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GEOLOGY AND MINERAL DEPOSITS OF AN AREA IN THE DEPARTMENTS OF ANTIOQUIA AND CALDAS (SUBZONE IIB), COLOMBIA

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with a section on Economic Geology
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ABSTRACT

The Inventario Minero Nacional (IMN), a four-year cooperative geologic mapping and mineral resources appraisal project, was accomplished under an agreement between the Republic of Colombia and the U. S. Agency for International Development from 1964 through 1969.

Subzone IIB, consisting essentially of the east half of Zone II, comprises nearly 20,000 km^2, principally in the Department of Antioquia, but including also small parts of the Departments of Caldas and Tolima.

The rocks in IIB range from Precambrian to Holocene. Precambrian feldspar-quartz gneiss occupies a mosaic of fault-bounded blocks intruded by igneous rocks between the Otú fault and the Río Magdalena. Paleozoic rocks are extensive, and include lightly metamorphosed graptolite-bearing Ordovician shale at Cristalina, and a major suite of graphitic quartz-mica schist, feldspathic and aluminous gneiss, quartzite, marble, amphibolite, and other rocks. Syntectonic intrusive gneiss intruded many of the older rocks during a late Paleozoic(?) orogeny, which was accompanied by Abukuma-type metamorphism ranging from lowermost greenschist to upper amphibolite facies. A Jurassic diorite pluton bounded by faults cuts volcanic rocks of unknown age east

of the Otú fault. Cretaceous rocks are major units. Middle Cretaceous carbonaceous shale, sandstone, graywacke, conglomerate, and volcanic rocks are locally prominent. The Antioquian batholith (quartz diorite) of Late Cretaceous age cuts the middle Cretaceous and older rocks. A belt of Tertiary nonmarine clastic sedimentary rocks crops out along the Magdalena Valley. Patches of Tertiary alluvium are locally preserved in the mountains. Quaternary alluvium, much of it auriferous, is widespread in modern stream valleys.

Structurally IIB constitutes part of a vast complex synclinorium intruded concordantly by syntectonic catazonal or mesozonal felsic plutons, and by the later epizonal post-tectonic Antioquian batholith. Previously unrecognized major wrench faults are outstanding structural features of IIB. Some are traceable for several hundred kilometers and probably have displacements measurable in kilometers, although only the Palestina fault, with right-lateral displacement of 27.7 km, is accurately documented.

Correlations of rocks mapped in IIB with those of outlying areas including neighboring IIA are discussed.

INTRODUCTION

The Inventario Minero Nacional (IMN) was a 4-year program undertaken cooperatively with the U. S. Geological (USGS), and jointly financed under an agreement between the Ministry of Mines and Petroleum of the Republic of Colombia and the Agency for International Development (AID), U. S. Department of State. The work of the Inventario formally began in September 1964.

The purpose of IMN was to study and evaluate the mineral resources (excluding petroleum, coal, emeralds, and alluvial gold) of selected areas in Colombia, designated Zones I through IV, that total about 100,000 km^2. Each zone was provided with one or more geologists of the USGS, to act as scientific and technical advisors. Field geologists and administrative personnel were Colombian. The geologists were provided chiefly by the Servicio Geológico Nacional and the schools of geology of the Universidad Nacional, Bogotá, and the Facultad Nacional de Minas, Medellín. Specialists in such fields as cartography, geochemistry, geophysics, paleontology, and phosphate rock were provided from time to time by the USGS, mostly on short-term contracts. The Inventario had three Project Directors, the late Dr. Aurelio Lara, and Drs. Darío Suescún G. and Andrés Jimeno V. Mr. Earl M. Irving was Chief U. S. Advisor.

Of the four zones slated for study under the Inventario program, Zone II, whose area exceeds 40,000 km^2, was by far the largest. Accordingly the zone was divided into two subequal parts along a convenient north-south boundary. The west part constitutes Subzone IIA and the east part Subzone IIB, hereafter commonly referred to as simply IIA and IIB, respectively. Subzones IIA and IIB were studied concurrently but independently of one another and with separate cadres of field geologists and USGS advisors. Drs. Hernán Vasquez C., Hector Rico H., and Jairo Alvarez A. were successive Zone Chiefs of Zone II. Tomas Feininger acted as advisor in IIB throughout the Inventario program.

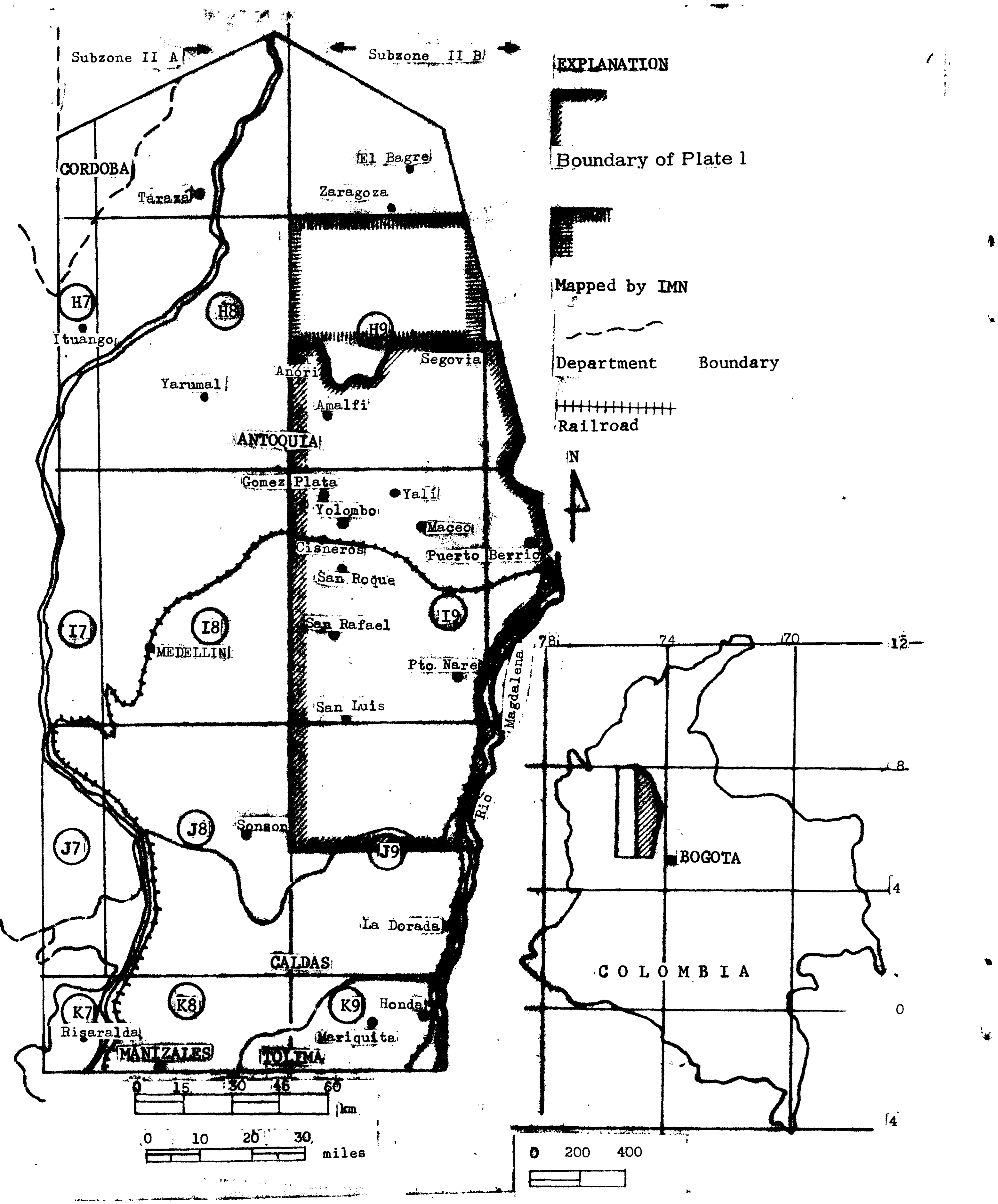


Figure 1. Index map showing location of Subzone II B, Colombia

Subzone IIB

Subzone IIB covers nearly 20,000 km^2, principally in the Department of Antioquia, although small parts are in the Departments of Caldas and Tolima (fig. 1).

Physical geography and geomorphology

The Andes mountains of western South America are part of a single complex orogen of great length. Near the Colombia-Ecuador border, approximately at the equator, the mountain chain divides into three distinct ranges, which in Colombia are called the Western, Central, and Eastern Cordillera. The cordilleras are separated by the north-draining longitudinal Cauca and Magdalena River valleys. This study is directed to a sizeable area along the east flank of the Central Cordillera; the Magdalena River forms its eastern border.

Nearly all of IIB is in a rugged area of maturely dissected mountainous topography. Slopes range from 20° to 40° or more. Local relief nearly everywhere exceeds 500 m. Total relief in IIB is nearly 3,000 m: from about 50 m on the Río Nechí in the north, to more than 2,900 m on the highest mountains along the border with IIA in the south. Mountains yet further south in IIB, in the Department of Tolima, may be higher. Topographic map coverage of that part of IIB, however, is unavailable. In general, relief decreases progressively from west to east toward the Río Magdalena, and local relief in a belt from 10 to 30 km wide along the east edge of IIB south from Puerto Berrío is generally 100 m or less. The only extensive level or gently rolling land occurs on Tertiary and Quaternary sediments in the valley of the Río Nechí in the northern part of IIB and along the Río Magdalena as mentioned before. Some upland valleys are partly filled with colluvial and alluvial deposits and have flat floors. The width of these valley floors, however, rarely exceeds 500 m.

All streams and rivers in the prevalent mountainous topography of IIB flow in steep-walled valleys or canyons from 50 to more than 1,000 m deep. The deepest canyons are those of the Río Porce between Amalfi and Anorí (1,200 m) and the Río Samaná Norte south of San Luis (1,000 m).

The Río Magdalena and its tributaries drain all of IIB. The largest of these tributaries are the Ríos Nechí, Samaná Norte, Samaná Sur, San Bartolomé, Ité, Cocorná Sur, and La Miel. Large tributaries to these streams in turn include the Ríos Nare, Porce, Bagre, Claro, Guatapé, Manzo, Nus, and Volcán.

The climate of IIB is equatorial. Seasonal variations of temperature are negligible; the average annual temperature ranges from nearly 30° C along the Magdalena and Nechí valleys, to perhaps 14° C on the highest mountaintops. Rainfall, on the other hand, has seasonal variations with January, February, July, and August normally the driest months. Throughout IIB rainfall is sufficient to keep the natural vegetation green through the year. Meteorologic data from several stations in IIB are given in table 1.

Forest covered all of IIB prior to colonization which began about 400 years ago. Most of this forest has been felled, but a few areas that cover hundreds of square kilometers have been left largely untouched. The most extensive of these forested areas are found north of the Antioquian batholith and between the towns of San Francisco

Table 1. Meteorologic data from stations in IIB[1]

Station	Elevation (m)	Average annual T (°C)	Average annual rainfall (mm)	Range of annual rainfall (mm)	Years of records
Medellín[2]	1538	21	1351	1002-1723	1942 - 1967
Amalfi	1600	20	1701		1950 - 1962
El Bagre	50		3995	3096-4978	1942 - 1944 1947 - 1962 1964 - 1966
Guatapé	1900		4951	4413-5239	1959 - 1966
Puerto Berrío	123	27	1655		1950 - 1960
San Luis	1115	21	4218	2423-6676	1950 - 1960
Segovia	650	24	2956	2111-4153	1923 - 1967
Yolombó	1845	21	2363	1549-3129	1950 - 1951 1953 1957 - 1962

1/ Data from Departamento de Planeación de la Gobernación de Antioquia except Data Consolidated Gold Dredging. Ltda. (El Bagre): Empresas Públicas de Medellín (Guatapé): and Frontino Gold Mines, Ltda. (Segovia).

2/ In IIA, included here for reference.

and Argelia (pl. 1). Land clearing has been most extensive on the Antioquian batholith and eastward to the Magdalena River.

Bedrock in IIB is deeply weathered and covered by a nearly ubiquitous mantle of clay-rich saprolite and soil. Fresh rock crops out only in stream beds where it may be plentiful. Continuous exposures of fresh rock hundreds of meters long are not uncommon in rivers and large streams.

Weathering of most of the rocks in IIB is pervasive, proceeding along closely spaced foliation or bedding planes and more or less uniformly and completely decomposing the rocks. Massive igneous rocks (such as the quartz diorite of the Antioquian batholith), nonfoliated amphibolite, and some feldspar-quartz gneisses poor in mica, however, weather in a distinctive manner. Where these relatively massive rocks are not closely fractured, decomposition can proceed only along joints. With time, such joint-controlled weathering leaves rounded residual boulders of fresh rock 1 to 10 m in diameter surrounded by shells each from 1 to 10 cm thick of partly weathered rock, which in turn are encased in saprolite. As the saprolite is removed by erosion, the residual boulders of fresh rock become exposed. Such boulders, for example, are conspicuous surficial features on the Antioquian batholith. With time, the boulders move down slopes and become concentrated in stream and river courses. Such concentrations of boulders are called organales (Botero A., 1963, p. 32-35), and some are so extensive and deep that streams flow entirely amongst the boulders and are completely hidden from view.

The saprolite is commonly undisturbed even at little depth where local relief is 100 m or less. Trenches eroded along mule trails that are two or three meters deep show adequate textural and structural features of the parent rock to give useful geologic information. In most places, however, local relief is considerably more than 100 m, and the mantle of saprolite has crept or slid so that even deep cuts fail to expose undisturbed weathered rock. Saprolite derived from certain rock types is particularly subject to movement and nowhere occurs in situ. Mafic igneous rocks, for example, produce a saprolite so unstable that movement of the saprolite mantle hundreds of meters or even several kilometers beyond the limits of the respective body of source rock was found to be common. This relationship is clearly seen in the field around the gabbro body at San Francisco (pl. 1, sheet 2).

Even the drastically disturbed saprolites commonly retain distinctive characteristics that serve to identify the rock from which they were derived. For example, amphibolite and gabbro produce a clayey dark red to maroon saprolite. Felsic intrusive igneous rocks (alaskite to quartz diorite) produce a sticky reddish-tan or beige saprolite. Saprolite derived from migmatite is flecked with dark maroon splotches a few centimeters long, the relics of micaceous laminae. Quartzite and quartz-rich gneiss produce a gray sandy saprolite that emits crunching sounds from beneath the hoofs of passing horses.

The population in IIB is sparse in most areas, and large areas in the north and west-central parts of the subzone are uninhabited. About two dozen incorporated towns ("municipios") and a larger number of unincorporated smaller settlements ("corregimientos" and "veredas") dot IIB. The largest towns are Puerto Berrío, La Dorada, and Honda, all on the Río Magdalena.

Transportation within most of IIB is arduous. The few roads in the part of the subzone mapped by IMN are unpaved, only one lane wide, and passable with difficulty during the rainier months. The yard-gauge Antioquian Railroad crosses IIB from the IIA border near Cisneros to Puerto Berrío, and thence parallels the Río Magdalena southward along the west shore. The railroad is the only means of access to most of the southern part of IIB mapped by IMN. Puerto Berrío, Puerto Nare, and Otú (near Remedios) have scheduled light aircraft service. The airline "SAM" has daily DC-4 service to El Bagre.

Previous investigations

Previous geologic investigations in IIB were few, largely owing to poor access. The earliest recorded geologic observations were made nearly a century ago by Javier Cisneros (1878, p. 32-35) pursuant to the surveying of the route of the Antioquian Railroad. The observations are, however, of greater historic than scientific interest. Don Tulio Ospina (1911) summarized the geology of the Department of Antioquia as then known and included several observations in IIB. He also made what are perhaps the earliest attempts at a classification of the rocks and mineral deposits of Antioquia. A quarter century later, Juan de la Cruz Posada (1936) published the first geologic map of Antioquia. This colored map, printed at a scale of 1:2,000,000, distinguishes three broad units: predominantly Paleozoic rocks, predominantly Mesozoic rocks, and predominantly Cenozoic rocks. The accompanying text contains few references to the area of IIB. Prof. Gerardo Botero A. (1940a, b; 1941; 1942) published perhaps the first modern geologic studies made in IIB, including a restudy (Botero A., 1940a, b) of the graptolite locality at Cristalina first described by Harrison (1930). In 1946 the Servicio Geológico Nacional issued ozalid copies of a geologic map of Antioquia more detailed than the earlier map by Posada (1936). This map, at a scale of 1:1,000,000, depicted 11 units and incorporated much of Botero's work. Other geologic investigations in IIB are restricted to studies of mines or cement rock and none includes discussions of regional geology. Few of these studies have been published; most are available as open file reports ("informes") in the Servicio Geológico Nacional, Bogotá, the Ministerio de Minas y Petróleos, Bogotá, or the Zona Minera, Medellín.

Field and laboratory methods

Although prior geologic knowledge in IIB was quite limited, the area had been thoroughly prospected (chiefly for gold) during more than four centuries. From the outset of the present studies it was clear that with this historical background the best hope of finding yet undiscovered mineral deposits lay in systematic and rather detailed regional geologic mapping. Accordingly, such mapping has formed the foundation of work by IMN in IIB, and the accompanying geologic map (pl. 1, sheets 1 and 2) are a direct product of the Inventario program. A summary of geologic mapping in IIB as of 1969 is given in table 2.

Most geologic information was taken from stream bed outcrops of fresh rock. Supplemental data were taken from exposures of weathered rock in mule trails and in road and railroad cuts that only locally reach fresh rock. Field data were plotted on 1:25,000-scale topographic maps (ozalid copies, "Cartas Preliminares" of the Instituto Geográfico Agustín Codazzi, Bogotá), or on high-altitude 1:60,000-scale aerial photographs. The actual scale of field mapping, however, ranged from 1:50,000 to 1:100,000 as in most places traverses were spaced 1 to 2 km or more apart. The locations of many places cited in this report are given by a simple coordinate system. The geologic map (sheets 1 and 2) has been divided into rectangles corresponding to areas 10 km N-S by 15 km E-W. These rectangles, which coincide with the 1:25,000-scale topographic maps used in the field mapping, are lettered in rows from west to east "a" through "f," and numbered from north to south 1 through 16. Thus the town of Maceo is located in c-7 (pl. 1, sheet 1), and the town of San Carlos is in b-11 (pl. 1, sheet 2).

Geologic observations were made at more than 40,000 outcrops, and about 10,000 rock samples were taken for laboratory study. Thin sections for petrographic study were made from more than 1200 of the samples. Descriptions of each thin section were made and are on file at INGEOMINAS, Medellín.

Reconnaissance and detailed studies were made of mineral deposits of potential economic importance.

Table 2.--Geologic mapping in IIB as of 1969.

Area	km²	Percent of IIB
Subzone IIB	19,033	100
Mapped by IMN (pls. 1, 2)	11,072	58
Previously mapped1/	1,293	7
INGEOMINAS2/	1,716	9
Unmapped3/	4,952	26

1/ Servicio Geológico Nacional (1957). Quadrangle K-9.

2/ Northern part of quadrangle H-9 mapped in 1969 by INGEOMINAS, successor organization to IMN. A generalized compilation of this mapping is presented on plate 2.

3/ Much of the south part of IIB, south of the mapping by IMN, was accomplished by INGEOMINAS, principally during 1970 and 1971. This work, also shown on plate 2, is not included in this table.

Rock nomenclature used in this report more or less follows conventional usage. Metamorphic rocks are named by their mineral composition as well as their texture and structure. Component minerals are listed in their estimated order of decreasing abundance, and accessory minerals are given in the rock name only if they are unusual or have petrologic significance. One example is quartz-plagioclase-biotite-sillimanite gneiss. Sillimanite may occur only in trace amount, but because its presence has strong petrologic implications, it is included in the rock name. Classification of igneous rocks follows that proposed by Wahlstrom (1947, p. 265-338) because it was found particularly easy to apply both in the field and in the laboratory. Quantitative point-count modal analyses were made of many samples of phaneritic igneous rocks, and several new chemical analyses were made. Fine-grained dike rocks are classified by the compositions and relative abundances of their phenocrysts. The sedimentary rocks have been given field names, most of which do not approach the refinement of the nomenclature of modern sedimentary petrography. Few of these rocks were studied in thin section, and, as most are fine-grained, they do not lend themselves to easy megascopic classification.

The size of some rock bodies, because they have either geologic or potential economic significance, have been exaggerated on the geologic maps. Chief among these are lenses of amphibolite, marble, and talc in feldspathic and aluminous gneiss, and beds of limestone in Cretaceous shale.

Acknowledgments

Thin sections were cut under the direction of Sr. Humberto Villegas in the laboratories of the Servicio Geológico Nacional, Bogotá. Fossils were identified chiefly by paleontologists of the Servicio Geológico Nacional, although some were identified in Washington, D. C., by paleontologists of the U. S. Geological Survey. Chemical analyses of rocks were made in laboratories of the U. S. Geological Survey, Washington, D. C., as was a single radiocarbon age determination. The K-Ar radiometric age of a sample of diorite was determined at USGS laboratories in Denver, and another on a sample from the Antioquian batholith was done at the Department of Geological Sciences, Brown University, under the direction of Prof. Bruno J. Giletti. Wet chemical analyses of sulfide samples and

carbonate rocks, and fire assays for gold and silver were done in the laboratories of the Zona Minera de Medellín, under the direction of Drs. Guillermo Serna, Pedro Hernández, and Leonardo Restrepo. Taissir Kassem made preliminary photointerpretations of some areas prior to field mapping, and final photointerpretations of areas of alluvium and Tertiary sediments along the Río Magdalena. William Jaramillo, Amaparo Ruiz, and María Eugenia Jiménez were draftsmen.

Several of the field geologists aided in various ways in the preparation of this report. Octavio Ramírez and Carlos J. Vesga helped with petrographic descriptions. Hernando Lozano assembled a bibliography of previous geologic studies in IIB and in addition compiled mining statistics and meteorological data. Octavio Ramírez drew isograds on the north half of sheet 1, plate 1, and the south half of sheet 2, plate 1. Elkin Oquendo compiled statistics of mineral assemblages of the metamorphic rocks from thin section descriptions. Hernán Gomez and Pedro Marin helped with drafting.

The following individuals and companies were helpful to the work of IMN in IIB: Mr. Hubert vom Staufen, Medellín mining consultant; Cementos Nare S. A.; Mr. Michael A. Burke, Frontino Gold Mines, Ltda.; Mr. E. Moseley-Williams, Pato Consolidated Gold Dredging, Ltda.; Messrs. Warren and Walter Ziebell, Mina La Viborita; Mr. J. M. O'Dowd and the Texas Petroleum Company; Sr. Ernesto Vélez, Industrias Roca, Ltda.; Ferrocarriles Nacionales de Colombia; Peace Corps Volunteers; Drs. Eduardo Gómez and Gonzalo Pérez and Srs. Mario Tabares and Octavio Gartner of the Facultad Nacional de Minas, Medellín.

Prof. Gerardo Botero A. generously gave of his time in discussions both in the office and in the field. His considerable personal acquaintance with the geology of Antioquia through more than 40 years of dedicated field study was freely shared, and greatly helped us. Prof. Roy J. Shlemon of the University of California at Davis, U.S.A., joined field parties on several occasions and made helpful observations on geomorphology and recent tectonic deformation. Prof. James E. Case of Texas A and M University, U.S.A., gave access to his gravity data of northwestern Colombia prior to publication. Much of this data was used in deciding between alternative structural interpretations and is here gratefully acknowledged.

The mapping would not have been possible without the splendid cooperation of campesinos and finca owners too numerous to mention individually. Finally, however, special praise must go to the Colombian geologists cited on the maps (pl. 1, sheets 1 and 2), all of whom had to work under primitive field conditions in remote areas that in many places were as much as two days' mule rides from the nearest road or railroad. The present report is in part a tribute to their enthusiasm and perseverance in the face of these obstacles.

STRATIFIED ROCKS

Metamorphic rocks

Precambrian rocks

Precambrian rocks crop out as a mosaic of fault-bounded blocks, partly covered by younger rocks, and extensively intruded by igneous rocks between the Otú fault and the Magdalena Valley (pl. 1, e-9, sheet 2). The Precambrian rocks are chiefly feldspar-quartz gneiss in which are sporadic lenses of amphibolite and calc-silicate marble. The rocks are considered Precambrian as they are unconformably overlain by Ordovician strata, a relationship that can be seen in Quebrada La Miguera and its tributaries near Cristalina (pl. 1, e-9, sheet 2).

Feldspar-quartz gneiss.--Fine- to coarse-grained light gray to pink, generally leucocratic feldspar-quartz gneiss consittutes the bulk of the Precambrian rocks in IIB. The most extensive outcrops are in the Río Cupiná between the Palestina and Cimitarra faults (pl. 1, e-6, sheet 1), in Quebrada El Vapor (pl. 1, e-8, sheet 1), and in Quebrada Malena downstream from Sabaletas Station on the Antioquian Railroad (pl. 1, e-8, sheet Much of the gneiss has a pronounced lineation, which in many outcrops is the only recognizable structure. The lineation is generally imparted by pencil-like aggregates, 3 to 5 mm in diameter and 5 to 10 cm long, of smoky quartz grains set in a matrix of granular feldspar, or by strung-out biotite flakes. Less commonly a lineation is imparted by parallel axes of minor folds.

Feldspar and quartz constitute more than 85 percent of the gneiss in most outcrops. Potassium feldspar and plagioclase are subequal. The potassium feldspar is orthoclase in some samples and microcline in others. It is generally fresh and slightly perthitic, and commonly shows evidence of mechanical deformation. The plagioclase is either oligoclase or andesine. It is feebly twinned, and alteration ranges from weak sericitization to extensive saussuritization. It also shows mechanical deformation. Biotite and muscovite coexist in most of the gneiss, being characteristically fine grained and imparting a silky sheen to foliation planes. Fractured subhedral crystals of monazite, as much as a millimeter long, are present; other accessory minerals are scarce.

The parent material of the gneiss was varied. In places the gneiss greatly resembles metamorphosed felsic plutonic igneous rock, elsewhere it is layered and appears to have been derived from sediments. Most samples, however, even those of metaigneous aspect, are too rich in quartz (generally 40 to 50 percent) to be simple derivatives of normal igneous rocks. On the other hand, none of the samples examined has the composition of such common sediments as shale or quartz sandstone. Apparently the metamorphism was not isochemical.

Amphibolite.--Medium-grained dark green-gray to black layered amphibolite forms sporadic concordant lenses from less than a meter to several tens of meters thick in the feldspar-quartz gneiss. The amphibolite, which was not studied in detail, is composed chiefly of green hornblende and partially saussuritized plagioclase. The origin of the amphibolite is unknown.

Marble.--Medium- to coarse-grained white to tan calc-silicate marble, commonly intensely folded, locally forms thin layers in the feldspar-quartz gneiss. These are particularly abundant east-northeast of LaSusana, in the triangle formed by the Otú fault and the Ríos Cupiná and Alicante (pl. 1, e-6, sheet 1). A thin section from one of these lenses shows the marble to be distinctly cataclastic, and to consist of calcite (72 percent), diopside (8 percent), and antigorite pseudomorphic after forsterite (20 percent). Five small lenses east of the Palestina fault and centered 22 km southeast of Remedios (pl. 1, e-3, sheet 1) are composed almost exclusively of calc-silicate minerals.

The marbles were produced by the high-grade regional metamorphism of magnesian limestone. The presence of the marble layers implies that the enclosing gneiss is of metasedimentary origin.

Ordovician rocks

Ordovician sedimentary and metasedimentary rocks exposed near Cristalina (principally in e-9, pl. 1, sheet 2) are the only rocks in IIB that have been discussed extensively in the geologic literature (Harrison, 1930, p. 407; Botero A., 1940a, 1940b). Nevertheless, their relation to the dominant metamorphic and igneous rocks of the Central Cordillera was heretofore unrecognized. It is now known, based on mapping by IMN, that the Ordovician rocks cover only a small area (about 45 km^2), and are separated from the bulk of the metamorphic rocks of the Central Cordillera by major regional wrench faults with large displacements.

The Ordovician rocks make poor outcrops because of their slight resistance to weathering and the low relief in the area where they occur. The only extensive outcrops are in Quebrada La Miguera upstream from the stock of diorite in e-9 (pl. 1, sheet 2). Gray to black shale, siliceous siltstone, and feldspathic metasandstone are the chief rock types. Sparse intercalated limestone also is present. The feldspathic metasiltstone is the most resistant rock and in places forms bold ledges in streams. Fine-grained metamorphic micas impart a sheen to some bedding planes, and metamorphic biotite constitutes as much as ten percent of some rock. In the west, the rocks have been little metamorphosed, but toward the southeast they are progressively more recrystallized and, near the fault contact with the volcanic rocks in the southern part of e-9 of sheet 2, pelitic beds now are represented by phyllite or even fine-grained schist.

The thickness of the Ordovician rocks is probably only a few hundred meters. A more precise figure is not attainable owing to complex folding, faulting, and poor outcrop.

Graptolites collected by Harrison (1930, p. 407) and identified by Dr. G. L. Elles as Didymograptus extensus Hall, D. nitidus Hall, D. gibberulus Nich., and D. hirundo Salt clearly establish a Lower Ordovician (Arenig) age for the rocks at Cristalina. The same fauna was recollected from several outcrops in Quebrada La Miguera by Botero A. (1940a, 1940b), and by geologists of the Texas Petroleum Company (William Wallace, III, oral commun., 1967). In May 1968, Prof. Botero, on a field trip with Héctor Rico, Darío Barrero, and Tomas Feininger, recollected Didymograptus sp. from outcrops in a small stream between Quebrada La Miguera and the Antioquian Railroad. All fossils collected by Prof. Botero are in the paleontological collection of the Facultad Nacional de Minas, Medellín.

About 20 lenses of limestone and marble are interbedded chiefly with pelitic beds of the Ordovician sequence. The westernmost lenses, well exposed in the abandoned quarries of Cementos Argos at Sabaletas Station (pl. 1, e-8, sheet 1), are composed of very fine grained, slabby, gray, argillaceous limestone. Toward the southeast the limestones as well as the enclosing rocks have undergone progressively more intense recrystallization. The southeasternmost lenses are white medium-grained marble. An exceptional lens of marble in Quebrada Las Iglesias (pl. 1, e-9, sheet 2) is 100 m thick; other lenses range from 1 to 30 m thick. A careful search in the abandoned quarries at Sabaletas Station by Hernando Lozano and Tomas Feininger in August 1967 produced no fossils. Prof. Fritz Stibane (oral commun., 1967) of the Geologisch-Paläontologisches Institut, Der Justus Liebig Universität, Giessen, West Germany, failed to find fossils in an earlier search in the same quarries.

Limestone and marble from two nearby localities tentatively have been correlated with the Ordovician limestones. The larger locality, at the confluence of Quebrada Normandía and the Río Alicante (pl. 1, e-6, sheet 1), is a body nearly 2.0 by 0.5 km of complexly folded laminated gray limestone with shiny graphitic partings. It rests on Precambrian gneiss. The smaller locality at Calera Station (pl. 1, e-8, sheet 1) has three lenses of white marble of extremely variable texture, which are currently being exploited for agricultural lime. The lenses are spatially associated with diorite and volcanic rocks.

Other Paleozoic(?) metamorphic rocks

The most extensive rocks in IIB are the metamorphic rocks of the Central Cordillera west of the Otú fault, hereafter referred to as other Paleozoic(?) metamorphic rocks, or simply the metamorphic rocks. Aside from their great extent, these rocks have a broad range of composition and have been subjected to varying intensities of regional and contact metamorphism.

Although ten units of metamorphic rocks were distinguished, in part on the basis of chemical composition, four broad chemical groups, modeled on those suggested by Turner (Williams et al, 1954, p. 175-176; Turner and Verhoogen, 1960, p. 455), were chosen as the most useful during field mapping, as follows: 1) Pelitic group: sericite schist, feldspathic and aluminous gneiss, and part of the hornblendic gneiss; 2) Quartzose group: quartzite, dark-colored biotite quartzite, and quartzose gneiss; 3) Calcareous group: marble, skarn, and calc-silicate gneiss; and 4) Mafic group: amphibolite, greenstone, and part of the hornblendic gneiss.

Stratigraphic succession of the metamorphic rocks is poorly known. Distribution of metamorphic facies, particularly along the east border of IIB, strongly implies that of the principal units, the relatively intensely metamorphosed feldspathic and aluminous gneiss underlies the quartzite, which in turn underlies marble, the least metamorphosed unit. On the other hand, these units are interbedded with one another at their mutual contacts, making it difficult to determine relative ages on the basis of stratigraphic relations. The sericite schist is the low-grade metamorphic equivalent of the feldspathic and aluminous gneiss.

The remaining six units (hornblendic gneiss, skarn, calc-silicate gneiss, amphibolite, greenstone, and undifferentiated rocks) are less extensive, and, with the exception of the undifferentiated rocks, are chiefly lenses in the four principal units.

Compositional layering in schist, quartzite, marble, and gneiss west of the Otú fault is inherited from sedimentary bedding (fig. 2). This is especially evident in the undifferentiated rocks of low metamorphic grade in which recrystallization is generally slight. In these rocks compositional layering is shown as bedding on the geologic map (pl. 1, sheet 2). The small-scale compositional layering prominent in the feldspathic and aluminous gneiss (fig. 3) and in most of the amphibolite, however, may be the product of metamorphic differentiation and not be related directly to original bedding.

The sequence of metamorphic rocks is incomplete in IIB; neither the top nor the base is known to be exposed. No accurate estimate of the total thickness of these rocks in IIB is possible, owing to their intricately folded condition and the absence of marker beds of proven reliability. The amount of tectonic thickening and thinning produced by folding is also unknown. In addition, appreciable changes in the thickness of the parent sedimentary rocks as well as fundamental lateral changes of their sedimentary facies is to be expected over an area as large as that of IIB.

Nevertheless, a few estimates of thickness are possible. The marble is thickest (about 300 m) where it is crossed by the Río Samaná Norte between the Palestina and Otú faults (pl. 1, d-10, sheet 2). It

Figure 2.--Light tan quartzite showing typical fine lamination. Río Guatapé at the mouth of Quebrada El Diablo, 3 km downstream from Balsadero Pencil gives scale.

Figure 3.--Feldspathic and aluminous gneiss with pods of medium- to coarse-grained light gray pegmatitic adamellite surrounded by dull-lustered, silver-gray micaceous laminae. Río San Bartolomé 0.5 km upstream from Quebrada La Guaira (pl. 1, d-6, sheet 1).

is appreciably thinner to the west in Quebrada Arabia, just east of the confluence of the Ríos Guatapé and Samaná Norte (pl. 1, c-11, sheet 2). Farther west the marble is thinner and perhaps pinches out only 30 km to the west of Magdalena Valley. The quartzite is probably 1,000 to 3,000 m thick. It thins to the east and west. Its maximum thickness is in the belt southeast of San Carlos (pl. 1, b-11, c-11, sheet 2), where it may be 2,000-3,000 m thick; it may be only a kilometer thick in the vicinity of La Susana (pl. 1, d-6, sheet 1). The feldspathic and aluminous gneiss and sericite schist are certainly the thickest units of the metamorphic sequence. Their maximum exposed thickness, greater than 5,000 m, is north of Amalfi and east of the Antioquian batholith north of Maceo.

The age of the metamorphic rocks of the Central Cordillera in IIB is not known directly. The rocks are continuous and correlative with metamorphic rocks in IIA near Medellín, the Ayurá-Montebello Group of Botero A. (1963, p. 55), and with the Valdivia Group and possibly the more intensely metamorphosed Puquí gneiss mapped by IMN. Fossils have not been found in these rocks in Zone II.

Sericite schist.--Six large areas of sericite schist of low metamorphic grade are known in IIB: 1) From Amalfi to Anorí along the west edge of IIB,(principally in pl. 1, a-1, a-2, and a-3, sheet 1) good, though mostly weathered exposures are found in cuts along the road to Anorí; fresh rock is well exposed in small quebradas within a three-kilometer radius of Amalfi; 2) Southeast of San Carlos (pl. 1, b-11, b-12, and b-13, sheet 2), good outcrops are found in Quebrada

Miranda, Río San Miguel, and Quebrada Aures; 3) West of San Francisco along the border of IIB with IIA (pl. 1, a-13, b-14, sheet 2), in an area of difficult access, is poorly exposed schist. The best outcrops are in the Río Melcocho and its tributaries; 4) A roughly north-south belt between the Cocorná Sur fault and the stock of quartz monzonite at Aquitania (pl. 1, b-14, b-15, sheet 2). Large outcrops of schist are found in the Río Claro and Quebrada Norcasia; 5) A slender belt more than 25 km long but no more than a kilometer wide is found between the Palestina and Cocorná Sur faults (pl. 1, b-15, c-13, c-14, sheet 2). Good exposures occur in the Río Claro and many of its tributaries; and 6) A large area near the south edge of IIB, chiefly between the Palestina and El Mulato faults (pl. 1, b-15, b-16, c-15, c-16, sheet 2). The Río Samaná affords a nearly continuous exposure of the schist.

The typical sericite schist is medium to dark gray and finely laminated. It is composed of sericite, quartz, biotite, and graphite with accessory chlorite, plagioclase (mainly albite), tourmaline, apatite, and zircon. The amount of sericite generally exceeds that of quartz, although the reverse is true in much of the rock. The laminae, which are from 1 to 3 mm thick, are composed chiefly of mica and of quartz, respectively. Graphite commonly exceeds 5 percent and is concentrated in the micaceous laminae as dust and flakes. In places the schist is only weakly laminated, or the lamination has been blurred or even destroyed by slip cleavage. Foliation planes commonly show marked crenulae or small folds. Porphyroblasts from one to more than 5 cm long of partially to wholly sericitized andalusite are common, especially near Amalfi and Anorí where they locally constitute as much as 50 percent of the rock, and in the southernmost area of sericite schist near the Río Samaná. They have axes only weakly oriented with the foliation.

Much of the schist southeast of San Carlos is exceedingly fine grained, and includes beds of phyllite and black shale that show only incipient recrystallization. These rocks have been even less metamorphosed than the schist elsewhere.

Other rock types that are present in this area are too thin to show on the geologic map. Numerous chlorite schist and phyllite layers are in the sericite schist between Aquitania and the Cocorná Sur fault, and these, in addition to greenstone, metawacke, and black and gray quartzite, are present between Amalfi and Anorí. The superior resistance to weathering of these rock types relative to the enclosing schist makes them particularly conspicuous.

The sericite schist was formed by low-grade regional metamorphism of siltstone and shale. The sedimentary origin is especially apparent in less metamorphosed samples where a clastic texture is clearly preserved. The lamination of much of the schist is largely inherited from fine rhythmic bedding of the parent sediments. Intercalated chloritic rocks and greenstone are of probable volcanic parentage.

The chemical composition of the sericite schist affords good supporting evidence that it was produced by nearly isochemical metamorphism of shale. The average composition of three representative samples of sericite schist from Anorí (table 3, col. 4) is almost identical to the composition of average shale recalculated free of carbonate

Table 3.--Chemical analyses of three samples of sericite schist from near Anorí and the comparison of their average to the composition of average shale recalculated free of carbonate.

	1.	2.	3.	4.	5.
Inventario no.	8147	8006	7905		
Field no.	HL-1813	HL-1740A	HL-1534		
USGS Lab. no.	W168-923	W168-928	W168-918		
SiO_2	71.6%	57.9%	57.0%	62.2%	61.8%
Al_2O_3	14.9	23.2	21.0	19.7	16.3
Fe_2O_3	0.94	0.87	1.5	1.1	4.3
FeO	2.6	5.3	6.1	4.7	2.6
MgO	1.3	1.7	2.4	1.8	1.9
CaO	0.65	0.66	1.5	0.9	0.6
Na_2O	0.98	0.62	1.8	1.1	1.4
K_2O	4.1	4.3	3.6	4.0	3.4
H_2O -	0.15	0.25	0.30	3.1	5.3
H_2O +	1.6	3.6	3.5		
TiO_2	0.66	0.97	0.98	0.9	0.7
P_2O_5	0.17	0.18	0.26	0.2	0.2
MnO	0.02	0.09	0.00	0.0	0.0
CO_2	0.00	0.00	0.00	0.0	0.0
SO_3	n.d.	n.d.	n.d.		0.7
C	n.d.	n.d.	n.d.		0.8
Total	99.67%	99.64%	99.94%	99.7%	100.0%
Bulk density (g/cm^3)	2.69	2.74	2.71		

1. Quartz-muscovite-albite-biotite-chlorite schist. Quebrada La Virgen 1.5 km east of Anorí (pl.1, a-1, sheet 1). 2. Muscovite-quartz-chlorite-graphite-biotite schist with sericitized porphyroblasts of andalusite. Rio Anorí 2.2 km S. 19° E. of Anorí (pl. 1, a-1, sheet 1). 3. Quartz-muscovite-graphite schist. Roadcut 11.7 km S. 3° E. of Anorí (pl. 1, a-2, sheet 1). 4. Average of 1-3. 5. Average shale carbonate free. Calculated from average shale (Pettijohn, 1949, p. 271) by removing calcite and dolomite in equal proportions by weight to use up all CO_2. The result was recalculated to 100 percent. Chemical analyses by rapid rock analyses methods, USGS, Washington, D. C. n.d. - not determined.

(col. 5). The composition of the schist differs from that of an average shale only in its higher content of Al_2O_3 and K_2O, slightly lower content of Na_2O_3, and higher FeO-to-Fe_2O_3 ratio. The relatively low water content of the schist reflects dehydration that accompanied metamorphism.

Feldspathic and aluminous gneiss.--Feldspathic and aluminous gneiss, ranging in texture and structure from schistose to migmatitic and agmatitic, is the most abundant rock unit of the metamorphic sequence of IIB. The bulk of the gneiss is in a single, though much faulted, north-south body, of which the north end is 3 km west of Remedios (pl. 1, d-2, sheet 1) and the south end is beyond the area mapped by IMN. Another extensive area of gneiss lies between sericite schist and quartzite northeast of Amalfi (pl. 1, a-2, b-2, b-3, sheet 1). A smaller area of gneiss, bounded by quartzite and the Antioquian batholith, is 17 km east of Amalfi (pl. 1, b-3, sheet 1). Two other areas of gneiss bounded by the Antioquian batholith, quartzite, and the Balsadero fault, lie 16 km east-northeast and 22 km east of San Carlos, respectively (pl. 1, c-10, c-11, sheet 2). Several smaller areas of gneiss are northeast, east, and southeast of Aquitania (pl. 1, b-15, sheet 2). The feldspathic and aluminous gneiss is markedly heterogeneous due to variations in the composition and texture of the parent sediment as well as in the conditions of metamorphism. The dominant gneiss is strongly foliated, gnarly, coarse-grained, silver-gray migmatite (fig. 3).

The body of gneiss along the east border of IIB from a point a little south of El Tigre (pl. 1, c-3, sheet 1) to a point a few kilometers south of where it is cut by the Palestina fault (pl. 1, d-11, sheet 2) is a migmatite. Good exposures are found along the Río Nus downstream from the Antioquian batholith to the Palestina fault (pl. 1, c-8, d-8, sheet 1; d-9, sheet 2), and in the nearby Río Monos (pl. 1, d-8, sheet 1) and El Socorro (pl. 1, d-9, sheet 2). The migmatite northeast of Amalfi is well exposed at the falls of the Río Riachón and in Quebrada La Víbora (pl. 1, a-2, sheet 1), both places of difficult access.

The granitic part of the migmatite consists of leucocratic medium- to coarse-grained, light-gray, commonly pegmatitic adamellite composed almost entirely of oligoclase, quartz, and orthoclase. Oligoclase everywhere exceeds orthoclase. Most of the granitic part of the migmatite is in pods a few centimeters long (fig. 3), but bodies several meters across occur locally. These granitic masses are enveloped by irregular and discontinuous dull, silver-gray, micaceous layers less than 1 cm to about 10 cm thick. These consist chiefly of chloritized biotite, muscovite, sericitized sillimanite or andalusite, lesser amounts of quartz, cordierite (generally altered to pinite), plagioclase, and sparse garnet, graphite, tourmaline, apatite, and zircon.

The same belt of gneiss north of El Tigre is generally not migmatitic, although locally it contains layers of migmatite identical to that described above. Most of this gneiss is fine- to medium-grained and well laminated. It is composed chiefly of oligoclase, quartz, and biotite, and is far less micaceous than the migmatite to the south. Potassium feldspar is generally absent. Layers of light gray-green gneiss with accessory pale amphibole are common. The gneiss is strongly cataclastic in Quebrada La Bomba and the Río Pescado (pl. 1, c-4, sheet 1).

Most of the gneiss of this belt to the south of the Palestina fault (pl. 1, d-11, sheet 2), particularly east of the Jetudo fault, is more variable than that described above. It includes agmatite and augen gneiss.

The gneiss bounded by quartzite and the Antioquian batholith east of Amalfi is also migmatitic, but differs from the migmatite described above. It is medium- to coarse-grained and gnarly, and has a better-developed linear structure than foliation, at least east of the La Clara fault. Also, fresh brown biotite and sillimanite are conspicuous in many outcrops. The small sliver of schistose gneiss west of the La Clara fault is strongly cataclastic, and has prominent rounded augen of white feldspar from 1 to 8 mm in diameter.

The gneiss north of the Balsadero fault and west of El Jordán (pl. 1, c-10, sheet 2) is largely an agmatite composed of roughly equal parts of granitic rock and rotated angular inclusions of fine-grained gneiss. Excellent exposures are found in Quebradas Llores and El Diablo and their tributaries. The granitic component of the agmatite is medium-grained, xenomorphic inequigranular, massive to schistose, two-mica quartz diorite peppered with subhedral to anhedral megacrysts of white plagioclase from 2 to 10 mm in diameter. The range of composition of this rock, estimated from five thin sections, is as follows (in volume percent): quartz (20-30), oligoclase (40-70), orthoclase (0-7), biotite

(6-15), muscovite (2-7), apatite (trace-2), and cordierite (0-15). The inclusions are fine-grained thinly laminated brownish-gray gneiss composed chiefly of pale to colorless amphibole, labradorite, and biotite, with minor quartz, apatite, opaques, and zircon. Greasy-lustered anhedral gray-green pinite porphyroblasts pseudomorphic after cordierite are locally conspicuous near Balsadero. Toward the north the agmatite grades into medium- to coarse-grained migmatite similar to that found in the belt along the east part of IIB. The southeast corner of the area of gneiss, near the confluence of Quebrada El Macho and the Río Guatapé (pl. 1, c-10, c-11, sheet 2), is fine-grained, finely laminated quartz-plagioclase-biotite gneiss, commonly with pale to colorless accessory amphibole. Neither this gneiss nor the migmatite to the north are well exposed.

Gneiss centered near the confluence of the Ríos Guatapé and Samaná Norte constitutes a body about 17 km^2 in area. Fresh rock is well exposed in cuts along the road under construction to Puerto Nare, in the Río Samaná Norte, and in large but virtually inaccessible exposures at the falls of the Río Guatapé. The gneiss, less altered than almost anywhere else in IIB, is gnarly and most is coarse to very coarse grained; complex small folds are common. It is composed chiefly of quartz, oligoclase, cordierite, muscovite, and sillimanite. Other minor accessory minerals include orthoclase, tourmaline, apatite, and opaques. Porphyroblasts of pinitized cordierite, not unlike those near Balsadero, are locally prominent.

Scattered outcrops of gneiss in the south part of IIB, namely those west of the Jetudo fault and south of the Río Cocorná Sur, and others west of the Cocorná Sur fault and south of the Balsadero fault (pl. 1, b-13, b-14, b-16, and c-12 through c-16, sheet 2), are chiefly silver-gray mica-rich schistose gneiss. Small porphyroblasts of staurolite and rare garnet occur locally. Large porphyroblasts of partially to wholly sericitized andalusite from one to more than 10 cm long are abundant. Good exposures are found in the Río Samaná Norte 13 km east northeast of San Luis, in the Río Claro between the Palestina and Jetudo faults, in Quebrada Norcasia, and in the Río Samaná Sur.

Probably all feldspathic and aluminous gneiss in IIB are at roughly the same stratigraphic horizon, and for reasons given earlier, are believed to underlie the quartzite of generally lower metamorphic grade. The gneiss is the middle- to high-grade metamorphic equivalent of the low-grade sericite schist, and similarly is believed to have been chiefly shale prior to metamorphism. The gradation from sericite schist to gneiss and migmatite through a simple increase of metamorphic grade is well exposed in several places.

<u>Hornblendic gneiss</u>.--The hornblendic gneiss is similar to the feldspathic and aluminous gneiss, but is distinguished by conspicuous essential hornblende. The hornblendic gneiss, south of Caracolí (pl. 1, c-9, d-9, sheet 2), forms a body about 11 by 1.5 km concordant with enclosing feldspathic and aluminous gneiss. It is a relatively resistant rock and outcrops are common even though topography on it has little local relief. The best exposures are in the Río El Socorro (pl. 1, c-9, sheet 2) and Quebradas San José and Horná near the southern limit of the gneiss (pl. 1, d-9, sheet 2).

Composition, texture, and structure of the hornblendic gneiss are variable. The gneiss is composed mainly of plagioclase (andesine to sodic labradorite), quartz, and pale green hornblende. Accessory minerals are partially chloritized biotite, sphene, apatite, pyrite, magnetite, and sporadic orthoclase, zircon, and allanite. Rare calcite and epidote occur as veins. Lenses and layers of amphibolite intimately associated with the gneiss have not been mapped separately.

The hornblendic gneiss is dark gray green to black. It ranges from fine-grained, finely laminated gneiss to medium-grained migmatite and agmatite. The agmatite is composed of blocks of medium-grained laminated gneiss and amphibolite set in a matrix of medium- to coarse-grained diorite pegmatite. Structural attitudes in many individual outcrops range widely.

The hornblendic gneiss is both gradational and interlayered with feldspathic and aluminous gneiss, and in many places the contact between the two rocks is difficult to map. Parts of the areas mapped as amphibolite between the Palestina and Jetudo faults about 40 km south of Caracolí (pl. 1, c-12, c-13, sheet 2) resemble the hornblendic gneiss. Extensive fracturing and retrograde metamorphism have so altered these rocks, however, that their correlation with the gneiss near Caracolí remains uncertain.

The origin of the hornblendic gneiss is obscure. Its composition suggests that the source was either an intermediate to mafic volcanic rock or dolomitic marl. The paucity of carbonate in the gneiss favors a volcanic source, but no primary textures that would favor either alternative origin are preserved. The restricted occurrence and gradational or interlayered contacts of the hornblendic gneiss suggests that its source material was deposited in a local area during the deposition nearby of the shale parent of the feldspathic and aluminous gneiss. The maximum thickness of the hornblendic gneiss is about 1000 m.

Quartzite.--Quartzite is the second most abundant rock of the metamorphic sequence, and because the rocks are most resistant to weathering, outcrops are abundant. Even where deeply weathered, the quartzite can generally be identified by the gray or light-yellow tan sandy soil that it produces. Particularly large areas are distributed as follows: 1) north of the Antioquian batholith south and east of Amalfi (pl. 1, a-3, a-4, b-4, sheet 1) and west of El Tigre (pl. 1, c-3, c-4, sheet 1); 2) roof pendents in the batholith (pl. 1, b-4, b-5, b-7, c-4, c-7, sheet 1); 3) along the east border of the batholith from Vegachi south to Maceo (pl. 1, c-5, c-6, c-7, sheet 1); 4) along much of the Otú fault on the west block (pl. 1, c-1, d-1 through d-8, sheet 1, and d-10, d-11, sheet 2); 5) south-central part of the zone in a much faulted belt from a point 5 km southwest (pl. 1, c-9, sheet 2) of Caracolí to the south limit of mapping (pl. 1, c-16, sheet 2); and 6) a north-south belt near the west border of the zone south from the settlement of San Francisco (pl. 1, a-13 through a-16, sheet 2).

Several quartz-rich rocks constitute the quartzite unit. None change appreciably in appearance in zones of different metamorphic grades.

The dominant rock is a fine-grained, thinly laminated light tan quartzite (fig. 2). The laminae (generally less than 3 mm thick) are composed of fine saccharoidal quartz and are separated from one another by micaceous partings a fraction of a millimeter thick composed chiefly of muscovite and biotite. This rock is generally more than 80, and in places more than 95, percent quartz. Accessory minerals are feldspar, apatite, zircon, tourmaline, and graphite. In zones of high-grade metamorphism, the quartzite commonly contains one or more of the following minerals: staurolite, andalusite, sillimanite, and cordierite.

Most of the rest of the quartzite unit is composed of fine-grained brown biotite quartzite and quartz-mica schist. The quartz-mica schist is well-laminated, but the biotite quartzite less so because the biotite tends to be distributed throughout the rock. The quartz content of these rocks is between 60 and 80 percent. Accessory minerals are the same as in the light tan quartzite. Biotite quartzite is particularly abundant south of the Antioquian batholith. Quartz-mica schist constitutes most of the belt mapped as quartzite along the Otú fault north from La Susana (pl. 1, d-6, sheet 1).

The only other type of rock within the quartzite unit is black indistinctly bedded graphitic quartzite with a saccharoidal texture found sparsely at several places. Weathering of this rock produces a distinctive black sandy soil. Near the Río Nare south of Caracolí (pl. 1, c-10, sheet 2), the black quartzite contains anhedral calcite and subhedral to euhedral crystals of white diopside as much as 2 cm long. In cuts on the road under construction in 1968 to Puerto Nare in the Canyon of the Río Samaná Norte 4 km downstream from the mouth of the Río Guatapé (pl. 1, c-11, sheet 2), the calcite has been leached from the black quartzite, possibly by hydrothermal solutions, leaving a breccia-like rock consisting of white crystals of diopside set in a porous black matrix composed of quartz and graphite.

The original sediment of the quartzite unit ranged from nearly pure quartz sand and silt for the light tan quartzite, to a quartz sand and silt-shale mixture for the biotite quartzite. Some may have been chert. The thin laminae of much of the light tan quartzite is a remnant sedimentary feature due to rhythmic deposition of quartz sand and extremely thin shale partings. The high graphite content of some of the quartzite and the apparently fine grain size of the original sediments suggest deposition under reducing conditions in a deep basin far from shore. Loose boulders of weathered quartz pebble conglomerate, found near quartzite in Quebrada La Plata, 1.5 km north of San Francisco (pl. 1, a-13, sheet 2), probably are remnants of Cretaceous conglomerate that formerly covered the area. Beds of such conglomerate are still preserved only a few kilometers to the east.

Marble.--Marble underlies nearly 90 km^2 of IIB, principally along or near the east border of the zone. Most of the marble occurs in three faulted belts. One is the west block of the Otú fault from a point 5 km N. 35° W. of La Susana, south to the Palestina fault (pl. 1, d-6, d-7, e-7, sheet 1). The others are on the east side of the Palestina fault extending from the intersection with the Otú fault south-southeast to where the marble disappears beneath Tertiary sediments in the Magdalena Valley (pl. 1, d-9 through d-12, sheet 2); and from the Río Samaná Norte just downstream from the mouth of the Río Guatapé, extending south-southwest nearly to the Río Samaná (pl. 1, c-11 through c-15, sheet 2). Many smaller areas of marble are found along this general belt, as well as dozens of small lenses in quartzite, and as hundreds of lenses and layers 10 m or less thick in feldspathic and aluminous gneiss throughout IIB (pl. 1, sheets 1 and 2).

The marble terrain has a distinctive topography (fig. 4) with hills 20 to 350 m high, which have rounded summits and steep to vertical sides, and commonly with only scanty tree cover. The most spectacular development of this topography is east of the Palestina fault 3.5 km south-southwest of its intersection with the Otú fault. Here, hills more than 200 m high are common, and the Río Samaná Norte, only 60 m wide, is in a gorge with nearly vertical 250 m high walls of marble. Some of the hills in this area contain large solution caverns (Feininger and Gomez M., 1968). Other caverns are said to exist east of La Susana (pl. 1, d-6, d-7, sheet 1). In many places, streams and rivers have undercut the bases of these hills leaving vast amphitheaters. Particularly fine examples are found along the Río Alicante (fig. 5).

Figure 4.--Sharp rounded hills typical of marble terrain. View to east-southeast from La Susana (pl. 1, d-6, sheet 1). Skyline ridge is quartzite.

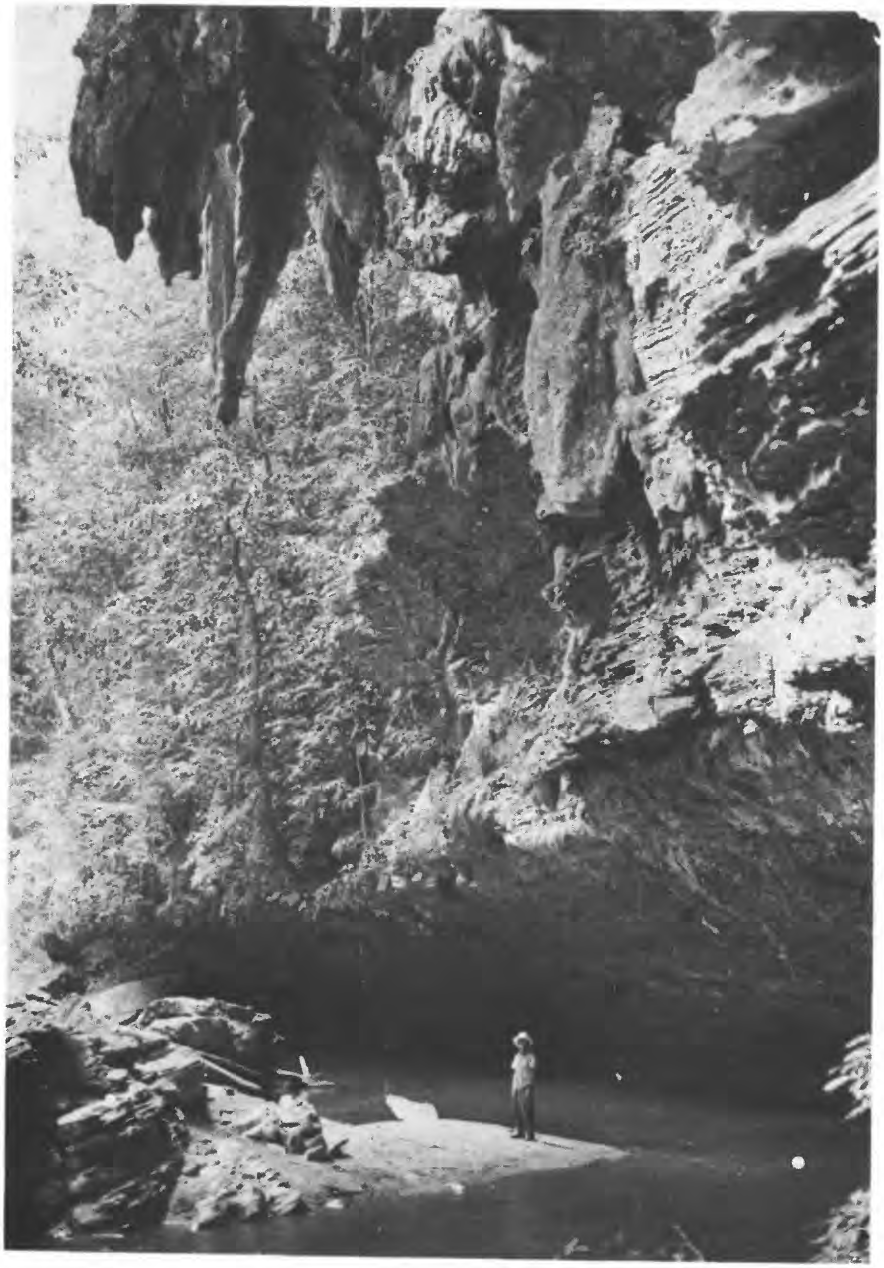


Figure 5.--Base of marble hill undercut by the Rio Alícante ("Cuevas de Doña Agustina"). Five kilometers S. 40° E. of La Susana (pl. 1, d-7, sheet 1). Note differential weathering of thin quartzite beds in marble of cliff above undercut.

The marble ranges from fine- to coarse-grained and from dark gray to white. Both grain size and color are related to grade of metamorphism. Most of the marble is of low metamorphic grade and its grain size ranges from fine to medium and its color from gray to dark gray. At higher grades of metamorphism, either regional or contact, the marble is medium- to coarse-grained and light gray to white.

Most of the marble is more than 80 percent calcite. Other minerals are chiefly quartz, graphite, feldspars, micas, and at higher grades of metamorphism, zoisite-clinozoisite, tremolite, diopside, and wollastonite. Color of the marble is due to graphite; at a low grade of metamorphism the graphite is very finely divided and imparts a dark color to the rock. With increasing metamorphism the graphite is recrystallized into successively coarser flakes, which less effectively darken the rock. Some coarse-grained marble is dark gray, however, probably owing to the submicroscopic inclusions (organic material?) in the calcite crystals. This marble emits a strong fetid odor when freshly broken.

In many places layers of fine-grained light gray quartzite 1 to 5 cm thick alternate with layers of marble of similar thickness. These relatively resistant quartzite layers stand out in relief (fig. 5) as the result of differential weathering.

Dolomite marble was found at only two places. One, long-known and currently under exploitation, is a small part of the west body of marble north-northwest of Amalfi. The other is between El Jordán and the Río Nare where several of the small lenses of marble in quartzite are diopside-bearing dolomite marble. The diopside content ranges from 20 to 50 percent. It is less in lenses of calcite marble in the same area.

The large belts of marble are in stratigraphic contact with quartzite, and each belt coincides with an axis of the lowest grade of regional metamorphism. It overlies the quartzite and is preserved in regional synclines.

The marble was produced from relatively pure calcite limestone by regional metamorphism, locally with the overprint of younger contact metamorphism by the Antioquian batholith or other plutons. The origin of the interlayered thin beds of quartzite is uncertain. They may record the periodic influx of detrital quartz during carbonate deposition in a shelf environment, or they may be recrystallized chert beds. The small and isolated bodies of marble in schist north-northwest of Amalfi were probably bioherms and may mark local shallows in an otherwise deeper geosynclinal basin.

Skarn.--Sporadic lenses of skarn, generally only a meter or two thick, occur in feldspathic and aluminous gneiss and quartzite, chiefly within two kilometers of the northeast corner of the Antioquian batholith. Readily accessible outcrops are along the road from Amalfi to Yalí at Quebrada La Puerta (north edge of pl. 1, b-5, sheet 1) and just east of the road (pl. 1, c-5, sheet 1) 1.9 km south of Vegachí.

The skarn is massive and coarse-grained, and generally white or pale green, although some is speckled with light brown garnets. It is a resistant rock, and residual boulders are cavernous where calcite has been leached out by weathering. The skarn is composed of varying proportions of diopside, grossularite garnet, wollastonite, vesuvianite, tremolite, epidote, calcite, quartz, and sphene.

Most of the skarn was produced by thermal metamorphism of thin marble beds in feldspathic and aluminous gneiss or quartzite.

Calc-silicate gneiss.--Much of the 14 km-long roof pendant in the Antioquian batholith west of Maceo (pl. 1, b-7, c-7, sheet 1) is composed of calc-silicate gneiss, calc-silicate quartzite, marble, and skarn. Owing to unusually poor exposures, these rock could not be separated in the field, and all were mapped as calc-silicate gneiss, the most abundantly exposed rock type.

Calc-silicate gneiss and quartzite, best exposed in Quebradas La Candelaria and Barbacoas (pl. 1, b-7, sheet 1), are fine- to medium-grained and sharply laminated. Diopside is the principal calc-silicate mineral. Intercalated marble is massive, light gray to white, and medium- to coarse-grained. It forms beds from one to several tens of meters thick and is well exposed only in abandoned quarries of Cemento Argos, 3 km north-northeast of Caramanta Station on the Antioquian Railroad. Skarn composed largely of fine- to medium-grained splintery wollastonite with accessory diopside, green vesuvianite, and pink sphene, occurs sporadically along the Monteloro fault, around a small cupola of the Antioquian batholith 4 km northeast of Caramanta Station, and in Quebrada La Calera 0.8 km south of San Cipriano (all in pl. 1, c-7, sheet 1). The skarn is best exposed in a quarry recently worked for wollastonite on the south bank of the Río Nus, 3.5 km east of Caramanta Station.

Amphibolite.--Sporadic thin lenses and layers of amphibolite are present within the metamorphic rocks, and large bodies crop out in three places. The largest in an irregularly shaped body west of

San Francisco (pl. 1, a-13, a-14, a-15, sheet 2), others are found between the Palestina and Jetudo faults, 24 km east of San Luis (pl. 1, c-12, c-13, sheet 2), and between the Palestina and El Mulato faults near the south limit of the mapped area (pl. 1, b-16, c-16, sheet 2). Small lenses of amphibolite, from 10 to 100 m thick, are particularly common in the feldspathic and aluminous gneiss, and many are shown on the geologic maps (pl. 1, sheets 1 and 2). Amphibolite is rarely associated with quartzite, and is associated with sericite schist only at San Francisco and in the extreme south part of the zone. Amphibolite and marble occur together only in the Río Cocorná Sur and its tributaries 23 km S. 84° E. of San Luis (pl. 1, c-13, sheet 2).

The amphibolite is generally more resistant to weathering than the enclosing rocks and its frequency of exposure is disproportionately large. The weathering of amphibolite produces a distinctive dark red saprolite that contrasts sharply with the lighter-colored saprolite derived from associated metamorphic rocks.

The amphibolite is dark gray-green to black and is schistose to gneissic; less commonly it is massive. It ranges from fine- to medium-grained. Nearly all the thin lenses and layers in feldspathic and aluminous gneiss are conspicuously layered. Layers range from 1 to 10 cm or more in thickness and differ in texture and in their relative proportions of mafic and felsic minerals. The amphibolite west of San Francisco is highly variable, ranging from fine-grained schist, to medium-grained pseudo-diorite, to a massive blocky breccia, commonly within single outcrops. These different types are well exposed in an outcrop in the Río Santo Domingo at the mouth of Quebrada Palmichal, 4.9 km N. 48° W. of San Francisco (pl. 1, a-13, sheet 2).

Hornblende and plagioclase make up more than 85 percent amphibolite in 58 thin sections of this rock. Hornblende averages 51 percent and exceeds plagioclase in 37 thin sections, whereas plagioclase averages 37 percent and exceeds hornblende in the other 21 thin sections. Hornblende is green to blue green in the amphibolite west of San Francisco and in the large body at the south edge of the zone. Elsewhere it is generally brownish green, although locally it is light colored where replaced marginally by a pale green or colorless fibrous amphibole (actinolite?). Plagioclase is andesine and less commonly either oligoclase or labradorite. In much of the amphibolite toward the east border of the zone, the plagioclase is extensively saussuritized. This is especially true of the large bodies between the Palestina and Jetudo faults (pl. 1, c-12, c-13, sheet 2). Where not saussuritized, the plagioclase is commonly in mosaic grains that are composed of crowded anhedral subgrains less than 0.1 mm in diameter. This texture gives the plagioclase a pronounced mottled appearance under crossed nicols. Mosaic grains of plagioclase in the amphibolite west of San Francisco are commonly shot through with subhedral to euhedral prisms of blue-green hornblende.

The chief accessory minerals present in the amphibolite are apatite, magnetite, pyrite, and sphene; less common are quartz, biotite, and secondary chlorite, calcite, epidote, and pyrrhotite. Diopside and garnet occur in a few samples from outcrops near the Antioquian batholith or the adamellite (pl. 1, sheet 2).

The amphibolite may have more than one parent rock. Some is clearly metaigneous, for example, in the Río Cocorná Sur (pl. 1, c-13, sheet 2), dikelike bodies of medium-grained amphibolite cut marble. Also, the amphibolite west of San Francisco is spatially and compositionally related to small stocks of hornblende gabbro much like amphibolites of proposed igneous origin from western Connecticut, U.S.A., recently described by Gates (1967). On the other hand, the many thin lenses and layers of amphibolite in feldspathic and aluminous gneiss may have been produced during regional metamorphism by the metasomatic reaction of calcareous and pelitic beds at their mutual contact, a mechanism recently suggested by Orville (1969). This proposed origin could explain the relative scarcity of amphibolite or rocks of similar composition in the sericite schist where metamorphic temperatures were probably too low to cause this metasomatic reaction. The striking layering of lenses of amphibolite in feldspathic and aluminous gneiss also may have been produced by small-scale metasomatic differentiation within the lenses themselves. Such a mechanism has been proposed by Seyfert and Leveson (1967) to account for similar layering in amphibolite near New York City, U.S.A.

Greenstone.--Layers of fine-grained schistose to massive dark gray-green to black greenstone crop out sporadically in low grade (greenschist facies) regionally metamorphosed rocks throughout IIB. Greenstone occurs with roughly equal frequency in sericite schist and in quartzite. Two bodies, each nearly a kilometer square in area, are intimately associated with diorite (pl. 1, d-11, sheet 2), near the Magdalena Valley.

The greenstone is composed of a pale green fibrous amphibole, probably actinolite, albite (locally oligoclase), chlorite, and epidote or zoisite. Accessory minerals include apatite, biotite, calcite, magnetite, pyrite, and sphene. Poikilitic diopside porphyroblasts occur in some rock near the Antioquian batholith southeast of San Carlos (pl. 1, b-11, c-11, sheet 2).

The composition and character of the greenstone suggest that the layers were basalt sills or flows emplaced prior to the regional metamorphism of the enclosing metasedimentary rocks. Nevertheless, definitive evidence of the origin of the greenstone was not found.

Undifferentiated rocks of low metamorphic grade.--An area of nearly 150 square kilometers near the southwest corner of Zone IIB has been mapped as undifferentiated rocks of low metamorphic grade. A more detailed division of these rocks was not practicable. Not only is the range of rock types broad, but the area in which they occur is one of extremely rugged topography, commonly with more than 1,000 m of local relief, and access is correspondingly difficult.

The undifferentiated rocks of low metamorphic grade are bounded on the west by the Chupadero fault, on the north by a northwest-striking fault that also bounds the stock at Aquitania on its southwest side, and on the east by the Palestina fault. The rocks are cut by quartz diorite of the Sonsón batholith and satellitic stocks to the west; northward they are unconformably overlain by Cretaceous sedimentary rocks that crop out 7 km south of Aquitania (pl. 1, b-15, b-16, sheet 2).

The following rock types are included in this unit: 1) black graphitic argillite and dark-gray metasiltstone and crinkled phyllite; 2) fine-grained laminated quartzite; 3) chert only slightly recrystallized; 4) fine-grained metawacke; 5) phyllite and fine-grained schist composed chiefly of actinolite and chlorite; and 6) very fine grained greasy-lustered, massive to feebly layered gray-green (metavolcanic?) rocks. Dikes of gray-green andesite and dacite from less than one to more than 15 meters thick are common. All these rocks are extensively fractured, and slickensides are common. How they correlate with the metamorphic rocks of the Central Cordillera, mapped in somewhat greater detail elsewhere in Zone IIB, remains uncertain.

Metamorphic recrystallization in most of the rocks is slight. Foliation has been developed only locally. Structural attitudes at most outcrops were measured on layering believed to be sedimentary or volcanic bedding. Accordingly, these attitudes are shown on the geologic map (pl. 1, sheet 2) as bedding rather than foliation.

Metamorphism

Three regional metamorphisms are recognized in subzone IIB, and each is described under the heading of the rocks which it most affected, namely the Precambrian rocks, the Ordovician rocks, and other Paleozoic(?) rocks of the Central Cordillera. Only the metamorphism of the Paleozoic(?) rocks, by far the most extensive of the three groups in IIB, was studied in any detail. Some retrograde metamorphism is observed in nearly all rocks, and thermal metamorphism is mainly associated with intrusive bodies. Dynamic metamorphism is noted in many rocks and is relatively evident near large faults.

Regional metamorphism

Granulite facies in Precambrian rocks.--Precambrian rocks in IIB probably were metamorphosed to the granulite facies of regional metamorphism. This is suggested by the presence of perthite and antiperthite, and of form-oriented rods of gray quartz, and the prevailing coarse grain of the rocks (see Turner and Verhoogen, 1960, p. 553, 555; Winkler, 1967, p. 135). No index minerals of the granulite facies were found, possibly because the rocks have undergone extensive cataclasis and retrograde metamorphism. The age of metamorphism of the Precambrian rocks in IIB is unknown, although it must substantially predate the weak metamorphism of Lower Ordovician rocks that unconformably overlie them.

Precambrian rocks in the Sierra Nevada de Santa Marta several hundred kilometers to the north contain orthopyroxene in assemblages diagnostic of granulite facies metamorphism (C. M. Tschanz, oral commun., 1966, 1968) and have undergone less intense retrograde metamorphism than those in IIB. Three radiometric dates on the rocks there give metamorphic ages that range from 1300 $\pm$ 100 to 752 $\pm$ 70 m.y. (Tschanz, oral commun., 1968).

The remarkable lithologic similarity of the Precambrian rocks in the Sierra Nevada de Santa Marta with those of IIB (a judgment based on field observations by Feininger), is considered evidence that the rocks in IIB were likewise metamorphosed in the granulite facies. The age of their metamorphism is believed to fall within the same age range as that of the Sierra Nevada de Santa Marta granulites.

Greenschist facies in Ordovician rocks.--The Ordovician rocks, and porphyries that intrude both them and Precambrian rocks to the north, have undergone a low greenschist facies metamorphism.

Sandstone, siltstone, and shale are extensively recrystallized although relic clastic textures can be seen in some thin sections. Small anhedral light-brown flakes of weakly oriented metamorphic biotite are common; locally they exceed 10 percent of the rock. Sericite, graphite, and possibly some of the feldspar are the only other metamorphic minerals encountered.

A sample of porphyry from a discordant intrusion in Ordovician strata in Quebrada La Miguera (pl. 1, e-9, sheet 2), is metamorphically recrystallized. The phenocrysts are broken crystals of subhedral to euhedral oligoclase and lesser subhedral quartz. Some of the quartz phenocrysts are composed of aggregates of anhedral grains. The oligoclase is homogeneous, without a trace of zoning. The matrix is fine-grained and has a granoblastic metamorphic texture. It is composed of an unidentifiable feldspar, quartz, sericite, and aggregates of anhedral golden-brown biotite.

The Ordovician rocks directly overlie the Precambrian rocks, and it is likely that the retrograde and cataclastic effects in the Precambrian rocks were produced in part by the weak metamorphism of the Ordovician rocks.

The age of the metamorphism is not known. It may be correlative with a "Caledonian" plutonic-metamorphic event recognized in the Santander massif and radiometrically dated from 410 to 450 m.y. (R. Goldsmith, oral commun., 1968; Ward and others, in press). It may also be the same metamorphism that formed the bulk of metamorphic rocks of the Central Cordillera of IIB and which is described in some detail below.

The anomalous low-grade metamorphism of Ordovician rocks compared to that of other neighboring Paleozoic(?) rocks may be due to a structural situation discussed in the chapter on structural geology.

Greenschist to upper amphibolite facies in other Paleozoic(?) rocks. The Paleozoic(?) metamorphic rocks of the Central Cordillera crop out over thousands of square kilometers and constitute the areally largest unit in IIB. More than 700 thin sections of these rocks were studied and described and the mineral assemblage of each was tabulated. Metamorphic index mineral localities, based largely on thin section determinations, are plotted on the geologic map (pl. 1, sheets 1 and 2). Isograds were drawn at the first appearance of index minerals.

Three metamorphic zones have been recognized over most of the mapped area of IIB, but only two in the northwest part. The lowest grade zone is greenschist facies. Higher grade zones, in ascending order, are lower amphibolite facies and upper amphibolite facies. These have been combined into a single zone of amphibolite facies in the northwest part.

The nine lithologic units recognized within the metamorphic rocks west of the Otú fault are not uniformly distributed among the metamorphic zones. Although some, notably quartzite and marble, are present in all facies, others are restricted to one or two. This is due in part to geographic distribution. For example, the hornblende gneiss is restricted to an area near Caracolí entirely in the upper amphibolite facies. Nowhere else in IIB is a mappable body of rock with the same chemical composition known. However, some units exist only in a restricted range of metamorphic facies because the minerals that define the unit are stable only within that range. The sericite schist is an example; it exists only in the greenschist facies. In the amphibolite facies, a rock of the same chemical composition would be a feldspathic or aluminous gneiss. The place of fine-grained sericite, quartz, and biotite in the schist would be taken by medium- to coarse-grained muscovite, biotite, feldspar, and alumino-silicates. The distribution of the nine lithologic units among the metamorphic facies is shown graphically in figure 6.

All the facies belong to a low-pressure facies series as postulated by Miyashiro. This is indicated (Miyashiro, 1961) by the absence of such higher-pressure minerals as kyanite and stilpnomelane, the paucity of garnet, the early appearance of biotite in pelites, and the regional development of andalusite.

Temperature gradients during metamorphism were exceptionally steep, as can be read from the narrowness of the middle-grade lower amphibolite facies zone in most places. It is not uncommon to pass from greenschist facies rocks to upper amphibolite facies rocks containing sillimanite over distances not much greater than a kilometer. Although such steep gradients may seem excessive, they have been described from other terrains of low-pressure facies series (Zwart, 1967, p. 506).

The age of the metamorphism is probably late Paleozoic, possibly Permian. The Permo-Triassic K/Ar ages from north of Puerto Valdivia

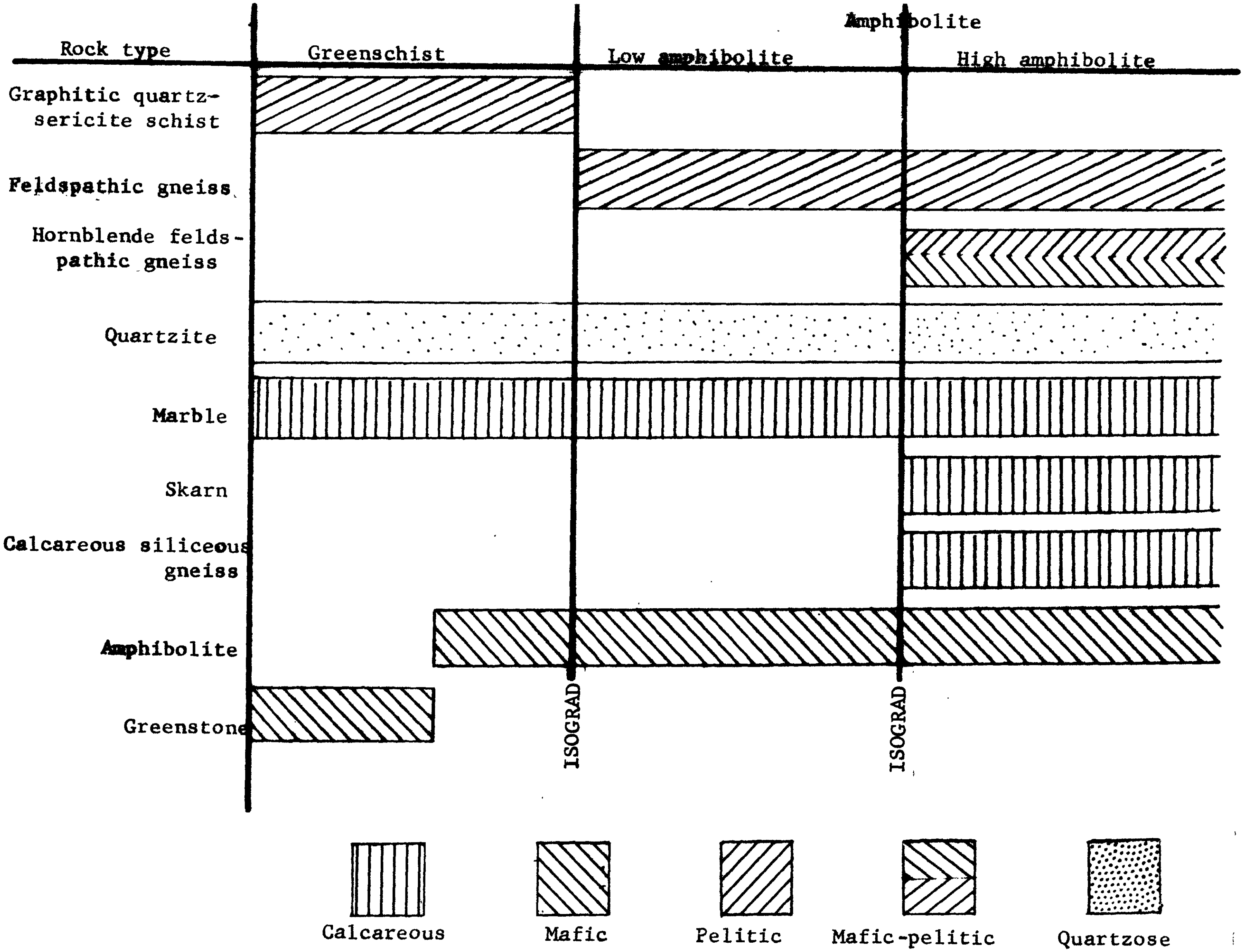


Figure 6.--The nine units of the Paleozoic(?) metamorphic rocks in IIB and their distribution among the metamorphic facies.

are from rocks intimately associated with this regional metamorphism in its higher grade parts, and are believed to closely reflect the age of the regional metamorphism.

Definition of facies.--The isograds between greenschist and lower amphibolite facies have been mapped at the first appearance of staurolite in pelitic rocks or diopside in calcareous rocks. The upper amphibolite facies is marked by the first appearance of sillimanite in pelites. In the northwest part of IIB, no rocks having mineral assemblages characteristic of the lower amphibolite facies were found. The transition from fine-grained sericite schist to medium-grained muscovite schist with sillimanite is abrupt. A similarly abrupt first appearance of sillimanite was noted by Harker (1950, p. 232) in pelitic rocks of the northeast highlands of Scotland.

Boundaries between facies are vaguely gradational and not as readily defined as in terranes of the classical higher-pressure Barrovian facies series. Harker (1950, p. 232) made the same observation in the northeast highlands of Scotland and interpreted the indistinctness of facies boundaries there to be a product of deficient shearing stress during the metamorphism.

Progressive changes of minerals through the three facies recognized in IIB for rocks of three broad chemical compositions are shown in figure 7. Common mineral assemblages in these rocks are given in table 4.

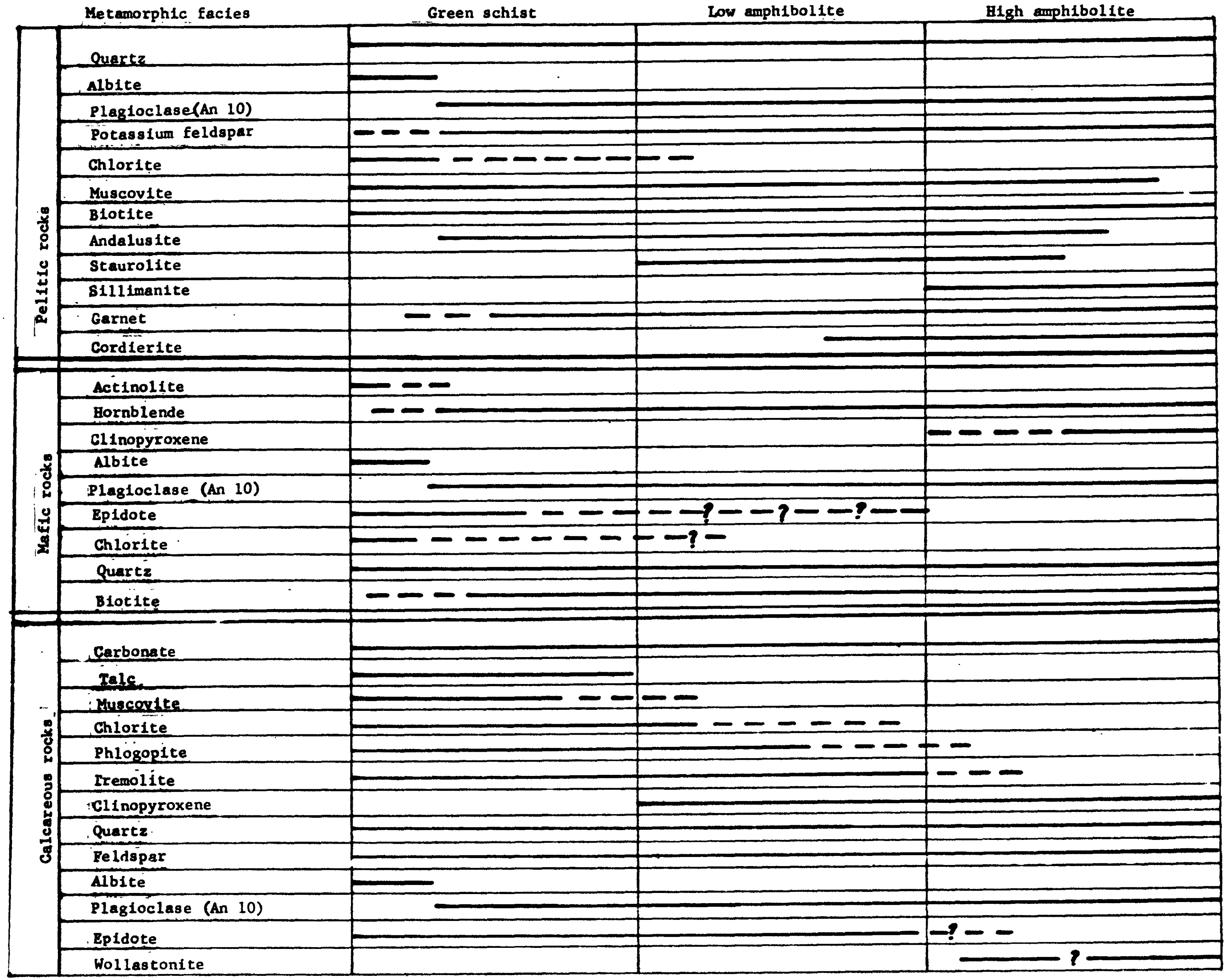


Figure 7.--Progressive mineral changes through the three facies in rocks of three broad chemical compositions.

Table 4.--Common mineral assemblages of the metamorphic rocks of the Central Cordillera in IIB.

	Facies Greenschist	Lower amphibolite	Upper amphibolite
Pelitic rocks quartzites, and quartzo-Feldspathic rocks	Q-Plag-Bio-Mos	Q-Plag-Mos-Bio	Q-Plag-Bio-Mos-Sill
	Q-Bio-Mos	Q-Bio-Mos-And-Plag-St	Q-Plag-Bio-Mos
	Q-Bio-Mos-Ab	Q-Plag-Bio-Mos-And	Q-Plag-Bio-Mos-Kfs
	Q-Mos-Cl	Q-Mos-Plag-St-Bio	Q-Plag-Bio-Mos-Kfs-Sill
	Q-Bio-Mos-And	Q-Plag-Bio-Mos-Kfs	Q-Plag-Bio-Mos-Sill-Gr
	Q-bio-Mos-Kfs-Ab	Q-And-Bio-Mos-St	Q-Plag-Mos-Bio-Cord
	Q-Bio-Mos-Cl	Q-Bio-Mos-St	
Rocks of mafic composition	Act-Cl-Ab	Hb-Plag-Bio	Hb-Plag-Q-Bio
	Hb-Plag-Bio-Mos-Ep	Hb-Plag-Ep	Hb-Plag-Bio
	Plag-Act-Bio-Ep	Hb-Plag-Q-Ep	Hb-Plag-Q
	Act-Plag-Bio-Cl	Hb-Plag-Bio-Q	Hb-Plag-Q-Cpx
	Ab-Act-Cl-Bio		Hb-Plag
	Act-Q-Plag-Ep		Plag-Hb-Cpx-Kfs
Calcareous rocks	Carb-Q	Carb-Cpx	Carb-Cpx-Tr
	Carb-Q-Mos	Carb-Q	Carb-Tr-Q-Kfs
	Carb-Q-Mos-Plag-Cl	Carb-Cl-Q-Flog	Carb-Tr-Q-Cpx-Kfs-Plag-Ep
	Carb-Tr-Flog	Carb-Cpx-Tr	
	Carb-Q-Flog	Carb-Tr-Cpx-Q	
	Carb-Tal	Carb-Tr-Q-Kfs-Plag-Cpx-Ep	
	Carb-Q-Tr		

Abbreviations:

Ab - **Albite**	Cl - chlorite	Gr - garnet	Sill - sillimanite
Act - actinolite	Cord - cordierite	Kfs - potassium feldspar	St - staurolite
And - andalusite	Cpx - clinopyroxene	Mos -- muscovite	Tal - talc
Bio - biotite	Ep - epidote	Plag - plagioclase	Tr - tremolite
Carb - carbonate	Flog - phlogopite	Q - quartz	

Biotite and chlorite:

Biotite forms in pelitic rocks almost at the onset of metamorphism in IIB, a characteristic of low-pressure facies series (Winkler, 1967, p. 117). Prograde chlorite is relatively scarce in the pelitic rocks; it occurs in rocks of mafic and calcareous composition, principally in the greenschist facies (table 4). Chlorite in rocks of the amphibolite facies in IIB is chiefly retrograde and is discussed in a following section on retrograde metamorphism.

Andalusite:

Andalusite first appears in pelitic rocks well within the greenschist facies in IIB. Fine-grained phyllites commonly contain euhedral sericitized andalusite porphyroblasts more than 2 cm long and 1 cm in diameter, with well-developed chiastolite crosses. Most of the sericite schist contains partly to wholly sericitized euhedral andalusites 2 to 6 cm long. Andalusite persists in the feldspathic and aluminous gneiss well into the upper amphibolite facies (fig. 7) as highly poikilitic subhedral to anhedral porphyroblasts some of which achieve spectacular proportions. An outcrop of gneiss in the Río Nus just downstream from the bridge at San Rafael Station on the Antioquian Railroad (pl. 1, d-9, sheet 2) has crystals of fresh andalusite as long as 45 cm. Even more spectacular crystals (fig. 8), though smaller and sericitized, are found in schist at the intake for the old hydroelectric plant for the town of Anorí on the Río Anorí.

Little agreement exists between petrologists on the occurrence of andalusite in regional metamorphism. In the Abukuma facies series,

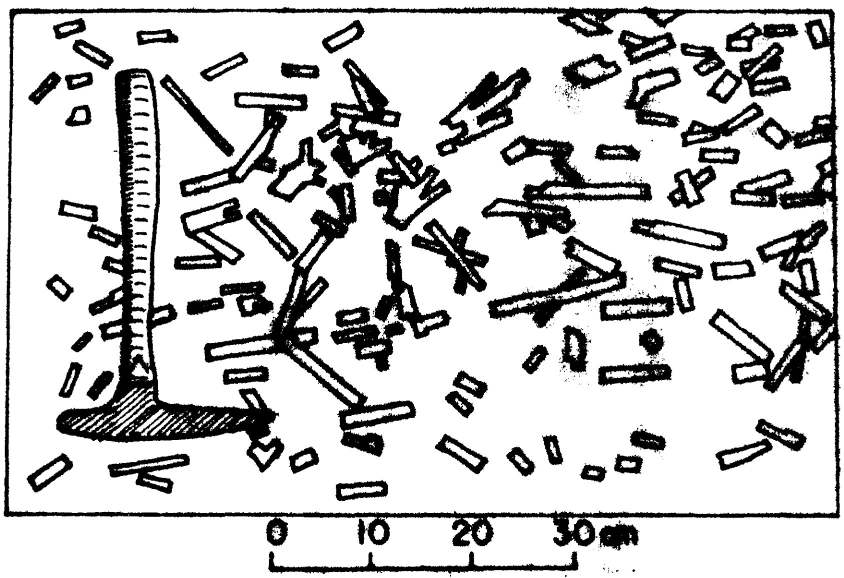


Figure 8.--Sericitized andalusite porphyroblasts in schist. Intake of old Anorí hydroelectric plant, Río Anorí (pl. 1, a-1, sheet 1).

Miyashiro (1961, p. 280; 1967, p. 402) restricts andalusite to the amphibolite facies. Winkler (1967, p. 118-120), on the other hand, considers andalusite an index mineral of the higher of the two sub-facies that he has erected within the greenschist facies of the Abukuma facies series. The stability field of andalusite falls entirely outside the amphibolite facies but within the hornfels facies on a P-T diagram drawn by Fyfe and Turner (1966, fig. 1).

The occurrence of andalusite in IIB is most in accord with the view of Winkler (1967, p. 118-120). It is interesting that in shallow contact metamorphism, andalusite develops very early, in many places even before biotite (Harker, 1950, p. 49). The early appearance of andalusite in IIB supports the interpretation that the rocks belong to a low-pressure facies series, possibly even of lower pressure than the rocks of the type Abukuma facies series in Japan.

Staurolite:

The status of this mineral within the facies series concept is not clear. Miyashiro (1961, p. 279) originally excluded staurolite as a possible mineral in the Abukuma facies series, but later (1967, p. 405-406) considered its absence from the low pressure facies series rocks with which he was familiar to be an accident of their chemical composition. Winkler (1965, p. 108-112; 1967, p. 65-66, 87-88, 119-120), on the other hand, pointed out that staurolite is found in relatively shallow contact aureoles and does not appear to be pressure dependent. Recent experimental work by Richardson (1966) supports this view.

The presence and distribution of staurolite in pelites in IIB is erratic. In the northwest part of the mapped area, between Amalfi and Anorí, staurolite is absent in rocks apparently of appropriate grade. In lower amphibolite facies rocks along the Otú fault in plate 1 (sheet 1), staurolite forms as small poikilitic porphyroblasts in schists. In the southern part of plate 1 (sheet 2), between the Palestina and Jetudo faults, it forms inclusion-free cores in subhedral porphyroblasts of andalusite. This appears to be unusual and apparently has not been described in the petrographic literature. Professor H. J. Zwart (written commun., 1969), however, states that staurolite cores in andalusite are common in the Bosost area of the Pyrenees that he has mapped. It is interesting that the metamorphic rocks of the Bosost area are considered to belong to a facies series of yet lower pressure than the Abukuma (Winkler, 1967, p. 125-126). The occurrence of this petrographic oddity both at Bosost and in part of IIB supports the evidence afforded by the early appearance of andalusite, that some, if not all the metamorphic rocks of the Central Cordillera in IIB, were formed in an unusually low-pressure facies series.

The irregular distribution and local absence of staurolite in IIB is tentatively interpreted as a reflection of regional variations in the chemical composition of the pelites. The problem needs additional investigation.

Garnet:

Garnet was found in a few samples of pelites from all but the lowest grades of metamorphism in IIB. It is however, a generally scarce mineral and is rarely visible megascopically.

Two lines of evidence suggest that the garnets may be spessartite rich and not common almandine. Their color is very pale pink, a color common in spessartite but unknown in almandine. Also, in some high-grade gneisses with garnet, the number of phases in the Thompson AFM projection exceeds by one the number allowed if the garnet is almandine. An example from a gneiss exposed in the Río Samaná Norte in d-10 (pl. 1, sheet 2) is: quartz-oligoclase-biotite-muscovite-sillimanite-andalusite-garnet-staurolite-orthoclase(?). The phases in this rock appear to be in textural equilibrium in thin section.

The occurrence of spessartite is controlled by the chemical composition of the rock in which it is found; it has no implication for the facies series in which the rock was metamorphosed. On the other hand, almandine is a major mineral of pelitic rocks from the middle greenschist and higher facies of the classical Barrovian facies series. The assured scarcity and even the possible absence of this mineral in pelitic rocks in IIB is additional evidence of the low pressure of the facies series in which they were metamorphosed.

No garnet was found in amphibolite except in some samples from the inner contact aureole of the Antioquian batholith. Garnet (almandine) in regionally metamorphosed amphibolites is characteristic of the Barrovian facies series, and indeed is the origin of the name "almandine amphibolite facies." The absence of this association in IIB is corroborative evidence that the regional metamorphism was of a low-pressure facies series.

Cordierite:

The status of cordierite in IIB is complicated by its lack of distinctive optical properties; it is identified only with difficulty in thin section. Cordierite in IIB is not pleochroic even in thick (0.010 mm) sections, nor are pleochroic halos developed bordering included zircons. Optically positive and negative grains coexist in the same thin section, exactly as reported in a gneiss from the State of Georgia, U.S.A., by Salotti and Fouts (1967).

Most locations where cordierite was positively identified are within a few kilometers of the Antioquian batholith. If the batholith has the sheetlike form postulated later, quartz diorite may underlie each locality at little depth. However, cordierite has been identified in samples from several outcrops many kilometers from igneous rocks. In these places the cordierite is considered to be of regional metamorphic origin.

Migmatites:

Migmatites dominate the feldspathic and aluminous gneiss in the upper amphibolite facies, and also occur locally within the higher-grade parts of the lower amphibolite facies.

Some field, petrographic, and chemical evidence bearing on the origin of the migmatites in IIB was found. The granitic part of the migmatites is composed of subequal parts of quartz and oligoclase with no potassium feldspar and occurs in pods and sills that are isolated from one another or are connected only rarely. The schistose part of the migmatites is composed of mica, sillimanite or andalusite, and rare cordierite or garnet. Plagioclase and quartz rarely exceed a few percent each and in places are wanting. The chemical composition of a typical sample of the schistose part of a migmatite from the Río San Bartolomé is given in table 5, column 1.

Field observations strongly indicate that the migmatites are composed of roughly equal parts of granitic and schistose material. This is a qualitative observation; it can be said with certainty only that neither component is conspicuously dominant over the other (fig. 3). As stated above, the granitic part is composed of subequal parts of quartz and oligoclase. The calculated chemical composition of this material is given in table 5, column 2. The calculated chemical composition of a mixture of equal parts by volume of the schistose (table 5, col. 1) and granitic (table 5, col. 2) parts of the migmatite is given in column 3 of table 5. This is the approximate composition of the whole migmatite. The departure of this composition from that of average carbonate-free shale (table 5, col. 4) is surprisingly small. Relative to the shale, the migmatite is somewhat enriched in Al_2O_3, CaO, and Na_2O. The reduced content of H_2O is the normal consequence of dehydration that accompanies prograde metamorphic reactions. If the parent sediment of the migmatites contained a few percent calcite (the CO_2 having escaped during metamorphism and migmatization), much of the discrepancy between the composition of the whole migmatite with that of carbonate-free shale (table 5, cols. 3, 4) could be accounted for.

Table 5.--Chemical analysis of the schistose part of a migmatite from the Río San Bartolomé, and some calculations pertinent to the origin of the migmatites of IIB.

	1	2	3	4
Inventario number	7749			
Field number	OR - 229			
USGS laboratory number	W168-931			
SiO_2	40.3%	81.7%	60.2%	61.8%
Al_2O_3	30.0	11.5	21.1	16.3
Fe_2O_3	1.7	---	} 4.7	6.9
FeO	7.4	---		
MgO	3.1	---	1.6	1.9
CaO	2.6	2.1	2.4	0.6
Na_2O	1.5	4.7	3.1	1.4
K_2O	5.8	---	3.0	3.4
H_2O-	0.2	---	} 2.5	5.3
H_2O+	4.6	---		
TiO_2	1.5	---	0.8	0.7
P_2O_5	1.2	---	0.6	0.2
MnO	0.1	---	0.1	---
Total	100.0%	100.0%	100.1%	98.5%
Bulk density (g/cm^3)	2.90	2.65 (est)		

1. Schistose part of migmatite, Río San Bartolomé near Quebrada La Guaira (pl. 1, d-6, sheet 1). 2. Calculated composition of granitic part of migmatite composed of equal parts by volume of quartz and oligoclase. 3. Calculated composition of a mixture of equal parts by volume of schistose (col. 1) and granitic (col. 2) parts of the migmatite. 4. Composition of average carbonate-free shale (table 3, col. 5), less SO_3, 0.7% and C, 0.8%. Chemical analysis of 7749 by rapid rock analysis methods, USGS, Washington, D. C.

An older theory on the origin of migmatites is that they are produced by the injection of granitic magma from an outside source along foliation planes of the pre-existing high-grade schist or gneiss. Even aside from the absence of either an igneous composition or texture of the granitic part, this theory is inadequate to account for the migmatites found in IIB. Under this theory, the "pre-existing rock," the schistose part of the migmatite, has a chemical composition (table 5, col. 1) different from that of any common sedimentary or volcanic rock. It seems unlikely that a rock of such an unusual composition once could have underlain the thousands of square kilometers now occupied by the migmatites.

Perhaps the theory of the origin of migmatites currently most favored by petrologists is that migmatites are the product of anatectic partial melting during high-grade regional metamorphism (Winkler, 1967, p. 192-224). It is unlikely that such a process produced the migmatites in IIB. The composition of the granitic part of the migmatites does not even remotely approach the composition of an anatectic melt derived from ordinary rocks. It is too rich in quartz and lacks potassium feldspar. Furthermore, the granitic part of the migmatites has a metamorphic texture. It neither has nor shows evidence of ever having had an igneous texture produced by crystallization from a melt.

The composition of the whole migmatite (table 5, col. 3) is similar to both the average composition of the sericite schist of IIB based on three analyses (table 3, col. 4) and carbonate-free shale (table 5, col. 4). These observations imply that the migmatites of IIB were derived from shale and that the processes of metamorphism and migmatization changed their bulk composition but little. The evidence against the formation of the migmatites by anatexis was given earlier. It is therefore concluded that the migmatites are the product of metamorphic segregation of initially more homogeneous rocks of shale composition into schistose and granitic components during medium- to high-grade regional metamorphism with little if any concomitant melting.

Retrograde metamorphism

Many middle- and high-grade metamorphic rocks in IIB have undergone partial to complete retrograde metamorphism. The most widespread manifestations are the sericitization of andalusite and sillimanite, pinitization of cordierite, chloritization of biotite, and saussuritization of plagioclase.

Chloritization of biotite and sericitization of alumino-silicates go hand-in-hand in many samples. It is tempting to suggest that the potassium liberated in the biotite-to-chlorite transformation reacted with adjacent andalusite or sillimanite to form sericite under conditions of relatively high water vapor pressure. Long-distance transport of potassium would thus not be a necessary mechanism.

In one sample (INV-8467) from c-14 (pl. 1, sheet 2), small prisms of chloritoid occur in sericite knots pseudomorphic after andalusite. No chloritoid in fresh andalusite is noted in the sample and clearly, like the sericite, it is a retrograde mineral. An identical occurrence of retrograde chloritoid has been described by Seki (1954, p. 241) in Japan.

The retrograde metamorphism may have taken place mainly during the closing stages of the late Paleozoic(?) regional metamorphism. The steep temperature gradients of the prograde metamorphism could not long have been maintained, which shows that the duration of the metamorphism was short. Time may thus have been insufficient for more than the partial escape of water liberated by the prograde metamorphic reactions, and much may have been retained as an intergranular phase. Upon the waning of metamorphic heat, some of this water may have recombined with the rock in which it was retained so as to partially or wholly destroy the high-temperature prograde minerals.

Thermal metamorphism

The effects of thermal metamorphism by igneous intrusions were noted at several places in IIB, but were not studied in detail. The effects, rarely pronounced, were noted chiefly adjacent to the Antioquian and Sonsón batholiths, the granodiorite at Tres Mundos, to the adamellite, and the diorite east of the Otú fault.

The temperatures and pressures of the regional metamorphism under which the high-grade rocks were formed were not unlike those realized in the innermost part of the thermal aureole of the Antioquian batholith. Accordingly, few mineral changes were imparted to these rocks surrounding the batholith.

The only obvious effect of the thermal metamorphism by the batholith is the development of coarse-grained skarn in the calcareous rocks near the contact. Common high-temperature minerals in the skarn include wollastonite, diopside, grossularite, vesuvianite, and farther from the contact, tremolite.

Another effect, visible only in thin section, is the development of cordierite. In aluminous rocks of low regional metamorphic grade, the heat of the magma formed anhedral sieved grains of cordierite near the batholith contact. Typical examples are found southwest of Amalfi (pl. 1, a-4, sheet 1) in micaceous quartzite. Where cordierite in gneiss of high regional metamorphic grade was present prior to the intrusion; however, high-temperature thermal metamorphism immediately adjacent to the batholith caused a partial breakdown of the cordierite, chiefly to dark green spinel and quartz. The spinel coexists with quartz in the same thin section, but the two minerals are nowhere in contact; the spinel is everywhere surrounded by cordierite, or less commonly, by some other alumino-silicate. In a few places, andalusite or sillimanite of regional origin appear to have broken down in the innermost part of the aureole to produce cordierite-spinel assemblages. The two most likely spinel-producing reactions are:

$$\underset{\text{Cordierite}}{(Mg,Fe)_2Al_4Si_5O_{18}} \longrightarrow \underset{\text{5 Quartz}}{5SiO_2} + \underset{\text{2 Spinel}}{2(Mg,Fe)Al_2O_4} \qquad (1)$$

$$\underset{\text{Biotite}}{K(Mg,Fe)_3Si_3AlO_{10}(OH)_2} + \underset{\text{Muscovite}}{KAl_2Si_3AlO_{10}(OH)_2} + \underset{\text{2 Andalusite}}{2Al_2SiO_5} + \underset{\text{3 Quartz}}{3SiO_2} \longrightarrow$$

$$\underset{\text{Cordierite}}{(Mg,Fe)_2Al_4Si_5O_{18}} + \underset{\text{Spinel}}{(Mg,Fe)Al_2O_4} + \underset{\text{2 Orthoclase}}{2KAlSi_3O_8} + 2H_2O \qquad (2)$$

That the innermost part of the aureole surrounding the Antioquian batholith achieved a very high temperature is also shown by the local development of sillimanite prisms several millimeters long in phyllite a few meters from the contact southeast of San Carlos (pl. 1, b-12, sheet 2). This occurrence is diagnostic of the potassium feldspar-cordierite hornfels facies of Winkler (1967, p. 73), or of the pyroxene hornfels facies of Turner and Verhoogen (1960, p. 521-522).

Andalusite of thermal origin occurs in phyllite in a zone a few tens of meters wide adjacent to some igneous rocks. These thermal andalusites are fresh pink crystals less than a centimeter long and only a millimeter or two across and are readily distinguished from the widespread andalusites of regional metamorphic origin described earlier. Good examples are found in black phyllite adjacent to the Antioquian batholith and adamellite in cuts on the road to Amalfi (pl. 1, a-3, a-4, sheet 1), and north of the stock of granodiorite at Tres Mundos (pl. 1, a-15, sheet 2).

The Cretaceous black shale south of San Luis (pl. 1, b-13, b-14, sheet 2), was surprisingly little affected where intruded by magma of the Antioquian batholith. The shale in a zone no more than 30 m wide adjacent to the contact is baked and has a faint maroon color. No aluminous contact minerals were developed. Siltstone and calcareous wacke in the Cretaceous sedimentary rocks southwest of San Luis (pl. 1, a-13, sheet 2) were more reactive. Extensive areas of these rocks near the batholith contain epidote and actinolite, an assemblage distinctive of the albite-epidote hornfels facies (Winkler, 1967, p. 65).

Inclusions of calcareous quartzite in adamellite at La Lejía (pl. 1, b-4, sheet 1) contain abundant wollastonite. It is not known whether the wollastonite was produced by contact metamorphism by the adamellite magma or by the younger Antioquian batholith magma which was intruded to within a few meters of the inclusions, or whether the wollastonite was produced in the regional metamorphism and precedes all the intrusions.

Ordovician limestone in the southmost lenses adjacent to the Magdalena Valley (pl. 1, e-9, e-10, sheet 2), has been thermally metamorphosed by diorite magma that formed the nearby stocks. The limestone, which in other lenses is a fine-grained gray rock, has been changed to a medium- to coarse-grained white marble.

Dynamic metamorphism

Several periods of dynamic metamorphism have affected the rocks of IIB. The three most prominent are here briefly discussed in their probable chronological order, from oldest to youngest.

The Precambrian rocks are cut by a series of shear zones of unknown age that trend roughly north-south. Cataclastic rock in these zones resembles sericite schist. It is tempting to correlate these shear zones with the adjacent and subparallel Nus and El Bagre wrench faults. However, as the shears were not found in the diorite, they may be older than that rock and thus antedate the wrench faults. An alternative interpretation is that the shear zones were formed during the low-grade regional metamorphism of the overlying Ordovician rocks.

Dynamic metamorphism has superimposed a cataclastic foliation parallel with the preexisting regional foliation over extensive areas of the metamorphic rocks of the Central Cordillera. This is especially evident where these rocks are in the amphibolite facies of regional metamorphism. This period of dynamic metamorphism predated the Antioquian batholith which truncates the sheared rock and was not affected by the cataclasis.

The youngest period of dynamic metamorphism produced the extensive shear zones in the Antioquian batholith. These may be, as suggested later, related to the cooling and crystallization of the batholith magma.

Stratified felsic and intermediate volcanic rocks east of the Otú fault

Highly fractured volcanic rocks, which are poorly exposed east of the Otú fault in the vicinity of Puerto Berrío, have been subdivided provisionally into a porphyritic unit and an aphanitic unit. The two are separated by north- to northeast-striking faults, with the porphyritic unit lying to the west. The grain size of the volcanic rocks is too fine to determine their composition solely through thin section study. They are tentatively classified as felsic and intermediate on the basis of color and specific gravity.

The age of the volcanic rocks cannot be precisely determined. At Calera Railroad Station, they appear to overlie marble that possibly is correlative with the Ordovician limestone. The volcanic rocks are older than the Jurassic diorite in which they occur as inclusions, as can be seen in Quebrada La Bramadora where it is crossed by the road 11 km west of Puerto Berrío.

Porphyritic unit

Rock of the porphyritic unit is fine-grained gray to beige with from less than one to about 30 percent phenocrysts. The phenocrysts range from 1 to 8 mm in diameter, though most are between 4 and 5 mm. They are chiefly subhedral feldspar, but locally they are hornblende or aggregates of shreddy biotite. The rock is massive to laminated. Lamination resembles flow structure of lavas.

The best exposures of the porphyritic unit are in Quebrada La Austria and the headwaters of Quebrada Santa Cruz (pl. 1, e-7, sheet 1), and in Quebrada La Blanquita (pl. 1, e-7, e-8, sheet 1).

Aphanitic unit

Aphanitic to fine-grained, mostly massive, light gray, gray-green, and black rocks comprise the aphanitic unit. In a few places the rocks are porphyritic and carry as much as one percent feldspar phenocrysts generally less than 1 mm in diameter. Locally the rocks are weakly laminated. This is best seen on weathered surfaces. The black aphanites weather to a light chalky gray, and appear to be recrystallized glassy lavas.

The best exposures of these rocks occur in Quebrada La Malena downstream from Calera railroad station (pl. 1, e-8, sheet 1), in cuts along the road west from Puerto Berrío (pl. 1, e-8, f-7, f-8, sheet 1), and in the lower reaches of Quebrada Santa Cruz (pl. 1, f-7, sheet 1).

Cretaceous sedimentary rocks

Cretaceous sedimentary and volcanic rocks, previously unknown in IIB, were found in several places and some are extensive. The largest area of these rocks is in the southern part of IIB, mostly south of San Luis. Another extensive area of similar rocks is in the northeast part of IIB east of the Otú fault. Smaller areas are near Amalfi (pl. 1, a-3, sheet 1), and in a north-south belt that crosses the Antioquian Railroad near Cabañas (pl. 1, d-9, sheet 2), east of the Palestina fault.

The Cretaceous rocks were studied in less detail than most of the other rocks in IIB. This is due in part to the fine grain of most of the sedimentary rocks and the altered state of the volcanic rocks. Also, as the topography developed on the Cretaceous rocks commonly is precipitous, the areas where these rocks occur are sparsely inhabited and access to them is difficult.

Four units, three sedimentary and one chiefly volcanic, have been distinguished. The aggregate thickness could not be measured owing to structural complexities, inadequacy of outcrop, and the absence of marker beds. Nevertheless, the wide extent of the Cretaceous rocks south of San Luis suggests that their thickness may locally exceed 1,000 m.

Shale

By far the most extensive of the four units is that mapped as shale. This unit is particularly widespread south of San Luis and east of the Otú fault in the northeast corner of IIB. Smaller areas underlain predominantly or exclusively by shale are at Amalfi and between the Nus and El Bagre faults in a north-south belt east of the Palestina fault. A small area of argillite and tough gray orthoquartzite at

El Huevo, about 15 km southwest of Amalfi (pl. 1, a-4, sheet 1), is continuous with a belt of sedimentary rocks named the San Pablo Formation in IIA to the west. The rocks at El Huevo are here included with the shale unit merely for convenience.

South of San Luis (pl. 1, sheet 2) large outcrops, locally continuous for hundreds of meters, are found in the Ríos Santo Domingo, Verde, and Samaná Norte and their tributaries. These outcrops afford a fairly complete east-west section across the strike of the unit. The shale east of the Otú fault is well exposed only in the extreme northeast corner of the map area where excellent outcrops occur in Quebrada El Salado (pl. 1, d-1, e-1, sheet 1) and in an unnamed north-flowing quebrada 10 km east of Segovia (pl. 1, e-1, sheet 1). Elsewhere east of the Otú fault outcrops of the shale are sparse and poor.

Black organic shale is the dominant rock type of the unit; some weathered shale is light gray. Shale is well exposed in cuts on the road from Amalfi to the airstrip (pl. 1, a-3, sheet 1). Other rocks interbedded with the shale include chert, cherty siltstone, graywacke sandstone, intraformational conglomerate with clasts predominantly of black shale, quartz pebble conglomerate, pebbly mudstone, and sparse gray-green volcanic rocks of intermediate composition. These rocks locally occur in amounts equal to the shale, but in most places they are 20 percent or less.

The shale is everywhere intensely folded, fractured, and crumpled. Bedding is commonly vertical or nearly so. Minor folds are common and bedding planes are crinkled or striated and generally have a weak phyllitic sheen. Where the shale is rich in carbonaceous organic material, shearing has produced shiny black surfaces without prevailing striae Such rock is particularly well exposed in the abandoned gold mine adjacent to the Nus fault 0.8 km north of Cabañas (pl. 1, d-9, sheet 2).

Fossils, generally poorly preserved and deformed, are found sporadically in the shale (table 6). Plant fragments are particularly common. These are followed in abundance by ammonites, pelecypods, and gastropods. Fossils from four widely spaced localities in Lower Cretaceous shale were identified (table 6, nos. 2-5). Based on its lithologic uniformity throughout IIB, the entire shale unit tentatively is considered to be Lower Cretaceous.

The unconformity between the shale and the metamorphic rocks of the Central Cordillera in IIB is obscure in most places. Many of the rocks in the shale unit are finely laminated and where bedding planes have a phyllitic sheen the rocks resemble and are only difficulty distinguishable from sericite schist or fine-grained laminated quartzite of the metamorphic rocks (see below).

At only one place is the unconformity at the base of the shale exposed. This locality is 2.5 km N. 30° E. of Amalfi, on the trail that passes over Alto El Español (pl. 1, a-3, sheet 1). Here a bed of quartz pebble conglomerate 80 cm thick lies concordantly below the black shale but discordantly overlies, at an angle of 90°, a sericite schist containing porphyroblasts of altered andalusite. Post-shale deformation has left the bedding of the shale vertical whereas the foliation of the schist is nearly horizontal.

Table 6.--Fossil localities, Cretaceous rocks.

No.	Plancha and Formation	Location and coordinates	Fossils	Age	Identified by
1	e-1 shale	Unnamed quebrada 10 km east of Segovia. X=1,275,100; Y=941,300	Ammonites		
2	e-1 shale	Quebrada Corrales, 8.4 km N.81°E. of Remedios. X= 1,270,600; Y=940,300	Acanthoplites (?)	Late Aptian to Early Albian?	R. W. Imlay, USGS
3	d-1 Ksh	Quebrada El Salado, about 8 km east southeast of Segovia. From X=1,272,450 Y=938,450, to X=1,273,150; Y=939,850	Weichselia sp. Neocomitinas (Cuyaniceras? sp.) Inoceramus sp. Trigonia sp. T. v-costata Lycett	Lower Cretaceous	Diana Gutiérrez P., IMN Bogotá
4	a-3 Ksh	Alto El Español, 2.0 km N.39°E. of Amalfi. X=1,257,300 Y=891,000	Perissonota nuculoides Gabb, Cardium? sp., and Corbis pulchelliphila Gerhardt.	Hauterivian to Early Albian	Hans Bürgl, Bogotá
5	b-14 Ksh	1.1 km N.86°E. of the confluence of the Ríos Samaná Norte and Chumurro. X=1,148,200; Y=903,400	Brancoceras (?)	Middle Albian?	Diana Gutiérrez P.,
6	b-14 Ksh	3.0 km N.47°W. of Aquitania X=1,140,000; Y=898,900	Ammonites		
7	b-16 Kv	Río Claro, 8.0 km S.4°W. of Aquitania. X=1.130,000; Y=900,500	Pelecypods		

Limestone

A few lenses of gray fine-grained limestone with anastomosing white calcite veins one millimeter thick are interbedded with shale at and near the Nus fault, 7 km south of the Antioquian Railroad. The lenses are thin and probably none exceeds a few tens of meters in thickness. No fossils were found.

Conglomerate

Conglomerate and interbedded siliceous sandstone in layers from less than one to nearly 100 m thick are sporadically intercalated with shale and volcanic rocks south of San Luis and near Amalfi. Other layers, probably hundreds of meters thick, are found capping Cerro Castellón, 2.5 km southwest of San Luis (pl. 1, b-13, sheet 2) and Alto Taparal, Alto Risaralda, and Cuchilla and Cerro Rabo de Chucha about a dozen kilometers south-southwest of Amalfi (pl. 1, b-4, sheet 1). Residual boulders of conglomerate from 0.5 to 1.0 meter in diameter lying on the Antioquian batholith are found 13 km east of San Rafael (pl. 1, b-10, sheet 2).

Most of the conglomerate is composed of nearly spherical clasts of milky quartz set in a sandy quartzose matrix. Clasts range from less than one to as much as ten centimeters in diameter, although most are between 1 and 3 cm. Most of the conglomerate is composed of nearly spherical clasts of milky quartz set in a sandy quartzose matrix. Clasts range from less than one to as much as ten centimeters in diameter, although most are between 1 and 3 cm. Most of the conglomerate is so thoroughly silicified that it resembles massive milky quartz. Careful inspection of weathered surfaces, however, generally reveals the texture and structure of the conglomerate. The silicified conglomerate is an especially resistant rock and forms bold ledges or hills.

Clasts of some of the conglomerate in shale and volcanic rocks south of San Luis are composed partly or wholly of chert, fine-grained volcanic rocks, and rarely igneous and metamorphic rocks.

Volcanic rocks

Volcanic rocks of mappable extent associated with the shale unit were recognized only in the northeast corner of IIB, east of the Otú fault. Outcrops, however, are sparse, and the only adequate exposures are found in eastward draining streams east-northeast of Segovia (pl. 1, d-1, sheet 1).

The volcanic rocks are principally light gray-green, massive to phyllitic, fine-grained to aphanitic, and thoroughly sheared, fractured, and altered. They are probably andesitic or dacitic, although the minerals in most are so altered to chlorite, actinolite, and saussurite that neither their original texture nor original mineral composition can be deciphered.

An exceptional fresh dacite, possibly a crystal tuff, is exposed in Quebrada Corrales, 7.2 km N. 77° E. of Remedios (pl. 1, d-1, sheet 1). The rock is porphyritic and light gray, massive to weakly laminated. Phenocrysts from 2 to 5 mm in diameter compose from one quarter to one third of the rock, and are chiefly zoned euhedral white oligoclase and chloritized biotite with lesser anhedral quartz. The rock is interbedded with fossiliferous black shale of Late Aptian to Early Albian(?) age (table 6, no. 2).

The volcanic rocks and interbedded sediments of the volcanic unit bear at least a superficial resemblance to the Quebrada Grande Formation near Medellín (Botero A., 1963, p. 44-54), about 90 km to the northwest. Prof. Botero (1963, p. 54; oral commun., 1969) assigned a tentative Late Cretaceous age to the Quebrada Grande, based on fossils of that age in lithologically similar rocks in the Western Cordillera between Cali and Buenaventura, about 300 km south-southwest of Medellín. However, as the correlation is a tenuous one, and as no Cretaceous fossils younger than Albian are known in the Central Cordillera, the volcanic rocks in IIB are here considered Lower Cretaceous.

Tertiary sedimentary rocks

Continental Tertiary sedimentary rocks border the Magdalena River along the east edge of IIB. Contacts were mapped chiefly on airphotos and the sediments were little studied in the field. In some places, areas mapped as Tertiary sediments include older high-level river terraces of the Magdalena Valley of probable Holocene age.

The Tertiary sedimentary rocks form a low rolling topography, and outcrops are poor and scarce. The best exposures are in fresh cuts near Puerto Berrío (pl. 1, f-7, f-8, sheet 1) in a road to San José which was under construction in 1969. Other outcrops are found in the banks of some streams and rivers.

Most of the Tertiary sedimentary rocks are well bedded, though unconsolidated or only weakly cemented. Dominant lithologies are conglomerate, well to poorly sorted sandstone, and siltstone. Clasts in the conglomerate are chiefly milky quartz, chert, and aphanitic volcanic rocks, with lesser quantities of schist and gneiss. No clasts of the Antioquian batholith were found. Clasts more than 5 cm in diameter are uncommon. Beds of feldspathic tuffaceous sandstone as much as 15 m thick are exposed in roadcuts just west of Puerto Berrío.

A poorly exposed isolated patch of well-cemented Tertiary rocks about 8.6 by 2.0 km occurs largely on hilltops 17 km west of Puerto Berrío (pl. 1, e-7, e-8, sheet 1). Lithologies are largely the same as those of the unconsolidated Tertiary except for thick beds of a curious sooty black rock, possibly volcanic, containing many light gray laths of plagioclase 1 by 10 mm. This rock is well exposed in road cuts 1 km east of Hacienda El Oasis, west of Puerto Berrío.

The Tertiary rocks are nearly horizontal or dip gently eastward, although the well-cemented rocks have more variable attitudes. All unconformably overlie the crystalline rocks and thicken eastward. That the Tertiary rocks once extended farther west is shown by the abundance of residual boulders of conglomerate and pieces of silicified wood that lie on crystalline rocks many kilometers beyond the present limit of the Tertiary rocks. It is possible that small remnant patches of Tertiary sediments on hilltops in the same areas were missed during the mapping.

The precise age of the Tertiary rocks is unknown. The only fossils are silicified wood, which in places is very abundant and affords specimens of museum quality.

The lithology and topographic setting of the Tertiary rocks are similar to the Pliocene(?) Mesa Formation (Servicio Geológico Nacional, 1957) in the Magdalena Valley near the southeast corner of Zone II, and the two may be correlative.

Alluvium

A group of perched high-level Tertiary alluvial deposits are found between Amalfi (pl. 1, a-3, sheet 1) and Anorí (pl. 1, a-1, sheet 1). The largest are at La Viborita 2 km north of Amalfi, at San Benigno and Chamuscados (recently renamed San Antonio), and at Anorí. The deposits range from clay to coarse gravel. They are poorly to moderately well sorted and fluvial bedding is common.

The alignment of the deposits and their general north-northwest gradient suggest deposition by a river that flowed in that direction. Also, clasts of sericitized andalusite occur in a remnant of similar alluvium west of the canyon of the Río Nechí in IIA, 16 km N. 81° W. of Anorí (A. Estrada, oral commun., 1966). This lies far beyond the northwesternmost occurrence of andalusite in the schist, and reinforces the interpretation that transportation was from south to north. The same interpretation was suggested more than 30 years ago by an unknown author of a map on file in the Ministerio de Minas y Petróleos. The map, dated 1935, is titled "Plan of the alluvial areas of the Nechí River," and clearly shows more than a dozen perched alluvial deposits connected by an ancestral northwest-flowing river and three tributaries. The elevation and topographic setting of the alluvium at La Viborita, which are somewhat different from the general setting, may have been modified by young faults not recognized in the field owing to poor exposure.

The age of the alluvium is not known. It predates regional uplift as the suggested course of the former river that formed the deposits is now interrupted by the canyons of the Ríos Porce and Nechí, each more than 1,000 m deep. Wood from the lower and probably younger of the two levels of alluvium at La Viborita dated in the radiocarbon laboratories of the U. S. Geological Survey, Washington, D. C. (sample W-2138) proved older than 42,000 years, the limit of the method.

Quaternary alluvium

Unconsolidated surficial deposits that form relatively flat floors in upland valleys, or extensive plains along the Magdalena and tributary rivers have been mapped as alluvium. In upland valleys these deposits are particularly common on the Antioquian batholith and marble, less common on feldspathic metamorphic rocks, and least common on sericite schist and quartzite.

The deposits are a mixture of alluvium and colluvium. They are composed chiefly of thoroughly weathered material that is feebly bedded and poorly sorted, or has only restricted well-sorted horizons. The deposits are generally no more than 100 m wide, and most are probably thin because knobs of bedrock that protrude through them are not uncommon. Terraces have not been recognized. Exposures are poor and limited to low banks along streams. Many of the deposits have been so disturbed during placer mining that their original morphology is entirely destroyed.

Alluvium at low elevations along the Magdalena and tributary rivers and along some of the larger rivers on the Antioquian batholith such as the San Bartolomé, Porce, Nus, and Guatapé, is well bedded and sorted silt, sand, and gravel. Terraces are present but have not been distinguished on the geologic map.

Alluvium along the Magdalena and its tributaries as well as the alluvial-colluvial deposits in upland valleys are of Holocene age. Aggrading streams continue to deposit alluvium in some places, but in others the deposits are being eroded by modern streams. These deposits may in part be Pleistocene. No distinction was made between Holocene and possible Pleistocene deposits.

INTRUSIVE ROCKS

Felsic porphyry intrusions east of the Otú fault

Hypabyssal felsic porphyry, chiefly dacite, crops out east of the Otú fault as small irregular bodies with maximum diameters 50 m or less. Conspicuous subhedral to euhedral phenocrysts of nonzoned beige oligoclase and gray quartz from 4 to 10 mm across, in a proportion of about 10:1, constitute 30 to 40 percent of the rock. The remainder is a fine-grained gray matrix composed of feldspar, quartz, biotite, and muscovite with minor allanite, apatite, and magnetite. The porphyry has been weakly metamorphosed so that phenocrysts are strained and microfaulted, and absence of zoning in the plagioclases suggests metamorphic homogenization. Small aggregates of alined shreddy biotite flakes in the matrix have a metamorphic texture as does associated sericite.

The porphyry intrudes only Precambrian gneiss and the Ordovician rocks. Their absence in all younger rocks suggests that they are Lower Paleozoic in age.

Intrusive gneiss

Gneissoid granitic rock southeast of San Luis was first noted by Radelli (1967, p. 249-250). Regional mapping has shown that this rock forms three enormous broadly concordant sheets that lie mostly west of the Palestina fault (pl. 1, sheet 2). Much smaller bodies occur near Caracolí (pl. 1, c-8, sheet 1) and east of Amalfi (pl. 1, a-3, sheet 1).

The westernmost sheet of intrusive gneiss (pl. 1, a-13, a-14, a-15, sheet 2) has several tongues, which cut amphibolite, sericite schist, and quartzite. The gneiss in turn is cut by hornblende gabbro at San Francisco and quartz diorite of the Antioquian batholith. To the south, the gneiss has been truncated by the Sonsón batholith.

The central sheet, generally less than 3 km wide, is nearly 30 km long and extends from the stock at Aquitania in the south (pl. 1, b-15, sheet 2), to a point 6 km east-northeast of San Luis (pl. 1, b-12, sheet 2). The north end of the sheet is bifurcated by a wedge of black sericite schist and phyllite. Elsewhere the sheet cuts feldspathic and aluminous gneiss and quartzite, and is itself cut by quartz diorite of the Antioquian batholith east of San Luis, and quartz monzonite of the stock at Aquitania. The sheet is bounded on the west by the Aquitania fault which has put the gneiss in contact with Cretaceous shale.

The eastern sheet is the longest, extending from the Balsadero fault in the north (pl. 1, c-11, sheet 2), to beyond the south border of the sheet (pl. 2), a distance of more than 60 km. Over much of its length the sheet is less than a kilometer wide; through about half this length the east side is the Cocorná Sur fault. The gneiss cuts sericite schist, quartzite, feldspathic and aluminous gneiss, and amphibolite. Some inclusions of gneiss and amphibolite are of mappable size (pl. 1, sheet 2).

The intrusive gneiss ranges from fine to coarse grained, and from nearly massive to schistose. Essential minerals are plagioclase (generally oligoclase), quartz, microcline, biotite, and muscovite. Much of the plagioclase forms conspicuous subhedral to anhedral round megacrysts from 5 to 20 mm across that give the gneiss a conspicuous porphyroblastic texture (fig. 9). Quartz exceeds 30 percent, and microcline ranges from 2 to 30 percent; the rock ranges from quartz diorite to quartz monzonite, with the former the most common. Dark reddish brown biotite, more abundant than muscovite, ranges from 5 to 25 percent. Accessory minerals are chiefly apatite, magnetite, tourmaline, and zircon. Apatite forms large subhedral crystals and commonly exceeds one percent of the rock. Tourmaline is in zoned yellow-brown subhedral crystals with greenish cores. Zircons, where included in biotite, are surrounded by distinct halos.

The intrusive gneiss possibly has been subjected to protoclastic deformation and features such as undulatory extinction of quartz grains and bent mica flakes are ubiquitous. In the most severely deformed rock, plagioclase crystals are bent and microfaulted, and mortar texture is well developed around grains of quartz and microcline. Gneiss in the western sheet is most intensely sheared, and much of it is fine-grained and schistose with silky foliation planes that are bowed apart by lenses of coarser-grained, less sheared rock, giving the gneiss an augen texture.

The intrusive gneiss has a metamorphic texture in thin section and only rare outcrops have an ingeous look. Nevertheless, evidence for an intrusive origin of most of the gneiss is strong. Although regionally

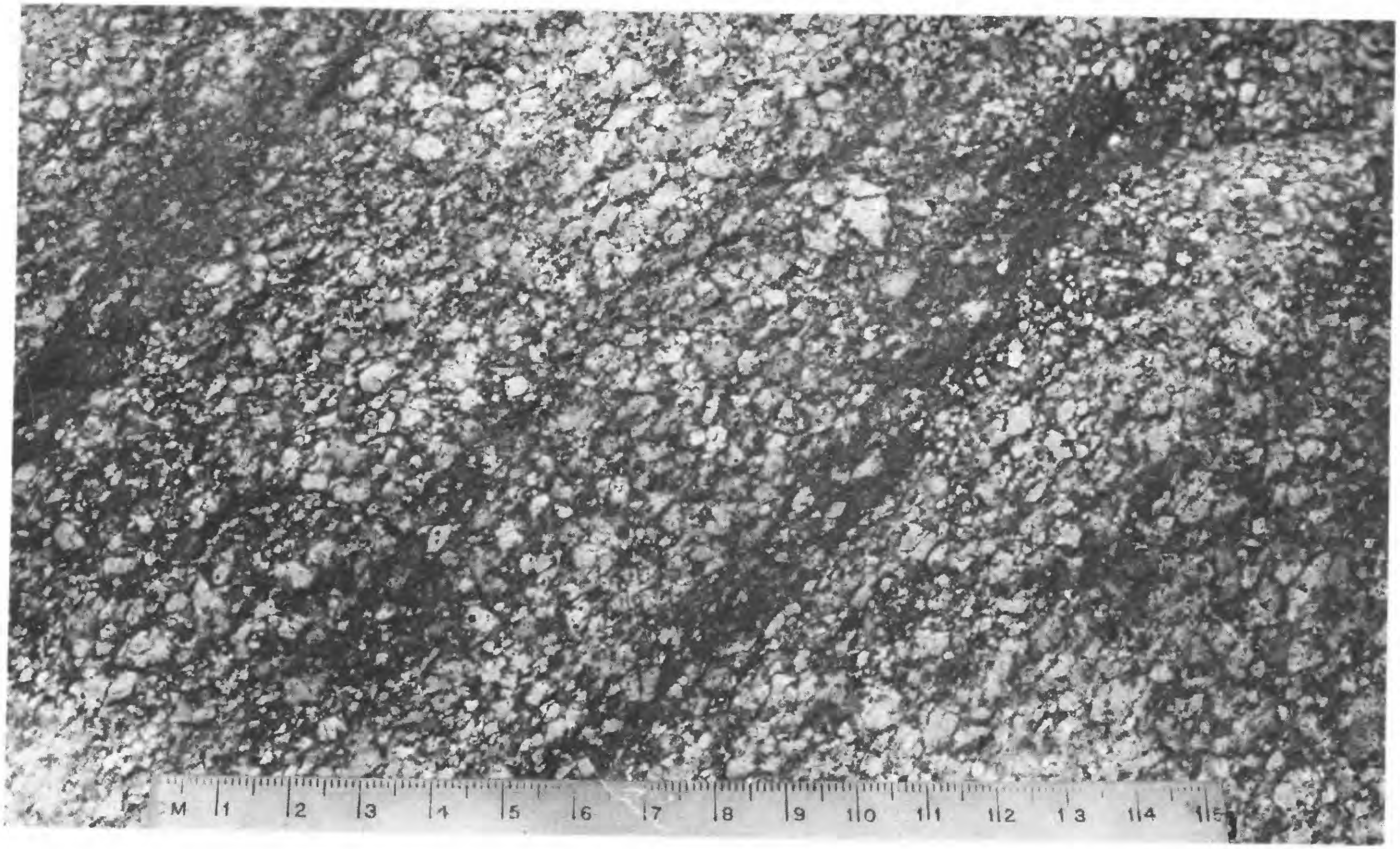


Figure 9.--Intrusive gneiss with typical "porphyroblastic" texture. Scale in centimeters. Quebrada El Pital, elevation 740 m, 10.7 km S. 69° E. of San Luis (pl. 1, b-13, sheet 2).

concordant, all three sheets gently transgress the stratification of the metamorphic rocks. At many outcrops, especially near contacts, the intrusive gneiss is crowded with inclusions which in many places constitute as much as 50 percent of the rock. In small bodies, such as those near Caracolí, the inclusions are concordant (fig. 10A). Elsewhere they are partly or wholly discordant (fig . 10B, C). Particularly good examples may be seen in the west sheet in Quebrada Palmosanto, 2.8 km S. 25° E. of San Francisco (pl. 1, a-14, sheet 2), and in the east sheet in Quebrada Rabihorcadal, 1.2 km S. 45° W. of La Inspección Samaná (pl. 1, c-12, sheet 2). Host rocks are commonly migmatitic near contacts, with intrusive gneiss in zones from less than 1 to 50 m wide. Only south of San Francisco (pl. 1, a-14, a-15, sheet 2) does the intrusive gneiss include extensive areas of fine-grained, gray, plagioclase-quartz-biotite gneiss of possibly metasedimentary origin.

The age of the intrusive gneiss is not precisely known. It is younger than the metamorphic rocks of the Central Cordillera, and older than the Antioquian batholith. It is presumed to be older than the Albian-Aptian Cretaceous rocks, inasmuch as it is not known to cut them at any place.

Ultramafic rocks

Talc and talc-tremolite rock

About a dozen thin concordant lenses of a light gray-green strongly foliated soft talc and talc-tremolite rock occur chiefly in feldspathic and aluminous gneiss (pl. 1, sheet 1, and the northern part of sheet 2).

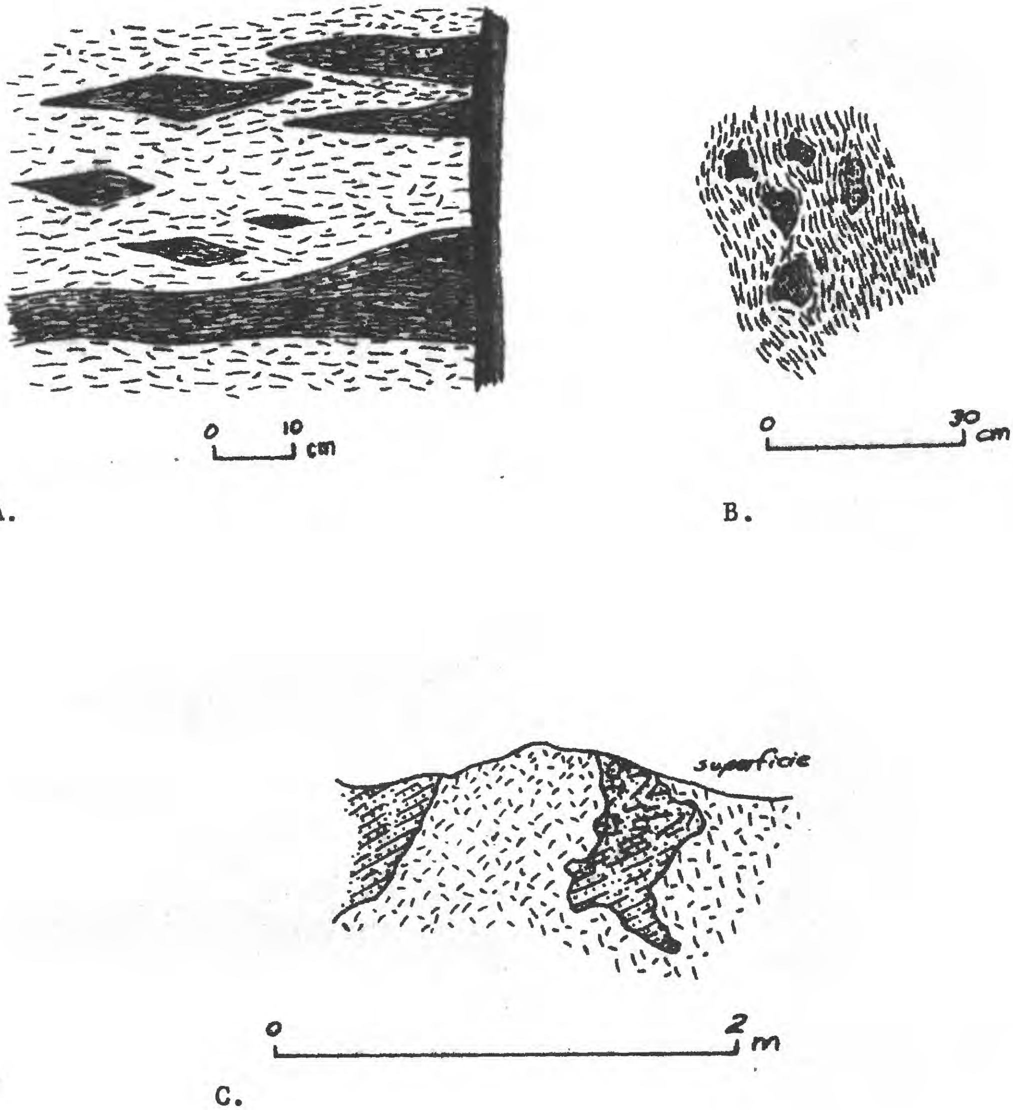


Figure 10.--Inclusions in intrusive gneiss. A. Concordant inclusions of schist. Andesite dike on right. Quebrada La Bonita, 5 km N. 5° W. of Caracolí (pl. 1, c-8, sheet 1); B. Partly concordant inclusions of biotite quartzite. Quebrada La Cruz, elev. 725 m, 15.6 km east of San Luis (pl. 1, c-13, sheet 2); C. Discordant inclusions of quartzose gneiss. Trail Aquitania-La Florida, 3.4 km N. 61° E. of Aquitania (pl. 1, b-15, sheet 2). Same location as F.

One lens was found in Precambrian feldspar-quartz gneiss between the Palestina and Otú faults south of the Río Cupiná (pl. 1, e-6, sheet 1). The ultramafic rocks do not form good outcrops, but are relatively resistant to chemical decomposition and leave conspicuous boulders that weather white. One outcrop showing the concordant relationship with the enclosing gneiss is found in the Río Monos 4.5 km northeast of Caracolí (pl. 1, d-8, sheet 1). Most of the lenses are one or two meters thick, although one, poorly exposed in a cut on the railroad between Monos and Pavas (pl. 1, d-9, sheet 2), may be as much as 8 meters thick.

The lenses consist of varying proportions of talc, tremolite, and chlorite. The talc is flaky and has an oriented and patterned texture suggesting that it has replaced a preexisting silicate. The tremolite occurs as colorless to very pale green subhedral grains with fibrous borders, or as fibrous aggregates. The chlorite is in aggregates of very fine colorless flakes that are length-fast and have gray interference color. Accessory minerals include calcite, magnetite, pyrite, and serpentine.

The talc and talc-tremolite rocks were derived by the alteration of ultramafic igneous rock, as is shown by textural relationships in which talc and tremolite are pseudomorphic after olivine or pyroxene. In one sample from Quebrada San Buenaventura, 3 km N. 24° W. of El Tigre (pl. 1, c-3, sheet 1), the pseudomorphic replacement is incomplete and small cores of olivine ($Fo > 88$) are preserved in talc.

The age of the talc and talc-tremolite rocks is not precisely known. They are here tentatively considered Cretaceous and may be correlative with more extensive bodies of talc to the west in IIA.

Serpentinite

A poorly exposed lens of serpentinite a few meters thick was found in Quebrada San Juanillo, 16.5 km S. 88^{o} E. of Yalí (pl. 1, d-6, sheet 1). The serpentinite is fine-grained, massive, dark green to almost black and greasy lustered. It weathers light brown. An estimated mode of a single thin section is: serpentinite 47 percent, olivine ($Fo>88$) 25 percent, tremolite 20 percent, chlorite and magnetite 4 percent each. Similar serpentinite occurs as boulders in the Río Bagrecito along the El Bagre fault (pl. 1, e-1, e-2, sheet 1). The source of the boulders is unknown, and they are not shown on the geologic map.

Hornblende gabbro at San Francisco

Black hornblende gabbro having a wide range of both texture and composition forms a stock about 3 km^2 in the vininity of San Francisco (pl. 1, a-13, a-14, sheet 2). Two satellitic plugs, each only a few thousand square meters in area, intrude amphibolite. No outcrop of the gabbro was found; the stock and plugs were mapped on the basis of distribution of colluvial boulders. Relations with adjacent rocks, therefore, could not be determined, and the size of the stock may be exaggerated on the geologic map.

The texture of the gabbro ranges from medium-grained allotriomorphic to coarse-grained pegmatitic, and the composition from a rock roughly half plagioclase and half hornblende, to one nearly 100 percent hornblende. The gabbro is generally massive, but some coarse-grained samples are foliated. In thin section, the component hornblende is in colorless to pale green or light brown euhedral to anhedral grains. Tiny prisms poikilitically included in plagioclase are common. The plagioclase is chiefly andesine in weakly twinned anhedral crystals with a distinctly mottled appearance under crossed nicols. Accessory minerals are apatite, pyrite, and magnetite rimmed with granular sphene.

The origin of the gabbro is uncertain. The texture is metamorphic and thin section characteristics of both hornblende and plagioclase are the same as they are in the enclosing amphibolite. In one outcrop at the confluence of Quebrada Palmichal and the Río Santo Domingo 4.9 km N. 48° W. of San Francisco (pl. 1, a-13, sheet 2), fine-grained vaguely laminated amphibolite grades into medium- to coarse-grained massive black gabbro indistinguishable from that in colluvial boulders at San Francisco.

The interpretation here favored is that the gabbro was emplaced as magma and later metamorphically recrystallized. Contact metamorphism by the mafic magma may have caused the recrystallization. If this interpretation is correct, then the gabbro should be younger than the quartzite, amphibolite, and sericite schist. On the other hand, that the gabbro is merely more coarsely recrystallized amphibolite cannot be ruled out. If so, then the gabbro would be contemporaneous with the adjacent metamorphic rocks but older than the intrusive gneiss, which has not been affected by such recrystallization.

Igneous rocks chiefly east of the Otú fault

A suite of medium-grained igneous rocks, principally diorite to quartz diorite, crops out chiefly east of the Otú fault. These rocks are somewhat variable in texture and composition, but they share common petrographic characteristics and are probably genetically related.

Diorite and quartz diorite

Diorite and quartz diorite, collectively shown as diorite on the geologic map (pl. 1, sheets 1 and 2), underlie nearly 600 km^2 of IIB. The bulk of the diorite is east of the Otú fault except the following: a stock 7 km^2 in area 14 km southeast of San Carlos (pl. 1, b-12, sheet 2), a fault-bounded block 2 km^2 in area in Quebrada Alejandría (pl. 1, d-7, sheet 1), a smaller body in the Río Samaná Norte near the Inmarco hydroelectric plant (pl. 1, d-10, sheet 2), and an irregular body about 10 km^2 seven kilometers west of Puerto Nare (pl. 1, d-11, sheet 2). Outcrops are generally poor, and most exposures are of decomposed rock or residual cobbles and boulders. Extensive outcrops of fresh rock, however, are found immediately east of the Otú fault in the large rivers that cross the diorite: the Ité (pl. 1, d-2, sheet 1), La Honda and Pescado (pl. 1, d-3, sheet 1), Volcán (pl. 1, d-4, sheet 1), San Bartolomé (pl. 1, d-5, e-5, sheet 1), and Alicante (pl. 1, e-7, sheet 1).

The diorite ranges from massive to vaguely laminated to strongly gneissic. The laminated rock is characterized by layers from 1 to 20 cm thick with diffuse contacts, and with differing ratios of felsic to mafic minerals. Much of the gneissic rock is cataclastic (some may be protoclastic), and in some places, as the northeast part of the body west of Puerto Nare, is so extensively sheared that its original texture is largely destroyed. This is well displayed in Quebrada Soná (pl. 1, d-11, sheet 2). Typical rock is medium-grained hypidiomorphic equigranular, dark greenish gray, with a salt-and-pepper texture. Pink potassium feldspar locally forms crystals; in some places, particularly in fractured rock in outcrops just east of the Otú fault in the Río La Honda, Quebrada Las Pavas (pl. 1, d-4, sheet 1), and the Río Alicante, these crystals have millimeter-thick rims of cream-colored plagioclase that produce a rapakivi texture. Fine-grained mafic clots and small faults are numerous in many exposures, particularly near the Otú fault. Fine-grained dark green irregular dikes, some with metamorphic textures, occur locally.

At several places the diorite is thoroughly mixed with and grades into amphibolite, hornblende gabbro, and greenstone, especially in outcrops in Quebrada Rocallosa in the south part of the body west of Puerto Nare (pl. 1, d-11, sheet 2). The diorite is intimately mixed with equal proportions of Precambrian feldspar-quartz gneiss roughly along the railroad between the Palestina and Nus faults. Such mixed rock may be seen in outcrops in Quebrada Malena and in the railroad ballast quarry at Monte Cristo, 1 km west of Cabañas Station (pl. 1, d-9, sheet 2). Elsewhere the Precambrian gneiss contains countless small irregular discordant and concordant bodies of diorite from 1 to 100 m across. Such an area of good exposures is between the Otú and Palestina faults in Quebrada Arrebol and the Río Cupina (pl. 1, e-6, sheet 1). These mixed rocks have been mapped either as gneiss or as diorite, in accord with which rock type predominates.

The range of mineral composition of the diorite, based on estimated modes of 30 thin sections is: quartz 2 to 32 percent, plagioclase 45 to 60 percent, orthoclase 0 to 20 percent, hornblende 0 to 22 percent, biotite and chlorite 4 to 16 percent, and accessories 0 to 5 percent.

Quartz is strained and dusted. Plagioclase (mostly An 32-38) forms subhedral or euhedral, bent and microfaulted, weakly zoned to nonzoned grains that range from fresh to completely saussuritized, commonly within a single thin section. Altered plagioclase is dominant and imparts a dull luster to much of the diorite. Orthoclase is interstitial or in anhedral grains, and clouded with fine brown dust; microcline twinning occurs sporadically. Hornblende (X = pale tan; Z = medium green or olive brown) is fresh and euhedral to subhedral, although it has been partly replaced in some rock by fibrous aggregates of pale green amphibole. Intergrowths of hornblende and biotite are common. The biotite (Y = Z = olive brown to dark golden brown) is from 10 to nearly 100 percent altered to green chlorite with strong anomalous blue interference color. It contains fine-grained sphene and anhedral crystals of light yellow epidote. Secondary calcite as tiny veinlets and films is sufficiently abundant that most samples of the diorite effervesce febbly with dilute HCl. Accessory minerals include allanite, abundant apatite, magnetite, pyrite, and zircon surrounded by weak halos in micas or hornblende.

The magmatic origin of the diorite is shown by its cross-cutting relationships with neighboring rocks, and by the texture and composition. The intimate mixing of intrusive diorite and hostrock indicates that the magma was intruded in the katazone or lower mesozone (Buddington, 1959).

The age of the diorite is Jurassic (160 ± 7 m.y.) based on a single K/Ar age determination by R. F. Marvin, H. H. Mehnert, and Violet Merritt, U. S. Geological Survey (Marvin, written commun., 1968), made on hornblende from a sample from the Monte Cristo quarry.

This diorite is hostrock for the auriferous quartz vein system in d-7 (pl. 1, sheet 1) exploited by Frontino Gold Mines Ltd., the largest lode gold mining operation in Colombia.

Amphibole gabbro

Thirteen small stocks of amphibole gabbro occur in the diorite and adjacent rocks east of the Otú fault. Outcrops are sparse and most of the stocks were mapped solely by the presence of residual boulders. The largest stock, 1.5 km^2, is 4 km northwest of Cristalina Station (pl. 1, e-8, sheet 1). The others are each less than one square kilometer in area, and are not shown on the geologic map.

The amphibole gabbro is massive, dark gray-green to black, and medium- to coarse-grained. It is composed chiefly of plagioclase and amphibole. Poikilitic crystals of dark amphibole several centimeters across conspicuously reflect sunlight from crystal faces and cleavage planes. Some samples show a weak cataclastic texture in thin section. The plagioclase is labradorite (andesine in a sample from the stock 11 km east of Remedios (pl. 1, e-2, sheet 1) and ranges from fresh complexly twinned phenocrysts to completely saussuritized grains. Two amphiboles are present, one is colorless to pale green and forms blocky subhedral crystals, some of which have irregularly shaped cores of colorless clinopyroxene. The other amphibole is colorless, fibrous, and forms irregular aggregates. Parts of both amphiboles may have been formed by the deuteric alteration of pyroxene. Neither amphibole is believed to be hornblende.

Accessory minerals include apatite, calcite, chlorite, epidote, pyrite, sphene, and zircon.

The amphibole gabbro is spatially and genetically related to, and may be a facies of the diorite. The two rocks are gradational with one another in outcrops in the Río Nus (pl. 1, d-9, sheet 2). In addition, the deformation and mineral alterations typical of the diorite are well developed in the amphibole gabbro as well.

Andesite

Sparse dikes and irregular intrusive bodies of fine-grained to aphanitic dark gray-green rocks in the diorite have been classified as andesite by hand lens inspection. The three largest bodies are shown on the geologic maps. One is a dike nearly a kilometer long that crops out in Quebrada El Pescado (pl. 1, e-10, sheet 2) 35 km southwest of Puerto Berrío. It is composed of a dull-lustered massive andesite with phenocrysts of gray plagioclase and prismatic green amphibole 0.3 by 5.0 mm. Another body, 0.2 km^2 in area, crops out in Quebrada Berlina (pl. 1, e-7, sheet 1) 11.5 km west northwest of Puerto Berrío. It is composed of intensely fractured and nearly aphanitic andesite containing some tiny phenocrysts of black hornblende. The third body, nearly circular in plan, crops out in Quebrada San Nicolás 5 km northeast of Segovia (pl. 1, d-1, sheet 1). It is composed of aphanitic andesite.

Adamellite

A suite of genetically related stocks of medium- to coarse-grained granitic rocks are here grouped together as adamellite (granodiorite to quartz monzonite), their dominant lithology. These rocks have common petrographic and structural characteristics and are restricted mainly to five stocks or groups of stocks, principally in plate 1, sheet 2.

The age of the adamellite is not precisely known. It is younger than the metamorphic rocks of the Central Cordillera for it intrudes and contains inclusions of them. It is probably also younger than the Jurassic diorite because the mineral alterations characteristic of the diorite are much less developed in the adamellite. The adamellite in turn has been intruded by, and thus predates, the Antioquian batholith (fig. 11A). Also, deformational effects characteristic of much of the adamellite are entirely wanting in adjacent batholith rocks.

Southwest of Amalfi

A discordant stock of adamellite 2 km^2 in area occurs 8 km southwest of Amalfi (pl. 1, a-3, sheet 1). Partly weathered rock is well exposed in road cuts west of the town hydroelectric plant.

The adamellite is a uniform medium-grained light gray hypidiomorphic equigranular massive rock composed of feldspar, quartz, biotite, muscovite, and accessories. Biotite is more abundant than muscovite, but nowhere exceeds 10 percent of the rock.

The stock was emplaced as magma in sericite schist of low metamorphic grade. Slender pink andalusite crystals as much as 12 mm long were developed in schist near the west contact of the stock. The east contact is faulted.

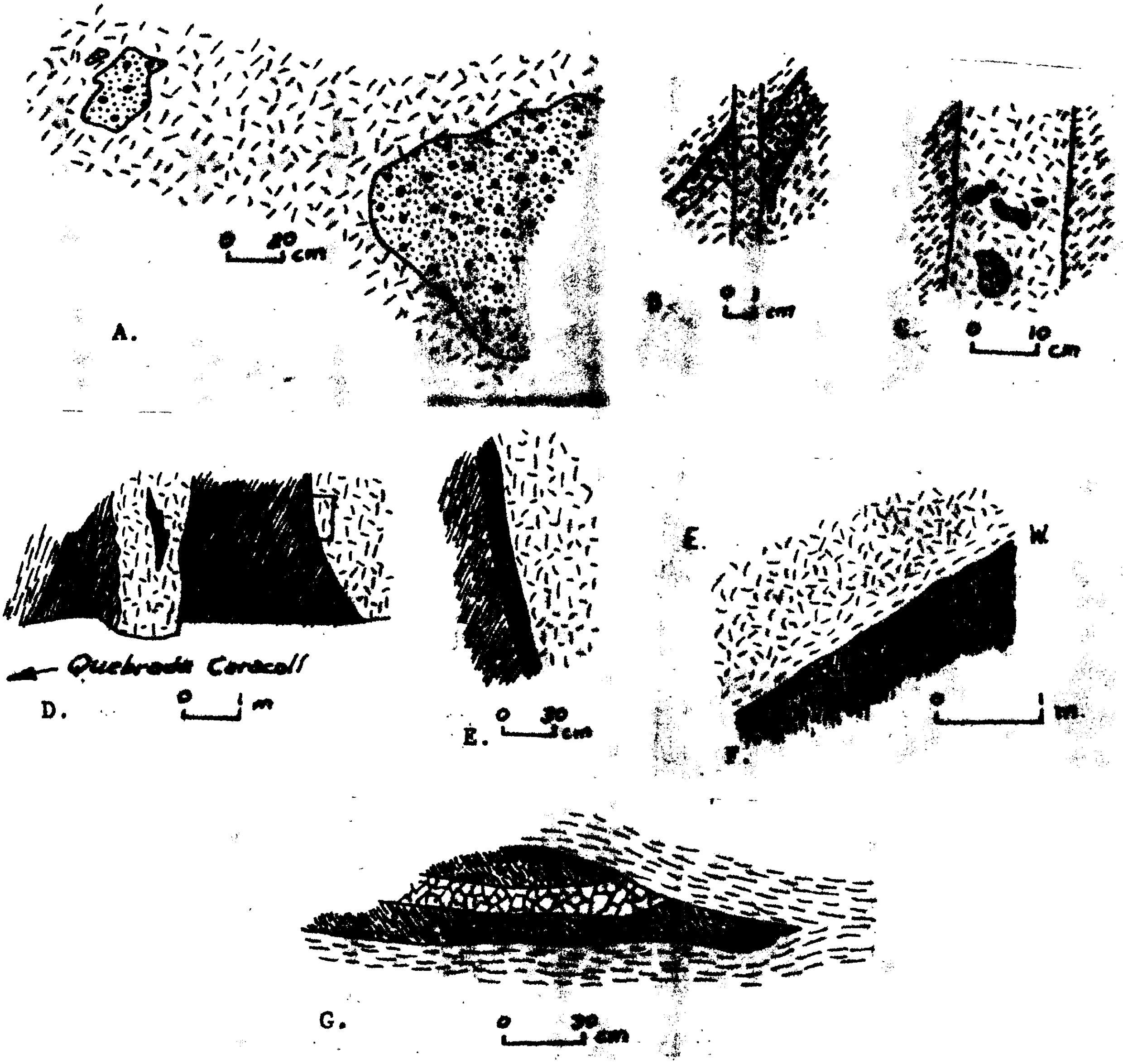


Figure 11.--Structural details of the adamellite. A. Inclusions of extensively recrystallized porphyritic adamellite in quartz diorite of the Antioquian batholith. Residual boulder, Quebrada La Le Lejía, elevation 1360 m (pl. 1, b-4, sheet 1); B-E. Apophyses of the stock southwest of Amalfi in low-grade schist. E is enlargement of rectangle in D. Note highly sheared schist at contact. Quebrada Caracolí, elevation 1360 m (pl. 1, a-3, sheet 1); F. Apophysis of adamellite in feldspathic and aluminous gneiss. Note alinement of biotites in adamellite parallel to contact. Quebrada La María (pl. 1, d-3, sheet 1); G. Inclusion of gneiss in adamellite. Same location as F.

Apophyses of the stock in schist exposed in Quebrada Caracolí emphasize the magmatic origin of the adamellite (fig. 11B through E).

Near Hda. Marta Habana

A group of stocks of adamellite whose combined area is about 10 km^2 is found between Hdas. Marta Habana and Monos (pl. 1, b-3, b-4, b-5, sheet 1). The stocks have been extensively intruded by magma of the Antioquian batholith and initially may have been parts of a single stock of irregular outline.

Outcrops are scarce. Residual boulders, however, are plentiful and afford samples of fresh rock. In the field the outlines of the stocks are further defined by the exceedingly infertile soil derived from them. The soil supports only a stunted vegetation and extensive bare patches are common.

The stocks are composed chiefly of granodiorite (table 7, cols. 1-4), but some samples are quartz monzonite. The rock is light gray to pale pink, medium- to coarse-grained hypidiomorphic to allotriomorphic granular, and massive to foliated. Much of it is porphyritic, and has conspicuous euhedral phenocrysts of orthoclase from 1 by 3 to 2 by 5 cm in size that constitute as much as 5 percent of the rock. The phenocrysts are twinned on the Carlsbad law and are generally poikilitic; inclusions are less than 1 mm in diameter of quartz and biotite. In foliated rock the phenocrysts lie with their long axes in the plane of the foliation. Small pockets of pegmatite with accessory black tourmaline are locally plentiful in the adamellite, particularly in the stock northwest of Hda. Marta Habana.

In thin section the adamellite has a granoblastic texture intermediate between igneous and metamorphic. All grains are subhedral to anhedral, and sutured contacts between felsic minerals are common.

Table 7.--Modal analyses of adamellite (in percent).

	Stocks at Hda. Marta Habana				Stocks south of Sta. Isabel			Stock east of Yali	Stock west of Caracoli
Field number	1. NC-371C	2. AA-1642	3. NC-340	4. AA-1364	5. OR-1015	6. OR-1568	7. OR-1542	8. OR-142	9. TF-40
Inventario number	7742	7686	7741	7670	7768	7800	7799	7551	7509
Quartz	32.7	31.1	28.4	26.6	30.3	29.7	27.1	34.8	32.6
Orthoclase	25.3	21.8	25.7	30.8	17.5	7.6	33.5	21.3	27.9
Plagioclase	34.9	31.4	42.4	33.4	46.1	55.9	35.1	34.6	35.7
Biotite	6.2	12.6	2.8	6.3	5.1	6.0	1.6	5.8	0.4
Chlorite	0.1	0.2	0.6	0.3	0.8	----	2.3	2.5	0.2
Muscovite	0.7	2.5	----	2.6	----	0.7	----	1.0	2.7
Apatite	0.1	Tr.	Tr.	Tr.	0.1	0.1	----	Tr.	----
Epidote	----	----	----	----	Tr.	----	Tr	Tr	----
Garnet	----	----	----	Tr.	----	----	----	----	0.5
Opaque	Tr.	0.4	Tr.	Tr.	----	Tr.	----	Tr.	----
Pinite	----	----	----	Tr.	Tr.	----	----	----	----
Sphene	----	----	----	----	Tr.	----	0.3	----	----
Zircon	Tr.	Tr.	Tr.	Tr.	0.1	Tr.	0.1	Tr.	----
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
An cont. of plag.	30	33	oligoclase	oligoclase	26	oligoclase	oligoclase	28	16

1. Granodiorite, residual boulder, Que. La Lejía, elev. 1375 m (pl. 1, b-4, sheet 1) 2. Granodiorite. 1.7 km north of Hda. La Lindona (pl. 1, b-3, sheet 1); 3. Granodiorite, residual boulder, Hda. Corralitos (pl. 1, b-4, sheet 1); 4. Granodiorite, residual boulder, Hda. Monos (pl. 1, b-3, sheet 1); 5. Quartz diorite, residual boulder, Hda. La Teresa (pl. 1, d-4, sheet 1); 6. Quartz diorite, Quebrada La Honda, elev. 875 m (pl. 1, c-3, sheet 1); 7. Granodiorite. Quebrada Buga, elev. 690 m (pl. 1, d-3, sheet 1); 8. Granodiorite. Hda. Manzanares (pl. 1, c-5, sheet 1); 9. Granodiorite alaskite. Río Nus, 1.5 km west of intake for hydroelectric plant (pl. 1, c-8, sheet 1).

Modal analyses in volume percent based on from 600 to 1,600 point counts spread over standard thin sections by T. Feininger (1-7, 9) and C. J. Vesga (8). Tr., trace.

Some quartz is fractured and contains dust-like inclusions in some samples, but without undulatory extinction. Orthoclase is fresh, faintly perthitic, and, excluding euhedral poikilitic phenocrysts, it is anhedral. Carlsbad twinning is common. Plagioclase is oligoclase or sodic andesine, either fresh or clouded with tiny inclusions of white mica. Grains have weak or blurred polysynthetic twinning and are not zoned, although many are rimmed with albite. Myrmekite at contacts with orthoclase is common. Biotite is in shreddy flakes and commonly is partly chloritized. Pleochroism is X = light tan, and Y = Z = dark and brown. Included zircons are surrounded by intense halos. Muscovite is in primary sieve-like anhedral crystals, or as aggregates of sericite derived by the alteration of feldspar or cordierite(?).

The magmatic origin of the adamellite at Hda. Marta Habana is evident from the crosscutting nature of the stocks. Furthermore, small inclusions of wollastonite quartzite and other metamorphic rocks having sharp contacts against the adamellite are found in residual boulders 0.9 km N. 25° E. of Hda. Marta Habana (pl. 1, b-5, sheet 1).

South of Sta. Isabel

The largest stock of adamellite, covering about 96 km^2, is south of Sta. Isabel (pl. 1, c-3, d-3, d-4, sheet 1) in feldspathic and aluminous gneiss. It has been intruded by quartz diorite of the Antioquian batholith at La Llana (pl. 1, d-4, sheet 1), and is bounded on the southeast by the Otú fault.

The only extensive outcrops are in the north part of the stock in the Río La Honda and its tributaries, and in Quebrada La María. Exposures elsewhere are largely restricted to residual boulders. The adamellite, like that at Marta Habana, has produced a conspicuously infertile soil.

The adamellite is medium-grained, light gray, allotriomorphic to hypidiomorphic granular and weakly foliated. Anhedral to subhedral poikilitic phenocrysts of white feldspar as much as 1.5 cm in diameter locally constitute 2 to 5 percent of the rock. Oligoclase, quartz, orthoclase, and biotite are the essential minerals, and have characteristics similar to those in the stocks previously described. Cataclastic and deformational effects, however, are widespread. Quartz has strong undulatory extinction and grains in some samples are surrounded by shells of finely triturated derbis in a typical mortar structure. Biotite is bent, and oligoclase is bent and microfaulted. Modal analyses of three samples are given in table 7, cols. 5-7. Vugs lined with crystals of white quartz and pyrite occur in fissures in the north-most part of the stock.

The igneous origin of the adamellite at Sta. Isabel is demonstrated where the adamellite and metamorphic rocks are mixed, and as shown on the geologic map (pl. 1, sheet 2), consists of intrusive breccia with subequal proportions of nonoriented, discordant inclusions of gneiss set in a matrix of massive or nearly massive adamellite. This relationship is depicted in figure 11 (F and G).

East of Yalí

An elongated stock 14 by 1.5 km and oriented north-south follows the contact between quartzite and feldspathic and aluminous gneiss 6 km east of Yalí (pl. 1, c-5, c-6, sheet 1). The stock is poorly exposed. The only extensive outcrops are in the Río San Bartolomé near the center of the stock, and in small quebradas at the south end of the stock.

The dominant rock is a medium-grained light gray, allotriomorphic to hypidiomorphic equigranular biotite adamellite. The rock is massive to weakly foliated but near contacts is strongly foliated. Associated pegmatite, seen only in boulders in the Río San Bartolomé, is composed chiefly of albite and black tourmaline in euhedral crystals as much as 3.5 cm in diameter and 15 cm long.

The composition and petrographic characteristics of the adamellite are much like those of the stocks previously described, although deformational and cataclastic effects are slight. A modal analysis of a representative sample is given in table 7, col. 8. Residual boulders of hornblende gabbro occur near the north end of the stock in Quebrada Guarquiná (pl. 1, c-5, sheet 1). The relation between the gabbro and adamellite is unknown.

The adamellite, which has formed spectacular intrusive breccias with its host rocks, particularly with quartzite, is well exposed in the Río San Bartolomé. Some of the inclusions are of mappable size.

West of Caracolí

The best exposed and most variable of the adamellite stocks lies west of Caracolí (pl. 1, c-8, sheet 1; c-9, sheet 2). This stock is roughly 5 by 3 km and has a very irregular outline. Small satellitic plugs and dikes are common. Excellent outcrops are found in the Ríos Nus and El Socorro, Quebrada Sta. Isabel, and several small quebradas that drain into the Nus.

The composition of the stock grades from alaskite with accessory garnet (northeast of the Río Nus and in the Río El Socorro), through granodiorite, to biotite diorite (south end of the stock, and in Quebrada Sta. Isabel to the northwest). Hornblende gabbro is found as residual boulders within the area of the stock, but its relation to the other lithologies is unknown.

The various types of rock in the stock are extensively mixed with the host gneiss. Spectacular intrusive breccias are common (fig. 12A, B, C) and some inclusions are of a mappable size. Apophyses from the stock in host gneiss (fig. 12D, E, F) are so abundant that in places the contact of the stock is mapped arbitrarily. The bulk of the stock is composed of medium- to locally fine-grained light gray massive biotite granodiorite or biotite diorite. These rocks are progressively richer in mafic constituents toward the south end of the stock.

Alaskite, which constitutes about one third of the stock and is the most distinctive rock type, is light gray to beige, massive, medium- to coarse-grained, hypidiomorphic equigranular. A modal analysis of a typical sample is given in table 7, col. 9. Two small areas of medium-grained massive beige alaskite very similar to that northeast of the

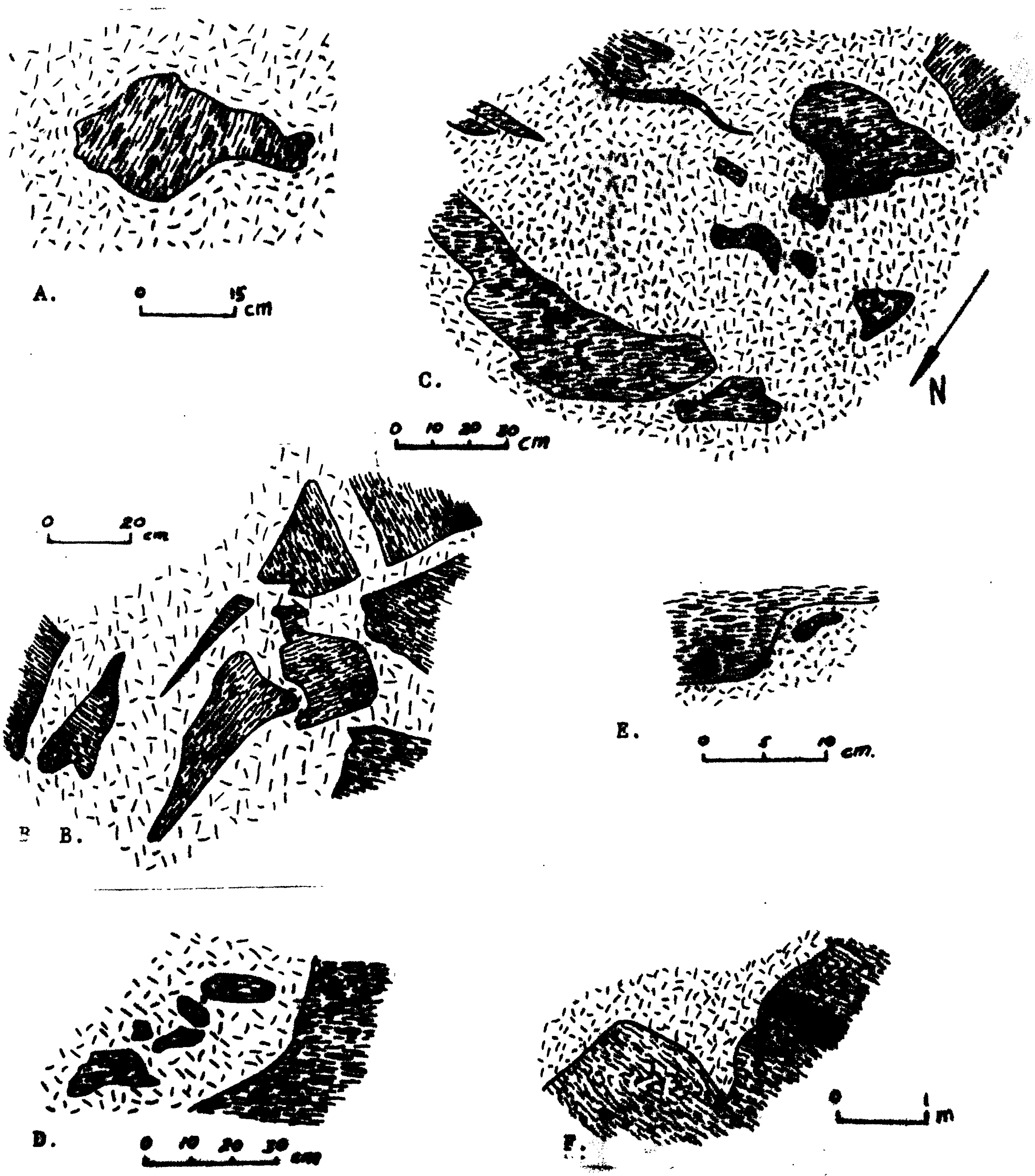


Figure 12.--Structural details of the adamellite of Caracolí. A. Inclusion of feldspathic and aluminous gneiss; Río Nus, 3.5 km upstream from Caracolí. B. Intrusive breccia, inclusions of gneiss. Intake for town water supply, 1.3 km west of Caracolí. C. Intrusive breccia, inclusions of gneiss Río Nus, 6 km upstream from Caracolí. D. and E. Apophyses with inclusions of gneiss. Río Nus, 3.5 km upstream from Caracolí and tributary quebrada to Río Nus, 1 km northwest of the intake for the hydroelectric plant respectively. F. Apophysis in pegmatitic feldspathic gneiss. Río Nus, 1.5 km southwest of Gloria Station. All from plate 1, c-8, sheet 1.

Río Nus occur adjacent to the Río Nare about 8 km south of the stock west of Caracolí (pl. 1, c-9, c-10, sheet 2). The alaskite, which is cut by the Antioquian batholith and two faults, is a remnant of a single stock that probably once covered more than 10 km^2.

Emplacement of the stock west of Caracolí may have followed an active period of dike intrusion. Fine-grained garnet-dacite (estimated mode: andesine 70 percent, quartz 16 percent, biotite and chlorite 11 percent, garnet 2 percent, accessories 1 percent) associated only with this stock, occurs as inclusions and dikes within larger inclusions of gneiss in medium-grained biotite quartz diorite of nearly identical composition (estimated mode: andesine 70 percent, quartz 16 percent, biotite and chlorite 10 percent, orthoclase 2 percent, accessories 2 percent) in Quebrada Sta. Isabel (pl. 1, c-8, sheet 1).

The Antioquian batholith

Description

The Antioquian batholith was recognized and named by Professor Gerardo Botero A. (1941, 1942) who in addition recently has described in some detail a large portion of the batholith in IIA (Botero A., 1963, p. 69-82; Inventario Minero Nacional, 1965).

About 3,324 km^2 of IIB, chiefly the west-central part of the subzone, are underlain by the Antioquian batholith. Three facies were recognized: normal quartz diorite (3,118 km^2), felsic quartz diorite (195 km^2), and gabbro (12 km^2). Quartz diorite petrographically indistinguishable from and probably genetically related to the normal quartz diorite facies of the batholith forms several satellite bodies.

The largest of these is in the valley of the Río Mata and adjacent areas eastward to the Otú fault in plate 1, sheet 1. Others are southeast of El Tigre (pl. 1, d-4, sheet 1), at Caracolí (pl. 1, c-8, sheet 1), and several small plugs in Cretaceous sedimentary rocks south of San Luis.

Outcrops of the batholith, particularly in the gabbro facies, are sparse because of deep weathering. A few enormous exposures of quartz diorite as much as 1,000 m^2, however, crop out in streams with steep gradients tributary to the Río Nus, Guatapé, and San Carlos. Also, residual surface boulders from 1 to 40 m in diameter are plentiful over much of the batholith and supply information about the rock where outcrops are not to be found.

Quartz diorite.--About 94 percent of the main body of the Antioquian batholith in IIB is gray, medium-grained, hypidiomorphic equigranular massive quartz diorite having pronounced salt-and-pepper texture. It is composed of andesine, quartz, orthoclase, biotite, hornblende, and accessories. Superficially this rock greatly resembles much of the quartz-bearing diorite east of the Otú fault. In thin section, however, the deformation and alteration of minerals characteristic of the rock east of the Otú fault are generally wanting in quartz diorite of the batholith.

Modal data on 20 randomly selected samples are given in table 8. The small standard deviation of the average content of each mineral (col. 3) sharply underscores the exceptional uniformity of the quartz diorite. Chemical and modal analyses of two additional samples from near Cristales (pl. 1, b-8, sheet 1) are given in table 9.

Table 8.--Modal data on 20 randomly selected samples of the normal quartz diorite facies of the Antioquian batholith.[1]

	Average (percent)	Range	Standard deviation
Quartz	24.9	15.7 - 31.3	3.6
Orthoclase	8.5	1.2 - 19.8	4.9
Plagioclase	47.9	38.6 - 58.1	5.9
Biotite	9.5[2]	3.2 - 19.8[2]	4.5[2]
Hornblende	7.4[2]	1.1 - 10.8[2]	2.7[2]
Clinopyroxene	0.1	0.0 - 0.7	0.2
Chlorite	1.0[2]	0.0 - 3.0[2]	1.1[2]
Nonopaque accessories	0.4	Tr. - 1.2	0.4
Opaque accessories	0.5	0.0 - 1.5	0.4
Total	100.2		
An content of plagioclase	44	38 - 55	3.8

1/ Volume percent based on modal analyses of from 600 to 2000 point counts spread over standard thin sections. Analyses by T. Feininger.

2/ Excludes one sample in which biotite and hornblende are totally chloritized.

Table 9.--Chemical and modal analyses of two samples of quartz diorite of the Antioquian batholith from near Cristales (pl. 1, b-8, sheet) (percent).

	1.	2.
Inventario number	8526	8527
Field number	MH-701	TF-1053
USGS laboratory number	W168-911	W168-912
SiO_2	63.6	62.5
Al_2O_3	16.2	15.2
Fe_2O_3	1.9	1.7
FeO	3.0	4.0
MgO	2.6	4.2
CaO	6.2	6.6
Na_2O	3.2	2.8
K_2O	2.0	1.3
H_2O -	0.20	0.22
H_2O +	0.38	0.34
TiO_2	0.41	0.58
P_2O_5	0.12	0.27
MnO	0.15	0.38
CO_2	0.06	0.05
Total	100.02	100.09
Quartz	27.3	21.8
Orthoclase	10.9	4.9
Plagioclase	43.1	52.6
Biotite	10.1	10.0
Hornblende	4.6	10.3
Clinopyroxene	Tr.	----
Chlorite	0.9	0.1
Nonopaque accessories	3.0	0.3
Opaque accessories	0.1	Tr.
Total	100.0	100.0
An content of plagioclase	39	47
Bulk density (g/cm^3)	2.75	2.79

Chemical analyses by rapid rock analysis methods, U.S. Geological Survey, Washington, D.C.

Modal analyses in volume percent based on 1000 or more point counts spread over standard thin sections. Analyses by T. Feininger.

8526, Río El Socorro, elevation 1,050 m, 1.1 km south-southwest of Cristales; 8527, 1 km northeast of Cristales.

Plagioclase is andesine (rarely labrodorite) and is in subhedral to euhedral well-twinned generally fresh crystals. Normal and oscillatory zoning are common, as are small inclusions of hornblende and clinopyroxene. Quartz and orthoclase occur as interstitial or anhedral grains. Quartz is nonstrained and poor in inclusions. Orthoclase is nontwinned, fresh, and rarely perthitic.

Biotite is undeformed and subhedral or euhedral. Pleochroism is strong with X = light yellow; Y = Z = deep golden brown. Commonly about ten percent of the biotite has been converted to bright green chlorite. In addition, some flakes contain lenses of a colorless to pale yellow alteration product with moderately high relief and low birefringence that has bowed apart cleavage planes of the biotite. It greatly resembles an alteration product of biotite in rocks near Boulder, Colorado, U.S.A., described by Wrucke (1965) which he found to be a mixture of prehnite and hydrogarnet(?).

Hornblende forms euhedral fresh grains with X = light yellow tan; Y = medium green, and Z = medium brownish green (X<Y<Z). Moderate to strong dispersion with r>v is common. The hornblende is probably calcic. This is suggested by its rather pale color and by its partial replacement by calcite where altered, whereas adjacent biotite is replaced exclusively by chlorite. Some grains have ragged small cores of colorless clinopyroxene. More common are bleached cores with inclusions of vermicular quartz. These cores probably were produced by the conversion of clinopyroxene to amphibole, a reaction that liberates free silica. Such a reaction has been described for tonalite in the Cornucopia stock, Oregon,

U. S. A., by Taubeneck (1967). His drawings of such hornblendes (1967, pl. 1) are identical to those from the Antioquian batholith.

Ubiquitous accessory minerals of the quartz diorite are apatite, magnetite, and zircon. Other accessories, in order of decreasing abundance, are sphene, epidote, pyrite, calcite, and prehnite. Apatite is particularly abundant and constitutes more than 0.5 percent of some samples. Relatively large grains (0.5 mm or larger) are anhedral to subhedral, whereas small grains (0.1 mm or less) are euhedral prisms. Zircon forms large (0.2 mm average) subhedral to euhedral clear crystals. The absence of pleochroic halos in adjacent mafic minerals suggests that the zircon is abnormally poor in uranium and thorium.

The quartz diorite is massive and retains its normal grain size at contacts, most of which are sharp. Only where in contact with amphibolite does a zone of mixing occur. This zone, as much as 100 m wide, consists of extensively recrystallized amphibolite, and of lenses and irregular masses of quartz diorite and diorite that give the mixture a migmatitic or agmatitic structure. Excellent examples are in the Río Nus 2 km upstream from Caracolí (pl. 1, c-8, sheet 1), and in Quebrada San Lucas, 1.4 km northwest of Maceo (pl. 1, c-7, sheet 1).

Inclusions are rare even near contacts. Mafic clots locally known as gabarros, however, are found over much of the batholith and do not seem to be related to contacts. The gabarros are fine-grained, dark gray, subspherical or spindle-shaped massive bodies from 5 to 50 cm in diameter (fig. 13). They are composed of the same minerals, possibly less quartz, as the enclosing quartz diorite, but are proportionately richer in the

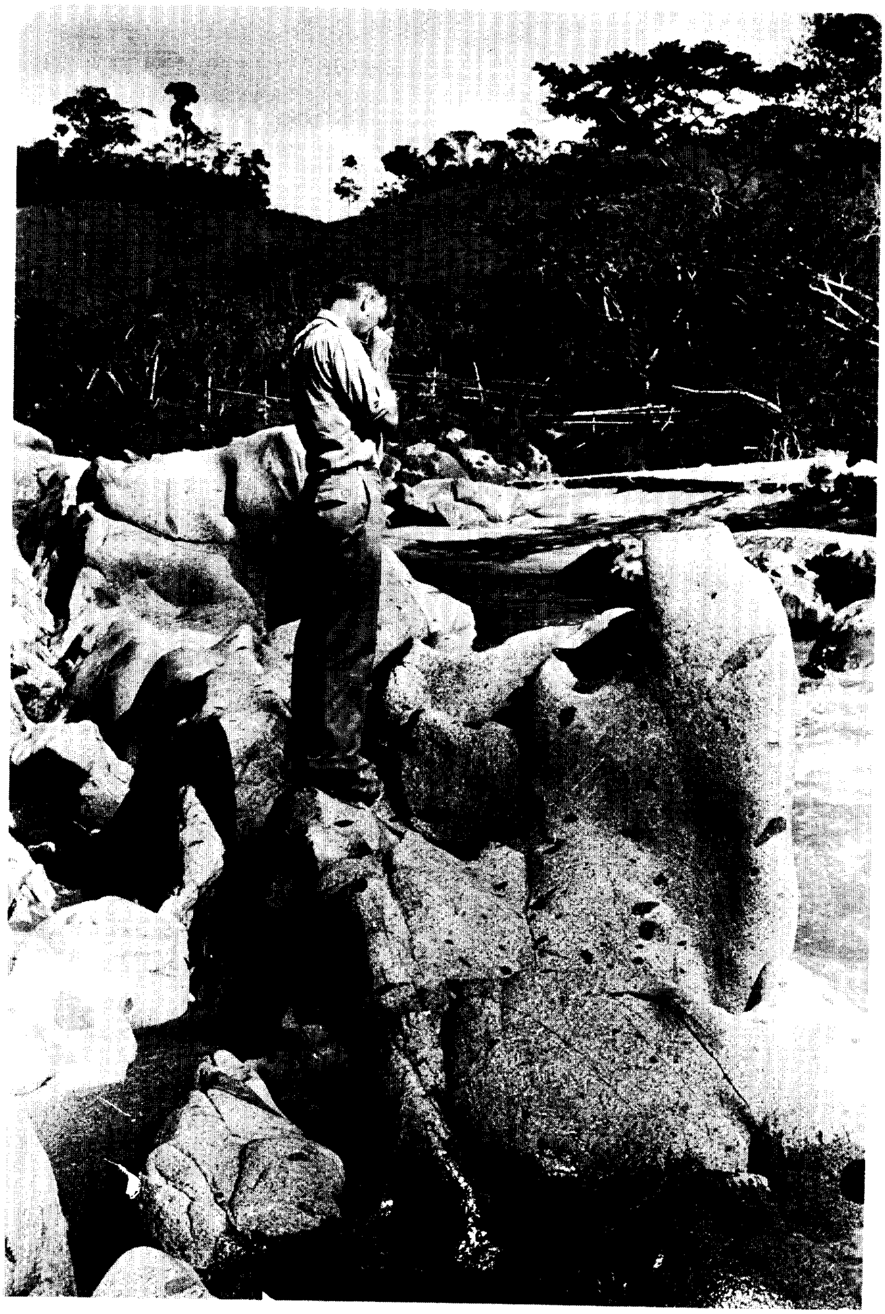


Figure 13.--Gabarros in quartz diorite of the Antioquian batholith. Río Guatapé 1.5 km downstream from Quebrada El Macho (pl. 1, c-11, sheet 2).

mafics. Some gabarros carry subhedral megacrysts of white plagioclase as much as 5 mm across. Modal analysis of a gabarro from b-3 (pl. 1, sheet 1) showed it to be composed of plagioclase (An_{39}) 38 percent, orthoclase 25 percent, biotite 24 percent, hornblende 13 percent, and accessories 1 percent.

Dikes of the quartz diorite in adjacent host rocks occur sporadically and are nowhere abundant. Those in noncalcareous rocks are a little finer grained but otherwise are identical to the normal quartz diorite. Dikes in calcareous rocks, on the other hand, have unusual compositions, probably due to desilication reactions between the quartz diorite magma and calcite. Modal analyses of samples from four of these dikes in calcareous rocks are given in table 10.

Several northwest-striking shear zones have been mapped in the batholith, chiefly in the quartz diorite in the southern part of plate 1, sheet 1. The largest, the Cristales shear zone, is 23 km long. Some of the sheared quartz diorite resembles biotite schist. Good exposures are found in cuts on the road to Cristales (pl. 1, b-8, sheet 1).

The quartz diorite is cut by dikes with sharp contacts, which range in composition from alaskite and felsite to andesite. The dikes are too small to show on the geologic map. They are few in some areas, whereas, in others (for example at Yolombó (pl. 1, b-6, sheet 1), they make up as much as 10 percent of the batholith. Most common are dark gray or gray-green, very fine grained to aphanitic, porphyritic dacite or andesite dikes from 5 cm to 1 m thick. Euhedral phenocrysts of black hornblende or white plagioclase are from 1 to 5 mm across. Near

Table 10.--Modal analyses of four samples from dikes of the Antioquian batholith in calcareous rock[1] (in percent).

Field number Inventario number	FEO-131 7628	AA-419 7687	AA-438 7735	NC-523 7747
Quartz	0.1	10.2	9.9	3.2
Plagioclase	72.0	41.0	Tr.	56.9
Orthoclase	---	20.4	11.9	1.2
Orthopyroxene	17.2	----	----	----
Clinopyroxene	----	25.0	65.2	35.0
Amphibole [2]	7.8	----	----	----
Biotite	0.8	----	----	----
Apatite	----	----	0.4	Tr.
Calcite	----	0.8	----	0.2
Chlorite	0.3	----	----	0.2
Clinozoisite	----	0.5	9.0	0.3
Opaque	1.8	----	0.2	Tr.
Scapolite	----	0.5	----	----
Sphene	----	1.6	3.4	3.0
Total	100.0	100.0	100.0	100.0
An content of plagioclase	64	38	----	46

1/ Modal analyses in volume percent based on from 750 to 1000 point counts spread over standard thin sections.

2/ Colorless to pale green uralite rims on orthopyroxene.

Tr., trace.

7628, dike in wollastonite marble. Quebrada La Calera 3.9 km west-southwest of Maceo (pl. 1, c-7, sheet 1); 7687 and 7735, dikes in wollastonite marble. El Torito (pl. 1, b-3, sheet 1); 7747, residual surface boulder at Hda. Suribio (pl. 1, c-4, sheet 1), calcareous quartzite nearby.

contacts the phenocrysts are alined parallel to the dike walls and the matrix is aphanitic. Many of the intermediate dikes are multiple. Successive intrusions have chilled borders against earlier ones.

Felsic quartz diorite.--A half dozen bodies of felsic quartz diorite have been mapped within the batholith. Good exposures are found as residual boulders on Cerro Tetoná west of Yalí (pl. 1, b-5, sheet 1), on Cerro Cancharazo (pl. 1, a-5, sheet 1), in place along the road from Sto. Domingo to the Río Nare (pl. 1, a-8, sheet 1), and in Quebrada La Doncella east of Maceo (pl. 1, d-7, sheet 1). The felsic and normal quartz diorites grade into one another.

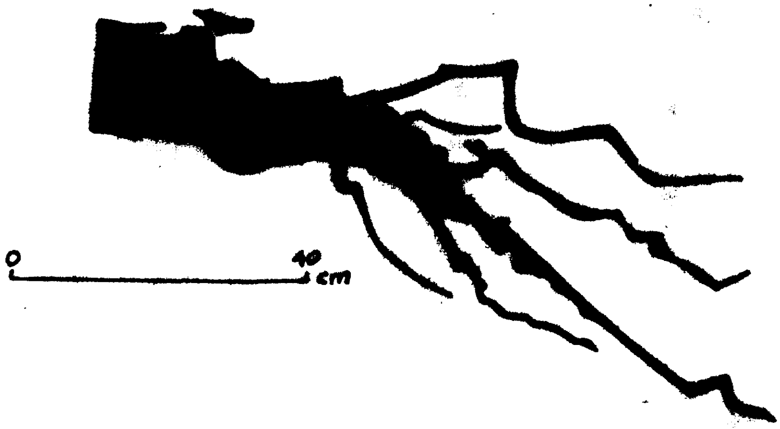
The felsic quartz diorite differs from the normal quartz diorite in texture as well as composition. It is light tan medium- to coarse-grained massive hypidiomorphic granular rock. Much of it is characterized by subhedral phenocrysts of quartz as much as 1 cm long. On the surfaces of residual boulders the quartz has weathered into relief to give the rock a pimply surface. Elsewhere the quartz has weathered free and is concentrated in the soil. This is especially well seen along the road under construction in 1968 between Maceo and La Susana (pl. 1, d-7, sheet 1).

A mode, the average of four randomly selected samples of the felsic quartz diorite, is: quartz 32.5 percent, potassium feldspar 22.7 percent, plagioclase 37.9 percent, biotite 4.3 percent, muscovite 1.9 percent, chlorite 0.4 percent, and accessories (apatite, garnet, magnetite, and zircon) 0.3 percent. Plagioclase exceeds potassium feldspar, but the proportions of the two feldspars vary widely and some samples have the composition of granodiorite. Quartz occurs as nonstrained subhedral to euhedral phenocrysts. Potassium feldspar is orthoclase or microcline with weak grid twinning. Some grains have thin incomplete rims of albite. Plagioclase is mostly zoned oligoclase. Twinning is not as well developed as in plagioclase of the normal quartz diorite. Myrmekite is developed at the margins of grains in contact with potassium feldspar. The mafic mineral is exclusively biotite, commonly partially chloritized. Absorption is less strong than that of biotite in the normal quartz diorite, with X = very pale straw yellow, and Y = Z = medium brownish green. Included zircons are surrounded by pronounced pleochroic halos.

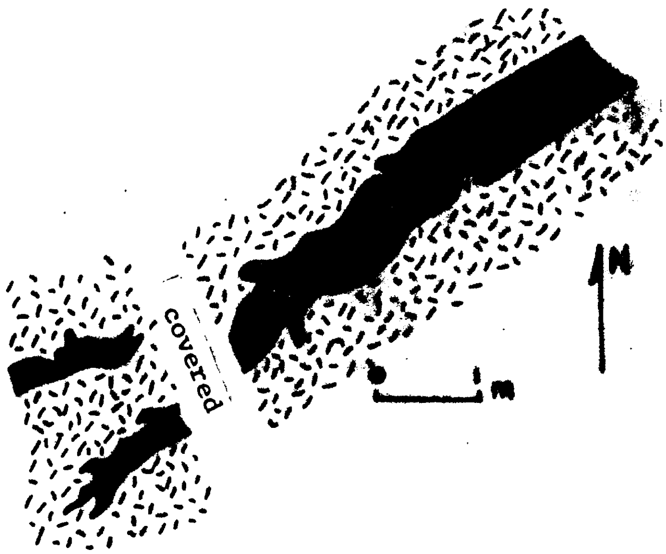
Dikes of medium-grained massive light pink alaskite composed of subequal amounts of sodic andesine, orthoclase, and quartz, crop out near the west border of IIB in the north half of plate 1, sheet 2. Some of these dikes were exposed during construction of the Nare hydro-electric project underground powerhouse near Quebrada Farallones (pl. 1, a-10, sheet 2). Pink pegmatite with accessory black tourmaline forms dikes and small irregular bodies just east of San Rafael (pl. 1, b-10, sheet 2). Thin dikes of aplite and felsite are sporadic, but rare.

Many of the intermediate dikes are curved or show finger-like projection (fig. 14) as though the batholith was fully crystallized when the dike magma was intruded, but still was hot enough to yield plastically.

Gabbro.--Several small bodies of gabbro whose aggregate area is only 12 km^2 have been mapped within the Antioquian batholith. The largest single body is between San José del Nus and Cristales (pl. 1, c-8, sheet 1), and covers 5.5 km^2. The others are generally less



A.



B.

Figure 14.--Intermediate dikes in quartz diorite of the Antioquian batholith and a satellitic body. A. Quebrada Cantayus, elevation 1,000 m, 5 km east of Cisneros (pl. 1, a-7, sheet 1); B. Río Nus 1 km upstream from Caracolí (pl. 1, c-8, sheet 1).

than 1 km^2 each. Outcrops of the gabbro are few; the gabbro has been mapped largely on the basis of residual boulders. These boulders are exceptionally abundant and particularly conspicuous because of their deeply pitted and rust-stained surfaces. As downslope creep has carried the residual boulders beyond the limits of the gabbro, sizes of most of the bodies may be exaggerated on the geologic map.

The gabbro is black to dark green or dark brown and coarse- to medium-grained, hypidiomorphic to idiomorphic and generally equigranular, although some rock contains poikilitic phenocrysts of black hornblende as much as 5 cm long. Composition is quite variable and ranges from pyroxenite to hornblende gabbro. A definitive contact between the gabbro and normal quartz diorite of the Antioquian batholith was not found. Field evidence suggests that the rocks are gradational. For example, the core of the gabbro body near Cristales is pyroxenite (table 11, cols. 1 and 2) which grades into hornblende gabbro (table 11, col. 6) in which lenses of coarse hornblende-plagioclase pegmatite are common. Outward this rock grades to normal quartz diorite (table 9). Other modal analyses of batholith gabbros along with two chemical analyses are given in table 11.

Table 11.--Modal analyses of seven samples and chemical analyses of two samples of gabbro and associated rocks of the Antioquian batholith (in percent).

Field no.	TF-488	TF-516	OR-245	NC-390	NC-93A	TF-515	OR-244
Inventario no.	7633	7634	7754	7744	7743	7636	7706
USGS Lab no.	W168-916	-917					
MODAL ANALYSES							
Quartz	----	----	0.6	----	0.3	Tr.	9.2
Orthoclase	----	----	1.7	----	----	----	----
Plagioclase	5.8	21.4	25.3	51.8	23.0	66.4	49.6
Olivine	0.3	11.9	0.6	----	----	----	----
Orthopyroxene	54.3	20.2	----	----	2.4	----	----
Clinopyroxene	27.6	20.4	20.0	11.5	1.2	0.1	----
Amphibole	11.0	25.7	50.4	30.5	67.7	26.1	29.1
Biotite	Tr.	Tr.	0.1	----	----	----	2.9
Apatite	----	----	0.2	0.1	Tr.	----	0.3
Alteration products	----	----	0.2	0.5	3.5	----	----
Calcite	0.2	Tr.	0.3	----	----	0.3	0.1
Chlorite	----	----	0.4	3.9	0.9	2.1	6.6
Epidote	----	----	----	0.9	0.4	4.1	----
Opaque	0.8	0.1	0.1	0.8	0.6	0.9	1.1
Sphene	----	----	0.1	----	----	Tr.	0.9
Spinel	----	0.3	----	Tr.	----	----	----
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
An content of plagioclase	88	80	70	73	53 ?	70	60
CHEMICAL ANALYSES							
Bulk density	3.26	3.10					
SiO_2	52.1	46.1					
Al_2O_3	5.6	12.2					
Fe_2O_3	1.4	1.8					
FeO	11.4	8.8					
MgO	21.3	17.8					
CaO	6.4	10.3					
Na_2O	0.32	0.96					
K_2O	0.08	0.18					
H_2O -	0.17	0.17					
H_2O +	0.63	1.00					
TiO_2	0.39	0.29					
P_2O_5	0.04	0.02					
MnO	0.09	0.02					
Total	99.92	99.64					

7633 and 7634, pyroxenites from core of gabbro near Cristales (pl. 1, c-8, sheet 1); 7754, gabbro 4 km east of Vegachí (pl. 1, c-4, sheet 1); 7744, gabbro, Hda. Verdún, 17 km southeast of Amalfi (pl. 1, b-4, sheet 1); 7743 gabbro-diorite, Hda. La Arabia, 17 km north of Yolombó (pl. 1, b-5, sheet 1); 7636, hornblende gabbro between pyroxenite of Cristales gabbro body (7633 and 7634) and quartz diorite (table 9, col. 2), 4 km southwest of San José (pl. 1, c-8, sheet 1); 7706, quartz-bearing hornblende gabbro between gabbro of the Vegachí body (7754) and quartz diorite, 4 km east of Vegachí (pl. 1, c-4, sheet 1).

Chemical analyses by rapid rock analysis methods, USGS, Washington, D.C.; Modal analyses in volume percent based on from 750 to 1,000 point counts spread over thin sections.; Tr., trace.

Form of the batholith.--Several features of the Antioquian batholith are unusual for such a large mass (about 8,000 km^2) of felsic to intermediate igneous rock and may have implications for the form of the batholith.

1. Map outline: Large batholiths are characteristically elongated parallel to regional tectonic trends. The outline of the Antioquian batholith, however, is quadrilateraloid (Servicio Geológico Nacional, 1962). The length of the batholith parallel to the tectonic trend of the Central Cordillera is 120 km, only 20 km longer than its breadth across the trend.

2. Discordant contacts: In IIB, wherever the relation of the contact of the Antioquian batholith to structure in adjacent hostrocks could be determined, the contact was found to be discordant. Even where the strike of the batholith contact and foliation in hostrocks are coincident, as along much of the eastern contact in the central part of plate 1, sheet 1, detailed mapping showed that the dips of the two differ.

3. Paucity of hostrock deformation attributable to intrusion: Excluding intrusion faults, little if any deformation of hostrocks that can be attributed to the intrusion of the Antioquian batholith was recognized in IIB. For example, neither the style nor intensity of deformation of hostrocks was found to change with distance from the batholith. Furthermore, regional folds in hostrocks are truncated rather than deflected at the north end of the batholith.

4. Gentle dips of contacts: In IIB, excluding the area where the batholith was emplaced in Cretaceous shale at its south end, the Antioquian batholith was found to have gently dipping to nearly horizontal contacts (pl. 1, sheet 1, cross sections A-A', B-B', C-C', D-D'; sheet 2, cross sections A-A', B-B'). As a result there is a progressive and uniform decrease in elevation at a rate of from 20 to 30 meters per kilometer from west to east of the north contact of the batholith. At Yarumal (pl. 1, d-6, sheet 1) the roof is at 2,400 m. Sixty kilometers to the east, near Amalfi (pl. 1, a-4, sheet 1), it is at 1,600 m. Near El-Tigre, 30 km further east (pl. 1, c-4, sheet 1), it is 1,000 m. Fifteen kilometers east of the longitude of El-Tigre, east of Maceo (pl. 1, d-8, sheet 1), the contact is at only 600 m.

5. Uniformity: The Antioquian batholith shows extraordinary uniformity of composition and texture. More than 99 percent of the area of the batholith in IIB is quartz diorite. Similar uniformity characterizes the rest of the batholith, a large part of which was not mapped by IMN (Prof. Gerardo Botero A., oral commun., 1968). In contrast, most large batholiths in other areas are composite; they comprise a range of rock types commonly as great as that from hornblende gabbro to granite, each of which is generally in sharp contact with its neighbor (Turner and Verhoogen, 1960, p. 342).

6. Internal structure. The overwhelming bulk of the Antioquian batholith is composed of massive or exceedingly feebly foliated or lineated rock. Where flow structure is discernable, it is chiefly defined by the alinement of the long axes of mafic clots. The bearing of this linear flow structure ranges widely, but plunges are mostly gentle and only rarely exceed 30°.

The above half dozen features of the Antioquian batholith are unusual only if related to the great size of the batholith. Each is a feature characteristic of small intrusions (Turner and Verhoogen, 1960, p. 331-332; 338-339).

One inference that can be drawn from these features is that the Antioquian batholith may have a smaller volume than is implied by its huge areal extent. The extreme uniformity of the batholith and the absence of field evidence of multiple intrusion suggests that it may have been emplaced as a single intrusion of rather uniform magma of low viscosity. The general sparseness of flow structures also implies a simple intrusive history.

Part of the batholith, for example much of the north half, may have the form of an enormous subhorizontal intrusive sheet with little thickness relative to its exposed breadth. Such a postulated form would be in accord with field observations on the batholith in the north, such as its lateral extent normal to the regional tectonic trend, its subhorizontal roof with discordant contacts, and the gentle plunge of its linear flow structures. If the intrusion of the magma lifted the roof of the batholith as an integral unit broken only by sporadic intrusion faults, the absence of deformation in hostrocks attributable to intrusion can be explained. The known steep contacts of the batholith in the south, south of San Luis (pl. 1, b-13, sheet 2), may be due to the relative incompetency of the Cretaceous shale compared to that of the more metamorphosed hostrocks of the north.

Examples of sheetlike intrusions are known elsewhere. The Curecanti Quartz Monzonite in south Colorado, U.S.A., forms a pluton wholly discordant to igneous and metamorphic hostrocks and has tapering to feathery edges (Hansen, 1964, p. D6-D10). A vertical feeder is postulated (Hansen, 1964, fig. 2). Igneous and metamorphic basement rocks in Victoria Land, Antarctica, are host to an enormous subhorizontal sheet of diabase at least 40 by 48 km (Hamilton, 1965, p. 17-20). Floor and roof, both exposed in many mountainsides (Hamilton, 1965, figs. 16-18), are everywhere discordant to hostrocks.

Recently, Hamilton and Myers (1967) have suggested that many batholiths have sheetlike forms similar to the one here postulated for at least a part of the Antioquian batholith. Volcanic rocks cited by those authors as common coeval associates of batholiths are lacking on the Antioquian batholith. The possibility that such rocks once existed, but have been selectively removed by erosion, cannot be excluded.

Origin

The origin of the Antioquian batholith has been ascribed to the injection of magma (Botero A., 1963, p. 81-82) and to <u>in situ</u> replacement of preexisting rocks (Radelli, 1965a, b, c). Field and laboratory criteria gathered during the work of IMN strongly support a magmatic origin for the Antioquian batholith in IIB. These criteria are briefly discussed below.

1. Sharp contacts (figs. 15, 17): The contact of the batholith is sharp except at two localities where the host rock is amphibolite as described earlier. In outcrops near the contact, nowhere was a gradation from batholith to host rocks observed.

2. Discordant contacts (figs. 15, 17): All exposed contacts of the batholith are discordant; batholith rock cuts foliation and compositional layering of host rocks. Elsewhere, spatial relationships between the batholith and host rocks suggest that their mutual contact is also discordant.

3. Rotated inclusions (figs. 16, 17): Inclusions of host rock in the batholith everywhere have their internal structures (foliation or layering) rotated with respect to neighboring inclusions and truncated by batholith rock. The lack of parallelism of foliation in adjacent inclusions cannot logically be interpreted as partially replaced foliated host rock.

4. Dikes (fig. 17): Dikes of batholith in hostrock are sharply discordant and, like the batholith itself, have knife-sharp contacts. Most have matching walls or show wall dilation by offset of host rock structures inclined to the dike.

5. High-temperature contact aureole: The batholith is surrounded by a high-temperature contact aureole (p. 48). The confinement of this aureole to rocks peripheral to the batholith is consistent with the emplacement of the batholith as hot magma.

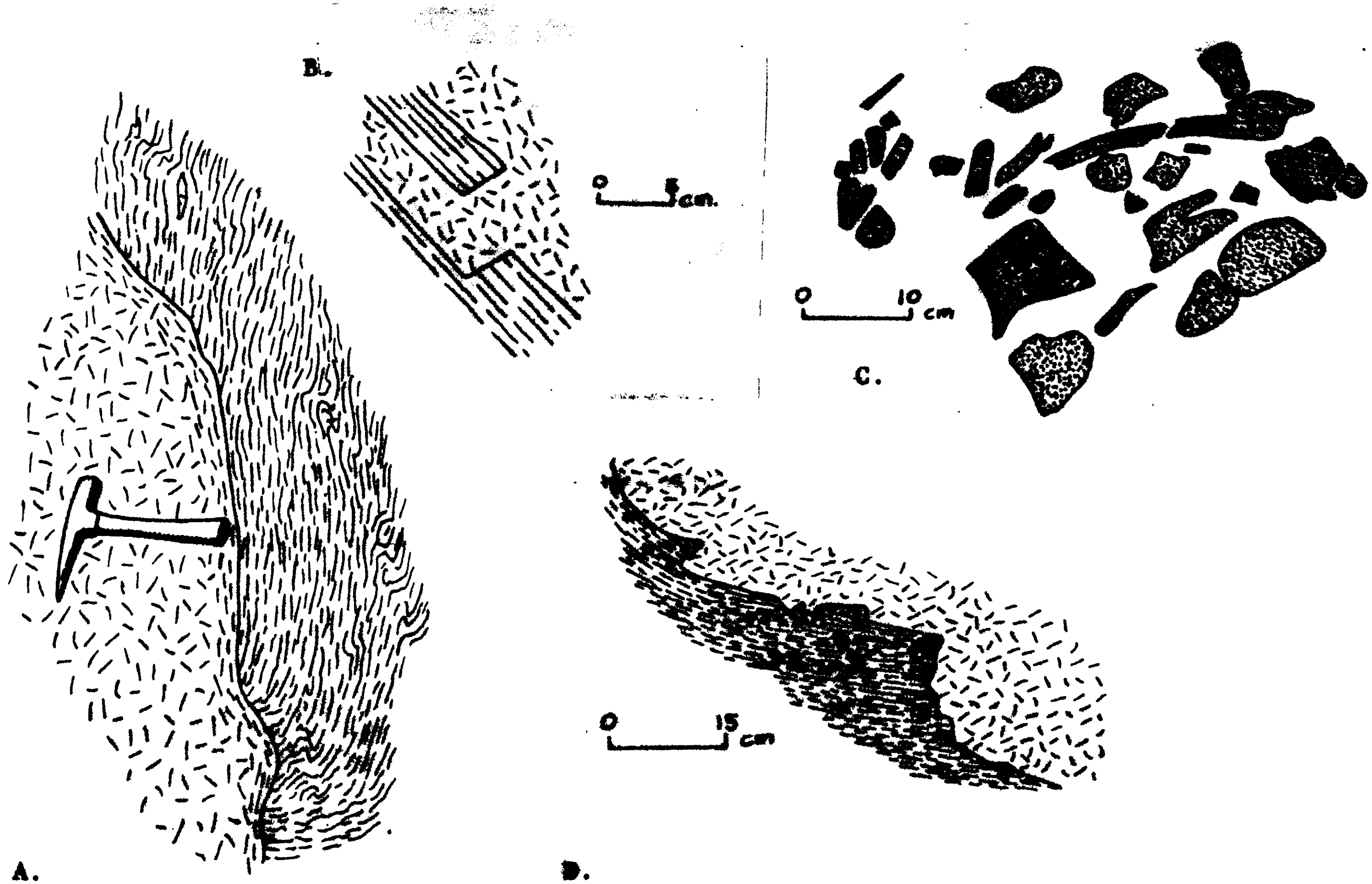


Figure 15.--The Antioquian batholith: contact and inclusions. A. Contact with feldspathic and aluminous gneiss. Northwest-trending exposure dips 70° toward observer. Tributary to Cañada Sta. Bárbara, 5 km north-northwest of Balsadero (pl. 1, b-10, sheet 2). B. Contact with laminated hornblendic skarn. Quebrada Sto. Tomás (pl. 1, b-5, sheet 1). C. Intrusive breccia. Crowded inclusions of fine-grained gneiss many of which preserve a faint foliation and have sharp contacts with the quartz diorite. Some have been completely recrystallized to a massive hornfelsic texture. Quebrada San Blas (pl. 1, b-12, sheet 2). D. Detail of an inclusion of laminated quartzose gneiss in quartz diorite. Quebrada Peñolgrande, elevation 325 m (pl. 1, c-11, sheet 2).

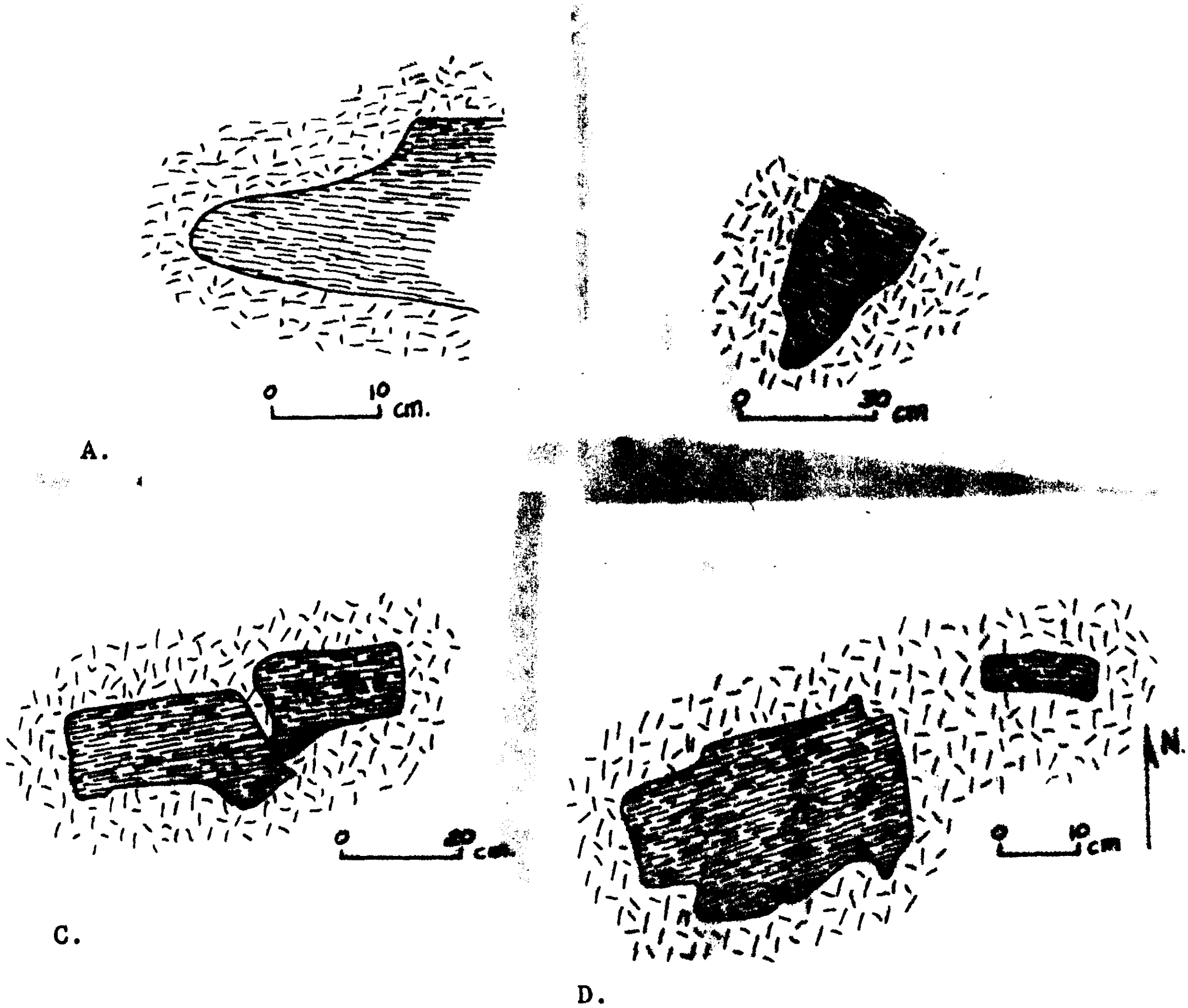


Figure 16.--Satellitic bodies of the Antioquian batholith:
A. Inclusion of feldspathic gneiss. Boulder in trail from Caracolí to Santa Isabel del Nus 800 m from Caracolí (pl. 1, c-8, sheet 1). B. Inclusion of migmatitic gneiss. Boulder in unnamed quebrada 1 km southeast of Caracolí (pl. 1, d-8, sheet 1). C. Inclusions of feldspar-quartz-mica gneiss. Boulder in Río Mata 5.5 km northwest of El Tigre (pl. 1, c-3, sheet 1). D. Inclusions of laminated quartzite, Quebrada Calabozo, elevation 1,450 m (pl. 1, b-3, sheet 1).

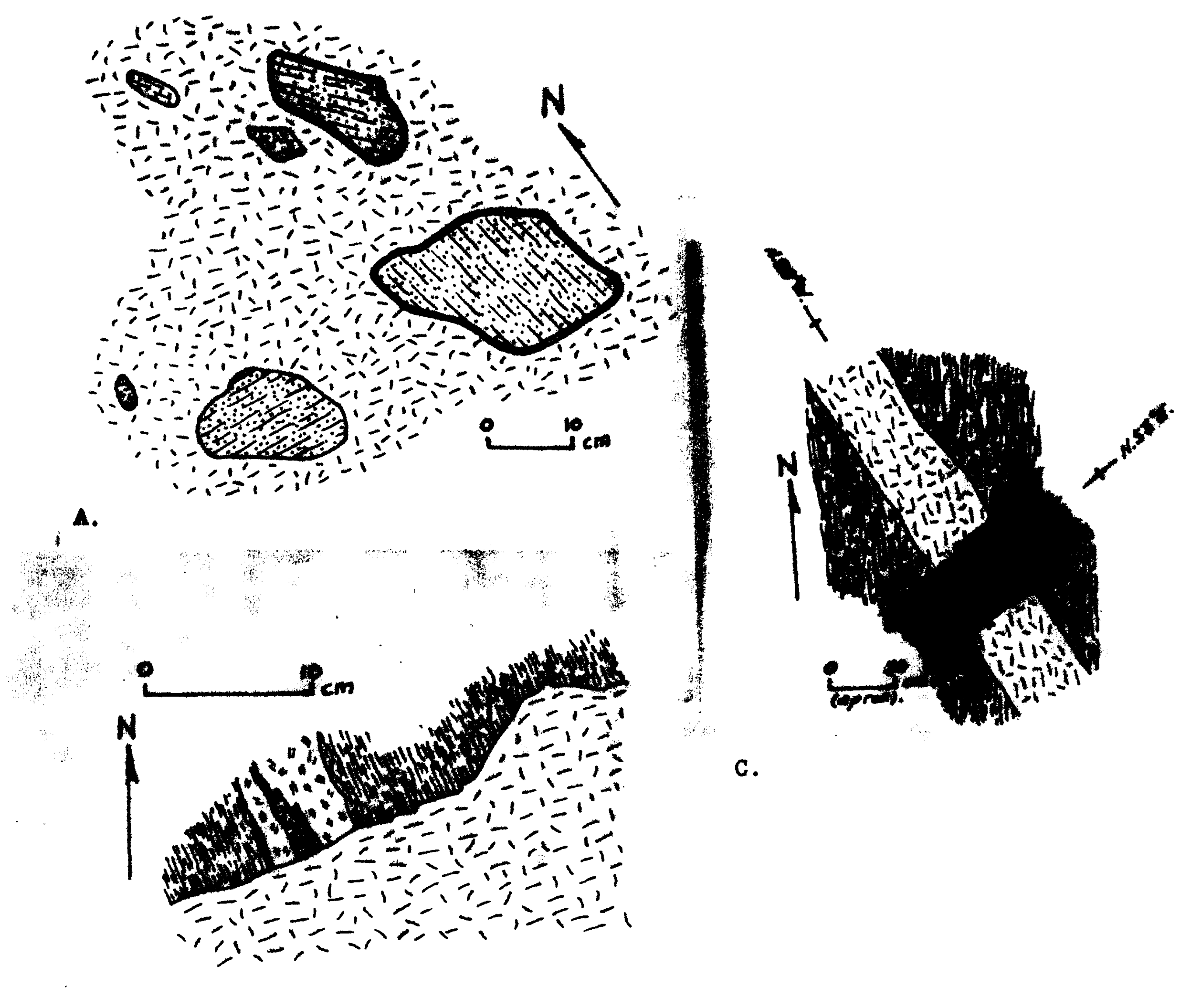


Figure 17.--Dikes of the Antioquian batholith: **inclusions and contacts.** A. Inclusions of quartzite in quartz diorite. Some have centimeter-thick dark flinty reaction rims. El Torito, 100 m north of the batholith (pl. 1, b-3, sheet 1). B. Contact of large dike (or main body of the batholith?) and migmatitic feldspathic gneiss. Note the orientation of mafic minerals parallel to the contact in the igneous rock. Quebrada Bélgica (pl. 1, c-4, sheet 1). **C.** A 30-cm dike of quartz diorite in gneiss that in turn has been cut by a dike of andesite. Unnamed quebrada 1 km southeast of Caracolí (pl. 1, d-8, sheet 1).

6. Desilicated dikes in calcareous host rocks: The unusual quartz-poor dikes (table 10) in calcareous host rocks are best explained by the reaction of siliceous quartz diorite magma with calcite to produce calc-silicate minerals in both the dikes and adjacent host.

7. Uniformity: The extraordinary textural and compositional uniformity (table 8) of more than 3,000 km^2 of quartz diorite is most adequately explained by the crystallization of the batholith from regionally homogeneous magma.

8. Texture: Features suggestive of incomplete replacement of metamorphic or other rock are nowhere visible. The hypidiomorphic equigranular texture of the batholith with euhedral to subhedral plagioclase, hornblende, and biotite among which are dispersed anhedral or interstitial orthoclase and quartz is best explained by crystallization from a melt, following the order experimentally determined by N. L. Bowen.

9. Zoned plagioclase: Plagioclases in the batholith are characteristically zoned; calcic cores are surrounded by successively more sodic shells. This texture is consistent with equilibrium crystallization from a silicate melt, i.e., the continuous reaction series of petrology.

10. Clinopyroxene cores in hornblende: Clinopyroxene cores are common in the hornblendes, and associated biotite is less euhedral than the hornblende. These relationships duplicate the order of crystallization of mafic minerals from silicate melts observed in the laboratory, the discontinuous reaction series of petrology.

The ten observations listed above support the view that the Antioquian batholith was emplaced as magma and are irreconcilable with a metasomatic origin. The gradational contact between the normal and felsic quartz diorites suggests that the felsic rock crystallized from local slightly less mafic domains in the batholith magma. The ultramafic composition of parts of the gabbro bodies suggests that they may be upper mantle rocks carried up as inclusions in the quartz diorite magma. Reaction between magma and inclusions probably produced the observed gradation from pyroxenite to quartz diorite, and explain why pyroxenite is preserved only in the cores of the largest bodies of gabbro.

The sharp and discordant contact of the batholith and the lack of foliation in it are characteristics of plutons intruded into the epizone as defined by Buddington (1959, p. 677-679).

Age

Late Cretaceous K/Ar radiometric ages ranging from 68 to 80 m.y. have been obtained on biotites from widely spaced samples of the normal quartz diorite (Botero A., 1963, p. 81; Perez A., 1967, p. 30). A single sample of felsic quartz diorite from Quebrada Doncella 5 km east of Maceo (pl. 1, d-7, sheet 1), gave a biotite K/Ar age of 68 ± 3 m.y. (Prof. Bruno J. Giletti, written commun., 1967).

Sonsón batholith

The Sonsón batholith covers nearly 1,000 km^2 of the Central Cordillera in the Departments of Antioquia and Caldas. It takes its name from the town of Sonsón in IIB, 110 km by road southeast of Medellín, 17 km west of the southwest corner of plate 1. On the preliminary geologic map of Botero A. (1942), the Sonsón batholith was shown as connected by a slender arm to the Antioquian batholith. Recent mapping by the Facultad Nacional de Minas, Medellín, and IMN has shown that the two batholiths are separate. Nearly 95 km^2 of the Sonsón batholith was mapped by IMN around the town of Argelia (pl. 1, 2-15, a-16, b-16, sheet 2). Excellent exposures are found along the road to Argelia from Sonsón.

The quartz diorite of the Sonsón batholith is uniformly medium-grained and differs little from the Antioquian batholith (table 12). The average of three estimated modes of samples of the Sonsón batholith in the southeast part of plate 1 is: quartz 20.3 percent, andesine 58.7 percent, orthoclase 7.7 percent, biotite 7.0 percent, hornblende 5.7 percent, and accessories 0.6 percent.

The Sonsón batholith in the southwest part of plate 2 cuts intrusive gneiss and metamorphic rocks. Additional field evidence of the intrusive origin of this part of the Sonsón batholith is afforded by the numerous inclusions of biotite quartzite at the confluence of Quebradas San Andrés and El Peñol, 2 km east of Argelia (pl. 1, a-16, sheet 2). Farther east, at La Osa and in Quebrada Mesones (pl. 1, a-16, b-16, sheet 2), metasiltstone has been migmatized in a zone 50 m wide adjacent to the batholith.

Table 12.--Differences between quartz diorite of the Sonsón and Antioquian batholiths.

	Sonsón batholith	Antioquian batholith
Deformation	Slight undulatory extinction of quartz, biotites locally bent.	Effects of deformation away from well-defined shear zones are generally wanting.
Hornblende	Green-brown, moderate 2V, no dispersion.	Green-brown, moderate to large 2V, moderate to strong dispersion ($r > v$).
Accessory minerals	Allanite is common. Apatite is common but not ubiquitous and rarely exceeds 0.1 percent by volume. Opaque is principally pyrite. Zircons in biotite are surrounded by weak to moderate pleochroic halos.	Allanite is rare. Apatite is ubiquitous and commonly exceeds 0.1 percent by volume. Opaque is principally magnetite. Zircons in biotite lack pleochroic halos.

As in the Antioquian batholith, the medium grain size of the quartz diorite at the Sonsón batholith persists to its contacts. Small stocks and plugs in metamorphic rocks to the east, however, are fine-grained (pl. 1, a-16, b-16, sheet 2).

A radiometric K/Ar age of 69 ± 3 m.y. was obtained on biotite from a sample from the Sonsón-La Dorada road southwest of Argelia (Pérez A., 1967, p. 30). This single age supports the contemporaneity of the Sonsón and Antioquian batholiths suggested by their petrographic similarities.

Granodiorite at Tres Mundos

Granodiorite forms an elongate stock 10 km^2 in area at Tres Mundos (pl. 1, a-15, sheet 2), about 12 km northeast of Argelia. The granodiorite is felsic; mafic minerals, exclusively biotite and accessory tourmaline, nowhere exceed 10 percent, and at the south end of the stock they are very sparse. The rock is light gray to beige, allotriomorphic to hypidiomorphic, medium-grained and equigranular. A modal analysis by C. J. Vesga of a sample from Quebrada Los Andes near the center of the stock gave the following: quartz 34.6 percent, orthoclase 21.9 percent, oligoclase 30.6 percent, biotite 5.3 percent, muscovite 2.8 percent, chlorite 3.6 percent, and accessories (apatite, epidote, sphene, magnetite, tourmaline, and zircon) 1.2 percent.

Quartz is dusted, fractured, and shows weak undulatory extinction. Perthitic orthoclase is interstitial and dusty. Oligoclase is in normally zoned euhedral to subhedral crystals. Biotite is dark reddish brown and extensively chloritized; included zircons are surrounded by prominent pleochroic halos. Muscovite is pale green and faintly pleochroic. The most abundant accessory is apatite.

The stock at Tres Mundos is crystallized from magma, as shown by its composition and crosscutting relationship with enclosing metamorphic rocks. A narrow contact aureole, which is particularly conspicuous at the north end of the stock, consists of porphyroblastic andalusite in metasiltstone.

The granodiorite is considered to be younger than the nearby Sonsón batholith on the basis of its more felsic composition.

Quartz monzonite at Aquitania

The small isolated town of Aquitania (pl. 1, b-15, sheet 2) lies near the north end of a stock 43 km^2 in area, composed chiefly of quartz monzonite. The west and northeast contacts of the stock are faulted. Elsewhere the stock intrudes sericite schist, intrusive gneiss, and Cretaceous shale. The stock is difficultly accessible and is poorly exposed owing to unusually deep weathering.

Superficially, the stock at Aquitania resembles that at Tres Mundos 8 km to the west. However, the two differ in detail. The stock at Aquitania is complex and may be composite. It is composed dominantly of quartz monzonite (table 13, col. 1), but local facies include granodiorite (table 13, col. 2), quartz diorite (table 13, cols. 3, 4), and fayalite quartz diorite (table 13, col. 5). The relationships between these rock types is unknown. In addition, dikes, chiefly felsic porphyry, and gabarros, both absent at Tres Mundos, are common in the stock at Aquitania.

Table 13.--Modal analyses of five samples from the stock at Aquitania (percent).

	1.	2.	3.	4.	5.
Field number	**DMT-988**		**DMT-989**	**DBL-825**	**PM-936**
Inventario number	8498		8499	8539	8141
Facultad Nacional de Minas number		2356A			
Quartz	31.5	24.8	25.2	21.7	23.0
Orthoclase	34.3	25.9	23.5	13.7	19.4
Plagioclase	30.1	41.9	43.8	56.3	43.1
Biotite	3.2	----	2.7	5.2	7.2
Chlorite	0.6	3.8	3.1	0.7	----
Muscovite	----	----	0.5	----	----
Hornblende	----	----	----	1.6	----
Fayalite	----	----	----	----	6.1
Nonopaque accessories	Tr.	2.7	0.3	Tr.	0.7
Opaque accessories	0.3	0.9	0.9	0.8	0.5
Total	100.0	100.0	100.0	100.0	100.0

1. Quartz monzonite. Río Claro 7.1 km S.15°E. of Aquitania ; 2. Granodiorite. Trail Aquitania - Miraflores, 4.3 km S.13°E of Aquitania ; 3. Quartz diorite. Río Claro 7.1 km S.10°E. of Aquitania 4. Quartz diorite. Quebrada Arrebol 2.5 km south of Aquitania ; 5. Fayalite quartz diorite, resid boulder. Alto San Pedro, 3 km north of Aquitania. Samples 1-4 from b-15 ; sample 5 from b-14.

Modal analyses based on 1000 point counts spread over standard thin sections. Analyses 1, 3, and 4 by C. J. Vesga ; analyses 2 and 5 by Humberto González I.

Tr., trace.

The dominant quartz monzonite, as well as the granodiorite and quartz diorite, have distinctive micropegmatitic textures not found in other rocks in IIB. They are medium-grained, hypidiomorphic granular, gray to beige, felsic, and massive. Subhedral to euhedral strongly zoned plagioclase crystals (andesine to oligoclase) are set in a matrix of orthoclase-quartz micropegmatite. Mafic minerals are partially chloritized red-brown biotite and aggregates of green hornblende-biotite. Accessories include unusual apatite crystals having enormous elongation ratios, and large clear prisms of zircon. One apatite in sample 8539 (table 13, col. 4), for example, is 0.345 by 0.0004 mm, an elongation ratio of 86. A large zircon in sample 8498 (table 13, col. 1) is 0.32 by 0.03 mm with an elongation ratio of nearly 11. Opaque accessory minerals are magnetite and pyrite.

The fayalite-bearing quartz diorite occurs as residual boulders on Alto San Pedro (pl. 1, b-14, sheet 2). Boulders in the plaza at Aquitania are similar and may have the same composition although no thin section of them was studied. This diorite is dark gray-green, fine- to medium-grained, massive, hypidiomorphic equigranular, and the rock has a slightly greasy luster. It is composed mainly of andesine, quartz, orthoclase, biotite, and fayalite.

Andesine occurs as weakly zoned and weakly twinned euhedral to subhedral grains, many of which are bent. Quartz is anhedral, lightly dusted and strained. Orthoclase is anhedral and feebly perthitic. Biotite is in strongly pleochroic red-brown flakes with included zircons surrounded by weak pleochroic halos. Fayalite is anhedral, colorless with high relief, and shows moderate (-) 2V and weak dispersion ($r > v$). It is partly altered, chiefly to dark brown iddingsite, and to a lesser extent fibrous amphibole, chlorite, magnetite, and calcite. Accessory minerals include allanite, apatite, magnetite, and zircon.

A breccia has been developed in the quartz monzonite at its contact with intrusive gneiss containing unmapped lenses of quartzite along the northeast contact of the stock (fig. 18). Cretaceous shale has been baked to a tough massive hornfels near the north contact of the stock.

The age of the stock at Aquitania is uncertain. It is younger than the Cretaceous shale, but its age relative to the other igneous rocks of IIB is unknown. Its general compositional similarity to the nearby granodiorite at Tres Mundos suggests that the two stocks may be related.

Dikes and other hypabyssal intrusives

Dikes related to plutonic intrusives range in composition from quartz diorite to aplite and cut all rocks in IIB. Some of the dikes described here form chonoliths or small stocks but are included because of lithologic similarity to certain dikes. Dikes are most abundant in the Antioquian batholith, and are least common east of the Otú fault. Many are related to the Antioquian batholith, but some in the surrounding rocks have been metamorphosed and are clearly older. These dikes are of several generations, and are here treated together for convenience. The pyroxene andesite dikes are probably younger than all of these, and are possibly related to a younger magma cycle.

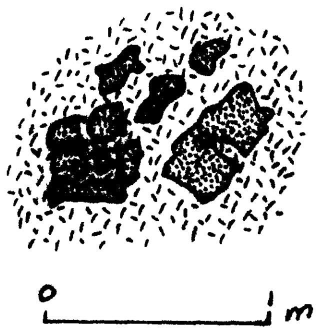


Figure 18.--Breccia in the quartz monzonite at Aquitania. Inclusions of quartzite (stippled) and intrusive gneiss (ruled). Quebrada La Víbora 1.6 km N. 16° E. of Aquitania (pl. 1, b-15, sheet 2).

Fine-grained quartz diorite constitutes a small body roughly 3.5 by 0.75 km, centered 5 km west of Cisneros (pl. 1, a-7, sheet 1), is intrusive into the normal quartz diorite of the Antioquian batholith, and has chilled contacts against it, a relationship well exposed on the trail north-northeast of La Quiebra. The rock is gray, hypidiomorphic equigranular, and massive, with locally conspicuous hornblende-rich schlieren a few centimeters long surrounded by thin felsic halos. A modal analysis of a representative sample taken 0.6 km N. 19° E. of La Quiebra gave: quartz 15.4 percent, plagioclase (An_{40}) 62.7 percent, orthoclase 4.3 percent, hornblende 8.4 percent, biotite 7.0 percent, clinopyroxene 0.9 percent, nonopaque accessories 0.5 percent, and opaque accessories 0.8 percent. The chilled rock at the contact is indistinguishable from that of most of the dikes of intermediate composition described previously under the Antioquian batholith. It is concluded, therefore, that many intermediate dikes and the fine-grained quartz diorite crystallized from silimar magma possibly derived from a common source. The coarser grain of the stock west of Cisneros is attributed to its larger size.

Pink to beige saccharoidal massive aplite forms sparse dikes, chiefly in the Antioquian batholith. An unusually large mass, 2.3 by 0.8 km, was observed south of San Luis (pl. 1, b-13, sheet 2). The rock is composed of one-third quartz, two-thirds feldspar (albite and orthoclase), and accessory muscovite and chloritized biotite.

Pegmatite composed of pink and white feldspar and gray quartz, commonly with accessory black tourmaline, forms sparse dikes a few centimeters thick and small irregular bodies less than a meter across in many rocks in IIB. Most pegmatites are too small to be shown on the geologic map. The pegmatite is of no single origin. Some pegmatite such as that east of San Rafael (pl. 1, b-9, b-10, sheet 2), is related to the Antioquian batholith. Other pegmatite fills small cavities in the adamellite. Small lenses of pegmatite in feldspathic and aluminous gneiss probably were formed during the metamorphism of those rocks.

Dark green aphanitic dacite 1.6 by 0.25 km cuts the Antioquian batholith 8.5 km west of San Carlos (pl. 1, a-11, sheet 2). The dacite is poorly exposed and may be a large multiple dike. It is cut by sporadic veins of pyrite. One such dike forms the footwall of the Silencio vein at the Frontino Gold Mines near Segovia (pl. 1, d-1, sheet 1).

Milky quartz

Milky quartz is described with the igneous rocks because much of it occurs in crosscutting bodies. Like the dike rocks, the milky quartz may be of many ages and origins. Outcrops are scarce, but because quartz is extremely resistant to weathering, it makes abundant surficial residual boulders.

The milky quartz is finely crystalline saccharoidal white quartz. Between San Rafael and Balsadero (pl. 1, b-10, sheet 2), residual boulders of milky quartz are vuggy and contain sparse sulfides and gold. This locality is shown on the geologic map.

Three principal modes of occurrence of milky quartz were noted in IIB: veins in the Antioquian batholith, in some faults, and as random veins and irregular bodies in metamorphic rocks.

In the Antioquian batholith milky quartz is chiefly in veins a few centimeters thick that have sharp contacts. During weathering, these veins become fragmented and concentrated in the saprolite. They are shown on the geologic map only where unusually abundant, as on Cerro Cancharazo (pl. 1, a-5, sheet 1).

Many faults in IIB contain abundant milky quartz, and their traces are marked by residual boulders. Many such occurrences are shown on the geologic map. A particularly fine example is found along the Riachón fault east of Amalfi (pl. 1, a-3, sheet 1).

In a few places veins or irregular bodies of milky quartz of unknown origin have been emplaced in the metamorphic rocks. The largest invididual bodies are 7.5 km N. 31° E. of Yalí (pl. 1, c-5, sheet 1) and 6.5 km south of Caracolí (pl. 1, d-9, sheet 9), respectively.

STRUCTURAL GEOLOGY

The structural geology of IIB is incompletely known because of the paucity of outcrops in much of the zone, the small size of most individual outcrops, and because outcrops in streams have little relief and commonly allow observations only in two dimensions. Nevertheless, many of the major structural features of the zone, especially regional faults and folds, have been recognized, as has the significance of foliation, lineation, and many other minor structural features.

Faults

The dominant structural features of IIB are faults. Some are more than 100 km long and have been traced on air photos additional tens or even hundreds of kilometers beyond the limits of the map area. More than a dozen faults that exceed 20 km in length are shown on plate 1. Many of the larger faults have been named for the first time in the present report. The names are mostly after rivers that follow the faults or locally well known cultural features where the faults occur or are well exposed.

Nine criteria were found useful to identify large faults in the field in IIB. Most of the large faults exhibit at least four of the criteria, and some exhibit all nine. The criteria are briefly discussed and outstanding examples of each are given.

1. Topographic expression: The large faults may be expressed topographically in one of three ways. Some faults are marked by deep straight canyons with sharp "V" cross sections (Nare fault southwest of Caracolí (pl. 1, c-9, sheet 2) and Palestina fault near the confluence of the Ríos Nare and Samaná Norte (pl. 1, d-10, sheet 2). Other faults are marked by broad alluvial valleys (Riachón fault southeast of Amalfi (pl. 1, a-3, sheet 1), and Otú fault southwest of Remedios (pl. 1, d-2, sheet 1). Finally, some faults separate blocks of markedly dissimilar topography (Aquitania fault (pl. 1, b-14, sheet 2).

2. Discontinuity of rock types: Nearly all large faults in IIB separate unlike rock types somewhere along their lengths. The Otú fault is a particularly striking example separating diorite and quartzite over a distance greater than 50 km.

3. Fractured rock: Belts of intensely fractured rock from 10 or more than 100 m wide are coextensive with most faults (Cimitarra fault (pl. 1, e-6, sheet 1)).

4. Sheared rock: Schistose cataclastic sheared rock occurs along all the faults, but, as it has little resistance to weathering and erosion, it is poorly exposed. An inclined diamond drill hole made for a study pursuant to the construction of a dam intersected the steeply dipping Balsadero fault near the mouth of Quebrada El Macho (pl. 1, c-11, sheet 2). The log of that hole (fig. 19) shows that the fault is marked by a zone at least 57 m thick that consists chiefly of highly sheared rock.

5. Altered rock: Hydrothermally altered rock occurs along some large faults in IIB, but is not easily distinguished from saprolite. Careful search along the Palestina fault between the Río Cupiná and the Otú fault (pl. 1, e-6, sheet 1) revealed patches of light grayish green clay produced by the hydrothermal alteration of diorite and Precambrian feldspar-quartz gneiss. This clay differs from saprolite in color and texture.

6. Breccia: Fault breccia is the most spectacular manifestation and was found associated with every large fault. Clasts are angular and generally range from less than 1 cm to 1 m across, although they are many times larger in the megabreccia of the Palestina fault. The clasts are set in a dull-lustered cataclastic matrix except in brecciated marble where the matrix is chiefly recrystallized white calcite. Clast-to-matrix ratios exceed 2:1. A particularly arresting example from the Riachón fault is shown in figure 20. The most extensive development of fault breccia in IIB occurs along the Cimitarra fault (pl. 1, e-6, sheet 1).

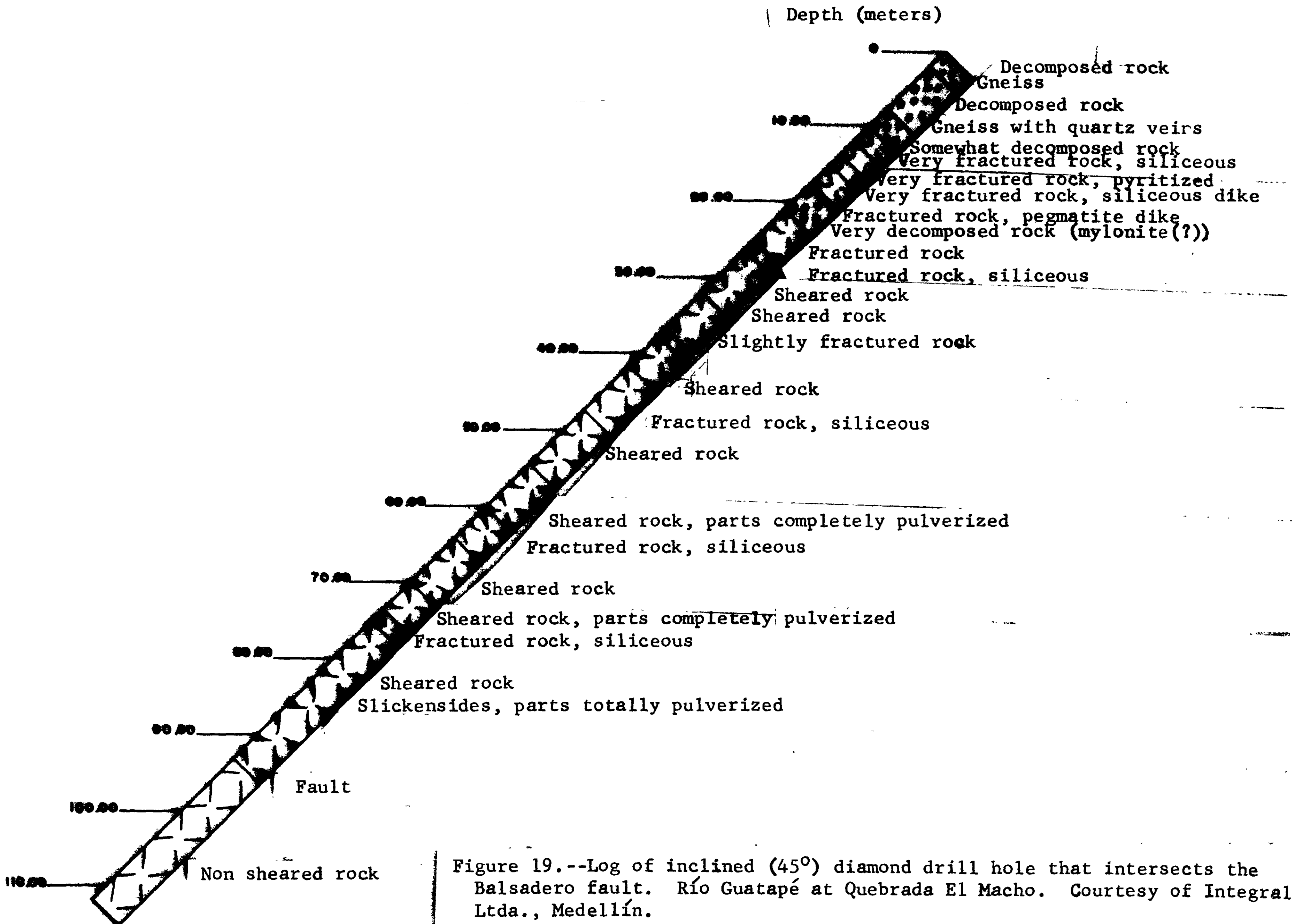


Figure 19.--Log of inclined (45°) diamond drill hole that intersects the Balsadero fault. Río Guatapé at Quebrada El Macho. Courtesy of Integral, Ltda., Medellín.

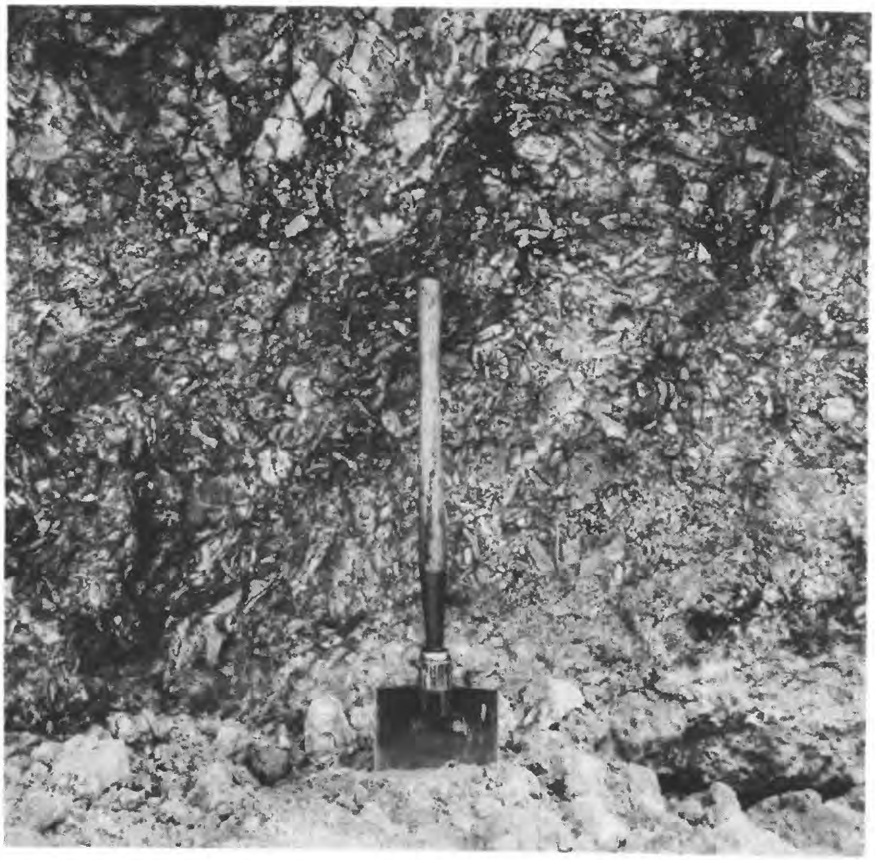


Figure 20.--Brecciated quartzite in the Riachón fault. Cut in weathered rock along the Amalfi-Yalí road at Hda. Singapur, 5 km southeast of the Amalfi airstrip (pl. 1, b-3, sheet 1). Shovel handle is 42 cm long.

7. Rodding: Rodding is the name here applied to the process that forms columnar masses (rods) of rock a few centimeters thick within a fault zone. The long axes of the rods parallel the direction of net slip. Rodding can be thought of as intense slickensiding along intersecting surfaces that allow rod-shaped masses of rock to become detached from one another. Such rods were found only along the Riachón fault (fig. 21), in a cut on the Amalfi-Yalí road 3 km southeast of Amalfi airstrip (pl. 1, a-3, sheet 1).

8. Boulders of milky quartz: Many of the large faults in IIB, and particularly certain faults, here called "intrusion" faults (discussed in detail below), associated with the Antioquian batholith are silicified with milky quartz. This quartz is relatively resistant, and through weathering and erosion becomes concentrated as surficial boulders along the trace of the fault. Such boulders are especially abundant along the Riachón fault near the Amalfi airstrip (pl. 1, a-3, sheet 1), and at several places along the Otú fault east-southeast of Sta. Isabel (pl. 1, d-3, sheet 1).

9. Discontinuity of metamorphic grade: Large faults in IIB commonly are found between rock units of markedly different metamorphic regional grade. Rocks northeast of the Balsadero fault (pl. 1, b-10, c-10, sheet 2), for example, have been metamorphosed to a very high grade, whereas those on the southwest have been metamorphosed only slightly. Similar examples are numerous elsewhere.

Faults of four types occur in IIB. They are: 1. Normal faults; 2. faults related to the cooling of the Antioquian batholith; 3. intrusion faults; and 4. wrench faults.

Figure 21.--Rodded quartzite in Riachón fault. Pencil gives scale. Cut on Amalfi-Yalí road 3 km southeast of the Amalfi airstrip (pl. 1, a-3, sheet 1).

Normal faults

Steeply dipping normal faults occur chiefly in the east-central and southwestern parts of IIB. Although the intrusion faults are also normal faults, they are treated separately because of their distinctive origin.

The largest normal faults bound a graben of Cretaceous sedimentary rocks south of San Luis. Each of these faults, the Aquitania fault on the east named after the town of Aquitania (pl. 1, b-15, sheet 2), and the unnamed faults on the west and south, probably has several kilometers of displacement. The Aquitania fault has been cut by the stock of quartz monzonite at Aquitania. None of the three faults is well exposed.

Cretaceous sedimentary rocks at Amalfi (pl. 1, a-3, sheet 1) lie in narrow semigrabens (pl. 1, sheet 1, section A-A'). The normal faults that bound them on the east are poorly exposed.

Precambrian gneiss, volcanic rocks, and diorite are cut by many small normal faults in the east-central part of IIB, chiefly in the area bounded by the El Bagre, Palestina, and Cimitarra faults and the Magdalena Valley (pl. 1, e-6, e-7, e-8, sheet 1). The faults are poorly exposed, although the traces of some are marked by residual boulders of milky quartz.

The remarkably straight boundary between the Tertiary sedimentary rocks of the Magdalena Valley and the crystalline rocks of the Central Cordillera, 110 km long in IIB alone (pl. 1, sheets 1 and 2), is most likely controlled by a strong subsurface fault, an interpretation first offered by Harrison (1930, p. 408). The fault does not crop out, however, and probably lies concealed beneath the Tertiary strata and alluvium east of the exposed crystalline rocks.

Faults related to the cooling of the Antioquian batholith

Faults from a few meters long to shear zones many kilometers in length occur in the Antioquian batholith. These faults and shear zones are confined to the batholith and most of them are believed to have been produced by stresses within the batholith caused by its contraction during cooling.

The small faults have random strikes and are best seen where they offset dikes. Displacements rarely exceed 10 meters and commonly are only a few centimeters. Two examples are shown in figure 22.

The shear zones strike from N. 40° W. to N. 85° W. and are from less than one to 23 km long. The longest are the Cristales and Sofía shear zones, both of which cross the Río Nus east of Cisneros (pl. 1, sheet 2). They are named after Sofía Station on the Antioquian Railroad (pl. 1, b-7, sheet 1) and the small town of Cristales south of the railroad (pl. 1, b-8, sheet 1), respectively.

Rock in the shear zones range from light gray-green vaguely laminated fined-grained to aphanitic mylonite to black medium-grained biotite schist. These rocks are relatively non-resistant and crop out poorly. The best exposures of mylonite are in the Cristales shear zone in Quebrada La Chinca 5 km S. 43° W. of San José del Nus (pl. 1, c-8, sheet 1) and in the Sofía shear zone in the Río Nus where it is crossed by the oil pipeline 5 km downstream from Cisneros (pl. 1, a-7, sheet 1). Biotite schist is well exposed only in new roadcuts 1 km east of Cristales (pl. 1, b-8, sheet 1).

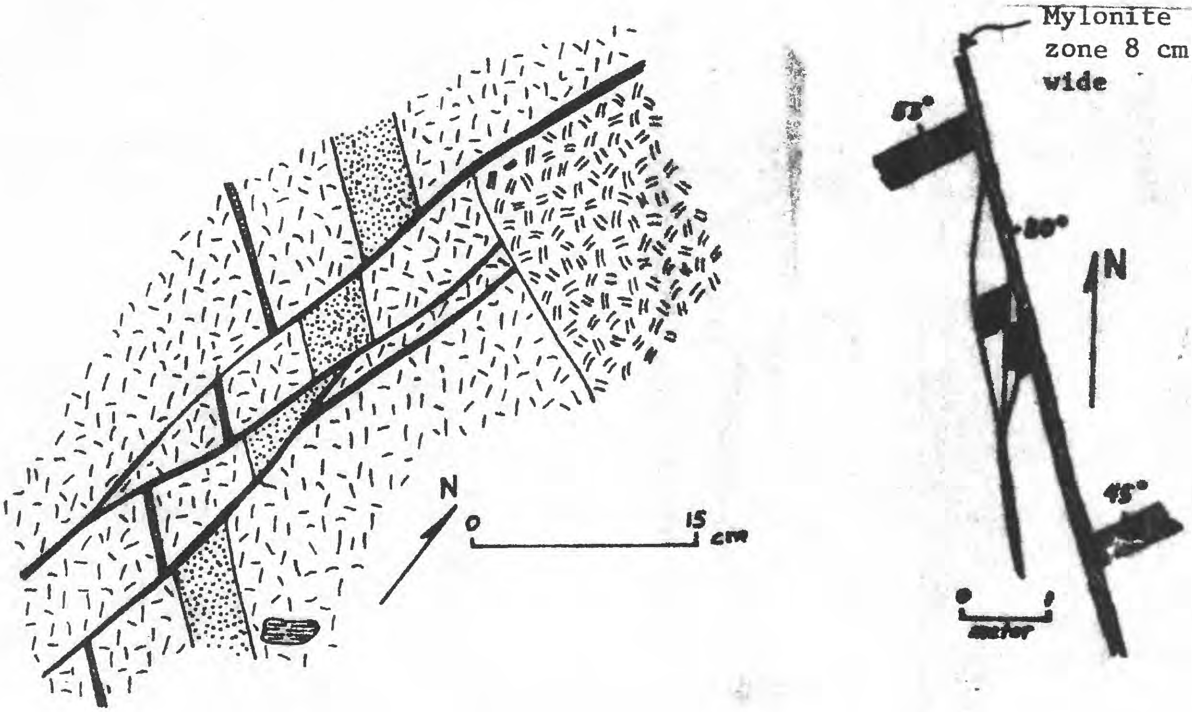


Figure 22.--Faults related to the cooling of the Antioquian batholith and a satellitic body. A. Hachures, quartz diorite; stipple, felsite, double hachures, alaskite; dark lines, mylonite. Note that the alaskite cuts some of the faults but is in turn cut by another. Inclusion at bottom of sketch is feldspathic gneiss. Quebrada Farallones, elevation 1,350 m (pl. 1, a-10, sheet 2). B. Blank, quartz diorite; black, dacite. Río Nus 2 km upstream from Caracolí (pl. 1, c-8, sheet 1).

Field and petrographic evidence indicate that the small faults and shear zones in the Antioquian batholith and satellitic bodies are related to the cooling of these rocks. Many of the small faults that cut dikes are in turn cut by other dikes (fig. 22A). This demonstrates that some of the faulting overlapped the period of dike emplacement, which as stated earlier, took place shortly after the intrusion of the batholith. The shear zones are entirely restricted to the Antioquian batholith; some of the zones come within a kilometer or two of surrounding rocks but none enters them. Furthermore, biotite schist developed in the Cristales shear zone contains such relatively high-temperature minerals as biotite and andesine whose cataclastic texture is partially healed by recrystallization younger than the shearing. As no metamorphic heating younger than the batholith has been recognized, it is concluded that the heat which caused the recrystallization of biotite and andesine came from the batholith itself which had only recently crystallized from magma.

Intrusion faults

Faults caused by stresses imposed on roof rocks by the intrusion of magma are here called intrusion faults. Such faults, all apparently with steep net slips, are numerous in rocks host to the Antioquian batholith, and many are shown on the geologic map (pl. 1, sheets 1 and 2) by a special symbol. The intrusion faults are longest in roof rocks on the batholith, and in several places they bound roof pendants. Movement on the intrusion faults is believed to have ceased prior to the freezing of the batholith magma and they probably do not extend downward into the batholith (pl. 1, sheet 1, sections A-A', D-D'; sheet 2, section A-A').

Careful examination of many outcrops of metamorphic rocks near the Antioquian batholith reveals a profusion of small faults with displacements of only a few centimeters. Such faults, which are scarce or wanting farther from the batholith, are interpreted as tiny intrusion faults. Some typical examples are shown in figure 23.

Several large intrusion faults many kilometers long and with displacements of hundreds of meters, have been recognized in IIB. Most strike from N. 20° W. to N. 60° W., although three strike roughly N. 45° E. The most prominent of the northwest-striking intrusion faults are the Riachón fault southeast of Amalfi (pl. 1, a-3, b-3, b-4, sheet 1), and its possible extension 13 km northwest of Yalí (pl. 1, b-5, sheet 1); the Monteloro fault west of Maceo (pl. 1, b-7, c-7, sheet 1); an unnamed fault 4 km west of Caracolí (pl. 1, c-8, sheet 1); and the Balsadero fault east of San Carlos (pl. 1, b-10, c-10, c-11, sheet 2). The northeast-striking intrusion faults are located 9 km S. 40° W. and 14 km S. 19° W. of Caracolí (pl. 1, c-9 and c-10, respectively, sheet 2), and 13 km N. 63° E. of San Carlos (pl. 1, b-10, c-10, sheet 2).

Some of the large intrusion faults appear to be related to structural features in the Antioquian batholith and are expressed topographically. For example, broad alluvial valleys on the batholith occupy the projected northwest extensions of the unnamed intrusion fault northwest of Yalí (pl. 1, b-4, sheet 1) and the Monteloro intrusion fault (pl. 1, b-6, sheet 1). The projected northwest extension of the Balsadero intrusion west of Caracolí is nearly coincident with a projected extension of the Cristales shear zone.

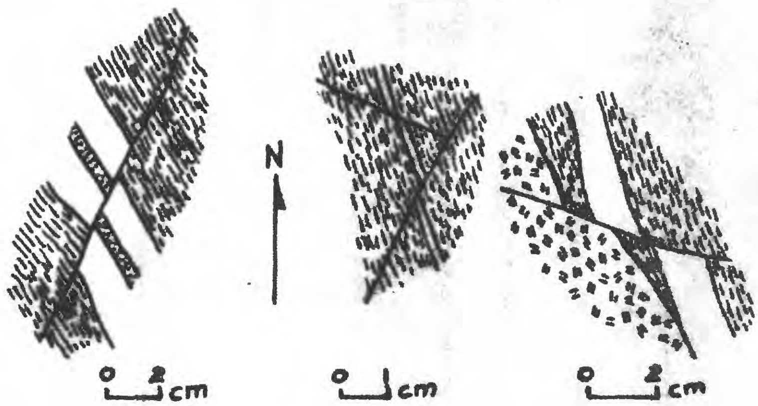


Figure 23.--Small intrusion faults. Layered feldspathic gneiss 20 m from the Antioquian batholith. Quebrada Bélgica 4.8 km S. 9° E. of El Tigre (pl. 1, c-4, sheet 1).

Only the Riachón intrusion fault extends a considerable distance (10 km) from the batholith. The others all end at, or within four or five kilometers of, the batholith contact.

Outcrops along the Balsadero intrusion fault at the confluence of the Ríos San Carlos and Guatapé (pl. 1, c-10, sheet 2) show how this type of fault developed. Gneiss on the northeast block 15 m from the fault is well exposed in a roadmetal quarry at Balsadero from where the fault takes its name. The gneiss is so thoroughly shattered and brecciated that pieces larger than 15 cm are not found (fig. 24A). On the other hand, quartz diorite of the Antioquian batholith in an adjacent outcrop in the Río Guatapé 15 m southwest of the fault is unfractured and shows no sign of its proximity to the fault (fig. 24B). A faint platy flow structure and oriented spindle-shaped gabarros (fig. 24B) show that magma flow was vertical. The quartz diorite is unaffected by the fault because movement on the fault had ceased prior to the freezing of the magma.

The geologic sketch map of the northwest end of the Balsadero intrusion fault and the series of cross sections given in figure 25 show the probable geometry of the fault at depth as well as above the present surface of erosion and also graphically convey the mode of origin of these interesting faults.

The preferential silicification of the Balsadero and other intrusion faults in IIB supports the postulated mode of their formation. The intrusion faults acted as channelways along which volatiles rich in silica could escape from the crystallizing magma.

Figure 24A.--Balsadero intrusion fault. Shattered and brecciated gneiss 15 m northeast of the fault. Road-metal quarry at the confluence of the Ríos San Carlos and Guatapé (pl. 1, c-10, sheet 2).

Figure 24B.--Quartz diorite of the Antioquian batholith 15 m southwest of the fault. Note gabarro inclusion with vertical long axis. Dark patch at point of hammer is water-filled depression. Río Guatapé at the mouth of the Río San Carlos.

Where metamorphic rocks occur in both blocks of the Balsadero intrusion fault, beginning 1 km southeast of the confluence of the Ríos San Carlos and Guatapé, the rocks in the northeast block are much higher metamorphic grade than those in the southwest block. This suggests that the northeast block moved up from a deeper level in the crust relative to the southwest block. Such a sense of movement is contrary to that depicted in figure 25. The most likely explanation of this apparent anomaly is that the fault existed as a normal fault with the southwest block downthrown prior to the intrusion of the batholith magma. The magma reactivated the fault, a ready zone of weakness in the roof of the batholith, but caused movement opposite to that on the prebatholith fault in the area of figure 25. On the other hand, movement caused by magmatic intrusion on the same fault farther to the southeast, south of El Jordán (pl. 1, c-11, sheet 2), appears to have been opposite to that produced by the intrusion to the northwest, for here the batholith occurs on the northeast block and the metamorphic rocks occupy the southwest block. The Balsadero intrusion fault may thus have had scissorslike motion about an axis normal to the fault located somewhere between the confluence of the Ríos San Carlos and Guatapé and a point south of El Jordán (pl. 1, c-10, sheet 2).

The remarkable parallelism of the northwest-striking intrusion faults suggests that they are genetically related and that they, like the Balsadero intrusion fault, may similarly have existed as regional normal faults before the emplacement of the Antioquian batholith.

Certainly their parallelism is not consistent with the view that the intrusion faults are the product of a random chaotic foundering of roofrocks over the Antioquian batholith.

An intrusion fault which coincides with Quebrada La Clara (pl. 1, b-3, sheet 1), although parallel to no other intrusion fault, likewise is an old normal fault reactivated by the intrusion of the batholith. Prebatholith displacement was considerable, judging by the poor match of rock types across the fault. Displacement produced by the batholith, on the other hand, was relatively small, about 100 m (pl. 1, sheet 1, cross section A-A').

Wrench faults

By far the most arresting regional structural features of IIB are wrench faults. Some of these are more than a hundred kilometers long and have displacements measured in dozens of kilometers. The wrench faults are confined to the east part of IIB chiefly between the Antioquian batholith and the Magdalena Valley. Most strike between N. 20° W. and N. 20° E. and have remarkably straight traces. Wrench faults have not previously been reported in the Central Cordillera of Colombia. The identification of these features, which pass from the cordillera into the Middle and Lower Magdalena basins, is one of the principal geologic discoveries of IMN in IIB and may have important implications in the search for oil in adjacent areas.

Eight major wrench faults have been mapped. The relative ages of these faults can in most cases be determined by offset relationships. Faults which branch at low angles ("horsetail" structure), in the manner that the Palestina, Cocorná Sur, El Mulato, and Jetudo faults branch, are considered genetically related and contemporaneous, or nearly so. Data on each of the eight faults, listed in their probable chronological order from oldest to youngest, are given in table 14.

The wrench faults, especially the younger ones, have the most conspicuous topographic expression of any faults in IIB. They are commonly followed by deep straight canyons and are easily mapped on air photos. On the ground the faults are less conspicuous. Breccia and mylonite zones are nowhere more than 50 m wide, and commonly less. These zones are bordered by parallel belts of shattered rock of similar width.

The Palestina fault is the most convincingly documented of the wrench faults and is described in detail elsewhere (Feininger, 1970). For example, the geologic map may be cut along this fault, and adjusted to restore 27.7 km of right lateral movement to bring into near perfect alinement a remarkable number of geologic features as shown on plate 1, sheets 1 and 2. Outstanding are the following:

1. Marble southeast of La Susana (pl. 1, d-7, sheet 1) on the west block is alined with marble in the Río Samaná Norte 6 km downstream from the mouth of the Río Nare (pl. 1, d-10, sheet 2).

2. Quartzite that bounds the marble to the west on both blocks is matched. The long southward-pointing "tail" of quartzite and associated small bodies of marble adjacent to the Palestina on the west block, not matched by similar features on the east block, were produced by drag along the fault. Structural attitudes in the "tail" are chaotic, and much of the marble in the small bodies is brecciated.

Table 14.--Characteristics of eight major wrench faults in Zone IIB.

Name	Known length	Displacement[1/]	Comments
Nus	76 km	50 km, R?	Named after the Río Nus which near its mouth (pl. 1, d-10, sheet 2) follows this fault. Age relative to El Bagre fault unknown, possibly the two are contemporaneous.
El Bagre	65 km	50 km, L?	Named after the Río El Bagre north of the mapped area.
Otú	120 km	66 km, L	Named after the Otú airstrip southwest of Remedios (pl. 1, d-2, sheet 1). Passes under Tertiary strata at Zaragoza in the north, Pto. Nare in the south. Offset by the Palestina fault.
Jetudo	40 km	12 km, R	Named after a Quebrada east-northeast of Aquitania (pl. 1, c-14, sheet 2). Passes under Tertiary strata in the south.
Cocorná Sur	47 km	26 km(?), R	Named after the Río Cocorná Sur (pl. 1, c-13, sheet 2).
Palestina	350 km	27.7 km, R	Named after Palestina Station where crossed by the Antioquian Railroad (pl. 1, d-9, sheet 2). Has been mapped far beyond the limits of IIB on aerial photographs. Displacement measured north of the Jetudo fault.
El Mulato	32 km	15 km(?), R	Named after a quebrada southeast of Aquitania (pl. 1, c-16, sheet 2).
Cimitarra	150 km	10 km(?), R?	Continuous with fault mapped in Barrancabermeja quadrangle (Servicio Geológico Nacional y Inventario Minero Nacional, 1967).

1/ R, right lateral; L, left lateral

3. Feldspathic and aluminous gneiss on both blocks that abuts against a variety of rock types across the Palestina fault, alines as a single body.

4. Diorite east of the Otú fault forms a single body of batholithic dimensions. Also, small bodies of diorite in the marble fall opposite one another to form a small stock.

5. The belt of Cretaceous shale bounded by the Nus and El Bagre faults on the west block just north of the Río San Bartolomé (pl. 1, e-5, sheet 1), falls opposite the same belt on the east block that is crossed by the Antioquian Railroad at Cabañas Station (pl. 1, d-9, sheet 2).

6. A group of six stocks of amphibole gabbro that occur on both sides of the Palestina fault between the Antioquian Railroad (pl. 1, e-8, sheet 1; pl. 1, d-9, sheet 2) and the Río Cupiná (pl. 1, e-6, sheet 1) are as much as 30 km apart. Restoring the displacement on the Palestina causes these stocks to fall into a relatively tight northeast-trending cluster in which the most distant stocks are only 12 km apart.

7. Metamorphic isograds in the quartzite west of the marble on the west block fall opposite corresponding isograds in the same rock type on the restored east block.

8. Small normal faults in the marble and quartzite southeast of La Susana (pl. 1, d-7, sheet 1), and the regional wrench faults, the Otú, Nus, and El Bagre on the west block of the Palestina fall opposite corresponding features on the east block.

Although the Palestina is a proven wrench fault, other faults here classified as wrench faults are not so easily documented. They are distinguished by the following criteria: 1) no reasonable amount of vertical displacement alone can restore a match of rock types on the opposing blocks; 2) field characteristics such as narrow zones of breccia and mylonite, strong topographic expression, and straightness, are similar to those of the Palestina; 3) most of the inferred wrench faults are straight over long distances; and 4) at least two faults, the Nus and El Bagre, like the Palestina have no gravity anomalies associated with them (Prof. James E. Case, written commun., 1968), suggesting little or no vertical displacement.

The large displacements postulated for the Otú, Nus, and El Bagre faults are based on the absence of rocks correlative across these faults over long distances. The Otú fault, for example, forms the west boundary of nearly all the diorite. This rock appears in the west block only in the south (pl. 1, d-11, d-12, sheet 2), where it increases in area southward and gives the impression that it forms the north end of a large stock or a batholith which passes under Tertiary strata and alluvium in the Magdalena Valley. Reconnaissance mapping on the east block of the Otú north of Segovia (north of the area of the geologic map) revealed that the diorite terminates northward in a fashion similar to that in the west block near the Magdalena Valley. It is tempting to correlate these features and to ascribe their separation to movement in the Otú and Palestina faults.

Marble between the Río Samaná Norte and the Antioquian Railroad (pl. 1, d-10, sheet 2) as well as 6 km southeast of La Susana (pl. 1, e-7, sheet 1) has been cut by the Otú fault. The distribution of the marble as seen on the geologic map suggests that only a small area should occur on the east block. Precisely such a small area of marble does occur on the east block at Cerro Cabeza, 10 km northwest of Segovia. Furthermore, the marble is lithologically indistinguishable from marble adjacent to the Otú on the west block, and is bounded on the east by a thin belt of quartzite which in turn has been intruded by diorite, exactly as is found 10 km west-northwest of Puerto Nare (pl. 1, d-10, sheet 2). These similarities are not likely the product of chance, and it is tentatively concluded that the area of Cerro Cabeza was once contiguous with that near Puerto Nare. If this is true, the Otú fault has 66 km of left-lateral displacement.

The areas of diorite on each side of the belt of Cretaceous shale bounded by the Nus and El Bagre faults are petrographically similar and show no evidence of displacement relative to each other. The belt of Cretaceous shale therefore may have been brought in as a tectonic wedge bounded by wrench faults. This view is supported by the restricted distribution of the amphibole gabbro adjacent to the wedge. The wedge may have come from the north judging by the observation that it narrows southward and is cut by diorite at its south end. If so, the Nus fault would be right lateral and El Bagre fault left lateral. Displacement on each would be large, probably more than 50 km. An alternate interpretation that the Nus and El Bagre are normal faults and that the Cretaceous shale lies in a narrow graben, however, cannot be ruled out, although Prof. Case's gravity data argues against this.

The oldest wrench faults are the Nus and El Bagre, for they are sharply truncated by the Otú which in turn has been displaced by the Palestina. The Cimitarra is judged the youngest wrench fault because of its bold topographic expression. Also, its relatively wide breccia zone suggests that the level of exposure of the Cimitarra is shallower than that of the other wrench faults, and therefore movement on it is younger.

The Otú, Nus, and El Bagre faults are post-Early Cretaceous because they cut shale containing Albian-Aptian fossils (table 4). The gently sinuous traces of these faults, produced by regional deformation younger than the movement on them, contrasts with the straight traces of the Palestina and its associated faults. This indicates an appreciable difference in age between the two groups of faults. The minimum ages of the wrench faults are not known. The Otú is shown to cut quartz diorite probably correlative with the Antioquian batholith northwest of Remedios (pl. 1, d-1, sheet 1), which would require latest Cretaceous or younger movement. However, possibly owing to deep weathering in the area, the fault could be identified neither in the field nor on air photographs between the Otú airstrip and La Cruzada. Furthermore, the petrographic differences between the quartz diorite west of the Otú fault and the rock mapped as diorite to the east are minimal. An alternative interpretation is that quartz diorite related to the Antioquian batholith has cut out the Otú fault in the area and that movement on the Otú is pre-Tertiary.

Relationships seen in weathered rock exposed in a new railroad cut at Palestina Station, support this view. Here brecciated migmatitic feldspathic and aluminous gneiss has been cut by two parallel 75-cm-thick fine-grained intermediate dikes whose texture and general aspect is most like those common in the nearby Antioquian batholith and satellitic body at Caracolí (pl. 1, c-8, d-8, sheet 1). This suggests that movement on the Palestina predates the period of dike emplacement that occurred at the close of the intrusion of the Antioquian batholith. If this interpretation is correct, movement on the older Otú fault must predate the batholith.

None of the wrench faults are currently active. This is shown by the absence of such morphologic features characteristic of active wrench faults as offset drainage, truncated spurs, or sag ponds, as well as by the paucity of seismic activity in the area (Father J. Rafael Goberna, S. J., written commun., 1966).

Wrench faults with large displacements in IIB have important implications for the geologic history of the area. Movement on these faults has transported large segments of the earth's crust considerable distances and has placed some rocks in sites far removed from where they formed. Accordingly, paleogeographic and paleogeologic reconstructions must be made with considerable caution. The extensive disruption of IIB by wrench faults is shown graphically in figure 26.

Megabreccia

Megabreccia is composed of rock masses many of which are tens to perhaps more than a hundred meters across that have been torn from the opposing fault blocks during movement.

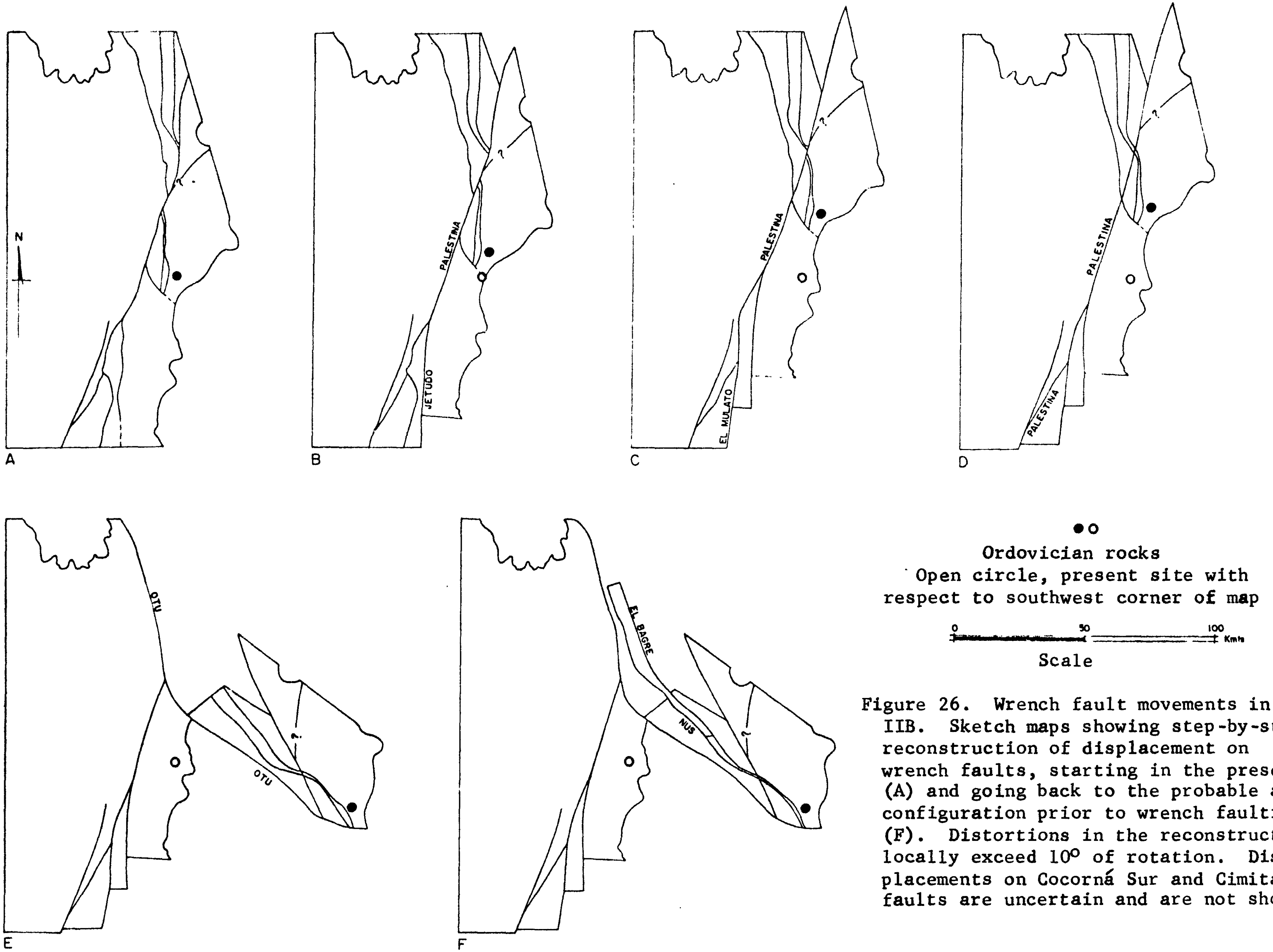


Figure 26. Wrench fault movements in IIB. Sketch maps showing step-by-step reconstruction of displacement on wrench faults, starting in the present (A) and going back to the probable areal configuration prior to wrench faulting (F). Distortions in the reconstructions locally exceed 10° of rotation. Displacements on Cocorná Sur and Cimitarra faults are uncertain and are not shown.

A notable example occurs in slivers of mappable size between branches of the Palestina fault, west of the Cimitarra fault (pl. 1, sheet 1). The largest sliver, in part followed by the Río Volcán, is 11 km long and less than 400 m wide. Outcrops are poor, but those rock types noted during mapping, in approximate order of decreasing abundance, are: diorite, Cretaceous shale, Precambrian feldspar-quartz gneiss, Precambrian marble, and small quantities of feldspathic and aluminous gneiss, quartzite, and marble of the metamorphic rocks west of the Otú fault, amphibole gabbro, and Precambrian amphibolite.

Lineaments

Linear topographic features, chiefly valleys, are conspicuous over most of the Antioquian batholith in IIB. These linear features, or lineaments, have beem mapped from air photos by Taissir Kassem (pl. 1, sheets 1 and 2). Most of the lineaments, especially long ones, strike within a few degrees of N. 50° W.

Some lineaments are due to differential weathering and erosion along faults. Rock exposed in these lineaments is commonly sheared and altered. Excellent examples are along the Nare, Bizcocho, and Miraflores faults. Other lineaments are probably joints, for they intersect at high angles without offsetting one another.

Folds

Regional folds

Bedding and foliation of stratified rocks in IIB are so contorted that the direct mapping of regional folds is not practicable. In the metamorphic rocks west of the Otú fault, however, some regional folds have been recognized in the north half of IIB. Their recognition is based on the distribution of the facies of regional metamorphism, on the outcrop pattern of the marble and quartzite, and on the attitudes of minor folds.

Most of the marble is of low metamorphic grade relative to the rocks adjacent to it. The quartzite is commonly of higher metamorphic grade than the marble but of lower grade than adjacent feldspathic and aluminous gneiss. These relations suggest that the marble was never at as great a depth in the crust as the quartzite, and that the feldspathic and aluminous gneiss was deeper than the quartzite at most places. These observations, and the stratigraphic equivalency of the feldspathic and aluminous gneiss and sericite schist cited earlier, are strong evidence that the marble overlies the quartzite, which in turn overlies the feldspathic and aluminous gneiss and sericite schist.

Further evidence of this suggested relationship is afforded by the plunges of minor fold axes. In the Amalfi area (pl. 1, a-3, a-4, sheet 1), the quartzite lies mostly south of the sericite schist and feldspathic and aluminous gneiss. Axes of minor folds, with few exceptions, plunge consistently south, and show that the quartzite structurally, and by inference, stratigraphically, overlies the rocks to the north. Amalfi is thus located near the axis of a broad regional anticline. Using the same methods as those outlined to define the anticline at Amalfi, eight additional regional folds were recognized west of the Otú fault. The axes of these are schematically depicted on the geologic map (pl. 1, sheet 1). Note that the anticlines are broad and open relative to the narrow and tight synclines. The single exception, the apparently narrow anticline whose axis roughly coincides with the valley of the Río Riachón, is steeply overturned to the west. The map pattern of this anticline has been severly modified by the Riachón intrusion fault which extends along its axis.

Few regional folds were recognized in the metamorphic rocks of the south half of IIB (pl. 1, sheet 2). This is due to the extensive disruption by large wrench faults and the intrusive gneiss in the area. Poor outcrops, absence of marker beds, and locally chaotic structure precluded the recognition of regional folds in the Cretaceous sedimentary and volcanic rocks.

Minor folds

Bedding in the Cretaceous sedimentary rocks and schistosity and compositional layering in the metamorphic rocks have been folded on a small scale in many places. These minor folds range in amplitude from several meters down to a fraction of a millimeter. The smallest folds are mere crinkles imposed on bedding planes of Cretaceous shale or on the schistosity of phyllite and sericite schist.

Particularly impressive disharmonic minor folds are found where thin beds of marble are intercalated with feldspathic and aluminous gneiss (fig. 27). Such folds resulted from the large difference in competency of marble and gneiss; the relatively incompetent marble flowed and filled crests and troughs of minor folds leaving the limbs much attenuated. In some places, where marble and quartzite are interbedded, the quartzite yielded by brittle failure and formed a breccia composed of angular blocks of quartzite set in a matrix of marble. This is well displayed in Quebrada Guardasol one kilometer upstream from Quebrada Alejandría (pl. 1, d-7, sheet 1).

Figure 27.--Disharmonic minor folds. Feldspathic gneiss and thin intercalated beds of marble (white). Quebrada El Bagre, elevation 270 m, 3.3 km N. 17° W. of the confluence of the Ríos Nare and Samaná Norte (pl. 1, d-10, sheet 2).

Foliation

Four types of foliation, each of a different origin, occur in IIB. These are schistosity, slip cleavage, platy flow structure, and cataclastic foliation.

Schistosity

The most common foliation is a schistosity imparted by the parallel or nearly parallel alinement of mica flakes in schist and gneiss. In the sericite schist (and phyllite not mapped separately), mica flakes only a fraction of a millimeter across tend to be concentrated in layers to the exclusion of most other minerals. In coarser grained rocks of higher metamorphic grade, the mica flakes are several millimeters across and are interspersed with nonmicaceous minerals such as quartz, feldspar, or aluminosilicates.

The schistosity was developed by crystallization of micas during regional metamorphism. The orientation of mica flakes was probably promoted by differential movements within the rocks during metamorphism. The nearly ubiquitous parallelism of schistosity and bedding is evidence that during folding and metamorphism, movement was largely by differential slippage of beds past one another.

Slip cleavage

An incipient slip cleavage was observed in the sericite schist in several places, particularly between Amalfi and Anorí (pl. 1, a-2, sheet 1), and in the Río Samaná Sur (pl. 1, c-16, sheet 2). Here the schistosity of the sericite schist is puckered into tiny crowded microfolds with amplitudes less than a millimeter. The limbs of these microfolds are sheared and form discontinuous foliation planes--a slip cleavage--that cut the schistosity and bedding of the schist generally at high angles. This relationship is well seen only in thin section. The slip cleavage is nowhere well enough developed that the schist parts along it in preference to the dominant schistosity.

Platy flow structure

Platy flow structure produced by the orientation of platy and tabular crystals by laminar flow during intrusion of magma is prominent in some of the plutonic igneous rocks. It is especially well developed in the intrusive gneiss, although it has been extensively modified by regional metamorphism and cataclasis. Weak platy flow structure is developed in the adamellite, particularly near the contacts of the stocks south of Sta. Isabel (pl. 1, c-3, d-3, d-4, sheet 1) and east of Yalí (pl. 1, c-5, c-6, sheet 1). Platy flow structure occurs sporadically in the interiors of the Antioquian and Sonsón batholiths, but is generally absent at their contacts.

Cataclastic foliation

Cataclastic or secondary shear foliation was developed by granulation, chiefly in narrow fault zones, and has produced fine-grained rocks that resemble phyllite or fine-grained schist formed by regional metamorphism. These rocks weather readily and outcrops are sparse.

Granulation on a regional scale has affected large areas of feldspathic gneiss west of the La Clara fault (pl. 1, b-3, sheet 1) and southeast of El Tigre (pl. 1, c-4, sheet 1). The gneiss is strongly cataclastic and has an augen texture. Cataclastic foliation parallels the older schistosity developed during regional metamorphism.

Lineation

The most common lineations in IIB are the axes of the minor folds and crinkles discussed above. These lineations have a small range of attitudes. Most have bearings within a few degrees of north and plunges of less than 30 degrees. Over areas of 100 km^2 or less, the attitudes are remarkably constant.

Other lineations, common only in the Precambrian feldspar-quartz gneiss, are produced by the linear orientation of mineral grains, particularly quartz and to a lesser extent biotite. These lineations, which have similar orientations to those described above were briefly discussed earlier under the description of the Precambrian rocks (p. 16).

Gabarros in the Antioquian batholith are commonly spindle shaped. They impart a pronounced lineation where their long axes are oriented parallel with one another (fig. 13). However, such orientation of gabarros is found only locally; regional orientations were not seen. Nevertheless, the elongate gabarros rarely plunge at angles of more than 30^o, and they commonly are nearly horizontal.

Boudinage

Boudinage is the necking during deformation of relatively competent layers sandwiched between relatively incompetent layers where tensional forces are oriented in the plane of the layers (Billings, 1954, p. 354).

Boudins were observed in only two places in IIB: 1) in feldspathic gneiss (fig. 28) in the Río Nus under the bridge at Hda. La Guinea 1 km downstream from the mouth of the Río El Socorro (pl. 1, d-9, sheet 2), and 2) in quartzite in Quebrada Guarquina 500 m downstream from the

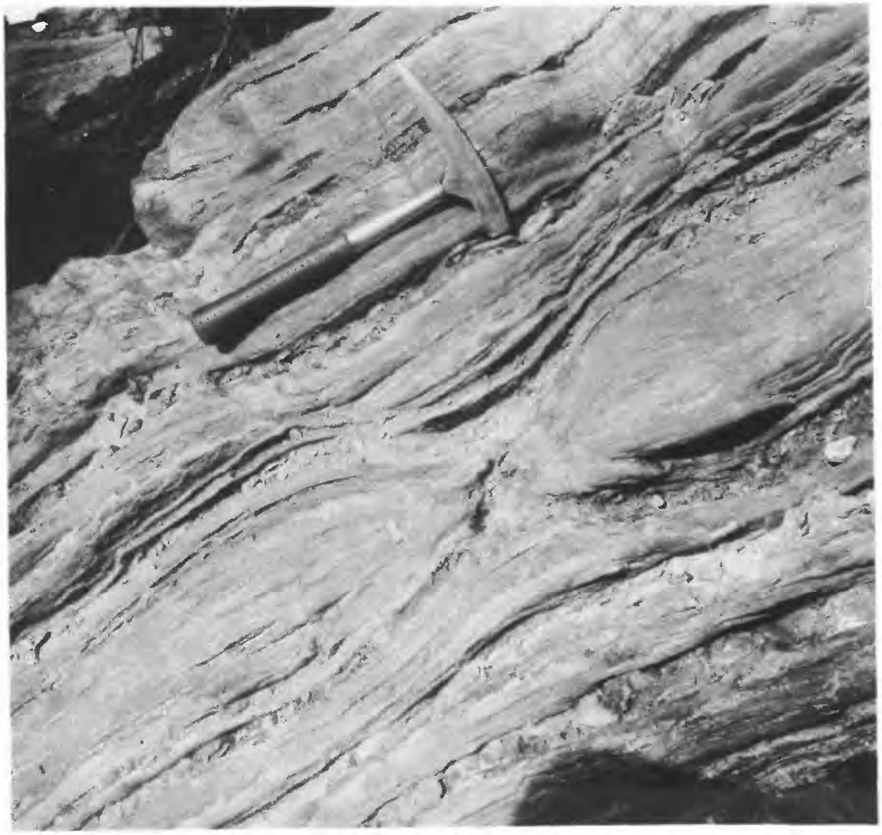


Figure 28.--Boudins in feldspathic gneiss. Río Nus under the bridge at Hda. La Guinea (pl. 1, d-9, sheet 2).

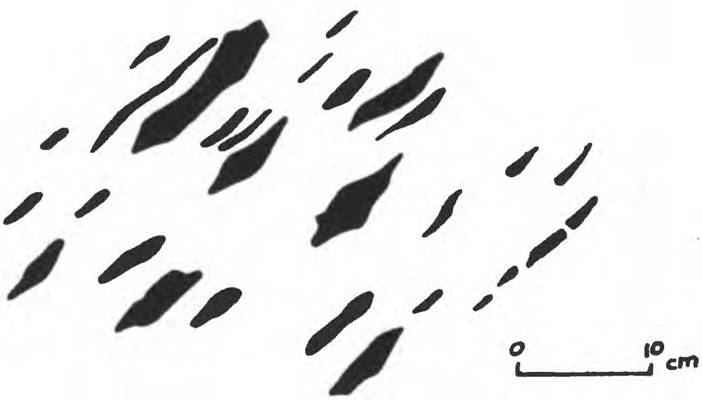


Figure 29.--Boudins(?). Fragments of tough, fine-grained scapolite-biotite-tremolite rock (black) in coarse-grained calcite marble (blank). Vertical exposure in quarry at Hda. Marta Habana, Río La Cruz (pl. 1, b-5, sheet 1).

contact of the Antioquian batholith (pl. 1, c-5, sheet 1). Boudin axes are steep, roughly normal to the attitude of the regional lineations.

Strongly oriented platy fragments of tough scapolite-biotite-tremolite rock in marble at Hda. Marta Habana (pl. 1, b-5, sheet 1) may have been produced by boudinage (fig. 29). The distribution of the fragments suggests that they once formed continuous thin beds in the marble that were necked and pulled apart by tensional forces during deformation.

GEOLOGIC HISTORY AND CORRELATIONS WITH OUTLYING AREAS

Subzone IIB is partly composed of the deposits of three or possibly four different geosynclines that range in age from Precambrian to Cretaceous. Regional wrench faults with large displacements have disrupted nearly all the formations recognized in IIB and may have transported some of them nearly 100 km from their original sites (fig. 26). Geologic mapping by IMN in the Sierra Nevada de Santa Marta (Tschanz and others, in press) and in the Santander massif (Ward and others, in press) allow a firmer base for long-distance correlations than that previously available.

Events discussed here are summarized in table 15, and mineral deposits of IIB are chronologically related to geologic history in table 15.

Small areas of highly metamorphosed Precambrian geosynclinal rocks occur in fault blocks east of the Otú fault. The age of metamorphism of these rocks is not precisely known. The rocks are, however, lithologically identical to granulite facies in the Sierra Nevada de Santa Marta which have given radiometric metamorphic ages as old as 1300 ± 100 m.y. (Tschanz and others, in press). A correlation between the Precambrian metamorphism in the Sierra Nevada and in IIB is likely.

Elsewhere in the Colombian Andes, Precambrian rocks are extensive only in the Santander massif (Ward and others, in press) and in the Garzón massif southwest of Bogotá (Radelli, 1962). On the east flank of the Central Cordillera near Payandé and Rovira (80 km south of IIB), part of what Nelson (1957, map) called Paleozoic granodiorite has been shown in recent mapping by Darío Barrero (oral commun., 1968) to be strongly lineated pink feldspar-quartz gneiss indistinguishable from Precambrian gneiss in the Sierra Nevada and in IIB. The gneiss is bounded on the west by a major fault, well exposed in Quebrada Perico along the road from Armenia to Ibagué; Nelson (1957, p. 65) interpreted the contact as a normal fault. In a detailed discussion of this fault, Nelson (1957, p. 16, 20-22; 1962, p. 178-180) described mylonite, highly sheared rock, and especially, lenses of marble and amphibolite that are foreign to the area. The features described by Nelson, and particularly the lenses of exotic rocks that are here interpreted to have been tectonically transported from afar, are characteristic of the large wrench faults well documented in IIB, particularly the Palestina (Feininger, 1970) and the Otú. It is therefore suggested that the fault exposed in Quebrada Perico is a major wrench fault, and that the Precambrian rocks east of it, like those east of the Otú fault in IIB, have been tectonically transported, possibly from the site of the present Eastern Cordillera.

Metamorphism of the Precambrian geosynclinal rocks was followed by a long interval of uplift and deep erosion that lasted to Cambrian or Early Ordovician time. The depth of this erosion was very great, as it bared rocks that had been metamorphosed in the granulite facies. This grade of metamorphism is achieved only at depths of several tens of kilometers (Winkler, 1967, p. 131-141). No rocks deposited during this interval have been recognized in IIB.

In early Paleozoic time, dark-colored shale, graywacke, and limestone were deposited on the deeply eroded Precambrian metamorphic rocks. Fossil graptolites near Cristalina Station on the Antioquian Railroad (pl. 1, e-9, sheet 2) show that at least some of these rocks are of Early Ordovician age. The deposits have eugeosynclinal affinities, although their thinness and the presence of limestone suggest that they may be transitional with miogeosynclinal rocks. These lower Paleozoic rocks and the Precambrian rocks were cut by small irregular bodies of hypabyssal felsic porphyry.

The lower Paleozoic rocks in IIB are presumably correlative with the extensive Ordovician or Cambrian Silgara Formation, which also unconformably overlies Precambrian high-grade metamorphic rocks in the Santander massif (Ward and others, in press). If tectonic transport of the Ordovician rocks near Cristalina Station by the Otú fault is as large as postulated (fig. 26), the position of these rocks in pre-Otú time was nearly on strike with Silgara rocks.

The sedimentary rocks and felsic porphyries near Cristalina Station were metamorphosed in the lower greenschist facies. This metamorphism may correlate with the low- to medium-grade (and locally high-grade) regional metamorphism of the Silgara Formation in the Santander massif, which on stratigraphic and other evidence is dated as Late Ordovician or Early Silurian (Ward and others, in press). This metamorphism may have produced the widespread shearing and retrograde effects in the Precambrian rocks in IIB.

In the Santander massif, a period of uplift and erosion followed the metamorphism of the Silgara Formation and preceded the deposition of the Floresta and younger formations beginning in the Middle Devonian (Ward and others, in press). In IIB the record is less clear and a major question is raised: What is the age of the parent sediments of the metamorphic rocks of the Central Cordillera, the largest single unit mapped in IIB? As discussed on earlier pages, these rocks are here considered correlative with the Valdivia Group in IIA as well as with the Ayurá-Montebello Group (Botero A., 1963, p. 55-65) near Medellín and the Cajamarca Group or Series (Nelson, 1957, p. 14; 1962, p. 168). Botero A. (1963, p. 65) had previously correlated the Ayurá-Montebello with the Cajamarca. Altogether, these rocks constitute one of the largest rock units in Colombia, an extensive, largely eugeosynclinal assemblage that forms a single uninterrupted belt from a point 300 km north of Medellín, south to the Ecuadorian border (Servicio Geológico Nacional, 1962). The eastward increase in abundance of quartzite and marble tends to indicate a miogeosynclinal environment toward the east. and the westward increase in abundance of intermediate and mafic volcanic rocks suggest a eugeosynclinal environment to the west.

Much has been said and written (Botero A., 1963, p. 62-65, 93) about a possible correlation of the metamorphic rocks of the Central Cordillera (Cajamarca, Ayurá-Montebello, etc.) with the Ordovician metasedimentary rocks near Cristalina Station in IIB, the only paleontologically proven Paleozoic rocks yet found in the Central Cordillera. Unfortunately, mapping by IMN cannot be used either to prove or to disprove such a correlation. The Ordovician rocks differ from the other metamorphic rocks of the Central Cordillera in that they are thin, areally restricted, and isolated structurally by major wrench faults (pl. 1), and the Precambrian floor upon which they were deposited is exposed. Whether these differences offer sufficient ground to rule out the correlation is a moot point. Perhaps the answer will come from radiometric age determinations on metamorphic rocks at Cristalina Station and the metamorphic rocks of the Central Cordillera.

The regional metamorphism that produced the rocks mapped as Paleozoic(?) metamorphic rocks of the Central Cordillera in IIB was accompanied by the intrusion of synchronous granitic rocks mapped collectively as intrusive gneiss.

The major metamorphic-intrusive episode in the Central Cordillera was presumably attended by uplift and erosion, and was followed by the emplacement of postmetamorphic granitic to dioritic (locally gabbroic) plutons. The oldest known of these plutons is the quartz monzonite stock at Amagá in IIA. This stock has given an Early to Middle Triassic K/Ar biotite age of 215 ± 7 m.y. (Pérez A., 1967, p. 30). Nearby and petrographically similar stocks in IIA may be of the same age. The most extensive postmetamorphic pluton recognized in IIB is the diorite, which covers hundreds of square kilometers east of the Otú fault and has been dated as Late Jurassic (160 ± 7 m.y.), on the basis of a single K/Ar determination on hornblende from a sample taken in the railroad ballast quarry at Monte Cristo, near Cabañas (R. F. Marvin, written commun., 1968).

The major batholiths of both the Sierra Nevada de Santa Marta (Tschanz and others, in press) and the Santander massif (Ward and others, in press) were emplaced during this same interval. In the Sierra Nevada, the pink Jurassic batholiths have radiometric ages from 162 to 189 m.y. and the central gray Jurassic batholiths have ages from 162 to 177 m.y. (Tschanz and others, in press). The major batholiths of the Santander massif range in age from 160 to 198 m.y. (Ward and others, in press).

Sedimentary and volcanic rocks deposited in a major Cretaceous geosyncline constitute more than half the Andes in Colombia, and are especially abundant in the Eastern and Western Cordilleras. Correlative deposits in IIB are relatively sparse, but important conclusions contributing to an understanding of the paleogeography and evolution of the Cretaceous geosyncline can be read from them.

In the Eastern Cordillera the rocks are miogeosynclinal, chiefly sandstone, siltstone, and shale, with minor carbonates and evaporites. Although the rocks are nearly all Cretaceous (some are Lower Tertiary), their total thickness exceeds 10 km. Volcanic rocks are absent.

The Western Cordillera is composed chiefly of eugeosynclinal Cretaceous rocks: graywacke, black shale, chert, and mafic and intermediate volcanic rocks. Their total thickness is unknown, but reconnaissance mapping by IMN has shown that it must be several kilometers.

Fossils found in 1964 by IMN geologists Néstor Castro, Alfredo Andrade, and Tomas Feininger in sedimentary rocks and chert near Buriticá (about 65 km northwest of Medellín) are Lower Cretaceous (Barremian to Albian).

Rocks in IIB correlative with the thick mio- and eugeosynclinal deposits of the Cretaceous geosyncline that lie to the east and west, respectively, are neither extensive nor thick. They are restricted to rocks mapped as Cretaceous sedimentary and volcanic rocks. All are eugeosynclinal.

During the existence of the Cretaceous geosyncline in Colombia much of the area of IIB may have stood above sea level as a north-trending arch composed chiefly of the metamorphosed deposits of the preceding geosyncline. This interpretation is reinforced by the sporadic and restricted distribution of the Cretaceous geosynclinal rocks in IIB, and the abundance of fossil plant fragments in them, a feature that shows the nearness of land to most sites of deposition. The arch probably had low relief because little coarse detritus from it was contributed to the flanking geosynclinal deposits.

The age of initial deposition in the Central Cordillera in IIB is uncertain. At Amalfi, shale containing Hauterivian to Early Albian fossils (table 4, no. 4) rests with angular unconformity on sericite schist. Elsewhere, however, deposition could have begun somewhat earlier. A fossil mollusc (Trigonia v-costata Lycett) from a stream cobble in Quebrada El Salado near Segovia (pl. 1, d-1, sheet 1) has a range from Upper Jurassic to Lower Cretaceous (Diana Gutiérrez P., written commun., 1968). This is the only fossil of possibly pre-Cretaceous age yet found in these rocks in IIB. Deposition in IIB ceased at the close of the Early Cretaceous. No fossils younger than Albian are known (table 4).

A major orogeny caused isoclinal folding, faulting, and shearing of the Cretaceous geosynclinal rocks in IIB. The age of this event is known with considerable precision. It followed the close of deposition in the Albian, but predates the oldest known post-orogenic intrusion, the Late Genomanian (96 m.y.) Pescadero stock of quartz diorite at Pescado in IIA.

The orogeny in IIB (early Late Cretaceous) was older than that which affected the Cretaceous geosynclinal rocks in the Eastern Cordillera where sedimentation appears to have progressed without interruption into the Lower Tertiary. Scant information suggests that the same is true in the Western Cordillera. Apparently orogeny began in the median zone of the orthogeosyncline, roughly coincident with the boundary separating mio- and eugeosynclines, and migrated both to the east and west with time. When orogenic folding was taking place in the Eastern Cordillera, for example, orogeny had long ceased in the Central Cordillera.

The Cretaceous orogeny in the Central Cordillera was followed by the emplacement of massive, medium- to coarse-grained epi- to mesozonal granitic batholiths and stocks. These are collectively the most extensive rocks in IIB. Chief among them are the Antioquian and Sonsón batholiths whose aggregate areas (in large part outside of IIB) are nearly 10,000 km^2. Other intrusions are the adamellite, the granodiorite at Tres Mundos, and the quartz monzonite at Aquitania. Pending radiometric age determinations, the possibility that the adamellite is pre-Cretaceous and followed the Paleozoic metamorphism rather than the Cretaceous orogeny cannot be ruled out. Some of the adamellite is petrographically similar to the quartz monzonite at Amagá (of Triassic age) in IIA.

The large wrench faults may have first developed at this time. Those in IIB are post-Albian. Their age relation to the Antioquian batholith remains uncertain (Feininger, 1970, p. 1210).

Major uplift of the Central Cordillera in IIB began in the Pliocene or Pleistocene (Feininger and Gomez M., 1968, p. 111) and may be still active. The youthfulness of the uplift is shown by many geomorphic criteria: entrenchment of major streams in canyons commonly 1,000 meters or more deep with hanging tributaries, stream capture, derangement of drainage, and solution caverns perched hundreds of meters above the modern water table (Feininger and Gómez M., 1968, p. 110). The uplift was epeirogenic, increased progressively in amount from the Magdalena Valley westward, and was not accompanied by faulting. Local relief and summit elevations concomitantly increase westward so uniformly that from any point in the Magdalena Valley in IIB, the Central Cordillera is hidden from view by the first low hills of crystalline rocks that rise above Tertiary strata west of the River. Peaks nearly 3,000 m high and only 50 km to the west are masked by intervening terrain.

The westward increase of summit elevations is remarkably uniform at about 50 m/km. This does not imply that the summit elevations are remnants of an uplifted and eastward-tilted peneplane. If such a surface ever existed, erosion would have long since destroyed it, leaving no vestiges. Rather, the uniform increase of summit elevations is considered the normal consequence of eastward epeirogenic tilt concomitant with erosion by uniformly distributed streams in a humid climate after the manner suggested by Hack (1960).

The epeirogenic uplift was accompanied by volcanism that produced rocks of intermediate to felsic composition. Many active and dormant volcanos are astride the axis of the Central Cordillera from a point just south of IIB to the Ecuadorian border and beyond.

MINERAL RESOURCES OF IIB
By R. B. Hall

Attempt has been made to locate and evaluate actual or potential economic mineral deposits or prospects inside the boundaries of Subzone IIB. Figure 30 shows the location of most of the known mines, quarries, and prospects. It is impractical to attempt to show on figure 30 the locations of the many abandoned small gold mines and prospects.

The mining industry in Antioquia was founded on the exploitation of gold, and a romantic aura continues to linger about this tradition. Even today, most persons think of mining in Antioquia as synonymous with gold mining. This is a deserved association, for Antioquia has been the main source of gold in Colombia, and is a significant gold province from the world standpoint; it has produced roughly one percent of all the gold recovered in the world since the beginning of man's history. Although the importance of gold and silver in relation to the value of other minerals produced in Colombia has declined steadily since the late 19th century, these two precious metals are still the most important mineral commodities produced in IIB. This is due primarily to the output of two major operators, Frontino Gold Mines Ltd. at Segovia, and Pato Consolidated Gold Dredging Ltd. at El Bagre. Cement raw materials and carbonate rock are the principal nonmetallic resources.

Two special exploration projects were carried out in IIB during the IMN investigation. These are: (1) the large-scale mapping, diamond-drilling, sampling, and reserve estimation of wollastonite deposits near Maceo (pl. 1, c-7, sheet 1), and (2) the large-scale mapping, sampling, and reserve calculation of dolomite near Amalfi (pl. 1, a-3, sheet 1). Results are given under the respective commodity headings.

Gold and silver

Historical background

Gold and silver deposits were not especially studied by IMN and most of our information comes from the literature or from personal communication with mine operatiors. The mining of gold and silver has been traditional in this region for more than 400 years--since before the Spanish colonization. The aborigines were extracting gold from veins and alluvium before arrival of the Spanish Conquistadores, although they probably worked only lodes with visible free gold and placers that contained nuggets and coarse gold. The desire to find gold and silver in the New World was one of the principal driving forces behind the expeditions and conquests of the Spaniards, beginning at the close of the 15th century.

Although historical accounts of the fabulous riches taken from individual mines or mining districts probably are exaggerated, there can be little doubt that the value of the gold and silver produced in Colombia from the time of the Conquests up to the present amounts to well over a billion US dollars reckoned at US $35 per troy ounce for gold and US $2 per troy ounce for silver, Most of this came from Antioquia. There are few gold mines or mining districts known today in Zone II that were not known several hundred years ago. Vincente Restrepo's famous memoir, "Estudio sobre las minas de oro y plate de Colombia" (1888, republished in 1937) includes glowing descriptions, extracted mostly from colonial reports and chronicles, of the numerous "rich" mines in this region. Undoubtedly there were some true bonanzas equal to these extravagant descriptions.

The 19th century saw changes and improvements in mining techniques. Notable among these was the stamp-mill, the first primitive model of which was brought into Antioquia in 1828 by an Englishman, Tyrell Moore (Restrepo, 1937, p. 52). This relatively simple machine, which reached its zenith in the gold mines of California, U.S.A., gradually came to replace the hand-crushing and primitive "arrastres" that had been used in Colombia for centuries. Since the early 20th century the stamp-mill has become obsolete in other parts of the world, but it is still in common use in Antioquia where it is called "molino californiano" (California mill), and a homemade adaptation of it is called a "molino antioqueño" (Antioquian mill).

The cyanidation process developed in the years after 1891 (Forbes and Smart, 1921, p. 6), eventually came to be adopted at some of the mines in Colombia, and resulted in recovery of a considerable part of the gold and silver that previously had been lost in tailings.

Placer mining techniques also were improved over primitive hand panning and sluicing. In 1883, the first mining dredge in Colombia was constructed on the Río Nechí by a French company. This venture failed eventually, but it was the fore-runner of a fleet of highly successful dredges that have been operating in Colombia since 1913, financed mostly by English, American, and Canadian capital. Later, hydraulic mining was introduced with the so-called "giants" or "monitors" which shoot powerful jets of water against banks of alluvium, washing it into a riffled channel; sand and gravel pass over the riffles where the denser mineral particles, including gold, are caught and retained between them. This method is adaptable to alluvial deposits too small or in terrain too broken to accommodate a dredge, and is still used in Antioquia.

Gold mining in Zone II continued through the latter half of the 19th century and into the 20th, but its relative importance to the national economy has gradually declined. Labor-saving techniques with relatively high productive capacity like those mentioned above were installed at a few mines, mostly by foreign-financed enterprises, but most continued to be individually small and operated in a comparatively primitive manner. When the price of gold was raised in 1934 from US $20.67 per troy ounce to $35.00, a new epidemic of gold fever swept Antioquia, accompanied by a great flurry of activity and speculation with the participation of hundreds of small syndicates and individual investors, the great majority of whom had little training and experience in geology or mining engineering. Old prospects that had been abandoned for many years were reopened and new concessions applied for, more often than not over uneconomic veinlets or barren quartz veins. Stamp-mills, mostly "molinos antioqueños," were commonly erected at sites prior to evaluation of the size of the ore body or its tenor, and in some cases, prior to even conforming the existence of ore. Most of these prospects and "mines" were closed by 1940 and have not been worked since.

It is popularly supposed that gold mining in Antioquia (and elsewhere) has declined because the deposits are exhausted. Certainly the richer and more easily worked deposits have been depleted. On the other hand, there can be no doubt that much gold remains in the ground and is not being exploited owing to the high cost of extraction. This situation might change dramatically if the world-wide price of gold were to be substantially increased.

Relation of silver to gold

There are no mines in the zone in which silver is the main or most valuable product; instead, silver is a byproduct of gold mining. These two metals coexist as natural alloys, such as electrum, or are occluded in sulfides. The ores of Zone II contain higher values in gold than in silver because of the much higher price for gold, although the actual weight of silver contained in a given ore may be greater than that of gold. Furthermore, an assay of raw ore usually shows a higher proportion of silver than the crude bullion produced from that ore. This seeming paradox is explained by the fact that a higher proportion of silver than of gold is occluded in sulfides and lost in tailing. But it is rarely practical or economical to recover base-metal sulfides at the scale of operations and with the methods used at the small mines being worked today (Frontino Gold Mines Ltd. is an exception). Cyanidation of stamp-mill tailing does reduce silver losses.

Placer gold usually has a higher gold-to-silver ratio than the crude bullion produced at the lode mines. Some of the silver alloyed with free gold in veins is leached out and lost during weathering, erosion, transportation, and final deposition in alluvium, because of the relatively higher solubility of silver in natural waters. The relatively small percentage of silver alloyed with placer gold is not subject to the same degree of loss as silver contained in the ores at small lode mines, because only native metal is taken at the placer mines, whereas the crude cyanidation of stamp-mill tailing does not effectively recover silver occluded in sulfides, especially in galena.

Lode mines

No attempt is made here to describe all the mines in IIB. Those discussed are believed to be representative. Figure 30 shows the location of the active lode mines known to IMN, and some of the more important abandoned mines. Placer deposits also are shown. It is impractical to show all of the numerous small mines and prospects on figure 30, but these are recorded in the archives of the Ministry of Mines and Petroleum in Bogotá and at the Servicio Minero in Medellín.

Frontino Gold Mines Ltd.--This is by far the most important lode gold mining operation in Colombia. It is located at the town of Segovia (pl. 1, d-1, sheet 1), 220 km by road northeast of Medellín. The company, now a subsidiary of International Mining Corporation of New York City, inherits its name from Compañía de Frontino y Bolivia, an English company organized in 1852 (Restrepo, 1937, p. 58).

Two unconnected underground workings are developed, El Silencio at the western outskirts of Segovia, and Cogote, 2.5 km east of El Silencio. Only the El Silencio, by far the larger of the two, is discussed here. The vein strikes N. 20° E., dips 30° E., and has a known down-dip extension of 1,300 m and strike extension of 2,000 m. The north end of the vein consists of two branches which converge to form a single vein south of the main inclined shaft. Vein widths range from a few centimeters to 3 meters, but the average width is slightly less than a half meter. The host rock is a medium-grained quartz diorite, cut by intermediate (dacite?) porphyry dikes roughly a meter thick which lie along the footwall and less commonly along the hanging wall of the vein. The dikes are pre-ore, and it seems probable that they were controlled by major fractures or faults, which, together with the dikes, also controlled the flow of hydrothermal mineralizing solutions that formed the veins. Fissure filling rather than replacement appears to have been the dominant mineralizing process, and alteration of walls is negligible. Gangue is massive milky quartz and minor calcite. Vugs of clear quartz crystals occur locally. Ore minerals, in addition to very fine grained free gold, include pyrite, sphalerite, pyrrhotite, galena, and very sparse scheelite and chalcopyrite.

The mine has been exploited for more than a century, but reserves are believed adequate to support operations for several years to come. Access from the surface is by a three-compartment inclined shaft that follows the dip for several hundred meters; it passes into the quartz diorite hanging wall where the dip steepens. Elevation at the portal is about 610 m (mine datum 724.2 m) and the bottom is about 134 m below sea level. Levels have been developed at 30-m intervals measured down the dip, equal to 15 m true vertical intervals. Stopes are excavated overhead from one level to the next level above, enough pillars being left to assure ground support. The mine has 39 working levels, and the aggregate length of underground galleries is measurable in tens of kilometers. Approximately 1,800 m of new drift and 1,400 m of raise were driven in 1967. Some dilution with wall rock is inevitable, owing to the thinness of the vein, and hand-sorting is practiced underground. Waste is used to fill old stopes. Ore is hoisted to the surface via the inclined shaft, in 2-ton capacity cars. The mine is comparatively dry, but 5,700 liters per minute of electric-driven centrifugal pump capacity is available when needed. Ground support has not been a serious problem, although occasional small rockbursts have been reported. Frontino is one of the few mines in Colombia that regularly uses diamond drilling as an exploration tool for maintaining ore reserves. About 17 holes, mostly underground, aggregating 427 m, were drilled in 1967.

A single mill, the "María Dama," adjacent to headframe of the El Silencio mine is fed by ore from both the El Silencio and Cogote mines, by far the greater part coming from El Silencio. Total ore milled in 1967 was 164,000 metric tons out of 179,000 tons mined. Average tenor of ore milled in 1968 from both El Silencio and Cogote was as follows (M. A. Burke, written commun., 1968):

Au	13.27	g per metric ton
Ag	24.63	g per metric ton
Pb	.50	percent
Zn	.80	percent
Pyrite	8.60	percent

Ore is treated at a rate of 550 metric tons per day in a modern cyanidation plant with auxiliary differential flotation circuits which remove sulfides for separate treatment. Until a few years ago, all sulfides were cyanided, then discarded in tailing. Now, however, separate concentrates, about 500 tons per year each of galena and of sphalerite, are extracted and exported via the port of Buenaventura to the American Smelting and Refining Co. smelter at Selby, California (galena), and to a smelter in Japan (sphalerite). The value of the lead and zinc helps to defray extraction and shipping costs, but it is the added recovery of the contained gold and silver that makes this differential flotation step attractive as compared to the previous system of simple cyanidation of a bulk sulfide concentrate.

Most of the gold and silver in the ore is recovered from the sand tailing from Wilfley tables and by cyanidation of pyrite. Sludges from the Merrill-Crowe precipitation unit are smelted to a bullion of about 500 fineness (that is 50 percent each of gold and of silver), which is shipped by air to Medellín for parting of the gold and silver and sale of refined gold to the Banco de la República.

Production for 1967 is shown below (in grams):

Gold		2,193,287
Silver in crude bullion	2,330,200	
Silver in galena concentrate..	2,532,513	
Total	4,862,713	2,193,287

Total payroll comprises 800 men of which 350 work underground. Administrative and technical staff includes about 40 persons.

El Limón mine.--This small lode mine is 6 km south of Zaragoza on the west side of the road to Segovia, in rolling terrane at an altitude of 150 m. The following data were supplied by Hubert vom Staufen, mining consultant in Medellín and present owner of the mine. The vein is reported to have been discovered in 1938 by a prospector named Nepo Mira, who erected a three-stamp mill and commenced exploitation on a small scale. Mira sold the mine in 1940 to Otto Feckler, a German physician, who worked the oxidized zone during the Second World War, but was obliged to shut down in 1946 because of financial and operational difficulties. Messrs. George R. Leland and Hubert vom Staufen examined the mine in 1947 on behalf of the N. A. Timmins Corporation. This company had just closed the Berlín mine northwest of Yarumal in IIA because of depletion of the Berlín vein after a decade of highly successful operation, and was looking for new ventures. El Limón was too small to be of interest to the Timmins Company, but Leland and vom Staufen bought the mine, improved the mill, and continued work as a partership until obliged to shut down in 1953 for lack of development capital, combined with the problem of resisting marauding bandits who had moved into the territory during the political unrest prevailing at that time. In 1958 the mine was leased to Cía. Minero Chocó Pacífico S. A., a subsidiary of South American Gold and Platinum Co. of New York. This company, whose main interest is in dredging for gold and platinum in the Department of the Chocó, further explored the El Limón vein by underground galleries and 5 diamond drillholes, and by 1961 the proven ore reserve was calculated at 25,000 metric tons with an average gold tenor of 39 grams per ton and a roughly equal tenor of silver. However, in 1962, the parent company (now called International Mining Corporation) decided to concentrate its efforts on the Frontino Gold Mines Ltd. properties at Segovia, which had just been acquired from English interests, and gave up the lease on El Limón. Squatters moved into the mine during the interim shutdown period, and vom Staufen, now the sole owner, was forced into litigation from 1964 until 1966 to recover his property. Development was resumed and a small pilot mill constructed in 1966 (H. vom Staufen, written commun., 1969).

The quartz vein strikes N. 5° E., dips 40° west, in quartz-feldspar-mica gneiss of Paleozoic age. The vein is offset commonly for a few meters in many places by crosscutting normal faults. Gold and silver are associated with disseminated sulfides, dominantly pyrite, that constitute up to 12 percent of the vein matter. About one-half percent each of galena and sphalerite also are present in the area. Vein width is fairly uniform, averaging about 40 cm, with developed strike-length in ore of 300 m and proven down-dip extension of 200 m. The ore-body has not been fully delimited (H. vom Staufen, oral commun., 1969).

Mine equipment includes a 125-cubic foot per minute portable compressor (a 330-cubic foot per minute stationary diesel compressor is soon to be installed), several pneumatic rockdrills, a compressed-airdriven ore loader, three 1-ton mine cars, rails, pipe, and auxiliary equipment. The mill has a capacity of 1 ton per hour and consists of a small jaw crusher, hammer mill, and Wilfley table. Gold in table concentrates is recovered by amalgamation in barrels. Tailing from the amalgamation barrels is being stored for further treatment by cyanidation in a small plant now under construction in Medellín (H. vom Staufen, written commun., 1969).

During the past 20 years development has been sporadic, but the proven reserve and geologic possibilities for additional reserves now justify the installation of a permanent mill. During the first seven months of 1968 about 40,000 grams of gold (and an approximately equal amount of silver) were produced by simple amalgamation from roughly 1,000 tons of ore extracted by hand drilling and transported to the mill on the miners' backs (H. vom Staufen, written commun., 1969).

Small lode mines in Zone II.--In the past more than 400 small lode mines have been worked in the zone at one time or another, and some of them have been known since the 16th century. More than a hundred small mines were reported active in 1937 (Singewald, 1950, p. 133). Today the number has shrunk to scarcely more than a dozen, and these are on such precarious footing that the slightest adversity could close any one of them. A typical small mine is worked by a team of campesinos, who are miners only when not engaged in agricultural work. The mine consists of a series of shallow adits driven by hand into the hillside in decomposed bedrock, commonly the Antioquian batholith, to intersect one or more narrow quartz veins, which then are drifted on with pick and shovel, rarely with drills and explosives, until fresh rock is encountered. This usually is cause for abandonment of the adit because the veins seldom are rich enough to pay for the additional cost of explosives and of drilling blastholes. A new adit is then driven nearby, so that after a time the hillside is pocked with many such openings. Reserves are rarely known because operations are strictly on a day-to-day basis, but probably do not exceed a few thousand tons of vein at any individual deposit. The miners work on the tributer system, receiving a share of the recovered free-milling gold in lieu of wages. The concession holder, typically a businessman or syndicate of businessmen living in Medellín or other urban center, rarely visits the mine, and has scant knowledge of the techniques and problems of the mining industry. The owner provides a stamp-mill, typically a water-wheel-driven wooden "molino antioqueño," and one or two concrete vats for cyanidation. Operations are overseen by the owner's hired supervisor. The gold recovered by cyanidation is the property of the owner; only the gold liberated in the stamp-mill and won by panning is shared with the miners. Total production from one of these operations seldom exceeds 1,500 grams of gold per month, and not uncommonly is only a few hundred grams. The miner's compensation is hardly better than the income earned by his nonmining neighbors, except on those rare occasions when he may strike a rich pocket. The lure of striking a rich lode keeps the miner at this arduous and dangerous job. So long as men are willing to work under these circumstances, small tributer mines will continue to operate indefinitely, but their contribution to the national economy is almost negligible.

Placer mines

Only one major placer mine is currently active in the zone. Other placer operations are mostly small, although a few are of moderate size. Probably more than 55 percent of all gold produced in Zone II is from placers. The placer deposits in the zone may be classified as follows:

1) Extensive, wide and deep alluvial fill in the lower reaches of major streams: potential gold-bearing material measurable in hundreds of millions of cubic meters, best exploited by large dredges. Example: the Río Nechí downstream from El Bagre in the northeastern corner of IIB.

2) Alluvium in floodplains and terraces of large streams: potential gold-bearing material commonly measurable in tens of millions of cubic meters; potentially exploitable by dragline ("doodle-bug"), hydraulicking, or by small dredges. Example: Río Nus near Providencia (pl. 1, b-7, sheet 1).

3) Pre-Holocene alluvium perched well above the base-level of modern drainage; potentially gold-bearing material commonly measurable in millions of cubic meters; exploitable by hydraulicking. Example: La Viborita mine near Amalfi (pl. 1, a-3, sheet 1).

4) Thin local patches of Holocene alluvium in the beds of small streams, or in narrow terraces along their banks, potentially contain exploitable material in individual deposits generally of not more than a few hundred thousand cubic meters. These deposits are exploitable locally by small-scale hydraulicking, but commonly are worked by individuals or small groups with pans ("bateas") and rudimentary sluices. Example: Río Anorí and its tributaries some 20 km north-northeast of the town of Anorí.

Pato Consolidated Gold Dredging Ltd.--Pato Consolidated Gold Dredging Ltd. operates a fleet of 5 electric-powered continuous bucket-type dredges, excavating to depths of 24 to 28 m below water level along the Río Nechí, downstream from the town of El Bagre in northeastern Antioquia. This is probably one of the largest gold-dredging operations active in the world today. The area is in the extreme northeast corner of Zone II, and beyond the area mapped by IMN. The summary presented here is based on a visit to the site in September 1967.

El Bagre is 285 km by road northeast of Medellín and 13 km north of the small historical town of Zaragoza. There is scheduled daily DC-4 air service between Medellín and El Bagre. The company also maintains its own twin-engine aircraft. Elevation is less than 50 m above sea level, and the climate is hot and humid throughout the year, although rainfall is markedly less during December to March than during the other months.

Zaragoza has been famous as a producer of placer gold since the 16th century. Dredging was successfully established in this district in 1913, and the present company, Pato Consolidated Gold Dredging Ltd., inherits its name from an earlier English company called Pato Gold Mines Ltd. (Singewald, 1950, p. 124), named after the tiny riverside village of Pato, 17 km southwest of El Bagre. In 1934, the company became a subsidiary of Placer Development Ltd. of Vancouver, British Columbia, and the number of dredges eventually was increased to 7, then reduced to 5, which are currently in operation (fig. 30). After 1961, the company became a subsidiary of International Mining Corporation, formerly South American Gold and Platinum Company, with headquarters in New York City, which also operates dredges in the Departments of Chocó and Nariño through other subsidiaries.

Besides the 5 active dredges, each of 13½-cubic-foot bucket capacity, Pato Consolidated also has three small dredges standing idle, one of 8½-cubic-foot, the others of 2½- and 6-cubic-foot-capacity buckets, respectively. Two of the idle dredges have been transferred to Cía. Minera de Nariño S. A. in the Department of Nariño, the third to Cía. Minera Chocó-Pacífico S. A. in the Department of Chocó, during 1969 (E. Moseley-Williams, Pato Consolidated Gold Dredging Ltd., written commun., 1969). The Río Nechí channel and flood plain from Dos Bocas (junction of the Ríos Porce and Nechí northward to the present dredging sites has been dredged during the past half century. The Río Porce, above Dos Bocas to its confluence with the Río Mata, a distance of 21 km, was dredged between 1949 and 1961 with outstanding success with a 2½-cubic-foot dredge (E. Moseley-Williams, oral commun., 1967). Broad alluvial flats near the riverside villages of Puerto Claver and Cuturú, 14 and 20 km respectively, downstream (northward) from El Bagre are presently being dredged, and are only partly within Zone II. The dredges are serviced by small powerboats from El Bagre camp, the site of employees' living quarters, school, recreational facilities, commissary, warehouses, and large fully-equipped and staffed repair shops. Power for the dredges, camp, and surrounding communities is generated at the company's hydroelectric stations, one located 3 km north of Dos Bocas, the second and much larger at Providencia, 32 km upstream from Dos Bocas on the Río Anorí. Seventy one kilometers of transmission line were constructed by the company to distribute current. Power is carried to the dredges by long heavy-duty cables mounted on temporary pole-lines which are shifted with the dredges when necessary. The dredges are operated continuously except for maintenance and repairs. Nearly 500 persons are directly employed, and several thousand others derive their support indirectly from the company's operations.

Each of the five active dredges has a capacity of 500,000 cubic yards (382,000 cu m) per month, but under normal operating conditions excavates only slightly more than 400,000 cubic yards (306,000 cu m) per month, or more than 2,000,000 cubic yards (1,529,000 cu m) per month for all five dredges combined. Digging depths of 80 to 91 feet (24 to 28 m) below water level are readily attained. Digging conditions generally are favorable except where clay overburden exceeds a thickness of about 18 m. These thick deposits make a serious operational problem because the sticky and plastic clay clogs buckets, hoppers, and trommels; furthermore, clay balls passing over the riffle tables tend to adhere to and pick up gold particles which are thus lost in tailings. Some of the richer gold-bearing gravel layers are overlain by thick layers of clay and cannot be dredged economically until some means of overcoming this problem can be devised (E. Moseley-Williams, oral commun., 1967). Samples of the clay were subjected to differential thermal analysis at the laboratory of Centrales de Servicios Corona S. A. in Medellín in an attempt to identify mineral components. DTA curves suggest that kaolinite predominates, with appreciable limonite contaminant.

Cobbles and boulders of igneous rock resembling the Antioquian batholith are common in the alluvium, although the nearest known outcrops of this rock are 95 km upstream on the Río Nechí and 100 km upstream on the Río Porce. Of possible interest to mineral collectors are abundant petrified wood and andalusite clasts. Heavy minerals and so-called black sands apparently are too sparse to have byproduct potential. Quantitative data on the average heavy mineral content of dredged ground are not available, but it may be as much as one percent by weight. Composition of black sand from Zaragoza, Antioquia, is quoted by Overstreet (1967, p. 292) from a 1906 paper by D. T. Day and R. H. Richards as follows:

Mineral	lbs/short ton
Ilmenite	1,484
Zircon	302
Quartz	192
Chromite	14
Magnetite	8
Monazite	trace
Total	2,000

The low concentration of magnetite in the above figures is not in accord with observation of black sand concentrates taken on the dredges today, in which magnetite is the dominant heavy mineral. Perhaps the quoted analysis is of a concentrate from which the greater part of the magnetite had already been removed with a magnet.

A semi-quantitative spectrographic analysis of one grab sample of heavy sand concentrate donated by the company was made by the U. S. Geological Survey (F. J. Flanagan, written commun., February 29, 1968). Some of the elements reported are as follows:

Element	Concentration (ppm)	Element	Concentration (ppm)
Barium	70	Nickel	70
Cerium	3000	Niobium	30
Chromium	1000	Praseodymium	300
Cobalt	20	Samarium	1000
Copper	500	Silver	15
Europium	10	Strontium	7
Gold	100	Tin	150
Iron	"major"	Titanium	"major"
Lanthanum	1000	Vanadium	200
Lead	50	Ytterbium	20
Molybdenum	5	Yttrium	300
Neodymium	1500	Zirconium	70,000

The above figures should be considered as within an order of magnitude, at best. Some inconsistencies in the above spectrographic analysis, probably ascribable to limitations of the method, are noteworthy. Zirconium, presumably in zircon, is reported to constitute 7 percent of the concentrate, yet hafnium was not read in the spectrogram. This may have been an oversight; Deer, Howie, and Zussman (1962, v. 1, p. 61) say, "Zircon always contains a certain amount of hafnium:

the HfO_2/ZrO_2 ratio varies but is normally about 0.01." Platinum and its usual companion elements were not detected, but small amounts of chromium, nickel, and cobalt, elements associated with ultramafic intrusive rocks, were detected. Chalcophile elements such as copper and lead are relatively sparse, and zinc was not detected. The number and quantities of rare earth elements reported is surprising. Their source is probably sphene, zircon, and allanite, all common minor accessories in Zone II rocks. The high Ti reported indicates that ordinary magnetite in the sand is accompanied by titaniferous magnetite or ilmenite as well as sphene. The above results suggest that heavy minerals of high commercial value are not present in sufficient concentration to be economically recovered.

Total 1967 production of Pato Consolidated is reported as follows:

Gold	2,762,624 g
Silver	295,094 g

The gold and silver were recovered from 26,606,000 cubic yards (20,342,000 cu m) of alluvium, indicating an average recoverable tenor of 0.1149 g of 903 fine gold per cubic yard (0.1503 g/cu m), which at US $35 per troy ounce for gold and US $2 per troy ounce for silver has a gross value of US $0.1173 per $yard^3$ (US $0.1534 per cu m^3).

Precise data on reserves are not available but doubtless many millions of cubic meters of dredgeable ground of tenor approximately equal to that currently being worked remain to be exploited.

La Viborita mine.--The La Viborita mine ranks a very distant second after Pato among placer mines in Zone II. The deposit is 2.5 km north-northwest of the town of Amalfi (pl. 1, a-3, sheet 1) at an altitude of about 1,450 m, and 1,000 m above the Río Porce, which flows northeasterly in a steep V-shaped canyon 3 km to the northwest of the deposit. An access road serving nearby dolomite and calcite marble quarries passes within a short distance of the mine, but there is no road directly to it. The nearest principal stream is Quebrada La Vibora, which passes to the east of the placer area and joins the Río Porce 6 km north of the mine. The Quebrada La Viborita, which gives the mine its name, flows northward 3 km from the placer area to join the Río Porce 2 km upstream from the mouth of the Quebrada La Vibora.

The deposit was worked by an American-financed company from 1911 until the concession was acquired in 1930 by Viborita Gold Mines Ltd., an English concern (Singewald, 1950, p. 125). During the latter company's tenure, a tunnel about 1 km long was driven through a low ridge to drain the placer area into the Quebrada La Viborita, and the operations became established on essentially the same basis that prevails today. In 1947(?) the property was acquired by Señor Manuel Celedon, who operated on a reduced scale owing to closure of the tunnel. Amalfi Development Company purchased Celedon's right in 1963, cleaned the tunnel, and resumed full-scale operations until June 1966, when ownership was transferred to Inversiones y Mineras, Ltda. In April 1968 the latter company contracted to sell the mine under an installment-payment plan to Señor Guillermo Mora, a prominent Medellín businessman and gold mine operator (Warren Ziebell, former superintendent at La Viborita, written commun., 1969).

The deposit is 2,000 m east-west by 800 m north-south and is as much as 50 m thick. It consists of alluvial gravel overlain by lacustrine clay that fills a basin formed possibly by an ancient landslide that dammed an east-flowing stream ancestral to the Quebrada La Vibora. Age of the deposit is not precisely known, but it predates regional uplift and is now perched a thousand meters above the present local base level. A sample of wood from the clay (sample W-2138) was analyzed by the radiocarbon laboratories of the U. S. Geological Survey, Washington, D. C., and yielded a radiocarbon age "older than 42,000 years," beyond the limits of this dating technique, and the writers assign it tentatively to the late Pliocene or Pleistocene.

The highest values are in gravel immediately above bedrock, which is chiefly sericite schist. The gravel is poorly sorted and ranges from fine to very coarse with the largest boulders reaching as much as 80 cm in diameter. The gravel is compact but not cemented, and disaggregates readily under the powerful jets from the monitors. Many rock types are represented, but vein-quartz, quartzite, and white quartz pebble conglomerate are especially prominent. Rodlike clasts, 2 to 4 cm long, of sericitized andalusite derived from porphyroblasts in adjacent schist are abundant. The gravel is overlain at most places by layers up to 25 m thick of stiff plastic clay essentially barren of gold. Much of this is dark bluish gray or dark green, probably due to ferrous iron. Samples of this clay were subjected to differential thermal analysis at the laboratory of Centrales de Servicio Corona, S. A., in Medellín. The curves are characteristic of the kandite group and show a weak but distinct endothermic peak at 130° C, suggesting metahalloysite. A subsidiary weak endothermic peak at 310° C is due to an impurity, possibly gibbsite or geothite. The clay has the plasticity of a ball clay, but contains too much iron to be useful as a high-grade ceramic or refractory raw material.

IMN has only scant firsthand information on the composition of La Viborita black sands, but riffle concentrates examined under low magnification contained magnetite, some of it probably titaniferous, accompanied by ilmenite, zircon, and sparse garnet, pyrite, aseno-pyrite, and sphene. Cassiterite was reported as an important component in La Viborita black sands (J. M. Restrepo Domenech, mining engineer, oral commun., 1968); however, our examination does not confirm this; if present, cassiterite is very sparse. Other minerals have been reported, including chalcopyrite, columbite-tantalite, beryl, corundum, and wolframite (Walter Ziebell, mining geologist, oral commun., 1967), but we are unable to confirm this.

The hydraulic mining system is employed; several batteries of 2 to 4 monitors shoot powerful jets of water against the bank, washing the gravel into heavy wooden sluices, each 1.3 m wide and 25 m long, fitted with round block riffles in removable sections. Water is delivered to the monitors via 2 km of 30-inch sheet-steel pipe from a reservoir on Quebrada La Vibora, under a hydraulic head of approximately 100 m. Approximately 90,000 cubic meters of alluvium are monitored during an average month. Normally three shifts per day are worked, employing 55 persons at an average wage of about 20 pesos (US $1.16) per day. Once about every 8 weeks the sluices are cleaned and gold separated from other heavy-mineral components by panning. Gold dust is sent to Medellín for refining and sale to Banco de la República.

Reserve estimates are not available to IMN, but the deposit, judged from visual inspection, contains several tens of millions of cubic meters not yet exploited; much of the richer ground may have been hydraulicked during the past half-century. Recovery during 1967 averaged about 0.13 g of gold per cubic meter (Walter Ziebell, oral commun., 1968). The clay overburden is essentially barren, hence the tenor of the gravel must be on the order of 0.25 or 0.35 g per cubic meter. Recovery is estimated roughly at 70 percent (Warren Ziebell, written commun., 1969).

Production of gold and silver for the municipality of Amalfi during 1967 is given by the Asociación Colombiana de Mineros as follows:

Gold	104,710 g
Silver	15,587 g

By far the greater part of this came from La Viborita. From the above figures, the average fineness is 871 gold, 129 silver.

Other Tertiary(?) alluvial bodies near Amalfi are probably gold-bearing also.

Anorí placer district.--The difficulty accessible Anorí area is historically known for placer gold, although it produces much less today than in former times. The district, which lies outside the area mapped by IMN has the form of a rectangle 40 km north-south by 30 km east-west, with the town of Anorí (pl. 1, a-1, sheet 1) at the southwest corner.

Hydraulicking was done by Minera El Hatillo S. A. from 1942 until 1950, at Madreseca near the junction of the Quebrada El Hatillo with the Río Anorí, some 20 km north-northeast of Anorí. Work was suspended in 1950 because of problems of public disorder and breaks in the pipeline that carried water to the monitors (P. Marín, IMN geologist, written commun., 1968). Production statistics and data on tenor or reserves are not available.

Mining is done with 3 monitors near the junction of Quebradas La Tinta and San Bartolo 40 km due north of Anorí; production is at a rate of 1,300 g gold-silver per month, and 20 workers are employed (A. Andrade, IMN geologist, written commun., 1968).

Small groups of miners have constructed log jetties at favorable places along the Río Tenche, 35 to 40 km airline northeast of Anorí, causing sand and gravel to collect behind them. Gold is recovered by panning. Although individual operations are very small, aggregate production may be as much as 9,000 g per month of 870 fine gold during the dry season (late December through March). At other times the water is too deep and the current too strong to allow hand panning (P. Marín, written commun., 1968).

Other placer districts.--Hydraulicking flourished along the Río Nus near Providencia (pl. 1, b-7, sheet 1) before and during the Second World War, but closed down soon afterward. One mine called the Gallinazo was worked with a dragline and floating washing plant (Singewald, 1950, p. 128). Data are lacking on production, tenor, and profitability of these operations. The Río Nare and its tributaries also were exploited in former times, but work today is negligible. Certain reaches of the Nare, especially southwest of Caracolí (pl. 1, c-9, sheet 2), are filled with huge boulders from the Antioquian batholith, some as much as 10 m in diameter, and the river disappears beneath them (Singewald, 1950, p. 126). These nests of boulders, called organales, act as giant riffles trapping coarse particles of gold, and have been mined in former times by men excavating and crawling through passages between the boulders and panning the gravel beneath. These deposits are small but rich, and cannot be mined by any other method. Similar organales in the Río Nechí north of Angostura in IIA are described by Botero A. (1963, p. 34).

Origin of the gold

Placer gold in Zone II has been concentrated by eluvial and alluvial processes during the weathering and erosion of auriferous veins that occur in a wide range of rock types. The origin of the veins is less evident. They are presumed to have been precipitated from residual hydrothermal solutions of the crystallization of magma. The fluids moved upward along faults or fractures in the frozen upper part of the plutonic rock itself, or in roof and adjacent rocks. Precipitation was effected by change of temperature or pH of the fluids resulting from contact with wallrock, or perhaps in some cases by mixing with other fluids migrating along the same channels.

Gold veins in Zone II are invariably composed chiefly of quartz, pyrite, and gold. Helgeson and Garrels (1968) discuss the intimate association of these three minerals from a thermodynamic viewpoint and demonstrate that exploitable veins can be formed by acidic hydrothermal solutions containing only 1 to 50 parts per billion of gold, extremely low concentrations, at temperatures between 175° and 300° C. Plutonic rocks in Zone II, ranging from diorite to adamellite in composition and from Paleozoic to Tertiary in age, all are gold-bearing, as demonstrated by gold-quartz veins in fractures or faults in the dated plutons themselves. These rocks constitute a metallogenetic province in which gold is the principal economic metal.

Gold and silver production in Zone II

Most of the gold and silver produced in Colombia in 1967 came from Zone II, and most of that (about 98 percent) from IIB, as shown in table 16.

The contribution from Zone II was 74.8 percent of all the gold and 88.8 percent of all the silver produced in Colombia in 1967. The statistics do not distinguish between lodes and placers, but we estimate that at least 55 percent of the gold, and roughly 12 percent of the silver came from placers. The very large production from the municipalities of Segovia and Zaragoza is attributable to the high output of Frontino Gold Mines Ltd. and Pato Consolidated Gold Dredging Ltd., respectively. A brief description of gold and silver refineries ("fundiciones") in Medellín is given in Hall and others (1973).

Future of gold mining in Zone II

The international official price of gold was fixed at US $35 per troy ounce in 1934. In the meantime, prices of almost everything else have risen considerably above 1934 levels, and gold mines everywhere have been caught in a squeeze between the fixed price of their product and the continuously rising costs of labor and materials. Gold production has

Table 16.--Gold and silver (in grams) from all sources in Zone II, 1967.[1]

Municipality	Gold	Silver
Amalfi	104,710	15,487
Anorí	24,900	3,509
Cáceres (IIA)	10,492	1,372
Carolina (IIA)	3,722	849
Marmato (IIA)	71,312	60,823
Remedios	12,323	7,693
Santa Rosa (IIA)	8,059	3,652
Segovia	2,493,248	2,485,489
Yarumal (IIA)	21,596	7,806
Zaragoza	3,112,049	351,995
All others	126,821	105,918
Totals		
Zone II	5,989,232	3,044,593
Colombia	8,011,904	3,423,268

[1]From Asociación Colombiana de Mineros, Apdo. Aéreo 874, Medellín. Figures do not include gold and silver in sulfide concentrates exported for metallurgical treatment. All localities in Antioquia except Marmato which is in the Department of Caldas.

declined appreciably in Zone II, as it has elsewhere in the world, during the past two decades. Obviously, a substantial increase in the international price of gold would stimulate exploration and production in all gold mining areas, and could cause an impressive gold mining revival in Zone II. Without a large and permanent price rise, operators will find it increasingly difficult to maintain even present output.

Copper, lead, and zinc

Rock specimens with sparse amounts of galena, sphalerite or marmatite, and chalcopyrite, together with pyrite or other sulfide minerals, were collected at a few places during the field mapping, but no minable deposits of copper, lead, or zinc are known in that part of IIB mapped by IMN. The recovery of byproduct galena and sphalerite at Frontino Gold Mines Ltd. has been mentioned under the section on gold and silver. Sparse amounts of base-metal sulfides are common in the gold-bearing quartz veins at small lode mines, but the very low base-metal tenor and small reserves preclude economic recovery.

Pyrite

Pyrite, FeS_2, is widespread in Zone II, but as accessory crystals a fraction of a millimeter across, sparsely disseminated in a variety of rocks. It has not been found concentrated in massive deposits. Pyrite, rarely exceeding 10 percent by weight and usually accompanied by very sparse amounts of other sulfides, is disseminated in the quartz veins exploited for gold. Frontino Gold Mines Ltd. near Segovia discards about 40 tons per day of pyrite in tailings from ore containing an average of 8.6 percent of pyrite. Some years ago, the company considered building a pyrite roasting plant to make sulfuric acid as a byproduct, but their study showed that 60 tons per day of pyrite concentrate was required for a minimum economic operation, and the project had to be abandoned (M. E. Burke, Frontino Gold Mines Ltd., oral commun., 1968).

Cement raw materials

The manufacture of portland cement is an important industry in Zone II, with three companies located in IIA (Hall and others, 1973) and one, Cementos del Nare S. A., in IIB. However, reserves of carbonate rock are much greater in IIB than in IIA, and it is conceivable that with improved access and infrastructure, the cement industry in IIB could be greatly expanded.

Cementos del Nare S. A.

The plant of Cementos del Nare S. A., constructed in 1933 near the confluence of the Ríos Nare (or Samaná Norte) and Magdalena, is connected to Medellín by 225 km of narrow-gauge railroad. Two rotary kilns have a combined capacity of 500 tons per day of portland cement; one smaller kiln has a capacity of 100 tons per day of white cement. A quarry is located on the banks of the Río Samaná Norte, 15 km upstream from the kilns. Raw marble mixed with clayey soil is made into slurry at the crushing and grinding plant near the quarry and delivered to the kilns via a 13-km-long double pipeline, one pipe 5-inches, the other 6-inches in diameter. Clay-rich saprolite from a small pit near the plant is added to the raw mix when needed. A small amount of alluvial sand is added at times to raise silica to required stoichiometric proportions. Iron-free kaolin from La Unión is added to the marble slurry for white cement.

Reserves of marble in the Nare area are measurable in millions of tons and much of it is 95 percent $CaCO_3$ with less than 1 percent each of Mg and Fe.

An associated company, Colombiana de Carburo y Derivados S. A., operates an electric furnace with capacity to produce 35 tons per day of calcium carbide, CaC_2 (Gomez A., 1966). The furnace operates on electricity produced by Cementos del Nare's hydroelectric power plant near the marble quarries. Raw materials include quick-lime made by calcining marble in a small rotary kiln, and coke from Belencito, Boyacá, or anthracite coal from northeastern Santander. Production is about 10,000 tons per year of which 7,000 tons is consumed in the manufacture of polyvinyl chloride at the company's plant in Cajicá, Cundinamarca, 30 km north of Bogotá, and the remainder is used in acetylene generators and in miners' lamps.

Carbonate rock reserves in eastern Antioquia

Reserves of calcite marble and crystalline limestone are measurable in billions of tons in eastern Antioquia, Subzone IIB. Plate 1 and figure 31 shows the distribution of carbonate rock bodies in a narrow belt between Segovia on the north and Aquitania on the south. Chemical data are lacking, but it seems probable that much of this carbonate rock would prove suitable for the manufacture of portland cement, as at Nare. Most of this region is sparsely inhabited in rugged terrane so that poor accessibility and distance from market, as well as an adequate source of energy, are handicaps to development.

Dolomite

Amalfi

An east-trending lens of marble 4 km northwest of Amalfi (pl. 1, a-3, sheet 1), 144 km by road northeast of Medellín, is about 1 km long and ranges in width from 160 m at its eastern and to 300 m at its western end. It is enclosed in sericite schist of presumed Paleozoic age. The bulk of the lens is fairly pure calcite marble, but the east end is dolomitic. Reserves of dolomite marble, based on a detailed study by IMN geologists Hernando Lozano and Hernán Restrepo, are only 600,000 metric tons. The remainder of the lens comprises an estimated 39 million metric tons of calcite marble.

It is not clear why only a small part of the lens is dolomitic, nor whether it is primary dolomite, or secondary. This body may have originated as a bioherm reef, as suggested for nondolomitic lenses near El Cairo, Antioquia and Neira, Caldas, which are sources of cement raw material (Hall and others, 1973). Marmorization would have destroyed any fossils in the original carbonate. The dolomitic marble is white or cream colored and has a fine-grained (0.5 mm) sugary texture. Adjacent calcite marble in the same lens is medium-grained (2 to 4 mm) and gray.

The two rocks are easily distinguished in the field. Analyses (in percent) of typical specimens follow:

	Marble	
	Dolomitic	Calcitic
CaO	33.29	55.51
MgO	18.07	.01
SiO_2	.42	.60
Fe_2O_3	.14	.11
Al_2O_3	.22	.05
Mn	trace	trace
Ti	trace	trace
P	nil	nil
H_2O -	.04	.00
Loss on ignition	46.77	43.28
Total	98.65	99.56

(Analyses made by Servicio Minero, Ministerio de Minas y Petróleos, Medellín)

Low silica, less than 1.5 percent SiO_2, and low iron, less than 0.4 percent Fe_2O_3, are characteristic of both materials. Not all of the dolomitic part of the lens is as high in magnesia as the above analysis would indicate; some parts contain only 6 to 12 percent MgO, equivalent to magnesian limestone rather than dolomite; theoretical dolomite, $CaMg\ (CO_3)_2$, contains 21.7 percent MgO.

Two separate quarries are in operation, one for calcite marble, the other a few hundred meters east, for dolomite marble. Approximately 11,500 metric tons of dolomite were quarried in 1967, of which 5,900 tons were consumed in glass manufacture by the Cristalería Peldar, S. A., factories in Medellín and Bogotá, and the balance in unspecified miscellaneous uses. Transport from quarry to end-users is by truck to Medellín, and by railroad from Porcecito station to Bogotá.

El Jordán

Lenses of dolomitic marble in quartzite occur near the village of El Jordán (pl. 1, c-11, sheet 2), 140 km by road of Medellín. Diopside is a contaminant mineral in much of this material and presumably limits its potential for use as conventional dolomite. Reserves are unknown.

Carbonate rock for other uses

Reserves of carbonate rock in IIB are very great, measurable in billions of tons. In addition to the quarry worked by the cement plant at Nare, five or six small quarries are worked for lime north of the town of Segovia, 220 km by road northeast of Medellín. The raw marble is calcined in small homemade wood-fired vertical-shaft limekilns to make quicklime, CaO, which then is wetted to make slaked lime, $Ca(OH)_2$. The latter is trucked to Medellín, ground to 100 mesh, bagged and sold to industries in Antioquia, Caldas, Risaralda, and Quindío. Sales of bagged slaked lime are reported to range between 500 and 600 metric tons per month, mostly for water purification, agricultural lime, leather-treatment, bleaching, and the manufacture of chemicals (L. Duque and B. Bran, lime plant owners, oral commun., 1968).

This belt of carbonate rock is reasonably near the railroad which follows the Magdalena River valley and terminates at the port of Santa Marta. The railroad, and indeed the river itself, provide means of transportation for delivering future low-cost agricultural lime to the large areas on both sides of the river valley.

Raw lump marble, mostly from the calcite marble quarry at Amalfi (mentioned under dolomite), is ground by various jobbers in Medellín and sold as whiting and filler to a variety of industries, especially those producing paints and plastics. Precise figures are not available, but an estimated 4,500 tons per year are consumed in this way. The Peldar glass factory in Medellín used 6,400 tons of calcitic marble from Amalfi in 1967.

Lightweight aggregate material

Apparently little attention has been given by the Colombian construction industry to lightweight aggregate materials. Black Cretaceous shale near Amalfi (pl. 1, a-3, sheet 1), 144 km by road northeast of Medellín, bloats at 950°C, and represents a potential source of lightweight aggregate. Further testing would be needed to prove feasibility, but the reserves of potentially bloatable shale are believed to be sufficient to support a commercial operation.

Clay

Clay was not especially studied during the regional mapping, but is abundant in soil and saprolite developed by weathering. Deposits composed dominantly of a single clay-mineral species valuable to industry, such as kaolinite or montmorillonite, were not observed, but a search made especially for such deposits might discover commercially exploitable bodies. Lack of easy access to much of IIB would be an immediate handicap to exploration and to development. Near some of the larger towns there are small hand-operated backyard kilns that make red brick and roofing tile from kaolinitic saprolite. Although crude, these brick and tile kilns supply local needs, and likely will continue to operate for years to come.

Quartz and silica

Ganister for silica brick

The Erecos ("Empresa de Refractarios Colombianos S. A.") refractories plant in Medellín makes about 10 tons per month of silica brick. In addition to sand from Titiribí in subzone IIA now being employed for this purpose, a potential source of good quality ganister is the Cretaceous quartz-pebble conglomerate near Amalfi (pl. 1, a-3, sheet 1). Massive beds as much as 5 m thick are composed almost wholly of pebbles of white quartz 1 to 4 cm in diameter in a tough silica matrix. Chemical analyses are not available, but SiO_2 content is visually estimated at more than 95 percent, and its white color suggests a very low iron content. Tests are needed to evaluate this material as ganister, but probably it would prove suitable for making silica brick.

Quartz crystals

Singewald (1950, p. 175-177) describes potential sources of optical and piezo-electric quartz crystals in Colombia. Two occurrences in IIB are mentioned, one at Santa María, 6 km east-northeast of Maceo, the other at Frontino Gold Mines Ltd. near Segovia. He says "..... at Santa María the deposit proved to be too small, and at Segovia large clear crystals were much too scarce, for either locality to be regarded as a potential source....." (Singewald, 1950, p. 176). No other localities of high-grade quartz crystals were found in IIB.

Wollastonite

Wollastonite, $CaSiO_3$, has come into prominence in the United States as an industrial mineral since 1949, especially as a ceramic raw material in fired floor and wall tiles, and in the manufacture of rock wool. It is not a rare mineral, but exploitable deposits are scarce. The principal commercial operations are at Willsboro, New York, and Blythe, California (Ladoo, 1960).

Geologists of the IMN investigated deposits of wollastonite west and southwest of Maceo (pl. 1, c-7, sheet 1), from August to October 1965 by detailed geologic mapping, and by 5 shallow (20 m average depth) diamond drillholes. The program was handicapped by poor core recovery (Néstor Castro, unpub. data, 1966). Similar wollastonite deposits at San José del Nus, a few kilometers south of the drilled area, were exploited sporadically on a small scale for several years prior to 1966. The wollastonite at both sites is of contact-metamorphic origin, occurring as irregular lenses and seams in locally quartzose calcite marble roof pendants near the eastern margin of the Antioquian batholith. The drilling indicated a reserve of 16,000 tons of wollastonite-rich rock as seams, mostly less than a meter thick, in an area less than one hectare, on the southwest bank of Quebrada La Calera, 4 km west of Maceo.

Wollastonite at San José del Nus had been used between 1963 and 1966, interchangeably with marble with which it is associated, as decorative chips in cold-process cement-base mosaic or terrazzo floor tiles. The quarries have been virtually abandoned since 1966 because the terrazzo tile company found it more economical to use marble chips from Amalfi and El Cairo. The wollastonite was never used as a fired ceramic raw material.

The prospects are favorable for locating reserves greater than those indicated by IMN drilling if uses as a ceramic raw material could be developed for the wollastonite near San José and Maceo. No other potentially exploitable sources of wollastonite are known in Colombia.

Andalusite

Andalusite in schists

Andalusite ($Al_2O_3.SiO_2$), together with its polymorphs, kyanite and sillimanite is used in the manufacture of artificial mullite refractories and electrical porcelains. Andalusite of regional metamorphic origin is particularly common as sericitized porphyroblasts 0.5 to 1 cm in diameter and 2 or 3 cm long, in quartz-sericite schist (pl. 1, a-1, a-3, sheet 1). Only rarely are the porphyroblasts fresh and not sericitized. Sericitized andalusite is of little economic value.

Placer andalusite at El Bagre

Extensive piles of sand and gravel tailing from gold dredging operations in the Río Nechí at El Bagre in northeastern IIB contain rounded water-worn crystals of relatively fresh andalusite. Less than 1 percent, perhaps less than 0.25 percent, of the tailings is andalusite, but if an economic extraction process could be developed, a large reserve exists disseminated in the millions of tons of dredge tailings along this reach of the Río Nechí. The undredged alluvium also has an unknown but low tenor of andalusite pebbles and granules. Placer andalusite has been exploited in alluvial silt in South Africa, but the grade in these deposits is about 40 percent (Van Rooyen, 1951, far richer than the Río Nechí alluvium.

Exploitability

The present potential domestic market for high-alumina refractory raw materials such as andalusite is estimated to be only a few hundreds of tons annually, far too small to support a mine and beneficiation plant at any of the known deposits, either in metamorphic rocks or in alluvium. Extraction and transportation costs would be too high to allow competition with known high-grade sillimanite and kyanite sources elsewhere in the world. The andalusite deposits of IIB must be considered as a potential resource with little chance of commercial exploitation in the foreseeable future.

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Table 15. Geologic history of Subzone IIB and correlations with outlying areas.
[Data in brackets are from Subzone IIA]

		Geologic history	Record	Radiometric ages	Mineral deposits	Outlying areas: Sierra Nevada de Santa Marta[1]	Outlying areas: Santander massif[2]
CENOZOIC	Late Tertiary and Quaternary	Major epeirogenic uplift of thousands of meters.	Youthful topography, major streams in canyons commonly more than 1000 m deep with hanging tributaries.		Gold placers. Saprolite, sand and gravel.	Uplift and glaciation.	Major regional uplift. Coarse-grained flank deposits. Glaciation.
CENOZOIC	Middle to Late Tertiary	Uplift. [Continental deposition in intermontane basins. Emplacement of small intermediate batholiths and stocks.]	[Coal-bearing sediments south and west of Medellín (Grosse, 1926). Small batholiths west of the Cauca River. Diorite and andesite south of Medellín (Grosse, 1926).]	[Middle Tertiary ages on small batholiths west of Cauca River (Prof. G. Botero A., oral commun.).]	High level auriferous gravel near Amalfi.	Uplift.	Continued and stronger uplift. Thick coarse-grained deposits on west flank.
MESOZOIC	Cretaceous and Early Tertiary	Deposition of eugeosynclinal sediments and volcanic rocks (possibly in part pre-Cretaceous). Major orogenesis in Late Cretaceous time. Widespread post-orogenic intrusions; major wrench faults.	Cretaceous sedimentary and volcanic rocks [mafic and ultramafic intrusions, syntectonic granitic bodies]. Post-tectonic intrusions: Antioquian and Sonsón batholiths, adamellite, quartz monzonite at Aquitania, and granodiorite at Tres Mundos. [Pescadero tonalite stock, Sabanalarga pluton, Altavista batholith (Botero A., 1963)]. Palestina, Otú, and related wrench faults.	68-80 m.y., Antioquian batholith; 69 m.y., Sonsón batholith (Pérez A., 1967). [96 m.y., Pescadero tonalite stock.]	Major gold veins related to the Antioqnian batholith. Wollastonite in skarn at Maceo.	Plutonic and volcanic felsic igneous activity. Radiometric ages 130 m.y. Major orogenesis in NW corner. Santa Marta batholith radiometric age 50 m.y.	Marine transgression. Local igneous activity radiometric age 127 m.y. Chert-phosphorite deposition in La Luna Fm. Early Tertiary mild uplift initiates continental deposition with coal beds off east and west flanks.
MESOZOIC	Pre-Cretaceous	Post-metamorphic intrusions, uplift and erosion.	Diorite, chiefly east of the Otú fault, [stock at Amagá].	160 m.y. K/Ar on diorite at Cabañas	Gold in diorite at Segovia.	Intrusion of major batholiths.	Intrusion of major batholiths.
PALEOZOIC		Deposition of Ordovician sediments at Cristalina Station. Contemporaneous(?) or later(?) deposition of great thicknesses of geosynclinal sediments followed by major regional metamorphism of low to high grade, orogenesis, and emplacement of synchronous granitic intrusions.	Ordovician metasedimentary rocks at Cristalina Station, metamorphic rocks of the Central Cordillera [Valdivia Group, Ayurá-Montebello Group, and micaceous gneiss(?)]. Intrusive gneiss [Puquí Metatonalite, porphyroblastic adamellite gneiss and cataclastic tonalite gneiss].	[214 and 239 m.y. K/Ar on micas from metatonalite north of Puerto Valdivia.]	Limestone in Ordovician rocks, major carbonate rock reserves in metamorphic rocks of Central Cordillera. Local development of andalusite in regionally metamorphosed rocks.	Devonian sedimentary rocks unconformably(?) overlain by Pennsylvanian limestone. Major orogenesis 225-250 m.y.	Deposition and metamorphism of Silgara Fm. Radiometric ages 410-450 m.y. Unconformably overlain by Devonian and younger Floresta and other fms. Low-grade regional metamorphism 221 m.y.
PRECAMBRIAN		Metamorphism of geosynclinal deposits, probably in the granulite facies. Followed by uplift and major erosion.	Feldspathic gneiss, amphibolite, and marble east of the Otú fault. Angular unconformity at the base of the Ordovician metasedimentary rocks.			Granulite basement radiometric ages 940-1300 m.y.	Bucaramanga gneiss. Radiometric ages 680-945 m.y. may have been retrograded.

[1] Tschanz and others (in press)

[2] Ward and others (in press)

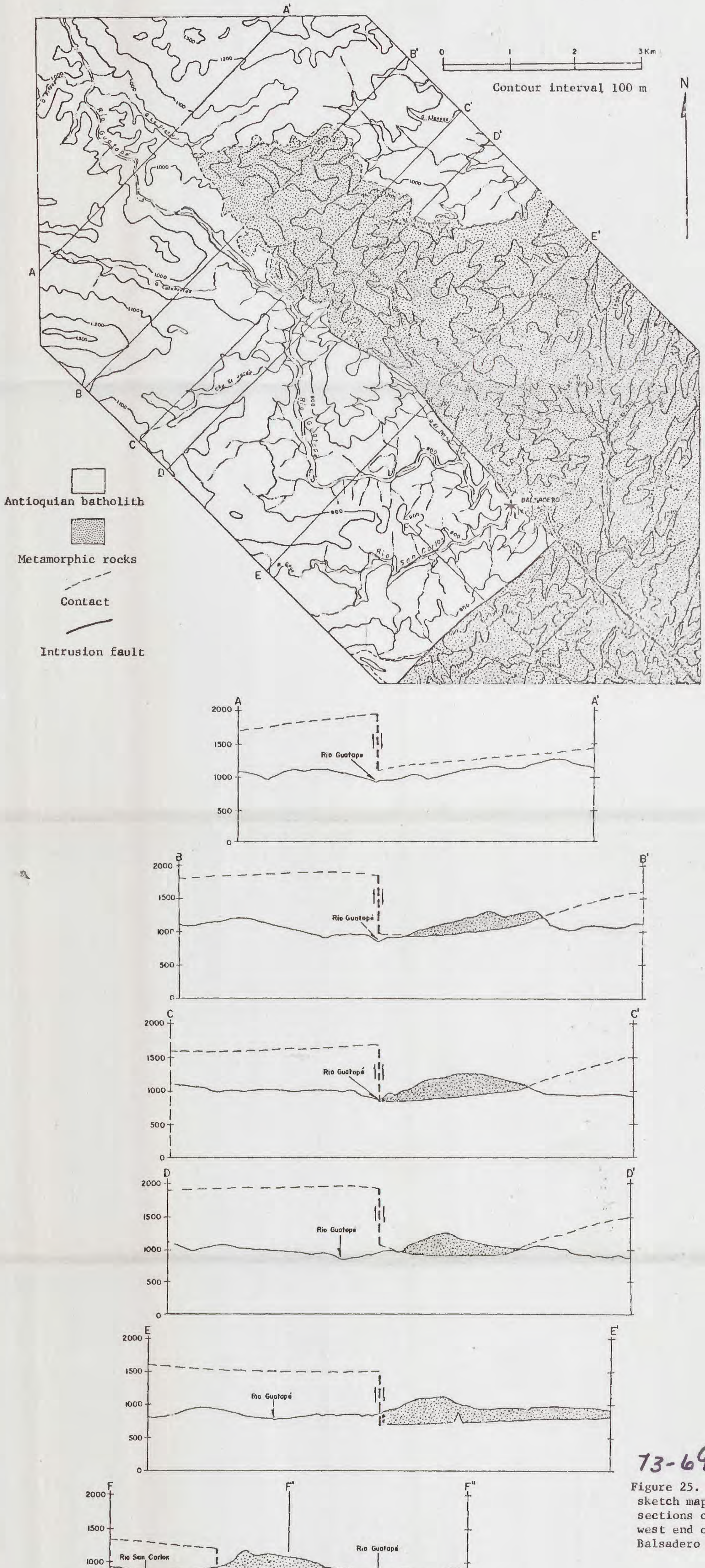

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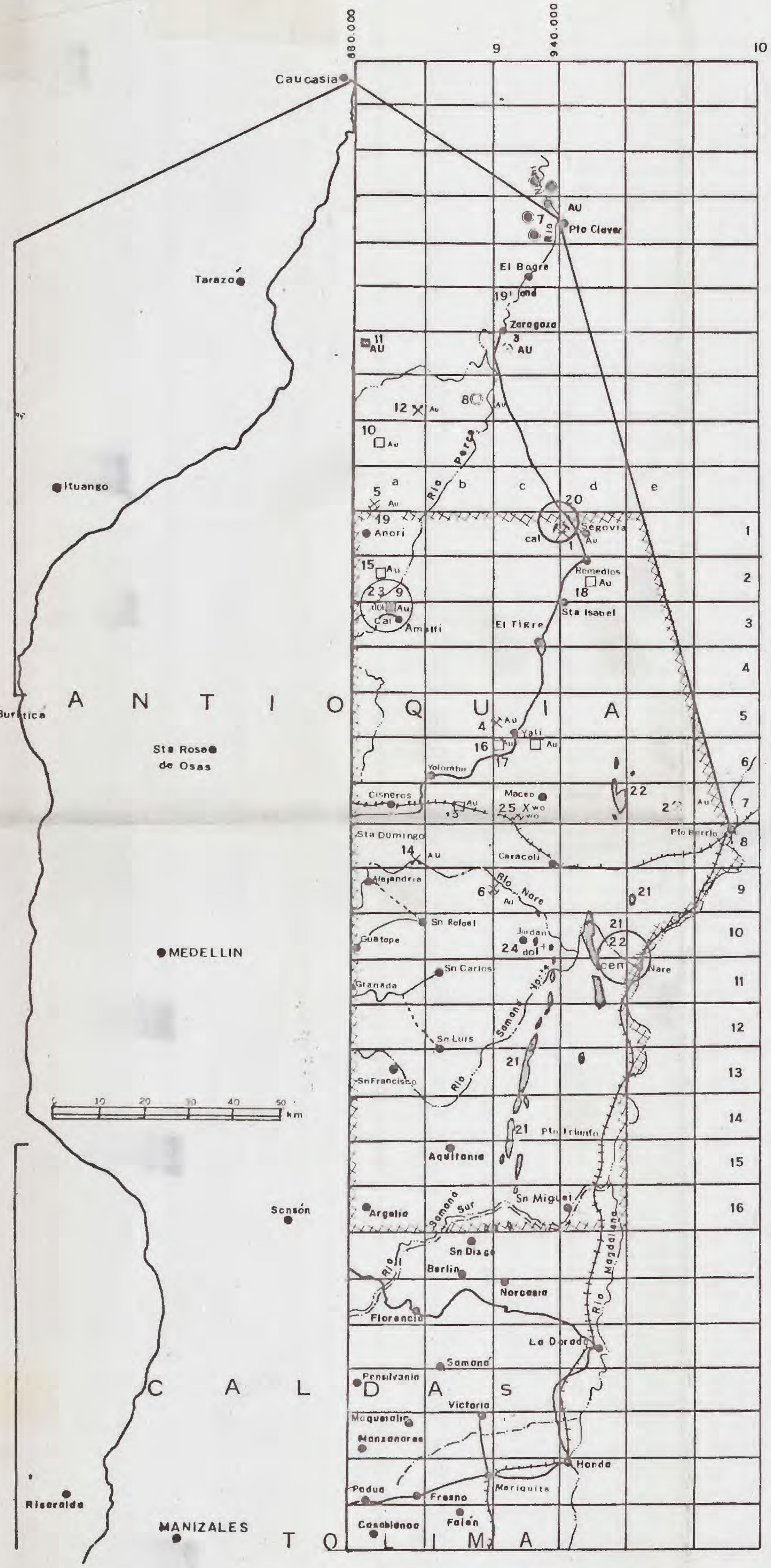
Figure 25. Geologic sketch map and cross sections of the north-west end of the Balsadero fault.



EXPLANATION

GOLD AND SILVER MINES AND PROSPECTS
(Note: No attempt is made to show all the numerous abandoned small mines and prospects

LODES

1. Frontino Gold Mines Ltd.
2. El Carmen
3. El Limón
4. El Corocito
5. La Constancia
6. Los Camelias

PLACERS

7. Pato Consolidated Gold Dredging Ltd.
8. Pato's former small dredge on lower Porce
9. La Viborita
10. Minera El Hatillo S. A. (Modreseca)
11. La Tinta-San Bartolo
12. Rio Tenche hand placers
13. Old hydraulic mines
14. Rio Nare hand placers
15. San Benigno-Norizal hydraulic mines
16. El Limon hydraulic mine
17. Old hydraulic mines on Rio San Bartolomé and tributaries
18. Old hydraulic mines south of Remedios

OTHER MINES, QUARRIES AND PROSPECTS

19. Andalusite prospects, various, see text
20. Carbonate rocks for quicklime, near Segovia
21. Carbonate rock outcrops
22. Cementos El Nare
23. Dolomite and calcite marble near Amalfi
24. Dolomite prospect at El Jordan
25. Wollastonite southwest of Maceo

SYMBOLS

and Andalusite
au Gold (byproduct silver)
cal Carbonate rock
Carbonate rock outcrops
cem Cement raw materials
dol Dolomite
wo Wollastonite

x Prospect of small potential
\+ Outcrop only

>100 tons per day

>10 tons per day, <100 tons per day

Producing lode mine >100 tons per day
Producing lode mine 10 to 100 tons per day
Producing lode mine <10 tons per day
Abandoned lode mine, size as indicated above

Active dredge, 13½ cu ft
Abandoned dredging site, <9 cu ft
Active hydraulic mine
Abandoned hydraulic mine
Active small hand placer
Abandoned small hand placer

Boundary of geological map published by Instituto Nal de Investigaciones Geologico-Mineras

FIGURE 30. MAP SHOWING LOCATION OF PRINCIPAL MINERAL DEPOSITS IN SUBZONE IIB, DEPARTMENT OF ANTIOQUIA, COLOMBIA