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SEDE BOGOTÁ
FACULTAD DE CIENCIAS
DEPARTAMENTO DE GEOCIENCIAS
RESEARCH GROUP IN GEOPHYSICS

STRATIGRAPHY

Lithofacies cyclicity determination in the guaduas formation (Colombia) using Markov chains

Mariño M. Jorge E.[1], Amaya Erika[2]

[1] Universidad Pedagógica y Tecnológica de Colombia- Escuela de Ingeniería Geológica; jorge.marino@uptc.edu.co
[2] Universidad Pedagógica y Tecnológica de Colombia- Escuela de Ingeniería Geológica; amayaer@gmail.com

ABSTRACT

Statistical embedded Markov Chain processes were used to analyze facies transitions and to determine the stacking pattern of the lithofacies of the Guaduas formation. Twelve Lithofacies were found and characterized based on lithology and sedimentary structures in four stratigraphic sections. The findings were compared with a previous assemblage of lithofacies, interpretations of sedimentary environments, and depositional systems. As a result, four depositional Systems were established. Through the statistical analyses of facies transitions it was found that tidal facies are prevalent in the Socota section, more specifically in the upper part. Whereas in the Sogamoso, Umbita and Peñas de Sutatausa sections, fluvial facies are prevalent in the upper part of the sections, and follow a regressive sequence with more continental deposits around the upper part of the sections. For each of these sections the Markov Chain transition matrices illustrate a strong interaction between tidal facies and fluvial facies, especially in the Peñas de Sutatausa matrix, where facies 6, made up of tidal deposits, appears several times. From the facies model and Markov Chain analyses, it is evident that the Guaduas formation is a cyclic sequence in which the Markov facies repetitions are consistent with the lithofacies analyses conducted in previous stratigraphic studies. The results reveal that the Markov Chain statistical process can be used to predict stratigraphy in order to correlate contiguous geologically unexplored areas in the Guaduas formation, where much work relating the correlation and the continuity of coal beds has yet to be done.

Keywords: Litofacies, Lithofacies, reservoir environment, facies maps, Guaduas, lithofacies maps.

Determinacion de la ciclicidad de las facies en la formacion Guaduas (Colombia) usando las cadenas de Markov

RESUMEN

Se utilizaron los procesos estadísticos de las cadenas de Markov para analizar las transiciones de facies y para determinar el patrón de apilamiento de las litofacies de la formación Guaduas. Se encontraron y caracterizaron doce litofacies en cuatro secciones estratigráficas según litología y estructuras sedimentarias. Los resultados fueron comparados con un ensamblaje anterior de litofacies, interpretación de ambientes sedimentarios y sistemas deposicionales. Como resultado, se establecieron cuatro sistemas deposicionales. A través de los análisis estadísticos de las transiciones de la facies se encontró que la facies de marea son frecuentes en la sección de Socotá, más concretamente en la parte superior. Mientras que en las secciones de Sogamoso, Umbita y Peñas de Sutatausa, las facies fluviales son frecuentes en la parte superior de las secciones y siguen una secuencia regresiva con depósitos continentales hacia la parte superior de las secciones. Para cada una de estas secciones, las matrices de las cadenas de Markov presentan una fuerte interacción entre facies mareales y facies fluviales, especialmente en la matriz de Penas de Sutatausa, donde la facie 6, compuesta de depósitos mareales, aparece varias veces. A partir de los análisis de facies y de las cadenas de Markov, es evidente que la formación Guaduas es una secuencia cíclica en la que las repeticiones de facies de Markov son consistentes con el análisis de litofacies en estudios estratigráficos anteriores. Los resultados revelan que el proceso estadístico de las cadenas de Markov se puede utilizarse para predecir la estratigrafía y para correlacionar áreas contiguas y geológicamente inexploradas en la formación Guaduas, donde aún hay mucho trabajo que hacer en la correlación y la continuidad de los yacimientos de carbón.

Palabras clave: : Litofacies, Ambientes de Depósito, Mapas de Facies, Formación Guaduas, Mapas de litofacies.

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INTRODUCTION

The Guaduas formation is the main source of thermal and coking coal for Central Colombia and is located on the Eastern Cordillera of the Andes Mountain Range. According to certain authors, the cyclic patterns found in this formation allow the use of statistical methods. Sarmiento (1994) identified the repetition of transitional environments during the transition between the Cretaceous sea invasion and the early Tertiary with its transitional deposits, and in 2010 Amaya et al. (2010) found a prevalent muddy composition with some key sandstones (guias) and coal beds, in which such coal beds are interbedded with mudstone and sandstone in a pattern beginning with tidal deposits followed by coastal deposits (such as lagoons) and lastly fluvial deposits. Markov Chains statistical analyses have been used by several authors to differentiate geological processes and construct facies models based on transition frequency (Harper, 1984) and can also be used to determine which lithofacies are generally found above or below other lithofacies. Each lithofacies has an assigned number according to its facies description (Miall, 1992). Using Markov Chain analyses, Mariño and Morris (1996) found 37 transitions between eolian and marginal facies, which helped in the development of the depositional model. And additionally found that most of these transitions follow the depositional model, although some random facies could indicate sudden events such as storms. The purpose of this research is to use Markov Chains to confirm the patterns of repetition found in the Guaduas formation by other authors using standard lithofacies analyses (Sarmiento, 1994; Amaya, 2009; Amaya et al., 2010). Amaya et al. (2010) described and reviewed 10 stratigraphic sections in outcrops and cores, and found 12 lithofacies that helped to establish four depositional systems (Figure 1). Four of such stratigraphic sections were chosen with the intent of discovering a pattern by using the statistical method known as the Markov chain, which orders successions of mutually exclusive states (i.e. facies) wherever a change of state occurs to find the significance of the succession. A statistical pattern is suspected in this formation as a result of the Cretaceous cyclicity that has been well documented in Colombia (Etayo-Serna et al, 1976). These patterns could help to understand the dynamics that allow the sediment accumulation in this part of the Eastern Cordillera by the end of Cretaceous and beginning of Paleocene, and can also be used to improve the correlation and learn more about the continuity of the coal beds in the Guaduas formation.

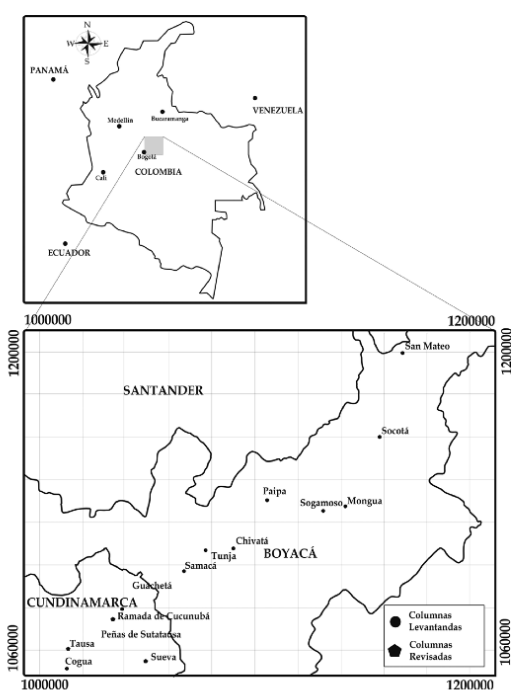


Figure1. Location of the stratigraphic sections in central Colombia which cover parts of the Boyacá and Cundinamarca provinces.

CYCLICITY IN SEDIMENTARY ROCKS AND MARKOV CHAINS

Long ago people began to evidence that the sea once covered areas that are currently dry land. Episodic sea invasions were found to be periodical and important through the study of sedimentary successions and as a result, cyclic patterns were found. In any stratigraphic succession one can see changes in lithologies, called facies, and several statistical methods have been used to differentiate geologic processes and construct facies models on the basis of transition frequency (Harper, 1984). In this study, the term facies is called lithofacies because it represents a rocky unit defined by its lithologic characteristics, which include composition, grain size, and sedimentary structure (Miall, 1990). Each lithofacies represents an individual depositional event, and is grouped according to characteristics of a depositional environment based on facies association (Miall, 1990; Amaya, 2009). The cyclic patterns, represented by cyclical lithofacies, go beyond relative and periodical changes in sea level, and include eustatic or global changes in sea level, non eustatic changes in sea level related to local and regional events, subsidence, compaction, climate, tectonics amongst other factors (Miall, 1990).

The statistical method best suited for the analysis of facies transitions data in stratigraphic sections is the Markov Chain Transition Matrix. Markov Chain analyses can be used to determine which lithofacies are usually found above and below other lithofacies, and thus is one of the methods used to differentiate geologic processes and construct facies models based on transition frequencies, some of which can be used as patterns to predict events or facies related to minerals resources and so on (Harper, 1984; Walker and James, 1990). A Markov Chain transition matrix groups lithofacies into a two dimensional array which tabulates the number of times that all possible vertical lithofacies transitions occur in a given stratigraphic succession. The analysis becomes more meaningful with increasing numbers of transitions. Each lithofacies has an assigned number or code according to the facies description (Miall, 1990). There are two ways to make a transition count matrix: transitions may be recorded at each new bed when lithofacies change in character, regardless of bed thickness, or transitions may be constructed by sampling the section at fixed vertical intervals. In this study, the first method, or "Embebed markov Chain analysis," was chosen because it emphasizes changes and focuses on depositional processes. Repeating lithofacies are measured as one, hence the row of zeros that spans from the top-left to the bottom-right corner of the transition count matrix (Table 1).

	1	2	3	4	5	6
1	0					
2		0				
3			0			
4				0		
5					0	
6						0

Table 1. Example of a 6X6 embedded transition matrix in which the transition numbers in the diagonal are all zero.

Geologic Setting of the guaduas formation

The Guaduas formation is part of the Eastern Cordillera Basin in east central Colombia and has a muddy composition with some sandy units and coal beds; such coal beds are of economic importance in Colombia due to their high rank, with some of them being coking coals (Luna et al., 2004). The formation presents a systematic thinning to the north and to the east. In the southwest, its thickness can reach 1100 m (Checua-Lenguazaque

Syncline), to the north 250-400 m, and to the east 80 m (Sarmiento, 1994; Cooper et al., 1995; Amaya et al., 2010: Duarte y Mariño, 2000). The Guadalupe group, Chipaque formation, and Une formation underlie the Guaduas formation, and the Cacho or Socha sandstone overlies the Guaduas.

The northern part of the Eastern Cordillera Basin was bisected by the Santander High (The Santander and Floresta Massives) until the emergence of the Cretaceous, which allowed for the development of two separated sub-basins: The Cocuy and the Magdalena-Tablazo. This barrier controlled deposition during the lower Cretaceous, with the accumulation of marine shallow facies mainly (Fabre, 1983), to the south, these sub-basins merged as the Cundinamarca sub-basin, where the cretaceous sequence reaches maximum thickness (Sarmiento-Rojas et al., 2006). The sub-basins Tablazo and Cocuy combined as one basin during Hauterivian due to the flooding of the Santander-Floresta High (Fabre, 1983). During the Aptian, a major transgression, followed by a relative sea-level rise, caused the flooding of the current area of the Eastern Cordillera, including the Cundinamarca sub-basin. By that time, the Santander High was not a barrier that would prevent the sediments movement (Cooper et a.l, 1995). In the Albian- Cenomanian, a relative fall in the base level favored the progradation of deltaic and littoral sands - Une formation (Fabre, 1983; Sarmiento-Rojas et al., 2006). During the Cenomanian-Turonian the eustatic level reached its maximum and allowed for the deposition of the Chipaque formation (Sarmiento - Rojas et al., 2006). By the Santonian, Campanian, Maastrichtian and Paleocene, a regression and general progradation lead to the accumulation of littoral and transitional facies during the deposition of the Guadalupe group; it was followed by coastal and alluvial flats and coal facies during the deposition of the Guaduas formation (Sarmiento, 1994). Finally, the entire sequence was covered by the fluvial deposits of the Cacho-Socha sandstone.

The Guaduas formation was deposited throughout the upper Cretaceous and lower Tertiary during the regression of the Cretaceous seas. Superimposed upon this big-tendency scale there are several smaller transgressive-regressive cycles that allow the repetition of the lithofacies and made the formation suitable for statistical analyses. The subsidence of the basin was fast, and the predominance of shallow muddy marine facies also suggests a quick deposition. (Cooper et al., 1995).

The 12 lithofacies found in the Guaduas formation can be grouped in 4 lithofacies associations (see tables 2 and 3). Lithofacies association A consists of interbeddings and interdigitation of sandstones, siltstones, claystones, and at times thin coal beds, which are interpreted as lagoon deposits based on the association, lateral continuity, and organic content of the lithofacies. Lithofacies association B is characterized by the interbedding of sandstones, and claystones with plant debris and coal, and is interpreted as being formed by tidal flats based upon heterogeneous stratification, and bidirectional cross-stratification. Lithofacies association C consists of claystones, coal, and certain sandstones. This association represents a great percentage of the stratigraphic record and is classified as an alluvial flooding flat. Lithofacies association D consists mainly of sandstones and is related to meandering channels based on sedimentary structures, especially big scale cross-stratification (see table 3) (Amaya *et al*., 2010).

DATA AND METHODS

The purpose of this study is to use Markov Chain Analysis to verify the facies stacking pattern discovered in the Guaduas formation using conventional lithostratigraphic facies analysis (Amaya et al., 2010; Sarmiento 1994). Figure 1 depicts the places where Markov Chain analysis was performed in the four stratigraphic sections of Socota, Sogamoso, Umbita, and Peñas de Sutatausa. These sections are well distributed and represent Guaduas formation stratigraphy in the provinces of Boyacá and Cundinamarca.

Facies determination and distribution was conducted in a five step process: (1) Stratigraphic data recollection, (2) Facies definition and description (3) Depositional environment determination, (4) Markovian analysis of lithofacies, and (5) Stratigraphic correlation and analysis. Each facies description was based on grain size and rock type (Folk, 1974), sedimentary structures, bed thickness, vertical and lateral change relationships based upon panoramic sections (Miall, 1990), as well as color and texture. After describing the stratigraphic sections of the Guaduas formation in the studied area, 12 lithofacies were found: 1) Sandstone with bidirectional cross-stratification, 2) Sandstone with irregular wavy bedding, 3) Rhythmic successions of sandstones and claystones, 4) Sandstones with heterolithic bedding, 5) Claystones with Sandy lenses, 6) Claystones with thin lamination, and plant debris, and coal, 7) Claystones and siliceous limestones with paleosols, 8) Sandstones with through-cross stratification, 9) Sandstones with planar cross-stratification, 10) Sandstone with planar stratification, 11) Sandstone with climbing cross-stratification, and 12) Massive sandstones (Table 2).

Lithofacies number	Lithofacies
1	Sandstone with bidirectional cross-stratification
2	Sandstone with irregular wavy bedding
3	Rhythmic succession of sandstones and claystones
4	Sandstones with heterolithic bedding
5	Claystones with Sandy lenses
6	Claystones with thin lamination, plant debris, and coal
7	Claystones and siliceous limestones with paleosols
8	Sandstones with through-cross stratification
9	Sandstones with planar cross-stratification
10	Sandstone with planar stratification
11	Sandstone with climbing cross-stratification
12	Massive sandstones

Table 2. Lithofacies number and lithofacies

According to the facies analysis, the repetition of different attributes was identified throughout the sections and along the basin. This association of lithologic attributes is presented in Table 3, which shows a prograding sequence that characterizes the transition between transitional and continental deposits. The lithofacies association allowed the determination of the depositional environments and the depositional systems. The facies model, by which the depositional environments were interpreted, indicates that tidal flat deposits were followed by coastal lagoons and topped by a fluvial system with alluvial flats interbedding with meandering channels. Description and interpretation of depositional environments was supported by research done by Reineck y Singh (1980), Walker y James (1990), Boggs (1987), Kvale y Archer (1990), Miall (1990), Walker and James (1990), Fichter (1993), Choi and Dalrymple (2004), and Mariño and Morrison (1996). For the construction of the Markov Chains, each section was labeled with facies number defined during the facies study (Table 2); this procedure eased the transition counting between one lithofacies and an adjacent one (above or below). Transitions were recorded based on the changes in character of lithofacies regardless of bed thickness. Through this process the transition between the same types of facies was not taken into account, this is why the elements of the main diagonal in each matrix are all zero, which follows the method known as “Embedded Markov Chain Analysis” (Ethier, 1975). These transitions were tabulated in a two-dimensional arrangement where the columns represent the overlying lithofacies while the rows represent underlying ones (Table 1).

Markov Chains are based on two considerations, the first is the supposition that lithology at any point n depends upon the lithology of the proceeding point n-1. This supposition is possible due to the fact that the Guaduas formation apparently behaves as a cyclic sequence, in which the same lithology is observed at different points in a stratigraphic section. The second is to consider a transition as a change between two different lithologies where the transition in the same lithology is not taken into account, thus the elements of the main diagonal in the matrix are all zero (Table 1).

RESULTS

The facies analysis using Markov Chains in the four stratigraphic sections was based upon that carried out by Amaya (2009) and Amaya et al. (2010), which determined 12 repeating lithofacies throughout the sections (Table 2). These facies were associated in order to establish a facies model with depositional environments and depositional systems for the Guaduas formation. Four depositional systems were established, from coastal lagoons, passing through tidal flats, to fluvial systems with meandering channels interbedded with alluvial flooding flats (Table 3). The change between transitional and continental environments seems to be oscillatory, which reflects sea level variations for that time. The Markov Chain analyses were used to test the stacking pattern found during the previous facies study. The stratigraphic sections and the resulting matrices of Socota, Sogamoso, Umbita, and Peñas de Sutatausa are as follows:

Socota stratigraphic section. Figure 2 presents the stratigraphic section and the Markov Chain matrix for the Socota area. In this matrix, the presence of lithofacies 6 (Claystones with thin lamination, plant debris, and coal) stands out, as it appeared 8 times in the section. Facies 6 is followed 4 times by lithofacies 1 (sandstones with bidirectional cross-section), and 3 times by lithofacies 5 (claystones with sandy lenses).

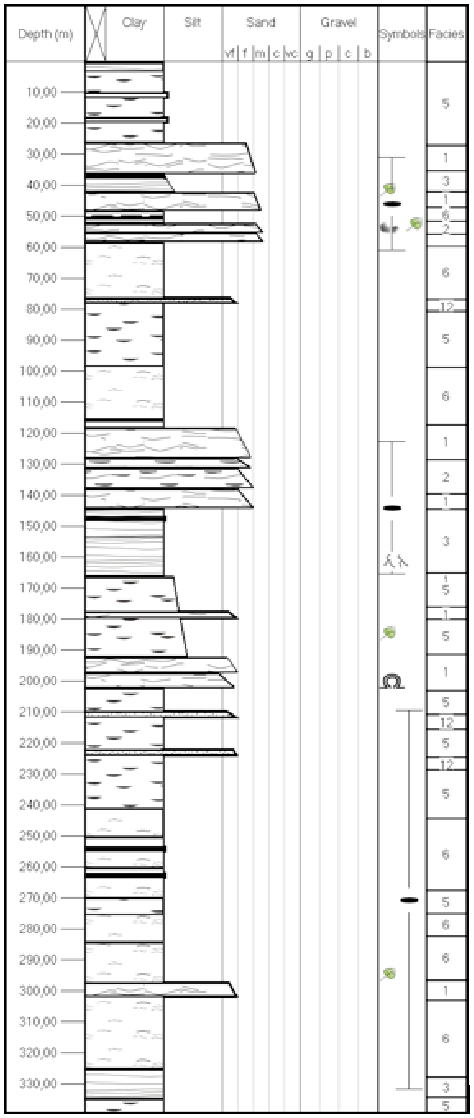
Sogamoso stratigraphic section. From the matrix completed for the Sogamoso stratigraphic section (Figure 3), lithofacies 6 (Claystones with thin lamination, plant debris, and coal) is the most abundant, appearing 6 times, 4 of which lithofacies 8 is underlain by lithofacies 6, and 3 of which by lithofacies 12 (Massive sandstones). Lithofacies 5 was found below lithofacies 12 in three instances. Lithofacies 12 was found 4 times below lithofacies 6.

Umbita stratigraphic section. From Figure 4 in the Umbita's section, it is clear that lithofacies 6 (claystones with thin lamination, plant debris, and coal) is the most abundant and usually relates with facies 1 (Sandstone with bidirectional cross-stratification) and facies 8 (Sandstones with through-cross stratification).

Peñas de Sutatausa stratigraphic section. Figure 5 presents the stratigraphic section and Markov Chain matrix for the Peñas de Sutatausa area. From the matrix, it is concluded that the most related facies are 6 (Claystones with thin lamination and plant debris and coal), 1 (Sandstone with bidirectional cross-stratification), 5 (Claystones with Sandy lenses), and 8 (Sandstones with through-cross stratification). Lithofacies 6 and 8 are closely related and follow each other 13 times (below and above).

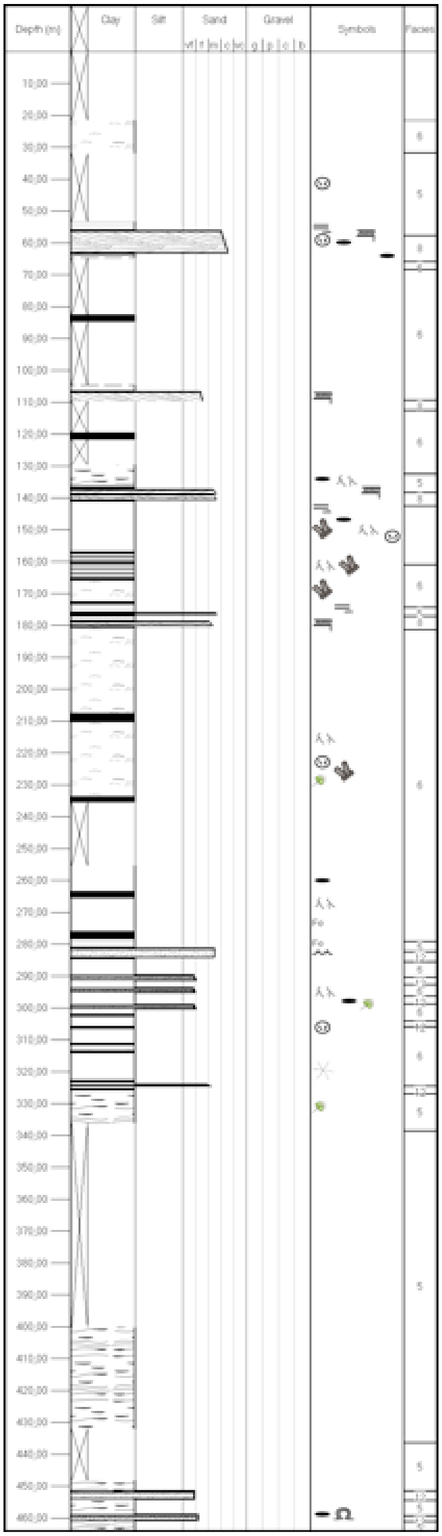
Lithofacies Association	Lithofacies number	Description	Depositional environment	Depositional System
D	8	Conglomeratic Sandstones with through-cross stratification	Fluvial channel	Meander channels
	9	Sandstones with planar high angle cross-stratification	Lateral bars	
	10	Sandstone with planar stratification, rich in organics	Upper flow regime channel	
	11	Sandstone with climbing ripple cross-lamination	Levee deposits	
C	6, 12	Laminated and massive claystones with Sandy lenses, Massive sandstones. Paleosols, iron stones, plant debris and coal.	Swamps	Alluvial flooding flat
	7, 12	Claystones and siliceous limestones with paleosols, Massive sandstones, paleosols, iron concretions	Overbank deposits	
	12	Massive sandstones with tabular and X-stra.	Crevasse splay	
B3	4, 5, 6, 7	Claystone with thin lamination, pyritic, coalbeds, desiccation cracks, roots, and fossil leaves.	Supratidal zone	Tidal Flat
B2	1, 2, 3, 4, 5	Sandstone with flasser estratification, Sandstone with irregular wavy bedding, Sandstones with heterolithic bedding, Claystones with Sandy lenses. Rhythmic sedimentation and coal.	Intertidal zone	
B1	1, 2, 4	Sandstone with flasser and herring-bone stra., Sandstone with irregular and lenticular wavy bedding, Sandstones with heterolithic bedding,	Subtidal zone	
A	1, 5, 6, 12	Sandstone interbedded and intefingered with claystones and siltstones with lenticular bedding, abundant coaly material.	Coastal lagoons	Lagoon

Table 3. Prograding lithofacies model for the Guaduas formation indicating continentalization of the basin. The lithofacies association result in a deposition environment that is related to a depositional system (Amaya et al. (2010).



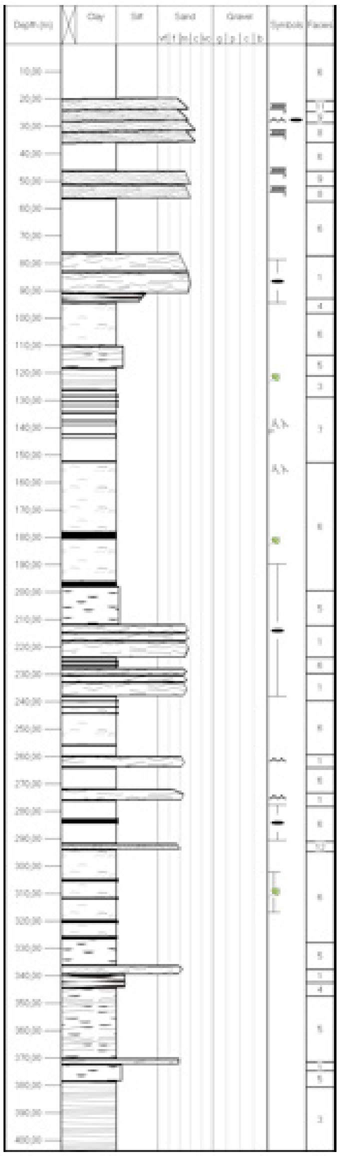
	1	2	3	4	5	6	7	8	9	10	11	12	Total
1	0				3	4							7
2		0											2
3			0		2								2
4	2			0									2
5	1			1	0	3							5
6	4			1		0	1	2					8
7			1				0						1
8								0	2				2
9						1			0		1		2
10										0			
11						1					0		1
12						1						0	1
Total	7		1	2	5	10	1	2	2		1		31

Figure 2. Stratigraphic section of the Guaduas formation in Socota with lithofacies numbers and Markov Chain transition matrix.



	1	2	3	4	5	6	7	8	9	10	11	12	Total
2		0			2	1							3
3			0										
4				0									
5	2				0	1						3	
6	1					0		4				3	6
7							0						8
8					1	3		0					4
9									0				
10										0			
11											0		
12					2	4						0	7
Total	3				5	9		4					21

Figure 3. Stratigraphic section of the Guaduas formation in Sogamoso with lithofacies numbers, and Markov Chain transition matrix.



	1	2	3	4	5	6	7	8	9	10	11	12	Total
1	0				3	4							7
2		0											1
3			0		1								3
4	2			0									
5		1		1	0	2							10
6	4			1		0	1	2				1	4
7						1	0						2
8								0	2				
9						1		2	0		1		
10										0			
11						1					0		
12						1						0	
Total	7	1	3		6	8	2						27

Figure 4. Stratigraphic section of the Guaduas formation in Umbita with lithofacies numbers and Markov Chain transition matrix.

DISCUSSION AND CONCLUSIONS

From the highlighted areas or more frequent transitions in each of the matrices, certain conclusions can be made:

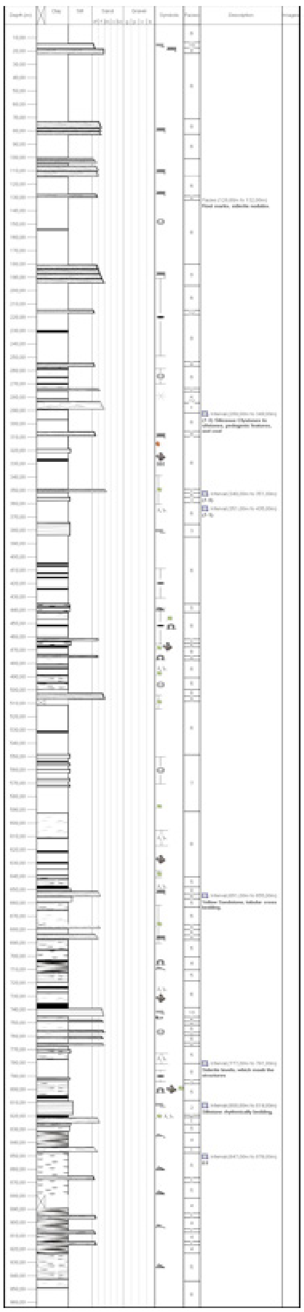
1) For the Socota Area, the presence of lithofacies 6 stands out due to its repetition (Claystones with thin lamination, plant debris, and coal), followed by lithofacies 1 and 5. The transitions of lithofacies 6 to other lithofacies are tenfold in this section. From this matrix, the presence of muddy areas with coal and the strong relationship between facies 1 (Sandstone with bidirectional cross-stratification) and 6 (Claystones with thin lamination, plant debris, and coal) is evident, and indicates the prevalence of transitional facies to the top, and a lateral relationship between fluvial and tidal flats, supporting the conclusions of the previous model in which the coal in that area was originated in tidal swamps (Amaya et al, 2010; Sarmiento, 1994). The Socota area is the only section where the transitional facies seem to be to the top of a section with tidal deposits at the base and top of the section, and alluvial facies in the middle.

2) From the Sogamoso matrix, it is evident that lithofacies 6 (Claystones with thin lamination and plant debris and coal) is the most abundant and is most related to lithofacies 8 (Sandstones with through-cross stratification) and 12 (Massive sandstones). This indicates the interbedding of clays and coal from swamps (which are part of an alluvial flat), with sandy units that represent the fluvial meandering channels. The prevailing lithofacies analysis in the Sogamoso section indicates continental dominance towards the top of the section, unlike that of the North-East section (Socota section) where tidal and fluvial environments prevailed. This could be explained by the progressive thinning of the formation to the north and to the east (Amaya et al, 2010).

3) For the Umbita area, the strongest associations are between the tidal facies (facies 6, 5 and 1), which could indicate that the coal beds in this area are more related to tidal flats and have some interaction with fluvial meandering channels, lateral bars, and fluvial channels (8 and 9 lithofacies). This follows the conclusions of previous studies that have shown a balance between tidal and fluvial environments, with the fluvial deposits prevailing to the top of sections (Amaya et al, 2010).

4) In the Peñas de Sutatausa area two associations are important: the first one relates tidal lithofacies (1-6), and the second associates tidal and fluvial facies (6 and 8), supporting the facts that in this area, fluvial, tidal, and fluvial with tidal facies influence were the prevailing lithofacies during the coal deposition. The fluvial influence is stronger to the top of the Peñas section (Sarmiento, 1994; Amaya, 2009). In Peñas, the fluvial influence is stronger than in the Umbita area.

From the facies model and Markov Chain analyses, it is evident that the Guaduas formation is a cyclic sequence in which the Markov facies repetitions are consistent with the lithofacies analyses done in the stratigraphic sections. The statistical facies analyses proved that the tidal facies prevails in the Socota section, especially to the upper part; the Markov Chain transition matrix found little interaction of the tidal facies with the fluvial facies, indicating fewer fluvial facies in that section (Figure 2). Note that in Figure 2 the facies repetitions are between tidal lithofacies 1 and 6, supporting the results of previous facies analyses (Amaya et al., 2010). On the contrary, the stratigraphic correlations of the Sogamoso, Umbita and Peñas de Sutatausa sections revealed fluvial facies prevailing to the upper part of the sections, following a regression sequence with more continental deposits toward the upper part of the sections (Table 2). In these latter sections, the Markov Chain transition matrix illustrates a strong repetition of fluvial facies following tidal facies, indicating strong interaction between them, as is evident in the Peñas de Sutatausa´s matrix where facies 6 related to tidal deposits repeats 13 times with facies 8 of fluvial origin (Figure 5).



	1	2	3	4	5	6	7	8	9	10	11	12	Total
1	0			4	1	4						1	10
2		0											
3			0			2							2
4	3			0	2								5
5	4		1	1	0	1		2					9
6	3		1		6	0	1	13					24
7						1	0						1
8						13		0		1		1	15
9									0				
11											0		
12						3						0	3
Total	10		2	5	9	26	1	15		1		2	71

Figure 5. Stratigraphic section of the Guaduas formation in Sogamoso with lithofacies numbers, and Markov Chain transition matrix.

The finding of transitional tidal facies located most often to the bottom, followed by fluvial flats and fluvial channel deposits shows a shallowing upward sequence with continental deposits more frequent near the top that was developing at the Upper Cretaceous and early Paleocene Epoch as a result of the regression forced by the Andean Orogeny (Cooper et al., 1995). However, in each transition, smaller cycles are present, allowing the cyclic deposition of different lithologies like key sandstones (guias) and 12 to 14 coal beds. This cyclicity allowed the deposition of a great deal of coal, especially in the south, making of this area one of the best coal sources in Colombia (mainly coking coals) (Luna et al., 2004).

Not only the vertical changes are evident in this area, but also the horizontal changes, due to the thinning of the stratigraphic succession to the north and east of the study area. The northward thinning of the Guaduas formation may be explained from a smaller subsidence to the north (Fabre, 1983, Amaya *et al*, 2010). The thinning may also be explained by erosion (Sarmiento, 1994). These hypotheses would explain why the Guaduas formation is thicker in the Cundinamarca province and has two coal bed members. On the contrary, to the north (Boyacá Province), the formation is thinner and has just one coal member, as the upper one possibly eroded. This along with erosional unconformity would better explain the thinning of the Guaduas formation to the north (Sarmiento, 1994; Duarte y Mariño, 2000).

The discovery of more continental facies found to the top by use of Markov chains is in agreement with facies maps, which indicate an upward shallowing of the environments with an increased presence of fluvial facies to the top, especially in the south (Amaya et al., 2010; Amaya, 2009). Initially the sea regression-transgression had a SW-NE tendency, which later became more E-W. These changes could be related to the reactivation and stratigraphic control of big trust faults like Soapaga that have caused differential subsidence (Krammer, 1999; Duarte y Mariño, 2000). From the facies association in the Guaduas formation, a progressive shallowing in the environments due to fluvial facies dominance is evident near the top of the section, with three main West to East transgressive episodes with tidal and fluvial environments prevailing to the top and NE of the basin, which could be explained by the progressive thinning of the formation to the north and east as a result of the sea receding to the west. This follows previous findings that used conventional facies analyses (Amaya et al, 2010).

These results demonstrate that the Markov Chain statistical process can be used as a quantitative tool to distill lithofacies transitions and define lithofacies trends with precision, as well as to predict stratigraphy in order to correlate contiguous unexplored geologic areas in the Guaduas formation where much work on correlation and coal bed continuity is still to be done.

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REFERENCES

Amaya, E. (2009). *Litofacies y ambiente de acumulación de la Formación Guaduas (Maastrichtiano tardío – Paleoceno)*. Proyecto de grado. UPTC Sogamoso – Ingeniería Geológica. Biblioteca UPTC.

Amaya, E., Mariño, J. & Jaramillo, C. (2010). Litofacies y ambientes de acumulación de la formación guaduas en la parte central de la cordillera oriental – implicaciones paleo geográficas. *Boletín de Geología*, 32(1).

Boggs, S. (1987). *Principles of Sedimentology and Stratigraphy.* Columbus: Merrill Publishing Co., 784 p.

Choi K. S., & Dalrymple, R. (2004). Recurring tide-dominated sedimentation in Kyonggi Bay. *Marine Geology*, 81-96.

Cooper, M., Addison, F., Alvarez, R., Coral, M., Graham, H., Hayward, B., Howe, S., Martinez, J., Naar, J., Peñas, R., Pulham, A. J., & Taborda, A. (1995). Basin development and tectonic history of the Llanos Basin, Eastern Cordillera, and Middle Magdalena Valley, Colombia. *A.A.P.G Bulletin*, 1421-1443.

Duarte, C. & Mariño, J. (2000). Utilización de las areniscas guías en la búsqueda y exploración de mantos de carbón. Caso Formación Guaduas – Sogamoso (Boyacá). Memorias V Congreso Nacional de Ciencia y Tecnología del Carbón. Valledupar, Cesar.

Etayo-Serna, F., Renzoni, G., & Barrero, D. (1976). *Contornos sucesivos del mar Cretácico en Colombia*. In: Primer Congreso Colombiano de Geología, Mem., Bogotá, pp. 217–252.

Ethier, V. (1975). Application of Markov Analysis to the Banff Formation (Mississipian). *Journal of Mathematical Geology*, 47-65.

Fabre, A. (1983). La subsidencia de la Cuenca del Cocuy (Cordillera Oriental Colombiana) durante el Cretaceo y el Terciario Inferior. *Geología Norandina*, 8.

Fichter, L. P. (1993). *Ancient Environments and the Interpretation of Geologic History*. Ontario, Canada: Macmillan Publishing Company.

Folk, R. L. (1974). *Petrology of Sedimentary Rocks*. Austin: Hemphill, 182 p.

Harper, C. W. (1984). Improved methods of facies sequence analysis, in: R.G. Walker (editor) Facies Models, second edition. Geoscience Canada, Reprint Series 1, 11-14.

Krammer, A., (1999). Observaciones acerca de un origen transpresivo de la Cordillera oriental. *Geologia Colombiana*, 24: 29-53.

Kvale, E., & Archer, A (1990). Tidal deposits associated with low-sulfur coals, Brazil Fm. (lower Pennsylvanian), Indiana. *Journal of sedimentary petrology*, 563-574

Luna, L., Rodríguez, E., Sánchez, C., Renzoni, G., Hernández, H., Maldonado, J., Alba, C.& Sanabria, A. (2004). El Carbón Colombiano - Recursos, Reservas y Calidad. Publicaciones Geológicas Especiales. Ingeominas, Bogotá.

Mariño, J. & Morris, T. (1996). Erg Margin and Marginal Marine Facies Analysis of the Entrada Sandstone, Utah. Museum of Northern Arizona Special Publication, 483-496.

Miall, A. (1992). Alluvial Deposits. In: Walker, R. Facies Models: Response to Sea Level Change (pp. 119-142). *Geological Association of Canada.*

Miall, A. D. (1990). Principles of Sedimentary Basin Analysis. New York: Springer -Verlag, 483 p.

Reineck, H., & Singh, I. (1980). *Depositional sedimentary environments.* Springer, Berlin, 551 p.

Sarmiento, G. (1994). Estratigrafía y medios de depósito de la formación Guaduas. *Boletín Geológic*o, 32 (1-3). Ingeominas, Bogota.

Sarmiento-Rojas, L., Van Wess, J., & Cloetingh, S. (2006). Mesozoic transtensional basin history of the Eastern Cordillera. *South American Earth Sciences*, 21, 383- 411.

Walker, R., & James, W. (1990). Facies Models: Response to Sea Level Change. Canada: *Geological Association of Canada*. 530p.