Cretaceous Paleogeography and Sedimentation in the Upper Magdalena and Putumayo Basins, Southwestern Colombia*

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Abstract

Integrated analysis of seismic, well logs, surface geology, and biostratigraphic data from the Cretaceous section of the Upper Magdalena Valley (UMV) and Putumayo basins of southwestern Colombia reveals a diachronous sedimentation pattern, as well as tectonic controls in the mid- and Late Cretaceous. Cretaceous deposits contain both the source and the main reservoirs in these important hydrocarbon basins.

The distribution of basal Cretaceous deposits in SW Colombia indicates a strong control of the pre-Cretaceous paleo-topography. Cretaceous sedimentation advanced from the northern UMV Basin to the Putumayo Basin in the south. A paleo-high along the western extension of the Florencia-Vaupés arch may have formed a barrier between the two basins, as suggested by the youngest age of the basal Cretaceous deposits and the reduced thickness of the entire Cretaceous sequence.

Cretaceous deposition initiated in the northern UMV Basin with the fluvial sediments of the Yaví Formation in Barremian times, while in the south the oldest Cretaceous sediments are late Albian in age. In the Oriente (Ecuador) and Putumayo basins, fluvial to tidally-influenced sedimentation began in Aptian times corresponding to the Hollín and Caballos formations, respectively, while in the northern Putumayo Basin the oldest Cretaceous rocks are of Cenomanian to Turonian age. In the late Albian - Cenomamian a compressive pulse correlating with the Mochica event in Peru produced structures in the basin, with reduced thickness of the Cenomanian Bambuca Shale developed.

Progressive marine sedimentation is also observed in a diachronous pattern, with first marine deposits varying from Aptian in the northern UMV to Turonian in northeastern Putumayo Basin. Marine sedimentation continued until the Campanian - early Maastrichtian, when widespread erosion led to the non-preservation of the upper portion of the Cretaceous marine sequence. Coarse-grained deposits of this age unconformably overlie marine shales along the western border of the UMV Basin, suggesting a rapid uplift of the Central Cordillera.

The upper Maastrichtian to Paleocene sequence was deposited in brackish to fresh-water environments and exhibits in some areas a basal sandstone or conglomerate. The lower erosive contact of this sequence is a paraconformity marked by an abrupt change in depositional environments, associated with a deformation episode well documented in northwestern South America.

Geological Framework

The Upper Magdalena Valley (UMV) and Putumayo basins are two of the most important oil- producing basins in Colombia, located in the southwestern portion of the country (Figure 1). While the UMV is an intermountain basin located between the Central and Eastern Cordilleras, the Putumayo is a foreland basin located between the eastern foothills of the Eastern Cordillera in the West and the Guyana Shield in the East. The UMV Basin has been divided by the Natagaima Uplift in two sub-basins, the Girardot Sub-basin in the north and the Neiva Sub-basin in the south (Beltrán and Gallo, 1968). During the Mesozoic and Paleogene the UMV and Putumayo basins were part of the same extensive mega-basin, and they were later separated during the Andean orogeny when the Eastern Cordillera was uplifted. The boundary between both basins is a poorly studied area in which the Eastern Cordillera of Colombia merges morphologically with the Central Cordillera.

Stratigraphic Markers

Seven stratigraphic markers characterized by distinctive lithological features and e-log signatures were used (Figure 2). Five of these markers were identified and calibrated biostratigraphically in previous studies carried out in the UMV Basin and the remaining two markers are proposed in this work.

For the Caballos Formation and the Villeta Group of the UMV, Mora (2003) described three markers with the oldest one being the middle Caballos flooding event (marker 1 in Figure 2), which according to Vergara (1994), contains the Aptian-Albian boundary. The second marker (called *Ticinella* marker), located towards the middle of the Tetuán Formation in the UMV, contains a peak in abundance of middle to late Albian planktonic forams of the *Ticinella* gender (Vergara, 1994). The third marker in the UMV Basin (marker 4 in Figure 2) was called Cenomanian-Turonian and corresponds to the abrupt change from the monotonous Bambuca shales to the La Luna Limestone.

Veloza et al. (2006) described two more markers located towards the top of the Cretaceous section which correspond to the two chert units (called “Liditas”) of the Olini Group (markers 6 and 7 in Figure 2). Based on micropaleontologic analyses, the lower chert has been assigned a Santonian age while the upper chert is of middle Campanian age.

In this study we propose two additional regional stratigraphic markers, the first one is the top of the Tetuán Formation of the UMV Basin (marker 3 in Figure 2), which can be correlated with the top of the B-Limestone in the Putumayo Basin. The age of this marker is late Albian in the UMV Basin while it is early Cenomanian in the Putumayo Basin. The second proposed stratigraphic marker corresponds to the top of the M-units of the Putumayo Basin, of late Turonian - early Coniacian age (marker 5).

Cretaceous Paleogeography - Yaví and Caballos Formations

The economic basement in most of the UMV and Putumayo basins consists of volcaniclastic red beds of Jurassic age (Saldaña Formation in the UMV and Motema Formation in Putumayo). The Cretaceous infill corresponds to a base-level rise within a 2nd-order sequence-stratigraphic cycle, which in turn includes at least seven 3rd-order cycles in the UMV and five in Putumayo. The oldest age and greatest thickness of all the Cretaceous mega-sequence shows that there was much more accommodation space towards the north and northeast of the UMV Basin (northern Girardot Sub-basin). While alluvial fan and fluvial sedimentation of the Yaví Formation began in this area probably during the Barremian, in the Neiva Sub-basin an early Aptian age was assigned to the unit (Vergara and Prossl, 1994). Deposition related to this Barremian to early Aptian sedimentary cycle did not reach the southern Neiva Sub-basin or the Putumayo Basin (Figures 3 and 4).

From the middle to late Aptian, the fluvial to tidally influenced sandstones of the lower member of the Caballos Formation were deposited on top of an irregular paleotopography as evidenced by the prominent facies and thickness changes. Using the stratigraphic markers, Mora (2003) showed how the base-level changes related to 3rd-order cycles allowed the UMV Basin to be filled from north to south in a highly diachronous way. The deposition of the Yaví Formation in the north coupled with the lower member of the Caballos Formation corresponds to the first and oldest 3rd-order cycle in the Cretaceous (K1), of Barremian to late Aptian age. The maximum flooding which occurred in late Aptian - early Albian times is represented by the middle member of the Caballos Formation, which onlaps the pre-Cretaceous basement in the southernmost UMV Basin (Figures 3 and 4).

During the early Albian the upper member of the Caballos Formation was deposited in tidally influenced coastal plain and shoreface environments representing a relative sea level fall within the second 3rd-order cycle (K2). The upper Caballos was deposited throughout the entire UMV Basin and reached only the deepest portions of the Putumayo Basin towards the west (Figure 4), where it occurs as a thin (approximately 100ft) basal sandstone package within the “Caballos” Formation, as informally defined in the Putumayo Basin. The basal “Caballos” sandstones, which correspond to the first Cretaceous sedimentation in the Putumayo Basin during the early Albian, were deposited in coarse-grained fluvial channel environments (Amaya and Centanaro, 1997).

The Tetuán Formation of the UMV contains most of the second 3rd-order cycle (K2) which started with the regressive deposits of the upper Caballos. Towards the middle of the Tetuán limestones is the *Ticinella* marker representing a middle to late Albian flooding event that is well expressed in e-logs. The use of this marker in well correlations showed how, as the upper Caballos shales-out towards the northern UMV, the lower Tetuán limestones gradually change to sandy facies towards the southern UMV and into the Putumayo Basin (Figures 2 and 3). In fact, the *Ticinella* marker of the Tetuán limestones in the UMV is roughly equivalent to the top of the “Caballos” Formation as informally defined in the Putumayo Basin. Field work in the northern Putumayo Basin (Mora et al., 1998) and our well correlations showed that the “Caballos” Formation onlaps the pre-Cretaceous basement towards the Florencia Vaupés Arch.

Villeta and Olini “Groups”

As seen in Figure 2, the mid-Albian to Santonian succession in the UMV Basin composes the Tetuán, Bambuca and La Luna formations, which comprise part of the Villeta Group, while in Putumayo the equivalent interval is informally called “Villeta” Formation and comprises several informal members. In the Putumayo and Oriente basins, the “Villeta” (Napo) Formation is characterized by transgressive-regressive 3rd-order cycles in which transgressive limestone-shale units alternate with regressive sandstone units (White et al., 1995). In general agreement with Roberston and Kairuz (2000), we identified four of these cycles within the “Villeta” Formation, with the T and U-sandstones representing abrupt base-level falls (Figure 2).

The third Cretaceous 3rd-order cycle (K3) comprises the uppermost Tetuán Formation and the lower Bambucá Formation in the UMV, corresponding in Putumayo to the regressive T-sandstone, the B-limestone and the Middle “Villeta” (Napo) Shale (Figures 2 and 3). In late Albian to early Cenomanian times, sedimentation in the UMV took place in a carbonate ramp (Peña et al., 2002), while in the Putumayo Basin it occurred in more proximal, distal-fluvial to shallow-marine environments.

A similar interpretation was done for the fourth 3rd-order cycle (K4), which in the Putumayo Basin, begins with the regressive U-Sandstone and continues upwards with the A-Limestone and M-units. Well correlations show that these units are equivalent to the upper Bambuca Formation and lower half of the La Luna Formation of the UMV Basin, of Cenomanian to Turonian age (Figure 2).

In the UMV Basin Jaimes and de Freitas (2006) documented a compressional deformation event in late Albian - Cenomanian times (Mochica Tectonic Phase), within the Bambuca Formation. This event, which was responsible for dramatic thickness changes in the Bambuca Formation in certain areas of the UMV, influenced both erosion and deposition of potential reservoirs in that basin. This event has not been identified in Putumayo, although it could be associated with. the Cenomanian sea-level fall, which is expressed by the regressive U-sandstone (base of K4 sequence, Figure 2).

Field work (Mora et al., 1998) and our well correlations in the northern Putumayo Basin also show that the T and U-sandstones onlap the basement towards the Florencia-Vaupés Arch, as they amalgamate into a series of stacked sand bodies. At the same time, the A-limestone and overlying units of the “Villeta” Formation change to sandy-shallow-marine facies. In fact, south of the city of Florencia, the basal Cretaceous sandstones (Masaya Formation of Mora et al., 1998) have a Turonian age and according to well data, they represent the Cenomanian-Turonian K4 cycle. This means that in Turonian times, most of the UMV and Putumayo Basins were covered by the Cretaceous sea, probably except eastern portions of the Florencia-Vaupés Arch which continuously acted as a paleo-high (Figure 4).

From latest Turonian to Santonian times, organic-rich shales displaying coarsening-upwards patterns were deposited throughout both basins, and one 3rd-order cycle was interpreted. This fifth 3rd-order cycle (K5), of mainly Coniacian age, composes the Upper “Villeta” (Napo) shales in Putumayo/Oriente and the upper La Luna shales in the UMV Basin.

From the Santonian to Maastrichtian it has been suggested that there was a renewed uplift of the Central Cordillera combined with a sea-level fall. The Santonian-Campanian facies in the basin are composed primarily of bedded cherts in distal portions of the basin and by regressive shallow-marine systems in proximal regions. These cherts are included in the two youngest Cretaceous 3rd-order cycles (K6 and

K7) which comprise the Olini Group and the Buscavida / Nivel del Lutitas y Arenas Formation in the UMV and which have been mostly eroded in the Putumayo and Oriente basins (Figures 2, 3, and 4) .

The upper contact of the “Villeta”/Napo formations in Putumayo and Oriente has been considered an unconformity, implying a small erosional hiatus (Tschopp, 1953, Cáceres and Teatín, 1985). Mora et al. (1998) in the northern Putumayo Basin and Veloza et al. (2006) in the UMV documented a related erosive event based on the abrupt change in sedimentary environments of the units above and below it, on the contrasting sediment source areas as shown by petrography, and on the absence of palynological zones. This regional paraconformity, which implies erosion of a great part of the Campanian and the lower Maastrichtian strata in the southern UMV and Putumayo basins (Figures 2, 3, and 4), can correlate with the Calima orogeny (Barrero, 1979). Our correlations show that only very few wells located towards the west of the Putumayo Basin exhibit thin chert beds towards the top of the “Villeta” that could be equivalent to the Lower Chert of the UMV (K6 cycle).

Paraconformably on top of the Villeta succession in the UMV and Putumayo Basins lies a upper Maastrichtian to Paleocene sequence called Guaduas or Guaduala Formation in the UMV, Rumiyaco in the Putumayo and Tena in the Oriente Basin. This sequence was deposited in brackish to fresh-water environments and exhibits in some areas a basal sandstone or conglomerate. According to petrographic analyses, while the “Villeta” Formation in Putumayo was sourced from the craton in the east, this sequence was sourced from a different area in the west, reflecting a pre-Andean deformation episode that has been documented in northwestern South America.

Conclusions and Implications for Hydrocarbon Exploration

The UMV and Putumayo basins were part of the same extensive mega-basin during Mesozoic and Paleogene times, and they were later separated during the Andean orogeny when the Eastern Cordillera was uplifted. Sedimentation and facies distribution during the Cretaceous were strongly controlled by the pre-existing paleo-topography, especially towards the boundary between the two basins which is considered the western extension of a major paleo-high (Florencia-Vaupés Arch). This is evidenced by the onlapping patterns of the two oldest sequences against the paleo-high, by the youngest age of the basal Cretaceous deposits, and by the reduced thickness of the entire Cretaceous mega-sequence. However, Cretaceous thicknesses have also been influenced by tectonic events which acted with different intensity depending on the location within the basin. The Maastrichtian tectonic episode (Calima) caused the erosion of most of the Campanian and lower Maastrichtian stratigraphic section in the southern UMV and Putumayo Basins, while the late-Albian to Cenomanian event (Mochica) caused the erosion of most of the Bambucá shales in localized areas of the southern UMV, which were considered paleo-highs. Main implications of the Mochica event in oil exploration in the UMV are the formation of potential unexplored traps and the improvement of reservoir properties (generation of secondary porosities in shallow uplifted areas). Concerning the Calima event, its main implication on exploration is the regional deposition of the Guaduala seal, paraconformably on top of the Upper Cretaceous Olini reservoirs in the Neiva Sub-basin. In fact, the combination of the resulting stratigraphy with structural factors allowed the accumulation of hydrocarbons in several fields which produce from Olini reservoirs in the Neiva Sub-basin. By contrast, in the Putumayo Basin Maastrichtian erosion was more intense, causing the complete removal of the potential Upper Cretaceous reservoirs. However, the facies models presented here suggest that the potential reservoirs would exhibit higher qualities towards the identified paleo-highs and basin borders.

Although the proposed regional paleogeographic and facies models can provide general insights about Cretaceous reservoir distributions and qualities, they are intended to be the starting point for the elaboration of much more detailed regional studies integrating the UMV and Putumayo Basins.

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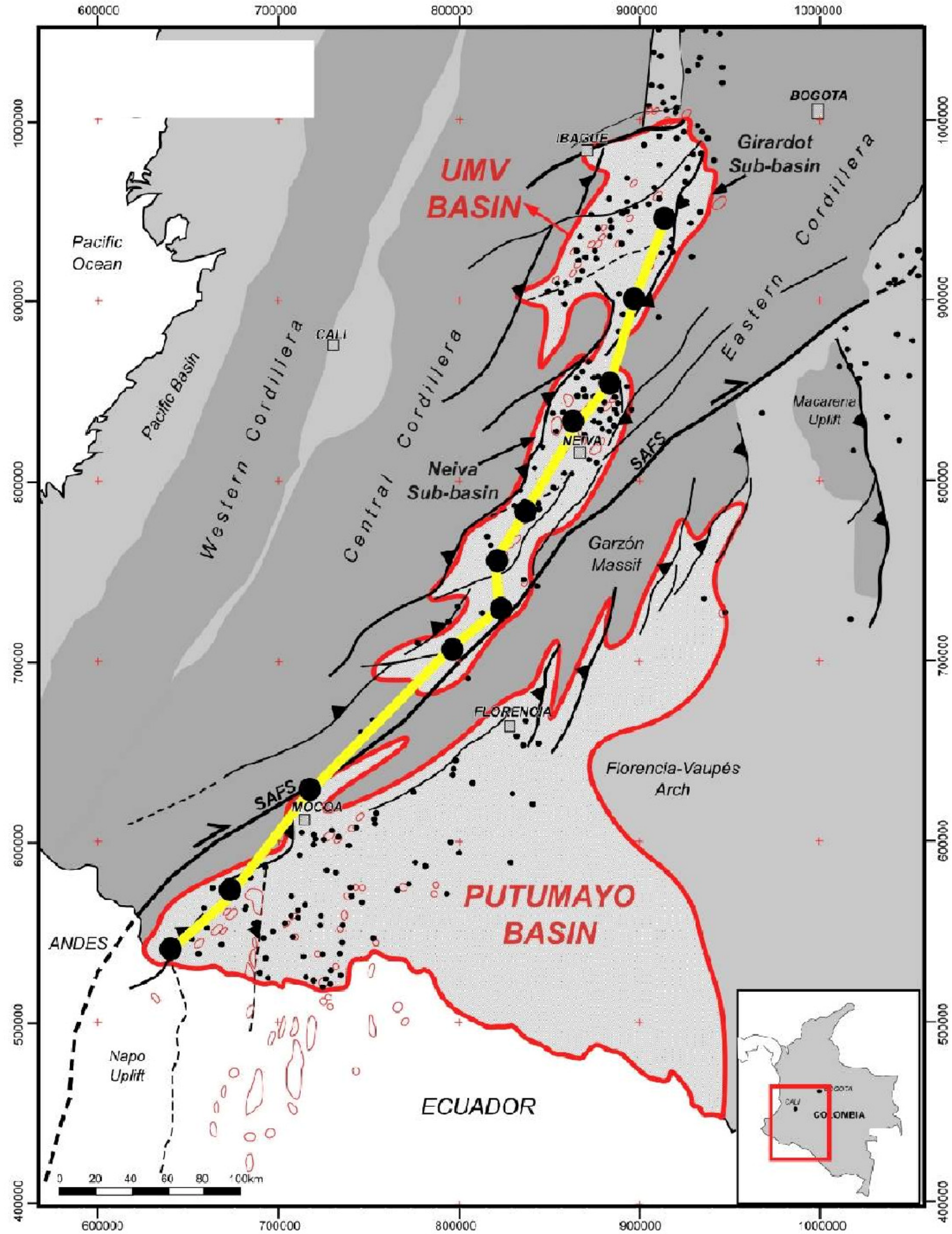

Figure 1. Location of the study area, showing well locations in the well correlation in Figure 3.

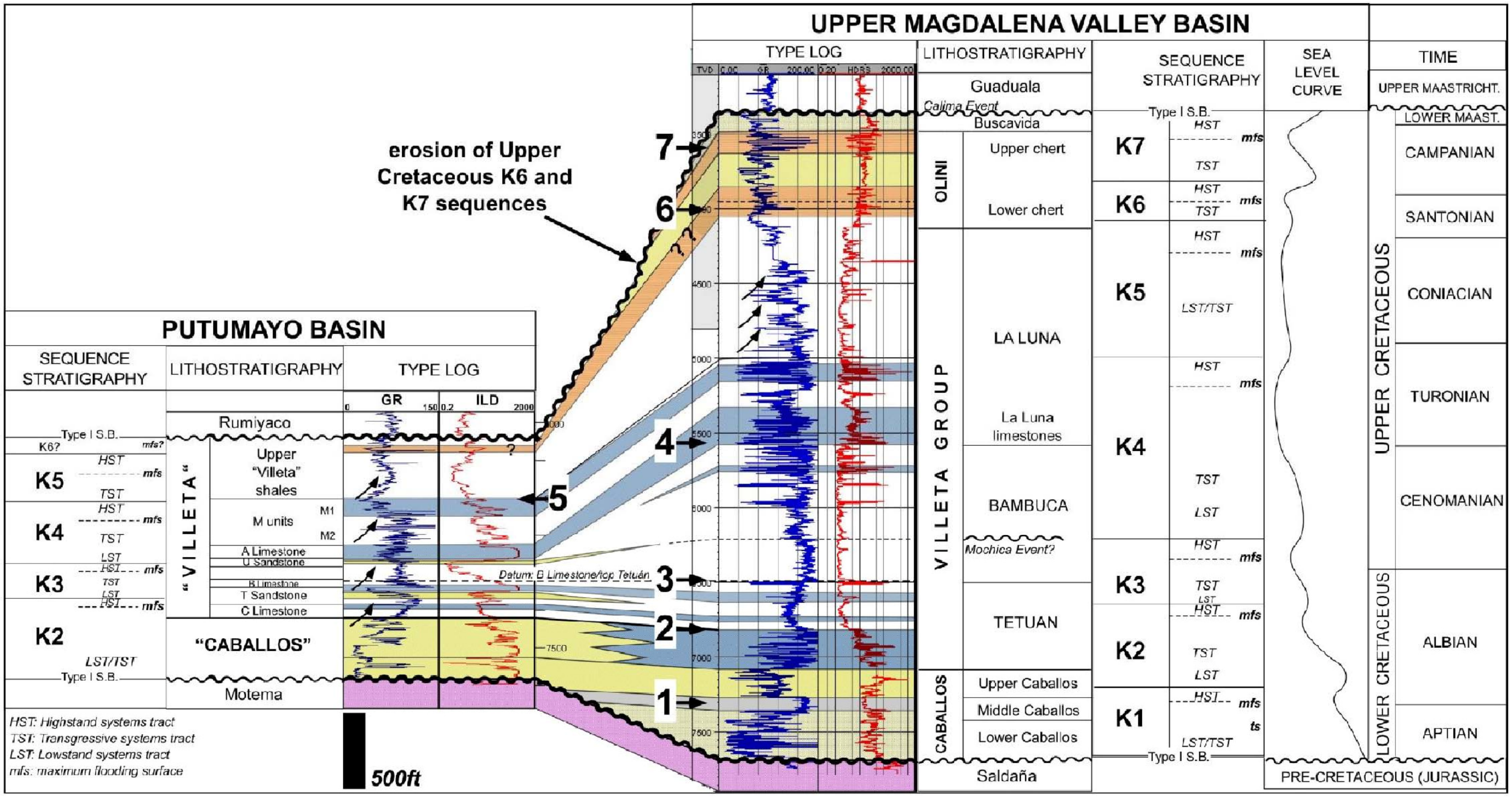

Figure 2. Lithostratigraphy, sequence stratigraphy, stratigraphic markers, and equivalents between the UMV and Putumayo basins.

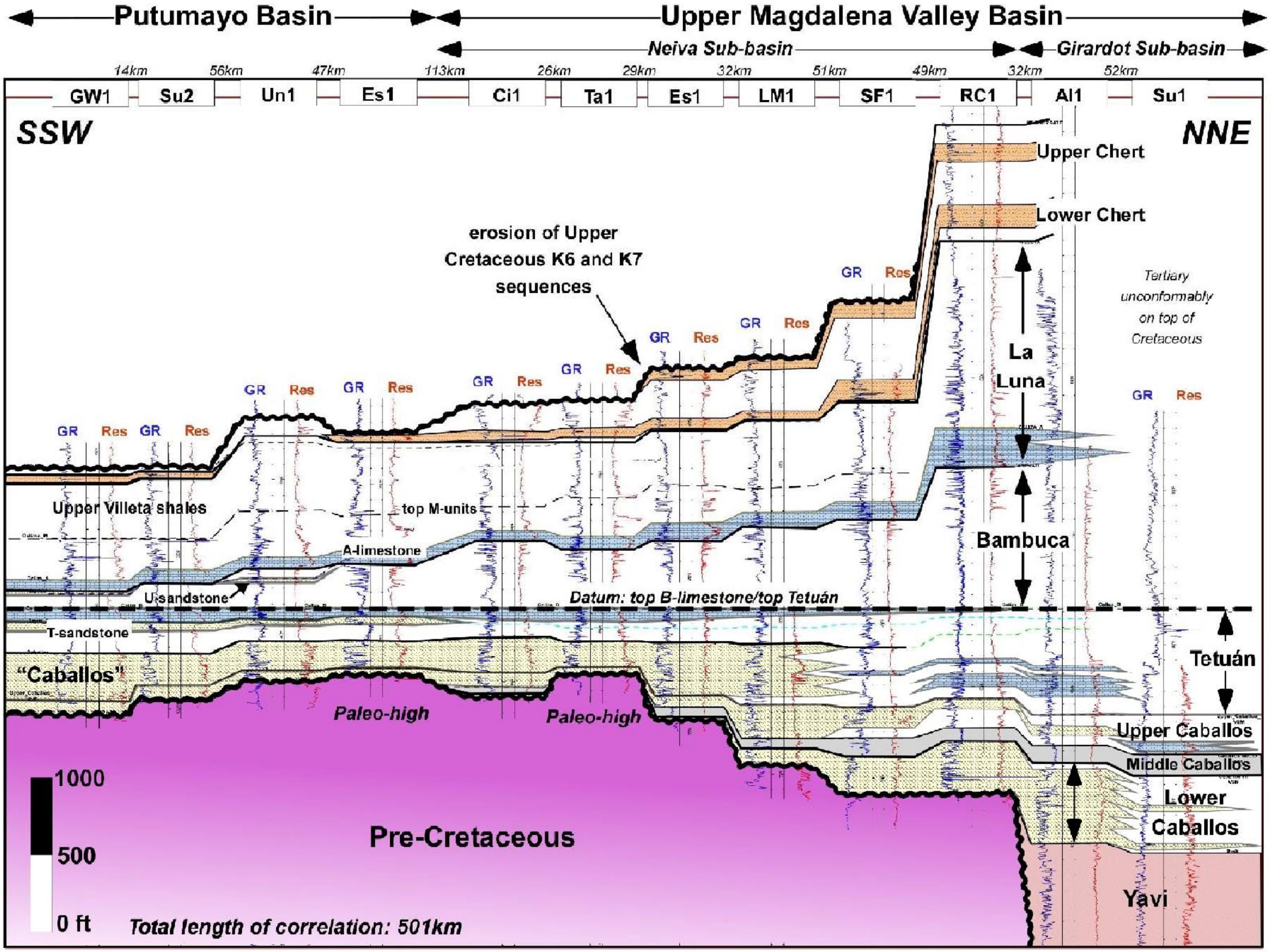

Figure 3. Well correlation of the Cretaceous between the UMV and Putumayo basins.

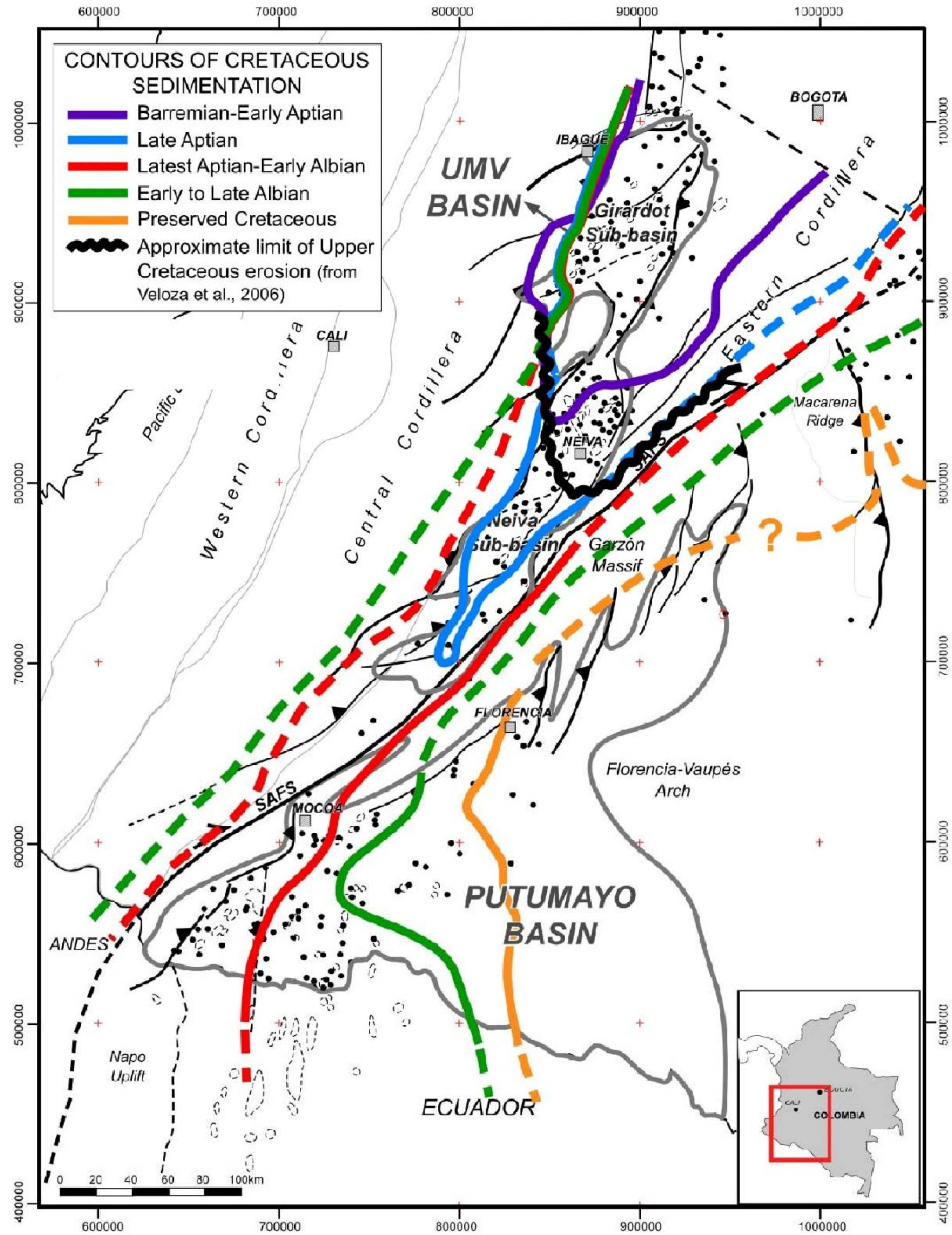

Figure 4. Regional sketch of the advance of Cretaceous sedimentation in the UMV and Putumayo basins.