A Proposal on the Classification of Systems Tracts: Application to the Allostratigraphy and Sequence Stratigraphy of the Cretaceous Colombian Basin. Part 1: Berriasian to Hauterivian.

JAVIER GUERRERO
Grupo de Investigaciones en Estratigrafía, Sedimentología y Paleontología. Departamento de Geociencias, Universidad Nacional de Colombia. Apartado Aéreo 14490, Bogotá, Colombia. E-mail: jaguer@ciencias.unal.edu.co

GUERRERO J (2002): A Proposal on the Classification of Systems Tracts: Application to the Allostratigraphy and Sequence Stratigraphy of the Cretaceous Colombian Basin. Part 1: Berriasian to Hauterivian.
GEOLOGIA COLOMBIANA 27, Pgs. 3-25, 4 Figs., Bogotá.

ABSTRACT

The systems tracts produced during relative sea level change cycles are subdivided in four instead of the three originally proposed by Exxon researchers. The new systems tract is named here Regressive Systems Tract (RST) and results from recognizing strata deposited in an interval of time during which relative sea level is falling. Because of these, the strata deposited during a sea level cycle are composed of progradational (RST), low aggradational, (LST), retrogradational (TST), and high aggradational (HST). The sequence boundary (SB) is placed at the base of the RST, at the horizon (Regressive Surface, RS) where relatively fast sea level fall is initiated. The base of the Lowstand Systems Tract is the Lowstand Surface (LS) reached at lowest sea level after a prolonged interval of sea level fall, and after which sea level stays low during a given interval of time. The base of the TST continues to be the Transgressive Surface (TS), as well as the base of the HST continues to be the Maximum Flooding Surface (MFS).

This subdivision of systems tracts in distinct packages of strata with more precise boundaries has been applied to the Cretaceous succession from Colombia. The systems tracts are used not only to subdivide sequences, but also to separate allostratigraphic units that can be identified in the whole basin, by identifying notorious boundaries and different patterns of sedimentation of strata above and below. The allostratigraphic units in which the predominantly marine succession of the Cretaceous Colombian Basin has been subdivided include the Cáqueza, Villeta, and Guadalupe Allogroups. The Tithonian/ Berriasian to Hauterivian Cáqueza Allogroup is subdivided into the Buenavista, Macanal, and Alto de Cáqueza Alloformations. The Barremian to Santonian Villeta Allogroup is composed of the Fómeque, Une, and Chipaque Alloformations. The Campanian and Early Maastrichtian Guadalupe Allogroup is subdivided into the Lower, Middle, and Upper Guadalupe Alloformations. These are finally capped by the Late Maastrichtian lower part of the Guaduas Alloformation.

Each allostratigraphic unit is composed of several lithostratigraphic units laterally adjacent and essentially synchronous, but with different types of lithology, due to lateral facies changes within a given time interval. These lithostratigraphic units deposited during evolution of the Cretaceous Colombian Basin, including valid and formally named members, formations, and groups, are discussed and compared so that a framework of correlation and exploration can be established.

Key Words: *Allostratigraphy, Back-Arc Basin, Colombia, Cretaceous, Hydrocarbon Exploration, Lithostratigraphy, Paleogeography, Sedimentology and Sequence Stratigraphy.*

RESUMEN

Se subdividen los sistemas (systems tracts) producidos durante ciclos de cambio relativo del nivel del mar en cuatro, en lugar de los tres originalmente propuestos por los investigadores de la Exxon. El nuevo elemento, que se denomina como Sistema Regresivo (Regressive Systems Tract, RST), resulta de reconocer estratos depositados en un intervalo de tiempo durante el cual el nivel relativo del mar está descendiendo. De tal manera, los estratos depositados durante un ciclo de cambio relativo del nivel del mar están compuestos por los sistemas progradacional (RST), agradacional bajo (LST), retrogradacional

(TST), y agradacional alto (HST). El límite de secuencia (Sequence Boundary, SB) se sitúa en la base del Sistema Regresivo, en el horizonte o Superficie Regresiva (Regressive Surface, RS) donde comienza la caída relativamente rápida del nivel del mar. La base del Sistema de Bajo Nivel (Lowstand Systems Tract, LST) es la superficie de bajo nivel (Lowstand Surface, LS), que se sitúa en el horizonte estratigráfico correspondiente al nivel más bajo alcanzado después de un intervalo prolongado de caída del nivel del mar, y después del cual el nivel permanece bajo durante un intervalo dado de tiempo. La base del Sistema Transgresivo (Transgressive Systems Tract, TST) sigue siendo la Superficie Transgresiva (Transgressive Surface, TS), así como la base del Sistema de Alto Nivel (Highstand Systems Tract, HST) sigue siendo la Superficie de Máxima Inundación (Maximum Flooding Surface, MFS).

Esta subdivisión de sistemas en conjuntos distintivos de estratos con límites más precisos se ha aplicado a la sucesión del Cretácico de Colombia. Los sistemas no sólo se usan para subdividir la sucesión, sino también para conformar unidades aloestratigráficas que pueden reconocerse en toda la cuenca, mediante la identificación de notorias superficies límite que separen diferentes patrones de sedimentación de los estratos situados encima y debajo de éstas. Las unidades aloestratigráficas en las que se ha subdividido la sucesión predominantemente marina de la Cuenca Cretácica Colombiana incluye los Alogrupos Cáqueza, Villeta, y Guadalupe. El Alogrupo Cáqueza (Titoniano/Berriasiano a Hauteriviano) se subdivide en las Aloformaciones Buenavista, Macanal, y Alto de Cáqueza. El Alogrupo Villeta (Barremiano a Santoniano) está compuesto por las Aloformaciones Fómeque, Une y Chipaque. El Alogrupo Guadalupe (Campaniano y Maastrichtiano Temprano) se subdivide en las Aloformaciones Guadalupe Inferior, Guadalupe Medio y Guadalupe Superior. Esta última unidad es finalmente cubierta por la Aloformación Guaduas, cuya parte inferior se depositó durante el Maastrichtiano Tardío.

Cada unidad aloestratigráfica está lateralmente compuesta por varias unidades litoestratigráficas adyacentes y esencialmente sincrónicas, cuyas diferentes composiciones litológicas se deben a cambios laterales de ambientes de depósito para un intervalo dado de tiempo. Estas unidades litoestratigráficas depositadas durante la evolución de la Cuenca Cretácica Colombiana incluyen miembros, formaciones y grupos formalmente propuestos, que se discuten y comparan para así establecer un marco de correlación y exploración.

Palabras Clave: Aloestratigrafía, Estratigrafía Secuencial, Colombia, Cretácico, Cuenca de Retroarco, Exploración de Hidrocarburos, Litoestratigrafía, Paleogeografía y Sedimentología.

INTRODUCTION

As will be discussed below, the application of some of the original concepts on sequence and seismic stratigraphy has encountered a variety of difficulties because of some non-precise definitions that leave too much room for interpretation. A discussion of the meaning of commonly used terms is presented here with a new proposal on the classification of systems tracts, with the hope that this will allow a more precise communication among those interested in using sequence stratigraphy concepts.

The subdivision of strata in systems deposited during a particular interval of time in which sea level was either falling, rising, or steady, is applied to the Cretaceous succession from Colombia. These progradational, retrogradational or aggradational systems are bounded by surfaces of discontinuity which are used here to separate formal allostratigraphic units, according to the North American Stratigraphic Code (NACSN 1983). The two most important surfaces used as boundaries of allostratigraphic units were the sequence boundary (SB) and the transgressive surface (TS), which basically separate strata deposited during relative fast sea level fall and low sea levels, from strata deposited during relative fast sea level rise and high sea levels. These allostratigraphic units include several laterally adjacent formations related to facies belts produced during particular time intervals.

The boundaries of allostratigraphic units are not exactly synchronous because from one to another place of the basin there were differences in the balance between eustatic sea level change, sediment supply and tectonic subsidence. For instance, this balance will be in a delta setting shoreline different from a shoreline with no near fluvial input, so that the surface itself will have slight age differences from one to another locality throughout the basin. However this small age differences due to the mentioned balance are difficult to tell apart from the inherent discrepancies in accuracy and interpretation of biostratigraphic age. Because of this, the ages of the boundaries are very precise in some localities, but in others the most that can be known is that a transgressive surface (TS) is at or near a particular age boundary. In all cases, ages are precise enough to know that a given bounding surface from one locality is the same one of another locality because the same pattern of relative sea level change was recognized.

According to Lundberg *et al.* (1998) and Guerrero *et al.* (2000), Cretaceous sedimentation in Colombia had place in a back-arc basin setting bounded on the W by an uplifted continental volcanic arc (Early Central Cordillera) and on the E by the Guyana Shield. Normal faults that controlled sedimentation on both sides of the basin were reversed during Miocene uplift of the Eastern Cordillera so that high-angle reverse faults in the eastern and western sides of the Cordillera Oriental dip in opposite directions, toward the previous axis of the basin. The Cretaceous Colombian Basin (Guerrero et al. 2000) had its axis along a line that coincides today with the western flank of the Cordillera Oriental, at the latitude of the Villeta town. The basin opened N to the proto - Caribbean, and connected S with other back-arc and foreland basins, along Ecuador, Peru, Bolivia, Chile, and Argentina.

Because of this tectonic and paleogeographic setting, the strata deposited in the E side of the basin can be compared to those of the W side of it. This means that during a particular sea level fall, progradation took place in opposite directions of the marine corridor and left two wedges that thin toward the depocenter of the basin. Consequently, it is very important information in hydrocarbon exploration of the Colombian Cretaceous succession to know the E or W provenance of terrigenous particles, the precise location of the axis of the basin, and the allostratigraphic unit to which a particular formation pertains. In this way, prediction and identification of lateral facies change can be used to understand in which direction and how the properties of the reservoir, including porosity and thickness change or disappear.

SEQUENCE STRATIGRAPHY

The application of some of the original concepts on sequence and seismic stratigraphy by the Exxon group (*e.g.* Payton 1977; Bally 1987; Wilgus *et al.* 1988; Van Wagoner *et al.* 1990) has encountered a variety of difficulties because of non-precise definitions that leave too much room for interpretation. New data sets continue to be produced and published as active research advances around the world, in order to interpret stratigraphic records from information of seismic lines, well logs, cores, and outcrops. Although many of the sequence concepts have been very useful for stratigraphers and sedimentologists, some of them have been a matter of debate and contradictory application. A well-balanced discussion with criticism on the contradictory aspects, as well as enhancement on the positive and very useful principles of sequence stratigraphy is presented in a textbook by Miall (1997) on "The Geology of Stratigraphic Sequences".

Some of the difficulties arise from the original interpretations of the seismic records in terms of eustatic sea level changes, which should better be considered as the result of unequal and non repetitive interaction of three major key elements: 1) eustatic sea level, 2) tectonic subsidence, and 3) sediment supply. The interaction of these three variables produces relative sea level changes in the basin, instead of just pure eustatic sea level changes. On the other hand, many basins in their mature post-rift stages have been documented as controlled mainly by eustatic change, once they reach equilibrium between sediment supply and tectonic subsidence. Because of that, many of the eustatic sea level changes proposed originally by the Exxon researchers have proved to be real; especially the ones that last more than 4 Ma, in the second and first orders of magnitude. These ones can be accurately dated and proved to be synchronous around the world. Other sequences of much shorter duration and eustatic origin are controlled by Milankovitch cycles that influence climate, producing variations in rainfall and glacial volumes. These shorter sequences (or parasequences?) of around 100.000 years or less are more difficult to date and correlate within a particular basin and around the world.

Regardless of the interaction of the three variables that control the stratigraphic architecture of a basin, the succession may be divided in sequences that provide nearly synchronous correlation of adjacent sedimentary facies and capability to predict lateral changes within the basin, with the consequent advantages in the exploration of resources.

The interpretation of the stratigraphic architecture in seismic sections in terms of relative sea level changes is complex because of the difficulty in assigning some parts of the seismic geometry to a particular portion of a theoretical sea level curve. Exxon's original theory (*e.g.* Posamentier & Vail 1988) considered the sea level curves to be sinusoidal and divided them basically in three parts, the Lowstand Systems Tract (LST), the Transgressive Systems Tract (TST), and the Highstand Systems Tract (HST). These systems tracts were constrained as respectively produced during times of relatively low sea level, marine transgressions, and high sea levels. Difficulty begins with the characterization of the systems and their boundaries since they are regarded in different ways because of non-precise definition and variations in interpretation by different authors. Most discrepancies are related to the precise location of the sequence boundary (SB), and the extent of the LST.

A confusing aspect of the theory is that the systems tracts were originally regarded as "associated with a segment of an eustatic curve" (*e.g.* Posamentier & Vail, 1988: p. 125), but later on that relationship changed. Van Wagoner *et al.* (1990: p. 23) indicated that "Lowstand and highstand are descriptive terms that refer to position within the sequence", and that "... when referring to systems tracts these terms do not indicate a period of time or position on an eustatic or relative cycle of sea level". The discrepancy is confusing because in most if not all of the Exxon diagrams the systems tracts are related to eustatic curves, although in their texts the other two variables, subsidence and sediment supply are also discussed. Because of that, according to Posamentier & Vail (1988: p. 143 and 144) a portion of a systems tract, such as the lowstand wedge of the LST is "a regressive stratigraphic unit characterized by a progradational parasequence stacking pattern"... "During the interval of lowstand wedge deposition, the rate of new shelf space added steadily increases as the rate of relative sea level rise gradually increases". The only possibility to interpret this is to consider that slow eustatic sea level rise (and basin subsidence) is less than sediment supply. This would be the only way to produce a progradational unit during eustatic slow sea level rise. The problem with all this is the lack of precision in the boundaries of the systems tracts, because of the many possibilities of interpretation of the models. Since these systems tracts where initially related to eustasy but later on they were not related with an eustatic curve or even a relative sea level curve, their nomenclature would have to be reduced to progradational, retrogradational, and aggradational, instead of "low, transgressive, and high"?

More recently, Miall (1997: p. 336) indicated that the updated discussion and new definitions of sequence terms by Van Wagoner (1995) and Van Wagoner & Bertram (1995), generate a whole new class of confusions. Especially, the proposed solution of the dilemma offered by Van Wagoner (1995), indicating: "whether one chooses to define systems tracts using rock properties or the relationship to a sea-level curve is currently a matter of personal preference". Miall stated that in recent years it has become increasingly clear that the relationship among systems tracts, sequence boundaries and relative sea-level change is far from straightforward.

In Posamentier *et al.* (1988: figs. 2 and 3) the LST is placed in the falling leg and bottom part of an eustatic sinusoidal curve. It includes an early part in which sea level is falling relatively fast, including sections before and after the inflection point (when the rate of sea level fall is greatest), and another late part at the bottom of the curve, which includes a slow fall and a slow rise. They placed the SB in different positions of an eustatic sea level curve, depending on the geometry of the basin and relative magnitude of sea level fall. The SB of Type I sequences was placed at the beginning of a relatively fast sea level fall, prior to the inflection point. The SB of Type II sequences was placed at the inflection point (Posamentier *et al.* 1988: figs. 5 and 6) of a sinusoidal eustatic sea level curve.

Van Wagoner *et al.* (1990: p. 42 and figs. 34 to 37) presented an idealized block diagram of a shelf, continental slope, and basin floor, including an eustatic sinusoidal sea level curve divided in four parts. Those include a rapid fall (early LST fan deposition), slow fall, stillstand, and slow rise (late LST wedge deposition), rapid rise (TST), and slow rise, stillstand and slow fall (HST). They indicated that the rate of eustatic fall exceeded the rate of subsidence and placed the beginning of sequence formation and sequence boundary earlier than the inflection point, right at the beginning of eustatic sea level fall. However, these four divisions on a sinusoidal curve have arbitrary limits because it is difficult to separate relative terms such as slow fall and rapid fall to place the sequence boundary. It also has the problem that includes a slow rise in the LST, because it would be probably more appropriate to place the entire sea level rise in the TST.

Van Wagoner *et al.* (1988: fig. 1) related the terms progradation, retrogradation and aggradation to a relationship between rate of deposition (sediment supply) and rate of accommodation (basin subsidence plus eustatic rise). When accommodation is less than sediment supply, there is a relative sea level fall and progradation of strata. When accommodation is more than sediment supply, there is a relative sea level rise and retrogradation of strata. If sediment supply equals accommodation, sea level remains stable and an aggradational pattern is produced. However, Van Wagoner *et al.* (1988: figs. 2 and 3) included in the LST a single progradational parasequence set, presenting contradiction with their text (Van Wagoner *et al.* 1988: p. 44), where they indicate that "lowstand wedge deposition is interpreted to occur during a slow relative rise in sea level". The inconsistency again is that if there is a relative sea level rise (rate of sediment supply is less than eustatic rise and basin subsidence), there should be retrogradation instead of progradation.

It could be argued that the terms progradation, retrogradation and aggradation refer to stratal geometry instead of relative sea level change, but they clearly imply relative sea level. In Van Wagoner *et al.* (1988: fig. 1), the succession of four parasequences indicates progradation as a result of relative sea level fall and retrogradation as a result of relative sea level rise. Aggradation is the result of the absence of a net tendency to either fall or rise sea level, because the long-term rate of deposition equals the rate of accommodation. The top of each parasequence in this last case represents the same environment of deposition as the preceding parasequence.

Van Wagoner *et al.* (1990: p. 22-30) indicated several differences in geometry and sedimentation pattern of well logs, cores, and outcrops, between at least three types of sequences in which the geometry of the basin and magnitude of sea level fall were considered. Type 1 sequences in Atlantic-type margins with shelf and continental slope in which the sea level fall is of a sufficient rate and magnitude to deposit the LST lowstand wedge at or just beyond the shelf break, and also including down dip a slope fan and a basin floor fan. Type 1 sequences in ramp margins, where sea level fall moves the lowstand shoreline beyond the shoreline break, but not to the shelf break, because the basin does not have a shelf and a slope. They cited as an example of a basin with ramp margins the Cretaceous interior foreland basin of the United States and Canada. Neither slope fans nor basin floor fans could be deposited in this type of basin margin, and instead the LST includes a lowstand wedge with narrow to broad incised valleys, lowstand deltas and other shoreline sandstones. The third type of sequence is developed also in a basin margin with shelf and slope, but classified as Type 2 because sea level fall is not enough to expose the entire shelf. The lowest systems tract is termed Shelf Margin Systems Tract (SMST) instead of LST and can be deposited anywhere on the shelf.

Van Wagoner *et al.* (1990: figs. 19, 20A, and 20B) included in all the three sequences a retrogradational parasequence set in the TST, but indicated differences for the HST, LST, and SMST, because in these systems the aggradational and progradational parts were either shared or not clearly individualized. In the HST of Type 1 and Type 2 sequences in shelf-slope margins, one aggradational to progradational parasequence set was included, in contrast with one aggradational and another progradational parasequence sets in ramp margins. Regarding the LST and SMST, they included in the Type 1 sequences in shelf-slope and ramp margins a progradational parasequence set in the lowstand wedge of the LST, but a progradational to aggradational parasequence set in the SMST of Type 2 sequences. Consequently, the aggradational sections deposited during relatively high (HST) and low (LST and SMST) sea levels would not be clearly individualized or at least not present in all types of sequences.

Another proposal to divide the sea level curve is by Hunt & Tucker (1992), who placed the sequence boundary in the lowest point of relative sea level instead of placing it at the falling inflection point or at the beginning of the sea level fall. They proposed a new Forced Regressive Wedge Systems Tract (FRWST) for the entire progradational sea level fall portion of the curve and divided the retrogradational portion in a Lowstand Prograding Wedge Systems Tract (LPWST), a TST and a HST. In this case, the SB would be placed above the "allocthonous debris" equivalent to the lowstand basin floor fan, instead of placing it below, as in the Exxon model. Another problem is that the retrogradational portion of the curve would have to be arbitrarily divided in an early slow sea level rise (LPWST), a rapid sea level rise (TST) and a late slow sea level rise (HST). It would be confusing to have a prograding wedge (LPWST) during a relative sea level rise, because progradation results of a relative sea level fall. This relative sea level curve would not include aggradational intervals at the highest and lowest sea levels. Plint (1996) also included the progradational strata deposited during sea level fall in a new systems track named Falling Stage Systems Tract (FSST).

The question remains where to place more appropriately the sequence boundary (Figs.1 A, B, C, D). At the highest sea level, maximum flooding surface (Galloway 1989), at the beginning of a rapid sea level fall (Posamentier *et al.* 1988: figs. 1 and 2), at the inflection point (Posamentier *et al.* 1988: figs. 5 and 6), or at the lowest sea level (Hunt & Tucker 1992). The parasequences of Van Wagoner *et al.* (1990) could also be considered as sequences of short duration (*e.g.* Milankovitch cycles) bounded by the TS, alternatively to their boundary in a MFS without a transgressive section. The last situation would mean an instantaneous sea level rise, represented by a straight vertical line in a sea level curve (Fig. 1 G).

All the difficulty to place the boundaries of the systems and sequences by assigning precise intervals of the seismic and stratigraphic sections to specific portions of a sea level curve has a lot to do with the supposed shape of the curve. This is because a sinusoidal curve could be divided in two sections, progradational and retrogradational (regressive and transgressive), instead of the three portions proposed by the Exxon group. However, such subdivision does not yet considers all the sedimentological possibilities in relative sea level, which could be better divided in four intervals: 1- rising retrogradational, 2- high aggradational, 3- falling progradational, and 4- low aggradational. In 1 the relative sea level is rising (transgressive section), in 2 sea level is maintained in its highest level for an interval of time, in 3 sea level is falling (regressive section), and in 4 sea level stays in its lowest for an interval of time. Apparently, the stratigraphic sections corresponding to the highest and lowest aggradational portions of the curve are not easily observed in the seismic sections, so that they are inferred, overlooked, or considered as a surface instead of a section.

The solution proposed here is based in two premises: 1- that any observed curve documented from real seismic or stratigraphic data is a relative sea level curve instead of an eustatic sea level curve, and 2- that such curve is not necessarily sinusoidal. In the first premise, suppositions on the interactions of sediment supply and tectonic subsidence with the eustatic curve are not necessary to explain how the seismic and stratigraphic patterns should be, but instead considers the resulting real curve. The question of global synchronism to prove the original idea that an eustatic sea level curve could be constructed depends on accurate dating of sections around the world, as long as the boundaries and systems are precisely defined and correctly identified. In the second premise, there is option for the existence of curves with two, three, or four components (Figs. 1 F, G), considering that all of them will be possible, with a variety of non-repetitive interactions between subsidence, eustasy, and sediment supply, during basin evolution.

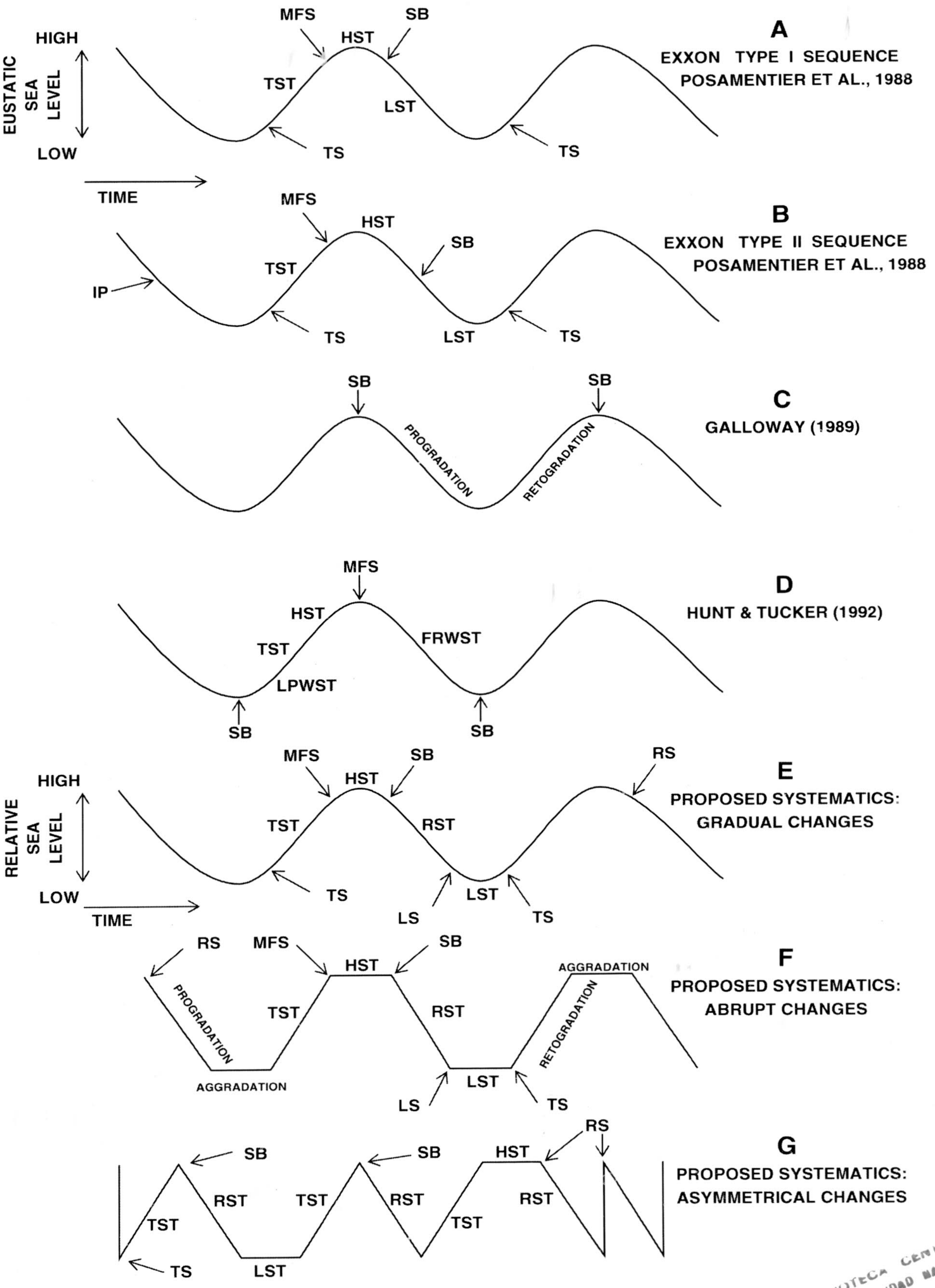
The retrogradational, progradational, or aggradational portions of stratigraphic and seismic sections should be precisely classified in systems tracts regardless of the magnitude and duration of the sea level fall, the geometry of the basin margin and the terrigenous or calcareous nature of the sedimentary fill. All that information is essential to study the evolution of a basin, but should not be involved in the classification of systems tracts. Those could be reduced in seismic and stratigraphic sections to progradational, retrogradational, and aggradational (Figs. 1 E, F), increasing precision in scientific communication.

A stratigraphic section with an aggradational lowstand pattern should be included in a LST, regardless of its supposed location on a ramp, a shallow shelf, a shelf edge, a slope, or a basin floor. The classifications of sequences in Type 1 and Type 2, along with the SMST, and other proposed systems tracts for special situations, should be avoided. In many seismic sections the continental slope clinoforms are not easily differentiated from the clinoforms of prograding deltas on a shelf or a ramp until detailed sedimentological and paleontological information is obtained. The shoreline is also difficult to differentiate in seismic sections because shoreface sandstones are not easily separated from coastal plain and alluvial sandstones.

Some relative sea level curves (Fig. 1 F) could have four subdivisions, including flat (or relatively flat) upper and lower components (high aggradational and low aggradational), besides the retrogradational and progradational components. The flat portions of the relative sea level curve indicate the absence of a net change in sea level (either highest or lowest) during a significant interval of time. A portion (a few meters to tenths of meters) of the stratigraphic section is aggradational and shows no notorious change in the sedimentary microenvironments that compose a single sedimentary environment. Good examples are an alluvial meandering plain (composed of the associated channel and floodplain microenvironments) or the coastal plain side of an estuary (composed of the associated lagoon, channel, and marsh microenvironments). An absence of a net change in a sedimentary environment in a stratigraphic section is the one that involves only the textural, compositional, and paleontological changes representing the microenvironments of a single environment. The best example is the repetitive cyclical or rhythmic superposition of channel and crevasse splay sandstones over floodplain mudstones. This is because of the autocyclical meandering style of a river, without implications in allocyclical relative changes of accommodation space, or sediment supply that could produce a relative sea level change in the basin.

The terms progradation, aggradation, and retrogradation are here applied to either stratigraphic or seismic sections indicating allocyclic changes (controlled by eustasy, subsidence, and sediment supply) in the depth of the basin, resulting in shallowing upwards (progradation), stillstand (aggradation), and deepening upwards (retrogradation). The architectural patterns of the basin that imply relative sea level change do have a geometric expression

Figure 1. Nomenclature of systems tracts in different types of relative sea level curves, with a comparison to previous systematics. Regressive Systems Tract (RST), Lowstand Systems Tract (LST), Transgressive Systems Tract (TST), Highstand Systems Tract (HST), Forced Regressive Wedge Systems Tract (FRWST), Lowstand Prograding Wedge Systems Tract (LPWST), Sequence Boundary (SB), Regressive Surface (RS), Lowstand Surface (LS), Transgressive Surface (TS), Maximum Flooding Surface (MFS), Inflection Point (IP).


A
EXXON TYPE I SEQUENCE
POSAMENTIER ET AL., 1988
EUSTATIC SEA LEVEL
HIGH
LOW
TIME
MFS
SB
HST
TST
LST
TS
TS
B
EXXON TYPE II SEQUENCE
POSAMENTIER ET AL., 1988
MFS
HST
SB
TST
IP
TS
LST
TS
C
GALLOWAY (1989)
SB
SB
PROGRADATION
RETOGRADATION
D
HUNT & TUCKER (1992)
MFS
HST
FRWST
TST
LPWST
SB
SB
E
PROPOSED SYSTEMATICS: GRADUAL CHANGES
RELATIVE SEA LEVEL
HIGH
LOW
TIME
MFS
SB
RS
HST
TST
RST
TS
LST
LS
TS
F
PROPOSED SYSTEMATICS: ABRUPT CHANGES
RS
MFS
SB
HST
AGGRADATION
PROGRADATION
TST
RST
RETOGRADATION
AGGRADATION
LST
LS
TS
G
PROPOSED SYSTEMATICS: ASYMMETRICAL CHANGES
SB
SB
HST
RS
TST
RST
TST
RST
TST
RST
TS
LST

in the seismic sections and can also be documented from sedimentological and paleontological information in well logs, cores, and outcrop sections.

The progradation of the strata resulting from allocyclic shallowing of the basin should be differentiated from local autocyclic processes such as the shallowing upwards of a lobe in a delta or the deposition of a basin floor fan. The last ones could be produced even during eustatic high or rising sea levels, because of local excess of sediment supply. Enough stratigraphic sections should be available to tell apart the local transgressions and regressions due to autocyclical processes, from the allocyclic changes that do affect the whole basin and are the important ones in reconstructing its relative sea level history. That is because the allocyclic changes are the ones that allow intrabasinal correlation of adjacent facies within systems tracts. Several sections and accurate dating of strata are essential to separate the allocyclical changes of the whole basin, from the local autocyclic changes that do not correlate with the rest of the sections. Precise comprehension of sedimentary environments is essential to document the relative sea level changes.

Following these concepts, the sinusoidal and nearly sinusoidal curves could also be divided in four parts: 1- The LST that includes the lowest sea levels at the (relatively flat) bottom of the curve. 2- The TST including a relatively fast sea level rise. 3- The HST including the highest sea levels at the (relatively flat) top of the curve, and 4- A new systems tract including the relatively fast sea level fall. The concept of no net change in sedimentary environments, because there is not a notorious sea level change (aggradational section), is also applied to the new concepts of HST and LST. In this case, the SB would be placed at the end of the HST aggradational section, so that the new sequence begins with a relatively fast sea level change, and includes the strata deposited during relative sea level fall.

Since a stratigraphic record could be divided in 4 sections including deposition during relative low sea level, transgression, high sea level, and regression, it is proposed that the progradational section corresponding to relative fall should receive a different name to avoid sharing this portion between the HST and the LST. However the FRWST name proposed by Hunt & Tucker (1992) is not of wide application because it implies 1- that there is no interval of time for aggradational deposits during highest and lowest sea levels. 2- the formation of a wedge or wedges during falling stage, and 3- basin geometry with a shelf-slope margin. It is preferred not to use the FRWST because the special names for different basin geometry or different magnitude of sea level are somehow confusing and difficult to apply, and would imply to create many more names for special situations. The word wedge leaves out strata that might not be contained in wedges but in a slice of variable thickness and present everywhere in the basin. The presence of aggradational strata deposited during intervals of time with relatively constant low or high sea level would force the creation of other two systems tracts.

Consequently, in consideration of the previous discussion and the wide application of most of the Exxon concepts, the new term Regressive Systems Tract (RST) is proposed for the progradational strata deposited during a relative fall of sea level (Figs. 1 E, F, G). The RST is composed only of progradational strata, which complement the opposite TST, composed only of retrogradational strata. It is probable that in most seismic sections the TST and the RST would be the only two systems tracts observed. Those curves composed of only two legs, and that not necessarily have a change on the rates of sea level fall or rise, would be plotted in straight lines forming a zigzag pattern (Fig. 1 G). It is preferred to use the term RST instead of the Falling Stage Systems Tract (FSST) of Plint (1996), because the Regressive Systems Tract (RST) makes emphasis in the contrary and complementary situation of the Transgressive Systems Tract (TST) proposed by the Exxon team. The FSST would be the complement of a Rising Stage Systems Tract, which has never been proposed.

The RST is bounded by two new surfaces (Figs. 1 E, F) that separate it from the HST and the LST. These new surfaces are: 1- the Regressive Surface (RS), which coincides with the SB and separates the RST of the new sequence from the HST of the underlying sequence, and 2- the Lowstand Surface (LS), which separates the RST from the overlying LST.

In some parts of the basin, there is the possibility that a progressive increase in the rate of sea level fall could produce enough erosion (because of the change in sedimentary environments) to remove the strata corresponding to the early part of the RST. That is to potentially erode the strata corresponding to the interval between the beginning of a relatively fast sea level fall and the inflection point. In such case, the age of the SB could have a range of variation within about 1/8 to 1/4 of the entire sea level cycle. The SB will be always placed at the first major RS of a stratigraphic or a seismic section.

Instead of three surfaces separating the systems tracts, now there are four surfaces. The RS is the base of the

RST, which is a progradational systems tract. The LS surface is the base of the LST, which is an aggradational systems tract. The TS is the base of the TST, which is a retrogradational systems tract. The MFS is the base of the HST, which is an aggradational systems tract.

As indicated before, sinusoidal and nearly sinusoidal curves can be divided in RST, LST, TST and HST. In this case, deposition of the RST would correspond to the time interval during which sea level fall is relatively fast. The TST remains as proposed by the Exxon team, and corresponds to the interval in which sea level rise is relatively fast. The LST would be restricted to the section deposited at the (relatively flat) bottom of the curve and, in the opposite side of the curve, the HST would be restricted to the section deposited at the (relatively flat) top of the sea level curve.

Curves that include clearly aggradational (flat) sections deposited during relatively high and low sea levels should also be divided in RST, LST, TST, and HST (Figs. 1 E, F). The terms LST and HST would be restricted to include only the aggradational sections deposited respectively during intervals of time of relatively low and high sea level. In such case, it is proposed that the SB should be placed at the end of the HST, below the strata deposited during the RST. This position of the SB also agrees with the original Exxon concept to place the strata deposited during relatively fast sea level fall above the SB. The Sequence Boundary would be in a position very much like the one proposed by Posamentier *et al.* (1988: fig. 2 and 3), and Van Wagoner *et al.* (1990: fig. 34), at the beginning of a relatively fast sea level fall, prior to the inflection point. In the cases where there is no change in the rate of sea level fall, but a single oblique straight line from high to low sea level, there is no inflection point, so that the SB has to be placed at the beginning of the sea level fall. That is the point with the most notorious and fast facies change from deeper to shallower deposited strata. The sequence boundary most probably would coincide with a notorious lithostratigraphic boundary.

A relative sea level curve could have surfaces easier to identify than others, in cases with a particular combination of the three variables. Since continuous (steady) basin subsidence and eustatic sea level rise work in the same direction to produce a relative sea level rise, the transgressive surface (TS) should be a prominent marker, as can be observed in many documented sections. On the other hand, continuous basin subsidence works in the opposite direction of eustatic sea level fall. The surfaces associated to the eustatic fall, including the beginning of the fall above the high aggradational portion of the HST, and the inflection point, are not as notorious as the TS. In fact, the SB seems to be difficult to identify in many stratigraphic sections and seismic profiles, and in many cases is erroneously placed coinciding with the TS. Regarding the relation of sediment supply and eustatic change, the sediment response is shown to work in the same direction. Eustatic sea level fall increases the relative altitude of source areas, so that sediment supply increases, contributing to enhance the relative sea level fall. Eustatic sea level rise diminishes the relative altitude of source areas, diminishing the sediment supply to the basin and enhancing its relative sea level rise. Sediment supply works independently of eustatic sea levels, only when the rate of uplift and erosion does change in the source areas.

The mechanism and rhythm of the sea level change (or absence of change during a time interval) dictates in part the shape of the resulting relative sea level curve, obtained from seismic or stratigraphic sections. Special cases are those in which the sea level fall or rise is produced instantaneously in relation to sedimentation rates, so that there is not an interval of strata with appreciable thickness to document a transgressive or a regressive episode (Fig. 1 G). In the Type I sequences it is assumed that some areas of the shelf are subjected to erosion during the sea level fall, so that sedimentation in those areas continues only during the next transgression. It places in contact the HST of the older sequence with the TST of the new sequence, without a RST or a LST. However, an alternative explanation is that the shoreface sandstones included in the transgressive deposits above a "ravinement" surface could instead belong to the RST deposited during sea level fall or to the LST deposited during lowest sea levels. Since the facies change represents a lowering of relative sea level, indicated by shoreface sandstones or biosparites over deep ramp/shelf mudstones or biomicrites, it is difficult to demonstrate that the "ravinement" is produced during sea level rise instead of sea level fall.

Another example of an "instantaneous" change is the interpretation of parasequences, bounded by MFS, which most probably are TS, including above a thin transgressive interval TST, indicating that transgression is relatively fast, but not instantaneous. These parasequences would be sequences of short duration bounded by choice in the TS (at the top of the RST or LST). However, if an instantaneous sea level rise could happen in nature, then the MFS is also the base of the RST, and the boundary (SB) would also be placed at the beginning of the sea level fall, as proposed here for the sequences.

The beginning of a sea level fall will be more easily observed in the strata deposited near the shoreline, because of the superposition of shoreface sandstones and biosparites on offshore mudstones and biomicrites. In the deeper parts of ramps or shelves the change could be indicated by the abrupt superposition of terrigenous mudstones on biomicrites or the superposition of packstone biomicrites on wackestone biomicrites. Even if the sea level fall is produced in steps (parasequences), like the ones produced during climatic cyclicity of the Milankovitch type, the SB should be placed at the beginning of the relatively fast sea level fall, at the end of the HST of the sequence.

All those cases of SB correspond to areas of sedimentation where deposition has already been initiated so that a relative sea level fall could be observed and a potential erosional unconformity is produced as a result. The initiation of sedimentation in a basin is a special case, because its lower boundary is an angular unconformity instead of an erosional unconformity. Sedimentation over basement begins during a transgression (TST) because immediately prior to that, during relatively lower sea levels, the area is subjected to erosion. Because of that, basal sequences over igneous, sedimentary or metamorphic basement begin with an angular unconformity and do not include a RST or a LST.

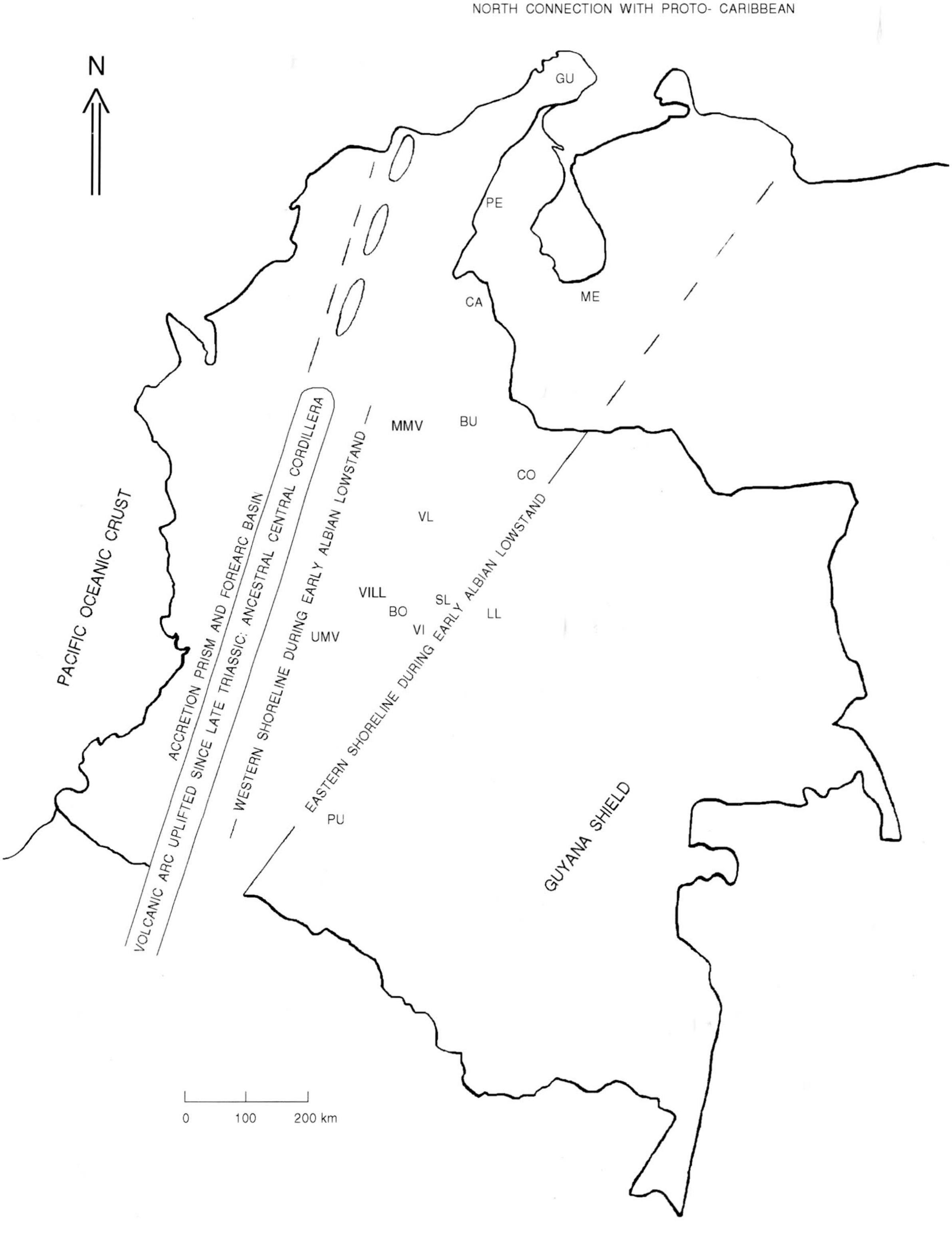
The succession begins when the basin depression (accommodation space) is created as a result of the tectonic driving mechanism that initiates subsidence in the area. Regardless of high or low eustatic sea levels, the difference in relief drives terrigenous particles from elevated source areas toward lower areas in the basin. Mainly tectonic subsidence and sediment supply instead of eustasy control the retrogradational pattern of basal TST successions. Eustasy has a minor influence at the earliest stage of basin evolution, which in the Colombian case is placed near the Jurassic/Cretaceous boundary, at the base of the Arcabuco, Buenavista, and Palanz Formations. Later on, the initiation of sedimentation farther away from the axis of the basin is still controlled by the propagation of subsidence toward the borders of the same, but apparently is greatly enhanced during eustatic sea level rise. Such is the situation of basal coarse-grained units of the Cretaceous System in Colombia, including formations of different Cretaceous ages, assigned here to TST. Those are the basal beds of the Tibasosa Formation (Late Valanginian), the Yaví Formation (Early Aptian), and the Masaya Formation (Turonian).

ALLOSTRATIGRAPHY

The stratigraphic succession of the Cretaceous Colombian Basin (Figs. 2, 3) has been divided into allostratigraphic units (Guerrero & Sarmiento 1996; Guerrero *et al.* 2000) that include several laterally adjacent and synchronous lithostratigraphic units. These allostratigraphic units correspond to facies belts and systems tracts deposited during time spans in which relative sea level was either falling (progradational units) or rising (retrogradational units), or was either relatively low or high (aggradational units). The relative sea level depth was obtained from sedimentological and paleontological characteristics that could indicate the steadiness or the variation of sedimentary environments of deposition through time. The boundaries of the allostratigraphic units correspond with nearly synchronous surfaces produced during the beginning and end of relatively fast sea level rise and fall. Because of that, a notorious facies change could be recognized in wells or outcrop sections, as well as a change in the large-scale geometry of deposition of strata, as identified in seismic sections.

The allostratigraphic units deposited in the Cretaceous Colombian Basin, to which any lithostratigraphic unit could be related include the Cáqueza, Villeta, and Guadalupe Allogroups, capped by the lower part of the Guaduas (Late Maastrichtian) Alloformation. The Cáqueza Allogroup is composed of the Alloformations Buenavista (Tithonian and Early Berriasian), Macanal (Late Berriasian, Valanginian, and Early Hauterivian), and Alto de Cáqueza (Late Hauterivian). The Villeta Allogroup is composed of the Alloformations Fómeque (Barremian and Aptian), Une (Albian and Cenomanian), and Chipaque (Turonian,

Fig. 2. Paleogeography of the Cretaceous Colombian Basin. Shoreline migration toward the Guyana Shield on the E, and Central Cordillera on the W, during high sea levels (Late Berriasian, Late Valanginian, Barremian and Aptian, Middle and Late Albian, Turonian to Santonian, Late Campanian, and Late Maastrichtian. Shoreline migration toward the axis of the basin during low sea levels (Early Valanginian, Late Hauterivian, Early Albian, Cenomanian, Early Campanian, and Early Maastrichtian). Localities are Guajira (GU), Perijá (PE), Catatumbo (CA), Mérida (ME), Bucaramanga (BU), Middle Magdalena Valley (MMV), Cocuy (CO), Villa de Leiva (VL), San Luis (SL), Bogotá (BO), Villeta (VILL), Villavicencio (VI), Upper Magdalena Valley (UMV), Llanos (LL), and Putumayo (PU). Modified from Guerrero *et al.* 2000.


NORTH CONNECTION WITH PROTO- CARIBBEAN
N
GU
PE
CA
ME
MMV
BU
CO
VL
VILL
BO
SL
VI
LL
UMV
PU
PACIFIC OCEANIC CRUST
ACCRETION PRISM AND FOREARC BASIN
VOLCANIC ARC UPLIFTED SINCE LATE TRIASSIC: ANCESTRAL CENTRAL CORDILLERA
WESTERN SHORELINE DURING EARLY ALBIAN LOWSTAND
EASTERN SHORELINE DURING EARLY ALBIAN LOWSTAND
GUYANA SHIELD
0
100
200 km

Coniacian, and Santonian). The Guadalupe Allogroup is divided in three Alloformations including the Lower Guadalupe (Early Campanian), Middle Guadalupe (Late Campanian), and Upper Guadalupe (Early Maastrichtian). Most of these allostratigraphic units were already proposed by GUERRERO & SARMIENTO (1996) and GUERRERO *et al.* (2000) but new ones are proposed here, including the Cáqueza Allogroup, composed of the Buenavista, Macanal, and Alto de Cáqueza Alloformations, and the Villeta Allogroup composed of three alloformations already proposed.

Cáqueza Allogroup (new unit). Late Tithonian to Hauterivian.

The Cáqueza Allogroup includes strata deposited during the Tithonian, Berriasian, Valanginian and Hauterivian, during two cycles of relative sea level rise and fall. It is divided in three units, including the Buenavista, Macanal, and Alto de Cáqueza Alloformations. The type locality of the allogroup is the same one of the Cáqueza Group (HUBACH 1945, 1957; RENZONI 1968; ULLOA & RODRIGUEZ 1979; DORADO 1992; PIMPIREV *et al.* 1992), on the vicinities of the road from Cáqueza to Villavicencio. Age data are mainly from BURGL (1961), who dated the group with ammonites.

Buenavista Alloformation (new unit). Retrogradational strata of Late Tithonian and Early Berriasian age.

The Buenavista Alloformation includes the strata deposited during the latest Jurassic and earliest Cretaceous (Tithonian to Berriasian), during the beginning of basin formation and relative sea level rise (TST). The base of the unit is placed at a major transgressive surface (TS) near the Jurassic/Cretaceous boundary. This is a relatively coarse grained unit which includes the Buenavista Formation, and the coeval basal strata of the Arcabuco and Palanz Formations (Figs. 3, 4).

The type locality of the Buenavista Alloformation is the same one of the Buenavista Formation, E of the city of Bogotá, W of Villavicencio. The base of the alloformation is an angular unconformity over older rocks, including mostly Jurassic and Paleozoic basement. The lithology of the formations included here in the Buenavista Alloformation illustrates the processes occurring during the Late Tithonian to Early Berriasian.

The Buenavista Formation (DORADO 1992) is the basal unit of the Cáqueza Group (HUBACH 1945, 1957; RENZONI 1968; ULLOA & RODRIGUEZ 1979; DORADO 1992; PIMPIREV *et al.* 1992). The formation has a variable thickness of 110 to 170 m and is composed of terrigenous conglomerate, sandstone, and minor interlayered black mudstone (DORADO 1992; PIMPIREV *et al.* 1992). The conglomerates reach pebble, cobble, and boulder size, and are composed predominantly of metamorphic and sedimentary rock fragments derived from the Guyana Shield.

The unit as a whole is fining upward and retrogradational, according to DORADO (1992: fig. 3) and PIMPIREV *et al.* (1992: figs. 4 and 5). The black mudstones interlayered in the upper member of the formation contain ammonites dated in the Late Tithonian and Berriasian (CAMPBELL 1962; DORADO 1992). The sedimentary environments have been interpreted in different ways, from shallow marine (RENZONI 1968; ULLOA & RODRIGUEZ 1979) to submarine fan turbidites (PIMPIREV *et al.* 1992). Regarding the last interpretation, it is very unlikely that sedimentary and metamorphic rock fragments in the boulder size could reach submarine fans during a marine transgression. Conglomerates deposited in submarine canyons and proximal parts of submarine fans are composed mostly of rip up mud intraclasts instead of rock fragments. The latter ones usually reach just the fluvial, delta front, and shoreface realms.

The succession most probably represents a rapid transgression including very coarse grained fluvial deposits in the lower part, to shoreface conglomerate and conglomeratic sandstone in the middle, and finally to interbedding of sandstone and mudstone in the transition from shoreface to offshore environments in the upper part of the unit. The occasional fining upward trend present in some individual beds corresponds most probably to storm events and delta front gravity flows. These beds were deposited in a shallow marine setting, with a depth of no more than about 30 m. Among the fossils reported by RENZONI (1968) are gastropods and bivalves along with the ammonites.

The Arcabuco Formation (SCHEIBE 1938; HUBACH 1957) is the basal sandstone unit of the Cretaceous System in the Boyacá and Santander areas, NE of Bogotá. The age of the formation is constrained by its stratigraphic position with an angular unconformity at its base, and Valanginian faunas in the transitionally overlying Ritoque Formation. Because of the overlying ages, and the thickness of the unit, the Arcabuco Formation has been considered as latest Jurassic to Berriasian.

The thickness of the Arcabuco Formation is approximately 740 m in the Iguaque River Section (Arcabuco Anticline), NE of Villa de Leiva, corresponding to the segments A, B, and C or Members Caisa, Iguaque and Cane (GALVIS & RUBIANO, 1985). The segment D, which has

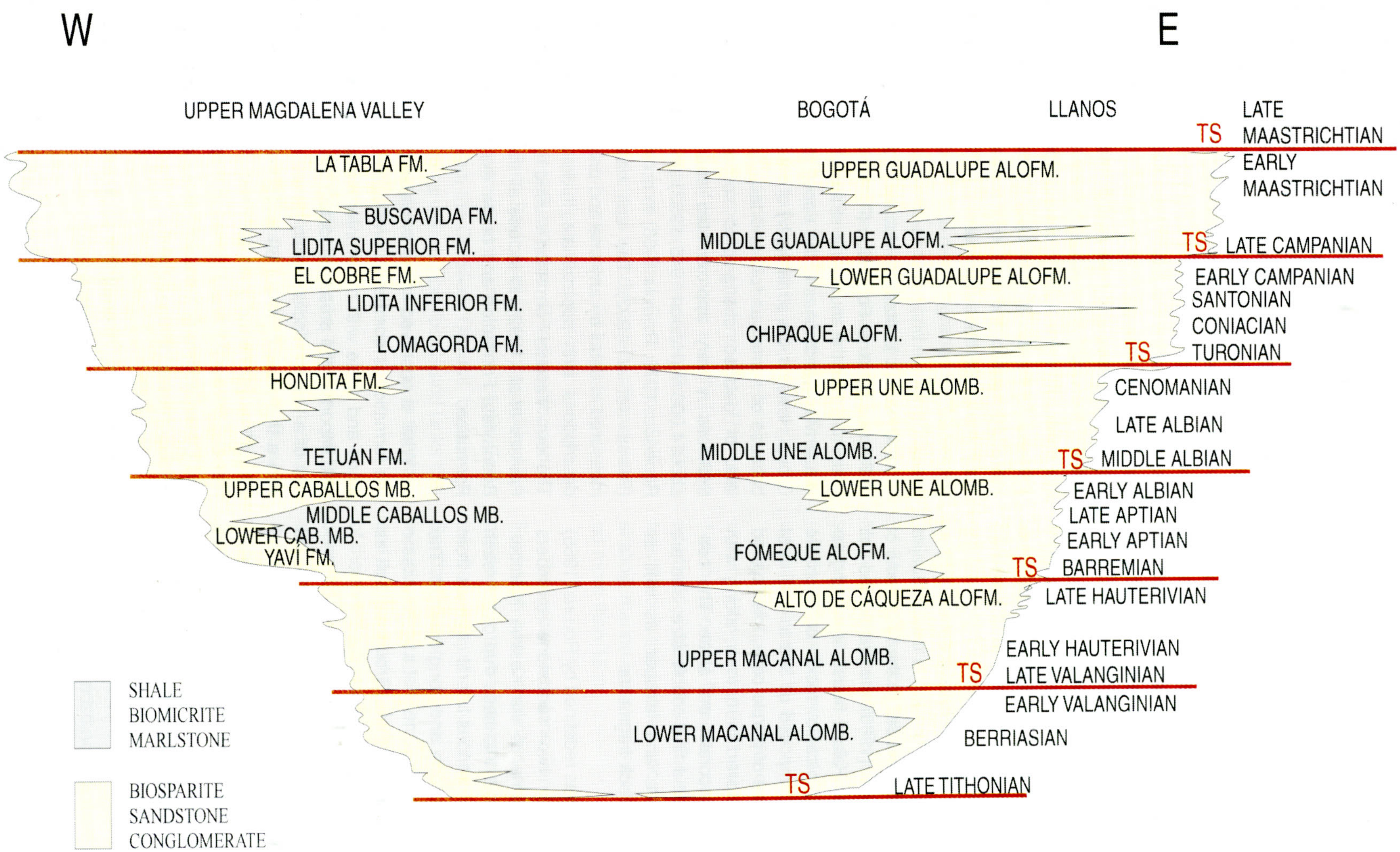


Fig. 3. Cross section of sedimentary fill of the back-arc Cretaceous Colombian Basin prior to tectonic compression and uplift during the Tertiary. Allostratigraphic units separated by transgressive surfaces (TS) across the basin are composed of synchronous lithostratigraphic units on opposite E and W sides of the basin. Maximum thickness of Cretaceous section is 4 to 5 km near the axis of the basin; maximum basin width is 400 to 500 km reached during deposition of the Chipaque (Turonian to Santonian) and Middle Guadalupe (Late Campanian) Alloformations. Sea floor topography composed of ramps inclined about 0.06°. Vertical scale exaggerated in relation to horizontal.

a thickness of 21 m and is characterized by bioturbated mudstone and very fine sandstone, should probably be included in the Ritoque Formation.

The lower sandstone Caisa Member, which is the one included here in the Buenavista Alloformation, has a thickness of at least 168 m, where the base is not exposed (Galvis & Rubiano 1985). The segment consists of thick beds of medium to coarse-grained sandstone and conglomeratic sandstone with large-scale cross bedding. Minor interbeddings of mudstone are also present, making up about 1/7 of the total thickness of the segment. The depositional environment of the segment was interpreted as corresponding to braided streams in distal alluvial fans. Current directions measured from cross-bedded strata indicated river flow toward the W and SW.

The Palanz Formation (Renz 1960; Rollins 1965) is the basal unit of the Cretaceous System in the La Guajira area, which faces the Caribbean Sea in the N extreme of the country. According to Renz (1960), the base of the unit in the type locality, near the Palanz house, is an angular unconformity over older volcanic rocks of probable Jurassic age. The unit is composed of 300 to 400 m of sandstone and conglomerate of purple color, interlayered with reddish and multicolored mudstone, along with interbedded limestones of corals and algae. The conglomerates reach pebble and fine cobble size, and are composed of quartz, chert, and feldspar, as well as sedimentary and volcanic rock fragments.

The Palanz Formation was redefined by Rollins (1965) to subdivide the unit in two sandstone members separated by coral limestone of the Kesima Member. The formation has a variable thickness that could reach 800 to 1.000 m, and also notorious lateral changes from limestone to coarse sandstone and conglomerate. The Palanz Formation overlies the Late Jurassic (Kimmeridgian) strata of the Cocinas Group, as well as volcanic rocks of possible Jurassic age.

The age of the Palanz Formation is constrained by the angular unconformity over Jurassic basement, and the Valanginian to Hauterivian age of the transitionally overlying Moina Formation. The Palanz formation itself includes shallow water marine mollusks (in the Kesima Member), including the genera *Trigonia*, *Exogyra*, *Ostrea*, and *Argentiniceras*, which would indicate a Berriasian to Valanginian age.

Only the sandstone and conglomerate beds of the Lower Sandstone Member of the Palanz Formation are included here in the Buenavista Alloformation.

Macanal Alloformation (new unit). Late Berriasian to Early Hauterivian.

The Macanal Alloformation includes strata deposited during the Late Berriasian and Valanginian, during continuation of sea level rise, followed by a relative sea level fall and posterior sea level rise. The unit is formally divided in three Allomembers, Lower, Middle, and Upper, which were deposited during different episodes of relative sea level rise or fall. The Lower Macanal Allomember (Late Berriasian) was deposited during continuation of relatively slow sea level rise and relative high sea levels (HST). The Middle Macanal Allomember (Early Valanginian) was deposited during relatively fast sea level fall (RST) and low sea levels (LST). The Upper Macanal Allomember (Late Valanginian and Early Hauterivian) was deposited during relatively fast sea level rise (TST) and high sea levels (HST).

The names Lutitas de Macanal (Ulloa & Rodriguez 1979) and Macanal Formation (Pimpirev *et al.* 1992) have been used for the mudstone strata underlying the Late Hauterivian sandstones of the upper part of the Cáqueza Group. However, the stratigraphy of the unit is complicated because of numerous fold and fault repetitions, and the lack of detailed stratigraphic sections. Its estimated thickness is very approximated and has varied from about 4.000 m (Hubach 1945, 1957) and 3.000 m (Ulloa & Rodriguez 1979; Renzoni 1968) to no more than 1.000 m (Pimpirev *et al.* 1992). The unit has not been really measured in detail by any one and only a few lithological descriptions with approximate thickness are available. The term Macanal Formation is used here in the sense of Pimpirev *et al.* (1992), to include all the strata above the Buenavista Formation and below the Alto de Cáqueza Formation.

What is observed in the available descriptions is that the formation is composed predominantly of black mudstone and shale with minor interbedded sandstone. It is also important the presence toward the middle part of the unit of a fine to medium grain quartz sandstone interval with a thickness of about 60 to 150 m. This sandstone interval is the one included here in the Middle Sandstone Member of the Macanal Formation, separating the Lower and Upper Mudstone Members, composed predominantly of black mudstone and shale.

Lower Macanal Allomember (new unit). Aggradational strata of Late Berriasian age.

The Lower Macanal Allomember includes the strata deposited during relatively slow sea level rise and mostly during high sea levels. The base of the allomember is placed at a maximum flooding surface at or near the Early Berriasian / Late Berriasian boundary. These strata are predominantly aggradational (HST), including the Late Berriasian Lower Mudstone Member of the Macanal Formation, the middle mudstone Iguaque Member of the Arcabuco Formation, and the coral limestone Kesima Member of the Palanz Formation.

The Lower Mudstone Member of the Macanal Formation would have a thickness of no more than 400 to 500 m of black mudstone with minor interbedded fine to medium grained sandstone in medium beds (10-30 cm) and occasionally thick beds (of no more than 50 cm). According to Pimpirev *et al.* (1992: fig. 8 and p. 303-304), who presented a section of about 15 m of the lower part of the unit, the minor interlayered sandstone beds are massive or show normal and reverse graded bedding, with pebbles and intraclasts at their sharp and erosional bases. Pimpirev *et al.* interpreted the environment of deposition as characteristic of middle and distal submarine fan turbidites, but it is considered here as a shallow marine environment with maximum depths of about 100 m. It was located in a ramp influenced by storms and gravity flows that deposited sandstones over the predominantly muddy offshore and prodelta environments. The unit includes the presence of plant remains and shallow water mollusks, along with abundant ammonites. Burgl (1961: p. 184, 185) reported from the Batá River section ENE of Bogotá a Late Berriasian age with *Berriasella aff. spinulosa*, *Neocomites aff. neocomiensis*, *Raimondiceras aff. raimondi*, *Spiticeras gigas*, and several species of *Cuyaniceras* including *C. inflatum*, *C. extremum*, and *C. transgrediens.* The Batá River section was considered by Burgl as a very important standard section of the Early Cretaceous strata from the Cordillera Oriental, because it has excellent exposures with datable fossils and lacks the tectonic complications of the Cáqueza Group in its type locality on the road Bogotá - Villavicencio.

The middle mudstone Iguaque Member of the Arcabuco Formation is composed of 169 m of mudstone with minor interbedded fine sandstone (Galvis & Rubiano 1985). The mudstones that dominate the unit are reddish and laminated to massive. The sandstones comprise about 1/3 of the unit and are present in thick to very thick beds with large scale cross bedding, and occasional mudstone intraclasts at their bases. The environment of deposition of the mudstone was interpreted as floodplains associated to meandering rivers.

The middle limestone Kesima Member of the Palanz Formation has a maximum thickness of 284 m (Rollins 1965), and is composed of marlstone and limestone with coral and algae. As indicated before, this member contains a shallow marine fauna with bivalves and a few ammonites. These coral limestones were most probably deposited in shoreface and shallow offshore environments.

Middle Macanal Allomember (new unit). Progradational to aggradational strata of Early Valanginian age.

The Middle Macanal Allomember includes the strata deposited during relatively fast sea level fall and low sea levels. The base of the allomember is placed at a sequence boundary (SB) at or near the Berriasian/Valanginian boundary. These strata are progradational (RST) to low aggradational (LST), including the Early Valanginian Middle Sandstone Member of the Macanal Formation, the upper sandstone Cane Member of the Arcabuco Formation, and the Upper Sandstone Member of the Palanz Formation.

The strata included here in the Middle Sandstone Member of the Macanal Formation are the fine grain quartz sandstones of about 50-60 m thickness, which Hubach (1945) included in his "horizon 5". This sandstone level was also referred by Renzoni (1968: fig. 5 and table 1) as "horizon of quartz sandstone of km 51 and 52". Finally, Ulloa & Rodriguez (1979) included in their "segment B" a 145-m interval of fine grain quartz sandstone with minor interbedded black shale. The depositional setting of these fossiliferous sandstones should correspond mainly to a shallow marine environment of shoreface, with depths of no more than 15 m.

The upper sandstone Cane Member of the Arcabuco Formation has a thickness of 389 m, and is composed predominantly of fine-grained sandstone with minor interbeddings of mudstone (Galvis & Rubiano 1985). Sandstones are present in thick and very thick beds including large scale cross bedding, horizontal bedding, and current ripples; their bases are erosive and some of them include mud intraclasts. Mudstone beds only constitute about 1/5 of the unit. The sedimentary environment of the member was considered as fluvial dominated by meandering channels, but the proportion of mudstone is too low to be characteristic of a meandering setting. The predominance of fine to medium sandstone in such an alluvial setting is interpreted here as pertaining to a braided stream system, in which usually a minimum amount of floodplain mudstone is preserved.

The Upper Sandstone Member of the Palanz Formation would have a maximum thickness of 500 to 600 m according to Rollins (1965: fig. 4) and is composed of sandstone with minor coral limestone. Sedimentary environment should probably correspond with a shallow marine shoreface setting.

Upper Macanal Allomember (new unit). Retrogradational to aggradational strata of Late Valanginian and Early Hauterivian age.

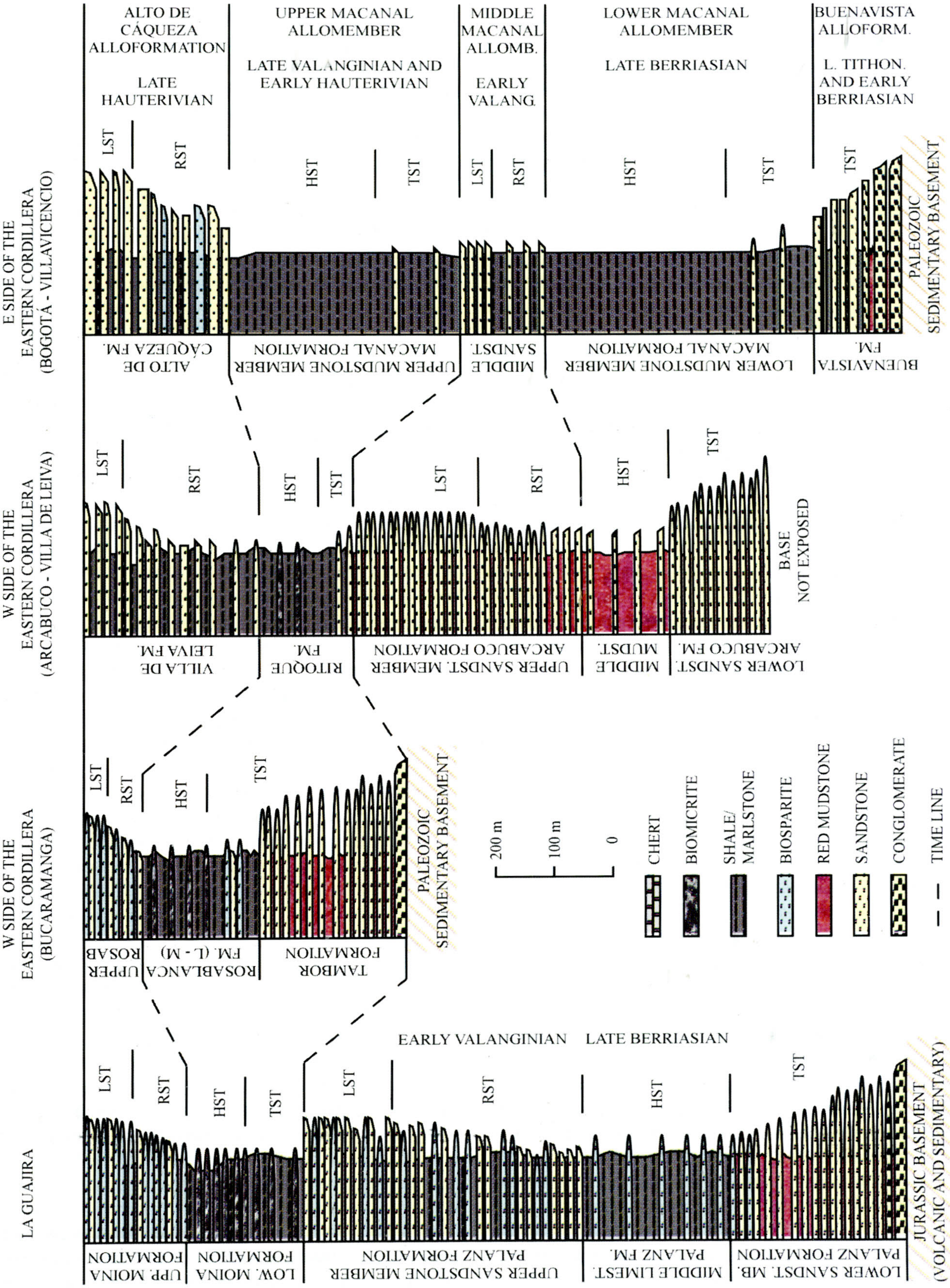
The Upper Macanal Allomember includes the strata deposited during relatively fast sea level rise and high sea levels. The base of the allomember is placed at a transgressive surface (TS) at or near the Early Valanginian / Late Valanginian boundary. These Late Valanginian and Early Hauterivian strata are retrogradational (TST) to high aggradational (HST), including the Upper Mudstone Member of the Macanal Formation, the Ritoque Formation, and the Lower Limestone/Marlstone Member of the Moina Formation. Basal transgressive successions initiated at that time include the lower conglomeratic and calcareous members of the Tibasosa Formation near the Villa de Leiva area, as well as the conglomerates/sandstones of the Tambor Formation and the limestones/mudstones of the lower to middle parts of the Rosablanca Formation near Bucaramanga.

The Upper Mudstone Member of the Macanal Formation would have a thickness of no more than 400 to 500 m of black mudstone and shale with calcareous lenses/concretions and minor interbeddings of fine to medium grained sandstone in medium beds. Fossils of the uppermost part of the unit include abundant ammonites, with specimens of *Olcostephanus astierianus*, *O. boussingaultii*, and *O. bosei*, which Burgl (1961: p. 186-187) considered of Late Valanginian age, but other authors include in the earliest Hauterivian. Sedimentary environment is interpreted here as shallow marine in the offshore domain, with depths of more than 15 and no more than 100 m. Minor interbeddings of sandstone are interpreted as the result of storm events as well as prodelta gravity flows in the areas beyond large river mouths.

Of the three names, Rosablanca, Cumbre, and Ritoque, that have been used to refer the strata that overlie the Arcabuco Formation in different localities of the Villa de Leiva area, the last one seems to be the most appropriate. Although the name Ritoque Formation (Etayo 1968a, b) was originally used to refer strata that overlie in their type section the Arcabuco Formation, and in other localities the limestones of the "rosablanca formation", a posterior study showed that the Ritoque Formation included minor limestone beds and lenses through the unit. Ballesteros & Nivia (1985) measured several sections of the Ritoque Formation indicating that it is composed of gray to black siltstones, mudstones, and biomicrites, with calcareous/terrigenous mixtures including fossiliferous mudstones and sandstones, along with impure biomicrites. The formation contains a shallow marine fauna including bivalves, echinoderms, ammonites, and foraminifers. In its type section on the Ritoque Creek, the unit measures 157 m and rests conformably on sandstone of the Arcabuco Formation. As indicated before, in some localities of the Villa de Leiva area the unit has been erroneously supposed to rest on the biomicrites of the "rosablanca formation", which in turn overlie either the "cumbre formation" or the Arcabuco Formation. However, this predominantly micritic limestone present in scattered beds and lenses, have no proven lateral continuity with a specific portion of the approximately 400-m thick Rosablanca Formation in its type locality. Huber & Wiedmann (1987) correctly indicated that those "rosablanca limestones" are present within the Ritoque Formation in lenses and beds with a thickness of no more than 12 m. The erroneously named "rosablanca formation" in the Villa de Leiva area would have a thickness of about 3 to 12 m in the Ritoque Creek and the nearby San Marcos Hill, where it overlies a 1 to 2 m thick "cumbre formation" (Cardozo & Ramirez, 1985: fig. 2). In the other hand, the approximately 130 m thick "cumbre formation" of Renzoni (1981) also rests conformably on the Arcabuco Formation and is composed of black mudstones and shales with interbeddings of sandstone and siltstone, so that it is an invalid synonym of the Ritoque Formation.

The Ritoque Formation is used here to include all the fine-grained strata that overlie the Arcabuco Formation, and that are composed predominantly of black mudstone, siltstone, and shale, which in some sections have minor interbedded sandstone and limestone. The upper part of the formation has been dated with ammonites in the Late Valanginian (Huber & Wiedmann 1987) and also in the Early Hauterivian (Etayo 1968a, b). The Ritoque Formation underlies Late Hauterivian sandstone and mudstone which were included in the "lutitas negras inferiores of the paja formation" (Etayo 1968a, b) and in the "lower sandstone member of the paja formation" (Renzoni 1981; Renzoni & Rosas 1983). However, the Hauterivian sandstones of the Villa de Leiva area should be included in a new formation, because they have no relationship with the Paja Formation in its type locality, where the unit is composed of Barremian and Aptian shales interbedded with biomicrites. These Late Hauterivian sandstones will be included here in the Villa de Leiva Formation.

Fig. 4. Composing lithostratigraphic units of the Cáqueza Allogroup. Top datum is the transgressive surface (TS) at the Hauterivian / Barremian boundary.



E SIDE OF THE EASTERN CORDILLERA (BOGOTÁ - VILLAVICENCIO)
ALTO DE CÁQUEZA ALLOFORMATION
LATE HAUTERIVIAN
UPPER MACANAL ALLOMEMBER
LATE VALANGINIAN AND EARLY HAUTERIVIAN
MIDDLE MACANAL ALLOMB.
EARLY VALANG.
LOWER MACANAL ALLOMEMBER
LATE BERRIASIAN
BUENAVISTA ALLOFORM.
L. TITHON. AND EARLY BERRIASIAN
LST
RST
HST
TST
PALEOZOIC SEDIMENTARY BASEMENT
ALTO DE CÁQUEZA FM.
UPPER MUDSTONE MEMBER MACANAL FORMATION
MIDDLE SANDST.
LOWER MUDSTONE MEMBER MACANAL FORMATION
BUENAVISTA FM.
W SIDE OF THE EASTERN CORDILLERA (ARCABUCO - VILLA DE LEIVA)
BASE NOT EXPOSED
VILLA DE LEIVA FM.
RITOQUE FM.
UPPER SANDST. MEMBER ARCABUCO FORMATION
MIDDLE MUDST.
LOWER SANDST. ARCABUCO FM.
W SIDE OF THE EASTERN CORDILLERA (BUCARAMANGA)
UPPER ROSAB
ROSABLANCA FM. (L - M)
TAMBOR FORMATION
200 m
100 m
0
CHERT
BIOMICRITE
SHALE/ MARLSTONE
BIOSPARITE
RED MUDSTONE
SANDSTONE
CONGLOMERATE
TIME LINE
LA GUAJIRA
EARLY VALANGINIAN
LATE BERRIASIAN
JURASSIC BASEMENT (VOLCANIC AND SEDIMENTARY)
UPP. MOINA FORMATION
LOW. MOINA FORMATION
UPPER SANDSTONE MEMBER PALANZ FORMATION
MIDDLE LIMEST. PALANZ FM.
LOWER SANDST. MB. PALANZ FORMATION

During the earliest Cretaceous, the present area of the Arcabuco Anticline near Villa de Leiva was a relatively low land, probably located in a graben, because just 60 km toward the ENE there is no deposition of Berriasian and Early Valanginian strata. Over there, the Tibasosa area was elevated a few hundred m and served as source of terrigenous detritus toward the W, to the fluvial strata of the Arcabuco Formation. The succession begins in the Tibasosa area with continental to shallow marine strata deposited during the Late Valanginian and earliest Hauterivian, as a result of relatively fast flooding produced by relative sea level rise. These basal strata were already included by Vergara & Guerrero (1996) in a TST. The maximum 700-m relief, which is the approximate measured thickness of the Arcabuco Formation, could have been reached during the beginning of basin formation or most probably during Tithonian to Valanginian subsidence of the Arcabuco area in relation to the Tibasosa Horst. In the last case, the relief at any time could have been much less than 200 m. Since Tithonian to Valanginian strata are known from areas E of the Tibasosa area, the earliest Cretaceous paleogeography corresponded to NNE elongated horsts and interconnected grabens produced during early rifting stage. The Tibasosa Formation (Renzoni 1981) rests with angular unconformity over basement composed of Devonian strata of the Cuche Formation. Its lower basal member is composed of 48 to 220 m of fluvial strata including poorly sorted conglomerates interlayered with sandstones and mudstones of green and purple color. The member has no fossils, and conglomeratic sandstone exhibits large-scale cross bedding. This basal member is transitionally followed by 87 to 120 m of marine strata composed of black shale, sandy limestone and sandstone, which Renzoni included in the "lower calcareous member". These calcareous beds contain fossils assigned to the Early Hauterivian (Etayo in: Renzoni 1981: p. 41-42), including *Acanthodiscus cf. magnificus*, *Thurmanniceras cf. novihispanicus*, *Olcostephanus paucicostatus*, and *Valanginites cf. santafecinus*.

In the Bucaramanga area and eastern Middle Magdalena Valley, Late Valanginian and Early Hauterivian strata are included in the Tambor Formation and in the lower to middle parts of the Rosablanca Formation. The Tambor Formation (Morales *et al.* 1958) is composed mainly of red strata including conglomerates, sandstones and mudstones. Conglomerates are mostly in the pebble and cobble range, with particles reaching maximum boulder sizes of 45 cm. The unit rests unconformably on older rocks and is transitionally overlain by the Rosablanca Formation. The Tambor Formation has also been referred as "los santos formation" and the "red conglomerate of the girón formation" (Cediel 1968), which are invalid synonyms of the Tambor Formation because they do have the same lithology and stratigraphic position. Cediel (1968: p. 58 and fig. 13) indicated that the unit in the Mesa de Los Santos rests with angular unconformity on the Jordán Formation (Permian) and has a variable thickness of 120 to 190 m. Later on, a stratigraphic section was measured again in La Mesa de Los Santos by Laverde (1985), who indicated a thickness of 218 m. Over there, the unit is composed of well rounded cobble to boulder conglomerate with sandstone interbeddings in the lower part, followed by pebbly sandstones with minor mudstone beds in planar and cross-bedded sets. Mudstones constitute a minor part of the unit and have a maximum thickness of 1-2 m. The uppermost 5 m of the unit include fine to medium grained sandstone interlayered with dark gray mudstone, having variable amounts of calcite, and containing fish teeth, gastropods, and bivalves. Laverde assigned a fluvial origin to the formation, indicating that the uppermost part contained the first evidence of marine setting. Clavijo (1985) also measured a section of the unit near the type locality published by Morales *et al.* in the railroad from Bucaramanga to Puerto Wilches, indicating a thickness of 287 m. The section has a general fining upward trend from the conglomerates in the lower part, that grade to pebbly sandstone interlayered with mudstone. The upper 8 m of the formation include dark gray mudstone with fish teeth, bivalves, and gastropods. Sedimentary environments were also interpreted as initially fluvial, to finally include marine influence toward the top of the unit.

The Rosablanca Formation (Morales *et al.* 1958) transitionally overlies the Tambor Formation and is composed of "hard, bluish-gray, coarse textured, fossiliferous, massive limestones". Morales et al. indicated that the name was derived from the Rosablanca Hill, but that the accepted type section was located in the Sogamoso River. According to a detailed study on the stratigraphy and petrography of the unit by Zamarreño (1963), the lower part of the Rosablanca Formation in the Sogamoso River, W of the Mesa de Los Santos, includes dolomitic limestone and a few gypsum beds, indicative of evaporitic events in a restricted environment. Above the dolomitic interval there is indication of higher energy environments, as shown by the presence of oosparite, and biosparite, along with impure, sandy sparites with quartz and feldspar particles that could reach 30% of the framework constituents. The middle part of the formation includes biomicrite, marlstone and shale indicative of deeper water environments, assigned here to shallow offshore domains. The lower and middle parts of the Rosablanca Formation, which have an approximate thickness of 200 to 250 m, are interpreted here as deposited during a transgressive to highstand event, including successive environments of lagoon, shoreface and shallow offshore. The deposition of limestone was probably favored by local barriers that stopped terrigenous input, due to the initial horst/graben configuration of this part of the basin.

The Moina Formation (Renz 1960) of the La Guajira area, in the N extreme of the country, includes in its lower 200 m a fine-grained lithology composed predominantly of marlstone and biomicrite. Regarding the age, Renz indicated an approximated Hauterivian based on the presence of *Olcostephanus cf. astieri*, *O. cf. athersoni*, *Choffatella sogamosae*, *Pseudohaploceras incertum*, *Trigonia hondaana*, and *T. tocaimaana*. Rollins (1965) included the Moina Formation in the Valanginian and Hauterivian with *Trigonia lorentii*, *Olcostephanus sp.*, *Choffatella sogamosae*, and *Exogyra reedi*. This fine-grained lower part of the Moina Formation will be included here in the Lower Limestone/Marlstone Member, which would be considered of Late Valanginian and Early Hauterivian age. Sedimentary environment should be shallow marine in the offshore domain.

Alto de Cáqueza Alloformation (new unit). Progradational to aggradational strata of Late Hauterivian age.

The Alto de Cáqueza Alloformation includes Late Hauterivian strata deposited during relatively fast sea level fall and low sea levels. The base of the alloformation is placed in a sequence boundary (SB) at or near the Early Hauterivian / Late Hauterivian boundary. These strata are progradational (RST) to low aggradational (LST), including the Alto de Cáqueza Formation, the Villa de Leiva Formation, and the upper part of the Rosablanca Formation in the E side of the basin. It also includes the upper part of the Murca Formation in the W side of the basin, and the Upper Member of the Moina Formation in the N side of the basin. The Late Hauterivian age is documented not only by the fossil content of the formations that compose the unit, but also for the well-established Barremian ages of immediately overlying strata.

The Alto de Cáqueza Formation (Renzoni 1968) has an approximate thickness of 250 m in its type locality near the town of Cáqueza. It is composed of gray, fine to medium sandstone in very thick beds, interlayered with a minor amount of mudstone in medium beds, and also medium beds of sandy biosparites with abundant bivalves. In some localities, coarse-grained sandstone is abundant. According to Espinosa (1986), the unit is 130 to 250 m thick, predominantly composed of fine to medium quartz arenites, with minor interbeds of sandy biosparite and black mudstone. Bivalves, echinoderms, foraminifers, and ammonites are abundant, including *Olcostephanus bosei*, *O. boussingaultii*, and *O. delicaticostatus*, which were assigned to the Hauterivian (Dorado in: Espinosa 1986). As indicated by Pimpirev *et al.* (1992), the "las juntas sandstone" of Ulloa & Rodriguez (1979) is an invalid synonym of the Alto de Cáqueza Formation. These beds correspond to the "segment 1 of the las juntas formation" of Aguirre & Candia (1988), who indicated a thickness of 152 to 260 m, composed predominantly of cross-bedded fine to medium quartz arenites in medium to thick beds, interlayered with minor amounts of mudstone in thin beds. The mudstones contain plant remains.

The strata included here in the Villa de Leiva Formation (new unit) are part of the ones previously included in the "lutitas negras inferiores of the paja formation" (Etayo 1968a, b) and in the "lower sandstone member of the paja formation" (Renzoni 1981; Renzoni & Rosas, 1983). The type locality is placed approximately 5 km SSE of Villa de Leiva, in the Negra Creek and in the proximity of the road Villa de Leiva – Tunja. The formation rests conformably on the Ritoque Formation and underlies the Early Barremian mudstones "arcillolitas abigarradas" of the Paja Formation. According to Etayo (1968 a, b), the town of Villa de Leiva is located on this shale/sandstone unit, which has a thickness of 340 m and a Late Hauterivian age. Fossil content from the lower part of the unit includes *Olcostephanus bosei*, *O. boussingaultii*, *O. delicaticostatus*, and *Crioceratites andinum* (Etayo 1968a: table 1). Etayo also stated that N of Villa de Leiva, near Arcabuco the unit includes more notorious sandstone beds that in the Villa de Leiva area. According to Renzoni (1981: p. 40), this interval of sandstone with minor interlayered shale has a thickness of 293 m in the area near Arcabuco.

The upper part of the Rosablanca Formation contains an important interval of clean sandstones and also the rudstones of large size (5-8 cm) bivalves, which are used in the cement industry and in decorative tiles, because of their beautiful shell designs and white crystalline to pale yellow color. According to Zamarreño (1963), the sandstones are very fine to fine grained quartz arenite, and the upper part of the formation is dominated by large mollusks and well-rounded fragments of them. Oosparite and intrasparite along with sandy sparite are also present. This upper part of the unit has a thickness of approximately 100 m. Re-crystallization of calcite cement in small crystals and darkening with iron or organic matter probably induced Zamarreño to classify biomicrite and fossiliferous micrite. However, most of the rocks of the upper part of the Rosablanca Formation are high-energy grainstone/rudstone biosparites, interpreted here as the result of shoreface deposition. Guzman (1985) indicated a sea level fall based in the ratio of the oysters *Aetostreon couloni* and *Ceratostreon boussingaultii*, showing that the last one appeared in the upper part of the Rosablanca Formation, associated with the appearance of biosparites and terrigenous particles.

The Murca Formation (Moreno 1990, 1991) is a unit located on the W flank of the Eastern Cordillera, NW of Bogotá and approximately 30 km NNE of the town of Villeta. Over there, the Murca Anticline exposes 900 m of strata that have been assigned to the Valanginian and Hauterivian. These strata are composed mainly of medium beds of muddy, coarse-grained sandstone interbedded with siltstone and shale. Many sandstone beds grade from coarse- to fine-grain and include mud intraclasts. Petrography of 32 sandstone samples indicated provenance from a recycled orogen and magmatic arc, that Moreno (1991) placed W, on the ancestral Central Cordillera. The mono-crystalline quartz content of the samples ranges from 10 to 50 percent of the framework particles, while lithic fragments reach 40 to 60 percent; feldspars are usually below 10 percent but could reach 49 percent. Samples are mainly lithic arenites with a minor amount of arkoses; they are muddy and in the range of very coarse to very fine grain size. Moreno (1991) indicated a turbiditic submarine fan environment based on the presence of fining upward successions, but there is now some doubt because of other indications of shallow marine environments, including the presence of terrestrial plant remains. Other indication of shallow marine environments is that only 10 km to the W in the Utica Anticline, the age equivalent "utica sandstone" includes quartz pebble and cobble conglomerates and a shallow marine mollusk fauna that also includes corals and terrestrial plant remains. These interesting Early Cretaceous successions that underlie the Villeta Group, still present age discrepancies and only a few generalized descriptions, which result in a confusing stratigraphy. Because of that, several different types of lithology are dumped together under informal names that group strata of Berriasian to Hauterivian age. The only part of this succession of the W side of the basin included in the Alto de Cáqueza Alloformation is the upper sandstone interval of the Murca Formation. Most of the Cretaceous strata from Colombia that have been previously interpreted as turbidites from submarine fans are just the result of shallow water storm events and other gravity flows in delta front and prodelta settings. Some slumps and slides could also have been the result of seismic events during the very active rifting stage of the basin. Another interesting Early Cretaceous unit W of Bogotá corresponds to the approximately 200 m thick La Naveta Formation (Hubach 1931; Cáceres & Etayo 1969; Etayo 1979). This unit, composed predominantly of very thick sandstone beds, underlies the Villeta Group in the area of Apulo. Sandstones of the unit have been referred as quartz arenites, but a preliminary petrographic examination indicates the presence of lithic arenites.

Finally, in the La Guajira area, the upper part of the Moina Formation is composed of 175 m of massive, sandy limestones, which are also included here in the Alto de Cáqueza Alloformation. This Upper Limestone/Sandstone Member is interpreted as resulting from relative sea level fall in relation with the underlying Limestone/Marlstone Member.

CONCLUSIONS

The subdivision of strata deposited during a sea level cycle in four systems tracts allows a more precise communication in terms of what can be observed and documented in the rock record, including outcrops, cores, well logs, and seismic lines. The new Regressive Systems Tract (RST) is deposited during a time interval of relatively fast sea level fall, so that it includes a package of progradational strata, which is separated from the Lowstand Systems Tract (LST), presently restricted to aggradational strata deposited during low sea levels.

The SB of the sequence is placed at the base of the RST, at the beginning of a relatively fast sea level fall. The upper boundary of the RST is placed in the Lowstand Surface (LS), at the point where relatively fast sea level fall stops and low sea level is reached. The base of the TST continues to be the TS, as well as the base of the HST continues to be the MFS. The TST includes a package of retrogradational strata deposited during transgression and the HST includes a package of aggradational strata deposited during high sea levels. It is possible that some sequences do not include one of the systems tracts, so that progradational strata could be follow by retrogradational strata, without aggradational strata separating them. It is also possible that sea level fall or rise are instantaneous, so that the progradational RST or the retrogradational TST might not be present. All combinations are possible given a particular interaction of eustatic sea level change, tectonic subsidence, and sediment supply. The important aspect in correlation and understanding of basin evolution is to recognize notorious bounding surfaces and clearly defined stratal patterns above and below such surfaces, which will be present in all localities within the basin. Those will be essentially synchronous, except for the minimum displacements in time produced by a particular interaction of eustasy, sediment supply, and subsidence. In all cases, what should be considered is the relative sea level change instead of the eustatic sea level change, because the rock record will always show the result of the three variables instead of just one of them. However, many relative sea level changes are mainly the result of eustatic sea level change when sediment supply and subsidence balance each other. In fact, many of the sea level changes illustrated from the Cretaceous Colombian Basin do correlate with those of the eustatic sea level curve first published by Exxon researchers.

Those bounding surfaces are discontinuity surfaces that have been also used as boundaries of allostratigraphic units to subdivide the rock record of the Cretaceous Colombian Basin. Each allostratigraphic unit includes several laterally adjacent and coeval formations, which allow improved correlation within the basin. The most notorious bounding surface is the TS because continuous basin subsidence works in the same direction of eustatic sea level rise, producing a sharp contrast between the strata deposited during low sea level and the overlying strata deposited during transgression. A good example presented here from the Early Cretaceous is the sharp lithological contrast exhibited at many localities between the Hauterivian sandstones and biosparites of the Alto de Cáqueza Alloformation and the Barremian mudstones and biomicrites of the overlying Fómeque Alloformation.

The other very important surface used here is the SB because of the same relatively sharp contrast between strata deposited during high sea level and those indicating progradation at the beginning of the RST. However, the SB is not as evident as the TS, because continuous basin subsidence works in an opposite direction of eustatic sea level fall, so that the SB might be contained within a gradual transit of relatively slow sea level fall to relatively fast sea level fall in some sinusoidal sea level curves. Examples of sequence boundaries are those placed at the base of the Middle Macanal Allomember (Berriasian / Valanginian boundary) and the base of the Alto de Cáqueza Alloformation (Early Hauterivian / Late Hauterivian boundary).

Another important surface is the MFS, which is identified in some successions better than in others because although it might be contained within a thin stratigraphic interval, it could still remain difficult to identify with centimeter or meter precision. The same goes with the LS at the end of sea level fall, because not all sequences include aggradational LST strata that could be clearly differentiated from the underlying RST, especially in some perfectly sinusoidal curves.

The differentiation of the RST from the LST, as well as the subdivision of the succession from the Cretaceous Colombian Basin in allostratigraphic units, offers improved tools of organization and classification of knowledge, as well as improved correlation tools for many still unexplored but very promising areas. It is hoped that the present proposal of stratigraphic classification will help to envision new horizons in hydrocarbon exploration in Colombia.

ACKNOWLEDGMENTS

Dr. Kristian Soegaard from Norsk Hydro Research Center (Norway), Professor Dr. Carlos Villarroel from the Universidad Nacional (Colombia), and Exploration Geologist Martha Suárez from Ecopetrol (Colombia) reviewed earlier versions of this paper and made valuable comments that helped to improve the text and figures.

The results presented here are part of the projects “Stratigraphy of the rocks with petroleum potential from the Colombian Andes”, “Micropaleontology and magnetostratigraphy of the rocks with petroleum potential from the eastern side of the Eastern Cordillera” and “Petrographic characterization of the Cretaceous and Tertiary succession from the Colombian Andes”.

REFERENCES CITED

AGUIRRE, H. & CANDIA, H. (1988): Sedimentología y estratigrafía de la Formación Areniscas de Las Juntas. Areas de Macanal, Miraflores, Pajarito (Departamento de Boyacá).- Unpublished B.S. thesis, no. 203A, Departamento de Geociencias, Universidad Nacional, Bogotá.

BALLESTEROS, C. & NIVIA, J. (1985): La Formación Ritoque: Registro sedimentario de una albufera de comienzos del Cretácico, in F. Etayo, and F. Laverde, eds, *Proyecto Cretácico*.- Publicaciones Geológicas Especiales del Ingeominas, no. 16.

BALLY, A. W., ed. (1987): Atlas of seismic stratigraphy.- AAPG Studies in Geology 27.

BURGL, H. (1961): El Jurásico e Infracretáceo del Río Batá.- Boletín Geol. Servicio Geológico Nacional, v. 5, no. 1-3, p. 169-211.

CÁCERES, C. & ETAYO, F. (1969): Bosquejo geológico de la región del Tequendama. 1er Congreso Colombiano de Geología, Opúsculo guía excursión pre-congreso, 22 p.

CAMPBELL, C. (1962): A section through the Cordillera Oriental of Colombia between Bogotá and Villavicencio.- Fourth Annual Field Conference of the Colombian Society of Petroleum Geologists and Geophysicists. Published in 1979 as: *Geological Field-Trips Colombia 1959-1978*, p. 89-118.

CARDOZO, E. & RAMIREZ, C. (1985): Ambientes de depósito de la Formación Rosablanca: Area de Villa de Leiva, in F. Etayo, and F. Laverde, eds, *Proyecto Cretácico*.- Publicaciones

Geológicas Especiales del Ingeominas, no. 16.

CEDIEL, F. (1968): El Grupo Girón. Una molasa mesozoica de la Cordillera Oriental.- Boletín Geol. Ingeominas, v. 16, p. 5-96.

CLAVIJO, J. (1985): La secuencia facial de la Formación Los Santos por la quebrada Piedrazul.- registro de una hoya fluvial evanescente, in F. Etayo, and F. Laverde, eds, *Proyecto Cretácico*.- Publicaciones Geológicas Especiales del Ingeominas, no. 16.

DORADO, J. (1992): Contribución al Conocimiento de la Estratigrafía de la Formación Brechas de Buenavista (Límite Jurásico-Cretácico. Región Noroeste de Villavicencio (Meta).- Geología Colombiana, no. 17, p. 7-40.

ESPINOSA, M. (1986): Formación Arenisca de Cáqueza: Columnas estratigráficas características.- Unpublished B.S. thesis, no. 153, Departamento de Geociencias, Universidad Nacional, Bogotá.

ETAYO, F. (1968a): Sinópsis estratigráfica de la región de Villa de Leiva y zonas próximas.- Boletín Geol. UIS, no. 21, p. 19-32.

ETAYO, F. (1968b): El Sistema Cretáceo en la región de Villa de Leiva y zonas próximas.- Geología Colombiana, no. 5, p. 5-74

ETAYO, F. (1979): Zonation of the Cretaceous of central Colombia by ammonites.- Publicaciones Geológicas Especiales del Ingeominas, no. 2.

GALLOWAY, W. E. (1989): Genetic stratigraphic sequences in basin analysis I: Architecture and genesis of flooding – surface bounded depositional units.- AAPG Bull., v. 73, no. 2, p. 125-142.

GALVIS, N. & RUBIANO, J. (1985): Redefinición estratigráfica de la Formación Arcabuco, con base en el análisis facial, in F. Etayo, and F. Laverde, eds, *Proyecto Cretácico*.- Publicaciones Geológicas Especiales del Ingeominas, no. 16.

GUERRERO, J. & SARMIENTO, G. (1996): Estratigrafía física, palinológica, sedimentológica y secuencial del Cretácico Superior y Paleoceno del Piedemonte Llanero. Implicaciones en exploración petrolera.- Geología Colombiana, no. 20, p. 3-66.

GUERRERO, J., SARMIENTO, G. & NAVARRETE, R. (2000): The stratigraphy of the W side of the Cretaceous Colombian Basin in the Upper Magdalena Valley. Reevaluation of selected areas and type localities including Aipe, Guaduas, Ortega, and Piedras.- Geología Colombiana, no. 25, p. 45-110.

GUZMAN, G. (1985): Los grifeidos infracretácicos Aetostreon couloni y Ceratostreon boussingaulti, de la Formación Rosablanca, como indicadores de oscilaciones marinas, in F. Etayo, and F. Laverde, eds, *Proyecto Cretácico*.- Publicaciones Geológicas Especiales del Ingeominas, no. 16.

HUBACH, E. (1931): Exploración en la región Apulo – San Antonio – Viotá.- Boletín Minas y Petróleos, t. 4, no. 25-27, p. 41-60.

HUBACH, E. (1945): La región de Panga Panga al NE de Choachí (Cundinamarca).- Compilación de Estudios Geológicos Oficiales de Colombia, t. 6, p. 27-37.

HUBACH, E. (1957): Contribución a la unidades estratigráficas de Colombia.- Instituto Geológico Nacional, Informe no. 1212.

HUBER, K. & WIEDMANN, J. (1987): Sobre el límite Jurásico – Cretácico en los alrededores de Villa de Leiva, Departamento de Boyacá, Colombia.- Geología Colombiana, no. 15, p. 81-92.

HUNT, D. &TUCKER, M. E. (1992): Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall.- Sedimentary Geology, v. 81, p. 1-9.

LAVERDE, F. (1985): La Formación Los Santos: un depósito continental anterior al ingreso marino del Cretácico, in F. Etayo, and F. Laverde, eds, *Proyecto Cretácico*.- Publicaciones Geológicas Especiales del Ingeominas, no. 16.

LUNDBERG, J. G., MARSHALL, L. G., GUERRERO, J., HORTON, B., MALABARBA, M. C. & WESSELINGH, F. (1998): The stage for neotropical fish diversification: A history of tropical south american rivers, in L. R. Malabarba, R. E. Reis, and Z. M. Vari, eds., *Phylogeny and Classification of Neotropical Fishes*.- Porto Alegre, Edipucrs, 603 p.

MIALL, A. D. (1997): The Geology of Stratigraphic Sequences.- Berlin, Springer -Verlag, 433 p.

MORALES, L., PODESTA, D., HATFIELD, W., TANNER, H., JONES S., BARKER, M., O´DONOGHUE, D., MOHLER, C., DUBOIS, E., JACOBS, C. & GOSS, C. (1958): General Geology and oil occurrences of Middle Magdalena Valley, Colombia.- AAPG habitat of oil symposium, p. 641-695.

MORENO, M. (1990): Stratigraphy of the Lower Cretaceous Rosablanca and Cumbre Formations, Utica Sandstone, and Murca Formation, west flank, Eastern Cordillera, Colombia.- Geología Colombiana, no. 17, p. 65-86.

MORENO, M. (1991): Provenance of the Lower Cretaceous sedimentary sequences, central part, Eastern Cordillera, Colombia.- Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales, v. 18, no. 69, p 159-173.

NORTH AMERICAN COMMISSION ON STRATIGRAPHIC NOMENCLATURE (1983): North American Stratigraphic Code.- AAPG Bulletin, v. 67, p. 841-875.

PAYTON, C. E., ed. (1977): Seismic Stratigraphy – Applications to Hydrocarbon Exploration.- AAPG Memoir 26, 516 p.

PIMPIREV, C., PATARROYO, P & SARMIENTO, G. (1992): Stratigraphy and facies analysis of the Caqueza Group, a sequence of Lower Cretaceous turbidites in the Cordillera Oriental of the Colombian Andes.- Journal of South American Earth Sciences, v. 5, no. 3/4, p. 297-308.

PLINT, A. G. (1996): Marine and nonmarine systems tracts in fourth-order sequences in the Early-Middle Cenomanian, Dunvegan Alloformation, northeastern British Columbia, Canada, in J. A. Howell, and J. F. Aitken, eds., *High resolution sequence stratigraphy: innovations and applications*.- Geological Society of London Special Publication 104.

POSAMENTIER, H. W., JERVEY, M.T. & VAIL, P. R. (1988): Eustatic controls on clastic deposition I – Conceptual framework, in C. K., Wilgus, B. S. Hastings, C. G. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., *Sea level changes – an integrated approach*.- SEPM Special Publication 42, 407 p.

POSAMENTIER, H. W. & VAIL, P. R. (1988): Eustatic controls on clastic deposition II – Sequence and systems tract models, in C. K., Wilgus, B. S. Hastings, C. G. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., *Sea level changes – an integrated approach*.- SEPM Special Publication 42, 407 p.

RENZ, O. (1960): Geología de la parte sureste de la Península de la Guajira (República de Colombia).- Boletín Geológico Ministerio Minas Hidrocarburos, public. esp. 3, memoria. 3 congreso geología venezuela, t. 1, p. 317-349.

RENZONI, G. (1968): Geología del Macizo de Quetame.- Geología Colombiana, no. 5.

RENZONI, G. (1981): Geología del Cuadrángulo J-12, Tunja.- Boletín Geológico Ingeominas, v. 24, no. 2, p. 31-48.

RENZONI, G. & ROSAS, H. (1983): Mapa Geológico escala 1: 100.00 de la Plancha 171 – Duitama.- Ingeominas.

ROLLINS, J. (1965): Stratigraphy and structure of the Guajira Peninsula, northwestern Venezuela and northeastern Colombia.- University Nebraska Studies, no. 30, 103 p.

SCHEIBE, E. (1938): Estudios geológicos sobre la Cordillera Oriental.- Estudios Geológicos Paleontológicos Cordillera Oriental, part 1, 58 p.

ULLOA, C. & RODRÍGUEZ, E. (1979): Geología del Cuadrángulo K-12, Guateque.- Boletín Geológico Ingeominas, v. 22, no. 1, p. 3-55.

VAN WAGONER, J. C. (1995): Overview of sequence stratigraphy of foreland basin deposits: terminology, summary of papers, and glossary of sequence stratigraphy, in J. C. Van Wagoner, and G. T. Bertram, eds., *Sequence stratigraphy of foreland basins*.- AAPG Memoir 64, 487 p.

VAN WAGONER, J. C. & BERTRAM, G. T., eds. (1995): *Sequence stratigraphy of foreland basins*.- AAPG Memoir 64, 487 p.

VAN WAGONER, J. C., MITCHUM, R., CAMPION, K. & RAHMANIAN, V. (1990): Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops.- AAPG Methods in Exploration Series 7, 55 p.

VAN WAGONER, J. C., POSAMENTIER, H. W., MITCHUM, R. M., VAIL, P. R., SARG, J. F., LOUTIT, T. S. & HARDENBOL, J. (1988): An overview of the fundamentals of sequence stratigraphy and key definitions, in C. K., Wilgus, B. S. Hastings, C. G. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., *Sea level changes – an integrated approach*.- SEPM Special Publication 42, 407 p.

VERGARA, L. & GUERRERO, J. (1996): Significado estratigráfico secuencial de algunos depósito s basales del Cretácico en Colombia: Caso de las Fromaciones Yaví y Tibasosa.- Geología Colombiana, no. 20, p. 133-140.

WILGUS, C. K., HASTINGS, B. S., KENDALL, C. G., POSAMENTIER, H. W., ROSS, C. A. & VAN WAGONER, J. C., eds. (1988): *Sea level changes – an integrated approach*.- SEPM Special Publication 42, 407 p.

ZAMARREÑO, I. (1963): Estudio petrográfico de las calizas de la Formación Rosablanca de la región de la Mesa de Los Santos (Cordillera Oriental, Colombia).- Boletín UIS, no. 15, p. 5-34.

Manuscript received, March 2002.