GEOLOGY OF THE CENTRAL WESTERN CORDILLERA, WEST OF BUGA AND ROLDANILLO, COLOMBIA

By

DARIO BARRERO-LOZANO

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ABSTRACT

The ophiolitic Central Western Cordillera of Colombia, west of Buga and Roldanillo, is a critical area to understanding the geology of the Western Cordillera and the interrelations of the Americas during Cretaceous and Tertiary time. Field and laboratory data support the conclusion that the Central Western Cordillera consists of three major lithologic units generated in different environments, but joined together by an accretionary process at a continental margin. These units, from older to younger are: The Dagua Group, The Diabase Group, and the mafic-ultramafic intrusives.

The Dagua Group consists of a lower formation, the Cisneros, consisting of pelagic sediments and minor distal turbidites sandstones which were deposited far from any continental mass on oceanic abyssal plains during Lower Cretaceous time. The upper part, the Espinal Formation, consists of pelagic sediments and proximal turbidites, with mixed shallow and deep water fauna, very probably deposited close to a continental rise, perhaps the ancestral Colombian Continental margin. The remarkable difference in environments of deposition, during a relatively short period of time strongly suggests that the Dagua Group represents layer one of a fast moving oceanic plate. Movement of this plate occurred largely during the well known lower Cretaceous magnetic quiet, believed to represent the fastest spreading rates in the Pacific known today.

The second lithologic unit, the Diabase Group, consists of basalts and minor pelagic and pyroclastic deposits. Basaltic rocks of the Diabase Group are low-potassium tholeiites generated during the earliest stage of formation of an island arc. This island arc, which in the study area began to form during the initiation of the Late Cretaceous, was located immediately west of a subduction zone; more precisely, on the arched portion of the plate.

The third unit, the mafic-ultramafic intrusives, were formed beneath basaltic volcanoes in magma reservoirs probably in the uppermost part of the mantle. The dunite, pyroxenite, peridotite and gabbros are crystal cumulates that originally crystallized as stratiform bodies, but which were later diapirically intruded into upper levels of the crust, resulting in a well-
developed zoned, mafic-ultramafic complex. During Santonian to Maestrichtian time, this ophiolitic sequence underwent folding and faulting accompanied by lowgrade regional metamorphism. During early Tertiary time, the Central Western Cordillera was uplifted and subsequently deeply eroded. It is formally proposed that all these events which resulted in the Central Western Cordillera and probably the entire Western Cordillera of Colombia, be named the Calima orogeny. Evidence from surrounding area indicates that the Central Western Cordillera underwent deformation and magmatic activity during late Tertiary time produced by the well known Andean Orogeny.

The geologic history of the Central Western Cordillera implies that major ophiolitic assemblages can be formed during the immature stage of the formation of an island arc.
INTRODUCTION

The geology of the Central Western Cordillera, west of Buga and Roldanillo, Colombia, provides a clear picture of the early succession of tectonic events in the formation of the Western Cordillera of Colombia. Since, in many cases, the early geologic events in the formation of a cordillera are difficult to observe in the rock record of folded and faulted mountain chains, emphasis is herein placed on observations made in the field. The description of the geology of this part of the Western Cordillera suggests that orogenesis in the Andes may result in mountain chains which are a collection of diverse crustal elements complexly assembled. In the case of the Colombian Andes, no single model or theoretical inference will approximate the true picture. Extensive geologic mapping is required prior to establishing with a good degree of confidence the orogenic model applicable to each cordillera.

PURPOSE OF THIS INVESTIGATION

The purpose of this investigation is to establish stratigraphic, compositional and structural relations in the Mesozoic sediments, volcanic and plutonic rocks of the central part of the Western Cordillera of Colombia, west of Buga and Roldanillo. In addition, the geologic data collected are used to develop an independent tectonic model for the area sufficient to provide a firm basis to evaluate the previously postulated plate-tectonic models for the Western Cordillera. Finally, this work is intended to be a contribution to the literature on oceanic island arcs and ophiolite complexes.

LOCATION AND ACCESSIBILITY

The area under consideration is in the central part of the Western Cordillera of Colombia, between 3°44' and 4°30' latitude north and 76°55' and 77°00' longitude west (Fig. 1). It is bordered on the north by the Roldanillo-Bitaco road; on the south by the Buga-Buenaventura highway; on the west by the Copoma River; and on the east by the Cauca River. Access to the towns of Buga and Roldanillo, on the eastern side of the area, is provided by paved roads from the cities of Medellin, Bogota, and Cali. Access into the eastern half of the area is by a few improved and dirt roads. The western half is reached by mule trails and foot-paths.

PHYSIOGRAPHY AND CLIMATE

The present topography of the study area has resulted principally from erosion of faults-controlled blocks of moderately complex lithology. Two very distinctive physiographic provinces characterize the area. These two provinces are separated by the Calima-Cristales fault system which extends more than 100 kilometers farther to the north and south (Fig. 2). The province east of the Calima-Cristales fault system, or Calima province, represents a composite landscape resulting from rejuvenation of an uplifted surface of subdued relief (Fig. 3).

A virgin forest covered the area prior to colonization which probably began in the 16th century (Hall, et al., 1972). This forest has since been removed and replaced by grass and coffee plantations. However, patches of dense forest with high quality commercial wood still remain in the headwaters of some drainage basins, as evidence of the original heavy rain forest which covered the area. Bedrock is deeply weathered and often is covered by more than 50 meters of a mantle consisting of saprolite and lateritic soils. For this reason, outcrops are difficult to find, and the best exposures generally are in deep road cuts and steep slopes, or along the major stream valleys, mainly on the east edge of the province. The saprolite cover is susceptible to masswashing and is responsible for maintenance problems on kilometers 12 and 40 on the Buga-Buenaventura highway. Most rivers and streams flow through wide shallow valleys in their upper courses and through very narrow V-shaped canyons along their lower courses to their base level at the Cauca River. The resulting topography consists of wide valleys with average elevations of 1,500 meters and rounded hills rising up to 1,900 meters.

The climate of the Calima province is equatorial highland with average temperatures of 15°C. Weather is dry most of the year, with a rainy season in April-May and a second period of heavy rains during October-November. Average annual rainfall is estimated at 2,000 mm (I.G.A.C.C., 1970). This province is joined on the east by the Cauca Valley, a flat land with elevation of 1,000 meters having an equatorial low-land, dry type climate (Fig. 9).

The western province, or San Juan province, represents a composite landscape resulting from rejuvenation of an uplifted surface of subdued relief (Fig. 4). It differs from the eastern or Calima province in that it has undergone stronger rejuvenation due to greater uplift. The resulting topography consists of deeply dissected ridges rising to 4,250 meters. Streams and rivers flow through very steep-walled canyons from 100 to 1,000 meters in depth; they end in the broad lowland jungle of the Pacific Coastal plain province where they become tributaries of the San Juan River, which flows into the Pacific Ocean. The entire San Juan province is
Figure 1. Index map of Colombia, showing location of thesis area.
Figure 1. Index map of Colombia, showing location of thesis area.
Figure 2. Physiographic provinces of the central Western Cordillera.
Figure 3. Low relief of the Calima physiographic province in the vicinity of the town of La Primavera. Bedrocks are diabases and basalts of the Diabase Group. View is to the northeast: the Cauca Valley lowland is in the background and the summit of the Central Cordillera is dimly visible on the skyline.
Figure 4. View southwest downstream of the Carrapatas River from Santa Teresa, showing the V-shaped valleys and rough topography characteristic of the San Juan province. Bedrock consists of slate and phyllite of the Dagua Group.
covered by a dense rain forest still virgin in some places up to elevations of 3,000 meters. In some localities flat remnants at the top of high mountains are evidence of the earlier landscape. There, a tundra soil more than 2 meters thick is observed covering an ancient saprolite. This saprolite is interpreted as coeval with the saprolite of the Calima province, now approximately 1,500 meters lower in elevation.

The climate of the San Juan province is equatorial highland humid and equatorial lowland humid, depending on elevation. Weather is extremely humid and rainy most of the year, with a dry season during December and January. Average annual rainfall is between 8,000 to 9,000 mm (I.G.A.C., 1970). This province is joined on the west by the jungle of the Pacific Coastal Plains.

PREVIOUS WORK

The first known geologic observation close to the area under study were made by Nelson (1957) along the railroad from Dagua to Buenaventura. This railroad parallels the new highway from Loboguerrero to Buenaventura and it is 100 meters south of the boundary of the area. A second geologic study was completed by Ortiz and Gomez (1971), but it included only the geology of the magnesite deposit, located one kilometer west of the town of Bolivar in the northeast corner of the thesis area. F. R. Stibane apparently collected one sample of basaltic rock near the town of Loboguerrero. A chemical analysis, an AFM diagram, and other plots are given for this and other samples, from the Western Cordillera in Pehler, et al. (1974). In 1974, a group of five students from the Department of Geology of the Universidad Nacional de Colombia, together with the author, studied the geology of the Buga-Buenaventura road. Their interpretation of the data gathered is included in Aluja, et al. (1975). All other publications mentioning the geology of the Central Western Cordillera refer to or quote the work done by Nelson (1957). The only available map of the geology of the area is the general, 1:1,500,000 scale geologic map of Colombia.

FIELD AND LABORATORY WORK

Field work was completed between September 1974 and February 1976. Side-looking radar imagery was used to locate major structural features. However, most of the field mapping was on conventional black and white aerial photographs (scale 1 to 40,000) and hydrographic maps prepared by the DANE. The base map for Plate 1 was compiled from the three sources mentioned above. The road profile for Plate 2 was compiled from maps (scale 1 to 10,000) provided by the Ministerio de Obras Publicas.

Description of the Central Western Cordillera lithology is based upon field observations and routine petrographic descriptions of about 100 thin sections. Detailed petrographic work was done on selected thin sections. 2V were determined for clinopyroxenes of the basaltic rocks using the Universal stage. Plagioclase composition was estimated by the Kittman zone method for the basaltic rock and by Michel-Levy for the intrusive gabbroic rocks. Chemical analyses of 13 samples of basalt and diabase were completed by wet methods in the laboratories of INGEOMINAS, Colombia, The C.I.P.W. norm for 13 samples was calculated in the computer center of the U.S. Geological Survey, Denver, Colorado. Trace element analyses for 13 samples were made by emission spectroscopy and atomic absorption techniques in the laboratories of INGEOMINAS, Colombia.

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REGIONAL GEOLOGICAL SETTING

The thesis area comprises a 60-kilometers-wide strip across the central part of the Western Cordillera of Colombia. It is composed of a Cretaceous ophiolitic assemblage (pelagic sediments - basaltic-gabbro-ultramafics) similar to that forming the 1,500 kilometers-long Western Cordillera of Colombia and Ecuador, which is considered one of the major ophiolitic cordilleras of the world (Gansser, 1959).

Except for a few cross sections, the Western Cordillera in Colombia is little known (Nelson, 1957; Bürgi, 1967; Radelli, 1967; Butterlin, 1969; Case, et. al., 1971 and 1973; Gansser, 1973; Krummenacher, 1976; Abuja, et al., 1975; Irving, 1975). This ophiolitic cordillera was folded and faulted in late Upper Cretaceous during the Calima Orogeny. Folks are mostly of the isoclinal type with a marked tendency to be inclined toward the west. Faults are of the high-angle reverse type in the western side of the Cordillera and mainly of the normal type in the eastern side toward the Cauca Valley basin. The Western Cordillera underwent low-grade metamorphism during the Upper Cretaceous, probably during the late Santonian to Maastrichtian. Metamorphic minerals of the zeolite, prehnite-pumpellyite and green schist facies have been identified at several places (Irving, 1975). Intruding this highly folded and faulted low-grade metamorphic sequence there are upper Cretaceous mafic-ultramafic complexes, some of them of the Alaskan-type, scattered throughout the entire cordillera. Of special interest are the quartz diorite stocks and batholiths cutting the previous metamorphosed and folded sequence. They extend from north to south along the entire cordillera. They range in age from Eocene to Miocene, but younger ages may be reported in the future. Most of the quartz diorite intrusives of the western Cordillera that have been radiometrically dated are in the range 36 to 24 m.y. (Irving, 1975). The youngest igneous rocks known so far in the cordillera are the small stocks, plugs and dikes, andesitic to dacitic in composition, that cut all the previously mentioned rock units.

The thesis area is paralleled on the east by the sedimentary sequence that filled the Late Jurassic - Early Cretaceous "Cauca Valley" trench and by the Romeral fault with its associated melange (Barrero, 1969; Case, et. al., 1971; Barrero, 1974 and 1976). To the west the area is paralleled by the trench-like filled depression known as the Atrato-San Juan basin of late Cretaceous early Tertiary age. Abyssal water depths of more than 4,000 meters have been suggested for the ancestral trench on the basis of fossils in sediments of the Atrato - San Juan basin; the total thickness of these sediments is considered to be close to 10,000 meters (Nygren, 1950; Bandy, 1970; Duque-Caro, 1971; Case, et al., 1971). These two major tectonic units bordering the area are flanked on their eastern sides by high-angle reverse faults and in their western sides by apparent normal faults. The high-angle reverse faults have been during recent years a major point of controversy among geologists working in the Colombian Andes. Barrero (1974) has suggested for one of these faults (the Romeral fault) a complex geologic history consisting of a first period of reverse faulting during the trench stage of the Cauca Valley basin; followed by a period of normal faulting during uplift and melange formation along the eastern side of the present Cauca Valley basin; and a letter period of strike-slip displacement producing and extensive zone of cataclastic rocks (Gonzalez, 1974). In the past, several people have followed the suggestion of Campbell (1965) and have considered these high-angle reverse faults as major strike-slip feature (Case, et. al., 1971; Malfait and Dickelman, 1972; Gossens, 1973; Campbell, 1974; Restrepo and Toussaint, 1974; Irving, 1975). The principal tectonic elements of Western Colombia and the location of the thesis area are shown in figure 5.

CRETACEOUS DAGUA GROUP

The name Dagua Group was given by N. F. Nelson (1957) to a series of phyllitic slates, limestone, sandstone, black chert and siliceous slates exposed along the Cali-Buenaventura road. Nelson divided the Dagua Group into lower, middle, and upper units. In the present work the lower and middle units of the Dagua Group are combined into the Cisneros Formation about 2,000 meters thick, and the upper unit is named the Espinal Formation, which is about 900 meters thick. The author proposes these names in order to designate the two easily mappable units of the Dagua Group. The generalized stratigraphy of the Dagua Group is given in figure 6. In order to discuss the sources of the sediments of the Dagua Group the author uses the classification of deep-sea deposits given in Retneck and Singh (1975).

CISNEROS FORMATION

The name Cisneros Formation is proposed to embrace a complex assemblage of low-grade metamorphic rocks, consisting mainly of still recognizable pelagic and terrigenous deposits well exposed along the roadcuts between the hamlets of Loboguerrero and Cisneros (Plates 1 and 2).
Figure 5. Principal structural Provinces of Colombia and location of thesis area. Modified after Irving (1978).
<table>
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<tr>
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<td>ESPIRAL FORMATION</td>
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<td>Pelagic sediments and proximal turbidites deposited on the ocean floor at depth below the calcite compensation level.</td>
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Figure 6. Generalized stratigraphic column of the Dagua Group.
LITHOLOGY

The bulk of the formation consists of black to gray phyllite and slate, gray metasandstone, gray metalcilstone, black to pale green metachert and a very conspicuous green and red slate. The green and red slate is a useful marker bed, and together with the graded metasandstone, it was used to work out the major structures of the area (Plate 2). However, no intent is made here to divide the Cisneros Formation into members because the two units separated by green and red phyllite are very much alike. Therefore, the formation has merely been divided into its major rock types for purposes of discussion.

Siliceous and Carbonaceous Phyllite and Slate

Phyllite and slate are medium-beded to thinly laminated. The color of fresh samples is dark gray and the color for weathered samples is olive-gray. These rocks break along cleavage planes which are subparallel to the original bedding. The phyllites and slates are made up mostly of fragments of quartz and plagioclase, carbonaceous material, iron oxides, and newly formed biotite, muscovite and chlorite. Phyllitic varieties show better development of mica plates.

Metasandstone

Medium- to thin-beded metasandstone is present in the upper part of the Cisneros Formation very often a few meters above the green and red slate horizon. Maximum thickness is 14 meters, but several other individual beds of metasandstone attaining thicknesses less than 1 meter are present at various stratigraphic levels throughout the Cisneros Formation. Grain size of metasandstone ranges from coarse sand to silt; however, fine sand to silt sizes predominate. The metasandstone is moderately sorted and the grains are subangular to rounded. Matrix is always less than 10 percent and consists of quartz, opaque minerals, and newly formed biotite, chlorite, and muscovite. Mineral grains are mostly quartz, plagioclase and biotite. Quartz generally shows undulatory extinction and dust trails, suggesting a metamorphic origin. Plagioclase is fresh and shows good albite twinning. It ranges in composition from oligoclase to andesine, a composition observed to occur in the Jurassic quartz diorite and granodiorite intrusives of the Central Cordillera. The biotite is present as anhedral laths with ragged terminations and zircon inclusions without pleochroite halos, suggesting a metamorphic origin. Most of the biotite is altered to chlorite. A remarkable aspect of the metasandstone is the scarcity or absence of potassium feldspar grains. Small amounts of lithic grains are found in most sandstones.

They consist of fragments of chert, phyllite or quartzite; fragments of basic volcanic rocks are absent. Detailed petrographic studies of eight samples indicate that the composition of the metasandstone beds varies from arkose to arkosic graywacke (Aluja, 1975). However, the metasandstone is predominantly a plagioclase arkose and the source area most probably was in the large Jurassic quartz diorite batholiths and metamorphic rocks of the Central Cordillera.

Internal sedimentary structures in the metasandstone are: graded plane parallel lamination, current ripple and convolute lamination. These structures are found on a macroscopic as well as microscopic scale. The most common external structures in the metasandstone are: scour marks, load cast and parting lineation. The succession of internal structures is consistent with the sequence reported by Bouma's A interval, which is not present, the metasandstones are usually composed of base-cut-out sequences of the type BCDE, BDE and CDE. These sequences represent the Facies D or distal turbidite in the classification of turbidite facies by Walker and Mutti (1973).

Metalimestone

Dark to light gray, carbonaceous to pure limestone beds are found at various intervals throughout the Cisneros Formation. Individual beds are less than one meter thick and they are usually interlayered with dark gray slate and black radiolarian chert. Some of these calcareous layers are better classified as homogeneous lime mudstone or very thin laminated lime mudstone. The finegrained limestone contains variable amounts of quartz and plagioclase. The only sedimentary structures observed are microscopic grading and a sequence of very fine parallel lamination, cross-bedding and current ripple lamination. Some of the laminated mudstone contains up to 10 percent siliceous and calcareous globules which could represent remains of radiolarians and foraminifers. The admixture of pelagic layers, the presence of quartz and plagioclase grains, and the internal structures are consistent with the sequence reported by Meischner (1964) for limestone turbidites (Allodapic limestone). An important observation is that the metalimestone beds lack the interval A of the limestone turbidite sequence proposed by Thomson and Thomason (1969). The most common arrangement of internal sedimentary structures observed in this rock consists of the intervals BCD and CD of the sequence of Thomson and Thomason (1969). Therefore, the graded lamination, the arrangement of internal sedimentary structures, the association with radiolarian chert, and lack of burrowing and shallow water structures, strongly suggest that the
limestone was deposited by a distal turbidite in a similar manner as the metasandstone. The possibility exists that some of the lime mudstone beds, without any internal sedimentary structure but with up to 10 percent or more of fossil remains, may be pelagic deposits of biogenic origin rather than turbidites. Preservation of carbonate material is possible due to rapid burial produced by the turbidite deposition.

Metachert

The metachert of the Cisneros Formation consists predominantly of thin beds of metacherts alternating with very thin bedded to laminated siliceous slate. In places these metasedimentary rocks make up sections more than 50 meters thick. The larger sequence of metachert is closely associated with the green and red slate found in the middle part of the formation. The color of the metachert varies with the content of organic matter, clay minerals and chlorite. The most common colors are dark-gray, light-gray and green. Hydrothermal activity or contact metamorphism give the chert a white or very light-gray color. This is especially true at the contacts with diabase sills. The metachert is usually found as beds 5 to 20 centimeters thick, or less common, as very thick laminae. A very thin, even parallel, lamination is observed in some chert beds. The fossiliferous metachert consists of a matrix of cryptocrystalline to microcrystalline quartz and organic matter enclosing radiolaria and small amounts of foraminifera. The non-fossiliferous types consist of either silica minerals and organic matter or silica minerals and chlorite. Some metacherts are composed of 50 percent radiolarian remains, 40 percent organic matter and 10 percent of cryptocrystalline silica. Therefore, the name radiolarian chert applies better to those varieties. The metachert shows evidence of having undergone different degrees of recrystallization and very often it shows a complicated network of veinlets composed of quartz, calcite and zeolites. Recrystallization of the chert by metamorphism may be responsible for destroying or obliterating some internal features of the chert, such as microfossils and fine lamination.

Both organic and inorganic processes may have formed the chert of the Cisneros Formation. The author believes that dark-gray chert rich in radiolarian and organic matter can be primarily of biogenic origin, with the organic matter probably representing the soft parts of the organism. For the light-gray to green cherts, without organic matter and fossil remains, a volcanogenic origin seems more probable.

Green and Red Slate

The green and red slate is a very conspicuous marker unit in the Cisneros Formation. It consists of about 40 meters of green to bluish-green slate and some 10 meters of red to brown-colored slate toward the top of the slate sequence. The only sedimentary structure present in these slates is a microscopic, even parallel, lamination which is better observed in thin section. Microscopically the green slate consists of silt-size grains of quartz, chlorite and epidote. The origin of these minerals seems to be low-grade metamorphism. The red slate consists mainly of quartz, chlorite, epidote and tiny particles of hematite. Therefore, the reddish color of the slate is a result of the oxidation state of iron. The sources of the material for these slates were most probably volcanic ash and wind-blown dust. The red slate, in the opinion of the author, represents the low-grade metamorphic equivalent of the red-to-brown colored clay which covers vast areas of the modern deep-ocean basins (Reineck and Singh, 1975).

CONTACT RELATIONS AND THICKNESS

The lower contact of the Cisneros Formation was not observed in the area studied. It is believed to be a depositional contact between pelagic sediments and weathered basalt. If present, it should occur somewhere in the western slope of the Western Cordillera. This presumption is based on the results of geophysical studies (Case, et al., 1971), suggesting the absence of continental crust in the Western Cordillera. The upper contact of the formation is a gradational contact with the overlying Espinal Formation. It should be placed at the base of a thick rhythmically bedded sequence of black chert and siliceous shale showing no visible metamorphic effects. In the field few chances of mistaking these two formations exist. Moreover, the two sequences in the area are always separated by sills of basaltic rocks.

The thickness of the sequence was estimated south of the area by Nelson (1957), to be several thousand meters. This estimate seems to be rather high, mainly because Nelson (1957) failed to recognize the many isoclinal folds present in the area. The author, using the green and red slate as a marker unit, has estimated from the cross-section (Plate 2) and from direct measurements in the field, an approximate thickness of 2,000 meters.

SOURCE AND ENVIRONMENT OF DEPOSITION

Three major sources were distinguished for the original sediments of the Cisneros Formation: biogenic, volcanic, and
terrigeneous. The biogenic and volcanic derived sediments consist of hydraulically light fragments that settled from the overlying water as particle by particle deposition in the absence of any major current activity as is indicated by microscopic parallel laminations. They are represented by the radiolarians, foraminiferal metachert, foraminiferal metamollusk, and the green and red slate. These metasediments grouped together constitute the pelagic sediments of the Ciñeros Formation and represent periods of plankton proliferation as well as intense subaerial volcanic dust emission. The source of the volcanic dust was probably a volcanic chain developed upon the ancestral Central Cordillera of Colombia during late Jurassic and Cretaceous time.

In contrast with these pelagic deposits and alternating with them are the metasandstone, some of the metagraywacke, and the gray phyllite and slate of definite terrigenous origin. These types of deposits are much coarser-grained than the pelagic deposits and were brought in and deposited under the influence of gravity mostly by turbidity currents from a somewhat distant continental margin. The source rocks for these deposits were the quartz diorite intrusives, the low-grade metamorphic rocks, and the basic volcanic rocks of the ancestral Central Cordillera located to the east of the area of deposition.

The marine character of the Ciñeros Formation, was confirmed during this work by the finding of planktonic radiolarian and foraminiferal remains. The complete lack of distinctive shallow-water sedimentary structures, the distal character of both the turbidite sandstone and limestone, and the interbedding of turbidites and pelagic sediments, the scarcity of carbonate deposits and the presence of the distinctive red slate strongly suggest that the Ciñeros Formation was deposited in a deep-sea environment, most probably toward the landward side of an abyssal plain. This latter point is well supported by recent studies of the deep-sea sediments off the East African coast (Reineck and Singh, 1975) and by the distribution of interbedded turbidites and pelagic sediments in the modern seas (Heese and Hollister, 1971).

AGE AND MICROFOSSIL CONTENT

The first reference of fossils in this formation was given by Aluja, et al. (1975) who refer to radiolarian and planktonic foraminiferal remains replaced by silica. Duque-Caro (1975) determined the fossils collected by Aluja as cf. Globoconoceras and he assigned a probable Aptian age to the sediments. Samples collected by the author from the marine locality reported by Aluja, et al. (1975) at kilometer 66.6 on the Buga-Buenaventura highway, show more than 30 percent of preservation radiolarian and silicized foraminifera of the Globigerinidae family. Duque-Caro (1976, written communication) believes these fossils are not older than Aptian. However, these fossiliferous samples belong to the pelagic-turbidite sequence on top of upper part of the Ciñeros Formation. If a slow rate of sedimentation of the pelagic sediments is considered, and also the fact that thin beds of pelagic deposits represent long periods of time is taken into account, a somewhat older lower Cretaceous age for the lower part of the Ciñeros Formation is very probable.

ESPINAL FORMATION

The name Espinal Formation was given by Hubach (1934) to a sequence of black cherts and siliceous limestones. This name is here redefined and refers to a heterogeneous sequence of well indurated sedimentary rocks consisting of pelagic and terrigenous deposits which crop out north of the hamlet of Lobo-guerrero (formerly called Espinal) and extend north as a narrow strip as far as the town of El Dovio, in the northern boundary of the studied area (Plate 1). Good exposures of the Espinal Formation are found between kilometers 48 and 50 of the Buga-Buenaventura highway, along the Trujillo-Dos Quebras road and between the towns of La Primavera and Naranjal.

LITHOLOGY

The basal part of the Espinal Formation consists of an alternating sequence of pelagic chert and black siliceous shale. Toward the middle part of the formation there is a preponderance of terrigenous black shale, sandstone and minor limestone. This terrigenous sequence grades toward the top of the formation into an alternating, usually rhythmic bedded sequence of black chert and siliceous shale of mainly pelagic origin. However, some of the material seems to have been introduced by turbidity currents and some represents normal pelagic sedimentation. Separation of the two was not attempted and may not always be possible.

Black Chert and Siliceous Shale

The chert is normally black but some red varieties are also found. It is commonly thin to medium-bedded, with an average bed thickness of 0.10 centimeters. Contact metamorphic effects produced by diabase sills and basaltic flows turn the chert to either a white or light-gray color and destroys the internal sedimentary structures. The most
conspicuous internal sedimentary structure of the chert is a thin lamination usually from 1 to 2 millimeters thick. In thin section some of the chert shows up to 30 percent of poorly preserved radiolarian-like remains, the cavities of which are filled with chalcoclastic quartz, in a matrix of microcrystalline quartz, organic matter and clay minerals in varying proportions. Some other fossil remains seem to be globigerinid-like foraminifera showing different stages of silification. Closely associated with the chert is the siliceous, black carbonaceous shale, which exhibits a microscopic parallel lamination. When fresh, the shale is black and when altered it shows a range of colors from light gray to olive gray. Some of the shale beds above the fossiliferous chert show silicified globules that could represent radiolarian remains. The author believes that most of the chert and the black siliceous and carbonaceous shale were derived directly from the plankton layer and accumulated very slowly on the ocean floor.

**Sandstone and Pebby Sandstone**

Greenish gray to dark gray sandstone beds occur at various intervals in the lower part, and more frequently, in the middle part of the Espinal Formation. They occur alternating with black chert, shale and limestone and they generally fit the description of graywacke. The sandstone grain size ranges from fine to very coarse and it is very poor to moderately sorted. Bedding is indicated either by orientation of detrital mica or by carbonaceous material. The sandstone is thin to thick-bedded; however, medium-bedded sandstone is a common feature. The individual beds exhibit distinctive internal and external sedimentary structures. Internal sedimentary structures in the sandstone are: graded bedding, very thin to thin even-parallel lamination, small-scale cross-bedding, convolute lamination and thin-section scale slumped structure. The external structures are: scouring and load cast structure. In thin section the sandstone seems to be composed of very angular to subangular grains of quartz, plagioclase, K-feldspar, biotite, calcite, epidote and opaque minerals, together with rock fragments mainly quartzite, phyllite and volcanic rocks. The matrix consists of carbonate, carbonate, micas and clay minerals. Quartz is both clean and dusty; the former shows embaymena and the latter has undulatory extinction suggesting a volcanic and metamorphic origin respectively for this mineral. Plagioclase is little altered, shows albite twinning and is oligoclase to andesine in composition; it, together with quartz are the predominant mineral grains. The next abundant mineral is chloritized biotite which is present as slender contorted flakes suggesting a metamorphic origin. The fossil content of these sandstones consists of remains of benthonic and planktonic foraminifera and radiolaria.

The sandstones are usually composed of top-cut-out sequences of the Bouma types ABC and AB and they can be assigned to the turbidite facies "C" of Walker and Mutti (1973). Good examples of top-cut-out sequences are present along the Trujillo-Dos Quebradas road (Figures 7 and 8).

Some massive thick bedded sandstone which occurs scattered throughout the formation and to which Bouma sequence is not applicable, fits better the turbidite facies "B" of Walker and Mutti (1973). Pebby sandstone beds were found alternating with sandstone and shale in the middle part of the formation. It is composed of pebbles of chert, phyllite, andesite and milky quartz in a sandstone matrix. The characteristics of these units are comparable with the organized pebbly sandstone described by Walker and Mutti (1973).

Therefore, the author considers this pebbly sandstone as a representative of the facies A2 in the classification of turbidites proposed by Walker and Mutti (1973). The sandstone and pebbly sandstone considered together represent a sequential facies model composed of Walker facies A, B, C and, therefore, they should be considered as proximal turbidites deposited in the middle part of a submarine fan.

**Limestone**

Light to dark gray, fine- to very fine-grained, calcareous beds are usually found associated with the sandstone in the middle part, or with chert in the lower part, of the Espinal Formation. Individual beds range in thickness from 10 to 60 centimeters and are either thick bedded or thin-bedbedded. Some of the limestones are so fine-grained that they are better termed homogeneous lime mudstones. This is especially true of those which do not show any internal sedimentary structure. The two most frequently observed internal sedimentary structures are: small scale cross bedding and a very thin even non-parallel lamination. Most of the limestone consists of twinned calcite grains and lesser amounts of very angular grains of twinned fresh plagioclase, quartz with undulatory extinction, minor epidote, some biotite and quartzite fragments. The internal sedimentary structure and the mineralogy of these limestones support the idea that they are of clastic rather than pelagic origin. The lime mudstone with abundant fossil remains and without terrigenous material might be of pelagic origin.
Figure 7. Horizon “A” of sandstone turbidite of the Espinal Formation, resting upon Horizon “B” of top-cut-out underlying turbidite. The contact between “A” and “B” is an erosional contact. Exposures along the Trujillo-Dos Quebradas road. Scale is in centimeters.
Figure 8. Sandstone turbidite showing thin parallel lamination of the horizon "B", followed to the top by small scale cross-bedding of horizon "C". Exposure along the Trujillo-Dos Quebradas road. Scale is in centimeters.
CONTACT RELATIONS AND THICKNESS

The lower contact of the Espinal Formation in the mapped area is always an intrusive contact with the underlying diabase sill. The basal chert has undergone contact metamorphism and the black original color turns to light-gray or white. The bedding and the internal thin lamination of the chert is very often obliterated by this contact metamorphic effect. Some 20 kilometers south of the hamlet of Lobuguerro, Nelson (1957, p. 51) found the lower contact of the Espinal Formation to be transitional with the underlying Cenaceras Formation.

The upper contact of the Espinal Formation is better exposed in the northern part of the area. It was observed at several places to be an irregular contact with the overlying diabase and basaltic flows. Contact metamorphism in the uppermost two meters of the formation was observed. The best exposure showing this effect is in the road cut of an unimproved dirt road leading from Alto Paez to an unnamed place 4 kilometers to the west of La Medarra (Figure 9). In the southern part of the area, the upper contact of the Espinal Formation with the Diabase Group is marked by the Calima fault.

The thickness of the Espinal Formation was estimated by Hubach (1957, p. 22) at the Quebrada Cogollo west of the town of Dagua, as 700 meters. The author has estimated along the Tufllo-Dox Quebradas and Naranjal-La Primavera roads an approximate thickness of 300 meters (Figure 6).

SOURCE AND ENVIRONMENT OF DEPOSITION

The sediments of the Espinal Formation were deposited from multiple sources by different mechanisms but apparently during one sedimentary cycle. Two major sources are recognized: biogenic and terrigenous. The biogenic source is represented by the radiolarian black chert and the siliceous shale; while of them, locally, have abundant radiolarian and foraminiferal remains. The microscopic lamination in these rocks suggest a particle by particle deposition through the water column from the uppermost organic rich water layer of the ocean. These sediments constitute the pelagic type of deposits of the Espinal Formation. The high percentage of chert and siliceous shale against pelagic carbonate deposits strongly suggests that the sediments were deposited below the calcite compensation level. The terrigenous or clastic source is represented by the turbidite sandstone, pebbly sandstone and limestone. The heterogeneous mineralogy of the sandstone, the presence of fresh and partly weathered plagioclase, the angular pebbles of milky quartz, and the volcanic fragments indicate that these sediments were derived from a metamorphic basement intruded by quartz diorite plutons and intermediate to basic volcanic rocks. These basement rocks, probably the Central Cordillera, were either undergoing rapid erosion due to intense uplift. The last point seems to be more probable.

The marine character of the Espinal Formation is confirmed by the presence of radiolarians remains in pelagic deposits.

The complete lack of distinctive shallow-water sedimentary features, the proximal character of the turbidite deposits, the radiolarian chert and the turbidite character of the limestone strongly suggest that the Espinal Formation was deposited in a deep-sea environment, most probably in the continental rise-abyssal plain transition zone.

AGE AND MICROFOSSIL CONTENT

The first reference of fossils in this formation was given by Aluja, and others (1957). The fossils were found in a turbidite sandstone at kilometer 48 on the Buga-Buenaventura highway. They are Siphogenerinoides sp. cf. clavata and Pectenofrondicularia rugosa proyecta. Duque-Caro (1975, written communication) identified the fossils collected by Aluja and he assigned them to the Coniacian age. An important point to be considered here is that the fossils came from the upper part of the formation and that the lower part of the formation is mainly of pelagic origin. If the fact that pelagic sediments represent long periods of time is taken into consideration, an older Cretaceous age might be expected for the basal part of the Espinal Formation.

The author found radiolarians and foraminiferal in black chert and siliceous shale but dating of these microfossils is not yet available. Localities where fossiliferous samples were collected are shown in Plate 2.

UPPER CRETACEOUS DIABASE GROUP

The name Diabase Group was given by Nelson (1957) to a sequence of submarine basic volcanics and their related pyroclastics and sedimentary rocks, which form the main element of the Central Western Cordillera. The volcanic rocks of this group are mainly diabase, pegmatite, basalt and pillow lava. These volcanic rocks occur as slivers intersected with metasedimentary rocks of the Dagua Group. The contact between slivers of both groups is either an intrusive or a fault contact.
Figure 9. Upper contact of the Espinal Formation with basalt of the Diabase Group. The basaltic flow (b) has produced contact metamorphism (Mk) upon the black chert (Ch). Outcrop on the road leading from Alto Paez to a place 4 kilometers west of la Medarda.
DIABASE, BASALTS AND PILLOW LAVAS

DISTRIBUTION AND FIELD CHARACTERISTICS

The diabase occurs either as independent sills or as the basal part of pillow lava flows. The sills may attain several hundred meters in thickness and they are emplaced either in the old metasediments of the Dagua Group or in older lava flows of the Diabase Group. In both cases, strong metamorphic effects are produced in the host rock at the bottom and top of the sill. Most of the sills show a gradational change in grain size from medium grained at the center toward fine grained at the borders, showing a gradual change from diabase to basalt with chilled borders. Xenoliths of thermally metamorphosed sedimentary rocks are very common toward the contacts of most of the sills. However, in a great number of observations, the contacts between the sill and the host rock are sharp and slightly irregular.

The pillow lava flows consist of a normal, medium grained diabase, at the basal part of the flows, which gradually changes to a fine-grained diabase or basalt toward the top of the flow. The uppermost part of the flows usually consists of successive layers of pillows. However, the pillow top rarely exceeds one tenth of the total thickness of each individual flow. Most of the pillows show an ellipsoidal shape, with the longest axis varying from 20 centimeters up to 2 meters, but sphenoideal and pahoehoe toe-like structures were also observed (Figs. 10 and 11). In no case were vesicles observed, but very often a poorly developed radial distribution of amygdaloides was found. At several places the pillows show a thin, less than 2 centimeters, glassy skin. Good examples of these features are found in excellent outcrops of pillow lava along the Buga-Buenaventura road.

PETROGRAPHY

Macroscopically the diabase and pillow lavas are green to dark green, medium- to fine-grained rocks. Porphyritic varieties are somewhat common. The phenocrysts are either pyroxene or plagioclase. Amygdaloidal types are often found, and the amygdaloids are mostly zeolites.

Microscopically these rocks show a variety of textures even within a single hand specimen. Most of the rocks of this unit are holocrystalline; varieties composed entirely of glass are only found in the glassy crust of pillow lavas. Microporphyritic texture is found in samples where an early pyroxene phase crystalized first, then plagioclase. In this case tiny plagioclase crystals are partially enclosed in pyroxene. Subophitic texture was observed in several samples, mainly in the fine-grained varieties. Intercrystal texture is very common and is probably the predominant texture. The glassy material that once filled the interstices is now represented by chlorite and tiny quartz crystals.

The diabases of this unit are fairly uniform in composition. Samples without noticeable alteration effects are characterized by pyroxene, plagioclase, ilmenite, magnete, and quartz. In some samples either bluish riebeckite amphibole, chlorite, epidote, or zeolites and pumpellyite are present and they may represent either regional or contact metamorphic products. K-feldspar and olivine are remarkably absent. The pyroxene of the diabase and the basalt as well is mainly augite and, in minor proportions, pigeonite. Variation of 2V measured with Universal stage in 13 samples of diabase rocks indicate that most of the pyroxene is augite, with 2V ranging from 38° to 56° (Fig. 12). Three samples show a pigeonite with 2V ranging from 28° to 30°. A remarkable feature in figure 12 is the existence of a gap in the 2V's of pyroxenes between 30° and 38°, which is in part the field of sub-calcic augite. The augite is almost undistinguishable from the pigeonite under the microscope. The pyroxene occurs as euhedral crystals in the porphyritic varieties or as subhedral and anhedral crystals in the nonporphyritic rocks; it is usually nonpleochroic, but pleochroic varieties are present and they usually change from colorless to a pale yellow or a greenish yellow. In all instances the pleochroism is very weak. Twinning is common in the pyroxenes of several samples and arborescent structure like the one described by Gansser (1950) from Gorgona Island, was also observed in a few samples. The pyroxene of the diabase, basalt and pillow lavas are very often altered either to a riebeckitic amphibole or to a uralitic amphibole. Alteration starts from the border of the crystals or along cleavage traces and progressively covers the whole pyroxene crystal. The author believes that formation of amphibole as well as chlorite from the pyroxenes is a result of hydration reactions produced by a pervasive regional metamorphism.

Plagioclase compositions are generally in the range of An 56 to An 70 in six samples containing fresh plagioclase crystals. Measuring was done with the Universal stage using the Rittman zone method and plotting results against the high temperature curve. Plagioclase usually occurs in subhedral or anhedral laths in random orientation. Zoning was observed in a few thin sections where the extinction of the plagioclase crystals gradually advances in from the border to the center of the crystal, indicating conditions of fairly...
Figure 10. Pillow lava dipping west (right). Abundant amygdules and interpillow hyaloclastites. Las Delicias - Mediacanoa road. View looking south.
Figura 11. Pillow lava dipping west (left). Kilometer 58.5 on the Buga-Buenaventura road.
Figure 12. Variation of measured $2V$ in pyroxenes of the Diabases and basalts of the Deebase Group.
uniform cooling. Twinning, on the contrary, is almost always present. It is albite-pericline or less frequently anorthite or a combination of both. However, untwinned plagioclase was observed in some samples and albite twinning predominates over the other type. Clouding is a frequent feature in the plagioclase of these rocks making it impossible, in most cases, to measure the extinction of the twin lamellas and, therefore, the plagioclase composition. Clouding is produced by a brownyellow dust which under high power resolution proves to be composed of chlorite, white mica, epidote, pumppellite, carbonate, and in some cases, extremely fine opaque oxides. The cloudiness, lack of zoning, loss of twinning and abitization of plagioclase are here considered to be mostly the result of regional metamorphism.

Opaque oxides are the next most abundant mineral in these rocks. The opaque oxides consist mainly of magnetite and a conspicuous, probably titanium-magnetite with a graphic-like texture produced by exsolved lamella of ilmenite that has been altered to leucoxene.

Chloritized glass is very frequent in these rocks. It occurs as irregular interstitial patches between plagioclase laths, sometime associated with quartz and zeolites.

Olivine completely altered to chlorite was found in one sample (IGM 140065) collected from a flow near the hamlet of Loboguerrro (see location of samples in plate 1). The olivine grains are phenocrysts up to 3 millimeters in longest dimension. They occur as subhedral to anhedral crystals with a berlin-blue birefringence. Kellyphitic borders are associated with the chloritized olivine. This rim consists mostly of pyroxene and minor amphibole or plagioclase. The olivine has lost its optical properties and it is recognized by the relict shape, cracks and the kellyphitic borders. This pseudomorphous transformation of olivine to chlorite, developing kellyphitic borders, is here considered mainly a metamorphic reaction involving loss of magnesium. It is possible that the orange-reddish tiny crystals with high relief, observed in the groundmass of some thin sections be altered olivine. Unfortunately, the mineral is too small to be resolved with the microscope. Olivine in a basalt sample collected near Loboguerrro has also been reported by H. Pitcher, et al. (1974).

Other minor constituents in the basalts are quartz and plagioclase though they are not always present. Other minerals such as chlorite, zeolites, pumpellyite, epidote, white mica, amphibole and calcite are products of either regional metamorphism or local hydrothermal alteration. Semi-quantitative graphic estimates for 13 samples give the approximate compositions shown in Table 1. The compositional range given in the table should be regarded as very general ranges that may be exceeded locally. Modal estimates of the diabase and basalts are difficult mainly because of the alteration and/or metamorphism affecting these rocks.

COARSE-GRAINED DIABASE AND DIABASE PEGMATITE

DISTRIBUTION AND FIELD CHARACTERISTICS

The coarse-grained diabase (gabbroid type) occurs exclusively as sills intruding early diabase and basaltic flows of the previously described unit. The sills are remarkably thick, obtaining thicknesses up to 1000 meters. However, the coarse-grained diabase usually is less than 50 meters thick, the remaining part of the sills being a normal diabase or basalt. The diabase pegmatite occurs scattered in the coarse-grained diabase mainly as lenses, patches, or very irregular veins. Good examples of diabase pegmatite are found along the Buga-Buenaventura road and adjacent to the Calima Dam (Plates 1 and 2). A remarkable feature of these coarse-grained (gabbro) diabase sills is the extensive and strong contact metamorphic aureole developed in the country rock. Large lenses of quartz-bearing gabbro are associated with these rocks. The quartz-bearing gabbro shows transitional contacts toward the coarse-grained diabase indicating that it is a part of the whole unit and not a different intrusive body. Excellent outcrops showing this relationship are found along the unimproved road from Mediacanoa to Darien.

PETROGRAPHY

The coarse-grained diabase and diabase pegmatite contain practically the same spectrum of minerals as the normal diabase, with two exceptions: chloritized glass is completely absent and greenish amphibole is generally a major mineral.

The coarse-grained diabase contains microppegmatite consisting of more or less graphic intergrowth between quartz and plagioclase. This microppegmatite occurs mostly as small interstitial patches between plagioclase and altered pyroxene. Iron ore is coarse grained and apparently more abundant.
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<th>SAMPLE NUMBER (INGEOMORAS NOMENCLATURE)</th>
<th>SEMIQUANTITATIVE ESTIMATE OF THE MODAL COMPOSITION OF DIABASIC ROCKS FROM THE DIABASE GROUP (GIVEN IN VOLUME PERCENT).</th>
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</table>
than in normal diabase. The plagioclase and pyroxene are in a subophitic relationship and both develop long, bladed forms often showing a pronounced curvature. This curvature of the two most abundant major minerals is better observed in the field and it is an excellent guide for mapping purposes in areas with highly weathered, poor exposures.

Plagioclase in the coarse-grained diabase is highly altered. Zoning, when present, is poorly developed. Twinning is common and it is either albite, pericline, carlsbad or a combination of two of them.

Pyroxene is augite, usually twinned and exhibiting a patchy extinction. Some crystals show a conspicuous median line which separate the twin lamellae. Most of the pyroxene has been altered to a uraltic amphibole.

Opaque oxides are mainly magnetite and ilmenite altered to leucoxene. Other minor minerals include quartz, epidote, and chlorite.

Amphibole is never absent and it is generally an important constituent. It is uraltic in nature but some bluish-green patches of fibrous habit are also present. This bluish-green amphibole is believed to be an alkali amphibole produced by low grade regional metamorphism.

HYALOCLASTITE, TUFF AND CHERT

Above several pillow lava flows there is a sequence of three different rock types which have gradational contacts and seem to be related to a single volcanic-sedimentary cycle. This sequence consists from bottom to top of hyaloclastite, tuff and chert. It is of major importance because it is the most effective way to recognize the top and bottom of each flow. It is useful in working out the major structures and it is also, in the cherty part of the sequence, where abundant microfossil have been found. The age of the Diabase Group is based on fossils found in these rocks. The sequence generally is tens of meters thick and very rarely is over 100 meters.

The hyaloclastite is always at the base of this sequence usually above pillow lava. It never attains thicknesses greater than a few centimeters. In hand specimen it is a dark-green mottled rock composed of dark-green angular fragments cemented, at least to some degree, by white irregular crystals. Under the microscope the dark fragments consist of a brown to reddish-brown glass, probably palagonite, showing different degrees of alteration to chlorite. Interstitial with the glass occur zeolites, and in minor proportions, epidote.

The tuffaceous sediments rest on the thin hyaloclastite layer. The tuff is brown to olive-green in color and shows a fine laminar. It is composed of fragments of palagonite, pyroxene and obsidian in a groundmass of devitrified glass and opaque oxides. Foraminifera and radiolaria are present mostly in the laminated tuffaceous layer below the transition to chert. At kilometer 42 on the Buga-Buenaventura road, the tuffaceous sequence contains isolated irregular shaped unbroken pillows like those described from Quadra Island by Carlisle (1963). The tuffaceous section has a few tens of meters thick and toward the top it grades into a tuffaceous tuff and finally to chert. The presence of isolated pillows and the transitional character to chert, strongly suggest that these tuffs were formed entirely beneath water. Hence, the term “squamene tuff” proposed by Carlisle (1963) can be applied to the fine laminated tuffaceous sediments intercalated between chert and pillow lava flows which crop out in the Central Western Cordillera.

The chert is always located at the top of this sequence, and very often it is overlain by pillow lava flows. The chert is thin, often less than a meter thick, and is a well-bedded, light to dark gray in color and sometimes contains abundant foraminifera and radiolaria. There is little doubt that this chert records a distinctive pelagic sedimentation following each period of intense volcanic activity.

SOME PETROLOGIC CONSIDERATIONS

Preliminary petrographic examination of about 80 thin sections of basalts and diabase led to the selection of thirteen of the least altered samples for chemical analyses and semiqualitative spectrophotometric study. Despite the selection, the samples here under investigation should be considered with care, since one of them shows evidence of having undergone low-grade metamorphism.

ALTERATION OF THE VOLCANIC ROCKS

Chemical composition of the major oxides and CIPW norms for 13 samples of diabase and basalt are given in Table 2. The presence of normative nepheline in one of the samples (140088) can be attributed to the high content of Na2O present in the rock. On the other hand, one sample (140085) shows phenocrysts of chlorite pseudomorphs after olivine, but it does not show normative olivine. These two examples indicate that at least some mobility of alkalis and magnesium took place. A plot of the Na2O/K2O ratio versus Na2O+K2O (Figure 13) shows that about 40 percent of the samples have a high Na2O/K2O content and they are localized above the V-V curve which represents the maximum Na2O/K2O for fresh Quater-
TABLE 2. Chemical Analyses and CIPW Norms for Basalts and Diabases of the Diabases Group.

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ADJUSTED OXIDES

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<td>47.840</td>
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Figure 13. Na₂O/K₂O ratio versus Na₂O + K₂O of a diagram showing the location of 13 samples of diabase and basalts from the Diabase Group. The line IV represents upper limit for all fresh volcanic rock as given by Miyashiro (1975).
nary volcanic rocks. These relationships can be interpreted as proof for mobility of alka-
lis. The increase or decrease of the Na₂O/K₂O ratio can be caused by changes in Na₂O and/or K₂O mainly by ocean-floor weathering, or alternatively by metamorphism and/or low-grade metamorphism. Miyashiro (1975) suggests that an increase of the Na₂O/K₂O ratio caused by a decrease in the amount of K₂O will not alter the place of plotting the Na₂O+K₂O content mainly because Na₂O is far greater than K₂O. On the other hand, an increase of Na₂O by metasomatic process during low-grade metamorphism will not only affect the position of the values of Na₂O/K₂O and Na₂O+K₂O but also will alter the position of samples in all the diagrams which use alkali relations. The chemical analysis of diabases and basalts (Table 2) show that samples with high values of Na₂O have correspondingly low values of CaO and high TiO₂ and Fe₂O₃ contents. Recently, Shibata, et. al. (1974a) indicated that commonly observed trends in ocean-floor weathering are increased K₂O and CaO and decreased Fe₃O₄/Fe₂O₃, TiO₂, and Fe₂O₃/FeO ratio from its former glassy surface toward the core of the pillow. This means that ocean-floor weathering is mainly confined to the upper-most surficial layer of the ocean-floor rocks. This type of weathering seems not to be applicable to samples here under consideration since all of them show very low K₂O and CaO content despite the fact that they were taken from the middle part of thick flows and sills or from the cores of large pillows.

Therefore, the author ascribes the low or high variations of some of the oxides (K₂O, Na₂O, CaO) mostly to metasomatic addition or leaching of elements caused by hydration reactions during low-grade regional metamorphism especially in the zeolite and prehnite-pumpellyite facies, a fact strongly supported by petrography.

CLASSIFICATION OF THE BASALTIC ROCKS

Recent investigations (Kuno, 1969, 1968a; Jakus and Gill, 1970; Jakus and White, 1972; Miyashiro, 1974, 1975) have discussed volcanic rocks under the general division of volcanic rock series. These rock series appear to represent compositional variations with advancing degree of differentiation. With the purpose of visualizing changes in composition, many authors in the past have used either variation diagrams or triangular diagrams. In the preceding sections these two types of diagrams will be used with the aim of recognizing the volcanic rock series to which the basalts rocks of the Diabase Group belong and also to visualize the fractionation pattern followed by these volcanic rocks. Prior to discussion of some diagrams there must be a consideration of the normative minerals. The CIPW norm calculations (Table 2) yields five samples containing normative quartz and hypersthene and seven samples with normative hypersthenololive components. These normative characteristics allow classification of these volcanic rocks in terms of Yoder and Tilley (1962) tetrahexedron, as oversaturated and undersaturated tholeites.

Na₂O+K₂O versus SiO₂ diagrams are shown in figures 14 and 15. Except for most of the altered samples, the volcanic rocks of the Diabase Group fall in the tholeite field of these diagrams.

In figure 16 most of the samples plot outside the field for abyssal tholeites suggesting that these low-K tholeites were probably originated in a different environment. A compositional variation SiO₂ versus FeO*/MgO diagram is given in figure 16. Despite the variations in FeO, MgO with low-grade metamorphism, the analyzed samples plot in the tholeite (TH) field, with one sample plotting in the calcalkaline (CA) field. Three other samples plot far off the Ca/TH line in the tholeite field. Regardless of the four anomalous samples, the remaining samples follow a trend almost parallel to the CA/TH line within the tholeite field. This suggests a moderate to low-iron concentration type of fractionation of a tholeitic series.

The AFM diagram for the analyzed samples from the Diabase Group brings out a typical tholeitic trend which shows a tendency to a moderate-iron concentration type of fractionation (Fig. 17). Therefore, the chemical relationships summarized above indicate that the basalts and diabases of Diabase Group are low-K tholeites with a low average content of silica.

SOURCE AND ENVIRONMENT OF FORMATION

Despite the scarcity of data to discuss the source of the basaltic magma, for the volcanic rocks of the Diabase Group, some comments can be made regarding the tholeitic nature of the rocks and the low contents of SiO₂ and K₂O. Kushiro and Kuno (1963) indicates that all theolites belong to their magma type A, which is supposed to be produced at very shallow depth, in the uppermost part of the upper mantle mainly by the incongruent melting of enstatite. Magma of this type may crystallize either as basalt with excess SiO₂ in the CIPW norm or may show normative olivine or even nepheline (Kushiro and Kuno, 1963). This might be an explanation for the oversaturated and undersaturated character shown by basaltic rocks of the Diabase Group, if this variation is not produced
Figure 14. Na$_2$O + K$_2$O Versus SiO$_2$ diagram for basalts and diabases of the Diabase Group.

Lines represent Kuno's field for (a) Alkalic (ha) High-Alumina and (th) Tholeiitic series.
Figure 15. $\text{Na}_2\text{O} + \text{K}_2\text{O}$ Versus SiO$_2$ diagram for basalts and diabases of the Diabase Group. Macdonal-Katsura's boundary between tholeiitic and alkalic series for Hawaiian rocks is shown as a reference line.
Figure 16. Compositional variation of the basalt and diabase rocks of Diabase Group, with increasing FeO*/MgO (on anhydrous basis). Calc-alkaline (CA), Tholeiitic (TH).
### DIABASES AND BASALTS WESTERN CORDILLERA - COLOMBIA

The following points were not plotted because they would have fallen on a previously plotted points D and F:

140067, 140215

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<td>9.61</td>
<td>44.72</td>
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**Figure 17.** AMF diagram showing the tholeiitic trend of the volcanic rocks of the Diabase Group. The Skaergaard (+) high-alumina basalt, the Isu-Hakone (th) tholeiite basalt, and the Isu-Hakone (clk) calc-alkali basalt trends given by Kuno (1968) are shown in comparison.
by weathering or low-grade metamorphism. Shallow depth environments generating tholeiitic magma can be found either in mid-ocean ridges or near the trench of island arcs. In preceding sections it was demonstrated that the basaltic rocks of the Diabase Group are chemically analogous to abyssal tholeiites but nevertheless different from them. Jakes and Gill (1970) advocate the island arc origin for some tholeiites and named them the "Island arc tholeiites". Figure 18 shows a Na_{2}O/K_{2}O versus Na_{2}O+K_{2}O diagram with three major tholeiite fields. Plotting of the analyzed samples in this diagram shows that several samples fall in or very near to the island arc tholeiite field.

Recently, Pearce and Cann (1973) attempted to determine the tectonic environment of formation of basic volcanic rocks using Ti, Sr, Zr, and Y. Atomic absorption analysis for Y and Sr and semiquantitative spectrographic analysis for Ti and Zr were completed on 11 samples from the Diabase Group. Results of these analysis are given in Table 8. Because the basaltic rocks under study have undergone low-grade metamorphism the most useful discriminant diagrams are those which use the less mobile elements Ti, Zr and Y (Smith and Smith, 1976). Discriminant diagrams using Sr are strictly valid only for fresh and slightly altered rocks but not for metamorphosed ones. Eleven samples were plotted in a Ti-Zr discriminant diagram (Fig. 19) and in a Ti/100, Zr, X Y triangular diagram (Fig. 20). Both diagrams show that basaltic rocks from the Diabase Group, even though they are metamorphosed, belong to the low-potassium tholeiites generated in an island arc environment. In this way, basaltic rocks from the Diabase Group are comparable to basalts from the Izu, Tonga, Marianas, and South Sandwich arcs. Consequently, basalts of the Diabase Group, which are an important element in the constitution of the whole Central Western Cordillera of Colombia, represent the very early stage of evolution of an island arc. This island arc was very probably formed upon a preexisting oceanic crust.

CONTACT RELATIONS AND THICKNESS

The lower contact of the Diabase Group with the underlying Espinal Formation is a normal but irregular contact between black chert at the top of the Espinal Formation and diabase of the basal flow of the Diabase Group (Fig. 9). The upper contact is an angular unconformity with overlying Tertiary rocks. Toward the Pacific coastal plains the diabase is unconformably overlain by the conglomerates and sandstones of the Miocene Naya Formation. Toward the Cauca Valley, some 20 kilometers south of the area under study, along the eastern slope of the Central Western Cordillera the Diabase Group is unconformably overlain by the marine Eocene Uribe Formation (Schwinn, 1969). The basal conglomerate of the Uribe Formation contains boulders and cobbles of highly weathered diabase, suggesting a period of intense subaerial erosion and weathering prior to its deposition.

The thickness of the Diabase Group in the thesis area cannot be established, mainly because of intense faulting and folding, but very probably the volcanic pile exceeds 6,000 meters.

PROBABLE AGE

Nelson (1959) concludes, on the basis of paleontological determinations, that an upper Cretaceous age seems very likely for the Diabase Group. Recently, Etayo-Serna (written communication, 1976) studied two ammonites collected by Raul Ordoñez, from Quebrada San Marcos, south of the small town of Viques, some 20 kilometers southwest of Buga. According to Etayo-Serna these ammonites are indicative of the Turonian. H. Burgl (in Nelson, 1959) studied some fossils from siliceous shale that crop out at Quebrada San Marcos, probably the same locality as the ammonites, and determined Inoceramus cf. peruensis Brug. This fossil, according to H. Burgl, is indicative of the lower Coniacian. The sedimentary intercalations cropping out in Quebrada San Marcos can be correlated with the sediments resting upon pillow lavas, which are found 12 kilometers west of Buga on the Buga-Buenaventura highway (Plate 2). Based on this correlation, and the fact that the lower part of the Diabase Group conformably rests upon the Espinal Formation, the author considers that the Diabase Group, in the thesis area (Plate 2), ranges in age from Cenomanian to Maestrichtian. This assigned range of age does not discard the possibility that volcanic activity, which made origin to the Diabase Group in other places of the Western Cordillera, had started prior to deposition of the Espinal Formation, and therefore, be older than the Diabase Group in the thesis area. As a matter of fact, this seems true to the north of the study area where barremian ages have been reported for sediments intercalated in the Diabase Group (Grosse, 1926; Botero, 1963; Etayo-Serna, et al., 1976).

A K/Ar determination was performed by Geochron Laboratories on a sample from the base of a pillow lava flow, which crops out at kilometer 12 of the Buga-Buenaventura highway (Plate 2). This sample, a slightly metamorphosed low-potassium tholeiitic basalt, gave an age of 136 ± 20 m.y. (Table 4). However, a great deal of care should be taken in using K/Ar determinations of typical low-potassium tholeiites.
V-V = Upper Limit of Na₂O/K₂O for all fresh volcanic rocks
Aby-th = Abyssal tholeiites
Ic-th = Icelandic tholeiites
IA-th = Island Arc tholeiites

Figure 18. Alkaline diagram for 13 samples of basalts and diabases of the Diabase Group. (Fields for different tholeiites taken from Miyashiro, 1975.)
TABLE 3. Atomic Absorption Analyses (Y and Sr) and Semiquantitative Spectrographic Analyses (Zr and Ti) for 11 Samples of Basaltic Rocks from the Diabase Group.

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Figure 19. Discrimination diagram using Ti and Zr in samples from basalts and diabases of the Diabase Group. (Discrimination fields after Pierce and Cann 1973).
Figure 20. Discrimination diagram using Ti/100, Zr, and Y x 3 for basaltic rocks from the Diabase Group. (Discrimination fields plotted after Pearce and Cann, 1973).
TABLE 4  K - Ar results from samples collected in the Central Western Cordillera, Colombia.

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<tr>
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<th>MATERIAL ANALYZED</th>
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<th>RADIOGENIC At$^{40}$ TOTAL As$^{40}$, K$^{40}$, p.p.m</th>
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<td>0759</td>
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<td>Hornblende Hornfels Mafic-Ultramafic Unit</td>
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</table>
generated in an island arc environment. Krueger (written communication, 1976) reporting the K/Ar determinations states:

... The two amphibole concentrates and the basalt samples were all so very low in potassium that analyses were among the most difficult we have handled. We performed extra K analyses on both amphiboles to try and refine the precision of the analyses, but probable analytical errors are still quite large. These three samples offer more difficulties than typical 1 m.y. old samples, and thus we have done the best job possible...

It is probable that the K/Ar age on the basalt is anomalously old since the analyzed sample came from the flow which underlies the genetically related tuff and sediments that have been correlated with the Turonian sediments cropping out at Quebrada San Marcos. The reason for such an old age can be found in the fact that the basaltic rocks of the Diabase Group have undergone depletion of potassium during low-grade metamorphism typical of the island arc environment. The low potassium content (0.0438 percent) may be due to: a) a low initial potassium content, and b) loss of small, but in this case important, amounts of potassium during low-grade metamorphism (Miyashiro, A., 1975). Such decrease of potassium even in small quantities affects severely the age equation, and consequently the computed age is older than the paleontologic age. A second possibility for this high anomalous age could be the presence of excess radiogenic Argon trapped in the analyzed sample during rapid cooling. It is the opinion of the author that the Diabase as well as the Dagua Group can be more precisely dated if careful and detailed biologic and geologic studies are completed. Identical age for the Diabase Group, in different sectors of the Western Cordillera should not be expected. This is an obvious conclusion; hence the Diabase Group is the result of anastomosing eruptions outpoured at different times during the Cretaceous from different volcanic centers.

UPPER CRETACEOUS MAFIC-ULTRA-MAFIC INTRUSIVES

The presence of mafic-ultramafic rocks were for the first time described, in a very general way, by Ortiz and Gomez (1971), in the report on the reconnaissance study of the granodiorite mine west of the town of Bolivar, Vale. The other two major gabbro bodies to the south of the Bolivar mafic-ultramafic complexes are here described for the first time. Previous workers failed to recognize the zoned pattern of the Bolivar mafic-ultramafic complex as well as other petrographic and stratigraphic features of this complex which will be pointed out in the forthcoming sections on these intrusives. The mafic and ultramafic intrusives are here considered to be genetically related and the presence of ultramafic rocks is mainly a matter of level of emplacement as well as level of erosion and amount of uplift of each intrusive unit. The bodies have a setting similar to some in southeastern Alaska, and their mafic as well as ultramafic units are apparently cumulates similar to those reported from layered intrusives. These mafic-ultramafic complexes should not be included in the alpine type ultramafics, since they show some remarkable differences. Typical alpine-type serpentinitized ultramafic bodies occur east of these complexes, along the Romeral fault zone associated with melange rocks (Barrero, 1969, 1976).

Of the intrusives referred to here, the one exposed west of the town of Bolivar, Vale, is the most outstanding because it shows the best layering, clear intrusive relationships between each rock unit and a conspicuous zonal arrangement.

The mafic-ultramafic intrusives occur as a narrow belt, east of the Calima and Rodanillo faults, trending approximately in a northeast direction surrounded by a wide envelope of amphibolites of complex metamorphic origin. Bedrock outcrops are relatively good except for the mafic body of Rio Volcanes in the south part of the belt (Plate 1). The best outcrops are found along streams and roadcuts. The mafic-ultramafic rocks are readily separated in the field from the amphibolites since the former have a red-brown color which strongly contrasts with the mottled green and white colors of the amphibolites. On the other hand, separation of the different mafic and ultramafic units is difficult in the field, and it was done mainly taking into consideration the plagioclase and olivine contents of the different rocks. During this reconnaissance study it was not possible to separate the peridotite from the pyroxenite bodies. Therefore, they are shown as a single unit in Plate 1.

RIO VOLCANES GABBRERO DISTRIBUTION AND FIELD CHARACTERISTICS

An elongated body, about 40 square kilometers in size, extends north and south of the headwaters of Rio Volcanes. Two different types of gabbro were determined in the least altered samples from the border toward the center of this body: normal gabbro and olivine gabbro. In addition to these two rock types, the complex is intruded by a great number of hornblende-pegmatite dikes.
These rocks are fine-to-very coarse-grained and they show a weak layering clearly produced by gravitational settling of mafic minerals, thus giving the impression that the rocks are cumulates. In outcrops the gabbroic rocks are dark-gray when fresh and greenish-brown when altered. Alteration in this particular complex is very prominent and, together with the dense forest covering most of the area, makes field observations very difficult. The eastern side of the complex is strongly affected by the Roldanillo fault and most of the samples collected show severe cataclastic deformation.

**PETROGRAPHY**

The normal gabbro occupies the external zone of the complex. It is moderately well exposed along the Rio Volcanes, where the gabbro shows clear cross-cutting relationships with the host diabase. The normal gabbro generally consists of 60 to 70 percent plagioclase, 25 to 30 percent clinopyroxene, plus variable amounts of opaque oxides and secondary amphiboles, epidote, and quartz.

The plagioclase is labradorite in composition and occurs as subhedral laths up to 3 millimeters in longest direction. It is frequently twinned and some crystals show a poorly preserved normal zoning. When altered the plagioclase shows a core composed of epidote minerals. Clinopyroxene, probably diopside, is present as anhedral to subhedral crystals most of the time strongly altered to urarilitic amphibole. In some places the gabbro shows a spotted texture. The spots are 2 to 4 millimeters oikocrysts of clinopyroxene containing small subhedral laths of plagioclase. Locally, the clinopyroxene and plagioclase show strong planar alignment in the layered variants of this rock unit. Opaque oxides seem to be magnetite with exsolved ilmenite.

The most important secondary mineral is amphibole which in some cases entirely replaces the clinopyroxene. Quartz and epidote occur in the altered varieties. Layering was observed at several places. It consists of layers of variable thicknesses ranging from a few millimeters to 20 centimeters that result from differences in proportions of the major minerals that make up the bulk composition of the normal gabbro. Therefore, the layering in the normal gabbro is a typical rhythmic layering. At some places the individual layers show a well-developed variation of grain size from bottom to top; thus, they become typical graded rhythmic layers. The mineral phases which by their variation, both in size and proportion, give rise to the graded rhythmic layering, resemble the precipitation of particles under the influence of gravity and closely reflect the graded bedding known in sediments. Some of the samples show a kind of planar lamination. This is due to the planar alignment of plagioclase and clinopyroxene with some interstitial clinopyroxene enclosing small subhedral crystals of plagioclase. This type of texture suggests that the normal gabbro is probably a cumulate of plagioclase and clinopyroxene with some of the clinopyroxene and opaque oxides being post-cumulus phases.

The second rock type is an olivine gabbro. It crops out toward the center of the gabbro body in the sector where there is a dense forest cover. It is composed of 50 to 60 percent plagioclase, 10 to 15 percent clinopyroxene, 15 to 20 percent olivine and 2 to 5 percent amphibole. This rock is strongly affected by cataclasis and all its mineral constituents are fractured and show strong undulatory extinction. The olivine is the most conspicuous mineral in the rock and it occurs as large phenocrysts showing kelyphitic rims. The pyroxene is probably augite or diassite and it is strongly altered to a urarilitic amphibole. The olivine gabbro was found in the headwaters of the Rio Volcanes and because the region is densely forested and deeply weathered, the lateral extent and other characteristics of this gabbro variant are poorly known.

**CONTACT METAMORPHISM**

The intrusive character of the Rio Volcanes gabbro is supported by direct observations of xenoliths of basaltic rocks, cross-cutting contacts and by the intense contact metamorphic effects produced on the country rock. These contact metamorphic aureoles were not mapped because of the scarcity of outcrops due to deep weathering and dense vegetation covering the area. However, very good outcrops showing the contact metamorphic effects were found in the Rio Volcanes and along the road from La Caviola to Darien. The innermost zone of the metamorphic aureole consists of hornblende-hornfels that locally has the appearance of an amphibolite due to superimposed cataclastic metamorphism. Excellent examples of these amphibolites occur in the Rio Volcanes near the Roldanillo fault zone. From the intrusive contact the metamorphic aureole decreases gradually from hornblende-hornfels to epidote-hornfels. The width of the contact aureole is about 400 meters in the Rio Volcanes area.

**DISTRIBUTION AND FIELD CHARACTERISTICS**

The Riofrío Gabbro is an elliptical body which crops out north and south of the town of Riofrío. It is elongated in a northeast direction and it is easily recognized from the distance because of its dome shape, gentle topography and varicolored alteration (Fig.21).
Figure 21. Riofrio Gabbro and adjoining amphibolite. The town of Riofrio is about 2 kilometers off the right side of the photograph. View is northeast from a point on the Riofrio-Salonica road; ga = normal gabbro, og = olivine gabbro, r = road from Riofrio to Trujillo, f = trace of the Roldanillo fault, a = amphibolite.
Excellent exposures of this gabbro body are along the paved road from Ríofrío to Trujillo. The entire body is enclosed in an envelope of strongly weathered, variegated amphibolite. Two different variants of gabbro were found: normal gabbro and olivine gabbro; the olivine gabbro occupying a lower stratigraphic position. In outcrops the gabbro is dark-green when fresh and greenish-brown when altered. It exhibits planar lamination, and in several places shows rhythmic layering gently dipping to the east. This fact, and the distribution of the olivine-rich layers toward the west and topographically below the olivine-free gabbro layers, strongly suggests that the gabbro body is a sheet-like intrusion that has been tilted to the east by movement along the Roldanillo fault. The intrusive character of the gabbro is supported by: the presence of a contact metamorphic aureole, the xenoliths of basaltic rocks, and the cross-cutting relationship between the gabbro and the host diabase observed in the Río Cuauhcus.

PETROLOGY

The normal gabbro crops out in the eastern half of the body, and in the field it gives the impression of dipping gently to the east and be overlying the olivine gabbro. One rock specimen classed as normal gabbro consists of approximately 50 percent plagioclase, 30 percent clinopyroxene, 15 percent amphibole, and about 5 percent opaque oxides. The plagioclase, labradorite in composition, is present as slightly altered prismatic crystals. The clinopyroxene is probably augite and is present both as crystals and as interstitial material. The amphibole is a uranitic hornblende, replacing the pyroxene. The opaque oxide is magnetite and occurs as irregular interstitial crystals. The fabric of the rocks suggests that plagioclase and pyroxene probably precipitated as cumulus crystals and the interstitial pyroxene and magnetite as post-cumulus material. This point is additionally supported by the fact that the normal gabbro shows a well-developed layering despite the intense weathering of the outcrops. The layers observed in this gabbro were usually in the range of 5 to 10 centimeters in thickness.

The olivine gabbro is a light-gray mottled rock exhibiting a very well developed layering. Grain size varies from fine to very coarse, the latter occurring almost always at the bottom of the layers. Composition of this gabbro varies from olivine-rich gabbro to olivine-poor gabbro. Designation of a given name depends upon which part of a layer or lamina is sampled. This gabbro, and the normal gabbro as well, have been extensively intruded by a hornblende-plagioclase pegmatite dike swarm. The characteristics of this pegmatite and its alteration effects will be discussed later in separate chapters. The olivine gabbro generally consists of variable amounts of plagioclase, olivine, clinopyroxene, magnetite and trace amounts of a green spinel. Alteration products are amphibole and epidote. For a better understanding of the compositional nature of this gabbro type, the two extreme varieties will be described, but it should be kept in mind that a whole spectrum of compositional variants may exist between these extreme examples. It is interesting to point out that the two extreme compositions correspond to samples taken at the bottom and top of the olivine gabbro unit.

The olivine-rich variant consists of 30 to 40 percent olivine, 30-40 percent plagioclase, 10 to 15 percent clinopyroxene, and 3 to 5 percent opaque oxides and traces of a green spinel. The plagioclase is subhedral and some crystals show what seems to be an adcumulus growth of plagioclase of similar composition. Euhedral and subhedral plagioclase crystals also occur enclosed in anhedral pyroxene. The olivine occurs as prismatic, rounded, or euhedral crystals up to 3 millimeters long showing very irregular fractures filled with opaque oxides. A remarkable feature associated with the olivine is its reaction rim, which consists of an internal layer of clinopyroxene growing almost normally to the faces of the olivine crystal and a second external layer consisting of a dust of opaque oxides. The clinopyroxene occurs as large, irregular, poikilitic, interstitial material dusted with opaque oxides, and engulfing small plagioclase and olivine crystals. The opaque oxides occur interstitially, enclosing tiny plagioclase crystals. The alteration minerals are epidote, amphibole, and minor serpentine. The former description strongly indicates that plagioclase and olivine are cumulus minerals while pyroxene and opaque oxides are post-cumulus material. Therefore, the rock can be considered as an olivine-plagioclase cumulate.

The olivine-poor variant occurs in the western part of the Ríofrío gabbro body and apparently in the lower part of the olivine gabbro unit. It consists of 60 to 70 percent plagioclase, 20 to 25 percent clinopyroxene, and 2 to 5 percent olivine. Plagioclase is bytownite in composition and occurs mainly as subhedral crystals. Clinopyroxene is probably diastase showing a very fine parting. It occurs as individual crystals and also interstitially with respect to plagioclase. Olivine occurs as large crystals showing numerous fractures filled with opaque oxides. This kind of disposition of the minerals suggests that this variant of olivine gabbro may correspond to a plagioclase-pyroxene-olivine cumulate with some pyroxene and opaque oxides as post-cumulus material.
From the above descriptions it can be concluded that the Ríofrío gabbro is very probably a sheet-like intrusion which crystallized as a series of cumulate layers, having the more calcic assemblages at the bottom of the intrusive sheet.

CONTACT METAMORPHISM

The intrusive nature of the Ríofrío gabbro, strongly supported by the cross-cutting relations between the gabbro and the surrounding amphibolite and the presence of xenoliths of amphibolitized diabase, is also confirmed by the presence of a contact metamorphic aureole, which has been partly obliterated by superimposed amphibolitization process. Rocks produced by contact metamorphism are found in patches, outward from the east and west side of the intrusive and scattered in the amphibolite. Isolated epidote-rich basaltic blocks with hornfelsic texture, surrounded by amphibolite, represent the former contact metamorphic rock. This complex superimposition of an early metamorphic event with a later metamorphic and/or metasomatic event is readily visible in the field because of the great difference between the granoblastic texture of the contact metamorphic rocks compared with the well-developed foliation of the latter metamorphic-metasomatic amphibolite. Under the microscope the contact metamorphic rocks, mostly diabase, show a good hornfelsic texture. Two mineral assemblages were observed: a) hornblende-plagioclase (relict pyroxene) and b) epidote-tremolite-chlorite. These two mineral assemblages indicate the presence of a metamorphic aureole representing the hornblende-hornfels and the albite-epidote-hornfels facies. The fact that the hornblende-hornfels facies was observed in a xenolith of diabase in the gabbro, rules out the possibility of the presence of the pyroxene-hornfels facies and sets some constraints for the physico-chemical conditions prevailing during the emplacement of the gabbro. Indeed, the extensive contact metamorphic aureole and the lack of the pyroxene-hornfels facies suggests that the gabbroic magma carried some water and was emplaced at relatively shallow depth.

BOLIVAR ZONED MAFIC-ULTRAMAFIC COMPLEX

The Bolivar zoned mafic-ultramafic complex is the northernmost intrusive body and is in one of the most accessible parts of the area under investigation. The complex is distinctive structurally in showing a good concentric zoning, which consists of a dunite core surrounde by successive shells of olivine clinopyroxenite, clinopyroxenite, and peridotite. This ultramafic sequence is enveloped by normal gabbro which in turn is surrounded by amphibolite. The sequence of intrusion from oldest to youngest is: gabbro-peridotite-pyroxenite-dunite. Finally, hornblende-plagioclase pegmatites intrude all rock types. Intense and widespread amphibolitization of the gabbro and diabase as well as local amphibolitization of the ultramafic rocks took place simultaneously with the replacement of the hornblende-plagioclase pegmatites. The proper host rocks of the complex are basalts and diabase of the Diabase Group. In several ways the complex can be compared with those from Southern Alaska described by Irvine (1974) and with those from the central Ural Mountains, Soviet Union, briefly described by Taylor (1967). Rhythmic layering and lamination are prominent at several outcrops and they are present in all rock types. Penecontemporaneous deformation represented by granulation, undulatory strain banding and patchy extinction were observed in several thin sections. Most of the rocks in the mafic and ultramafic intrusives are cumulates with post-cumulus plagioclase, thus suggesting the idea that the ultramafic rocks were derived from a parent gabbroic magma. The graded and cross-stratification in the mafic and ultramafic rocks indicates strong physical activity in the magma chamber with formation of turbidity-like currents. The above mentioned features suggest that the Bolivar mafic-ultramafic complex was probably formed in a magma chamber beneath a volcano.

CLASSIFICATION, DISTRIBUTION AND FIELD CHARACTERISTICS

The ultramafic rocks have been separated into several rock types which are distinguished by different contents of olivine and pyroxene. Plagioclase is present in all rock types except dunite in amounts ranging from traces up to 10 percent and always with a post-cumulus character. The rock type divisions and their nomenclature are essentially based on the classification and nomenclature of gabbroic-ultramafic rocks by Billups and Kelsall (1974). For mapping purposes, at the reconnaissance scale, the peridotite and pyroxenite have been grouped together in one mappable unit (Plate 1).

The Bolivar zoned mafic-ultramafic complex is an elliptical body some 12 kilometers long by 3.5 kilometers wide, extending from the hamlet of Robledo in the south as far as the town of Bolivar in the northern end of the complex. It is enclosed in amphibolites which extend farther north and south. This characteristic rock-type assemblage is bounded on the west by the Roldanillo fault and on the east by the Cauca Valley depression, therefore, giving the impression of being a tectonically uplifted block.
The complex is well exposed, with the best outcrops in the stream beds. The different rock units give different weathering colors, facilitating their discrimination in the field. However, rock-type discrimination in the peridotite-pyroxenite unit (Kup, Plate 1) has to be established by thin section study.

**PETROGRAPHY**

**Gabbro**

The gabbro unit forms an envelope around the ultramafic rocks and it is the largest and most altered unit of the complex. Its inner contact with the other units is sharp and at several places peridotite, pyroxenite and even dunite dikes cut the gabbro and produce intense metamorphic effects on it. The outer contact of the gabbro shell is mostly gradational or very irregular in trace into amphibolitized gabbro or amphibolite. Near the northeast corner of the complex several small irregular masses of more or less fresh gabbro are engulfed in amphibolite. South of Bolivar and east of Redanillo strongly amphibolitized but still recognizable gabbro cuts the diabase and basalts of the Diabase Group. The best example of the intrusive nature of the gabbro was found in the headwaters of a small stream west of the town of Ricauri, where the gabbro intruded and metamorphosed a diabase (Fig. 22).

The gabbro is a fine- to medium-grained, hypidomorphic granular rock composed of 40 to 60 percent plagioclase; 35 to 50 percent clinopyroxene and variable amounts, from trace to 3 percent, of magnetite. This approximate modal composition can be modified greatly in the well-layered gabbro variants where the modal estimate depends upon individual laminae represented in a thin section.

The plagioclase is labradorite in composition and occurs as subhedral to anhedral cumulate crystals as well as interstitial postcumulus material between plagioclase and/or pyroxene crystals. Alteration products are serpentine and brown dust. The clinopyroxene is probably diassalage; very often it shows fine exsolution lamellae and/or fine parting and it is slightly pleochroic in some orientations from colorless to pink. The opaque oxide is magnetite. Amphibole, probably a uraite, is commonly present replacing the pyroxene. A remarkable feature of this gabbro unit is the absence of olivine.

At several places the gabbro shows a well developed layering and lamination. Layering in the gabbro can be either graded (Fig. 23) or it can be a composite, rhythmic, graded layering and cross stratification (Figs. 23 and 24). The rhythmic layering at several places was observed to change gradually to a rhythmic graded lamination (Fig. 25). This feature closely resembles the graded bedding and lamination observed in sediments deposited by turbidity currents. If a mechanism similar to a turbidity current was responsible for the layering observed in the gabbro, then the gabbro was probably formed by deposition or accumulation of suspended solid particles out of a flowing viscous liquid. The particles will precipitate as a mixture, thus producing the layering and lamination. Disturbance of the flowing liquid will generate the cross-stratification. Irvin (1974) has advocated a turbidity current in the magma to explain the origin of the layering well-displayed by the Duke Island ultramafic complex.

**Peridotite**

The second shell from the margin to the core of the complex is a plagioclase-bearing peridotite. The rock is medium- to coarse-grained, brown in color and spotted with black pyroxene crystals. Under the microscope it shows a subidiomorphic texture and consists of clinopyroxene and olivine with minor amounts of plagioclase. The clinopyroxene and the olivine are cumulate minerals and the plagioclase crystalized from a postcumulus liquid. The clinopyroxene occurs as anhedral crystals, sometimes enclosing rounded olivine grains. Most crystals show a fibrous texture that could be either a deformed parting or a very fine exfoliation lamellae. Undulatory extinction is common. The olivine is anhedral, rounded or eusidipized with abundant fractures. Alteration to serpentine minerals has occurred along the fractures. Several crystals show a broad twinning, suggesting that the rock has undergone penetrative deformation probably of protolithic origin.

Plagioclase occurs as interstitial material and shows good twinning. Opaque oxides are present in variable amounts. Layering in the peridotite was observed at several places, and it consists of graded as well as ungraded rhythmic layering (Fig. 26).

**Clinopyroxenite**

Next to the peridotite toward the core of the complex there is a wide shell of clinopyroxenite. This rock type is probably the most abundant among the ultramafic rocks of the complex. It is a medium- to coarse-grained, dark gray to black rock when it is fresh, and greenish-brown when it is altered. It consists of clinopyroxene, with plagioclase and olivine in some samples in amounts less than two percent, and traces of magnetite. The clinopyroxene, probably diassalage, occurs as anhedral crystals showing partings and exfoliation lamellae. Twinning and undulatio-
Figure 22. Intrusive "arm" of gabbro (g) in diabase (d). The diabase is metamorphosed close to the contact with the gabbro. Outcrop in small stream west of the town of Ricasurie. Scale in centimeters.
Figure 23. Boulder of gabbro showing a composite rhythmic graded layering and cross stratification. Small stream west of the town of Ricaurte. Light layers (pl) are made up mostly of plagioclase cumulus crystals and minor clinopyroxene. Dark layers (px) consist of clinopyroxene cumulus crystals and minor plagioclase.
Figure 24. Graded layering in gabbro. Outcrop in small stream west of the town of Ricaurte. Layer (a) consists of medium grain size crystals of clinopyroxene and plagioclase. Layer (b) consists of coarse grain size plagioclase and clinopyroxene crystals. Layer (c) consists mostly of clinopyroxene and lesser amounts of plagioclase. Notice the "scouring" in the left corner of layer (b).
Figure 25. Rhythmic graded lamination in gabbro. Outcrop west of the town of Riesurte. Contacts between laminae are sharp. Dark laminae consist mostly of clinopyroxene and lesser amounts of plagioclase. Light layers consist of plagioclase and minor amounts of clinopyroxene.
Figure 26. View looking northeast. Ungraded layering in peridotite. The Cauca Valley and the Central Cordillera in the background. The layering dips steeply southeastward toward the Cauca Valley. Note hammer for scale.
ry extinction was observed, and they indicate that the rock has undergone penetrative deformation, probably of protoclastic origin.

The olivine when present occurs as large, rounded isolated crystals. The plagioclase, instead, always occurs as interstitial material showing strong deformation. Rhythmic graded layering and lamination was observed at several places, and they are well-displayed in the outcrops of this rock type in a small stream that runs in a southerly direction from the southernmost dunite core.

**Olivine Clinopyroxene**

This rock type was found at several places close to the dunite core, giving the impression of being a shell surrounding the dunite. This rock type is medium-grained, with albitic clinochlore texture and it consists of 70 to 90 percent clinopyroxene, 10 to 5 percent olivine, 1 to 5 percent plagioclase, and trace amounts of magnetite.

The clinopyroxene, probably diagenesis, occurs as anhedral grains showing a well-developed exsolution texture. The olivine occurs as anhedral crystals showing broad twinning. The plagioclase, as in the other rock types, occurs as interstitial material.

**Dunite**

The dunite occurs in the ultramafic complex as 3 separate small cores forming the highest topographic features of the area. It consists of more than 95 percent olivine and minor amounts of clinopyroxene and chromite. The rock is brown to reddish-brown, fine- to medium-grained, and in several samples, free of serpentinization (Figure 27). Weathering of the dunite produce a reddish-brown soil which is very distinctive in the area. The olivine occurs as rounded or euhedral crystals fractured and altered to serpentine along the fractures. Some specimens show broad twinning and strong undulatory extinction. Because layering was locally seen in dunite the olivine is believed to be largely cumulus, and the planar alignment shown in some samples may have been produced by deposition and compaction. Clinopyroxene was observed in one sample as large anhedral crystals. Chromite usually is anhedral but with rounded corners and is situated between the olivine grains. It also is believed to be a cumulus mineral. Secondary magnetite occurs in very small amounts associated with serpentine.

**Hornblende - Plagioclase Pegmatite**

Numerous pegmatite dikes cut all the rock units that have been described. They occur throughout the amphibolitic rocks that surround the mafic intrusives and the ultramafic complex. The pegmatite is a conspicuous rock in the field, consisting of coarse-grained gray-green hornblende prisms and somewhat greater amounts of plagioclase. Quartz may or may not be present. Most of the dikes are from 5 centimeters to 60 centimeters wide and no more than 50 meters long. The largest dike which has the longest hornblendic crystals crops out eight kilometers from the town of Bolivar on the road to La Primavera (Fig. 28).

The hornblende is found as twinned subhedral crystals with a pleochroism of pale brown to greenish brown, and the crystals tend to be oriented normal to the dike walls (Fig. 28). Plagioclase occurs as anhedral crystals, twinned with intersecting albite and periclase sets, and is labradorite in composition. Undulatory extinction and garnet are very common. The pegmatite is more abundant in the amphibolite unit than in any other rock type, and the two rock types are compositionally transitional. Small pegmatite dikes less than one centimeter wide are surrounded by extensive amphibolitization in the country rock. This suggests that at least part of the amphibolitization was associated with emplacement of pegmatites.

A K/Ar determination was performed by Geochron Laboratories on hornblende concentrate from a sample of hornblende-plagioclase pegmatite taken from a dike, which crops out 8 kilometers west of the town of Bolivar, on the Bolivar-La Primavera road (Figure 28). This sample, a hornblende with low-K content, gave an age of 106 ± 18 m.y. (Table 4). This figure seems to be too high since the pegmatite cut all the rock types of the ultramafic complex which in turn is emplaced in diabase and basalts of the Diabase Group to which a Turonian age have been assigned. Two possibilities arise to explain the anomalous older age: a) the hornblende was contaminated with a mineral of much older age during its crystallization, and b) the age is too old because of the low potassium content of the hornblende, producing the large analytical error. Assuming that the age deviation has a negative sign, the 106 m.y. age can be reduced to 88 m.y. This latter age is about the boundary between the Coniacian and Turonian (Harland and others, 1964). Therefore, the author considers that a maximum Coniacian age can be assigned to the pegmatite.

**Amphibolite and Amphibolitized Gabbro**

The Bolivar mafic-ultramafic complex and the Riofrío gabbro as well are surrounded by a wide and well-developed shell of amphibolites. Large blocks of amphiboliti-
Figure 27. Reddish-brown dunite with some serpentinite along fracture planes. Photograph from small dunite outcrop along the Bolivar-Primavera road.
Figure 28. Hornblende-plagioclase pegmatite dike (hp) cutting a brown dunite (d) 8 kilometers west of Bolivar on the road to La Primavera. Hornblende crystals are up to 16 cm in length.
posed gabbro are found scattered in the amphibolite, and all degree of amphibolitization of the gabbro is observed. Locally amphibolitization of the gabbro is so intense and with the original gabbrold texture preserved, that the rock is better called a hornblende gabbro. In all places the amphibolite is accompanied by a great number of hornblende-plagioclase pegmatite dikes. At several places the pegmatite dikes parallel the foliation of the amphibolite and there is a compositional gradation from one rock type to another (Fig. 29). The amphibolite is a fine- to medium-grained rock made up of 40 to 60 percent hornblende, 40 to 50 percent plagioclase and minor magnetite. It shows a good foliation but in some places it exhibits a hornfelsic texture.

South of the town of Bolivar the amphibolite consists of more or less alternating layers of fine- and medium-grained amphibolite (Figs. 30 and 31). The medium-grained amphibolite cuts the fine-grained amphibolite, suggesting an intrusive character for the parent rock of the medium-grained amphibolite. These textural and structural features indicate the existence of two different periods of amphibolitization: a) amphibolitization produced on the basaltic rocks of the Diabase Group by the intrusion of the gabbroic rocks, and b) amphibolitization of the basalt, gabbrons and to a lesser extent the ultramafic rocks, produced by the emplacement of a water-rich pegmatite phase at the end of the whole intrusive episode. The first period of amphibolitization is simply a contact metamorphic effect and it accounts for the amphibolite with hornfelsic texture.

The second period of amphibolitization is somewhat more difficult to explain since it develops inward from the edge of the complex, therefore affecting mostly the gabbro shell. A possible explanation for this pattern of amphibolitization, in relation to the large size of the amphibolite aureole, and to the penetrative deformation accompanying all the intrusive rocks would be to assume that the second period of amphibolitization was produced when deep faulting allowed water to enter the magma chamber, forming the water-rich pegmatite phase which was emplaced mostly along the shear zones on both sides of the mafic-ultramafic complex. This faulting could be the ancestral to both the Roldanillo fault (Plate 1) and the subsurface fault running parallel to the Cauca River on the east side of the complex (Schwinn, 1969).

One K/Ar determination was performed by Geochron Laboratories on a sample from fine-grained amphibolite, which crops out in a small stream south of the town of Bolivar, gave an age of 88.9 ± 13.8 m.y. (Table 4). This age is in fair agreement with the estimated age of the hornblende-plagioclase pegmatite which is supposed to be coeval with the second period of amphibolitization. It can be assumed therefore that the second period of amphibolitization as well as the earliest stage of faulting and compression which affect the mafic-ultramafic complex took place in Coniacian time.

**AGE OF THE COMPLEX**

The age of the Bolivar zoned mafic-ultramafic complex can be readily deduced because the ages of the country rock, the amphibolite, and the hornblende-pegmatite are known. The complex was emplaced in basalt of the Diabase Group dated as Cenomanian-Turonian in age. Therefore, the complex is Turonian or post-Turonian in age. On the other hand, it was demonstrated that amphibolitization and intrusion of the pegmatite were the latest events in the complex and they post-date all other rocks. The age of these two rock types is roughly 88 m.y., that is, near the boundary between Turonian and Coniacian. Taken into account the range of error in the radiometric age of the amphibolite, it is possible to say that emplacement of the complex began during the Coniacian and probably extend into the Santonian. However, submarine eruption of basalt of the Diabase Group was coeval with crystallization at depth of a stratiform cumulate mafic-ultramafic complex, that is, during the Cenomanian-Turonian.

**MECHANISM AND ENVIRONMENT OF FORMATION**

Recently, a number of mechanisms have been proposed to explain the zoned ultramafic complexes of Alaska and Venezuela. Generally, the different authors agree that they were formed in a magma reservoir underneath a volcano. The idea of forming ultramafic rocks at shallow depth beneath a volcano was first suggested by MacDonald (1965) and later complemented by Kuno (1969) during studies of Hawaiian volcanoes. McDonald (1965) suggested that the probable dense rocks beneath the Hawaiian volcanoes could be olivine-rich cumulates. Kuno (1969) proposed that the whollite series in the Hawaiian nodules represents the lower portion of solidified magma reservoir underneath the Hawaiian volcanoes. He explained the different rock types as being produced by crystal settling.

Murray (1972) proposed that zoned ultramafic complexes of the Alaskan type could be feeder pipes of andesitic volcanoes originating by fractional crystallization and flow differentiation of basaltic magma, the parent magma being an olivine-rich tholeiitic basalt. He devised a similar scheme to explain the zoned ultramafic complex which occurs
Figure 29. Compositional gradation from amphibolite (a), dark patches, to hornblende-plagioclase pegmatite (pg) light mottled rock. Outcrop at kilometer 7 on the Bolivar - La Primavera road. View looking south.
Figure 30. Fine- and medium-grained amphibolite outcrop south of the town of Bolivar. End of hammer handle is at contact.

Figure 31. Close-up of medium-grained amphibolite. Same outcrop as fig. 30. Scale is in centimeters.
west of San Juan de los Morros and west of Acarigua, Venezuela.

Irvine (1974) proposed that the zoned ultramafic complexes of Duke Island, southeastern Alaska, were formed as stratiform cumulates precipitated by fractional crystallization. These stratiform bodies, while still "mushy" due to the presence of intercumulus liquid, and in response to lateral compression, were then squeezed diapirically upward and laterally. Irvine shared Murray's view that the ultramafic complexes probably represent magma reservoirs beneath volcanoes and commended his ideas concerning their relation to subduction zones.

Prior to selection of a model that approximates the mechanism of formation of the Bolivar mafic-ultramafic complex, it is important to summarize some of the striking characteristics of the complex and the host rocks: a) the basalt and diabase that form the host rock of the complex are low-potassium island arc tholeiites of Cenomanian to Turonian age; b) the age of the complex is roughly the same as that for the basalts; c) in the field, intrusive contacts as well as transitional contacts were observed among the different rock types of the complex; d) graded layering, graded lamination, cross-stratification, and the cumulus character of the crystals indicate that rocks of the complex were formed by gravity precipitation of suspended solid particles in a flowing viscous liquid or magmatic turbidity current; e) plagioclase is present in all the rock types except dunite and occurs mostly as post-cumulus crystals which roughly decrease in amount from the margin to the core of the complex, suggesting a genetic relation between the gabbro and the ultramafic rocks; f) the contact between gabbronor diatexite-pyroxenite units in some places is clearly intrusive, while the contact between dunite and pyroxenite is either sharp and tectonized or gradational; g) all the rock types show considerable penetrative deformation of probably protoclastic origin; h) the dunite contains small amounts of clinoxyroxene that most likely crystallized from trapped intercumulus liquid; i) the rock types forming the complex are in accordance with the wehrlite series of dunite, clinopyroxenite, wehrlite, clinoxyroxene gabbro; j) the order of precipitation of the crystal phases from the liquid in the Bolivar complex was olivine, clinoxyroxene, plagioclase.

Based on the above points, the author suggests that the Bolivar zoned ultramafic complex and the Ríofrío and Rio Volcanes gabbro are genetically related and probably generated from a parental tholeiitic basalt solidifying in magma chambers beneath volcanoes of Turonian age. The different rocks were formed by precipitation of solid particles under the influence of gravity at the base of the chambers in the following stratigraphic succession: dunite, olivine-clinoxyroxenite, clinoxyroxenite-peridotite (wehrlite), clinoxyroxene gabbro plus residual liquid at the top of the stratiform body.

Intrusive emplacement of material in the stratiform body began by compressional effects producing a doming of the crystal mush and migration of the residual liquid toward the margin of the domical body. Subsequently, the body was squeezed diapirically upward. This diapiric emplacement produced faulting on both sides of the complex allowing penetration of water and generation of the water-rich pegmatitic phase, thus converting the pyroxene-plagioclase residual liquid into a hornblende-plagioclase pegmatitic phase that intruded the complex mainly along the shear zones related to the peripheral faults. Later uplift along the faults brought the concentrically zoned diapir close to the surface. Deep erosion during Paleocene and later times has resulted in the present surficial expression of the Bolivar zoned ultramafic complex. The diapiric mechanism of emplacement of the zoned ultramafic complex explains several features such as: presence of gradational and sharp intrusive contacts, penetrative deformation, different shapes, and extensive and peripheral character of the amphibolites. Strong deformation during diapiric emplacement due to poor lubrication effects of intercumulus liquid may have disrupted the zonal pattern. It is the opinion of the author that a well-displayed zonal character should be more the exception than the rule. The sequence of formation of the Bolivar ultramafic complex is shown in a series of schematic diagrams (Fig. 32).

**UPPER TERTIARY ROCKS**

The area under study is bordered on the east and west by large, deep Tertiary basins. On the east, the Tertiary rocks are covered by Quaternary alluvium and outcrops of the older rocks are seen only in major stream beds as in the Río Guadalupe west of Buga. On the west, conglomerate, sandstone and bluish claystone assigned to the Naya Formation (Nelson, 1959) unconformably overlap different rock units of the Dagua and Dianita Groups. Nelson (1959) believes that these rocks were deposited in a lentic-fluvial environment and he assigned a Miocene age to them. These Tertiary sediments show almost no deformation. The regional dip of the Naya Formation is about six degrees and it should be considered more of an initial depositional dip rather than a dip of tectonic origin. Malfait and Dinkelman (1972) were
Figure 32. Schematic diagrams showing the formation of the Bolivar zoned ultramafic complex by diapirc emplacement of a stratiform sequence of cumulates lubricated by intercumulus liquid.
the first to recognize the “Bolivar geosyncline” as a trench and they named it the Bolivar trench. Later, different authors have accepted the idea postulated by Malvolti and Debitante and have used it to build tectonic models for western Ecuador and Colombia (Gosseyn, 1973; Barrero, 1974; Restrepo and Toussaint, 1975).

QUATERNARY SEDIMENTS

The distribution of the surficial deposits was determined mainly by the study of aerial photographs and the compositional character of the deposits was studied by widely scattered observations on the ground.

ALLUVIUM

Some major alluvial deposits were mapped in the area studied. The most important of them is the alluvium deposited by the Cauca River. It consists of gravel, sand, and large amounts of silt. Toward the eastern slope of the Western Cordillera, the better sorted Cauca River alluvium interfingers with very poorly sorted slope debris and ravine-fill material. There are four alluvial deposits which are of importance because small towns have been built on them. They are: Loboguerrero, Darién, El Dovio, and Roldanillo alluvium.

LANDSLIDE DEPOSITS

Landslide deposits are widespread throughout the area, but almost all of them are rather local features that were formed by relatively recent landsliding. The most important, and certainly the oldest, is a large landslide deposit west of the town of Darién (Fig. 36). This deposit consists mainly of clay, shale, sandstone and diabase material of different sizes, derived from the Esparra Formation and the Diabase Group. The landslide deposit is younger than the Quaternary alluvium of Darién but pre-dates any historical information available.

METAMORPHISM

The types of metamorphism and metamorphic facies used here are those proposed by Miyashiro (1973). Three types of metamorphism occurred in the study area during Upper Cretaceous time: a) low-grade regional metamorphism, b) contact metamorphism, and c) cataclastic metamorphism. The contact metamorphism has been discussed previously in connection with the intrusive bodies.

REGIONAL METAMORPHISM

Most of the rocks in the Central Western Cordillera contain newly formed mineral assemblages characteristic of low-grade regional metamorphism.

Regional metamorphism is pervasive throughout the Central Western Cordillera. The pelitic and psammitic rocks of the Dagua Group show a well-developed slaty and phyllitic foliation in a subparallel relation with the primary stratification. The trend of foliation is variable from N. 10° E. to N. 50° E., but most slates and phyllites show a foliation trending N. 20°-30° E. In contrast, basalt and diabase do not exhibit this foliation and most, but not all, samples from these rocks show a lower metamorphic grade than the pelites and psammites of the Dagua Group. This fact has confused most geologists in the past who have considered the Diabase Group a non-metamorphic unit, resulting in a very difficult interpretation of the geologic history of the Central Western Cordillera.

Three metamorphic facies are represented by the metamorphic mineral assemblages found in the pelitic, quartz-feldspathic, calcareous and basic rocks of the Dagua and Diabase Group. These metamorphic facies are: a) the zeolite facies, b) the prehnite-pumpellyite facies, and c) the greenschist facies.

The zeolite facies predominates in the basalts and diabases of the Diabase Group in the upper part of the stratigraphic sequence. However, locally these rocks contain the higher grade prehnite-pumpellyite and greenschist facies. Rocks belonging to the zeolite facies show the diagnostic assemblage heulandite-quartz, which occurs mainly in microveins and amygdules.

The prehnite-pumpellyite facies occurs sporadically in the basalts of the Diabase Group. In this case, pumpellyite, chlorite, epidote is the characteristic mineral assemblage.

The greenschist facies is the easiest of the three metamorphic facies to be recognized in the field. It is well developed in the older rocks of the Dagua Group. The most common metamorphic minerals in these rocks are muscovite, chlorite, biotite, epidote, calcite and quartz. The presence of two or three of these minerals gives the different assemblages observed in the several rocks types. Monomineralic metamorphic rocks are represented by recrystallized limestone and chert. However, in most cases the rocks contain impurities and, therefore, in addition to the major rock forming minerals, a newly formed white mica or chlorite is present in small amounts.

The metamorphic minerals identified in rocks from the Dagua and Diabase Group indicate that the higher metamorphic grade attained by the sequence was the upper temperature field of the greenschist facies, indi-
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The metamorphic minerals identified in rocks from the Dagua and Diabase Group indicate that the higher metamorphic grade attained by the sequence was the upper temperature field of the greenschist facies, indi-
cating a very low temperature increase during metamorphism. On the other hand, the three metamorphic facies are diagnostic of none of the basic types of metamorphism (Abukuma, Barrovian, Franciscan) and they do not allow any definite conclusion as far as the prevailing pressure conditions are concerned. Therefore, at present, a classification on pressure conditions of the metamorphism of the Central Western Cordillera is not possible.

A second major problem is that concerning the dating of the low-grade metamorphism of the Central Western Cordillera. Two samples of gray phyllitic slates were collected and sent to Geochron Laboratories to be analyzed by the whole-rock K-Ar method. The samples were collected at kilometers 59.5 and 68.5 on the Buga-Buenaventura road, and the ages obtained were 81.8 ± 3.3 and 61.9 ± 2.7 m.y., respectively (Table 4).

Taking into consideration the whole problem involved in dating the metamorphic events and the fact that metamorphism is a process which lasts for several million years, the author considers that the two ages are valid and they represent different thermal histories of the two samples. The oldest age may represent either the moment when the metamorphic maximum was reached for that specific sample or it could also be the result of the presence of “unmetamorphosed” relics of feldspar. However, study of thin sections of the dated samples indicates that this possibility is valid for both samples. The youngest age is somewhat more difficult in interpretation. The author believes that the 61.9 ± 2.7 m.y. age may represent the approximate time when the rock sample cooled down through some critical isotherm due to the rapid uplift which follows the metamorphism at the end of the Cretaceous and beginning of the Tertiary periods. Consequently, it is logical to say that the regional metamorphism of the Central Western Cordillera took place during the late Santonian-Maastrichtian.

CATACLASTIC METAMORPHISM

The term cataclastic metamorphism was given by Miyashiro (1973) to the process of crushing and grinding of rocks which usually takes place as a result of faulting. Nomenclature of cataclastic rocks is here used as proposed by Higgins (1971).

Most of the faults present in the area, especially those west of the Calima-Andinapoli faults, are traced readily by following a wide, 10- to 200-meter zone of cataclastic rocks. Protomylonites are commonly present in the Calima fault zone (Fig. 33) while mylonite gneiss is the common feature of the Rio Bravo, Cristales and other faults to the west (Figs. 34 and 35, and Plate 1). Other cataclastic rocks such as mylonite, ultramylonite and blastic mylonite are also present along the major fault zones.

STRUCTURAL GEOLOGY

MAJOR STRUCTURAL FEATURES

The largest conspicuous structural features in the area are north-northeast trending faults and folds. The true nature of these two structures is difficult to interpret because the area has undergone at least two periods of deformation: the “Calima Orogeny” and the Andean Orogeny.

Several features, such as regional and cataclastic metamorphism, physiography, faults and folds, point to a division of the area in two different structural regions, separated by the Calima-Cristales fault system. Moreover, these two regions correspond with the Calima and San Juan physiographic provinces. This dual structural character seems to extend south and north beyond the study area probably over the entire Central Western Cordillera.

FOLDS

Folds in the study area show a general trend of N. 5-40 E. In the San Juan province west of the Calima-Cristales fault system, folds are mostly of the isoclinal type with wavelengths from 400 to 1000 meters (Plate 2). With few exceptions, folds in this region are overturned toward the west. All the exceptions are more or less upright isoclinal folds, which locally, as in the Rio Garrapatas area, may be slightly overturned to the east. A tectonic polarity toward the west is well-displayed by the folds: no only in the study area but in the entire Central Western Cordillera. In the Calima province, east of the Calima-Cristales fault system, folds are less numerous and they are of the open symmetrical type. The province is divided in two halves by a NE trending fault located near the town of Salónica. The southern half contains a major anticline with minor structures on both limbs (Plate 2). On the other hand, the northern half is a homocline, dipping gently toward the east. The presence of only one type of folding probably means that the Diabase Group was folded during the first period of deformation due to an increase of the mean ductility of the sequence produced by regional metamorphism, and during the second period of deformation, the Diabase Group behaved in a brittle manner such that the entire province deformed by faulting.
Figure 33. Protomylonite of the Calima fault zone developed on diabase of the Diabase Group. Outcrop 4 kilometers east of the hamlet of Loboguerrero.
Figure 34. Mylonite gneiss in the Cristales fault zone. Outcrop at the Rio Cristales headwaters. Original rock was a diabase of the Diabase Group.

Figure 35. Close-up of mylonite gneiss in the Cristales fault zone shown in figure above. The original rock was a diabase of the Diabase Group.
FAULTS

North-northeast trending faults are the most striking structural feature of the area. Toward the northern border of the area this fault system displaces the Carrapatas fault, a major NS0-60°E-trending fault which extends from the Pacific coast into the present continental area as far as the Cauca Valley. The author believes that the Carrapatas fault may represent a paleotransform fault which probably behaved as a strike slip fault during the Andean Orogeny. This major break in the crust is considered here to be the north boundary of the Central Western Cordillera. In the southern part of the area, younger NW-trending faults displace the N-NE fault system.

The N-NE fault system consists of high-angle reverse faults and, in lesser number, normal faults. Normal faulting was either originated or reactivated during the second period of deformation, that is the Andean Orogeny. The relative movement and magnitude of displacements on the faults are very difficult to interpret. In the San Juan province faulting is well developed. The relative movement of these faults seems to have been mostly of the reverse type. However, along an individual reverse fault, contradictory relations can be found. Apparently normal faults exhibit wide and well-developed cataclastic zones. Protomylonites and mylonite gneisses are very common in these fault zones and were probably formed by deep-seated faulting under conditions of high confining pressures. This is suggested by the fact that the cataclastic rocks show primary cohesion. These observations strongly suggest that the early history of such faults goes back in time prior to the Lower Tertiary denudation. Most of these discrepancies can be understood by unraveling the major deformational and erosional periods of the study area. On the other hand, in the Calima province faulting is less frequent and widespread. The only regionally important fault in that province is the Roldanillo fault. This fault seems to be a normal or vertical fault related to the diapiric emplacement of the mafic-ultramafic complex. The history of this fault also goes back prior to the main period of denudation. Its elongated S-shape may indicate some later rotation and change of the direction of dip toward the west, produced by Late Tertiary or Quaternary rotation. A fault running subparallel to the Cauca River, now covered by the Quaternary alluvium of the Cauca Valley, has been postulated by several geologists on the basis of subsurface data (Schwinn, 1969). This subsurface fault appears in almost any regional study of Colombia as the Cauca fault. Strong shearing of the basaltic rocks close to the Cauca River could be interpreted as supporting evidence for this fault.

MAJOR DEFORMATIONAL AND EROSIONAL PERIODS

The structural geology of the area is the consequence of two major deformational periods separated by a span of extensive denudation. The structural configuration as it appears today is therefore the sum of these three events plus the effects of uplift and rotation during Quaternary time.

LATE CRETACEOUS DEFORMATION

The first period of deformation in the study area took place during the middle stage of increasing regional metamorphism. Convergent folding took place throughout the area by a flexural slip mechanism under conditions of low mean ductility and high ductility contrast. Under these conditions, the Calima province developed broad concentric folds while in the San Juan province a complicated pattern of short wavelength, concentric folds was produced. During the progression of metamorphism, when the maximum metamorphic grade was attained, penetrative deformation developed mostly in rocks of the Dagua Group, resulting in overturned, isoclinal folding well-displayed in the San Juan province. Toward the east, in the Calima province the diapiric folding of the still "musty" Bolivar ultramafic complex was accelerated.

Deformation following the temperature maximum was mostly brittle, producing deep-seated faulting with well-developed cataclastic metamorphic zones, mainly in the San Juan province. To the east, in the Calima province the still more brittle Diabase Group failed in a block-faulting manner. The diapiric emplacement of the ultramafic complex was attained by detachment of the cumulative domical body and accelerated upward movement along the Roldanillo and Cauca faults.

The structural, metamorphic and magmatic differences between the two provinces can be explained on the basis of the different mechanical properties of the Dagua and Diabase Group; the lower stratigraphic position of the more highly metamorphosed Dagua Group; and by the fact that the volcanic centers were localized toward the east side of the area.

The author believes that magmatic activity of tholeiitic nature, regional metamorphism, folding, faulting, and intrusion of mafic-ultramafic complexes in the Central Western Cordillera represent an entire orogenic sequence of events developed upon a basement of Lower Cretaceous oceanic crust.
The entire orogenesis took place during Late Cretaceous-Early Paleocene time as is indicated by a post-orogenic Eocene conglomerate which overlies in nearly perennial unconformity the Eocene conglomerate (Schwinn, 1969). This orogenesis includes all of the features that are described from well-known immature enigmatic island arcs.

The author proposes the name of "Calima orogeny" to characterize the island arc type of orogeny that created the Central Western Cordillera and probably the entire Western Cordillera of Colombia.

EARLY TERTIARY DENUDATION

Following the end of this deformational period, the area was subjected to uplift and intense erosional activity during Late Paleocene and Early Eocene time. This denudation period produced a smooth topography on the Central Western Cordillera. Vestiges of this denudation surface are found in the rolling topography of the entire Calima province and in the thick lateritic soils found at high elevations on the plateau-like top of the mountains of the San Juan province. The end of this erosional period is marked by a regional unconformity. The Upper Eocene basal conglomerate of the transgressive marine Urbe Formation, which crops out south of the study area, contains boulders and cobbles of rocks from the Diabase Group. Some 20 kilometers southwest of Buga, near Quebrada San Marcos, the Lower Miocene limestones and other rock units of the Vijes Formation, unconformably overlie the Turonian rocks of the Diabase Group. In the study area, the rocks of the Dagua and Diabase Groups are unconformably overlain by the Miocene Naya Formation. These examples testify to the existence of a major unconformity of Early Eocene age in the Central Western Cordillera.

LATE TERTIARY-QUATERNARY DEFORMATION

Following the deposition of the marine sequence during the interval between the Eocene and the Miocene, the study area was affected by a second period of deformation. The Miocene sediments of the Dagua and Viyes Formation, which crop out immediately east and south of the area, have been strongly deformed, supporting the well-documented Late Miocene-Pliocene orogenic episode known as the Andean orogeny. Deformed Tertiary rocks were not found cropping out in the area but evidence for Late Tertiary deformation is given by the contrasting physiographic features of the Calima and San Juan provinces, which were explained in detail in an early section.

The compressive effects produced by the Andean Orogeny were superimposed on the earlier deformational features. This compression divided the whole area into two major blocks separated by the Calima-Cristales fault system (Plates 1 and 2). The more or less isotropic rocks of the Calima province remained stable after minor readjustment of individual blocks. The anisotropic and more ductile rocks of the San Juan province were folded and faulted again. Following or coeval with this initial period of compression, quartz-dioritic intrusives were emplaced elsewhere north and south of the study area. At the end of the Tertiary, the Late Cretaceous fault system was reactivated. The San Juan province was uplifted roughly 1,200 meters above the Calima province along the Calima-Cristales fault zone as is demonstrated by the present-day vertical separation of the Early Tertiary denudation surface (Fig. 36). Strike-slip movement caused by a reorientation of the stress field, possibly occurring at the end of the Tertiary, is suggested by the following observations: a) the Rio Volcanes and Riffio gabbro which are petrographically identical could have been in the past a single unit. If displacement occurred, it was along the Roldanillo fault and was left-lateral in nature, and b) the Espinal Formation, southwest of the town of Salomé, seems to have been offset by a northeast trending fault; if so, the movement was of the left-lateral type (Plate 1).

Finally, during Quaternary time the whole Central Western Cordillera underwent uplift as demonstrated by the rejuvenated character of the present-day physiography. MacDonald (1976, personal communication), recognized north of the study area, on the basis of paleomagnetic studies, that the northern Western Cordillera has rotated, between the Pliocene and the present, to the west. If this rotation has influenced the area under investigation, then the elongated S-shape of the faults, the variations in foliation, and the left-lateral strike-slip movement that have developed since Pliocene to recent time can be easily explained.

PLATE TECTONIC MODEL FOR THE AREA

The purpose of this chapter is to postulate an independent plate tectonic model on the basis of field and laboratory data that may serve to explain the composition, deformation, age, time of emplacement, and present-day position of the Central Western Cordillera. The model proposed is aimed to be consistent with the facts observed not only in the area but also in the adjacent San Juan-Atrato and Cauc Valley basins. A tectonic model for the area has not been proposed.
Figure 36. Calima fault scarp west of the town of Darien. View looking north from a point on the Buga-Buenaventura highway. The Calima reservoir is between the diabase (d) of the Diabase Group and the chert and shale of the Espinal Formation (ch). North of the reservoir is the landslide of Darien (Q1). To the east of the trace of the fault (f) is the Calima Province. To the west is the San Juan Province. Vertical offset on this fault is about 1,200 meters.
before. However, very general tectonic models have been suggested before to explain the complexities of the Western Cordillera. The following will be discussed: a) major tectonic units, and b) proposed model.

MAJOR TECTONIC UNITS

Three major tectonic units are present in the study area and they are from older to younger: a) The Cauca Valley basin, b) the Central Western Cordillera, and c) the San Juan-Atrato basin (Fig. 5). The Cauca Valley basin is a filled paleotrench which developed during Late Jurassic-Early Cretaceous time and was probably active until Aptian time. It consists of a complex assemblage of Upper Jurassic-Lower Cretaceous oceanic crust, trench deposits of Early Cretaceous age, Upper Cretaceous-Tertiary back-arc deposits and Quaternary fill.

The Central Western Cordillera represents an immature island arc developed upon a Lower Cretaceous oceanic crust. It consists of the typical ophiolite assemblages, with pelagic sediments, turbidites, tholeiitic basalts and mafic-ultramafic rocks. This tectonic unit will be the main entity in the proposed tectonic model.

The San Juan-Atrato basin is a filled paleotrench of Santonian age that was probably active until the end of the Eocene when subduction ceased. It consists of Campanian to Maastrichtian oceanic crust, Tertiary trench deposits and Quaternary fill (Bandy, 1970; Irving, 1975).

PROPOSED TECTONIC MODEL

Assembling all the data presented in the preceding sections, the following plate tectonic model is proposed. During Early Jurassic time the cratonic continental margin of northwestern South America began to be underthrust by an oceanic plate originating a deep trench (Cauca Valley trench) along the western border of the ancestral Central Cordillera. At the end of the Jurassic a plutonic-oceanic arc was well-established along the east side of the present Central Cordillera. Evidence for magmatic activity during Late Jurassic time is documented by Barreto and Vergy (1976). The oldest radiometrically dated igneous intrusive in the Central Cordillera related to this subduction episode is Late Jurassic in age. Rapid denudation of the continental margin filled the trench beginning in Cretaceous time. Elimination of this barrier allowed the abyssal plains located west of the trench to begin to receive the terrigenous material from the continental rise present on the eastern side of the trench. During Early Cretaceous time, turbidite currents originating in the continental rise transported and deposited the distal turbidites which are found intercalated with pelagic sediments in the upper part of the Cisneros Formation. Coeval subaerial volcanic activity in the Central Cordillera volcanic arc, caused deposition of a thick tuffaceous sequence, the green phyllite of the Cisneros Formation. Continuous movement of the Pacific plate brought the Cisneros Formation closer to the continental margin.

The early Late Cretaceous is characterized by a complex assemblage of events: deposition of proximal turbidites derived from the Continental rise simultaneously with pelagic or hemipelagic sedimentation formed the Espinal Formation, Coeval, intense tectonic faulting at the site of bending of the oceanic plate, originated a series of graben-horst like structures parallel to the trench. Beneath this tensional zone an upwelling convective cell was created and this, in turn, worked as a driving force to produce spreading of the oceanic plate and generation of low-potassium, tholeiites. This basaltic volcanism formed the Diabase Group. A series of volcanic centers were probably formed at the intersection between transform faults and faults of the rifting zone, creating the island arc which formed the Central Western Cordillera.

During Turonian and Coniacian time there was rapid production of large amounts of basaltic magma. However, the convective cell generated a compression zone to the west of the spreading center and by the end of Coniacian time, spreading was greatly reduced as a new trench began to form. This trench is known as the San Juan-Atrato basin, Bolivar geosyncline, or Bolivar trench. Coeval with eruption of tholeiitic magma during Turonian and Coniacian time, stratiform mafic-ultramafic cumulates were formed in individual magma chambers beneath volcanoes.

During Santonian to Maastrichtian time, the South American plate overrode the Cauca Valley trench, mainly because the detachment and sinking of the leading edge of the Jurassic plate. The compressional effects produced low-grade regional metamorphism, folding and faulting of the ophiolitic sequence of the present Central Western Cordillera. Simultaneously, the stratiform mafic-ultramafic cumulates were diapirically emplaced to upper levels in the crust. At the end of the Cretaceous, the continuous overriding of the South American plate welded the Central Western Cordillera to the continental mass. At this time, the Central Western Cordillera and very probably the entire Western Cordillera of Colombia and its southern extension into Ecuador, acquired the status of a folded mountain belt. The different stages in the tectonic evolution of the Cordillera di-
ring the Jurassic-Cretaceous periods are shown in time-sequence in figures 37 through 42.

During Late Paleocene to Eocene time the Central Western Cordillera underwent extensive erosion. The clastic products of this erosional period were deposited interbedded with pelagic sediments in the San Juan-Atrato trench.

During Oligocene to Miocene time, the Western Cordillera was the site of intense magmatic activity. Quartz-diorite and other felsic differentiates were generated by the San Juan-Atrato subduction zone. They are found as stocks and batholiths throughout the Western Cordillera north and south of the study area. This magmatic activity is interpreted by the author as the beginning of the Andean Orogeny.

By the end of the Tertiary period, the San Juan-Atrato trench was strongly folded by the overriding Western Cordillera and South American Plate. This period represents the folding and probably the metamorphic stage of the Andean Orogeny. The Central Western Cordillera reacted as a cratonized block and consequently underwent faulting, mostly of the normal type. Vertical displacement up to 1,200 meters has been documented in this work along the Calima-Cristales fault system (Fig. 36).

During Quaternary time, the Central Western Cordillera and probably the entire Western Cordillera of Colombia underwent uplift, probably as a result of isostatic rebound that usually follows the intense periods of subduction and/or orogenesis.

CONCLUSIONS

The present research on the geology of the Central Western Cordillera has resulted in the following conclusions:

1. The Cineros Formation represents layer one of a Lower Cretaceous oceanic crust which moved eastward, underthrusting the continental margin.

2. The Espinal Formation is a part of a continental rise prism. Turbidites have part of large submarine fan deposition.

3. The Diabase Group consists of low-potassium island arc thelites that were generated during a rifting stage in the oceanic plate along a zone located on the outer margin (outer rise) of the late Jurassic Cauc Valley trench. Emission of basaltic magma took place in individual volcanic centers that formed a typical immature enigmatic island arc.

4. The age of the Diabase Group may be different from place to place depending on time of activation of the respective volcanic centers. The ages may be found to show a random pattern rather than a systematic one in any direction. Interbedding with the Dagua Group may occur.

5. The low-potassium island arc thelites were erupted almost in situ when a major decrease in spreading of the Pacific plate took place at the end of the postulated "magnetic quiet" (Larson and Pitman III, 1972), and close to the beginning of the late Cretaceous to present day period of magnetic polarity reversals. If, this island arc thelites were generated during a rifting period early in the formation of the arc, a sharp distinction between them and true ocean-ridge thelites may not be possible.

6. The Dagua and Diabase Groups were folded, metamorphosed and intruded by mafic-ultramafic complexes during Late Cretaceous time as a result of overriding by the South American plate. This was accompanied by the detachment and sinking of the leading edge of the Late Jurassic plate and renewed subduction of oceanic crust to the west along the San Juan-Atrato trench.

7. The mafic-ultramafic complexes are genetically related to the Diabase Group. They were formed first in a magma reservoir beneath volcanoes, as stratiform cumulates. Later, during folding and metamorphism, they were diapirically intruded into the Diabase Group.

8. Presence of mafic and/or ultramafic complexes indicates major centers of volcanic activity that may be related to intersections of paleotransform faults with faults of the rifting zone. These intersections may be the location of economic accumulation of metals.

9. During Early Tertiary time, the Central Western Cordillera underwent a period of intense erosion.

10. For all the described events from Upper Cretaceous to beginning of the Tertiary, the author proposes the name of Calima Orogeny.

11. Evidence from surrounding areas indicates that the Central Western Cordillera underwent deformation during the Andean Orogeny in Late Tertiary time.

12. Isostatic rebound following the Andean Orogeny caused uplift and rejuvenation of the Central Western Cordillera during Quaternary time.

13. Finally, the rifting mechanism here proposed to originate the Central Western Cordillera thelites may be a useful tool to explain the shifting character of some subduction zones.
Figure 37. Underthrusting of the Pacific plate beneath the ancestral Central Cordillera. Plutonism and volcanism of late Jurassic age. Faulting at the continental margin and beginning of the Romeral fault, with a reverse sense of movement, during the entire period of destruction of the continental margin.
Figure 38. Subduction proceeded at a fast rate, corresponding with faster spreading rates of the Pacific. Volcanism occurred in the Magdalena Valley and Eastern Cordillera. Deposition of proximal turbidites at the end of the lower Cretaceous occurred in the site of the present Western Cordillera.
Figure 39. Major faulting at bend in Pacific plate. Beginning of local spreading by initiation of a small-scale convection cell. Abundant proximal turbidites in the Espinal Formation in the site of the present Western Cordillera.
Figure 40. Emission of large amounts of basaltic magma. Formation of volcanic centers and volcanic island arc in the site of the present Western Cordillera. Spreading rates still very high for the Pacific Plate.
Figure 41. Spreading is highly reduced as the San Juan-Atrato trench is formed; basaltic volcanism proceeds in the island arc in the site of the present Western Cordillera.
Figure 42. Compression from the Upper Cretaceous Pacific plate (UKPP) and detachment of the leading edge of the Jurassic plate (DJPP). Overriding of the South American plate (SA) originates the Cauca Valley (CVF) and Central Western Cordillera metamorphosed folded belts during the main deformational phase of the Calima Orogeny. Continuous overriding of the South American plate produced accretion of the Lower Cretaceous Pacific plate (ALKPP). During this period, probably at the end of the Cretaceous, a mixture of continental, oceanic and upper mantle rocks are emplaced by isostatic rebound along the Romeral Fault zone thus forming the High-pressure metamorphic Romeral Melange.
REFERENCES CITED


GOSSENN, P. J., 1973.- Late Mesozoic-Early Tertiary volcanic island arc along the northwestern South American continental margin: II Congreso Latinoamericano de Geología, Caracas.

GONZALEZ, H., 1974.- Metamorfismo dinámico en la zona de la falla de Romeral: Simposio sobre ofiolitas, Medellin.


SHIDO, F., MIYASHIRO, A., AND EWING, M., 1974a.- Compositional variation in pillow lavas from the mid-Atlantic Ridge: Marine Geology, v.16, p.177-190


