining cordilleras is particularly revealing. Along the western side of the Middle Magdalena Basin, Tertiary beds lie upon and wedge out over pre-Cretaceous metamorphic and igneous rocks, whereas eastward they dip and thicken toward the Eastern Cordillera (Taborda, 1965). The strata of the eastern margin are either sharply folded upward and are now eroded away (D. E. Ward, Richard Goldsmith, Jaime Cruz B., and H. Restrepo, unpub. data, 1973), or are limited by vertical or steep reverse faults that dip eastward beneath the adjoining Eastern Cordillera (pl. 2). In the Llanos Basin east of the Eastern Cordillera, on the other hand, the Tertiary beds thicken westward from a thin veneer over the Guayana shield to several thousands of meters at the margin of the cordillera, where they butt against westward-dipping high-angle reverse faults. Cenozoic sedimentary thickening in the basins on each side of the Eastern Cordillera, therefore, is in a direction toward the cordillera itself. This relation together with the presence of synclinal trough remnants of lower Tertiary beds within the cordillera (pls. 1, 2) strongly suggests that, prior to principal Andean folding (Miocene), the Middle Magdalena and Llanos Basins probably connected across the area of the present Eastern Cordillera, and constituted a single large interior basin (megabasin) that opened eastward into the Barinas Basin and possibly extended northward into the Maracaibo Basin of Venezuela (fig. 7).

Even during the existence of this megabasin, however, the axial area of what is now the Eastern Cordillera anticlinorium probably was a positive relief feature relative to the adjoining Middle Magdalena and Llanos Basin areas. This relation is indicated by van der Hammen (1958) in a series of stratigraphic columns in which the Tertiary sections in the respective basins are much thicker than those within the Eastern Cordillera.

Comparable stratigraphic and structural relations are noted on the east and possibly on the west sides of the Western Cordillera at the latitude of Cali (3° 26′ N.), south of the mapped area on plate 1. There the lower Tertiary sedimentary rocks are strongly folded along the margin of the cordillera and are also terminated against high-angle reverse faults that are believed to dip toward the cordillera. Unfortunately, geologic mapping in that area is very deficient and does not permit reconstruction of middle and late Tertiary events. However, the limited data suggest that a similar Tertiary megabasin existed west of the Central Cordillera, facing the Pacific Ocean, and that it also was broken along marginal reverse faults by uplift and rejuvenation of the Western Cordillera.

Nonmarine Miocene sedimentation in the interior basins was complex. As many as four sedimentation cycles have been detected within the sedimentary strata of the Upper Magdalena Basin (Van Houten and Travis, 1968). On the basis of sedimentary provenances, van der Hammen (1958) noted similar cycles in other Colombian basins. H. Duque (written commun., 1970) observed that there is a notable stratigraphic hiatus during the middle Miocene over much of Colombia. This break in sedimentation may represent the zenith of the Andean paroxysm. Because of the paucity of fauna and flora in the predominantly nonmarine sedimentary beds and the considerable distances between present basins, individual formations are not readily correlated from basin to basin. Van Houten and Travis (1968) pointed out that the source of sedimentary debris varied greatly in response to local diastrophic movements and particularly in response to volcanic activity.

Prior to the principal Andean folding in the Miocene, the drainage pattern of northwestern South America may have been different from that of the present. Although considerable debris was undoubtedly derived from the Central Cordillera and deposited along its eastern margin by eastward-flowing streams, a good part of the present upper Orinoco and Amazon drainage during Cretaceous and early Tertiary time was to the north and northwest, bringing with it large quantities of debris from the interior of the continent; this debris was deposited in broad areas of general subsidence.

All the Miocene and older strata in present Colombian intermontane basins are folded. Termination of sedimentation over tectonically positive areas toward the close of the Oligocene, and continuation of sedimentation in negative areas during the Miocene suggest that the coarse clastic Miocene deposits were folded as they were accumulating.

This Miocene Andean folding is particularly significant because it undoubtedly gave rise to the rejuvenation of the Central and Western Cordilleras and the formation of the Eastern Cordillera. The result was the present three-prong configuration of the Colombian Andes. Uplift of the Eastern Cordillera along sharp flexures and marginal reverse faults was sporadic over a long period of time, and indeed may be continuing to the present.

PLIOCENE AND PLEISTOCENE

During and after Andean folding, large quantities of material, particularly the poorly consolidated Tertiary formations, were stripped off the cordilleras and transported through the drainage systems of the Cauca and Magdalena Rivers (pl. 1). Most of the Pliocene and Pleistocene deposits consist principally of uplifted unconsolidated alluvial-fan deposits that form terraces, mesas, and cuestas along the margins of the principal drainage systems. In some areas these deposits have been tilted or gently folded and faulted, but in general they are little disturbed. Pliocene and Pleistocene volcanism along the southern Central Cordillera contributed much debris to adjoining valleys.

Uplift in valley areas was negligible; in fact, certain valley areas must have been considerably depressed to permit deposition of as much as 5,000 feet of sediments, the thickness, for example, of the Mesa Group (Pliocene) in the Upper Magdalena Basin. Howe (1969) has shown from paleocurrent studies that the lower beds of the Mesa Group require an east-flowing drainage system during deposition. This drainage direction would imply uplift of the southernmost Eastern Cordillera, the area known as the Garzón massif, in late Pliocene time. Wellman (1970) concluded from similar paleocurrent studies of the Honda Group (Miocene), which underlies the Mesa Group some distance to the north, that it too was deposited by eastward-flowing streams descending from the east flank of the Central Cordillera. Both observations support the probable existence of the postulated eastern megabasin before principal Andean folding.

Epeirogenic uplift began in late Pliocene time as van der Hammen has so clearly demonstrated in his excellent studies of the little-deformed Tilatá Formation north of Bogotá. The basal Tilatá contains pollen of a humid tropical flora that could not have flourished at altitudes greater than 1,500 feet (van der Hammen, written commun., 1969). K/Ar analysis of biotite from ash beds in the basal Tilatá gave a minimum age of 3.5 m.y., or latest Pliocene. Higher in the section, the pollen indicates a progressively cooler climate, and pollen in the uppermost beds indicates a climate comparable to that at present altitudes of 8,500 feet.

HOLOCENE

Denudation of cordilleran areas, a consequence of the Andean orogeny, was increased by late Tertiary epeirogenic uplift and continued actively into the Holocene. Holocene uplift is also expressed in the "old-land" plateau area of the Central Cordillera north of Medellín that reaches an altitude of nearly 10,000 feet. The plateau slopes gently eastward toward the Magdalena Basin. Similar remnant surfaces ("paramos") in the Eastern and Western Cordilleras may be correlated with it genetically, if not in precise altitude, because epeirogenic uplift was not everywhere of equal magnitude. Uplift must have been largely accomplished before the later part of the ice age, as evidence of Pleistocene glaciation can be seen on present topography down to altitudes of 10,000 feet (van der Hammen and González, 1963).

During the Holocene, volcanism in the Central Cordillera diminished greatly, but the presence of volcanic ash in some present soil profiles at great distances from known volcanic centers indicates that volcanism continued until comparatively recent times and perhaps to historic time (Ramirez, 1968).

MAGMATISM

Igneous activity took place in all three cordilleras of the Colombian Andes (fig. 8) but is least evident in the Eastern Cordillera, which is largely blanketed by sedimentary rocks (pl. 1). Igneous rocks are volumetrically large in the Central Cordillera, the Western Cordillera, and the Sierra Nevada de Santa Marta. Most plutonic rocks and silicic volcanic rocks appear to be associated with orogenic cycles, whereas mafic volcanic rocks are related to eugeosynclinal sedimentation.

PRECAMBRIAN

The only known igneous rocks of Precambrian age in Colombia are in the Guayana shield. In the Serranía Macarena, southeast of the area shown on plate 1, granitic magmas pervaded mafic schists to form migmatitic augen gneiss (Trumpy, 1943). These gneisses are overlain by Cambrian and Ordovician sedimentary rocks. On the Guaviare River, 230 miles east of the Serranía, similar rocks were dated radiogenically at 1,205 m.y. (fig. 2) by K/Ar analyses of biotite (Pinson and others, 1962).

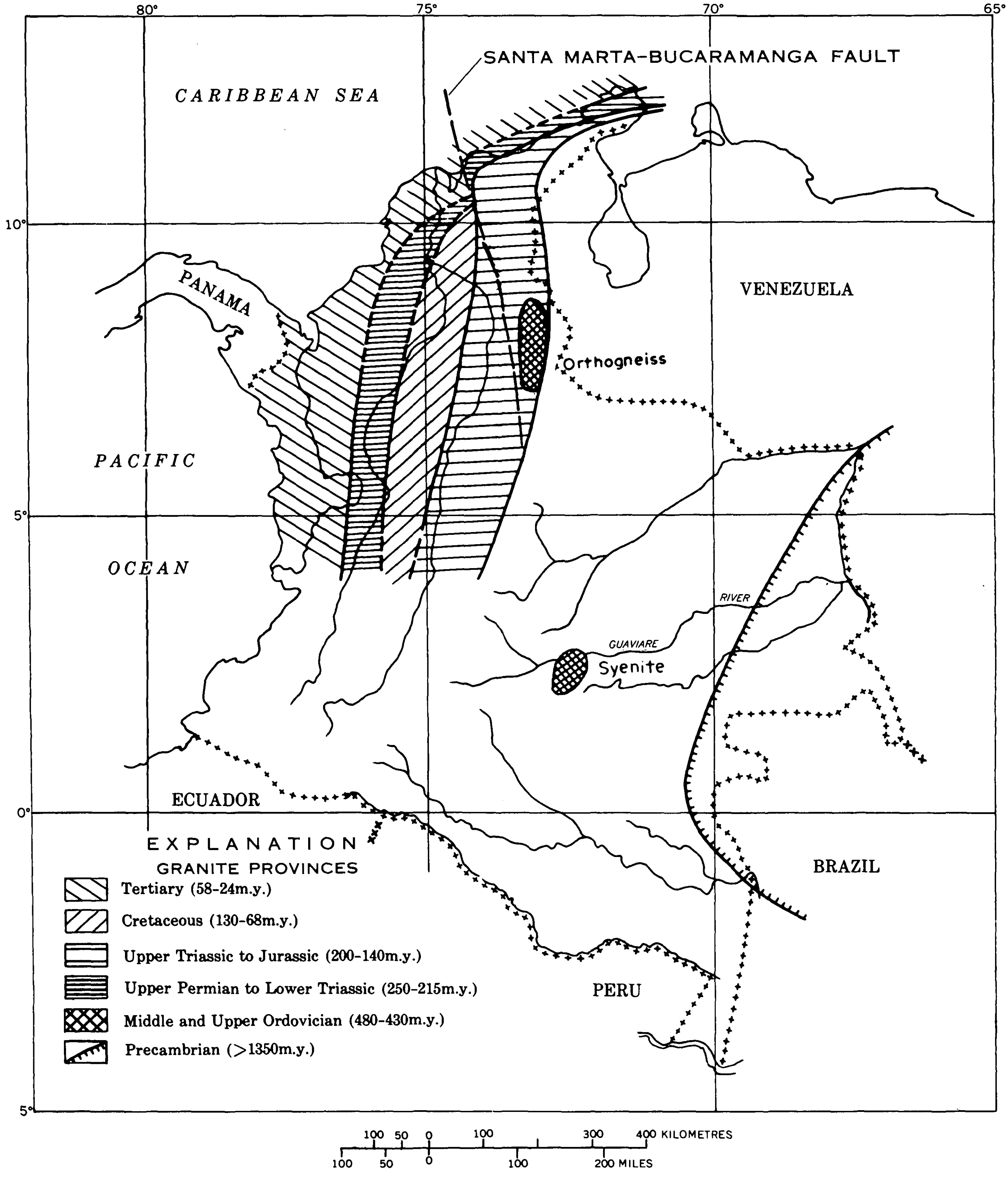

FIGURE 8.—Sketch map showing tentative distribution of granitic intrusive rocks by age provinces.

LATE ORDOVICIAN

Syntectonic biotite-quartz-feldspar orthogneiss forms sills of considerable thickness concordant with the foliation of the Bucaramanga Gneiss and Silgará Schist in the Bucaramanga region (Santander massif) in the Eastern Cordillera. This magmatism, which ranges in age from 450±80 to 413±30 m.y. (fig. 3), is associated with the Late Ordovician orogeny.

At San José de Guaviare on the Guaviare River in eastern Colombia, alkalic syenitic rocks range in age from 485±25 m.y. to 445±22 m.y. (fig. 3; Pinson and others, 1962). These intrusions on the shield appear to be removed from the Upper Ordovician granitic province, and their alkalic composition may be a reflection of the cratonic environment in which they were emplaced.

LATE PALEOZOIC

Late Permian to Early Triassic magmatism is represented by intimately mixed rocks that crop out over wide areas of northern Antioquia in the Central Cordillera. East and west of the Romeral fault at the latitude of Puerto Valdivia, gneissoid metatonalite is regarded by R. B. Hall (Hall and others, 1972) as synmetamorphic, and possibly anatectic, in origin. The metatonalite is so intimately mixed with high-grade gneiss of the Puquí Metatonalite that it is very difficult to map separately. K/Ar ages on muscovite and biotite, respectively, are 214 and 239 m.y. (pl. 1). The biotite age (Late Permian) is believed to date most closely the regional metamorphism of the Central Cordillera. At Amagá (southwest of Medellín), a postmetamorphic quartz monzonite stock gave a reported age of 215± m.y. (Early to Middle Triassic) by K/Ar analysis of biotite.

Some ultramafic intrusive rocks in the Central Cordillera have been metamorphosed to talc schist and may have been emplaced during a late stage of the development of the Paleozoic eugeosyncline. The bodies are generally of small dimensions. Most serpentine bodies, however, are little metamorphosed, and these are most probably associated with the younger Mesozoic eugeosynclinal suite.

The Don Diego Gneiss (metadiorite?) of the Sevilla arc in the Sierra Nevada de Santa Marta gave a K/Ar age on hornblende of 250 m.y., or Late Permian (MacDonald and Hurley, 1969).

Retrograded gneiss and metamorphosed granite enclosed in the Macuira Formation of the Guajira Peninsula are probably of late Paleozoic age (Alvarez, 1967). K/Ar analysis of muscovite from a pegmatite associated with the granite gave an age of 195±8 m.y. (MacDonald, 1964). Metamorphism and granite intrusion certainly preceded the apparent Upper Triassic pegmatite.

TRIASSIC AND JURASSIC

Magmatism in Colombia was exceedingly widespread throughout the Mesozoic Era, producing mesozonal and epizonal plutons, shallow hypabyssal intrusive rocks, and large volumes of submarine and subaerial volcanic rocks. Earliest volcanic activity is expressed in the spilitic volcaniclastic sedimentary rocks, ignimbrites, and volcanic breccias of the Corual and Guatapurí Formations of the Sierra Nevada de Santa Marta, regarded by Tschanz (written commun., 1969) as mainly of Triassic age. If the lower Dagua Group of the Western Cordillera is as old as Jurassic, as some believe (Bürgl, 1961), then its basaltic rocks are contemporaneous with and strongly contrast with the heterogeneous differentiated Jurassic volcanic rocks of the Sierra Nevada de Santa Marta and the Central Cordillera.

Most impressive are the many granitic plutons of the Sierra Nevada de Santa Marta and of the Santander massif in the Department of Santander. Six or more plutons that approach or exceed batholithic dimensions crop out in each of these areas. Intrusion in both areas appears to have begun about 200 m.y. ago (latest Triassic) and continued intermittently to about 143 m.y. ago (early Late Jurassic). In the Santander massif, the southern plutons are pink and potassic, whereas the northern plutons are gray and calc-alkalic. In the Sierra Nevada de Santa Marta, potassic and calc-alkalic plutons, although trending northeast have the same spatial relationship with one another as do those in the Santander massif.

Within this period of magmatism, several diorite to quartz diorite plutons intruded Precambrian gneiss and Paleozoic metamorphic rocks east of the Otú fault along the eastern flank of the Central Cordillera. A K/Ar determination on hornblende from a diorite near Virginias gave an age of 160±7 m.y. (fig. 5; Feininger and others, 1973). A sample collected by Darío Barrero L. south of the mapped area shown on plate 1 from the very large Ibagué quartz diorite batholith gave a K/Ar age on hornblende of 143±9 m.y.

Volcanic rocks of intermediate to silicic composition and subaerial origin are abundant in the Sierra Nevada de Santa Marta, are less common along the east side of the Central Cordillera, and are rather sparse in the Eastern Cordillera. In the Sierra Nevada de Santa Marta, postspilitic volcanic rocks have been dated by K/Ar analysis as 177 m.y. to 129 m.y. old, or ranging from penecontemporaneous with the Jurassic batholiths to postbatholithic in age.

CRETACEOUS

On the west side of the Sierra Nevada de Santa Marta, biotite from the Río Sevilla granodiorite stock was dated as 131±4 m.y. (Early Cretaceous), which is considered about the same age as the Golero Rhyolite farther east (Tschanz, written commun., 1969). Biotite from a granite drill core from a well in the Cicuco oil field, 125 miles to the south, was dated (Pinson and others, 1962) as 100–115 m.y. (late Early Cretaceous). Northwest of Puerto Valdivia in northern Antioquia, the small Pescado quartz diorite stock intruding the Puquí Metatonalite gave a K/Ar age (fig. 6) on biotite of 95.6±3.3 m.y. (early Late Cretaceous).

In the Central Cordillera, several massive medium- to coarse-grained epizonal to mesozonal granitic batholiths and stocks were emplaced during the Late Cretaceous orogeny. The most outstanding among these are Antioquian batholith (3,000 sq miles) and the smaller Sonsón batholith to the south (pl. 1). Radiogenic ages from the Antioquia and Sonsón batholiths range from 68 to 80 m.y. This range of ages suggests that emplacement may have extended over a considerable period of time.

These data show that a belt of silicic intrusions passes beneath the Tertiary and alluvial fill of the Lower Magdalena Basin and extends from the Sierra Nevada de Santa Marta to the central part of the Central Cordillera. The age of the intrusive rocks ranges from Early Cretaceous in the Sierra Nevada de Santa Marta to Late Cretaceous (Maestrichtian) in the Central Cordillera. The progressive southward decrease in age suggests a migrating magma front, which moved along and parallel with the general strike and grain of the Central Cordillera.

In the Eastern Cordillera, a sanidine concentrate from a rhyolite porphyry probably associated with the Ocaña porphyritic microgranite gave a K/Ar age of 127±3 m.y. (Early Cretaceous; fig. 6), approximately correlative with the igneous activity of the Sierra Nevada de Santa Marta.

In the Western Cordillera, in the northeastern Sierra Nevada de Santa Marta, and in the northwestern corner of the Guajira Peninsula, submarine basaltic and diabasic rocks were extruded intermittently on the floor of the eugeosyncline. These rocks became parts of the "Porphyrite" or "Diabase" formations of the Western Cordillera; the greenschist of the Taganga Group and amphibolite-grade schist of the Gaira Group of the Sierra Nevada de Santa Marta; and the greenschist of the Jarara and equivalent formations of the Guajira Peninsula. Also, small isolated ultramafic and serpentinite bodies form several prominent north-striking belts along the west side of the Central Cordillera and in the Western Cordillera, and irregular ultramafic bodies are on the Guajira Peninsula (pl. 1). Most of the ultramafic bodies are faultbounded, and it is difficult to determine their age relative to enclosing rocks; they are of Alpine type, serpentinized but little metamorphosed, and mainly predate the neighboring batholiths. The mafic volcanic and ultramafic intrusive rocks of Cretaceous age contrast strongly, and perhaps significantly, in composition with the Cretaceous silicic volcanic rocks of the Central and Eastern Cordilleras, and of the Sierra Nevada de Santa Marta.

TERTIARY

Tertiary intrusive rocks crop out at several points on the Guajira Peninsula, the northwest Sierra Nevada de Santa Marta, and along the Western Cordillera. One K/Ar age on biotite from the fine-grained Parashi quartz diorite stock of the Guajira Peninsula is 48±4 m.y. (fig. 7, pl. 1; Lockwood, 1965). In the Sierra Nevada de Santa Marta, a coarse-grained quartz diorite pluton extends from the city of Santa Marta to the northern coast and reappears at several points along the northern flank of the Sierra Nevada de Santa Marta. Several K/Ar analyses on both hornblende and biotite from this pluton yield radiometric ages between 49 and 51 m.y. (fig. 7, pl. 1; Tschanz, written commun., 1969). A sample collected from the El Bosque batholith north of Ibagué (quadrangle K–9, south of the area of pl. 1) gave a K/Ar age on biotite of 49.1±1.7 m.y. (Marvin, written commun., 1971), indicating that the extensive Cretaceous magmatism of the Central Cordillera continued locally into the early Tertiary. Igneous intrusive rocks of the Western Cordillera east of Quibdó, Chocó Department (pl. 1), on the highway between Buenaventura and Cali in Valle Department, and near Pasto in the Department of Nariño, have ages reported to be 24–36 m.y. (fig. 7, pl. 1; Gerardo Botero A., oral commun., 1970).

Tertiary plutonism is mainly early Eocene to early Miocene in age. The intrusions are predominantly along the outermost fold belt of the Andean

Cordillera and extend from the Guajira–Sierra Nevada de Santa Marta area in the north to and along the Western Cordillera, at least as far south as the Ecuadorian border.

Along the valley of the Cauca River, many steep-sided hypabyssal porphyritic volcanic plugs intrude Tertiary strata. The plugs are regarded as late Tertiary in age and possibly are related to upper Tertiary and Holocene volcanic rocks that surmount the southern Central Cordillera.

At least 45 Tertiary to Holocene volcanic centers have been recognized along the summit of the Central Cordillera between Manizales (pl. 1) and the Ecuadorian border. Several centers are more than 15,000 feet in altitude, and the highest, El Nevada de Ruíz, reaches 17,700 feet. The present altitude of these volcanic centers is due in part to late Tertiary and Holocene uplift, which in some areas may have been as much as 6,000 feet. Because volcanic detritus is prominent in the upper Tertiary beds of both the Cauca and Upper Magdalena Basins, on both sides of the Central Cordillera, volcanism probably began in the Miocene and has continued almost to the present. Although no detailed petrographic studies are available, the rocks appear to be mainly of intermediate composition.

The upper Tertiary and Holocene volcanic centers are in a well-defined line along the summit of the Central Cordillera. Volcanism may be localized along a rift zone that extends deeply into the crust.

AGE PROVINCES OF GRANITIC INTRUSIVE ROCKS

The granitic intrusive rocks, when plotted by age groups, fall into fairly definite linear patterns (fig. 8). The oldest intrusive rocks are in the shield area, and the Ordovician and Permian to Lower Triassic intrusive rocks are arranged sequentially from older to younger toward the oceanic basins. The Triassic-Jurassic, Cretaceous, and Tertiary intrusive rocks are also sequentially arranged from older to younger toward the ocean basins, but the Triassic-Jurassic intrusive belt overlaps the Ordovician belt, and the Permian to Lower Triassic intrusive belt is between the Cretaceous and Tertiary belts.

Precambrian intrusive rocks are associated with the Guayana shield; none have yet been identified in the Andean Cordillera. Upper Ordovician granitic rocks crop out in the Santander massif and on the Guaviare River (figs. 1, 2, and 8) some distance east of the Serranía de Macarena, forming a north-trending belt well within the Precambrian platform area; they are therefore intracratonic. A belt of upper Paleozoic and Lower Triassic plutons and anatectites closely related to and associated with highly metamorphosed sedimentary and volcanic rocks of Paleozoic age crop out along the Central Cordillera and along a curving arc that passes through the Sierra Nevada de Santa Marta as the Sevilla Complex (as denoted by Tschanz, written commun., 1969) and through the Guajira Peninsula as the Guajira Complex (Alvarez, 1967). These plutons appear to be situated along the extreme edge of the underlying Precambrian platform (fig. 2). Triassic-Jurassic plutons underlie a wide belt that includes the Eastern Cordillera, the eastern side of the Central Cordillera, the Sierra Nevada de Santa Marta, and perhaps the Guajira Peninsula; they are clearly intracratonic.

Cretaceous plutons, on the other hand, are mainly along the axis of the Central Cordillera; hypabyssal rocks related to these plutons crop out over small areas in the Sierra Nevada de Santa Marta.

Lower to middle Tertiary granitic intrusive rocks are clearly related to the outermost, oceanward, fold belt.

This preliminary attempt to distinguish magmatic provinces could be significant in distinguishing metallogenic provinces.

GEOLOGIC STRUCTURE

FOLDS IN METAMORPHIC TERRANES

Folding has been intense in many metamorphic terranes in the Colombian Andes. The extremely thick section, greater than 30,000 feet, of Precambrian granulites (Los Mangos Granulite Series) on the southeast side of the Sierra Nevada de Santa Marta probably represents tight isoclinal folding of sediments at shallow depth or during metamorphism after their depression to depths of 20 km or more within the crust. The amphibolite-grade Bucaramanga Gneiss, probably also Precambrian, may not have been buried as deep as the granulities, but kneading structures are common.

Detailed mapping also shows folding in metamorphosed Paleozoic rocks such as the Silgará Schist (Cambrian and Ordovician) in the Santander massif northeast of Bucaramanga and in the Cajamarca and equivalent Groups (upper Paleozoic) of the Central Cordillera; folding in the Quetame Series (probably Cambrian and Ordovician) southwest of Bogotá is severe. The greenschist adjoining the Santa Marta batholith and the Etpana and Jarara Formations (Cretaceous) along the northwest side of the Guajira Peninsula are moderately to intensely folded. All Phanerozoic deformation was accomplished under comparatively light load, as metamorphic minerals are mainly of the low-pressure type. The strongly folded and faulted thick Mesozoic sedimentary and volcanic rocks of the Western Cordillera generally show only incipient metamorphism.

FOLDS IN UNMETAMORPHOSED TERRANES

In nonmetamorphic terranes, extraordinarily thick prisms of sedimentary rocks, such as in the Sinú Fold Belt (fig. 1), along the central part of the Eastern Cordillera, and in the Western Cordillera, are notably folded. In the Sinú Fold Belt, Tertiary strata are as much as 30,000 feet thick (pl. 1). In the central part of the Eastern Cordillera northeast of Bogotá, the 50,000-foot sequence consists of as much as 40,000 feet of Cretaceous strata and remnant synclinal troughs of lower Tertiary beds that may have been as much as 10,000 feet thick before Andean folding (McLaughlin and Arce, 1969). North and northeast of Bogotá, harmonic concentric folds of great length are the rule; where salt deposits are locally interstratified, the folds become sharply disharmonic. In this area many folds are associated with high-angle thrust faults. In the Western Cordillera, as revealed in recent mapping by Ingeominas, the enormous sections of the Mesozoic volcanic ("Diabase Group") and sedimentary (for example, Cañasgordas Group) rocks are intensely deformed.

In the intermontane Tertiary sedimentary basins and in the Llanos Basin (fig. 1) east of the Eastern Cordillera, folding is much less intense, even though considerable thicknesses of strata (as much as 25,000 ft) are involved. However, adjacent to the cordilleran front in areas of high-angle reverse faulting (pl. 2), folds are more compressed and locally may be overturned.

Where comparatively thin sedimentary sequences overlie competent cratonic platform rocks, some of the deformation of strata resulted from differential vertical movements of cratonic basement blocks along fault surfaces; that is, faults generated below were translated into flexures and drape folds above. Stibane (1967) and others considered this type of vertical movement to be the predominate cause of the structures in the region. Viewed in a broad way, however, certainly the moderate to intense folding in the Sinú Fold Belt and Eastern and Western Cordilleras, together with the high-angle reverse faults along the margins of many of the cordilleras, indicate that much deformation must have been produced under compression.

HIGH-ANGLE REVERSE FAULTS

Reverse faults in Colombia are being recognized with increasing frequency as geologic mapping is accomplished at larger scale and as field techniques improve. The Salinas fault (pl. 1; fig. 9) along the east side of the Middle Magdalena Basin forms the east boundary of the Tertiary sedimentary basin; the Salinas was first recognized as a reverse fault by Taborda (1965). The fault has been traced continuously for about 100 miles, and displacements are large. Middle and Upper Cretaceous strata east of the fault are in juxtaposition with upper Tertiary strata west of the fault. The opposing terranes indicate a throw of at least 10,000 feet.

On the Guajira Peninsula, MacDonald (1964) and Lockwood (1965) found that displacement along two major east-trending thrust faults, the Ororio and Iitujuru, has brought phyllite and quartzite of the deep-water Etpana Formation of Cretaceous age over the coeval shallow-water Jarara Formation. The fault surface dips 45° to 65° N. Twelve miles to the south, a regional thrust fault, the Alas, brings hornblende gneiss of the Macuira Formation (Paleozoic?) over low-grade metasedimentary rocks, some of which are Lower Cretaceous. The Alas fault dips 10° to 45° N. and locally is overlain unconformably by middle Tertiary limestone. The Uraitchipa fault in the southern part of the Macuira area differs from the Ororio, Iitujuru, and Alas faults in that it dips moderately to the south. MacDonald (1965) and Lockwood (1965) generally considered the rocks to have been overthrust from the north, probably during the Late Cretaceous-early Tertiary orogeny. In the Simarua area to the west, Alvarez (1967) noted overthrusting from the north on the Kasipoch and Santa Ana faults. The thrust faults in turn are now offset by many northwest-trending normal faults of late Tertiary age, which produced much of the present relief of the area.

The southwestern edge of the Maracaibo Basin (fig. 1) is delimited by thrusting of pre-Devonian metamorphic and igneous rocks over Cretaceous and Tertiary formations (see geologic quadrangle maps F–13 and G–13, Colombia Ingeominas). The Mercedes thrust fault (pl. 1; fig. 9) is interpreted to dip westward beneath the Eastern Cordillera. Folds in the basin to the east, however, are overturned both to the east and west.

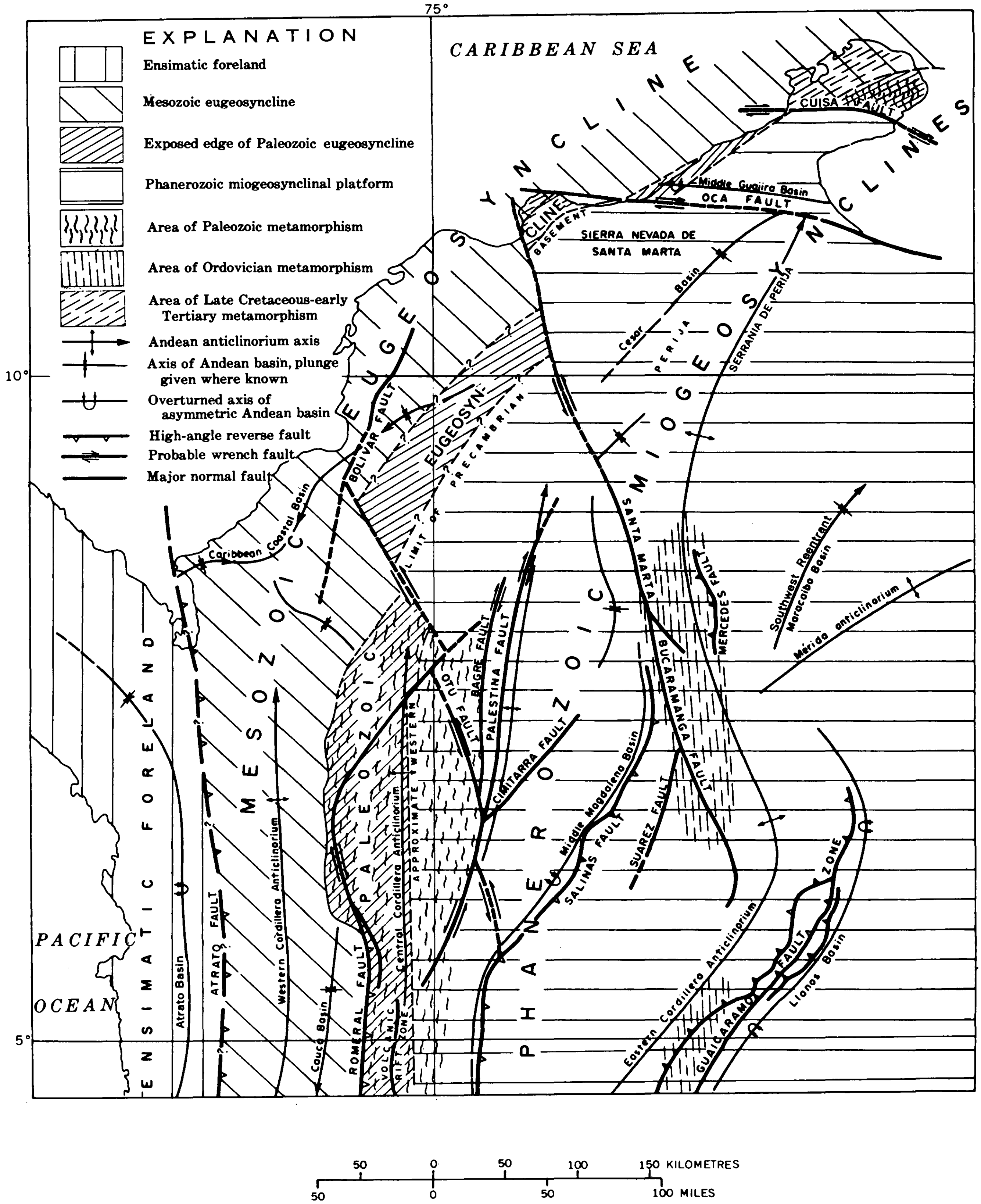

FIGURE 9.—Principal tectonic elements of northernmost Andes, Colombia.

The most notable high-angle reverse faults appear to be those along the eastern margin of the Eastern Cordillera, adjoining the deeply filled Tertiary basins of the eastern great plains (Llanos Basin). Mapping and study of aerial photographs show that Paleozoic and Cretaceous strata are thrust over steeply dipping and locally overturned Cretaceous and Tertiary strata of the basin. The fault pattern is not simple, and in many places throw is distributed among several parallel faults, as it is along the Santa María, Yopal, and Guaicaramo at the latitude of Bogotá (pl. 1). The faults apparently dip at high angles to the west, toward the cordillera.

Structure profiles of the Tertiary and Cretaceous across the Eastern Cordillera and into the eastern Llanos Basin indicate vertical displacements of several miles (pl. 2). Because lower and middle Tertiary strata are involved, it is clear that the thrusting is post-middle Tertiary and probably was related to the Andean orogeny. The extraordinary topographic relief along the cordillera front, much of it carved in soft rocks, indicates that deformation may have continued to a comparatively recent date. This interpretation is supported by the strong earthquake activity in the region and by many terraces at various elevations along rivers draining the Cordillera.

McLaughlin and Arce (1972) mapped many high-angle reverse strike faults in the high savanna north of Bogotá. These faults are predominantly parallel to the axes of folds in Cretaceous and Tertiary rocks, and most dip toward the axial planes of the folds; the folds thus appear to have been broken by distension of overturned limbs.

High-angle reverse faults have been mapped in the Cauca Basin in the vicinity of Cali (Schwinn, 1969). The Cauca Basin between the Central and Western Cordillera (fig. 1) was long considered to be a graben. Mapping by geologists of the International Petroleum Company, however, shows that intrabasin faults are reverse faults and that the marginal faults are high-angle reverse faults, which dip beneath the adjoining Western and Central Cordillera, respectively. Recent mapping of the Romeral fault from Aranzazu southward (Darío Barrero L., written commun., 1970), indicates that it dips 50° to 70° E., so thrusting from the east is evident (pl. 2). The attitude of this western bounding fault of the Central Cordillera, combined with the gentle eastward slope of the old land surface of the Central Cordillera toward the Middle Magdalena Basin, suggests that the Central Cordillera block has ridden upward toward the west.

STRIKE-SLIP FAULTS

Santa Marta-Bucaramanga fault.—Rod (1956) and Raasveldt (1956) simultaneously argued for the probability of strike-slip faulting in Venezuela and Colombia. More recently, Campbell (1965) adduced additional generalized evidence for wrench movement along the Santa Marta-Bucaramanga fault. He pointed out the general similarity and attitudes of the Cretaceous and Tertiary strata of the Middle Magdalena and Cesar Basins (fig. 9) and suggested that the two basins were once united and were displaced by left-lateral movement during late Tertiary and Quaternary time. Displacement may have been as much as 65 miles. Polson and Henao (1960) argued that there is little evidence for wrench movement along the fault; in fact they believed that the Santa Marta and Bucaramanga faults are separate structures. Tschanz concluded (unpub. data, 1969) that major left-lateral displacement, similar to that postulated by Campbell, took place after late Mesozoic–early Tertiary metamorphism, but that the present altitude of the Sierra Nevada de Santa Marta block was achieved mainly by vertical displacement in late Tertiary time.

The following observations bear on the location and scale of wrench faulting along the Santa Marta-Bucaramanga fault:

1. The Sierra Nevada de Santa Marta crystalline complex, which includes the oldest known rocks in Colombia (1,350 m.y.), forms a block that juts abnormally northward upon the Caribbean coastline, intercepting much younger sedimentary deposits of adjoining areas along the coast. Miocene beds adjoining it on the west have extremely low sand-shale ratios, indicating either that the mountain mass was low during deposition of the Miocene sediments or that the mountain mass was transported to its present position relative to the Miocene beds by many miles of left-lateral strike-slip movement.
2. The Santa Marta-Bucaramanga fault, nearly 360 miles long, is remarkably straight. Although much of its trace in the north is beneath alluvium, it has strong topographic expression from the Cesar Basin southward.
3. The fault maintains a fairly constant N. 15° W. strike throughout its length and in the Sierra Nevada de Santa Marta intersects Precambrian basement structures at small to large angles; only in the southern part does its trace coincide with Jurassic and pre-Jurassic structural

grain. The structure, moreover, is little affected by the strong northeast-striking faults in the Sierra Nevada de Santa Marta, in the basement rocks of the Santander Departments, and in the Tertiary strata of the Middle Magdalena Basin.

4. Basement-rock formations are poorly known along the west side of the Santa Marta-Bucaramanga fault in its northern segment, but some metamorphic rocks of the Sierra Nevada de Santa Marta are similar to those of the northern end of the Central Cordillera. The Sierra Nevada de Santa Marta rocks may have been displaced en masse northward from a former southerly position. Metamorphic rocks in the Algarrobo No. 7 well drilled by the Superior Oil Company, near the San Angel No. 2 well (Tschanz and others, 1969), consist of huge blocks of phyllite very similar petrographically to that of the Taganga Group (Cretaceous) or San Lorenzo Schist of the extreme northwest corner of the Sierra Nevada de Santa Marta. Furthermore, the south-flanking Cretaceous limestone and Triassic-Jurassic volcanic rocks in the Sierra Nevada de Santa Marta may have been displaced northward from similar rocks near Morrocoyal.

   If such left-lateral displacement has occurred, amounting to 65 miles, as suggested by Campbell (1965), then the structural grain of the basement rocks on each side of the fault is restored to approximate coincidence across the faulted area. The grain of the rocks in the western Sierra Nevada de Santa Marta, according to this interpretation, represents part of a curving regional grain that has been laterally offset.

Oca fault.—The north side of the Sierra Nevada de Santa Marta is bounded by the east-west Oca fault zone, which passes eastward into the northern part of the Maracaibo Basin of Venezuela (pl. 1, fig. 9). Recent mapping by Tschanz, Jimeno V., and Cruz B. (1969) has shown that the western segment of the fault is not a single structure, but one that has split into several subparallel splays, along which large vertical displacement associated with the uplift of the Sierra Nevada de Santa Marta has probably been distributed. Eastward, in the Department of Guajira and in Venezuela, the fault is a single structure. Isopachs of the Cenozoic strata north of the fault show pronounced thickening of Cenozoic strata southward in the Guajira Basin toward the fault (pl. 1), as if depression took place contemporaneously with basin filling. Similar filling and depression farther to the east led to the truncation and burial of the extreme north end of the Serranía de Perijá. Many authors have suggested right-lateral movement on the fault, but few have presented concrete evidence to support this contention. Tschanz (written commun., 1969) believes that schist from the Perico well might be correlated with the Taganga Group on the northwest corner of the Sierra Nevada de Santa Marta; if so, horizontal displacement, depending upon effects of erosion on respective sides of the Oca fault, has been as much as 40 miles. Feo-Codecido (1970), on the basis of a subcrop geologic map drawn from well data at the base of post-Eocene sedimentary rocks in westernmost Venezuela, concluded that right-lateral displacement on the Oca fault may have been as much as 12 miles.

Cuisa fault.—Approximately 50 miles north of and nearly parallel to the Oca fault is the Cuisa fault of the Guajira Peninsula. Alvarez (1967), who mapped its western part, thought that possibly there had been right-lateral displacement of as much as 15 miles, on the basis of the offset of phyllite-gneiss and gneiss-sedimentary rock contacts. Because the Cuisa and Oca faults are nearly parallel to one another, displacement similar to that of the Oca fault may be inferred on the Cuisa. Continuation of the Cuisa fault along its western projection below sea level is said to be clearly recognizable in offshore seismic records made for petroleum companies.

Otú fault.—The Otú fault strikes N. 15° W. and has been traced for nearly 75 miles from Zaragoza southward to a point near Puerto Berrío. At each extremity the fault trace is covered by Tertiary sedimentary rocks or Holocene alluvium (pl. 1, fig. 9). Distinctive intrusive relations between diorite and quartz-rich metamorphic rocks on opposite sides of the fault are interpreted by Feininger (Feininger and others, 1973) to indicate left-lateral displacement of as much as 30 miles. The Otú fault has cut other faults that displace Cretaceous shale containing Aptian-Albian fossils; hence, the Otú is post-Albian, and principal displacement is probably post-middle Maestrichtian. By reconstruction of movements on the Otú and associated faults, Feininger's interpretation is that the Precambrian block with its overlying Ordovician shale near Cristalina was transported into the area from a point 35 miles east-southeast.

Projecting the Otú fault northward beneath the

Tertiary strata, one notes that Cenozoic strata east of the fault are thin, whereas Cenozoic strata west of the fault attain great apparent thickness (pl. 1). Because the Otú fault is approximately parallel to the Santa Marta-Bucaramanga fault and displacement on both appears to be left lateral, the two structures are considered to be related to similar tectonic forces.

Palestina fault.—The Palestina fault (Feininger, 1970) trends about N. 15° E. and can be traced for nearly 200 miles along the east side of the Central Cordillera (pl. 1, fig. 9). Right-lateral strike-slip movement has been well documented (Feininger, 1970). The Otú fault has been displaced 17.2 miles by the Palestina, and earliest movement may predate the Upper Cretaceous Antioquian batholith. The Jetudo and Mulato faults to the south appear to be horsetail splays of the Palestina fault; Feininger inferred that right-lateral displacement has also occurred on these two faults, collaterally with Palestina movement, although in amounts of only 7 and 10 miles, respectively.

Cimitarra fault.—The Cimitarra fault extends to the Palestina fault from the Barrancabermeja area to the northeast (pl. 1). Because of its strong topographic expression, and because it cuts Miocene and younger formations in the Middle Magdalena Basin, it is considered to be the youngest major fault in the area. It can be traced for almost 100 miles on the surface and in the subsurface. Feininger (1970) was unable to ascertain the nature of displacement upon it, but inferred that it is a wrench fault.

Romeral fault.—A major north-south fault now called the Romeral fault has been traced for several hundred miles. North of latitude 7° N., it has a northeasterly course (pl. 1). Its topographic expression is much clearer than that of the Otú fault zone, which suggests that it is younger than the Otú. Thus, the Romeral fault probably transects the Otú fault beneath the Tertiary cover to the north. To the south, the Romeral fault dips 50°–70° E. at various points along its trace (Darío Barrero L., oral commun., 1970), and metamorphic rocks of the Central Cordillera thrust over continental Tertiary strata and Cretaceous volcanic rocks. In its northeast-trending northern segment, the fault intercepts geologic formations in a manner suggesting right-lateral movement (Alvarez and others, 1970).

Atrato fault.—A recently recognized north-trending lineament, the Atrato fault, appears to form the western boundary of the Western Cordillera (pl. 1; fig. 9). Its trace is remarkably linear. Generally northwest-trending fold axes in Tertiary beds east of the Gulf of Urabá swing north in the area of the presumed northerly extension of the fault, and appear to cross the direction of thickening of the Tertiary rocks. Elsewhere in the Sinú Fold Belt and in the Lower Magdalena Basin (pl. 1), fold axes trend northeast. These relations mildly suggest that the fault has been under compression and that left-lateral movement may have taken place along it.

INTERIOR BASINS

During early Tertiary time a large basin existed east of the Central Cordillera and was probably originally coextensive with the Barinas Basin south of the present Merida Andes of Venezuela (fig. 7). During the Andean orogeny it underwent taphrogenesis. Wellman (1970) in his study of the Honda Group (Miocene) of the Upper Magdalena Basin, concluded that its sediments were deposited by streams flowing eastward from the Central Cordillera. Howe (1969) has also shown that paleocurrents during deposition of the overlying Neiva Formation (probably lower Pliocene), lowest unit of the Mesa Group, were also predominantly eastward. At some later time, the eastward-flowing streams were evidently intercepted by uplift of the Eastern Cordillera across their path and were turned to their present northward course.

No paleocurrent studies have been made of the Middle Magdalena Basin area. The Honda Group of the Upper Magdalena Basin passes into and is probably correlative with the thick, coarse clastic Real Formation of the Middle Magdalena Basin. The overlying Mesa Group is common to both basins. The Real Formation in turn is approximately correlative with the Guayabo Formation of the southwesternmost Maracaibo Basin in the vicinity of Cucuta (pl. 1). Uplift of the Eastern Cordillera similarly may have separated this part of the former coextensive basin into the present smaller basins.

Van der Hammen (written commun., 1969) has shown that the base of the little-deformed Tilatá Formation (upper Pliocene) of the Eastern Cordillera contains humid tropical pollen and that upward in the section, the Tilatá contains pollen of flora of progressively cooler climates. This observation suggests that much Andean folding took place at comparatively low altitudes, for the Tilatá was deposited across the eroded edges of folded older Tertiary formations. It is concluded, therefore, that the Upper and Middle Magdalena Basins had achieved their depressed positions and the beds therein were folded before uplift of the Eastern Cordillera along its marginal high-angle reverse faults. Thus, the thick lower Tertiary section in the Magdalena Basins seems to have resulted from compression in association with reverse faulting along the basin margins, and not, as long interpreted, from infilling of a graben.

Folding of the Tertiary strata within the present Upper and Middle Magdalena Basins, the southwesternmost Maracaibo Basin, and along the western margin of the Llanos Basin, is generally less intense than that of the Tertiary strata within the Eastern Cordillera. This fact suggests that the rocks underlying the cordillera were less competent than those in the adjoining basins.

Data on Tertiary structural history of the Cauca Basin, on the other hand, is limited, and little can be said about the relation of Tertiary strata of that basin to Tertiary strata of the Pacific Coastal Basin to the west. Moderately thick sections of nonmarine beds within the Cauca Basin are folded and thrust faulted in a manner comparable with their analogs in the Upper and Middle Magdalena Basins; both the eastern and western margins of the Cauca Basin are delimited by high-angle reverse faults (pl. 2). The similarity of the structural style of both these longitudinal intermontane basins is remarkable, but detailed study is required before well-based conclusions on their similarity can be reached.

COASTAL WEDGES

Tertiary strata of the Sinú Fold Belt and Lower Magdalena Basin (fig. 1) thicken northward from the overlap on the pre-Tertiary rocks of the Western and Central Cordilleras and appear to reach maximum thicknesses along a northeast-trending axis approximately parallel to, and slightly southeast of, the Caribbean coastline. The Tertiary reaches a thickness of 30,000 feet near the town of Montería (pl. 1). Along the coast the strata are tightly folded, but southeastward toward the interior they are only gently flexed. The sharp difference in structural style in the two areas may be the result of contrasting thickness of sections, but a part may be due to differences in the nature and competence of the basement rocks, as suggested by Zimmerle (1968). The folded coastal sedimentary belt appears to overlie the Mesozoic eugeosynclinal rocks, whereas the little-deformed interior sedimentary beds probably overlie crystalline Paleozoic and Precambrian rocks (fig. 9).

The Tertiary strata of the Pacific Coast Basin were deposited apparently as a littoral wedge adjacent to the Western Cordillera. The northern part of the wedge underlying the Atrato River is synclinal, whereas the southern part—for example, south of Buenaventura—slopes oceanward toward the continental platform as a simple homocline. The Tertiary strata thicken oceanward as indicated by offshore drilling. As indicated above, data on the structural and stratigraphic relation of these strata to those within the Cauca Basin are insufficient for drawing conclusions at this time. Possibly prior to the Andean orogeny (Miocene) the present two basins were coextensive, nonmarine landward and marine seaward, and constituted part of what Nygren (1950) referred to as the Bolivar geosyncline.

ISTHMUS OF PANAMA

The bifurcation of the Isthmus of Panama from the South American continent is not well understood. The isthmus, as shown by bathymetric maps, forms an elevated narrow ridge upon a much broader submarine platform whose margins break sharply into the Caribbean Basin northeastward and into the Pacific Basin southwestward. The exposed part of the ridge is synclinal and its axis veers southward into the Atrato synclinorium west of the Western Cordillera (fig. 9). A side-looking radar map of the area (Raytheon Company, written commun., 1969) shows an extraordinary rift zone, here referred to as the Atrato fault (pl. 1; fig. 9), along the eastern margin of the Atrato River valley and at the western margin of the Western Cordillera. The fault extends for several hundred kilometers south from the Gulf of Urabá.

Gravimetric profiles across the Pacific Coast Hills near the Colombia-Panama border (Case and others, 1969) show extremely high Bouguer gravity anomalies. Because of the mafic composition of the basement rocks and the excessively high anomalies, Case interpreted the underlying rocks of the area to be oceanic crust.

In his paleontological studies of faunas from rocks along Routes 17 (eastern Panama) and 25 (northwestern Colombia), for the Interoceanic Canal Commission, Bandy (1968) confirmed the mafic composition of the basement rocks and stated that the oldest faunas found are of Late Cretaceous age. The Upper Cretaceous and lowermost Tertiary strata contain abyssal to bathyal faunas in contrast to the shallow-water forms in upper Tertiary strata. The data tend to suggest that the isthmus belongs to an oceanic geologic province that formed separately from the

Andes and became connected to the Andes during the Andean orogeny (Miocene).

GEOLOGIC CROSS SECTIONS

Geologic cross sections across the northernmost Colombian Andes drawn at parallels of latitude 5° and 7° N. are shown on plate 2. At the present stage of mapping of Colombia, these parallels of latitude have the best geologic control; even so, control for the western parts of the cross sections is poor.

The cross sections illustrate the tripartite geologic subdivisions of the Colombian Andes. The Eastern Cordillera is composed mainly of Mesozoic and Paleozoic rocks overlying Precambrian basement rocks; the Cordillera is elevated along high-angle reverse faults or sharp marginal flexures. The Central Cordillera is composed predominantly of metamorphosed Paleozoic strata that have been intruded by small upper Paleozoic-Lower Triassic plutons and by large upper Mesozoic plutons. And finally, the Western Cordillera consists almost exclusively of thick sections of folded and faulted upper Mesozoic eugeosynclinal sedimentary and volcanic rocks intruded by middle Tertiary plutons, forming a belt oceanward and alongside the metamorphosed rocks of the Central Cordillera.

The approximate positions of orogenic belts and of plutonic rocks, with radiometric ages where known, are indicated on the sections (pl. 2).

STRUCTURAL EVOLUTION

PRECAMBRIAN

During Precambrian time the Guayana shield of northern South America (fig. 2) acquired cratonic characteristics during the Akawaian episode (Guyanese or Transamazonas igneous cycle) about 2,000 m.y. ago. This event is established by the fact that the widespread overlying sedimentary Roraima Formation, intruded by mafic sills dated at 1,700 m.y., is little disrupted. From its broad exposed area in the eastern part of the continent, the shield surface descends gently northward toward the Venezuelan Andes and westward toward the Colombian Andes and passes beneath an extensive cover of younger rocks mainly of Cenozoic age. Precambrian rocks again crop out in the Venezuelan Andes and, as shown in this study, in the Colombian Andes. It is concluded, therefore, that the northernmost Andes are situated along the northwestern margin of the Guayana shield, and in part are underlain by shield rocks.

The outermost rocks of the Guayana shield are clearly younger than those of the central shield. The oldest radiogenic ages for rocks in Colombia range from 1,400 m.y. to 1,300 m.y. Younger ages of 950 m.y. and 700 m.y. may represent late Precambrian disturbances which reset isotopic clocks of older rocks, or indeed may also represent late Precambrian cycles of sedimentation, metamorphism, and igneous intrusion. The structural grain of these outermost shield rocks appears to be north-northeast in Colombia, but in the Sierra Nevada de Santa Marta the grain swings northeast. In the Guajira Peninsula, it is east-northeast, and from there it swings eastward into northern Venezuela. The outermost Precambrian shield rocks in Colombia are highly metamorphosed and range from biotite schist through amphibolite to rocks of the granulite facies, similar to those of the central shield.

The long span of geologic time recorded by radiogenic ages in the Precambrian terranes, as compared with that in the Phanerozoic terranes (which are so much better known), admits the possibility that several as-yet-unrecognized cycles of sedimentation, metamorphism, and plutonic intrusion may have taken place in this area near the margin of the Precambrian continent where the sialic crust has undoubtedly interacted with the oceanic crust. Detailed mapping and additional radiogenic determinations are needed to unravel the detailed history of these outermost Precambrian terranes in Colombia.

PALEOZOIC

During the Paleozoic Era, epicontinental and miogeosynclinal seas transgressed upon the Precambrian shield platform on various occasions. During Cambrian and Ordovician time (fig. 3), fossiliferous clastic strata were deposited over much of the area of the present Eastern Cordillera, and according to present information as far east as longitude 72° W. in central Colombia. Graphite content in these sedimentary rocks increases westward, indicating that the seas deepened westward. In Late Ordovician time the sedimentary rocks of the Silgará Schist (Cambrian and Ordovician) were strongly folded along north-south axes, metamorphosed to as high as sillimanite grade, and were extensively intruded by large syntectonic, gneissoid, granitic masses that are radiogenically about

450 m.y. old. Small peralkalic syenite bodies near San Josá de Guaviare intrude Precambrian rocks and are approximately 460 m.y. old. Metamorphism in the Cambrian and Ordovician rocks decreases in intensity to the north and south along the orogenic axis, and in the extreme north and south the sedimentary rocks are little metamorphosed. As Precambrian rocks crop out extensively in the Central Cordillera west of this orogenic axis, folding and igneous intrusion in this orogen were clearly intracratonic. Uplift associated with the orogeny prevented reentry of seas during the Silurian, and no rocks of Silurian age have been found in Colombia, although C. Martin-Bellizzia (oral commun., 1970) informed me that Silurian faunas are present locally in Venezuela.

Fossiliferous Devonian strata (fig. 4) are widely distributed over approximately the same area as the Cambrian and Ordovician strata and unconformably overlie these older rocks. East of Bucaramanga (pl. 1), rocks equivalent to the Floresta Formation (Devonian) are strongly folded and metamorphosed to low greenschist facies. Lower Carboniferous (Mississippian) rocks are poorly represented. Thus, it is concluded that a sharp disturbance in Late Devonian or early Carboniferous time was localized approximately over the axis of the preceding Late Ordovician orogeny and caused a general retreat of seas from much of Colombia. No Upper Devonian or Mississippian igneous rocks associated with this disturbance have yet been identified.

Unmetamorphosed fossil-bearing Pennsylvanian and Permian strata—very thick sections in some areas—are found in scattered outcrops over much the same area as the Cambrian-Ordovician and Devonian strata and overlie all older rocks with angular unconformity. No important stratigraphic break or unconformity, however, is noted at the top of the Permian; in the Bucaramanga area the Permian Tiburón beds pass upward into the paralic Bocas Formation of Triassic age with little discordance. Triassic strata, however, are of limited distribution, and it is concluded that there was a general withdrawal of seas from the platform area at the close of the Paleozoic Era.

The Paleozoic record of the area to the west is less clear because sedimentary rocks probably equivalent to those deposited upon the Precambrian platform are severely metamorphosed. Along the eastern flank of the present Central Cordillera the original Paleozoic sedimentary rocks consisted of shale, graywacke, impure to pure sandstone, and included a prominent limestone member. These rocks, which were also deposited upon Precambrian basement rocks, as indicated by Precambrian outcrops in the area, are now regionally metamorphosed (fig. 4) and range from greenschist to high amphibolite facies. In northern Antioquia Department, the rocks may have approached temperatures of fusion and are now represented by migmatites and anatectites (?) of the Puquí Metatonalite. Along the west flank of the Central Cordillera, mafic volcanic material associated with the sedimentary rocks is converted to greenstone, chlorite schist, biotite-hornblende schist, and amphibolite. Here, however, no Precambrian basement rocks have been identified.

This distribution of Paleozoic and Precambrian rock types suggests that conditions of deposition along the east side of the present Central Cordillera were miogeosynclinal to epicontinental upon the sialic Precambrian continental platform, whereas conditions along the west side of the cordillera were eugeosynclinal upon simatic oceanic crust adjoining the Precambrian continental platform. Judging from the structural grain and distribution of metamorphic rock types, the Paleozoic miogeosynclinal-eugeosynclinal couple appears to have extended northward, curving northeastward through the Sevilla arc in the Sierra Nevada de Santa Marta, and possibly continued east-northeastward through the Guajira arc on the Guajira Peninsula.

A profound late Paleozoic orogeny converted the Paleozoic miogeosynclinal rocks and the adjoining eugeosynclinal sedimentary rocks to metamorphic rocks of low to high rank. The rocks were intruded by plutons that have apparent ages of 250 to 240 m.y. This orogeny is regarded as most significant because it gave rise to the ancestral Central Cordillera. It is certainly the most severe orogeny experienced in Colombia during Phanerozoic time. The total width of the orogen is unknown because deposits of younger rocks overlie it along its west and north sides. In addition, it passes out to sea to the north and northeast beneath the present Caribbean Basin. The now-crystalline rocks of the orogen appear to have added a fringe of unknown width to the Precambrian continental platform, and it is concluded that some continental accretion took place at this time (figs. 9, 10).

MESOZOIC

During the Mesozoic Era, sedimentation upon the continental platform east of the ancestral Central

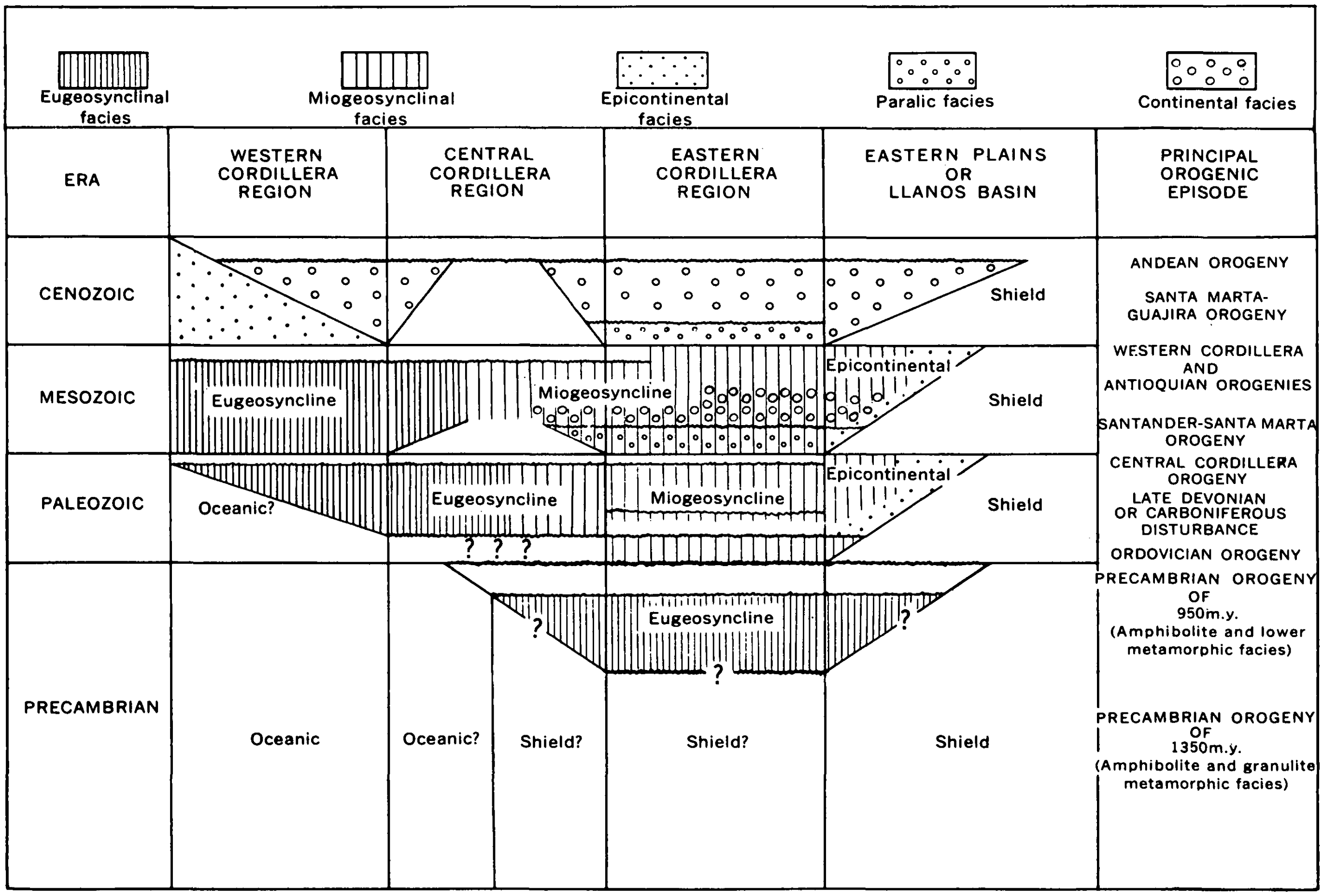

FIGURE 10.—Progressive westward shifts of eugeosynclinal axes and resulting continental accretion, northernmost Andes, Colombia.

Cordillera was again miogeosynclinal. Marine incursions were limited during Triassic time, but expanded somewhat in Jurassic time (fig. 5). Particularly noteworthy during the Triassic was the advent and increasing tempo of volcanism in the Sierra Nevada de Santa Marta where abundant spilites and keratophyres of Triassic age are found. Triassic-Jurassic volcanic and volcanogene sedimentary rocks are widely distributed on the Guajira Peninsula, in the northern Eastern Cordillera, and along the east side of the Central Cordillera.

Jurassic and Cretaceous volcanic rocks range from andesite through dacite and latite to rhyolite in lesser amounts. What triggered this widespread volcanism is not clear. Volcanism apparently preceded, accompanied, and postdated the intrusion of several batholiths in the Sierra Nevada de Santa Marta. In the Santander massif (fig. 2) similar batholiths were intruded during the same time interval but apparently were accompanied by considerably less volcanism. Batholithic intrusion was contemporaneous in the Santander massif and the Sierra Nevada de Santa Marta, two widely separated areas, and began 200 m.y. ago. In the Sierra Nevada de Santa Marta, it reached a culmination at about 175 m.y. In the Central Cordillera, however, it continued to 143 m.y. ago. Uplift accompanying igneous intrusion in the Santander region gave rise to the widespread molassic red beds of the Girón Group (Jurassic).

The lower basaltic volcanic rocks of the Dagua Group, which is to the west of the ancestral Central Cordillera, are considered to represent early manifestations of an extensive Mesozoic eugeosyncline that developed oceanward from the ancestral Central Cordillera. West of Cali, Hubach and Alvarado (1934) and Nelson (1957) mapped mafic volcanic and sedimentary rocks of the Dagua Group beneath a very thick mafic volcanic sequence ("Diabase Group") that is considered by most authors as Cretaceous. The Dagua Group rocks could represent Jurassic deposition in view of the extraordinary thickness of the overlying mafic volcanic sequence. In the absence of fossils, the lower part of the Dagua Group is here considered Jurassic until radiogenic dating of the complete volcanic section determines otherwise. No rocks representing the Triassic Period have been recognized west of the Central Cordillera.

In Late Jurassic time (Tithonian), transgressing marine seas in the Guajira Peninsula and northeast of Bogotá began the infilling of an extremely broad Cretaceous miogeosyncline that occupied the continental platform east of the ancestral Central Cordillera (fig. 6). Sedimentation was variable in response to irregular rates of subsidence and to local diastrophism. Along an axis passing north-northeast through Bogotá, as much as 40,000 feet of clastic sedimentary rocks accumulated. For a brief interval in Aptian-Albian time, there was a seaway connection across the Central Cordillera (Department of Antioquia) to the Pacific, shown by fossiliferous sandstone and shale overlying metamorphic rocks there. The Cretaceous miogeosynclinal seaway receded from south to north; nonmarine sedimentation (Guaduas Formation) began in middle Maestrichtian time in the Bogotá region, whereas nonmarine beds appear at higher stages successively northward, and in the extreme northern part of the country (Cucuta, pl. 1), sedimentation became nonmarine in the Paleocene. In the Sinú Fold Belt, marine deposition continued well into the Cenozoic.

West of the ancestral Central Cordillera enormous thicknesses of mafic volcanic and flysch-type sedimentary rocks accumulated in a Cretaceous eugeosyncline that extended along the Pacific coast, through the northwestern edge of the present Sierra Nevada de Santa Marta, and possibly to and beyond the northwest side of the Guajira Peninsula, forming a pericontinental arcuate belt (fig. 6) that conforms generally with the outline of the continent. The sedimentary rocks are mainly dark shale, graywacke, and impure siltstone. The associated volcanic rocks are basaltic and contain some radiolarian cherts. Small ultramafic and serpentinite bodies cut the deposits and are commonly fault bounded. Mapping to date seems to indicate a concentration of these ultramafic bodies in the vicinity of the Romeral and other major faults (pl. 1); this concentration may be illusory, however, because of the lack of comparable detailed mapping to the west.

The Mesozoic Era closed with an important orogeny that involved the eugeosyncline throughout its length. This orogeny formed the Western Cordillera and its analogs along the northeast coastal region of Colombia. In middle Maestrichtian time, the great Antioquian batholith and its satellites (age 70 to 80 m.y.) were emplaced along the inner side of the orogenic arc (fig. 6). Contact metamorphism is observed in rocks immediately adjoining the intrusive rocks, and resetting of isotopic ratios seems to have been widespread. Only incipient metamorphism is evident in the rocks of the Western Cordillera, but in the northwestern Sierra Nevada de Santa Marta and Guajira Peninsula, metamorphism locally reached the lower amphibolite facies. This orogeny is significant, for it gave rise to the Western Cordillera as an outer parallel counterpart to the ancestral Central Cordillera. This range formed the second prong of the present trident Colombian Andes.

CENOZOIC

In early Tertiary time, a large inland basin formed over the continental platform east of the Central Cordillera. The basin extended toward the Guayana shield and probably merged with the east-west Barinas Basin of southern Venezuela and possibly connected with the Maracaibo Basin in the area of the present Táchira Gap in western Venezuela (fig. 7). Much detrital material came from the rejuvenated Central Cordillera, as evinced by the composition of the basal Tertiary strata, but the enormous volume of Tertiary sedimentary material, including that of the Barinas Basin, requires that substantial contribution must also have been derived from the interior of the continent. For brief intervals the rate of subsidence increased, and short-lived marine embayments invaded the otherwise nonmarine environment. A similar geologic setting may have been present along the west side of the Central Cordillera, but lack of information does not permit a clear understanding of the conditions of deposition there.

Probably beginning in the Late Cretaceous and culminating in middle Eocene time, a sharp orogeny took place along the northwest side of the Guajira Peninsula, extending through the northwest corner of the Sierra Nevada de Santa Marta and continuing southward along the Central Cordillera at least to near Ibagué. This orogeny is widely reflected in Eocene strata by unconformities, by thick and coarse conglomerate and sandstone horizons, and by transgressive overlaps by younger formations. Cretaceous sedimentary rocks were locally metamorphosed to greenschists, and the orogeny culminated with the intrusion of the Parashi quartz diorite stock in the Guajira Peninsula and the Santa Marta batholith in the Sierra Nevada de Santa Marta. Southerly directed thrust faulting in both these areas postdates the orogeny. This orogeny, following the nomenclature of van der Hammen (1958), is referred to as "pre-Andean."

Nonmarine sedimentation continued over the continental platform in the interior of the country. Upper Oligocene sedimentary rocks show some increase in grain size, indicating that transporting agents were acquiring greater competence. During the Oligocene and extending into early Miocene time, several granitic plutons were emplaced along the Western Cordillera. This event and evidence of local diastrophisms that produced multiple sedimentary cycles, are regarded as "proto-Andean" (van der Hammen, 1958).

Along the area of the present axis of the Eastern Cordillera, Paleocene to Oligocene strata are less thick than Paleocene to Oligocene strata in the Magdalena Basin to the west or in the Llanos Basin to the east. Of great significance is the fact that rather complete lower Tertiary sections are preserved in sharp, deeply infolded synclines at altitudes of 8,000 to 12,000 feet along the crest of the Eastern Cordillera. This suggests that these lower Tertiary formations were once coextensive widespread deposits. They are regarded as stratigraphic equivalents of lower Tertiary beds in the adjoining present basins.

Because of the suspension of deposition along the present summit areas of the Eastern Cordillera in Miocene time and the sudden appearance of distinctive lithologies in Miocene strata in adjoining basins, it is concluded that the principle Andean orogeny began during the Miocene, when the third prong of the Colombian Andes (the Eastern Cordillera) began to take its present form.

During the Andean orogeny, moderate to intense folding took place in those areas where Cretaceous and (or) Tertiary sedimentary beds were extraordinarily thick, such as along the axis of the Cretaceous miogeosyncline (fig. 6) and along the Caribbean coast between the Gulf of Urabá and the Sierra Nevada de Santa Marta (pl. 1). Where the Cretaceous and (or) Tertiary sedimentary cover was thin over competent continental platform rocks, folding was much less intense and may have resulted from differential vertical movements along faults in the subjacent basement rocks. Most northern Andean Cordilleras are bounded by sharp flexures, by high-angle reverse faults, or by strike-slip faults. In all detailed mapping to date, no important gravitational sliding has been noted as a cause for folding in northern Colombia, in spite of the great and sharp relief between cordilleras and adjoining basins. Compressed folds, which locally are strongly overturned and have associated longitudinal reverse faults, indicate that deformation was accomplished under compression.

During Late Cretaceous and early Tertiary time, strike-slip displacements on major faults were left lateral, as shown by displacements on the Otú and Santa Marta-Bucaramanga faults. These left-lateral displacements offset large segments of the continental platform and displaced Paleozoic and Mesozoic eugeosynclinal rocks in a northerly direction (fig. 9). At a later date, perhaps beginning with the middle Tertiary Andean orogeny, a new stress field formed in the crust and caused right-lateral strike-slip faulting; a well-documented example is the Palestina fault (fig. 9), which displaces the trace of Otú fault by 17.2 miles, in right-lateral manner.

The present altitudes of the Western, Central, and Eastern Cordilleras appear to be the result of epeirogenic uplift after principal Andean folding. This interpretation is confirmed by the existence of high-level erosion surfaces along various parts of the cordilleras, often upon soft sedimentary rocks. The Tilatá Formation (Pliocene) in the Bogotá region was deposited on one such erosion surface. As the lowermost beds of the Tilatá were reported by van der Hammen to contain humid tropical pollens that could not have flourished above 1,500 feet, uplift in this area was on the order of 6,000–7,000 feet. Epeirogenic uplift began before the advent of Pleistocene glaciation because deposits of glacial origin are observed in many high mountain areas. Van der Hammen and Gonzales (1963) and Raasveldt (1956) reported moraines down to altitudes of 10,000 feet.

Where the Isthmus of Panama joins the South American Continent, high positive Bouguer gravity anomalies indicate that the Panamanian platform differs markedly from that of the Andean region. The northwesterly trend of the isthmus, basement rocks of mafic composition, high positive Bouguer anomalies (Case and others, 1969), and the fact that the Upper Cretaceous and lowermost Tertiary strata contain abyssal to bathyal faunas (Bandy, 1968) in contrast to the shallow-water forms in upper Tertiary strata, suggest that the isthmus belongs to an oceanic geologic province that formed separately from the Andes. Comingling of vertebrate faunas between the North and South American Continents began in middle Tertiary time, suggesting that the present isthmus came into being during the Andean orogeny in Colombia (Van Houten and Travis, 1968).

CONCLUSIONS

A study of the geologic history of the northernmost Andean area from early geologic time to the present, suggests that the trident Colombian Andes formed during a series of events that took place along the margin of the Precambrian Guayana shield, where the shield meets the Pacific oceanic crust. These events are as follows:

1. During Paleozoic time, a pericontinental eugeosyncline formed around the northwestern edge of the Precambrian Guayana shield. At the close of the Paleozoic, a powerful orogeny involved miogeosynclinal platform deposits on the margin of the shield and the eugeosynclinal deposits; metamorphism in the orogenic axial area included anatexis and was followed by granitic intrusion to produce the ancestral Central Cordillera and its northeast extension through the Sierra Nevada de Santa Marta (Sevilla arc) to the area of the Guajira Peninsula (Guajira arc).
2. During the Mesozoic Era, a second pericontinental eugeosyncline formed outside and oceanward from the late Paleozoic orogenic belt, and in Late Cretaceous time the eugeosyncline became involved in an orogeny which resulted in the ancestral Western Cordillera.
3. Throughout Phanerozoic time, the area east of the Central Cordillera was underlain by the Guayana shield and, except during the intracratonic Late Ordovician and Jurassic orogenies, behaved as a comparatively stable platform upon which epicontinental and miogeosynclinal deposits accumulated.
4. Beginning in the Miocene the present Eastern Cordillera rose along sharp marginal flexures, steep reverse faults that dip toward the cordillera, and locally along strike-slip faults.

Thus the three Andean Cordilleras of Colombia are distinctive geologically (pl. 2) and formed at different times: (1) the Central Cordillera in late Paleozoic time, (2) the Western Cordillera near the close of the Mesozoic, and (3) the Eastern Cordillera in middle Tertiary time. All three cordilleras experienced vertical uplift in late Tertiary time, and this deformation accounts for part of their present relief.

Throughout this presentation observations have been directed mainly to the hinterland regions back of present coastlines. This stance has been justified, it is believed, owing to the absence of detailed geological mapping in the heavy rain forest region along the Pacific coast and of the region where the Isthmus of Panama links with the South American Continent. Perhaps more importantly, it is well known that the geology of the northern, central, and southern Andes varies greatly (Gansser, 1973) and perhaps fundamentally, such that conclusions drawn from one sector are only partially valid, or invalid, for another. For these reasons hypothetical discussions of continental drift or plate tectonics have been held in abeyance until such time that a better observational base is developed for the entire cordillera system.

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