PROVENANCE OF THE LOWER CRETACEOUS SEDIMENTARY SEQUENCES, CENTRAL PART, EASTERN CORDILLERA, COLOMBIA

by

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Resumen

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Se presentan los probables terrenos de aporte y ambiente de depósito para las unidades clásticas del Cretaceo Inferior basado en análisis petrográficos y estratigráficos. La cuenca durante el Valanginiano Tardío fue dividida en un depocentro (Formación Murca) y una plataforma hacia el sur (Areniscas de Utica), depositadas en profundidad por corrientes de turbidez y en aguas someras respectivamente y, en una plataforma hacia el norte (Formaciones Cumbre y Rosablanca), depositadas en ambiente marino somero.

Abstract

This work presents a probable Provenance Terrains and Depositional Setting for the Lower Cretaceous clastic units based on petrographic and stratrigraphic analysis. The Late Valanginian basin was divided into a central depocenter (Murca Formation), a southwestern shelf (Utica sandstone) which were deposited in deeper water by turbiditic currents and shallow water respectivaly; and a northern platform (Cumbre and Rosablanca Formations), deposited in shallow marine environments.

Introduction

The study area is located 100 km northwest of Bogotá, on the west side of the Cordillera Oriental, the easternmost range of the Northern Andes mountain chain. It occupies the region between 5° 10' —5° 50' N latitude and 73° 50' —74° 15' W longitude, on topographic sheets 169, 170, 189, 190, and 208, published by the Instituto Geográfico Agustín Codazzi (IGAC). It is bounded on the west by the Magdalena Valley (Figure 1).

The area is characterized by mountain ranges of deformed Cretaceous rocks with elevations that reach up to 2,800 m above sea level in the central part of the area and descend to 200 m above sea level in the Middle Magdalena Valley in the northewestern portion of the area. The climate follows the vertical zonation common to mountainous regions near the Equator: cold in the highlands and hot in the lowlands. There are several roads in the area, but access is principally by unpaved or partially paved roads such as the Bogotá — Pacho, Pacho — La Palma, Chiquinquira — Otanche, La Belleza — Florian and Puerto Boyacá — Otanche roads. Access to many parts is by trails or old paths.

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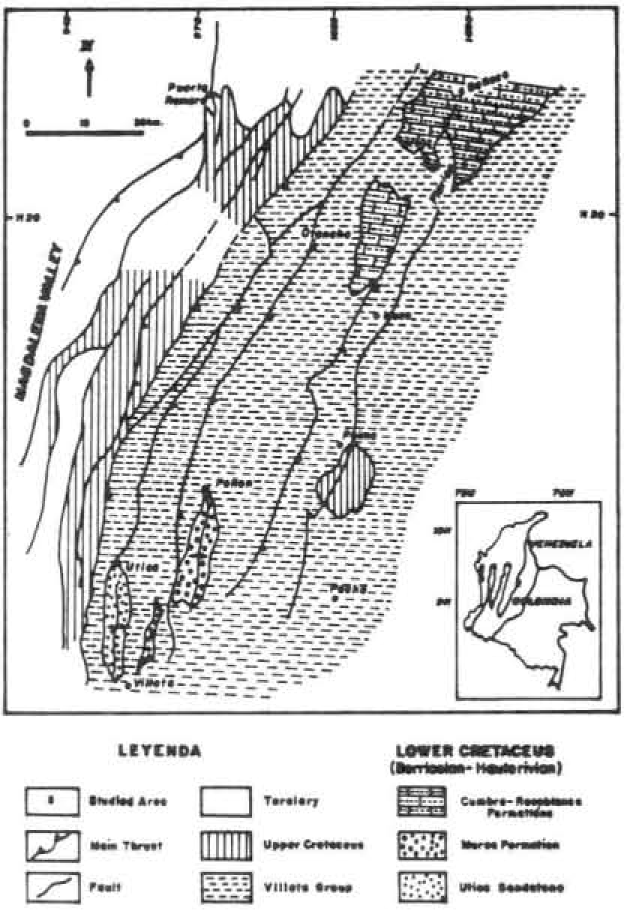

Figura 1. Location and geologic map of study area.

In the northern portion of the area, the Lower Cretaceous succession is formed by the Cumbre and Rosablanca Formations which extend from the Late Berriasian to Valanginian (**Alfonso**, 1985; **Etayo-Serna** and **Rodríguez**, 1985). In the southwestern part of the area, in the Villeta anticline, the Utica sandstone is dated as Late Berriasian to Upper Valanginian (**Etayo-Serna**, 1987, writing comunication). In the central portion, in the Murca Anticline, is the Murca Formation, which has a Late Valanginian age based on fossils collected where the type section was measured. This is overlain by the Villeta Group. These latter units, the Utica Sandstones and Murca Formation, have been recognized in previous works as the Caqueza Sandstones, the upper part of the Caqueza Group which extends from the Tithonian to Hauterivian (**Bürgl**, 1961; **Champertier**, et al., 1961; **Campbell** and **Bürgl**, 1965; **Thompson**, 1966; **Julivert**, 1968; Ingeominas, 1975; **Gallo**, 1977; **Espinel** and **Pinilla**, 1989, **Rondon** and **Vega**, 1989). This study shows a petrographic and provenance analysis of the lower Cretaceous clastic basal units on the western margin of the Cordillera Oriental as part of the requirements for the Degree of Master of Sciences in the Department of Geological Sciences-University of South Carolina. The objetives to carry out this project were the preparation of geological map of the estudy area; preparation of representative stratigraphic columns for the sedimentary sections; collection of a representative suite of samples for paleontologic and petrographic analysis.

This report summarizes the results of the geological field work conducted in the Magdalena Study area (Area 2) during 1987 in the Thecnique Cooperation Agreement between the Universidad Nacional de Colombia and the University of South Carolina – Earth Science and Resource Institute.

Stratigraphy

The Utica Sandstone (Berriasian-Hauterivian), Murca Formation (Valanginian), Cumbre Formation (Berriasian), Rosablanca Formation (Valanginian-Hauterivian), and Villeta Group (Valanginian-Coniacian), comprise the Lower Cretaceous sedimentary sequence in the study area.

Utica Sandstone

In previous works, the informally named Utica Sandstone was referred to as the Caqueza Sandstone, of the upper part of the Caqueza Group (**Champertier**, 1961; **Thompson**, 1966; Ingeominas, 1975; **Gallo** 1977; **Acosta** and **Obando**, 1984; **Espinel** and **Pinilla**, 1989; **Rondon** and **Vega**, 1989). The Utica Sandstone was named the Trapiche Group by **García** (1983), who proposed subdivision into the Los Monos and Cune Formations with a total thickness of 600 m. Later **Sarmiento** et al., (1985) and **Sarmiento** (1985) presented a stratigraphic synthesis of the informally named Utica Sandstone.

The Utica Sandstone is exposed in the southwestern portion of the study area, and was recognized on the railroad between Utica and Tobia in the core of the Utica anticline, (Figure 1). This basal sandstone is approximately 500 m in thickness and consists mainly of yellow gray coarse to fine grained, graded sandstone with black shales interbedded, with some limestone at the top of the unit. The lowermost part of the unit consists of black shales (mudstone, **Dott**, 1964) interlayered with massive, parallel bedded, yellow-gray sandstones (arkosic wackes, **Dott**, 1964, Figure 2a).

Petrographic analysis of the mudstones shows 90% clay minerals, 3% quartz grains and 7% heavy minerals such as pyrite and mica sheets. The petrographic analysis of the sandstones shows a large amount of siliceous material in the sense of **Dott** (1964), who included the chert fraction in the quartzose fraction. The sandstone contains igneous and sedimentary lithic fragments. These petrographic characteristics and the high amount of matrix permit classification of these rocks as arkosic wackes (Table 1).

The coarse grained sandstones start with a sequence of coquina lenses and conglomeratic, fine grained sandstone with cobble sized clasts and intraclasts of black mudstone. The conglomeratic sandstones are present as lenses with quartz pebbles within parallel laminated beds 20 – 80 cm thick. Up—sections the sandstones are more abundant, and

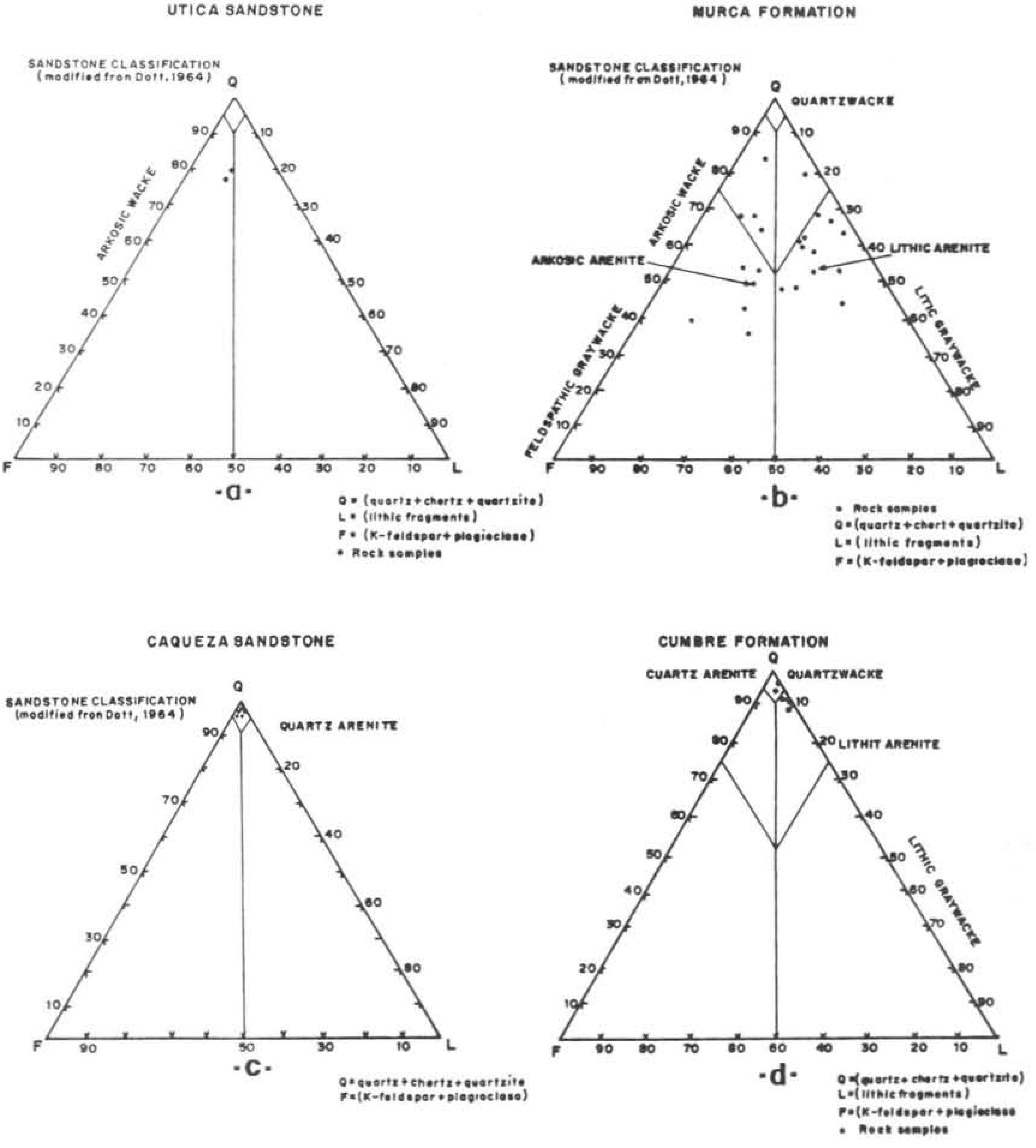

Figure 2. Triangular QKL plots showing mean sandstone classification of the: a–Utica Sandstone, b–Murca Formation, c–Caqueza Sandstone, d–Cumbre Formation (After, Moreno 1990).

grade to siltstone and mudstone. The upper part of this unit consists of conglomeratic sandstones and coarse to fine grained sandstones with abundant coquina lenses, and conglomeratic sandstone beds 12 — 20 cm thick. The sandstone beds contain cross-bedding in sets 5 — 10 cm thick. The coquina lenses consist of small fragments of bivalve shells, which are interlayered each 2 meters. Sedimentary structures such as cross-bedded sandstones beds interlayered with very finely parallel laminated mudstone with assymetric ripples on the bedding planes were recognized.

The stratigraphy described here were determined on the eastern flank of the Utica anticline on the railroad between Tobia and Utica. On the road between Villeta and Utica, near La Magdalena, the Utica Sandstone also crops out. Here the unit consists of interlayered beds of mudstone, with lenses of gastropods and oysters, and calcareous sandstones with plant fragments, coral fragments, and low angle cross-stratification with symmetrical ripple marks. The sandstone beds exposed in that location contain coarse to fines grained, massive beds 1 — 2 m thick with some conglomeratic lenses.

The upper part of the Utica sandstones was observed near Utica where it consists of black limestone beds with intercalations of black shales. They present sigmoidal cleavage perpendicular to the stratification, indicating tectonic activity near the main fault systems such as the Alto del Trigo and Canoas-La Peña thrusts (**Moreno**, 1989). According to both the textural and structural characteristics of the intervals analyzed, and the petrographic analysis, the Utica Sandstones was deposied in a shallow marine environment **Moreno**, (1990). The presence of plant remains and coral fragments, reported by **García** (1983) and **Allen** et al., (1988), support a shallow marine environment.

An ammonite *(Sarasinella cf. hondana* Hass was collected from the lowermost part of the Utica Sandstone. This ammonite was dated by **Etayo-Serna** (writing comunication) as Late Berriasian. Fossils collected by **Bürgl** according to **Thompson** (1986) and **Gallo** (1977) to assign a Hauterivian age to the Utica Sandstone. The basal part of this unit was assigned by **García** (1983) to the Middle Jurassic, based on a specimen of *Nerinea decorate*. **Piette** from an outcrop on the Río Negro river (X = 1,058,600; Y = 956,900) along the railroad between Utica and Tobia very close to where the Late Berriasian ammonite was collected. This latter fossil is thus in disagreement with the age reported by **García** (1983) and nevertheless, this author based on a specimen of *Neocomites capistratus* Bürgl. collected near Utica assigned a Berriasian age for the upper part of this unit. There are inconsistencies about the assigned age for the Utica Sandstone, however the latest age assigned for this unit ranges from Late Berriasian to Hauterivian.

Murca formation

The Murca Formation has been refered to as the Caqueza Sandstones, the upper part of the Caqueza Group (**Champertier** et al., 1961; **Campbell** and **Bürgl**, 1965; Ingeominas, 1975; **Ulloa**, 1988; **Espinel** and **Pinilla**, 1989; **Rondon** and **Vega**, 1989), **Sarmiento** et al., (1985) have called this unit Interval A (of sandstone and shale), and used the name of Nimaima-Guayabal anticlinorium for the Murca anticline proposed by **Champertier** et al., (1961) and **Campbell** and **Bürgl** (1965).

They were informally called the Murca-Pinzaima Sandstone in the Middle Magdalena Basin project by **Allen** et al. (1988). The name Murca Formation is used in this study for the Lower Cretaceous sandstones that crop out in the core of the Murca anticline, as was defined by **Moreno** (1990). The anticline has an aerial exposure of approximately 20 km^2 on sheet 208, at scale of 1:100,000 published by the Instituto Geográfico Agustín Codazzi (IGAC; Figure 1).

The type locality is proposed at the intersection of the Río Murca and Río Negro along the road between Pacho and La Palma near to Talauta, in the Departamento de Cundinamarca (X = 1,072, 625, Y = 971,350). At this location the Murca anticline is cut by the Negro River. The measured stratigraphic section is 920 m in thickness, (Figure 3).

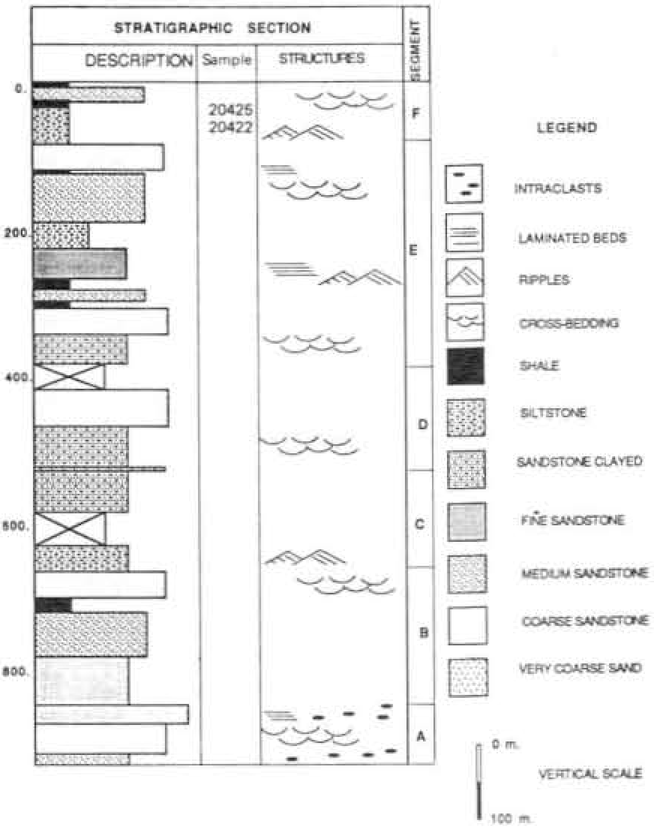

Figura 3. General Stratigraphic column of the Murca Formation. (Moreno, 1989).

The formation also crops out toward the south in the Caquero area, along the road between Villeta and Nimaima, were the Murca Formation is intensely folded. The contact with the underlying unit could not be observed. The contact with the overlying Villeta Group is transitional.

At the type locality, the rocks are composed of coarse grained, locally cross-bedded sandstones and intercalations of siltstone and shale. There are intraclasts at the base of the sandstone beds. The sandstone grades to fine towards the top, and contains intercalation of siltstone and shale measuring up to 20 cm in thickness. There are large pyrite crystals in the basal part of the sandstone beds. The sandstone beds are described as black and grey feldspathic and lithic graywackes (**Dott**, 1964 Figure 2b), in fining—upward cycles (Figure 3). There are shale intraclasts at the base, some siltstone interbeds higher in the section, and black shale towards the top. Petrographically, the sandstones are immature and have a framework fraction that ranges from feldspathic to lithic graywackes, some times with a calcareous matrix-cement (Table 1).

In general the beds are graded, with reworked lithic fragments and assymetric ripple-marks. Some contain small scale cross-bedding and shale interlaminations. These characteristics are considered the most diagnostic criteria for recognizing sandstone bodies deposited from turbiditic currents (Stanley, 1963; Potter, 1967).

The Murca Formation presents characteristics of a turbiditic sequence, deposited below wave base. According to the sedimentary and textural characteristics analyzed here, the Murca Formation is considered to be deposited by turbidity currents in the lower cycle of the Cretaceous basin of the Eastern Cordillera. At the type locality the Murca Formation has been subdivided into six segments Moreno, (1990). The lowermost part of the Murca Formations, segment A, crops out in the core of the Murca anticline, at the mouth of the Murca river. This 90 m thick segment consists of very coarse fine toward the top in continuous cycles or microsequences of 1 to 20 cm thickness. Siltstone intraclasts ranging from 1 to 5 cm are present at the base of each microsequence. Large authigenic pyrite crystals are common at the base of the sandstone beds. The presence of siltstone intraclasts in a coarse grained sandy matrix suggests a debris flow facies for the basal segment of the Murca Formation. Subaqueous debris flows and slumps require greater slopes than classical turbidity currents (Walker, 1986). This segment may correspond to coarse interchannel layers or to channel turbidity currents of the upper fan.

Segment B consists of sequences of coarse grained graded, medium dark-gray sandstone and light gray medium grained sandstone interbedded with sets of siltstones and black shales. These sequences are comparable with Bouma's classic sequences, which are separated by erosive surfaces. The majority of the sandstone beds contain large pyrite crystals at their bases.

The segment C consists of 10 — 20 cm thick beds of interlayered gray fine grained sandstone, black shale and black siltstone. The shale beds of this segment contain some fossils which were used for dating. Petrographic analysis of samples of this segment shows mainly lithic graywackes (Table 1). The segment is approximately 80 m thick.

Segment C of the Murca Formation corresponds to the lobe fringe facies, or facies D of the classic distal turbidite proposed by Mutti and Ricci Lucchi (1972), in Walker and Mutti, 1973). It begins with Bouma's sequence C, and is described as a distal turbidite which can be defined as turbidity current deposits on the opposite (seaward) side or downslope from the sediment source Bouma and Hollister, 1973).

Segment D corresponds to the middle part of the Murca Formation, with approximately 110 m total thickness. It consists of 5 — 10 cm black shale and gray, fine grained, graded sandstones, interlayered with fine and very fine dark gray sandstones. Sometimes it consists of shale and 10 — 20 cm thick, coarse grained, graded massive sandstone. The shales beds present sandy lenses. Petrographic analysis of samples from this segment shows principally lithic graywackes which are coarse grained and graded toward the top of the segment. Segment D is in accordance with the hypothetical upward coarsening stratigraphic sequence developed during a fan progradation.

Segment E is approximately 300 m thick and consists of gray massive sandstones with intercalations of black shales with sandy lenses. At the bottom of this segment the sandstone beds contain cross-bedding and ripple marks. The middle part of the segment consists of coarse grained graded sandstones to very fine grained sandstones, silstones and shales in cyclic beds. The upper part contains parallel laminated beds. Coarse grained graded sequences in this thick segment correspond to the classic Bouma sequences. In these Bouma sequence, rip-up clasts are concentrated in the bottom of the sandstone bed. Segment E corresponds to a thinning upward sequence of a new lobe in the middle fan. It represents a regradational deposit. Where it is possible to distinguish Bouma sequences.

Segment F corresponds to the upper part of the Murca Formation, which has a transitional contact with the overlying Villeta Group. This segment consists of black shales with interbedded 20 — 30 cm thick, fine grained gray sandstones. The sandstone beds contain cross-stratification and ripple marks in the shale beds. The upper part of the Murca Formation (segment F), corresponds to noncyclic basin plain deposits in an area fringing the fan (Shanmugan and Moiola, 1988). This segment may also correspond to the Bouma E subdivision, consisting of a turbiditic and hemipelagic mud with some sandstone interbeds, and facies G of Mutti and Lucchi in Moreno, (1990), with pelagic and hemipelagic shales deposited from very dilute suspension. The process of deposition includes the normal pelagic rain of sediments onto the sea floor (Mutti and Lucchi, 1972, in Walker and Mutti, 1973).

Ammonites and plant remains found within the black shale interbeds (station 20425 — 20422) include *Berriasella colombiana* Haas; *Pseudoosterella ubalaensis* Haas; *Berriasella* sp.; *Santafecites santafecinus* (d' Orbigny); *Karakaschiceras?* cf. *bakeri* (Imlay); *Neohoploceras? magnifica* (Imlay); *Neocomites* sp. ?, and *Cupressinocladus* sp. (land Plant) on the Pacho-La Palma road. These yield an Late Valanginian age for the Murca Formation. Ammonites and plant debris, including *Sainoceras* n. sp., aff. *hirsutum* Fallot & Termier; *Pseudooesterella ubalaensis* Haas; fish scales; and *Weichselia reticulata* (Stokes & Webb), collected from the El Caquero area on the Villeta-Nimaima road also give a Late Valanginian age.

Cumbre formation

The rocks of the Cumbre Formation crop out on the road from La Belleza to Otro Mundo in the valley of the Río Minero, an area located in the southernmost part of the Departamento de Santander (Figure 1). The Cumbre Formation outcrops are in the core of the Portones Anticline. The contact with the underlying Arcabuco Formation was not observed, but a transitional contact with the overlying Rosablanca Formation was observed.

In the section studied, the Cumbre Formation is composed of a few layers of quartzarenites (Figure 2c), and clayey sandstones with intercalations of red-purple and black argillaceous siltstones which have parallel laminated layers with wavy beds toward the top of the section with 15 – 20 cm thick segments. The total thickness estimated, for this formation in the area is approximately 50 m. Due to the poor exposure of the unit, it was not possible to measure a detailed stratigraphic section. The studied section corresponds to the upper part of the Cumbre Formation described in the type locality by Mendoza (1985; segments G and H), and segments 56 to 83 described by Renzoni (1985) in the Cordillera de los Cobardes. For this work, the section in the la Belleza area was subdivided into two segments B and A from bottom to top.

The segment B is formed principally of quartzarenites that vary from medium to very fine grained, with intercalations of clay siltstones. In general de sandstone bodies of the lower part of segment B consist of parallel laminated beds of 15 – 20 cm thickness. Wavy beds and faint cross-lamination occur toward the top of the segment. The upper part of segment B consists of clayed sandstone and very fine grained sandstone. These sandstone are micaceous quartzarenites in composition.

The segment A consists of red-purple claystones and argillaceous siltstones with some very fine to fine grained micaceous clayed sandstone. This segment has parallel laminated beds of 10 – 15 cm thickness. The upper part of segment A consists of clayey siltstone which change in color from yellow to black. The presence of kaolinite in segment A suggests a possible deposition in low salinity waters near to a river mouth, in a shallow water marine environment. Both the textural and structural characteristics suggest depositional environments ranging from foreshore for segment B to shoreface and transitional offshore in the upper segment A. The facial analysis suggests that the Cumbre Formation represents a transgressive sequence produced by the first advance of the Cretaceous Sea (Moreno, 1990).

Pyrite occurs as euhedral crystals and disseminated grains in the sandstones and clayey sandstones. This is the product of diagenetic processes in the rocks, as is the presence of authigenic clay minerals such as chlorite within the matrix. An ammonite dated by Etayo-Serna (*Sarsinella cf. honda* Haas; Ballesteros, 1989) gave a Late Berriasian age for the upper part of the Cumbre Formation.

Rosablanca formation

The Rosablanca Formation was originally named by Wheeler (1929 in Moreno 1990) from Cerro Rosablanca at the northeast corner of the De Mares Concession. The best exposure of the Rosablanca was found and measured on the road between the towns of Florian and La Venta (limit between Boyacá and Santander Departments) in the northeast section of the study area. (Figure 1). The Rosablanca Formation crops out over an area of approximately 80 km, and consists of black to grrenish-gray limestone with intercalations of laminated calcareous shale and thick mudstones and wackestones (Table 2). The exposed section is 175 m thick. The outcrops on the road between La Belleza and Pueblo Nuevo range up to 5 – 19 m thick. The Rosablanca Formation lies concordantly over the Cumbre Formation. The contact with the overlying Villeta Group is also concordant, but the upper part of the formation was not measured.

It was not possible to collect fossils samples for dating from the study area, but fossils collected to the north in the underlying Cumbre Formation (*Sarsinella cf. hondana* Hass) gave a Late Barriasian age (Ballesteros, 1989). The Rosablanca Formation in the area is constrained as no younger than Late Valanginian by fossils of this age in the upper shales of this formation (Allen et al., 1988). Similar ages for this formation have been reported from the Middle Magdalena Basin Alfonso, 1985; Etayo-Serna and Rodríguez, 1985).

Caqueza sandstone

The Caqueza Sandstone upper part of the Caqueza group which extends from the Thithonian to Hauterivian times crop out on the Eastern margin of the Eastern Cordillera, and was previously correlated with the Murca Formation on the Western margin of the Eastern Cordillera. This sandstones are red, white or gray, immature, poorly sorted, very angular to angular quartzarenite, (Figure 2c) coarse grained siltstone and very fine grained quartzarenite, with lamination and beds averaging 0.8 – 3.0 m in thickness (Aalto, 1972).

The average sandstone composition for the Caqueza sandstones was given by Aalto as 53% quartz grains and 47% matrix—cement, which were recalculated by Moreno (1990). The matrix cement is essentially of iron oxide, sericite and chlorite. Only one sample presents calcite matrix, without feldspar grains or lithic fragments. The probable source for the Caqueza Sandstones was Precambrian polycyclic sandstones such as Roraima Formation and possibly gneisessose and granitic Precambrian rocks (Aalto, 1972). The continuous supply of the quartzose sand from the Devonian to Tertiary in the area studied by Aalto suggests a stable source area and probably cyclic resedimentation.

Petrographic classification

Rock samples from the Lower Cretaceous detrital units were classified using ternary plots of sand-size framework grains of quartz, feldspar and lithic fragments. Clean sand or arenites contain less than 15% matrix and dirty sand or wackes contain more than 15% matrix. The analysis was done using the **Dott** (1964), ternary diagrams and using matrix content in the sense of **Pettijohn** (1972). This classification is based on mineral composition and generally has minimal dependance on the environment of deposition. The character of the source rocks very largely determines mineral composition. Thus, classification is largely relatable to source area composition and ultimately to tectonics (**Pettijohn**, 1972).

The components of the ternary diagrams correspond to total quartz, including monocrystalline and poolycrystalline quarzt and chert; total lithic fragments including sedimentary, igneous and metamorphic fragments.

Key to petrographic data (Table 1)

Sample:	Number stations's samples
Gs:	Grain size m.m.
Sd:	Sorting (phi)
Qm:	Monocrystalline quartz
Qp:	Polycrystalline quartz
F:	Monocrystalline Feldspar (K — fel. + Plagioclase)
Lch:	Chert lithic fragment
Ls:	Sedimentary lithic fragment
Li:	Igneous lithic fragment
Lm:	Metamorphic lithic fragment
Acc:	Accesory minerals (Pyrite, Zircon, Heavy)
P:	Porosity
C:	Cement
Mc:	Clay matrix
Ma:	Authigenic matrix

Framework: (Dott, 1964, Dickinson and Suczek, 1979, Dickinson et al., 1983).

Q:	Qm + Qp + Chert
Qp:	Polycristalline quartz + chert
F:	K — feldspar + Plagioclase
L:	Lithic fragments
Lt:	Total lithic + Qp
Lith. Wacke:	Lithic wacke sandstone
Arko. Wacke:	Arkosic feldspathic sandstone
Felds. Wacke:	Feldspathic wacke sandstone
Arko. Arenite:	Arkosic arenite
Pro. Key:	Provenance from Dickinson, et al., (1983).

Provenance

Relative proportions of different types of terrigenous sand grains are guides to the nature of the source rocks in the provenance terrain from which the sandy detritus was derived (**Dickinson** et al., 1983). Provenance terrains and related basins of deposition can be classified according to their plate-tectonic settings. Consequently, detrital framework modes of sandstone suites provide information about the tectonic settings of depositional basins and associated provenances.

Framework

The most significant compositional variations in terrigenous sandstone can be displayed as ternary plots on triangular diagrams. The three poles represent recalculated proportions of key categories of grain types determined by modal point counts (**Dickinson and Suczek**, 1979; **Dickinson** et al., 1983). Two altenative sets of poles (QFL and QmFLt) are used to display the petrographic results.

A. For QFL diagrams, the poles are: 1) total quartzose grains (Q), including polycrystalline lithic fragments such as chert and quartzite; 2) monocrystalline feldspar grains (F); and 3) unstable polycrystalline lithic fragments (L) of either igneous, sedimentary or metamorphic parentage.

B. For QmFLt diagrams, the poles are 1) quartz grains (Qm) that are exclusively monocrystalline; 2) feldspar grains (F) and 3) total polycrystalline lithic fragments (Lt), including quartzose varieties.

Dickinson and **Suczek** (1979) distinguished nine provenance types based on tectonic setting, and four ternary diagrams were then used to demostrate the compositional distribution of the detritus derived from the nine provenance types. The mean compositions of sandstone suites derived from different kinds of provenance terrains controlled by plate tectonics lie within discrete and separate fields on QFL and QmFLt diagrams. The three main categories of provenance terrains thus distinguished were those within continental blocks, magmatic arcs, and recycled orogens (**Dickinson and Suczek**, 1979; **Dickinson** et al., 1983).

Jurassic plutonism

The Jurassic intrusive episode represents the most extensive period of plutonic activity in the Colombian Andes. Intrusive rocks of this age form a series of major batholiths which can be divided into eastern and western belts. The western belt is located along the eastern margin of the Central Cordillera in zone II of Figure 4 (**Campbell** and **Bürgl**, 1965, **Bürgl**, 1967. **Aspden** et al., 1987). The eastern belt of Jurassic intrusives consists principally of plutons in the Santander-Floresta paleomassifs (zone I, Figure 4). According to **Mojica**

Table 1

Textural and compositional petrographic data of the Murca Formation, Utica sandstone and Cumbre Formation.

UNIT	Sample No.	GS (mm)	S.D. (phi)	Qm	Qp	F	Lch	Ls	Li	Lm	ACC-pyrite	ACC-Other	CLAY MATR	Ma	CEM	PORO.	FRAME WORK						NAME (Dott, 1964)	PRO. KEY
																	Q	Qm	Qp	F	L	Lt		
MURCA	20427C	0.5	0.5	23.6	6	2.6	9.9	16.7	0.8	0	1	2	17.5	7.7	1.7	0.5	66.2	39.6	26.6	4.3	29.5	56.1	LITH. WACKE	8
MURCA	20427B3	0.25	0.5	14.5	2.5	9.5	15.5	13	5	3	2.5	3	14.55	6	0	11	52	23	28.6	15	33	61.9	LITH. WAKE	8
MURCA	20427B2	0.06	0.5	17.5	2	4.5	13	1.5	0	1	1	4	47.5	1	7	0	82.8	44.3	38	11.4	6.3	44.3	ARKO.WACKE	8
MURCA	20427B1	0 25	1	28	2.9	7.5	5	10.8	2.5	2.1	0	2.1	24.3	10.5	4.2	0	61	47.5	13.5	12.8	26.2	39.7	LITH. WAKE	8
MURCA	20427A2	0.5	0.5	17.5	0	12	13	13	4.5	1.5	1	2	21	7	0.5	0	47	27.6	19.6	25	28.5	48.1	LITH. WAKE	4
MURCA	20427A1	0.25	0.5	9	1.5	6	1	15.5	3	1.5	1	2.5	2	5	7.5	0	44.1	19.3	24.7	13	43	67.7	LITH. WAKE	9
MURCA	24724.A	0.25	0.5	17	2.5	4.5	8	12	8	0	1	2	27.5	4	2	0	52.9	32.7	20.2	8.7	38.5	58.6	LITH. WAKE	8
MURCA	20426C2	0.06	2	7.5	0	0	3.5	5	0	4	4.5	2	69.5	1	2.5	0.5	55	37.5	17.5	0	45	62.5	LITH. WAKE	8
MURCA	20426C1	0.5	1	24.5	7.8	4.7	12	16.7	0	0	2.9	1	23.3	4.6	0.4	1.9	67.44	37.2	30.2	7.1	25.4	55 6	LITH. WAKE	8
MURCA	20426B3	0.12	0.5	24.5	0	1.5	1	3.5	0.5	3.5	1	2	38.5	9.5	2	3	79.3	56.3	23	3.5	17.22	40.2	LITH. WAKE	8
MURCA	20426B2	0.5	1	34.9	8.2	0	4.6	16.5	0.5	0	0.5	4	16.5	0	0	14.2	73.7	53.9	19.7	0	26.2	46	LITH. WAKE	8
MURCA	20426B1	0.25	1	21.7	5.9	8.6	8.1	12.7	1.6	1	3.8	2	10.9	13.1	5	5.4	59.8	36.3	23.4	14.4	25.8	49.2	LITH. WAKE	8
MURCA	20426A2	0.5	2	21.5	3.5	2	15.5	16.5	2	3.5	3	9	11.5	6.5	1	4.5	62.78	33.3	29.5	3.1	34.1	63.55	LITH. WAKE	8
MURCA	20426A1	0.002	0	7.5	0	0	1	6.5	0	2	0	0.5	78.5	1	0	3	50	0	0	0	0	0	MUDSTONE	0
MURCA	20425B4	0	0	3	0	0	0	0	0	0	0	4	90	2	0	1	0	0	0	0	0	0	MUDSTONE	0
MURCA	20425B3	0.12	0.5	15.3	10.1	1.5	28.1	10.3	1	0.6	0.5	1	20.1	10.1	1	1	35.3	25.8	9.4	1	63.8	73.2	LITH. WAKE	9
MURCA	20425B2	0.25	0.5	22.2	2.8	5.6	1	11	0	1.9	2	6.3	22	11.1	5.6	8.3	58.3	50	8.3	12.5	29.2	37.5	LITH. WAKE	8
MURCA	20425B1	0.25	1	20	3	7.8	7.5	9.5	3	0.5	5.5	1	21	12	1	9	60.2	39.6	20.8	14	25.8	46.53	LITH. WAKE	8
MURCA	20425A4	0.12	0.5	16.9	8.8	12.6	14	6.4	4.4	4.4	2	2.8	9.2	9.1	10	0.8	61.1	26	35.2	19.7	19.1	54.3	LITH. WAKE	5
MURCA	20425A3	0.25	0.5	14.1	7.6	17.9	12.4	10.2	2.1	0.9	1.7	3	14.9	7.26	5.1	0.4	52.3	21.6	30.7	27.4	20.2	51	FELDS. WAKE	5
MURCA	20425A2	0.5	1	19.3	5.3	21.9	11.4	8.8	5.2	0.9	2.6	7	7.9	5.2	0	2.1	49.4	26.5	22.9	30.1	20.5	43.3	ARKO. ARENITE	4
MURCA	20425A1	0	0	1	0	0	0	0	0	0	0	1	97	0	1	0	0	0	0	0	0	0	MUDSTONE	0
MURCA	20424B3	1	0.5	22.6	4.6	15	8	10	11.3	0.8	2	0	10	7.1	5	3	48.5	31.2	17.3	20.6	30.6	48	LITH. WAKE	4
MURCA	20424B2	1	0.5	17.9	12.2	16.5	15	4.5	1.6	0	2.8	0	9.6	7	9.7	2.4	66.4	26.3	33	24.6	6.9	41.9	ARKO. WACKE	4
MURCA	20424B1	0.12	1	20	10.6	13.5	12.2	5.3	1.1	0.8	2.5	2	8.4	11	9.1	3	67.5	31.3	36.1	21	11.43	47.6	ARKO. WACKE	4
MURCA	20424A	1	1	23	4.5	20.5	8	5	4.5	1	1.5	0	15.5	9.5	2.5	4.5	53.27	34.6	16.8	30.6	15.6	34.6	ARKO. WACKE	4
MURCA	24787 D	0	0	19.1	1.8	0	29.6	0	26	0	0	2.3	26.4	4.7	5.4	0 9	45.8	31.8	14	0	54.2	68.2	LITH. WAKE	8
MURCA	20423D	0.1	2	27.5	3	15	12.5	2	3	5	4.5	2.5	23.5	0	0	1.5	63.2	40.4	22.8	22.1	14.7	37.5	ARKO. WACKE	4
MURCA	20423C	0.5	1	22.6	2.5	34.2	2.5	4.5	2.9	1.2	0	2.5	16	7	3.3	0.8	39.2	32.16	7	46.5	12.3	19.3	ARKO. WACKE	4
MURCA	20423B	0	0	21.5	0	0	0	0	0	1.5	1	0.5	7.5	0	0.5	0	0	0	0	0	0	0	MUDSTONE	0
MURCA	20423A	0.71	1	13	0.5	10.5	5.5	37.5	9.5	3.5	0.5	0.5	17	1	1	0	23.74	16.25	7.49	13.12	63.11	70.6	ARKO. WACKE	9
MURCA	20423A1	1.1	0.5	16.5	11.5	29	6.3	10.5	5.1	2.9	4	0	10	2	2	0	38.13	10.12	21.71	35.3	26.64	54.45	ARKO. WACKE	5
UTICA	21071	0.25	1	18.5	3.5	22	11.5	3	12	2.5	0.5	0	12	1	7	6.5	46	25	21	30	24	45	ARKO. WACKE	5
UTICA	21072	0.12	2	20.5	3.5	7.5	21	4	1	1	1.5	1	22.5	0	16.5	0	77	35	42	13	10	52	ARKO. WACKE	8
UTICA	21073	0.12	0.5	21.5	5.5	6.5	16.5	1	1	4	5	3.5	30.5	1.5	1.5	2	79	39	40	11	10	50	ARKO. WACKE	8
UTICA	21075	0	0	10	0	0	0	0	0	0	1	0	99	0	0	0	0	0	0	0	0	0	MUDSTONE	0
CUMBRE	21023A	0	0	5	0	0	1	0	0	0	1	0	93	0	0	0	0	0	0	0	0	0	MUDSTONE	0
CUMBRE	21023B	0.25	0.5	45.1	10.9	1.9	8.06	0	2.6	0	2	4.04	24.2	3.6	2.4	0	93.4	75.5	17.87	1.9	4.6	22.5	QUARTZ WACKE	7
CUMBRE	21023C	0.26	0.5	35.6	7.6	1.12	7.6	0	1.7	2.1	0	7.6	16	7.6	5	8	91.8	64.7	27.6	1.1	6.8	34	LITH. WAKE	7
CUMBRE	21023D	0.25	0.5	47.6	6.3	1.27	0.8	0	4.2	0.8	2	5.5	7.5	7.5	13	2.5	89.7	78.8	11.63	1	8	19.8	LITH. WAKE	7
CUMBRE	21025	0.25	0.5	55.9	7	1.71	2.7	0	1.6	0.4	0.6	6	2.3	9.4	7	2.8	95.5	81.6	13.9	1.1	2.8	16.6	QUARTZARENITE	7
CUMBRE	21024	0	0	47	1.5	0	0.5	0	4	0	2	4	14.5	7	1.5	15	92.7	89.8	2.72	0	7.2	10	LITH. WAKE	1
CUMBRE	21031	0.025	0.5	24	0.5	0	0	0	0	0	2	7.5	64	0	1	10	99	97.5	2.4	0	0	2.04	QUARTZ WACKE	1

(1984), Jurassic extensional tectonics were accompanied by important intrusive activity that partially affected the Early Jurassic units.

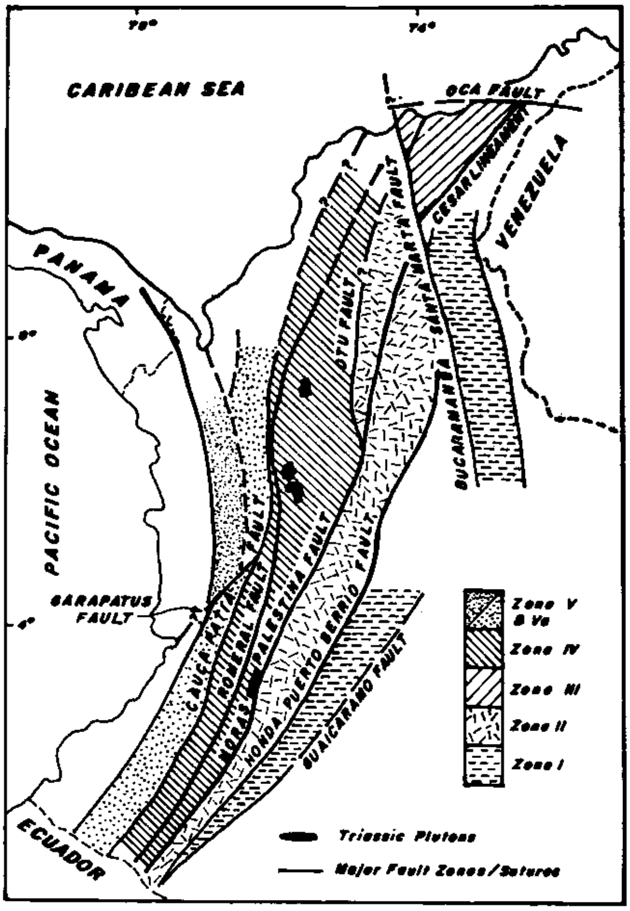

Figure 4. Principal structural and plutonic zones of the Colombian Andes (Aspden, et al, 1987).

Paleo-Central Cordillera

The Central Cordillera is made up of a pre-Mesozoic polymetamorphic basement which consists largely of a disrupted Paleozoic paired (medium/low pressure) metamorphic belt of both continental and oceanic character. It also includes isolated Precambrian remnants and is intruded by numerous Mesozoic batholiths and stocks. The eastern portion of the Central Cordillera (zone II, Figure 4), represents the most aerially extensive exposure of plutonic activity during Jurassic time (c. 200 — 140 Ma), which in turn represents the most widespread period of plutonic activity of the five episodes recognized by Aspden et al., (1987).

Santander-Floresta Paleomassif

The eastern belt of Jurassic plutonic intrusives, together with a Paleozoic schist belt (zone I, Figure 4), form the Santander-Floresta paleomassif. The early magmatism (200 ± 7 to 192 ± 7 Ma) seems to be confined to the Santander Massif. It is possible that the eastern belt plutons represent a separate early province which was subjected to later overprinting during the principal Jurassic magmatic event (183 ± 5 to 142 ± 6 Ma), the main axis of which was located immediately to the west along the eastern edge of the Central Cordillera (Aspden et al., 1987). The Floresta massif consists mainly fo a Cambrian-Ordovician metamorphic unit with Ordovician-late Paleozoic granitic intrusives and clastic units ranging up to the Upper Jurassic (Mojica and Villarroel, 1984).

Jurassic plutonism, which extended throughout Colombia and Ecuador, is interpreted as part of a calc-alkaline volcano-plutonic subduction-related arc (McCourt et al., 1984; Aspden et al., 1987). They envisage that at this time the oceanic plate approached the continental block from the NW, and this resulted in a straight-on high angle subduction regime and widespread magmatism along much of the Northern and Central Andes (Aspden, et al. 1987).

Key to provenance types (QFL and QmFLt diagrams, modified from Dickinson and Suczek, 1979 and Dickinson et al., 1983).

A — CONTINENTAL BLOCK
1. Craton Interior
2. Transitional Continental
3. Basement Uplift

B — MAGMATIC ARC
4. Dissected Arc
5. Transitional Arc
6. Undissected Arc

C — RECYCLED OROGENIC
7. Quartzose Recycled
8. Transitional Recycled
9. Lithic Recycled

X — MIXED ZONE

Utica sandstone provenance

Only three sandstone samples were used for the QFL and QmFLt framework of the Utica sandstone. Although this number is not statistically representative, the unit can be tentatively assigned to provenance terrains proposed by Dickinson and Suezek (1979) and Dickinson et al., (1983).

According to the QFL ternary diagram (Figure 5a.) the Utica sandstone correspond to a recycled orogenic provenance. The QmFLt diagram (Figure 5b) shows the unit with a transitional recycled orogen provenance (sample 21072 and 21073) and a transitional arc provenance (lowermost sandstone, sample 21071, table 1).

The basal part of the Utica sandstone (sample 21071), classified as coming from a transitional arc, corresponds to sediments sourced mainly in the volcanic carapace capping the igneous belt and in granitic plutons of the are roots (Dickinson, 1983). The basal sandstone contains higher amounts of igneous fragments and feldspar that the upper units

(Tabla 1), suggesting a dissected arc provenance. Many of the feldspars are plagioclase and occur as separate clasts and as components of the volcanic clasts (Dickinson and Suczek, 1979).

PROVENANCE OF UTICA SANDSTONE

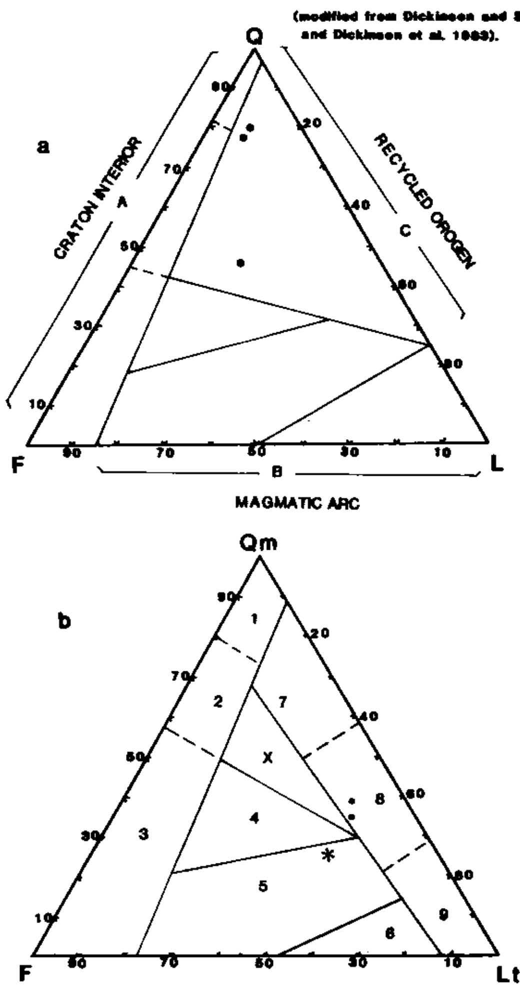

Figure 5. Ternary plots of the detrital sandstone of Utica Sandstone. a) QFL diagram shows the three main provenance types. b) QmFLt diagram shows results suggest recycled orogen (8) and magmatic arc (5) provenances.

The upper samples of the Utica sandstone correspond to the transitional recycled orogen provenance where the sediment sources are sedimentary strata and subordinate volcanic rocks, in part metamorphosed, exposed to erosion by orogenic uplift of fold belts and thrust sheets (Dickinson et al., 1983). Due to the similarity in the quartz and chert percent, it is difficult to distinguish between the variants proposed by Dickinson et al., (1983). Sample 21072 has a high percentage of chert which may correspond to sources in uplifted oceanic terranes of eugeosynclinal belts. Sample 21073 corresponds to recycled material derived from deformation and uplift of miogeoclinal successions Dickinson et al., 1983).

Murca formation provenance

The petrographic analyses of thirty two samples from the Murca Formation suggest a sediment sypply for this unit from recycled orogenic and magmatic arc provenances. The magmatic arc sediments may have come from the paleo-Central Cordillera formed by calc--alckaline Jurassic volcanoplutonism (Aspden, et al., 1987). The samples from the Murca Formation coming from an arc orogen provenance are characterized by abundant feldspar (F) and volcanic lithics (Lv). The QFL and QmFLt plots (Figures 6a. and 6b) show the more lithic nature of the Murca Formation in comparison with the orthoquartzitic Caqueza sandstones (Figure 2c.). Sediments of the Caqueza sandstone have been considered as supplied from a stable source such as the Guyana shield (Aalto, 1972). The QmFLt diagram shows the effect of including polycrystalline quartz (Qp) in the total lithic (Lt) fraction, and again emphasizes the lithic nature of the Murca Formation as a recycled orogen, dissected and transitional arc provenances.

PROVENANCE OF MURCA FORMATION

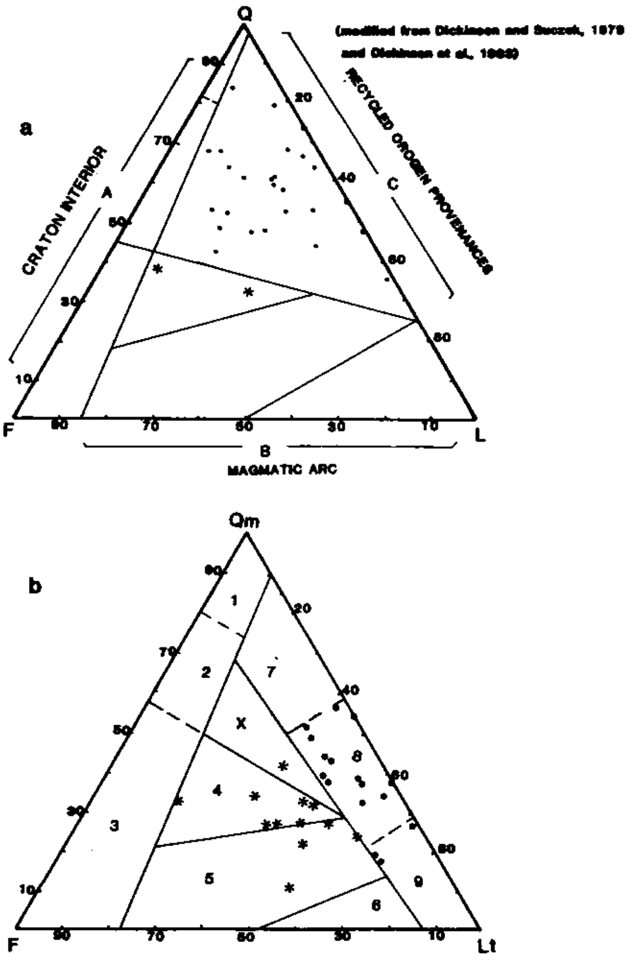

Figure 6. Ternary plot of detrital sandstone of the Murca Formation. a) QFL diagram shows the three main provenances types. b) QmFt diagram results suggests recycled orogen (8) and magmatic arc (4 and 5) provenances.

Cumbre formation provenance

Provenance analyses of six samples from the Cumbre Formation suggest recycled orogenic and cratonic interior provenances (Figures 7a. and 7b). The percentage of polycrystalline quartz appears to increase upward in the section and percentages of feldspar and lithic fragments decrease. This is probably indicating a change in provenance to a more recycled orogen, samples from the basal segment of this formation suggest a provenance from a stable cratonic interior with low relief (Dickinson et al., 1983). Sediments from positive cratonic or shelf areas accumulate upon the platforms and along rifted continental margins in shield slope and rise environments (Dickinson and Suczek, 1979).

The upper segment of the Cumbre Formation corresponds to a recycled quartzose orogen (Figure 7) comprising uplifted terrains of folded and faulted strata (Dickinson and Suczek, 1979). The sediments deposited as the Berriasian Cumbre Formation in the westernmost depocenter, located between the Santander-Floresta paleomassifs and the paleo-central Cordillera, came from both of these paleohighs (Figure 9). The basin was affected by a strong extension phase in Upper Jurassic (?) or Berriasian time (Fabre, 1987).

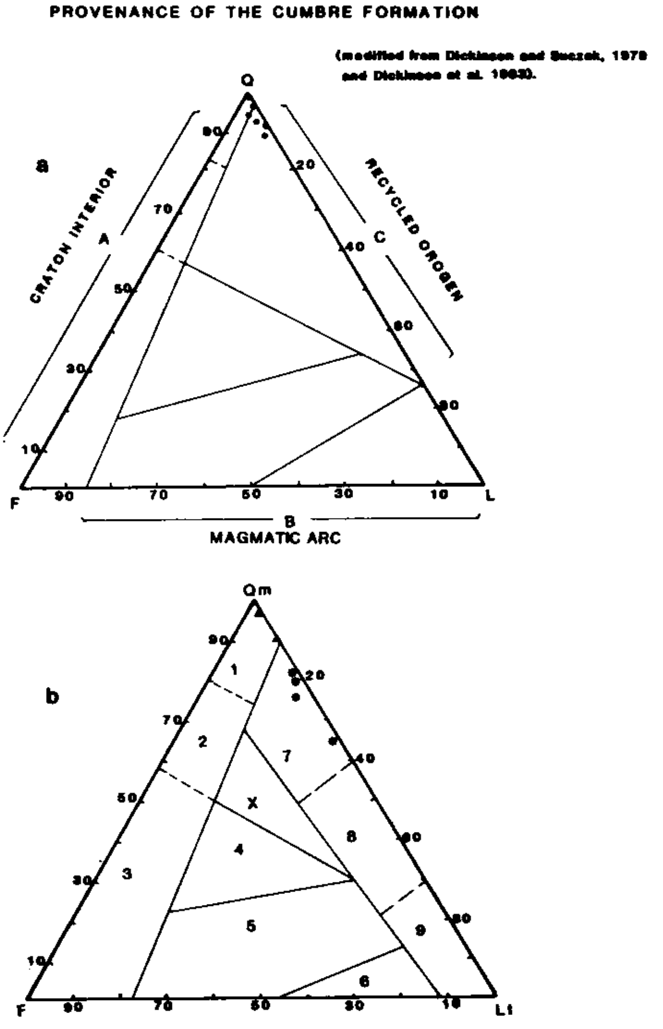

Figura 7. Ternary plots of detrital sandstone of the Cumbre Formation. a) QFL diagram show the three main provenance types. b) QmFLt diagram results suggest recycled orogen (7) and craton interior (1) provenances.

Rosablanca formation

The limestones of the Rosablanca Formation from the northern part of the study area were classified according to the three main limestone families proposed by Folk (1962), based on determination of the relative proportions of allochemical components, microcrystalline ooze and sparry calcite cement (Table 2).

Allochemical components represent the framework of the rock, and include fossils, ooids, intraclasts or pellets. Microcrystalline ooze (micrite) represents a clay-size matrix, while sparry calcite cement fills up pore spaces in the rock. When the relative percentages of these three componentes are plotted on a ternary diagram, it is possible to distinguish three limestone families:

Type I	limestone (Sparry allochemical limestone)
Type II	limestone (microcrystalline allochemical rocks)
Type III	limestone (microcrystalline rocks)

The Rosablanca Formation samples fall within the type III family of microcrystalle rocks (Figure 8). Most of the rocks consists of microcrystalline ooze with little or no allochemical material. These samples imply a rapid rate of precipitation of ooze together with a lack of persistent strong currents. Texturally they correspond to claystones, and must have formed in very shallow sheltered lagoonal areas or on broad submerged shelf of little relief and moderate depth where wave action was limited by the width of the shelf.

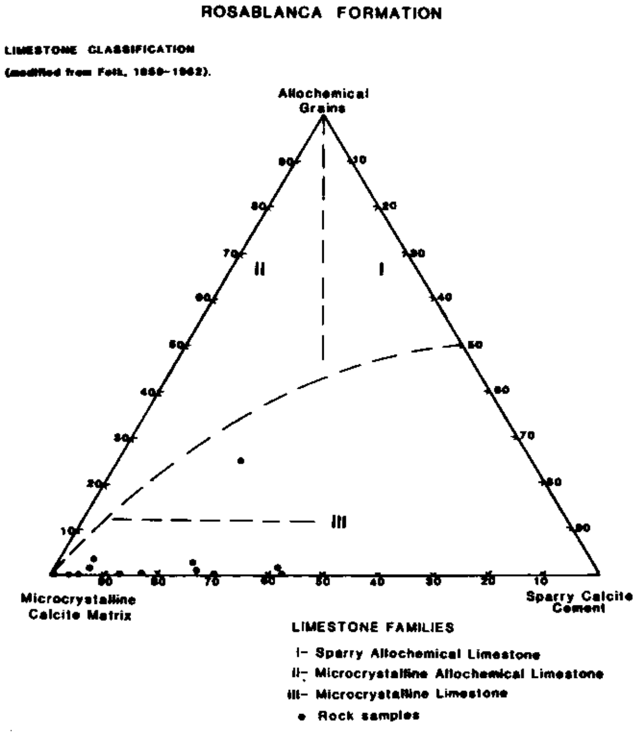

Figure 8. Ternary plot of Rosablanca Formations. The triangular Grains, Matrix and Cement plot shows the mean Limestone classification (modified from Folk, 1959, 1962).

Table 2

Petrographic data from the Rosablanca Formation (Classification according to Dunham, 1962; Folk, 1959, 1962).

SAMPLE	ORTHOCHEMICAL				ALLOCHEMICAL				TERRIG.		FRAMEWORK			NAME DUNHAM,-62	NAME FOLK,-62
	MICR.	SPAR	DOLO	Oth.	INTR.	PELLS	OOL	FOSS	SAND SIZE	CLAY	ALLO.	M.M.	S.M.		
21027	75	11.5	-	-	-	-	-	-	1	12.5	0.0	87	13	MUDSTONE	MICRITE
21018	96	-	-	-	-	-	-	-	1	3.	0.0	100	0	MUDSTONE	MICRITE
21043	60	2	-	6.5	-	-	-	-	6.5	25	0.0	95	5	MUDSTONE	MICRITE
21044	57	25	3.5	4.5	-	-	-	-	10	-	0.0	70	30	DOLOMITIC MUDSTONE	MICRITE
21044A	48	9.5	1	4.0	-	-	-	-	11.5	26	0.0	83	17	DOLOMITIC MUDSTONE	MICRITE
21045	59.5	2.5	-	2	-	-	-	-	2	34	0.0	96	4	BOUDSTONE	BIOLITHITE
21045C	45.5	34	-	4.5	-	-	-	-	8.5	7.5	0.0	57	43	MUDSTONE	MICRITE
21045B	51	22.5	-	2	-	10	-	14.5	-	-	25	52	23	WACKSTONE	MICRITE
21045A	11.5	8.5	6	2	-	-	-	-	23.5	48	0.0	58	42	TERRIGENOUS MUDSTONE	SANDY MICRITE
21046	56.5	19	3.5	4.5	-	-	-	1	15.5	-	1.0	73	26	MUDSTONE	MICRITE
21047	90.5	7	-	-	-	-	1	-	1.5	-	1.0	92	7	MUDSTONE	MICRITE
21048	69	23	-	1	2	-	-	-	1	4	2.	73	25	MUDSTONE	MICRITE
21050	86	4	-	7	2	-	-	1	-	-	3.	90	7	MUDSTONE	MICRITE

Limestone petrographic classification

Ortochemical:

Micr:	Microcrystalline calcite matrix
Sprarry:	Sparry Calcite
Dol:	Dolomite
Oth:	Other ortochemical grains (Pyrite)

Allochemical grains

Fossi:	Fossil fragments
Intra:	Intraclasts
Pells:	Pellets
Ool:	Oolites

Terrigenous grains

Sand Size:	Terrigenous quartz grains of sand-size
Clay:	Clay-size Matrix

Framework

Allo:	Total percent of allochemical components
M.M.:	Total percent of microcrystalline matrix
S.S.:	Total Sparry cement

The ternary plot of the Rosablanca formation samples shows the main limestone families according to total percent of the end members.

Discussion

The Lower Cretaceous units of the study area, the Cumbre, Rosablanca and Murca Formations and the Utica sandstone, were deposited in depocenters in the Tablazo-Magdalena and Cundinamarca-Bogotá basins (Figure 9). These units are partial time equivalents. Analysis of their petrographic composition and sedimentary environments shows that the units were deposited in distinct paleogeographic settings in the Early Cretaceous, (Figure 10).

The Late Berriasian sandstones of the Cumbre Formation were deposited in a shallow marine enrivonment associated with wave-dominated microtidal barrier island to offshore facies. The sandstones of this formation were classified petrographically as quartzarenites and quartzwackes. The composition suggests craton interior and quartzose orogen provenance. The main source was probably part of the paleocentral Cordillera and Santander-Floresta paleomassif. The overlaying Valanginian-Hauterivian limestones of the Rosablanca Formation were deposited in a shallow marine carbonate platform, associated with supratidal marsh, intertidal mud flat and subtidal environments, (Figure 10). Rock samples from this formation are classified mainly as mudstones.

The Berriasian-Valanginian Utica sandstone was deposited in shallow marine environments, associated with prograding wave-dominated shoreline and storm dominated coquina facies. Rock samples from this formation are classified mainly as arkosic wackes with lithic fragments from volcanic, sedimentary and metamorphic rocks. The Utica Sandstone correspond to a recycled orogenic provenance.

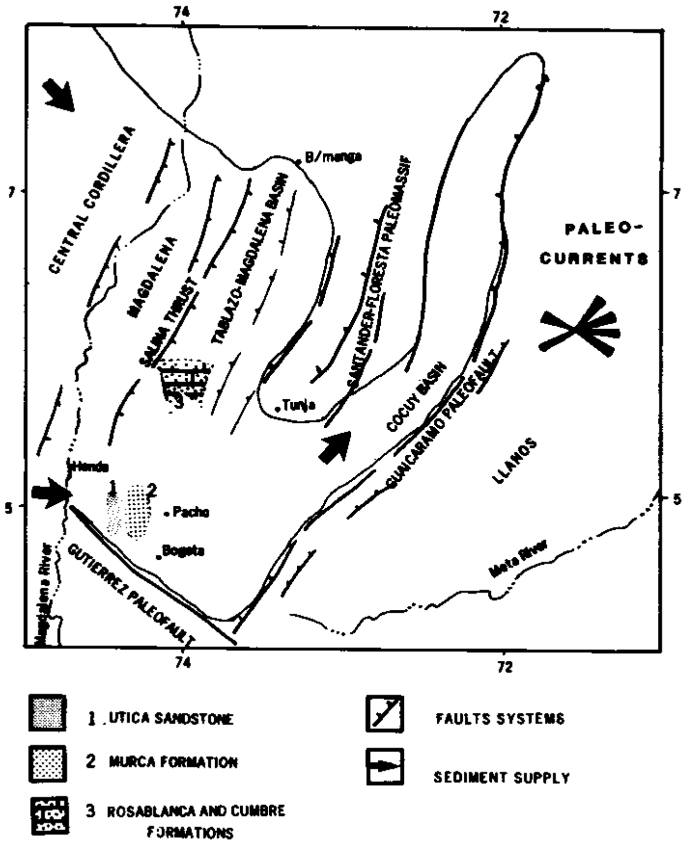

Figure 9. Geological setting of the Lower Cretaceous units: 1- Utica Sandstones, 2- Murca Formation and 3- Rosablanca and Cumbre Formation, into the sedimentary basins to the east of the Central Cordillera (modified from Fabre, 1987).

The Upper Valanginian sandstones of the Murca Formation were deposited by turbidity currents as a retrogradational sequence in a distal fan depossitional setting (Figure 10). The name Murca Formation was proposed for the Upper Valanginian turbiditic sandstones, (previously correlated with the Caqueza Sadstone of the upper Caqueza Group on the Eastern margin of the Cordillera Oriental), exposed in the core of the Murca anticline, were the type section is designated. Rock samples from this formation are mainly lithograywackes and arkosic wackes. The homogeneous Murca Formation, present lithologic and petrographic characteristics distinct from the Caqueza sandstone.

The petrographic and provenance analysis of the Murca Formation samples suggests that the main sediment supply came from the paleo-Central Cordillera, which in Early Cretaceous time consited of an uplifted Jurasic plutonic-volcanic arc (Figure 4), McCourt et al., 1984; Aspden et al., 1987).

According with the model for the Lower Cretaceous of the central part of the Cordillera Oriental-Magdalena Valley proposed by Moreno (1990), the northeast Cumbre and Rosablanca Formations were deposited in shallow marine and carbonate platform environments in the Tablazo-Magdalena basain, with main source area for these units from the Paleocentral Cordillera and the Santander-Floresta paleomassifs, while to the south in the Cundinamarca-Bogotá basin the Utica sandstone was deposited shallow marine environment probably developed on a shelf and with a sediment

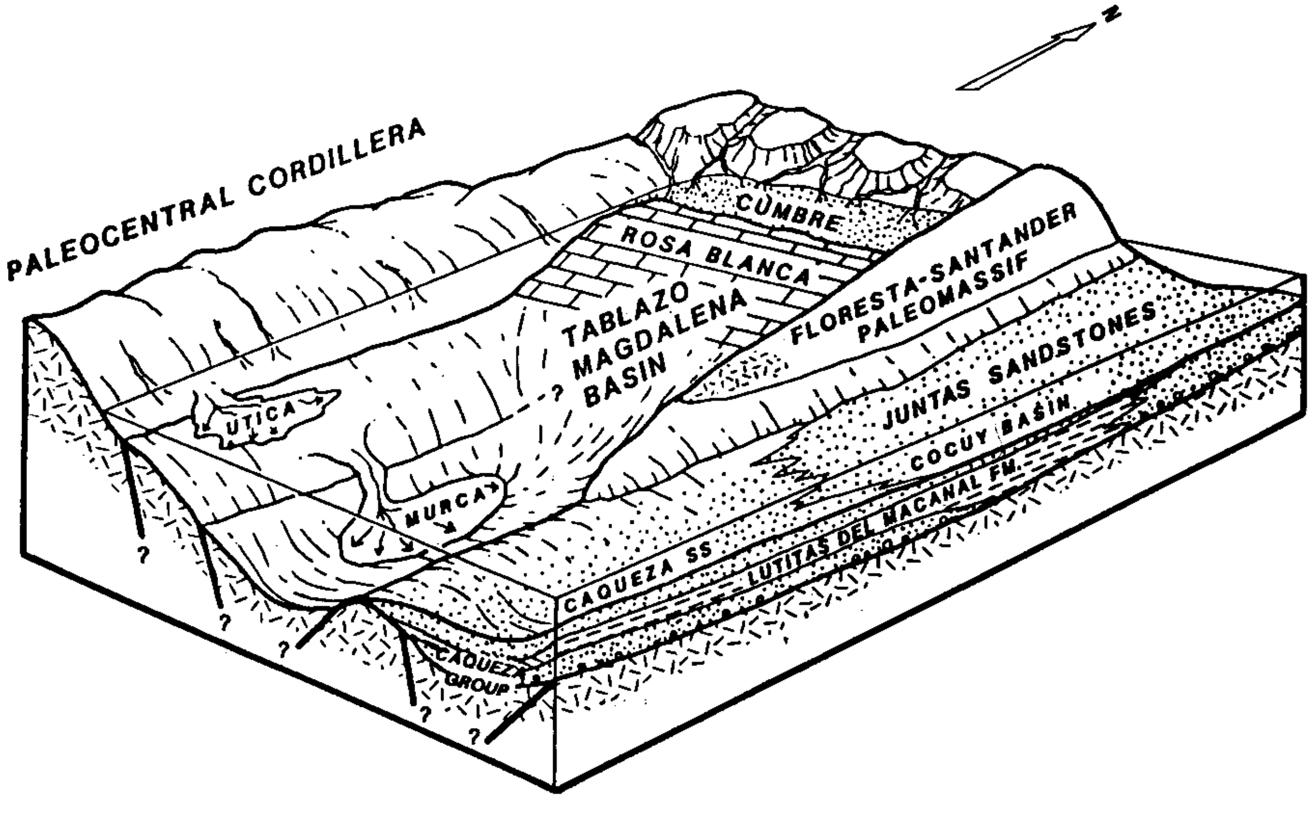

Figure 10. Diagrammatic model of the Lower Cretaceous basin of the Cordillera Oriental-Magdalena Valley. (After, Moreno 1990).

supply from a Jurasic plutonic-volcanic arc in the Paleocentral Cordillera, and the Murca Formation was deposited in deeper water to the east of the Utica as a turbiditic deposit developed by the activation of a extensional phase in the basin, limite by normal faults, and subsequent thermal subsidence may have produced the paleoslope on which the turbiditic currents deposited the Murca Formation Thus, the Late Valanginian basin was divided into a central depocenter (Murca Formation), a western or southwestern shelf (Utica sandstone) and a northern or northeastern platform (Rosablanca Formation).

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