Turonian-Campanian Foraminifera Zonation for the La Luna and Lower Umir Formations, Middle Magdalena Valley Basin, Northern Colombia

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Abstract. Well-site biostratigraphy using planktonic foraminifera, palynomorphs, and calcareous nannofossils was performed in Chuira-2ST well, Middle Magdalena Valley Basin, Colombia. Biostratigraphic analysis was focused in the latest Early Campanian marly and sandy-shale deposits of the Umir Formation and the limestone and shale deposits of the La Luna Formation. In this contribution, foraminifera results are discussed and correlated with palynomorphs and calcareous nannofossil data. A foraminifera zonation for the Middle Magdalena Valley Basin is proposed, which is based on the Chuira-2 and Chuira-2ST wells and other exploration wells and outcrop sections in the area. In the La Luna Formation, a total of six globotruncanids zones were established: *Whiteinella archaeocretacea*, *Helvetoglobotruncana helvetica*, *Marginotruncana sigali*, *Dicarinella primitiva*, *Dicarinella concavata*, *Dicarinella concavata–Rugoglobigerina pilula*, and *Dicarinella asymetrica* (earliest part). In the Umir Formation, *Globotruncanita elevata* (latest part), *Globotruncana ventricosa*, and *Globotruncanita calcarata* zones were recognized. The *Dicarinella asymetrica* and *Globotruncanita elevata* zones are not developed in its total range since there is a regional unconformity in the Santonian/Campanian boundary, which corresponds to the La Luna and the

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Umir Formations contact and involves a 4.4 Myr hiatus. In the La Luna Formation, paleoenvironments correspond to a marine inner to outer neritic, epicontinental sea with oxygen-depleted bottom waters and episodic upwelling events. Anoxia was more intense at the Middle Turonian and the Coniacian/Santonian boundary. In the Umir Formation, a shallowing trend is observed that ends in littoral to marginal marine paleoenvironments.

Keywords: Planktonic foraminifera · Cretaceous biostratigraphy
Colombian biostratigraphy · Cretaceous South America · La Luna Formation
Umir Formation

1 Introduction

This work presents the results of the foraminifera recovered on a well-site biostratigraphy (WSB) performed at Chuira-2ST well. The wells were drilled in the northeastern area of the Middle Magdalena Valley Basin, (MMVB) Colombia. WSB advanced technology is a tool, which results to assist with the placement of corings, casings, and terminal depth (TD), aids in the reduction of drilling risk and uncertainty assisting in the stratigraphic positioning while supports the caving analysis, to identify stratigraphic position of borehole instability. WSB was achieved by means of integrated biostratigraphy using foraminifera (planktonic and benthonic), calcareous nannofossils and palynomorphs. WSB verified inverse faulting between 8230 and 8263 ft. The fault causes Upper Cretaceous to repeat (Rodríguez et al. 2016a), and WSB reveled the Santonian and Coniacian strata above and under the fault. The biostratigraphy and zones here discussed eliminates 310 ft, which corresponds to the fault zone (8130–8440 ft). Thus we use two intervals: Campanian-Late Coniacian, interval (7880–8130) and Early Coniacian to Early Turonian, interval (8440–9365 ft TD). The 310 m thick of La Luna Formation includes pelagic calcareous deposits rich in planktonic foraminifers also bearing calcareous nannofossils and marine palynomorphs, mostly dinocysts, ranging in age from the Turonian to the Santonian. Overlying, Campanian strata of the base of the Umir Formation also yield calcareous microfossils and palynomorphs dominated by pollen and spores. As exposed by Schiebel (2002) the calcareous tests of planktonic foraminifera produce a substantial amount of carbonate in the world oceans. They just began their radiation in the Early Aptian and contribute 32–80% of the total deep marine carbonates production, therefore planktonic foraminifera figure as one of the most important carbonate producers within the La Luna Formation. Calcareous and mixed rocks are very rich in pelagic components, also including nannofossil and dinocysts.

One-hundred and thirty-three samples from the La Luna Formation were analyzed using foraminifera, calcareous nannofossils (see Pérez Panera et al., this volume) and palynomorphs. These were used to gain insight about ages and hiatus, and also were used to establish a first approximation to the recognition of Oceanographic Anoxic Events (OAE) characterized by the widespread deposition of pelagic sediments rich in organic matter such as black shales that are considered as key mechanisms for organic

carbon burial (Arthur et al. 1990; Schlanger and Jenkyns 1976). A dominance of these black shales in shallow water settings in Atlantic and Caribbean regions was noted by some authors (see Arthur and Schlanger 1979; Jenkyns 1980; Hofmann and Wagner 2011). All samples were analyzed in well site. A total of 3785 specimens (17 genera with 47 species) of planktonic foraminifera were counted and classified. The foraminiferal vertical distribution was calibrated with dinocysts (Navarrete-Parra et al. 2015, 2016a, b) and calcareous nannofossils (Pérez Panera et al., this volume). The proposed zonation in this contribution is also tied to the geological time scale based on absolute ages and data from previous studies conducted on two cored boreholes and three outcrop sections distributed across the MMVB. They are Colón-2, Colón-3. Chuira-1 and Chuira-2 wells, and surface outcrops of the La Luna Formation in Aguablanca creek, El Salto creek, and Cuesta El Diablo section (Fig. 1). Additionally, Turonian and Coniacian faunas were also correlated with ammonite biostratigraphy from Aguablanca and El Salto. Previous works on the La Luna Formation showed that Turonian/Coniacian and Coniacian/Santonian boundaries are challenging to establish. This difficulty is due to low recovery of double-keeled planktonic foraminifera using conventional process and picking methods. Biostratigraphic markers as *Dicarinella*, *Marginotruncana* and *Globotruncana* genera are scattered, either missing or very rare. However, those difficulties were overcome by the achievement of total and rapid disintegration of rock obtaining an excellent recovery of specimens from these groups. Additionally, data was also improved using key dated age ranges of non-complex planktonic foraminifera and thin section analyses. The results from thin-slides analyzed are in full-agreement with routine methods. Standard foraminifer's zones of Caron (1985) were identified and *Dicarinella concavata* and *Dicarinella asymetrica* sensu Caron were lightly modified. Two subzones are introduced: *D. Concavata* sub-zone [*D. concavata* Zone Caron (1985) modified], and *Dicarinella concavata–Costellagerina* (*Rugoglobigerina*) *pilula* association sub-zone. This sub-zone has been previously recognized in other scenarios and although it has not been published before, it has been used in the private industry. By means of this sub-zone, the O and G have gained better resolution in stratigraphical interpretations. The Santonian/Campanian boundary is missing due to an hiatus and the late early Campanian shows condensed sedimentation.

The aim of this article is to introduce a zonal scheme for the La Luna and Umir formations that represents a first approximation to the vertical distribution of the deposits of these formations and even further, a review of the spatial distribution of organic-rich sediments in the MMVB (Colombia). The planktonic foraminifera studies allow us to propose this first biostratigraphic framework from the La Luna Formation in the MMVB, which can be applied in Rancheria and Catatumbo basins (Colombia) with high reliability, and to other equivalents as the Villeta Group in the Upper Magdalena Valley, and "Villeta informal group" in the Putumayo Basin. This paper is a first contributive effort using well-site Cretaceous tied with geochronological datings. This will improve our understanding of the biostratigraphy based on microfossils, and helps us to constrain the age of the units and the hiatus. Furthermore, briefly introduce us by means of foraminifera a first vision of the Cretaceous Oceanographic Anoxic Events during sedimentation in the MMVB (Colombia), which are implicit objectives in O and G Exploration.

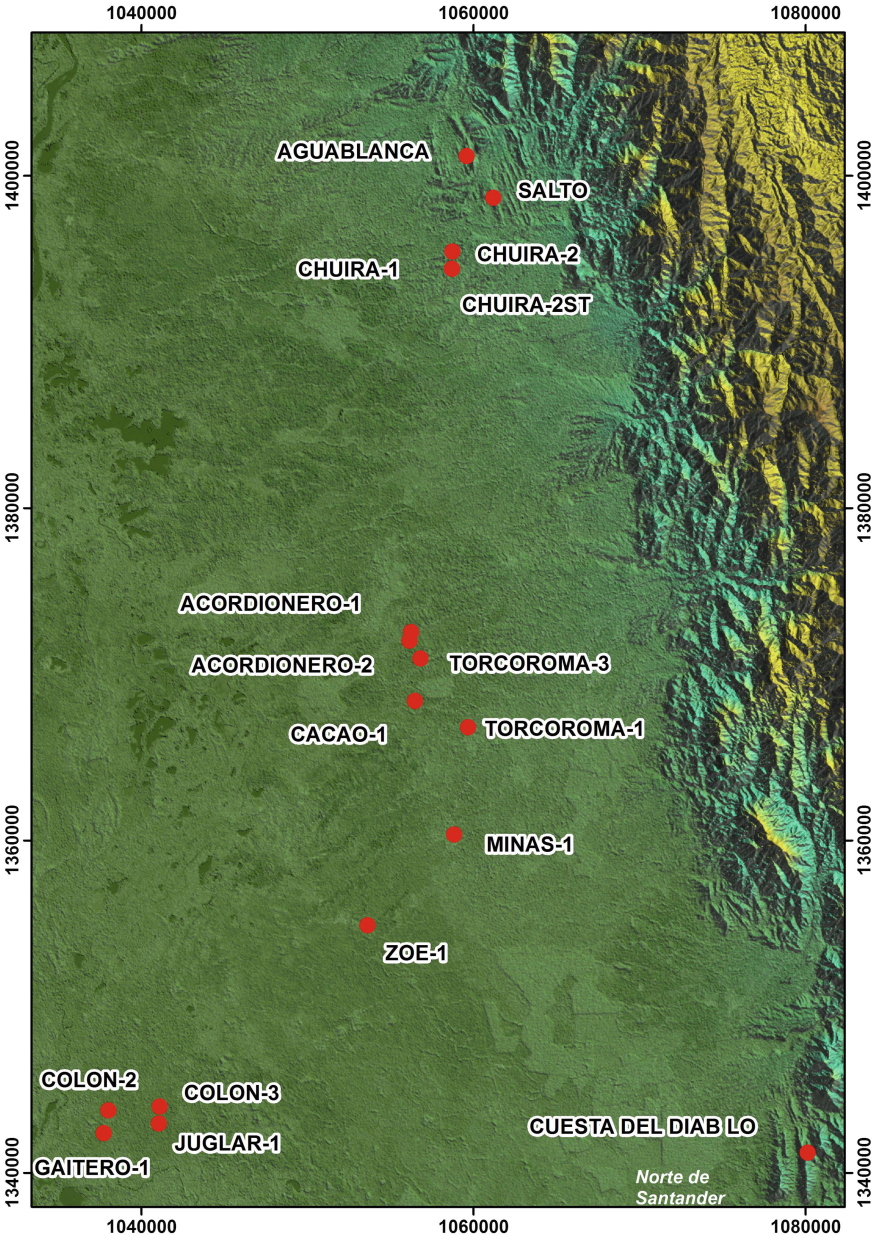

Fig. 1. Localization of Chuira-1, Chuira-2, and Chuira-2ST wells in the northern Middle Magdalena Valley Basin and surface outcrops more referred in the text

The well-site biostratigraphy in Chuira-2ST disclosed a Turonian to earliest Late Santonian age for the La Luna Formation in the MMVB and a hiatus spanning 4.4 Myr in the contact with the overlying latest Early Campanian condensed strata of the lower Umir Formation (Navarrete-Parra et al. 2016c). The very base of the La Luna Formation was not drilled in Chuira-2ST, but in Aguablanca and El Salto sections its base (Salada Member) is of Cenomanian to Early Turonian age.

1.1 Middle Magdalena Valley Basin Background

The Andes Mountains of South America consist of three distinct ranges in Colombia: The Western, Central, and Eastern Cordillera. Each one represents an accretionary and/or deformational event resulting from various instances of rifting, oblique collisions, and transpressional/transtensional tectonics, occasioned by the movements and interactions of the Caribbean, the Nazca and the South America tectonic plates (Barrero et al. 2007). The modern Middle Magdalena Valley Basin (MMVB) (Fig. 2) is an asymmetric, south-north trending intermountain depression in the middle of the Central and Eastern Cordilleras of the Colombian Andes extending over 30,000 km^2. The MMVB according to Barrero et al. (2007) is bound on the north and south by the Espiritu Santo fault system (ESFS) and the Girardot folded belt (GFB), respectively. The Bucaramanga-Santa Marta fault system (BSMF) marks the northeast boundary, and the Bituima and La Salina Fault Systems (BSFS) mark the southeast boundary. The western limit is delineated by the onlap of Neogene sediments over the Serranía de San

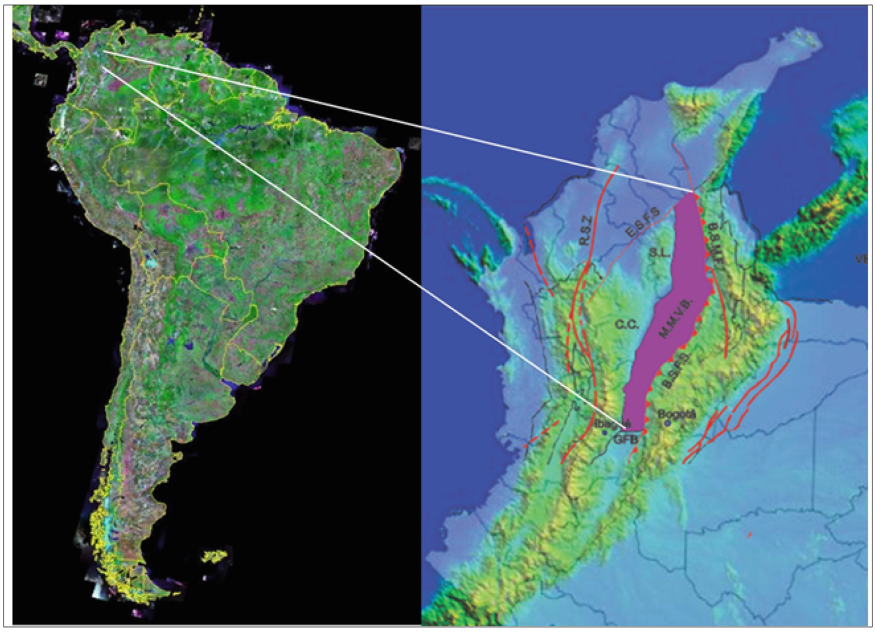

Fig. 2. Colombia in South America, structural boundaries from Middle Magdalena Valley Basin (abbreviations description in text)

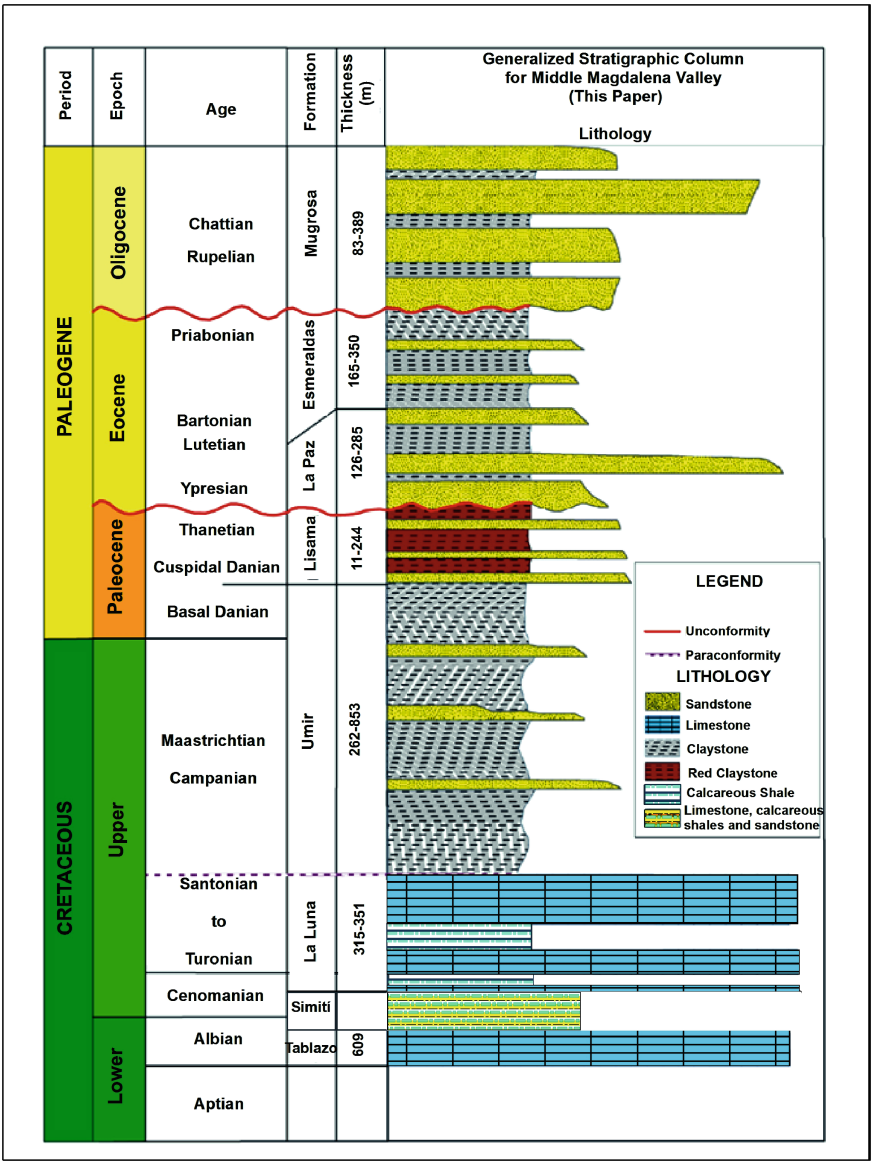

Fig. 3. Generalized stratigraphic column in Middle Magdalena Valley Basin MMVB

Lucas (SL) and Central Cordillera (CC) basement boundary. The Magdalena Valley Basin separates the Central and Eastern Cordillera; however, the underlying basin represents a major regional sedimentary basin that received sediment from the Triassic through the Cenozoic (Fig. 3).

According to Cooper et al. (1995) from the Triassic to the middle Miocene, the MMVB was part of a greater regional sedimentary basin including Eastern Cordillera

and Llanos basins. The separation of North and South America during the Triassic and early Cretaceous triggered the development of an extended rifting phase in the Proto-Caribbean. This marked the beginning of a large transgression and deposition into what became the sedimentary basins of Colombia. The MMVB expansion began with an epicontinental transgression deposited in the rifts, related to the separation of North and South America and the opening of the Proto-Caribbean Sea (Cediel et al. 2011). The sedimentary record shows a succession of pre-Cretaceous continental conglomerates deposits. These deposits correspond to Jordan and Girón formations (Cooper et al. 1995). The pre-Cretaceous in MMVB is overlaid by calcareous and siliciclastic rocks deposited in a shallow marine shelf during Lower Cretaceous. These deposits correspond to Cumbre, Rosablanca, Paja and Tablazo formations (basal group) which resemble a marine platform wider than the modern MMVB (Cooper et al. 1995).

Basin development continued into the Cretaceous in a back-arc setting at the east of the Andean subduction zone. The back-arc sedimentation was mainly shallow marine and produced the excellent source rock of the La Luna Formation during the Turonian-Coniacian. Albian to Campanian period includes sedimentation in a shallow marine basin controlled by eustatic changes [(Simití and the La Luna formations: Rolon (2004)]. Marine deposition was abruptly interrupted during the early Maastrichtian due to the final accretion of the Western Cordillera (Cooper et al. 1995). During this time, mafic magmatism associated with the accretion of the Western Cordillera overheated the middle- and outer-shelf shales (Cediel et al. 2011). Deposition was re-established in the early pre-Andean foreland basin after accretion of the Western Cordillera in the late Maastrichtian (Cooper et al. 1995). Paleocene is represented by the siliciclastic Umir Formation. The Paleogene sequence is made up of siliciclastic rocks. These deposits consist of alluvial, coastal plain and estuarine deposits Eocene deformation, caused by the uplifting of the Central Cordillera, temporarily interrupted deposition into the basin once again subsidence and deformation eventually re-established sedimentation in the basin, into which late pre-Andean foreland basin sediments were deposited. These Cenozoic deposits represent environments similar to those in the early pre-Andean foreland basin; coal-rich alluvial plain, coastal plain, and estuarine deposits (Cooper et al. 1995). The Paleogene to early Neogene sedimentation includes continental deposits (i.e. fluvial, lacustrine) which correspond to La Paz, Esmeraldas, Mugrosa, and Colorado formations (Cooper et al. 1995; Caballero et al. 2010). By the middle Miocene, transpressional deformation of the Eastern Cordillera fully isolated the MMVB from adjacent basins. The resulting accommodation space was filled with the Andean foreland basin megasequence (Cooper et al. 1995). This megasequence corresponds to the Real Group and subsequent sedimentation (Caballero et al. 2010). Marine mudstones are present in the lower part of the megasequence; however, fluvial sands and conglomerates dominate the upper portions of the continental interior sequence (Cooper et al. 1995; Cediel et al. 2011).

1.2 Overview of the La Luna Formation

The La Luna Formation was originally named “La Luna limestone” by Garner (1926) in the La Luna creek in the Perijá range (Zulia state, Venezuela). It was formally described as a Formation by Hedberg and Sass (1937) as follows: “It consists of

thin-bedded and laminated dense dark gray to black carbonaceous-bituminous limestone and calcareous shale. The limestone beds vary from a few inches to about a foot and one-half in thickness. The formation is particularly characterized by hard black ellipsoidal and discoidal limestone concretions ranging from a few inches to several feet in diameter. Black Chert is common as seams and nodules. The uppermost part of the formation is sometimes lighter in color than is the bulk of the formation. When freshly broken, the limestone frequently has a strong petroleum odor.'' Later, Notestein et al. (1944) introduced it in the "Barco Concession" (Catatumbo Basin, Colombia). Subsequently, the La Luna Formation was described by Morales (1958) in the MMVB and divided it into three members (from base to top): Salada, Pujamana and Galembo. These members have been described by various authors (e.g., Morales 1958; Reyes et al. 2000; Rangel et al. 2000a, b; Torres et al. 2012). According to Kuuskraa et al. (2013), best organic-rich layers (3–12% TOC) are in the 150 m thick Salada Member, which consists of hard, black, thinly bedded and finely laminated limy shales (40% $CaCO_3$), along with thin interbeds of black fine-grained limestone. Pyrite veins and concretions are common, as are planktonic (but not benthonic) foraminifera and radiolarians. The lower-TOC Pujamana Member consists of gray to black, thinly bedded and calcareous shale (43% $CaCO_3$). The Galembo Member has moderate TOC (1–4%) and consists of black, thinly bedded, calcareous shale, but with only thin argillaceous limestone interbeds. The Galembo also has abundant blue to black chert beds (Kuuskraa et al. 2013). In Venezuela and Colombia, organic-rich, cyclic strata such as laminated black shale-limestone couplets prevailed for most of the Coniacian–Santonian up to the Lower Campanian (de Romero et al. 2003; Rey et al. 2004). Near the Chuira-2ST Rodríguez et al. (2016a) found that in the Cuesta el Diablo, El Salto and Aguablanca creeks outcrops La Luna Formation develops a large stratigraphic sequence, with 211.5, 328 and 382 m of thickness, respectively. Recently, Galvis-Portilla et al. (2014) introduced a detailed description for the La Luna Formation. Unfortunately, great part of their description does not permit to differentiate objectively between the three members as previously described. This is due to disparity in lithological descriptions from the La Luna Formation and, mainly, because the three member sensu Morales (1958) are not always recognized. In this work, we use the scheme for the La Luna Formation as occurring in field sections cited by Rodríguez et al. (2016a) and in Chuira-2ST, without differentiating in the tree members.

The detailed and new biostratigraphical analyses carried out by Paleosedes E.U. biostratigraphic consultant (1987 to present), shows that, indeed, limy shales from the Salada Member correspond to the lower part of globigerinids-mud, with calcareous nannofossils, dinocysts, radiolarians and pithonellids of Cenomanian age (e.g., Cuesta El Diablo). The Chuira-2ST well did not drill the Salada Member lower part, but reached to a stretch of the upper part of this member. The upper hard part consists in black, limy shales with occasional black fine-grain limestones, very rich in calcareous and non-calcareous dinocysts, coccolithophorids and non-keeled foraminifers, frequent calcisphaerulids and rare radiolarians of earliest Turonian age.

In Chuira-2ST, the La Luna is an organic-rich Upper Cretaceous formation, consisting of dark gray to black, white gray and brown-gray laminated and massive calcareous rocks. From base-up, it discloses fossiliferous wackestones and packstones (micrite, biomicrite and spate-micrite) strata, interbedding with calcareous mudstone

and subordinate siliceous mudstone and calcareous concretions. This conjunct is rich in foraminifera, calcareous nannofossils, dinocysts, pithonellids, and ammonites. The middle part consists, in general, of white gray and brown-gray colored limestone (micrite and biomicrite), dark brown to black colored calcareous and siliceous mudstone (margas), with benthonic foraminifera richness, in less proportion but abundant planktonic foraminifera, calcareous nannofossils and dinocysts. Bivalves are abundant and ammonites are present. Subordinately, wackestones, packstones and thin sandstones beds, also occur. The upper strata consist of brown gray, dark brown and dark green limestones in wackestones and packstones (micrite, biomicrite and spatemicrite), interbedded with white gray limestones and calcareous mudstones, with subordinated siliceous mudstone. Big and abundant calcareous concretions are characteristic of these levels. It also yields finely disseminated tuffaceous material. Toward the top, bluish and blackish chert beds are common. At the top, mature glauconite and hardgrounds are abundant. The La Luna Formation, marine unit rich in black calcareous shale and limestone with organic-rich facies, was formed in a widespread epicontinental sea. The environments and facies distribution were controlled by the paleo-topography, eustasy, accommodation space, oceanographic events, and climate change while post-depositional tectonics and diagenesis altered its thickness and obliterates its paleontological content in most places. The upper contact with the Umir Formation is well defined in electric logs. The gamma ray log shows a peak at the top of the La Luna Formation due to the glauconitic layers. The Resistivity log abruptly increases due to calcareous concretions and high organic matter contents. Glauconite and hardgrounds are recognized both in surface and subsurface.

1.3 The La Luna Formation in Oil and Gas Reservoir

The MMVB is a mature basin in terms of oil exploration and production and its activity has been largely focused on Cenozoic conventional hydrocarbon reservoirs (Prince et al. 2011). Since the first giant oil field discovery in 1918 (Cira-Infantas Oil Field), more than 100 oil fields had been discovered, adding more than 3990 MMboe of recoverable reserves and cumulative production (Rodríguez et al. 2016a). These proven conventional oil accumulations confirm an active and effective petroleum system. As 40% of the generated hydrocarbons are retained in the source rock (Jarvie et al. 2007), there is a great potential for hydrocarbon accumulations in unconventional organic shales in the MMVB. Thus, this basin has begun to attract efforts in looking for these unconventional reservoirs. La Luna Formation is notoriously the great source rock in Colombia and Venezuela (Talukdar et al. 1985), and one of the most important worldwide (West 1996). Most recent assessment of technically recoverable, continuous shale oil and shale gas resources estimates 233 million barrels of oil (MMBO) and 0.87 trillion cubic feet of gas (TCF) within Cretaceous units in the MMVB (Schenk et al. 2017)

1.4 La Luna Formation Biostratigraphy Background

The northern area of Middle Magdalena Valley produces oil from the La Luna Formation and there is high expectative about a better understanding of its time and space

distribution. It has been extensively studied by the Oil and Gas (O and G) industry, but little, or certainly nothing, of these works had been published. The age of the unit has not been accurately constrained or is simply very poorly understood. No planktonic foraminifer's zonation has been published for the Cretaceous of the Middle Magdalena Valley, neither for the La Luna Formation in Colombia. The local stratigraphy was based on benthonic foraminifers (Cushman and Hedberg 1941; Petters 1954, 1955). Petters (1954) introduced the first benthonic zonation that included the La Luna Formation at MMVB. In this zonation, he mentioned high abundance of small Globigerinidae, *Güembelina* spp. and few *Globotruncana* spp. and Radiolarians in the lower part of the La Luna Formation. He also described the ammonite assemblage in those levels. The *Globigerinella–Güembelina* assemblage, mainly composed by pelagic forms, is present in black to dark shales, limestones, and cherts. The ammonite assemblage reported contains the Lower Turonian genera *Fagesia*, *Mammites*, *Metoicoceras*, *Neoptychites*, and *Vascoceras*. Upper Turonian ammonites are characterized by the genera *Coelopoceras*, *Prionotropis*, and the Coniacian assemblage by *Baculites*, *Barroisiceras*, *Peronoceras*, and *Prionocycloceras*. The Upper Cretaceous planktonic foraminifera from Colombia were first studied by Gandolfi (1955), who concentrated his studies on the *Globotruncana* genera. Later local publications like Martinez (1989) on the Maastrichtian of the Catatumbo basin, Tchegliakova (1993, 1995, 1996) and Rodríguez et al. (2016a) on the Upper Cretaceous of the MMVB and Tchegliakova and Pérez (1995) in the Central Eastern Cordillera; resume all the published works on Cretaceous planktonic foraminifera of Colombia. An important contribution is the one of Tchegliakova and Pérez (1995) where the authors recognize for the first time the Coniacian *Dicarinella concavata* Zone. Most micropaleontological studies in the La Luna Formation are available within the literature of Maracaibo Basin (Venezuela). For instance, Boesi et al. (1988) examined nannofossils and foraminifera in surface sections of the southwestern part of the Maracaibo Basin. Davis (1995) examined the planktonic foraminifera from the Alpuf-6 well core in northwestern Maracaibo Basin, and de Romero et al. (2003) developed calcareous nannofossils zonation correlated with foraminifera and stable isotopes analysis for the La Luna Formation in the Maracaibo Basin. For the La Luna Formation in Colombia, although several foraminiferal, dinocysts and calcareous nannofossils biostratigraphical studies have been carried out recently published results correspond to short abstracts in congresses (Navarrete-Parra et al. 2016a, b, c). There are not descriptions of MMVB or Colombian Cretaceous Planktonic Foraminifera, probably due to the lithological characteristics of these units. Late Aptian to Campanian sedimentites are hard calcareous and recrystallized carbonates and have been very poorly and sporadically explored. Most biostratigraphic works were taken for petroleum private industry and due to the hardness and recrystallization of limestone and carbonate biostratigraphic analysis in the La Luna Formation have been improved through thin section analysis.

2 Materials and Methods

Forty-seven micropaleontological samples of La Luna Formation and six of the Umir Formation from Chuira-2ST well (N: 1′394.42504 m and E: 1′058.71599 m Magna Sirgas, Bogota origin) in the middle Magdalena Valley, northern Colombia were studied. The sampled interval (310 m thick) from the Luna Formation consists of massive dark grayish limestones (biomicrites and biosparites) with very rare laminated fine black calcareous mudstone. Sub-mature and highly mature glauconitic grains were observed at the top of the formation. The Umir Formation yields gray siliceous mudstones, calcareous mudstones, and discrete sandstone lamina interlayer. Mature reworked glauconitic grains, from the upper La Luna Formation, were observed in the lower levels. Sediment samples were processed using standard micropaleontological methods. The picking, although attentive on foraminifers, reported also other fossil occurrences as ostracods, echinoids, mollusks, radiolarians, and conspicuous minerals such as pyrite, glauconite, and phosphates, among others. Approximately, 300 foraminiferal tests were picked from the >63 μm fraction and identified under the stereomicroscope, while representative specimens were examined in detail under scanning electron microscope and microphotographs are included. The foraminiferal taxonomy follows classic Cretaceous papers (e.g., Gandolfi 1955; Caron 1985; Bolli 1966; Sliter 1989). The age was sharpened from correlation with surface or reference sections with independent age control, mostly planktonic foraminifers and isotopes. Consequently, our foremost control for the La Luna and Umir Formations is from strata types, other surface sections and multiples core samples. For this paper, we utilized especially the results from well-site biostratigraphy (Chuira-2 and Chuira-2ST), Colon-2 and Colon-3 core samples, and Aguablanca, El Salto and Cuesta El Diablo outcrop sections (Navarrete et al. 2015). These reference sites are located at northern MMVB, Colombia. The proposed zones are calibrated to time scale using 25 absolute dates in those sections and cores, and correlated to palynomorphs (mainly marine dinocysts) and calcareous nannofossils. As a result, foraminiferal biostratigraphy has been integrated with Palynostratigraphy and Calcareous nannofossils biostratigraphy to suggest a geological column within the temporal framework. This column might be helpful in further studies from La Luna Formation in the MMVB and the adjacent Rancheria Basin (northeastern Colombia) and probably in equivalent units across Colombia (e.g., Villeta Group in the Upper Magdalena Valley, “Villeta informal group”) in Putumayo Basin, Chipaque in Cordillera Oriental, and Gacheta in Llanos Basin, northern South America sub-Andean basins, Napo Group in Equator and Chonta Formation in Peru, as cited by Mello et al. (1995). For effects of calibration age, we adopted the Gradstein et al. (2004) and Cohen et al. (2013) timescales.

3 The Data Set in Chuira-2 ST and Biostratigraphy

As it has been evident among micropaleontologist, foraminifera species from one basin to another present stratigraphic range differences and mostly range differences occur regionally, a foraminifer’s species is infrequently synchronous worldwide. The standard planktonic foraminifer’s zonal scheme of Caron (1985) was followed with

modifications in the ranges of foraminifer's genera and species from Premoli-Silva and Sliter (1999) and Patterson et al. (2004), together with unpublished absolute dating and stratigraphic distribution of selected genera and species in the MMVB. In this paper, we use the stratigraphic ranges of Late Cretaceous planktonic foraminifera (Table 1) (Paleosedes E.U 2008 to 2016). Stratigraphic ranges are given as first appearance (FA) and last appearance (LA) in mega-annum age (Ma) for each taxon.

In the 1485 ft studied, seven calcareous nannofossil zones (UC-6 a UC-12) (Pérez Panera et al., this volume) and seven dinocysts zones (UKP-03 to UKP-7 and UKP-8 to UKP-10) range from Early Turonian to Early Campanian. La Luna Formation and lower part of Umir Formation (Navarrete-Parra et al. 2015, 2016a, b, c) were also identified and here used for correlation with foraminifera data (Fig. 4).

In the scarce 310-m-thick section of the La Luna Formation, six Globotruncanids zones were identified: *Whiteinella archaeocretacea* (53–54 m), *Helvetoglobotruncana helvetica* (84–85 m), *Marginotruncana sigali* (39–40 m), *Dicarinella primitiva* (67–68 m), *Dicarinella concavata* (22–23 m), *Dicarinella concavata–Costellagerina* (*Rugoglobigerina*) *pilula* (24–25 m) and *Dicarinella asymetrica* (earliest part) (7–8 m). According to that, sedimentation of the Late Cretaceous pelagic limestones started in the Turonian and last until the earliest Late Santonian. In the 54-m-thick section corresponding to the lower part of the Umir Formation, *Globotruncanita elevata* (latest part) (4–5 m), *Globotruncana ventricosa* (4–5 m), and *Radotruncana* (*Globotruncanita*) *calcarata* (44 m) zones were recognized.

Pelagic sediments from the succession of carbonates of Turonian to late Santonian age and the overlying siliciclastic succession of early late Campanian age are separated by a hiatus which includes the latest Santonian and earliest Campanian. This hiatus involves the latest part of *Dicarinella asymetrica* and earliest part of *Globotruncanita elevata* planktonic foraminifer's zones, as well as the calcareous nannofossil zones UC-13 and UC-14 and dinocyst zones UKP-9 and UKP-10.

Planktonic foraminifera, calcareous nannoplankton and palynomorphs mostly dinocysts, suggest an Early Turonian to earliest Late Santonian age for the studied deposits of the La Luna Formation in the Chuira 2ST well (7880–8130 to 8440–9365 ft) and a latest Early Campanian age for the overlaying deposits of the lower Umir Formation (7700–7915 ft). The planktonic foraminifera record allows differentiation of five intervals in the studied intervals of the Chuira-2ST well. They are here characterized in chronostratigraphic order (Fig. 5a–j).

Interval 9365–8660 ft; ≈210 m thick (17 samples) is a very hard biomicrite and spate-micrite, bearing abundant calcispheres (recrystallized planktonic foraminifer fragments and pithonellids) and high planktonic foraminifera species richness. Minor components are a few small-sized benthonic foraminifera (mainly recrystallized buliminids) and bad preserved radiolarians. Moderate preserved planktonic foraminifera are very abundant. They are commonly silicified and/or infilled with silica and/or recrystallized and always infilled with kerogen and/or black amorphous organic matter. The planktonic foraminiferal fauna is characterized by very abundant small hedbergellids, whiteinellids and heterohelicids abundant marginotruncanids, common dicarinellids, and rare helvetoglobotruncanids, *Globigerinelloides* and *Schackoina*. Most relevant species are *Planoheterohelix* (*Heterohelix*) *reussi* (very abundant), *Muricohedbergella* (*Hedbergella*) *delrioensis* and *M.* (*H.*) *planispira* (common),

Table 1. Stratigraphic ranges in mega-annum age (Ma) for each selected Late Cretaceous planktonic foraminifera species in the Northern Middle Magdalena Valley Basin and the Luna and Umir Formations (after PALEOSEDES 2016)

Late Cretaceous planktonic foraminifera species	Range (FA-LA) (Ma)
Archaeoglobigerina blowi Pessagno 1967	(86.3–65)
Archaeoglobigerina bosquensis Pessagno 1967	(87–83.6)
Archaeoglobigerina cretacea (d'Orbigny 1840) Pessagno 1967	(89.8–69.9)
Contusotruncana fornicata (Plummer 1921) Korchagin 1982	(85.2–67.4)
Costellagerina (*Rugoglobigerina*) *pilula* (Belford 1960)	(86.3–78)
Dicarinella canaliculata (Reuss 1854) Porthault 1970	(93–84.7)
Dicarinella concavata (Brötzen 1934) Porthault 1970	(87–83.9)
Dicarinella imbricata (Mornod 1949) Porthault 1970	(92.7–86.3)
Dicarinella primitiva (Dalbìez 1955) Porthault 1970	(89.8–85.6)
Falsotruncana maslakovae Caron 1981	(92.8–89.2)
Globigerinelloides asper (*asperus*) (Ehrenberg 1854) Pessagno 1967	(92.8)
Globigerinelloides ultramicrus (*ultramicra*) (Subbotina 1949) Caron 1985	(101.6–70.4)
Globotruncana ventricosa White 1928	(79.4–68.4)
Globotruncanella havanensis (Voorwijk 1937) Reiss 1957	(73–66)
Globotruncanita elevata (Brötzen 1934) Reiss 1957	(83.7–73.6)
Helvetoglobotruncana helvetica (Bolli 1945) Reiss 1957	(93–92.5)
Helvetoglobotruncana praehelvetica (Trujillo 1960) Reiss 1957	(93.9–90.7)
Marginotruncana coronata (Bolli 1945) Hofker 1956	(92.52–82.1)
Marginotruncana marginata (Reuss 1845) Bolli, Loeblich and Tappan 1957	(90.3–83.5)
Marginotruncana pseudolinneiana Pessagno 1967	(90.7–83.6)
Marginotruncana renzi (Gandolfi 1942) Hofker 1956	(93–85)
Marginotruncana sigali(Reichel 1950) Hofker 1956	(92.7–85.6)
Muricohedbergella (*Hedbergella*) *simplex* (Morrow 1934) Huber and Leckie 2011	(110.3–89.8)

(*continued*)

Table 1. (*continued*)

Late Cretaceous planktonic foraminifera species	Range (FA-LA) (Ma)
Muricohedbergella (*Hedbergella*) *delrioensis* (Carsey 1926) Huber and Leckie 2011	(117.5–85.4)
Muricohedbergella (*Hedbergella*) *holmdelensis* (Olsson 1964) Huber and Leckie 2011	(FA 89.8)
Muricohedbergella (*Hedbergella*) *planispira* (Tappan 1940) Huber and Leckie 2011	(118.1–89.8)
Planoheterohelix (*Heterohelix*) *moremani* (Cushman 1938) Georgescu and Huber 2009	(101.6–92.7)
Planoheterohelix (*Heterohelix*) *reussi* (Cushman 1938) Georgescu and Huber 2009	(91.8–83.6)
Planoheterohelix (*Heterohelix*) *globulosa* (Ehrenberg 1840) Georgescu and Huber 2009	(83.5–69.3)
Planoheterohelix (*Heterohelix*) *striata* (Ehrenberg 1840) Georgescu and Huber 2009	(80.3–66)
Radotruncana (*Globotruncanita*) *calcarata* (Cushman 1927) El-Naggar 1971	(75.4–72.1)
Rugoglobigerina rugosa (Plummer 1926) Brönnimann 1952	(80.3–65)
Whiteinella archaeocretacea Pessagno 1967	(93.9–86.3)
Whiteinella baltica Douglas and Rankin 1969	(94.7–85.2)
Whiteinella inornata (Bolli 1957) Pessagno 1967	(92.7–84.7)
Whiteinella paradubia (Sigal 1952) Pessagno 1967	(94.5–89.8/88.5)

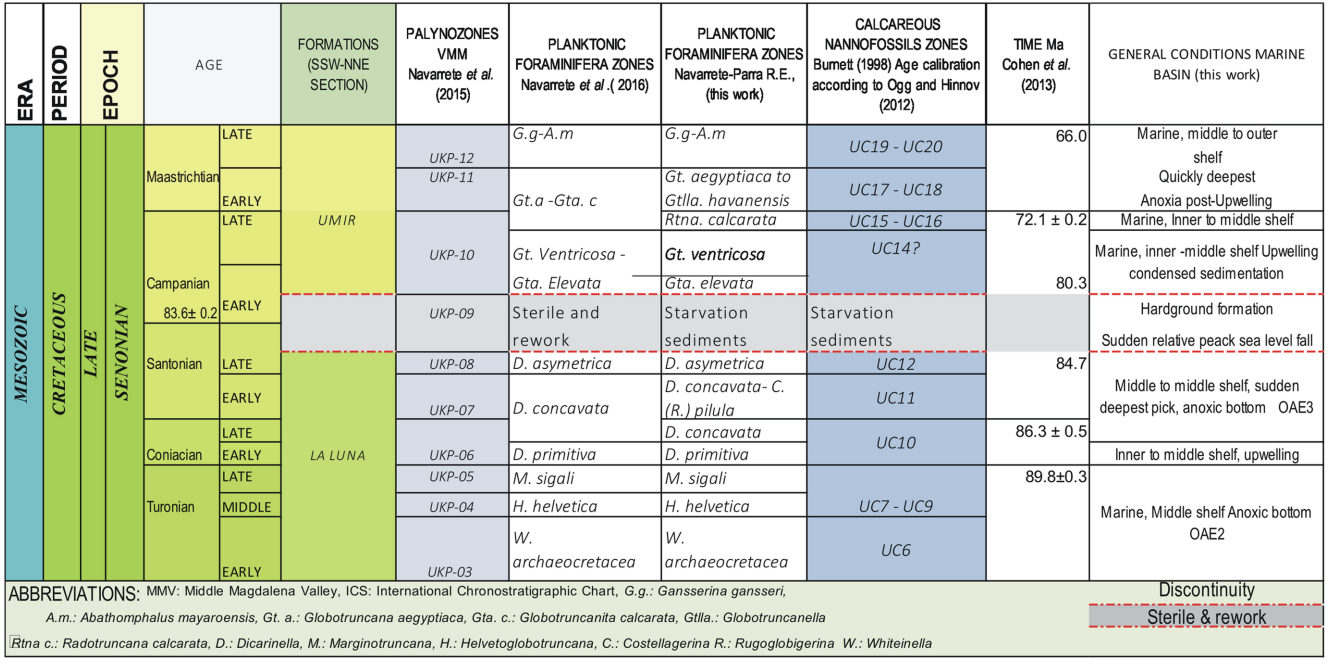

Fig. 4. Summary planktonic foraminifera zones versus palynomorphs (mainly dinocysts) and calcareous nannofossils in Chuira-2ST, Middle Magdalena Valley (northern Colombia)

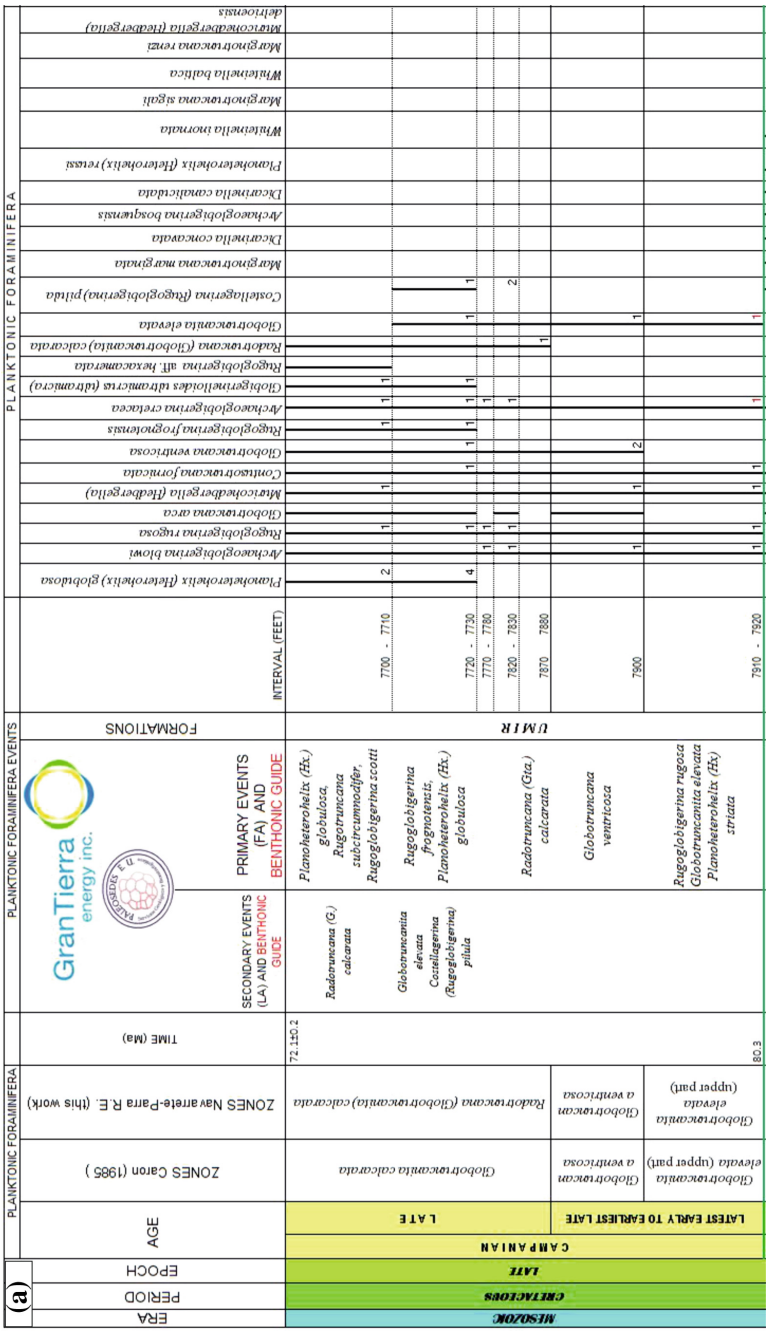

Fig. 5. a–j Range chart planktonic foraminifers from Chuira-2ST well in the northern Middle Magdalena Valley Basin (Colombia)

Fig. 5. (*continued*)

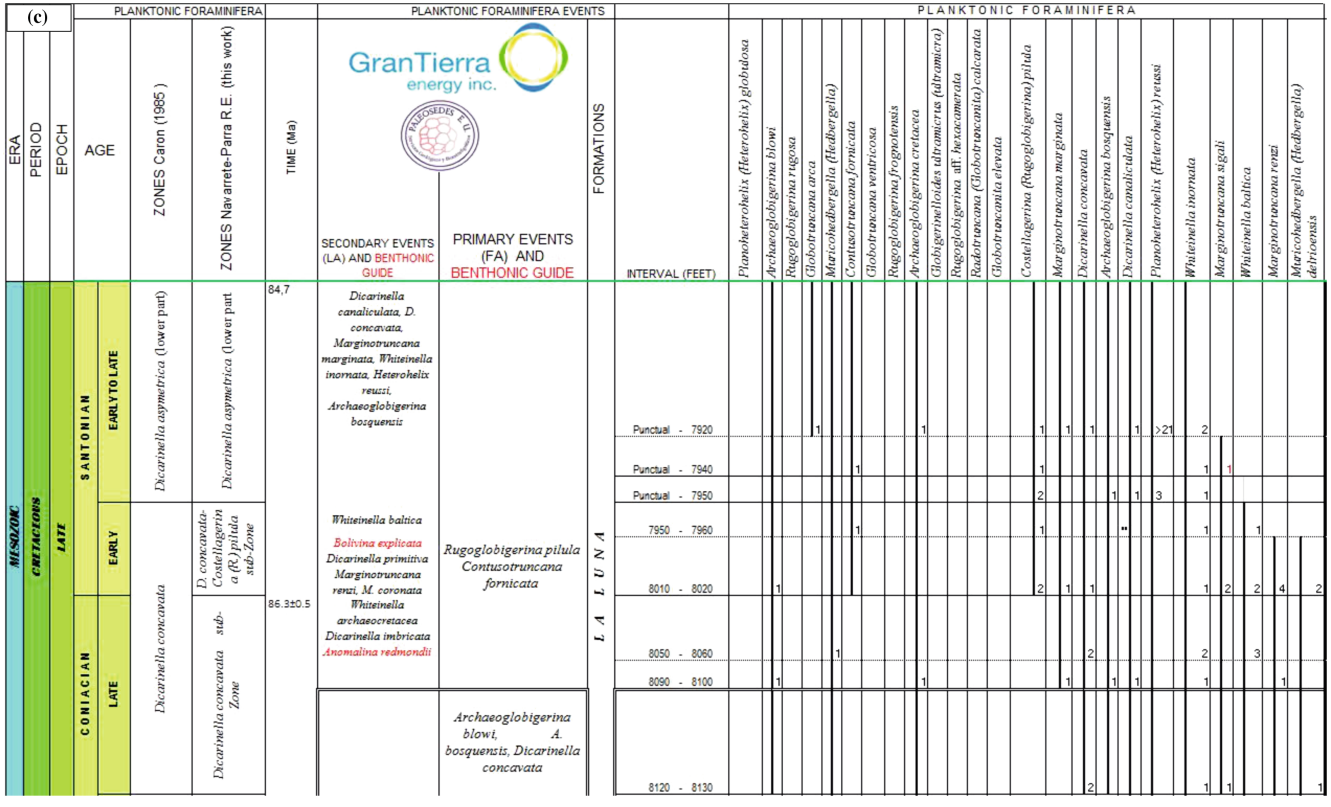

Fig. 5. (*continued*)

(d)
ERA
PERIOD
EPOCH
AGE
MESOZOIC
CRETACEOUS
LATE
SANTONIAN
CONIACIAN
EARLY TO LATE
EARLY
LATE
PLANKTONIC FORAMINIFERA
ZONES Caron (1985)
Dicarinella asymetrica (lower part)
Dicarinella concavata
ZONES Navarrete-Parra R.E. (this work)
Dicarinella asymetrica (lower part
D. concavata-Costellagerin a (R.) pilula sub-Zone
Dicarinella concavata sub-Zone
TIME (Ma)
84.7
86.3±0.5
PLANKTONIC FORAMINIFERA EVENTS
SECONDARY EVENTS (LA) AND BENTHONIC GUIDE
Dicarinella canaliculata, D. concavata, Marginotruncana marginata, Whiteinella inornata, Heterohelix reussi, Archaeoglobigerina bosquensis
Whiteinella baltica
Bolivina explicata
Dicarinella primitiva
Marginotruncana renzi, M. coronata
Whiteinella archaeocretacea
Dicarinella imbricata
Anomalina redmondii
PRIMARY EVENTS (FA) AND BENTHONIC GUIDE
Rugoglobigerina pilula
Contusotruncana fornicata
Archaeoglobigerina blowi, A. bosquensis, Dicarinella concavata
GranTierra energy inc.
PALEOSOL S.L.U.
LAGUNA
FORMATIONS
INTERVAL (FEET)
Punctual - 7920
Punctual - 7940
Punctual - 7950
7950 - 7960
8010 - 8020
8050 - 8060
8090 - 8100
8120 - 8130
PLANKTONIC FORAMINIFERA
Dicarinella primitiva
Marginotruncana coronata
Dicarinella imbricata
Whiteinella archaeocretacea
Racemiguembelina sp.
Pseudotextularia varians
Dicarinella hagni
Globigerinelloides sp.
Marginotruncana sp.
Muricohedbergella (Hedbergella) planispira
Clavihedbergella (Hedbergella) simplex
Marginotruncana pseudolinneiana
Ralstoniella maslakovae
Hedbergella (Hedbergella) luterbacheri
Hedbergella (Hedbergella) planispira
Globotruncanella havanensis
Globotruncanella petaloidea
Globotruncanella minuta
Globotruncanella pschadae
Globotruncanella sp.
Globotruncana arca
Globotruncana bulloides
Globotruncana elevata
Globotruncana linneiana
Globotruncana rosetta
Globotruncana ventricosa
Globotruncana sp.
Globotruncana aegyptiaca
Globotruncana calcarata
Globotruncana carinata
Globotruncana falsostuarti
Globotruncana gansseri
Globotruncana hilli
Globotruncana lapparenti
Globotruncana mariei
Globotruncana orientalis
Globotruncana stuarti
Globotruncana tricarinata
Globotruncana sp.
Globotruncanita angulata
Globotruncanita conica
Globotruncanita elevata
Globotruncanita pettersi
Globotruncanita stuartiformis
Globotruncanita stuarti
Globotruncanita sp.
Contusotruncana contusa
Contusotruncana fornicata
Contusotruncana patelliformis
Contusotruncana plicata
Contusotruncana walfischensis
Contusotruncana sp.
Rugoglobigerina pilula
Rugoglobigerina rugosa
Rugoglobigerina sp.
Archaeoglobigerina blowi
Archaeoglobigerina bosquensis
Archaeoglobigerina cretacea
Archaeoglobigerina sp.
Planoglobulina acervulinoides
Planoglobulina brazoensis
Planoglobulina carseyae
Planoglobulina glabrata
Planoglobulina multicamerata
Planoglobulina sp.
Pseudoguembelina costulata
Pseudoguembelina excolata
Pseudoguembelina hariaensis
Pseudoguembelina kempensis
Pseudoguembelina palpebra
Pseudoguembelina sp.
Racemiguembelina fructicosa
Racemiguembelina powelli
Racemiguembelina sp.
Globigerinelloides aspera
Globigerinelloides bentonensis
Globigerinelloides caseyi
Globigerinelloides sp.
Heterohelix globulosa
Heterohelix moremani
Heterohelix reussi
Heterohelix sp.
Pseudotextularia elegans
Pseudotextularia nuttalli
Pseudotextularia varians
Dicarinella hagni
Dicarinella imbricata
Dicarinella primitiva
Marginotruncana coronata
Marginotruncana marginata
Marginotruncana pseudolinneiana
Marginotruncana renzi
Marginotruncana sinuosa
Marginotruncana sp.
Muricohedbergella (Hedbergella) planispira
Clavihedbergella (Hedbergella) simplex

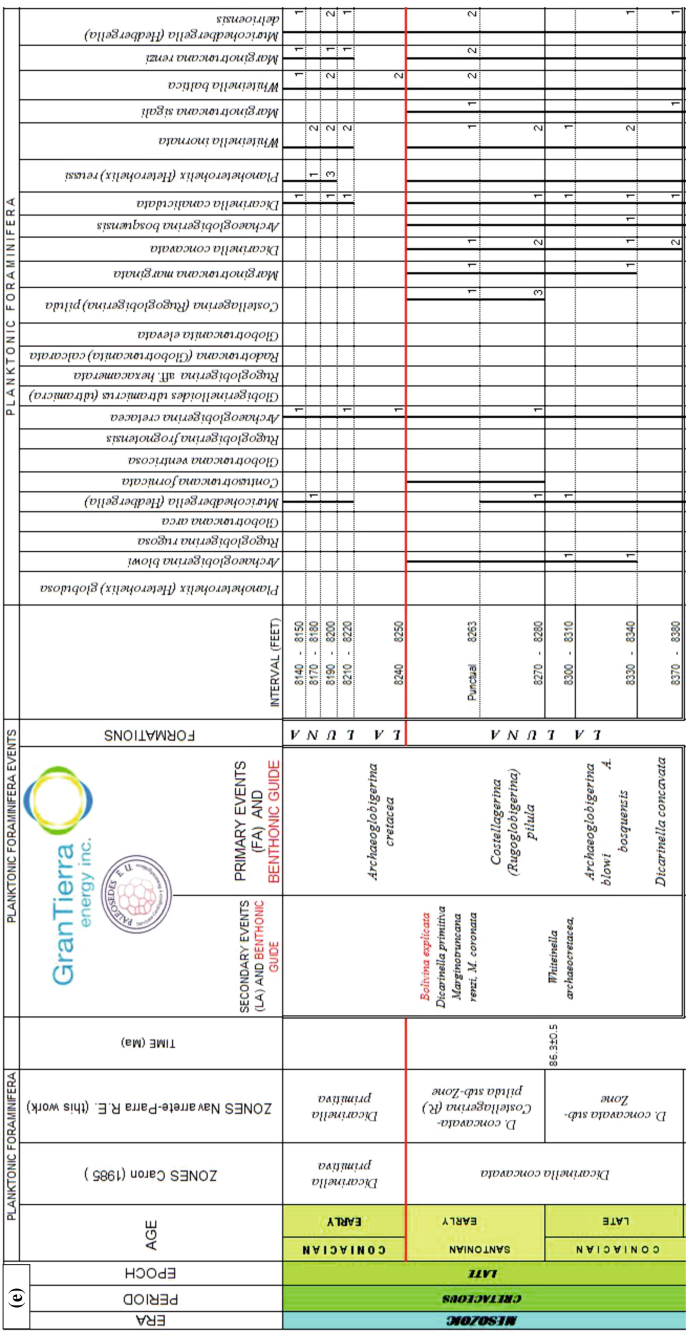

Fig. 5. (*continued*)

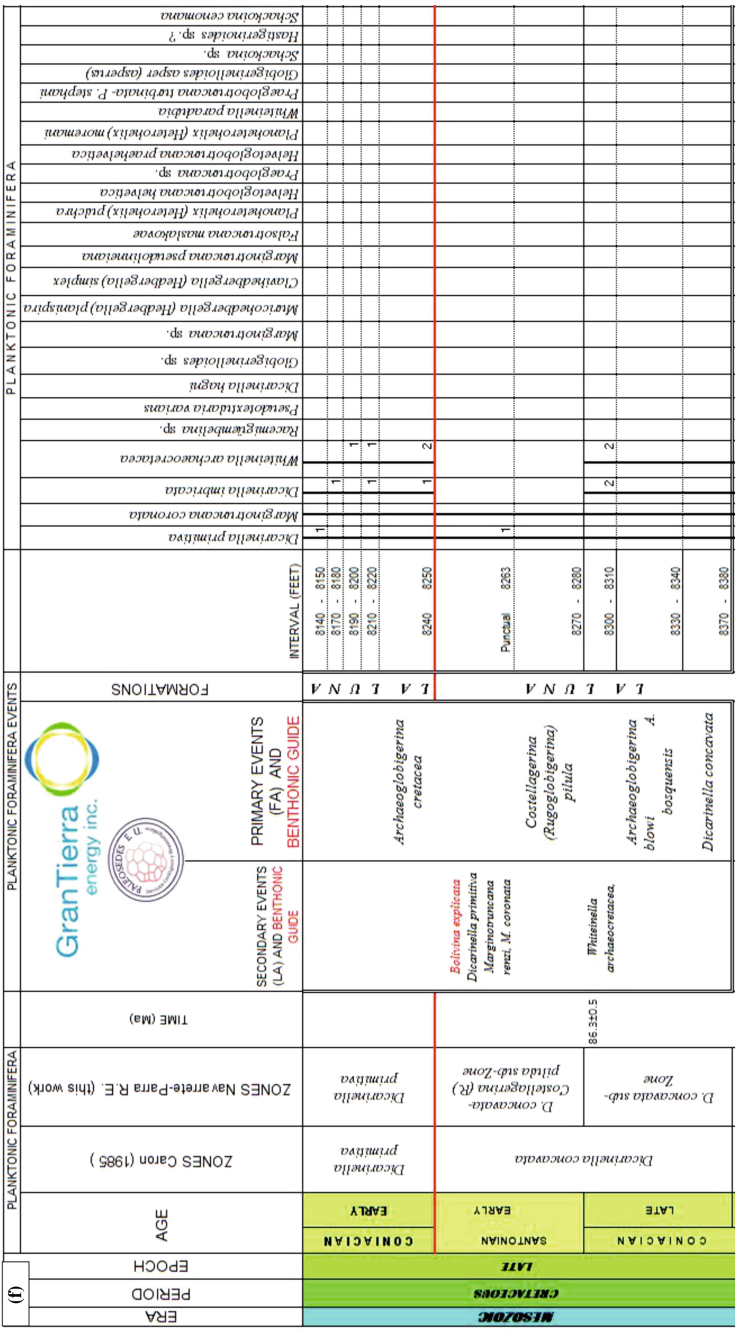

Fig. 5. (*continued*)

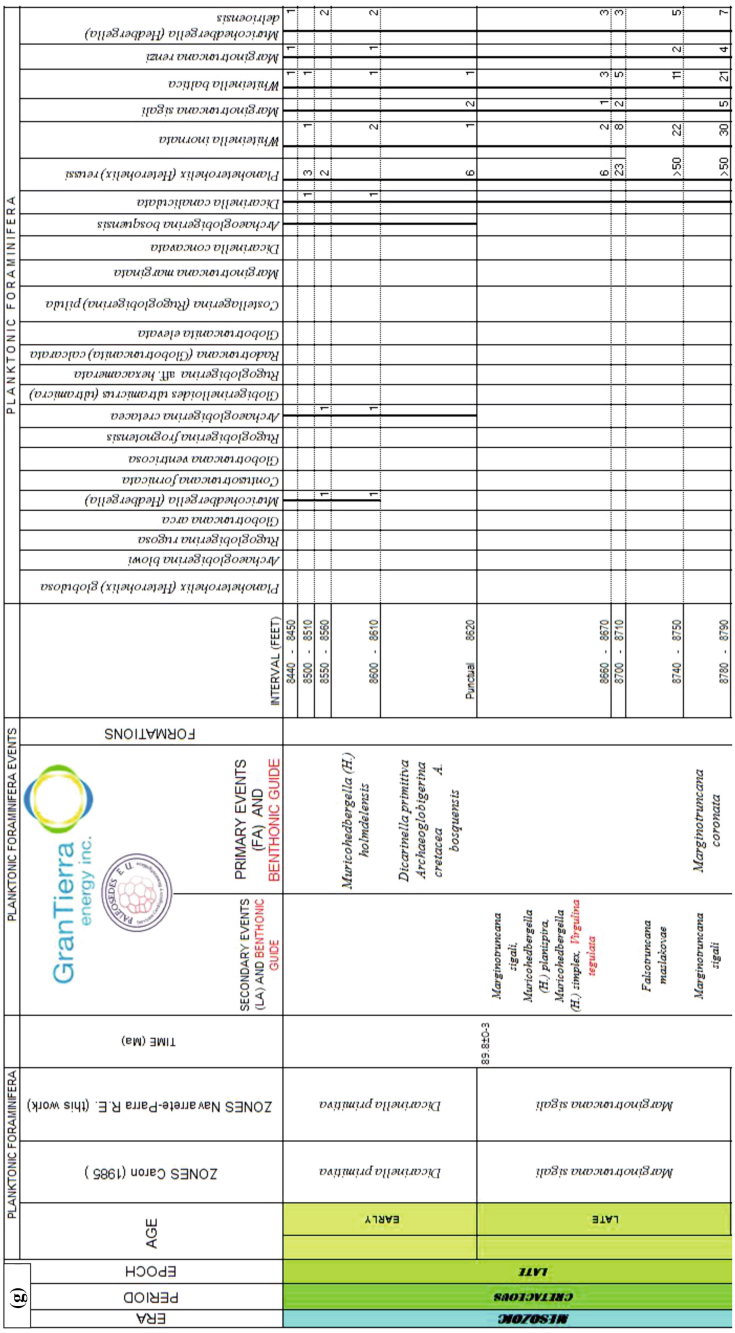

Fig. 5. (*continued*)

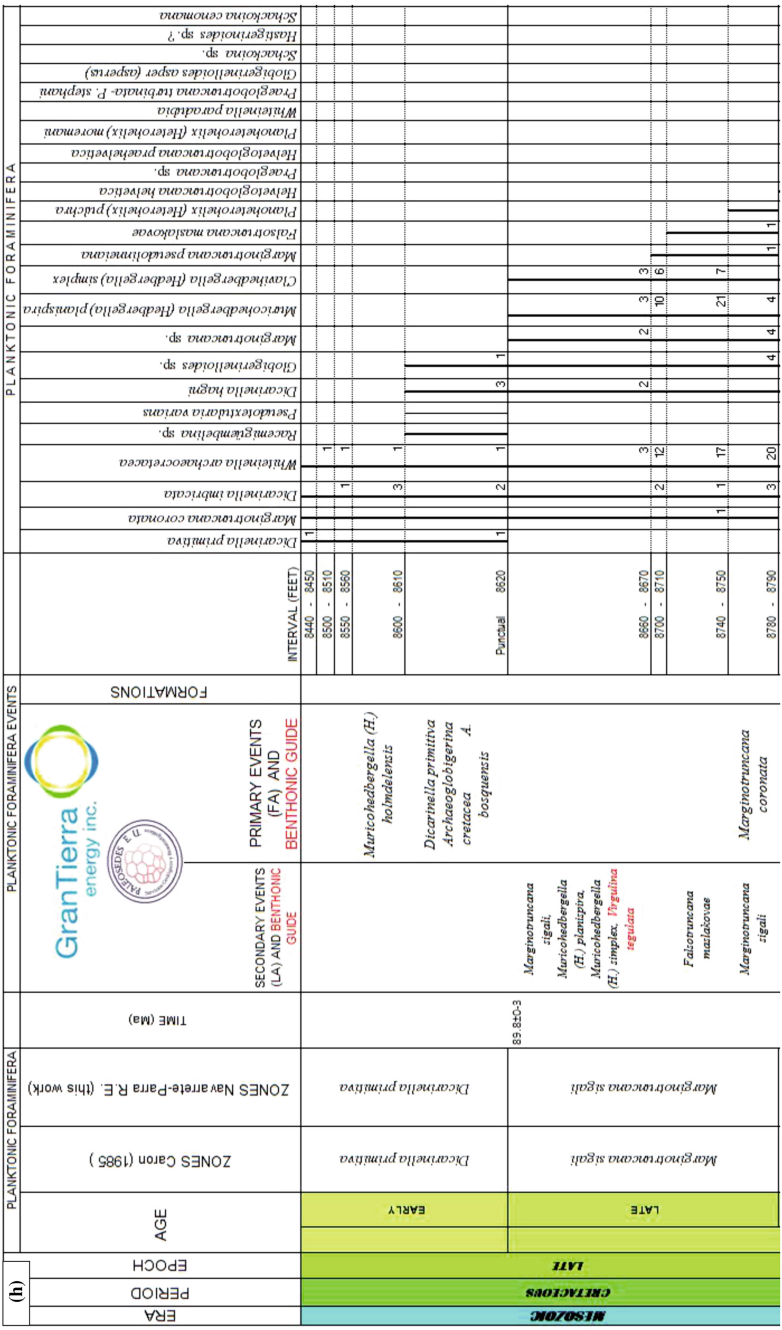

Fig. 5. (*continued*)

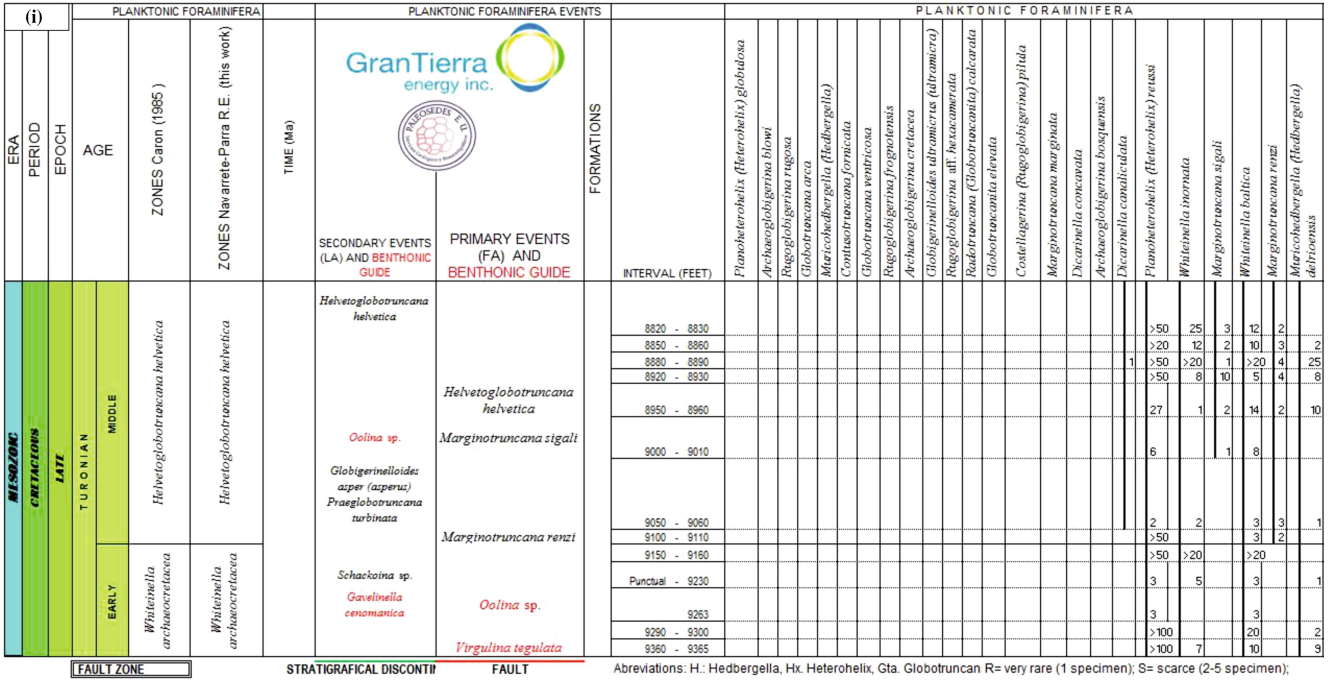

Fig. 5. (*continued*)

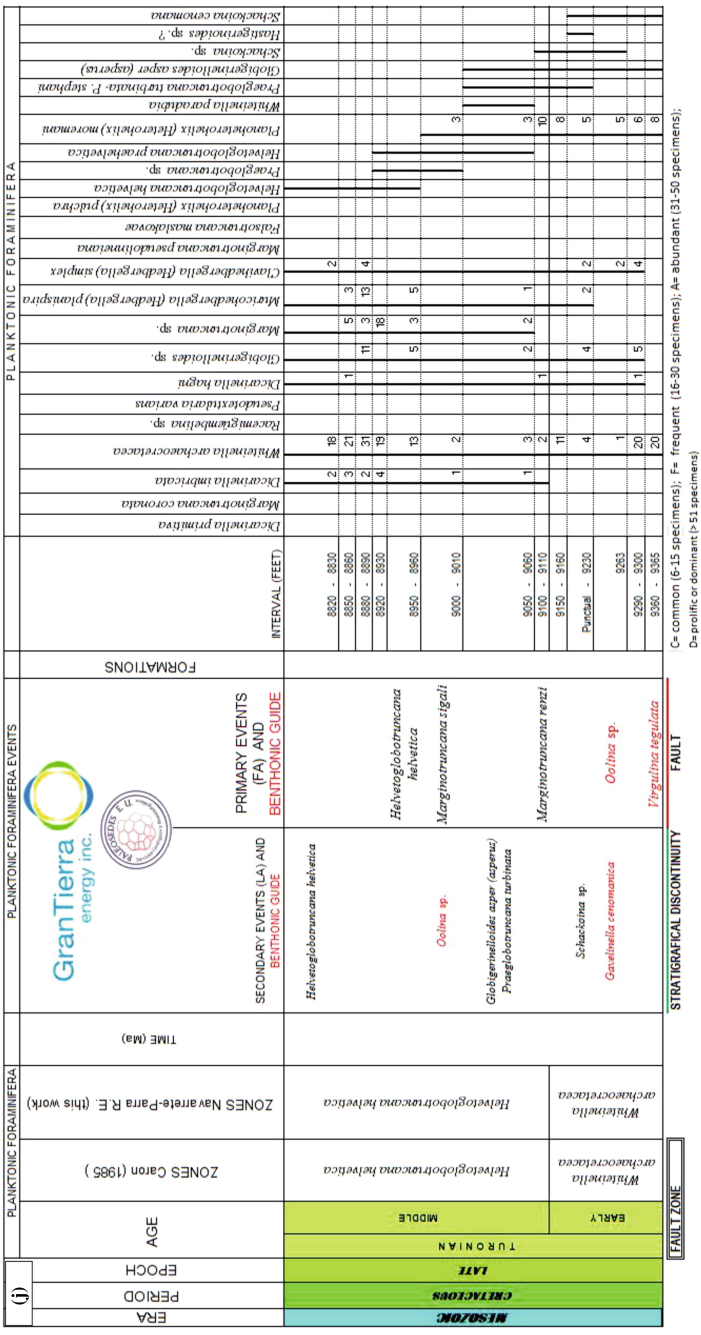

Fig. 5. (*continued*)

Clavihedbergella (*Hedbergella*) *simplex* (scarce), *Whiteinella archaeocretacea* (very abundant), *W. inornata* and *W. baltica* (abundant) and *Marginotruncana sigali*, *M. renzi*, and *Dicarinella canaliculata* (common). Other identified species are *Dicarinella imbricata* (few) *Marginotruncana* sp. (few), *M. coronata* (few), *M. pseudolinneiana* (rare), *Helvetoglobotruncana helvetica* (scarce), *H. praehelvetica* (rare), *Falsotruncana maslakovae* (rare), and *Planoheterohelix* (*Heterohelix*) *pulchra* and *Praeglobotruncana* sp. (rare), which occur dispersed in the upper part only. The lower interval also yielded rare specimens of *Planoheterohelix* (*Heterohelix*) *moremani* (scarce), *Whiteinella paradubia*, *Globigerinelloides asper* (*asperus*), *Praeglobotruncana turbinata–P. stephani*, *Schackoina* sp., *Hastigerinoides* sp.? and *Schackoina cenomana*.

Intervals 8650–8380 ft; ≈67–68 m thick (5 samples) and 8130–8050 ft; ≈22–23 m thick (3 samples) are moderately hard biomicrite, spate-micrite and scarce and dispersed layers rich in silica and phosphates. The biomicrites yield abundant calcispheres, pithonellids, and planktonic foraminifera and abundant homeomorphic, very small-sized, benthonic foraminifera, mainly small buliminids and rotalids. The planktonic foraminiferal fauna contains abundant median and small-sized archaeoglobigerinids, hedbergellids, and heterohelicids, frequent whiteinellids, common marginotruncanids and dicarinellids and rare *Globigerinelloides*, *Pseudotextularia*, and *Racemigüembelina.* Most characteristic species are *Archaeoglobigerina cretacea* (common), *A. bosquensis* (few), *Dicarinella canaliculata* (few), *Planoheterohelix* (*Heterohelix*) *Heterohelix reussi* (few), *Whiteinella inornata* (few), *Marginotruncana sigali* and *Whiteinella baltica* (rare), *M. renzi*, *Muricohedbergella* (*Hedbergella*) *delrioensis* (rare), *Dicarinella primitiva*, *D. imbricata*, and *W. archaeocretacea* (few). *Archaeoglobigerina blowi* (few), *Dicarinella concavata* (few), *Muricohedbergella* (*Hedbergella*) *holmdelensis* (few) and *Marginotruncana marginata* (rare) only occur in the upper levels (8050–8100 ft). Minor components are rare *Racemigüembelina* sp., *Pseudotextularia varians*, *Dicarinella hagni*, and *Globigerinelloides* sp., which occur only at bottom interval (8620–8650 ft).

The interval 8050–7920 ft; ≈32–33 m thick (5 samples) is a very hard and moderately hard biomicrite and spate-micrite. Discrete mixed (calcareous-terrigenous) rocks are interbedded, and they yield phosphatized fish remains and pyrite. The top of this interval has mature glauconite. The biomicrite is rich in robust planktonic and benthonic foraminifera, moderately to poorly preserved and abundant calcispheres and pithonellids. Minor components are few small-sized ooliths and pellets. Planktonic foraminifera are commonly broken and/or infilled with silica, glauconite, kerogen, or amorphous organic matter. Only minor proportion is recrystallized. The planktonic foraminiferal fauna contains abundant heterohelicids, low abundance of hedbergellids, whiteinellids, dicarinellids, and rugoglobigerinids, and rare globotruncanids. The identified species are *Planoheterohelix* (*Heterohelix*) *reussi* (abundant), *Archaeoglobigerina bosquensis*, *Costellagerina* (*Rugoglobigerina*) *pilula*, *Dicarinella canaliculata*, and *Whiteinella inornata* (common); *Archaeoglobigerina blowi*, *A. cretacea*, *Contusotruncana fornicata*, *Dicarinella concavata*, *Muricohedbergella* (*Hedbergella*) *holmdelensis*, *Marginotruncana marginata* (rare). *Globotruncana arca* (rare) occurs in the upper part of the interval (7920 ft). Rare specimens of *Dicarinella primitiva*, *Muricohedbergella* (*Hedbergella*) *delrioensis*, *Marginotruncana coronata*, *M. renzi*, and *Whiteinella baltica* occurs in the lower part of the interval (8010–8050 ft).

Interval 7920–7700 ft; ≈54–55 m thick (6 samples) is a monotonous soft gray mudstone and dark greenish gray shale with subordinated fine sandstone interbedded. The lower strata had few calcareous content, abundant blackish organic matter and carbonaceous particles. Disseminated pyrite is frequent, and toward the base, highly mature reworked glauconitic grains are abundant. The shale and mudstone are poor in planktonic foraminifera, but moderately to poorly preserved benthonic are abundant. There are not calcispheres, which are very abundant in the oldest intervals. Scarce components are few small-sized pellets and bioturbation. Moderately preserved planktonic foraminifera are commonly broken and/or lack the shell. Inner molds and crusts are always infilled with glauconite or kerogen and amorphous organic matter, and only a minor proportion of foraminifera is recrystallized. Specimens with regular preservation are scarce. The planktonic foraminiferal fauna contains rare heterohelicids, hedbergellids, rugoglobigerinids, and globotruncanids. The identified species are *Radotruncana* (*Globotruncanita*) *calcarata*, *Globotruncanita conica*, *G. elevata*, *Globotruncana arca*, *G. aegyptiaca*, *G. ventricosa*, *Contusotruncana fornicata*, *Globotruncanella citae*, *Rugoglobigerina rugosa*, *R. scotti*, *R. frognotensis*, *R.* aff. *hexacamerata*, *Costellagerina* (*Rugoglobigerina*) *pilula*, *Rugotruncana subcircumnodifer*, *Archaeoglobigerina blowi*, *A. cretacea*, *Globigerinelloides ultramicrus*, *Pseudogüembelina excolata*, *Planoheterohelix* (*Heterohelix*) *globulosa*, and *Muricohedbergella* (*Hedbergella*) *holmdelensis*.

4 Foraminiferal Zonation for the La Luna Formation (Turonian-Santonian) and the Overlying Lower Umir Formation (Campanian)

We studied the foraminifera and palynomorphs (mainly marine dinocysts) from six localities in the MMVB. Upper Cretaceous was recognized in stratigraphical profiles including the sections of Aguablanca and El Salto streams Cuesta El Diablo section, Chuira-1, Chuia-2, and Chuira-2ST wells. Chuira-2ST well spans great part of the stratigraphy of the La Luna Formation, and calcareous nannofossils were also studied in well-site (Pérez Panera et al., this volume). We also include absolute dates (Paleosedes unpublished Reports 2010; 2015 for Petrocaribe, Petronorte and Petronorte-UTMidas) of the most significant taxa. The zones were compared with the calcareous nannofossils (Pérez Panera et al., this volume) and dinocysts results for calibration purposes (from Chuira-2, Chuira-2ST) well-site integrated biostratigraphy and Navarrete-Parra et al. (2015). The outcrops and core samples were used to estimate error by caving occurred in normal drilling processes. Private Biostratigraphical Program (Paleosedes 2015) was used to improve the framework. Chuira-2ST completed a total depth 9365 ft and Cenomanian stage was not drilled. The constrained biostratigraphy spans from the Turonian to Early Campanian stage. The selected taxa for the proposed biozonation have wide-world distribution, are relatively common, and were recognized in each analyzed profile (Figs. 6a, b and 7a, b) and microphotographs are included. Keeled foraminifera were relatively scarce, whereas unkeeled were very abundant, as it commonly occurs in epicontinental seas. When transcontinental zonal

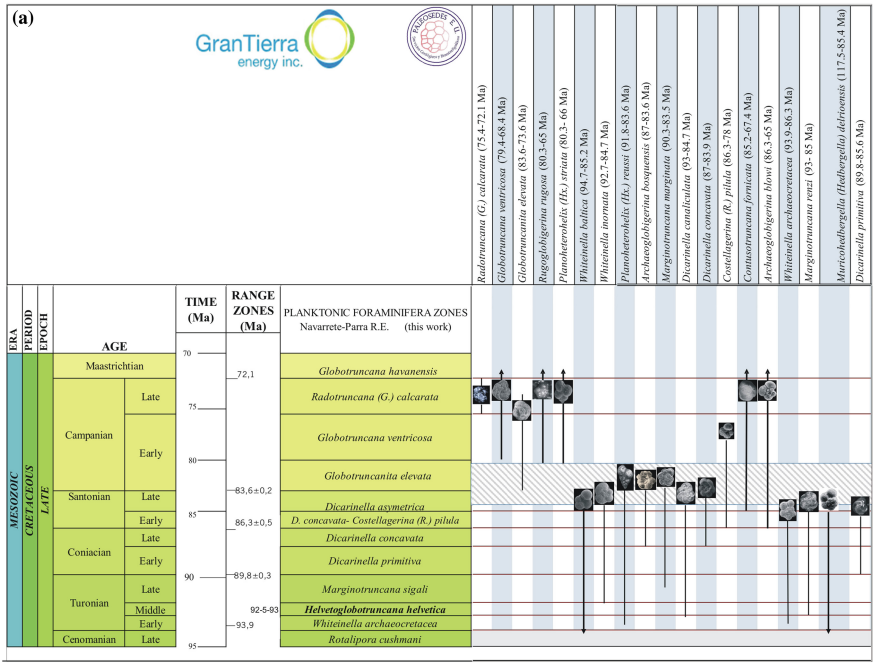

Fig. 6. a, **b** Stratigraphic ranges, in mega-annum age (Ma) for selected Late Cretaceous planktonic foraminifera species in the Northern Middle Magdalena Valley Basin and the Luna and Umir Formations

index keeled foraminifers were absent, they were replaced by other species with the same zonal value. Early Turonian and Early Coniacian zones were additionally constrained by means of ammonites from Aguablanca and El Salto sections according to Etayo-Serna (2010).

4.1 Turonian

High richness planktonic foraminiferal assemblages characterize the Turonian stage. Three foraminiferal zones Caron (1985) were identified: (1) *Whiteinella archaeocretacea*, (2) *Helvetoglobotruncana helvetica*, and (3) *Marginotruncana sigali* zones. The Turonian comprises the coeval zones UKP-03–UKP-05, *Florentina mantellii* interval dinocysts zones, of Turonian age (93.9–89.8 ± 0.3 Ma) (Navarrete-Parra et al. 2015), and the calcareous nannofossil UC-6 to UC-9 zones of Burnett (1998) and (Pérez Panera et al., this volume). These Turonian zones were also identified in the Aguablanca and El Salto creeks and Cuesta El Diablo section.

***Whiteinella archaeocretacea* Partial Range Zone**. This zone was originally defined as the interval with *Whiteinella archaeocretacea*, from the last appearance (LA) of *Rotalipora cushmani* to first appearance (FA) of *Helvetoglobotruncana helvetica.* The age of this zone is Early Turonian (Bolli 1966; Caron 1985). According to Gradstein et al. (2004) and Cohen et al. (2013), it spans from 93.9 to 93 Ma.

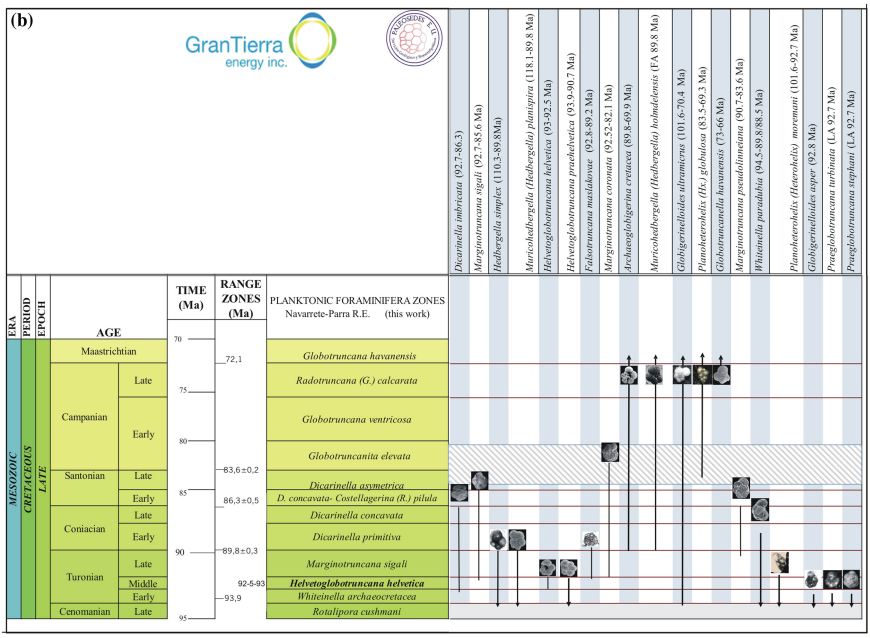

Fig. 6. (*continued*)

This partial range zone was identified in Chuira-2ST well (interval 9365–9150 ft), in Aguablanca and El Salto creeks and Cuesta El Diablo section. The bottom interval in Chuira-2ST well (9365–9150 ft) probably corresponds to the upper part of *Whiteinella archaeocretacea* Zone. This interval (9365 ft) yields abundant *Whiteinella inornata* (FA 93.1 Ma), *W. baltica*, and *Planoheterohelix* (*Heterohelix*) *reussi* (93.1–83.6 Ma), common *Whiteinella archaeocretacea* (93.9–86.3 Ma) and *Planoheterohelix* (*Heterohelix*) *moremani* (101.6–92.7 Ma). These suggest an age not older than 93.1 Ma, and it could be said that *W. archaeocretacea* Zone, whose duration is very brief (0.6 Ma), was reached until the 93.1 Ma, early Middle Turonian. The lower part was probably not reached by the perforation, since *R. cushmani* was not found. *Marginotruncana sigali* (92.7–85.6 Ma) and *M. renzi* (93–85 Ma) are present at 9110 ft, with their FAs constrained at 92.7 and 93 Ma, respectively, occur in the upper part of the zone. *Helvetoglobotruncana praehelvetica* occurs at 9060–9050 ft, and *Helvetoglobotruncana helvetica* (93–92.5 Ma) at 8960–8950 ft suggesting a Middle Turonian age. In addition, the dinocyst *Alterbidinium acutulum* (92.9–56 Ma) is present in the interval 9140–9250 ft, which indicates an age no older that early Turonian. Therefore, the early Turonian/Middle Turonian boundary is located at 9140 ft.

The precedent Early Turonian foraminifera were also found in the early part of *Whiteinella archaeocretacea* Zone in Aguablanca and El Salto creeks, accompanied by singular ammonite assemblages. According to Etayo-Serna (2010): ES-243 m sample contains *Benueites mosquerae* (Karsten 1858), *Kamerunoceras* cf. *seitzi* (Riedel 1933) and *Anomia* cf. *papyracea* (Deheé 1924?), and ES-245 m sample contains *Benueites*

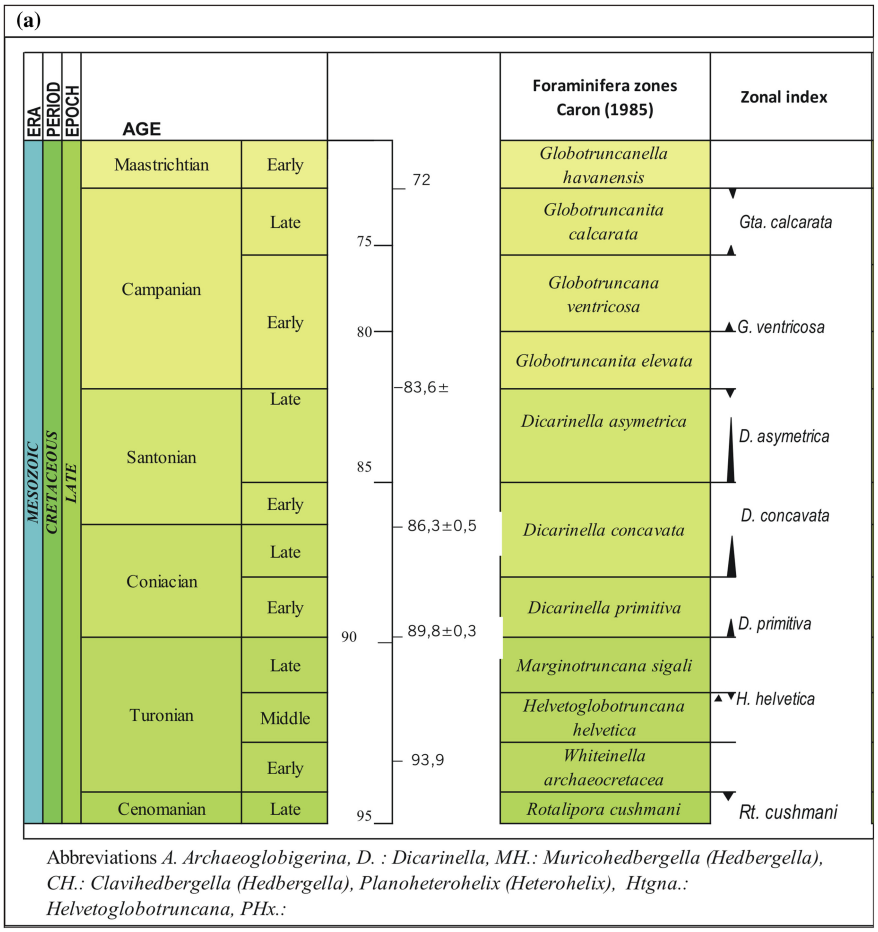

Fig. 7. **a**, **b** Schematic planktonic foraminifera zones (this paper) indicating respective First Appearance Datum (FAD) and Last Appearance Datum (LAD) compared to Caron (1985)

spinosus (Reyment 1954), all taxa from late Early Turonian age. The AB-305 m sample contains *Mammites nodosoides* (Schlueter 1871), from lower Early Turonian age. The ammonites found here confirm an Early Turonian age. The Cuesta El Diablo section ammonites were not found, but foraminifera span a coeval interval with *Whiteinella archaeocretacea* to *Helvetoglobotruncana helvetica* zones.

***Helvetoglobotruncana helvetica* Total Range Zone**. This zone was originally defined as the total range interval of *Helvetoglobotruncana helvetica* and was assigned to the Middle Turonian (Sigal 1955; Caron 1985). According to Gradstein et al. (2004) and Cohen et al. (2013), it spans 93–92.5 Ma. *Helvetoglobotruncana helvetica* Zone is recognized in Chuira-2ST interval 9110–8820 ft. This was also recognized in Aguablanca and El Salto creeks and Cuesta El Diablo section. *H. helvetica* was found in the 8960–8820 ft interval, but some taxa with coeval or close FA of occurs in lower levels.

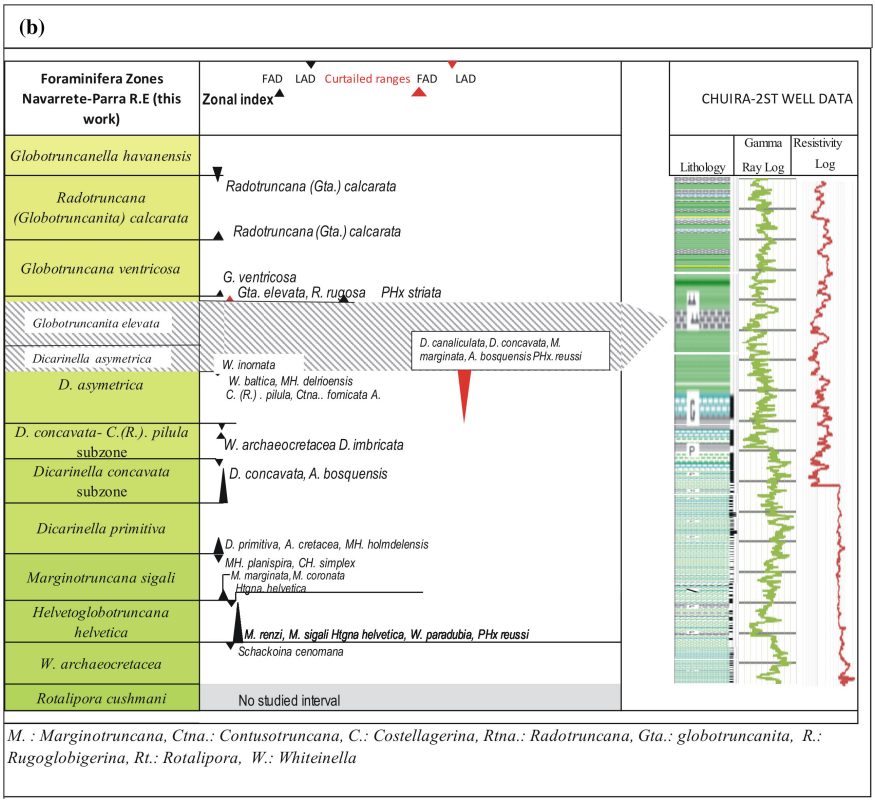

Fig. 7. (*continued*)

Those are *Helvetoglobotruncana praehelvetica* (93–92.5 Ma), *Marginotruncana renzi* (93–85 Ma), *M. sigali* (92.7–85.6 Ma), *Planoheterohelix* (*Heterohelix*) *moremani* (101.6–92.7 Ma), *Praeglobotruncana turbinata–P. stephani* (LA 92.7 Ma), *Whiteinella paradubia* (94.5–89.8/88.5 Ma), and *Globigerinelloides asperus* (LA 92.8 Ma). Therefore, we included *Helvetoglobotruncana helvetica* Zone in those lower levels.

***Marginotruncana sigali* Partial Range Zone**. This Zone was originally defined as the interval with *Marginotruncana sigali*, from LA of *Helvetoglobotruncana helvetica* to FA of *Dicarinella primitive*. Late Turonian age was assigned (Barr 1972; Caron 1985). According to Gradstein et al. (2004) and Cohen et al. (2013) timescales, it spans from 92.5 to 89.8 Ma. The lower boundary is placed at the LA of *Helvetoglobotruncana helvetica* (92.5 Ma) at 8820 ft and the upper at the FA of *Dicarinella primitiva* (89.8 ± 0.3 Ma) at 8620 ft. This zone also comprises the LA of *Muricohedbergella* (*Hedbergella*) *planispira* and *Clavihedbergella* (*Hedbergella*) *simplex* and an unusual record of *Falsotruncana maslakovae*, which is very rare in the Middle Magdalena Valley. It also comprises the FA of *Marginotruncana sinuosa*, *M. marginata*, and *M. coronate*. *Planoheterohelix* (*Heterohelix*) *reussi*, *Whiteinella baltica*, and *W. archaeocretacea* are common. The *Marginotruncana sigali* sensu *strictu* was

identified in Aguablanca and El Salto creeks; and a coeval interval was recognized in the Cuesta El Diablo section, although in the absence of *Marginotruncana sigali* zone marker species, Late Turonian age is revealed by the co-occurrence of *Clavihedbergella* (*Hedbergella*) *simplex* and *Planoheterohelix* (*Heterohelix*) *reussi*, and also based in the presence of *Trichodinium castanea* (dinocysts), which only coexist at that stage (see Turonian-Coniacian boundary).

4.2 Coniacian (89.8–86.3 Ma)

The Coniacian stage in Chuira-2ST intervals (8620–8440 and 8130–8020 ft) is characterized by moderate abundance of planktonic foraminiferal, and the planktonic foraminiferal zones *Dicarinella primitiva* and *Dicarinella concavata* were identified. The *D. concavata* has been here modified, and Coniacian/Santonian boundary is included. We divided it into two sub-zones; they are *Dicarinella concavata* sub-zone of Late Coniacian age and *Dicarinella concavata–Costellagerina* (*Rugoglobigerina*) *pilula* association sub-zone of Early Santonian age. *Dicarinella primitiva* and *Dicarinella concavata* sub-zones correlates to UKP-06 *Dinogymnium microgranulosum*, interval dinocyst zone from Coniacian age, (89.8 ± 0.3–86.3 ± 0.3 Ma) (Navarrete-Parra et al. 2015), which was established in Aguablanca and El Salto creeks sections and in Chuira-1 well, and also recognized in Chuira-2ST. The Coniacian stage correlates to UC-10 calcareous nannofossil zone of Burnett (1998) in the Chuira-2ST well, according to Pérez Panera et al. (this volume).

***Dicarinella primitiva* Interval Zone**. This zone was originally defined as interval from the FA of *Dicarinella primitiva* to the FA of *Dicarinella concavata*, and an Early Coniacian age was assigned (Caron 1978, 1985). According to Gradstein et al. (2004) and Cohen et al. (2013) time scale, it spans from 89.8 to 87 Ma). The lower boundary FA of *Dicarinella primitiva* (89.8 Ma) occurs at 8620 ft and the upper FA of *Dicarinella concavata* (87 Ma) at 8440 ft in Chuira-2ST. This zone comprises the FA of *Archaeoglobigerina cretacea* and *Muricohedbergella* (*Hedbergella*) *holmdelensis;* the LA of *Falsotruncana maslakovae* (98.8–89.2 Ma) occurs close to the lower boundary of the zone. The *Dicarinella primitiva* zone is also characterized by abundant heterohelicids with *Planoheterohelix* (*Heterohelix*) *reussi* dominant and high diversity of whiteinellids and common calcispheres and pithonellids. This interval zone was also recognized in the Aguablanca and El Salto creeks and Cuesta El Diablo section.

***Dicarinella concavata* Interval Zone** (**modified**). *Dicarinella concavata* Zone was originally defined as the interval from the FA of *Dicarinella concavata* to the FA of *Dicarinella asymetrica* and a Late Coniacian to Early Santonian age was assigned (Sigal 1955; Caron 1985). According to Gradstein et al. (2004) and Cohen et al. (2013) this zone spans from 87 to 85 Ma. As cited, this zone includes the Coniacian/Santonian boundary (Chron 86.3 ± 0.5 Ma). The *Dicarinella concavata* Zone sensu Sigal (1955) occurs in the interval 8130–7950 ft. *Dicarinella asymetrica* is not present in the analyzed samples, but its FA is replaced by coeval events. Those are the LA of *Whiteinella baltica* and LA of *Muricohedbergella* (*Hedbergella*) *delrioensis* (85 Ma) which occurs at (7950–7960 ft in Chuira-2ST). Within this zone, as recorded in outcrops and wells of the MMVB, it also occurs the FAs of *Costellagerina* (*Rugoglobigerina*) *pilula* (86.3 Ma), *Contusotruncana fornicata* and *Archaeoglobigerina blowi* (86.3 Ma). Other LAs

occur in this Zone: *Whiteinella archaeocretacea*, *Marginotruncana renzi*, *M. coronata*, *Dicarinella imbricata*, and *D. primitiva*. When recognized or established, the *D. concavata* Zone sensu Sigal (1955) does not reveal the Coniacian/Santonian boundary. Nevertheless, it is possible to constrain that boundary based on *Whiteinella archaeocretacea* (LAD 86.3 Ma) and *Dicarinella primitiva*, species marker of the Coniacian top, but also, based on the FA of *Costellagerina* (*Rugoglobigerina*) *pilula* and/or *Contusotruncana fornicata* and/or *Archaeoglobigerina blowi* (86.3 Ma); which co-occur within the *D. concavata* Zone sensu Sigal (1955) and are markers of the Santonian base. Thus, *D. concavata* Zone could be divided into two sub-zones (this paper): *D. concavata* interval sub-zone of Late Coniacian age, and *Dicarinella concavata–Costellagerina* (*Rugoglobigerina*) *pilula* association sub-zone of Early Santonian age. Additionally, the *Dicarinella concavata* sub-zone was calibrated at El Salto section and Aguablanca creek. In the latter outcrop, age was constrained by the presence of *Didymotis variabilis* (Gerhardt 1897) in AB182 sample, *Baculites maldonadi* (Karsten 1858) and *Paralenticeras spathi* (Reyment 1958) in HB14a sample; typical mollusks of Early Coniacian age (Etayo-Serna 2010).

***Dicarinella concavata* Interval sub-zone**. This sub-zone is defined as the interval with *D. concavata* from the FA of *Dicarinella concavata* (87 Ma) to the FA of *Costellagerina* (*Rugoglobigerina*) *pilula* (86.3 Ma). Age of this sub-zone is Late Coniacian (87–86.3 Ma) according to Gradstein et al. (2004) and Cohen et al. (2013) timescales. This sub-zone was defined in cores Colon-2 and Colon-3 by Navarrete et al. (internal report, Petronorte 2010). Subsequently, it has also been identified in Aguablanca and El Salto creeks, and Cuesta El Diablo section. In Chuira-2ST (interval 8130–8050 ft), this sub-zone comprises also the LAs of *Whiteinella archaeocretacea* and *Dicarinella imbricata*, which co-occur at (8050–8060 ft), it includes moreover the FA of *Archaeoglobigerina bosquensis* and *A. blowi* at (8130–8120 ft). *Whiteinella archaeocretacea* (LA) and *A. blowi* (FA) are marker species of the Coniacian/Santonian boundary, while *Archaeoglobigerina bosquensis* (FA) is a marker Late Coniacian base. Those taxa are excellent alternative regional markers when keeled *Dicarinella imbricata* and *Dicarinella concavata* are not present. The top of this sub-zone is coeval with the upper boundary of UKP-06 *Dinogymnium microgranulosum* Interval dinocysts zone [86.3 ± 0.3 Ma Navarrete-Parra et al. (2015)]; in addition, its base is correlated to the FA of the dinocyst *Dinogymnium acuminatum* in sample (8040–8050 ft). It also correlates with the LA of *Eprolithus moratus*, a calcareous nannofossil marker of the Santonian/Coniacian boundary (Pérez Panera et al., this volume) found at 8140–8130 ft in Chuira-2 ST (see Coniacian/Santonian boundary).

4.3 Santonian

The Santonian in Chuira-2ST (7920–8130 ft) is characterized by high richness of planktonic foraminiferal assemblages and was possible to identify one zone (*Dicarinella asymetrica* Zone) and to propose one sub-zone (*Dicarinella concavata–Costellagerina* (*Rugoglobigerina*) *pilula* sub-zone). These were also identified in Chuira-1 well, Colon-2, Colon-3, and Cuesta el Diablo section. They are coevals with the UC-11C and UC12 calcareous nannofossils zones (Burnett 1998), as recognized Chuira-2-ST (Pérez Panera et al., this volume), and with dinocysts interval zones

UKP-7/UKP-8 *Dinopterygium cladoides* (Navarrete-Parra et al. 2015) of Santonian age (86.3 ± 0.3–83.6 ± 0.2 Ma), in Chuira-2ST and in Aguablanca and El Salto creeks. However, in those localities, *D. asymetrica* Zone is not complete, and the last 1.1 Myr of the top is missing.

***Dicarinella concavata–Costellagerina* (*Rugoglobigerina*) *pilula* Association sub-zone**. This sub-zone was defined in cores Colon-2 and Colon-3 by Navarrete et al. (internal report, Petronorte 2010). Subsequently, it has also been identified in Aguablanca and El Salto creeks, and Cuesta El Diablo section. This sub-zone is defined in Chuira-2ST at 8050–8130 ft as the interval with *D. concavata* from the LA of *Whiteinella archaeocretacea* (86.3 Ma) and FA of *Costellagerina* (*Rugoglobigerina*) *pilula* (86.3 Ma) at 8130 ft; to the FA of *Dicarinella asymetrica* and/or LA of *Whiteinella baltica* (85 Ma) at 8050 ft. An Early Santonian age is assigned, and it spans from 86.3 to 85 Ma according to Gradstein et al. (2004) and Cohen et al. (2013) timescales. This sub-zone comprises multiples extinction events in its upper boundary, among them: *Whiteinella baltica*, *Muricohedbergella* (*Hedbergella*) *delrioensis*, *Marginotruncana renzi*, *M. sigali*, *Dicarinella imbricata* and *Dicarinella primitiva.* It also comprises FAs of marker species of the Coniacian/Santonian boundary. First appearances of *Contusotruncana fornicata*, *Archaeoglobigerina blowi*, and *Costellagerina* (*Rugoglobigerina*) *pilula* (calibrated at 86.3 Ma) are excellent regional events for recognizing the Santonian/Coniacian boundary. This sub-zone correlates with the UC11c calcareous nannofossils zone of Burnett (1998) as it has been recognized in Chuira-2ST (Pérez Panera et al., this volume). The *Dicarinella concavata–Costellagerina* (*Rugoglobigerina*) *pilula* Association sub-zone proposed here has been recognized along diverse sections in Colombian basins.

***Dicarinella asymetrica* Total Range Zone**. This zone was originally defined as the total range of *Dicarinella asymetrica*, and a latest Early Santonian to Late Santonian age was assigned (Postuma 1971; Caron 1985). Calibrated with Gradstein et al. (2004) and Cohen et al. (2013) timescales, its age is Late Santonian and it spans from 85 to 83.6 Ma. In this survey, *Dicarinella asymetrica* is not present; nevertheless, a coeval interval with its early part was identified due to the LA of *Whiteinella baltica* (85 Ma), at 7950–7960 ft. This event occurs at the same time that the FA *Dicarinella asymetrica* (85 Ma). Just indicating the upper boundary of the *D. concavata–Costellagerina* (*Rugoglobigerina*) *pilula* sub-zone. Thirty feet up, in sample 7920 ft, multiple LAs of marker species near the top of *Dicarinella asymetrica* Zone co-occur. They are the LA of *Whiteinella inornata* (84.7 Ma), *Archaeoglobigerina bosquensis* (87–83.6 Ma), *Marginotruncana marginata* (90.3–83.5 Ma), *Dicarinella canaliculata* (93–84.7 Ma), *D. concavata* (87–83.9 Ma) and *Planoheterohelix* (*Heterohelix*) *reussi* (91.8–83.6 Ma). According to those events, the age at 7920 ft is not younger than 84.7 Ma. In resume, the interval 7950–7960 to 7920 ft correspond to the early part of the *Dicarinella asymetrica* zone, defined from the LA of *Whiteinella baltica* (7950–7960 ft) to the LA of *Whiteinella inornata* spans 85–84.7 Ma. At the top of this interval (9720 ft), the LAs of *Archaeoglobigerina bosquensis*, *Marginotruncana marginata*, *Dicarinella canaliculata*, *D. concavata*, and *Planoheterohelix* (*Heterohelix*) *reussi* also occur. The time interval documented (85–84.7 Ma) reveals the absence of a record of the latest Santonian (1.1 Myr).

4.4 Campanian

The Campanian in Chuira-2ST (7920–7700 ft) corresponds to the Lower Umir Formation. This stage is characterized by moderate abundance of planktonic foraminifera and high richness of benthonic foraminiferal assemblages. Three known planktonic foraminifer zones are described for Campanian stage: (1) *Globotruncanita elevata*, (2) *Globotruncana ventricosa*, and (3) *Radotruncana* (*Globotruncanita*) *calcarata* zones. Dinocysts and calcareous nannofossils did not allow the recognition the early or middle Campanian, but dinocysts UKP-10 *Dinogymnium heterocostatum* interval zone (Navarrete-Parra et al. 2015) and UC-12 calcareous nannofossils zone Burnett (1998) were identified in Chuira-2-ST (Pérez Panera et al., this volume) and allowed the recognition of Late Campanian. Chuira-1 and Chuira-2ST revealed the absence of the UKP-9 Isabelidinium cretaceum Zone (Navarrete-Parra et al. 2015), and new evidence in Chuira-2ST shows the absence of UC-13 to UC-14 calcareous nannofossils zones of Burnett (1998) (Pérez Panera et al., this volume) zones.

***Globotruncanita elevata* Partial Range Zone**. This zone was originally defined as the interval with *G. elevata* from the LA of *Dicarinella asymetrica* to the FA of *Globotruncana ventricosa* and an Early Campanian age was assigned (Postuma 1971; Caron 1985). According to Gradstein et al. (2004) and Cohen et al. (2013) timescales, it spans between 83.6 and 79.4 Ma. In Chuira-2ST well, FA of *Globotruncanita elevata* (83.6 Ma) at 7920–7010 ft co-occur with the first record of *Rugoglobigerina rugosa* (80.3 Ma) and *Planoheterohelix* (*Heterohelix*) *striata* (80.3 Ma). These species constrain a range not older than 80.3 Ma. They post-date the LAs of multiple taxa whose extinction levels occur in the Santonian stage, and in Chuira-1 they are not younger than 84.7 Ma. This evidences that *Globotruncanita elevata* Zone is not complete; there is no record of their first 3.3 Ma. The zone is here defined as the interval with *G. elevata* from the LA of *Archaeoglobigerina bosquensis*, *Marginotruncana marginata*, *Dicarinella canaliculata*, *D. concavata*, and *Planoheterohelix* (*Heterohelix*) *reussi* at 7920 ft) to the FA of *Globotruncana ventricosa* at 7900 ft. As described, this zone was also identified in Cuesta El Diablo section and Chuira-1 well.

***Globotruncana ventricosa* Interval Zone**. Originally defined as the interval from the FA of *Globotruncana ventricosa* to the FA of *Radotruncana* (*Globotruncanita*) *calcarata* and an age late Early Campanian to Late Campanian was assigned (Dalbiez 1955; Caron 1985). According to Gradstein et al. (2004) and Cohen et al. (2013) timescales, it spans from 79.4 to 75.4 Ma. The *Globotruncana ventricosa* Zone was also recognized in Cuesta El Diablo section. In Chuira-2ST (7900–7880), this zone is relatively very poor in planktonic foraminifera. Nevertheless, it is recognized sensu Dalbiez (1955), from the FA of *Globotruncana ventricosa* (7900 ft) to the FA of *Radotruncana* (*Globotruncanita*) *calcarata* (7870–7880 ft). *Globotruncanita elevata*, *Archaeoglobigerina blowi*, and *Muricohedbergella* (*Hedbergella*) *holmdelensis* are common in the assemblage.

***Radotruncana* (*Globotruncanita*) *calcarata* Total Range Zone**. This zone was originally defined by total range of the *Radotruncana* (*Globotruncanita*) *calcarata*, and a latest Late Campanian age was assigned (Herm and Barthel 1962; Caron 1985). It occurs in Chuira-2ST interval 7880–7700 ft, spanning from 75.4–72.1 Ma, according to Gradstein et al. (2004) and Cohen et al. (2013) timescales, Late Campanian. In the

MMVB, this zone yields poor planktonic foraminifer assemblages, but the FAs of *Globotruncanella havanensis*, *Planoheterohelix* (*Heterohelix*) *globulosa* and LA of *Globotruncanita elevata* were recorded. The *Radotruncana* (*Globotruncanita*) *calcarata* Zone sensu *strictu* was also recorded in Chuira-1 well and Cuesta El Diablo section. In Chuira-2ST, a Late Campanian age has also been constrained with the identification of the UC-15 to UC-16 calcareous nannofossil zones of Burnett (1998), based on the FA of *Eiffellithus parallelus* at 7890–7880 ft and LA of *Broinsonia parca expansa* at 7690–7680 ft. It also correlated to the UKP-10 *Dinogymnium heterocostatum* dinocyst zone of Late Campanian age (Navarrete-Parra et al. 2015).

5 Stratigraphic Boundaries and Hiatus–Discussion

5.1 Turonian/Coniacian Boundary

The determination of the Coniacian/Santonian boundary is difficult to achieve through foraminifera, since the markers *Helvetoglobotruncana* and the *Marginotruncana* groups are either missing or scattered. That boundary has been successfully established using foraminifera and calcareous nannofossils. Turonian and Coniacian faunas contain Tethyan species, and taxa are well differentiated. This boundary comprises various extinction events of no complexes planktonic foraminifera, as *Clavihedbergella* (*Hedbergella*) *simplex*, *Muricohedbergella* (*Hedbergella*) *delrioensis* and *M.* (*H.*) *planispira*, and the double-keeled *Helvetoglobotruncana* group. Also, the FAs of simple forms like *Whiteinella* group, *Planoheterohelix* (*Heterohelix*) *reussi*, and other heterohelicids. Coniacian faunas are characterized by double-keeled *Dicarinella* and *Marginotruncana* groups. *Dicarinella primitiva*, *Archaeoglobigerina cretacea*, *Muricohedbergella* (*Hedbergella*) *holmdelensis* first appear in the Coniacian, and they are common to abundant taxa. The boundary is suggested at 8620 ft with the FA of *Dicarinella primitiva* of Coniacian age. The calcareous nannofossils revealed latest Turonian with LA *Eprolithus octopetalus* in interval (8780–8790 ft) and the FA of *Micula staurophora* at 8690–8700 ft, which occurs at the base of the Coniacian (Pérez Panera et al., this volume). The Turonian/Coniacian boundary was not identified with palynomorphs. At the boundary, they show abundant *Odontochitina costata*, *Dinogymnium digitus*, *Manumiella* sp., *Alterbidinium acutulum*, and *Palaeotetradinium silicorum.* This assemblage characterizes the UKP-03-UKP-06 dinocysts zones of Turonian–Coniacian age in Chuira-1 well, Aguablanca, El Salto creeks and Cuesta El Diablo section, without record of marker species that could identify the Turonian/Coniacian boundary. The bias in the Turonian/Coniacian boundary according to foraminifera and calcareous nannofossils would not be related strictly with temporary differences; it could be explained in minor proportion to very-bad preserved specimens and taxonomical difficulties.

5.2 Coniacian/Santonian Boundary

The Coniacian/Santonian boundary is difficult to locate since such an important stratigraphic marker as the *Dicarinella* and *Marginotruncana* groups are either missing

or very rare. *Whiteinella*, *Rugoglobigerina*, and *Archaeoglobigerina* groups help to substitute those double-keeled taxa, whose records are poor and obscure due to preservation problems. The base and top of involved sediments are gradational in the wells and subsurface and high-resolution biostratigraphical studies show they represent conformable facies boundaries. The Coniacian/Santonian boundary is recognized by the LAs of *Whiteinella archaeocretacea* and *Dicarinella imbricata* at latest Coniacian and FAs of *Costellagerina* (*Rugoglobigerina*) *pilula*, *Contusotruncana fornicata*, and *Archaeoglobigerina bosquensis* at earliest Santonian. These events indicate the top of *Dicarinella concavata* sub-zone of Late Coniacian and base of *Dicarinella concavata–Costellagerina* (*Rugoglobigerina*) *pilula* sub-zone of Early Santonian, respectively. The top of the UKP-06 *Dinogymnium microgranulosum* Zone (86.3 ± 0.3 Ma) also indicates the Coniacian/Santonian boundary, which in Chuira-2ST is located at interval 8040–8050 ft, according to foraminifera, nannofossils, and dinocysts.

5.3 Santonian/Campanian Boundary

Campanian spans from 83.6 ± 0.2 to 72.1 ± 0.2 Ma and Santonian from 86.3 ± 0.5 to 83.6 ± 0.2 Ma (see Gradstein et al. 2004; Cohen et al. 2013). The earliest Santonian is 85–84.7 Ma, underlying to late Early Campanian (80.3–75.4 Ma). The *Dicarinella asymetrica* Zone and/or its coeval interval Santonian age reveals a hiatus of 1.1 Myr from the latest Santonian. The *Globotruncanita elevata* of Early Campanian age shows a hiatus of 3.3 Myr (see *Dicarinella asymetrica* and *Globotruncanita elevata* zones). The *Globotruncana ventricosa* Zone contains the Early Campanian/Middle Campanian boundary; therefore, they are not always sharply separated and are currently referred as Middle Campanian. Only the upper part of *Globotruncanita elevata* Zone is present in the La Luna Formation in MMVB (cf. Chuira-2ST, interval 7910–7920 ft) as it was shown by the dense sampling, multidisciplinary biostratigraphy and geochronology. According to the integrated biostratigraphy, at 7920 ft sediments are not older than 80.3 Ma. (see *Globotruncanita elevata* Zone). *Globotruncanita elevata* and *Globotruncana ventricosa* zones, from the FA of *Globotruncanita elevata*, *Rugoglobigerina rugosa*, and *Planoheterohelix* (*Heterohelix*) *striata*, to the FA of *Radotruncana* (*Globotruncanita*) *calcarata* (7760–7880 ft), comprises an age from 80.3 to 75.4 Ma. We found that it would be the lower part of *Globotruncanita elevata* Zone which is missing, so *Globotruncanita elevata* Zone only reveals the last 0.9 Ma of Early Campanian. When compared with standard geochronology, the Santonian/Campanian boundary (Chron 83.6 ± 0.2: Cohen et al. 2013), at Churia-2ST shows that the earliest 3.3 Myr are not present.

5.4 Santonian/Campanian Hiatus and Condensed Sedimentation

Foraminiferal analyses, palynology, calcareous nannofossils (Pérez Panera et al., this volume) and sedimentological evidence obtained from subsurface and outcrops (e.g., Cuesta El Diablo and Chuira-2 (Rodríguez et al. 2016a) and Chuira-2ST drill-down), revealed a condensed Campanian (interval 7920–7880 ft in Chuira-2ST) which resume the *Globotruncanita elevata* and *Globotruncana ventricosa* zones, and no record from latest Santonian (1.1 Myr) and Early Campanian (3.3 Myr), which excludes an

abnormal distribution of those species. The distribution and frequency of *Globotruncanita elevata* and *Globotruncana ventricosa* are not abnormal, and their virtual absences and/or not differentiated apparition or poor record have diverse explanations. This could be due to epicontinental sea environment, where keeled foraminifera are always absent, or due to condensed sedimentation. In fact, in the interval 7880–7920 ft ≈ 9–10 m thick, the occurrence of autigenic glauconite-rich horizons (grains and infill), phosphates, pyrite, and high abundance of ostracods, microbivalves, tooth and another fish remains, suggests periods of slow, condensed sedimentation. Formation of glauconitic sediments occurs on the marine shelves during prolonged intervals of sediment starvation (Odin and Fullagar 1988). The Santonian/Campanian boundary in MMVB revealed a hiatus of 4.4 Myr approximately. This hiatus corresponds to the La Luna and Umir Formations contact and was calibrated in other localities, among them, Chuira-1, Chuira-2, Chuira-2-ST, and other adjacent Colombian sedimentary basins. Although, the hiatus has been identified regionally, but its details remain unpublished (see Rodriguez et al. 2016b, Fig. 19). The recognition of this hiatus and its duration is key for the oil and gas exploration, as it corresponds with a paraconformity that allow the recognition of the La Luna and Umir Formations contact in surface and most important, in subsurface. The hiatus reveals a glauconitic-rich layer, which is a regional guide horizon at the top of the La Luna Formation. This paraconformity is the surface for the development of a 10-m-thick condensed deposit of 4.9 Myr (Middle to Late Campanian) that correspond to the upper part of the *Globotruncanita elevata* and *Globotruncanita elevata* zones (79.4–75.4 Ma).

6 Paleoenvironmental Interpretations

A general overview on the sedimentation and paleoenvironmental conditions prevailing during the deposition of the La Luna Formation is possible to introduce (see Ecozones Fig. 8), after detailed micropaleontological studies in different sections and wells in the MMVB and adjacent basins (e.g., Catatumbo, Rancheria, and Upper Middle Magdalena Valley). During the sedimentation of La Luna Formation and equivalent units, benthonic foraminifera are scarce and always very small-sized (Fig. 9a, b). Across different profiles in the basin, most conspicuous benthonic could be grouped in robust buliminids (Type C: 80–120 μ), small-sized buliminids (Type B: 120–140 μ), and very small-sized buliminids (Type A: 140–200 and <200 μ). They are very diverse and constitute the most persistent benthonic group along the La Luna and Umir (lower part) formations. Thus, for instance, buliminids type A, with the very small *Virgulina tegulata* and *Oolina* sp. occur in Turonian stage. They are scarce at Early Turonian but abundant ending the Middle Turonian. During Coniacian, buliminids Type B occurs accompanied by small *Fursenkoina* and diverse rotalidae as *Anomalina redmondii* (abundant). This assemblage increases up, but precludes before ending the Santonian. For example, *Bolivina explicata* is a guide benthonic foraminifer along the upper La Luna Formation from northern corner of the MMVB to Venezuela. *Bolivina explicata* and *Anomalina redmondii* are cited sensu zonule by (Petters 1954) in the La Luna Formation (upper part). There are no other records of benthonic foraminifera in the Colombian literature of the La Luna Formation. This level is an important seismic

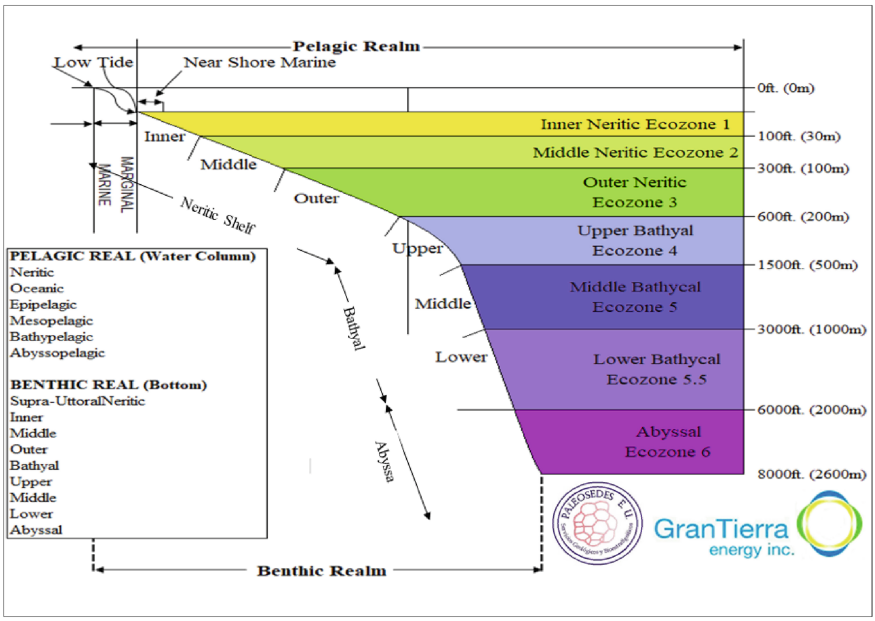

Fig. 8. Ecozones, shelf marine, and ocean profile used in this work

reflector at top of the La Luna Formation and is rich in mature glauconitic grains. This level coincides with the early part of *Dicarinella asymetrica* zone and an anoxic event in the Santonian. There are some turnovers in Santonian/Campanian boundary, for example, whiteinellids, dicarinellas, and marginotruncanas practically disappear, and *Planoheterohelix* (*Heterohelix*) *reussi* highest abundance records precede their extinction. The latest Early Campanian (in Umir Formation) shows a toward-up increase in buliminids Type C (robust). They are the main component clustered with a very diverse infauna and epifauna, which contain mainly robust specimens and high diversity and abundance. Calcareous rotalidae, *Siphogenerinoides*, *Bolivina*, diverse buliminids Type C and agglutinated foraminifera as *Ammobaculites*, *Haplophragmoides* spp. among very others, are common.

The La Luna Formation in the MMVB yields very abundant planktonic foraminifera, with noticeably affinities to the Tethyan realm according to biostratigraphical zonation from western areas of the Tethys [e.g., Gulf Coast Trinidad and Caribe Sea (Brönnimann and Brown 1958; Gandolfi 1955; Bolli et al. 1957; Bolli 1966)]. Planktonic foraminifera in the La Luna Formation range in age from early Turonian (*Whiteinella archaeocretacea* Zone), to early late Santonian (*Dicarinella asymetrica* Zone), while in the base of the Umir Formation, *Globotruncanita elevata–Radotruncana* (*Globotruncanita*) *calcarata* zones, indicates a Campanian age. In the La Luna Formation, simple globigerinidae dominates the assemblages, a characteristic shared with other basins in Colombia as the Rancheria and Catatumbo basins. Among them, heterohelicids are the most important in abundance, but with low diversity; followed by whiteinellids, abundant and high diversity; hedbergellids, abundant and moderate

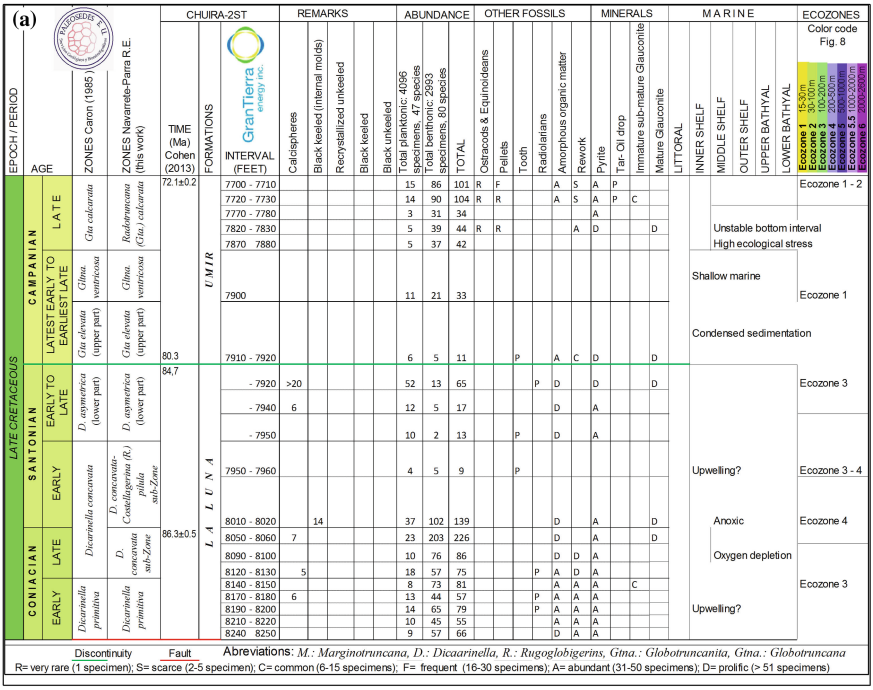

Fig. 9. **a**, **b** Chuira-2ST well in the northern Middle Magdalena Valley Basin, some conditions of deposit and paleobathymetry. Paleobathymetry and anoxic conditions strongly influenced the foraminiferal distribution

diversity. During the Turonian to the Coniacian/Santonian boundary, small keeled planktonic foraminifera had a moderate presence. The Planktonic/Benthonic ratio suggests that sedimentation occurred in a shallow sea, from middle to outer neritic marine environment, controlled by cyclic events of upwelling and depletion of oxygen content, from the Turonian to the Santonian, with important anoxic events in the Middle Turonian and Coniacian/Santonian boundary. These events could be associated with the OAE 2 and OAE 3 proposed by Jenkyns (1980). Paleobathymetry and anoxic conditions strongly influenced the foraminiferal distribution.

The lower part of Chuira-2ST (9365–8670 ft) corresponds to a 745 ft black to clear brown calcareous interval (biomicrite and spate-micrite). This interval is similar to the upper Salada and lower Pujamana members. This Turonian sequence shows a variation from inner to outer marine shelf (Ecozone 1 to Ecozone 3, Figs. 8 and 9a, b) as indicated by poorly developed associations of benthonic foraminifera of very small size and high abundance of small-sized opportunistic species as heterohelicids, hedbergellids, and whiteinellids (*Planoheterohelix* (*Heterohelix*) *reussi* disclose 80% planktonic fauna). This sequence begins with an upwelling event, very rich in black marine organic matter, quickly increasing in depth, ending in anoxic conditions. The Early Turonian is very poor in keeled foraminifera (*Praeglobotruncana turbinata–P. stephani* are present), and it is rich in small-sized whiteinellids, and hedbergellids,

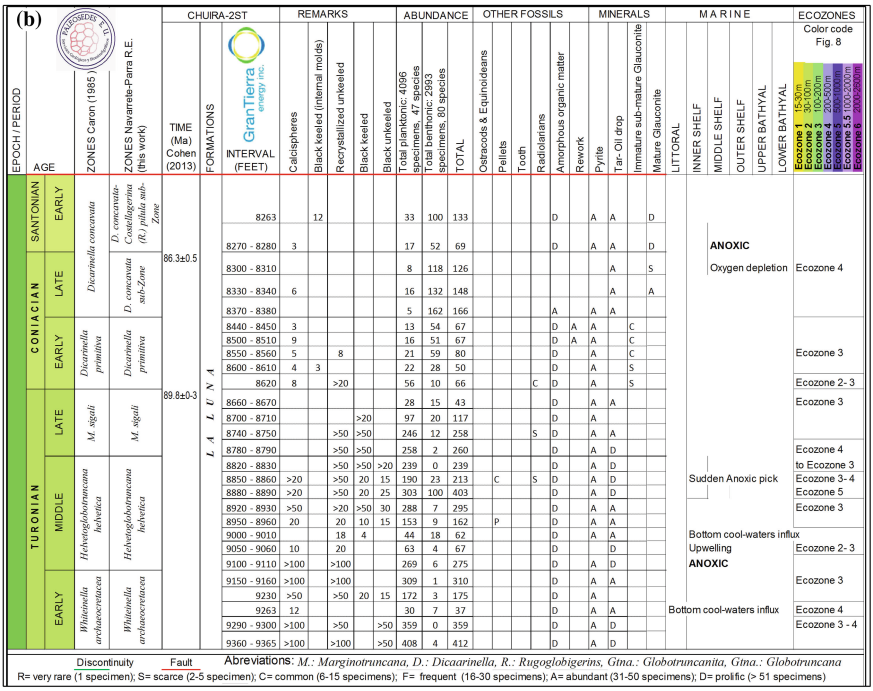

Fig. 9. (*continued*)

and highly abundant on small *Planoheterohelix* (*Heterohelix*) *reussi*. Insulated cameras of planktonic recrystallized (calcispheres, pithonellids) are common and so are the scattered homeomorphic small benthonic foraminifera accompanied by microbivalves, ostracods, and phosphates.

The great abundance of whiteinellids and heterohelicids indicate high environmental stress and /or biotic stress maximum. According to Keller (2003), heterohelicids are extremely tolerant to low oxygen concentration. The dominance of heterohelicids (Pardo and Keller 2008) more precisely *Planoheterohelix* (*Heterohelix*) is an important global marker of OAE2. Moreover, the dominance of *Planoheterohelix* (*Heterohelix*) in any moment would indicate expansion of the oxygen minimum zone, normally associated to an increase of organic productivity.

Especially in the Atlantic and in the Western Tethys, numerous black shale horizons occur in regional and supraregional distribution. Given that some of these events can be correlated across a large area and various marine environments (e.g., deep water, marginal basins, and platform sediments), they were called global Oceanic Anoxic Events (OAEs) (Schlanger and Jenkyns 1976). These OAEs are defined by a massive deposit of organic matter in marine environments (Schlanger and Jenkyns 1976; Arthur et al. 1990). The OAE2 would be present in the lower part *Whiteinella archaeocretacea* Zone, interval 9365–9290 ft, when heterohelicids had its acme (80–90% on total planktonic fauna) and hedbergellids and whiteinellids are dominant, accompanied by rich black amorphous marine organic matter and rare benthonic with *Virgulina tegulata*

and *Oolina*, typical of cold marine waters. The OAE3 would be present in the interval 8060–8010 ft at Chuira-2ST well, corresponding with Coniacian *Dicarinella concavata* sub-zone and Santonian *D. concavata–Costellagerina* (*Rugoglobigerina*) *pilula*, coincident with the sudden appearance of benthonic with high abundance and diversity of buliminids Type B, accompanied by double-keeled planktonic and very abundant amorphous marine organic matter. Only 30 ft up, before the end of Early Santonian, the inverse event occurs. Sudden fall of the precedent species and increase in phosphate, probably related to upwelling episodes, took place.

Diverse keeled foraminifera as *Helvetoglobotruncana helvetica*, *H. praehelvetica*, *Marginotruncana sp. M. coronata*, *M. pseudolinneiana*, *Dicarinella hagni*, *D. imbricata*, *D. canaliculata*, *Falsotruncana maslakovae*, *Marginotruncana sigali*, and *M. renzi*, first appear by mid-Turonian, during *H. helvetica* zone. They are taxa related to oceanic waters and reach high abundance. In a shallow marine environment, only few of these keeled species were found, probably brought by surface currents or by the action of strong tides. Their abundance and variety near the coast is more linked to oceanographic events and later burial histories, than with their position into the water column. The keeled forms also exhibit an excessively small size. Dissolution and recrystallization is the most common taphonomic process, which suggests offshore deposition. The eventual co-occurrence of *Oolina* spp., a benthonic form with cold water affinity, suggests an epicontinental environment, with cold-bottom waters that produced upwelling events. The great productivity of these groups associated to phosphatized fish remains and pellets also suggests a poorly stratified water column. Upwelling predates levels with very abundant buliminids Type A < 200 (e.g., *Virgulina tegulata*) and high abundance of not keeled planktonic and high diversity of keeled planktonic foraminifera. The high concentration of amorphous marine organic matter indicates anoxic bottoms and deepest environments during the increase of keeled forms at the Middle Turonian. The co-occurrence of buliminids Type A and *Virgulina* and *Oolina* sp. interbedded in at some levels, discloses disoxic conditions into the anoxic interval. The Middle Turonian interval (9110–8820 ft) shows variations from middle to outer shelf (Ecozone 2 to Ecozone 3, Figs. 8 and 9**a**, **b**), and a notable sudden deepest peak interval (8890–8850 ft), reaching outer shelf to upper bathyal (Ecozone 3 to Ecozone 5 ≈ 500–1000 m depth (Figs. 8 and 9**a**, **b**).

The Late Turonian reveals a decreasing-up in both, planktonic and benthonic foraminifera abundance. A lower diversity of keeled planktonic and bigger size of whiteinellids and *Planoheterohelix* (*Heterohelix*) *reussi* is recorded, together with a diminution in the radiolarians and buliminids Type A. Buliminids Type B first appear in these levels. These suggest a shallowing-up until Earliest Coniacian.

The second and third dated sequences (89.8–84.7 Ma) are represented in Chuira-2ST well by the intervals 8670–8440 and 8130–7920 ft. The first corresponds to 230 ft of calcareous mudstone (biomicrite and spate-micrite), black and blackish brown colored and a phosphate-rich interval with submature glauconite and pyrite at the base. This interval is similar to Pujamana Member of the La Luna Formation in MMVB. Planktonic foraminifera from this interval in Chuira-2ST range in age from Latest Turonian, upper part *Marginotruncana sigali* Zone, to Early Coniacian, *Dicarinella primitiva* Zone. The upper interval (8130–7920 ft) corresponds to 210 ft of bio-micritic and spate-micritic limestone with concretions, and gray and blackish clear brown

interbedded chert levels toward the top. It reveals abundant mature glauconitic grains and euhedral pyrite at the top. This interval is similar to Galembo Member of the La Luna Formation in MMVB. Planktonic foraminifera in this interval in Chuira-2ST range in age from Late Coniacian, *Dicarinella concavata* sub-zone and *D. concavata* Zone, to Late Santonian, *Dicarinella asymetrica* Zone (lower part). Lithological changes between members are not necessarily a time line. The Early Coniacian is characterized by low abundance of planktonic and poor abundance in benthonic foraminifera, with buliminids type B and disperse anomalinids. Micro-plankton contains mainly calcispheres, pithonellids, and scarce foraminifera with scattered representation of the whiteinellids, hedbergellids, and heterohelicids. Keeled foraminifera are rare, and *Archaeoglobigerina* is present. Relatively quiet waters and variable depths, from inner-middle to outer marine shelf (Ecozone 2 to Ecozone 3, Figs. 8 and 9a, b) are interpreted for this sequence. The Late Coniacian is characterized by a dominance of benthonic over planktonic foraminifera. Type B buliminids dominates over small rotalids, accompanied by microbivalves and radiolarians remains. Keeled foraminifera are scattered and less diverse than in lower strata of the La Luna Formation, and the first small-sized *Archaeoglobigerina* appears. The Coniacian interval records some maximum flooded levels, developed in strata of transgressive facies and severe anoxic intervals; which are concurrent with minor abundance of planktonic foraminifera and proliferation of Type B buliminids. These characteristics are interpreted as sedimentation in an epicontinental sea, on the middle shelf (Ecozone 3 to Ecozone 2, Figs. 8 and 9a, b), relatively far from the coast and with oxygen depletion conditions. The Late Coniacian/Early Santonian boundary is characterized by a sudden planktonic foraminifera abundance (8010–8060 and 8330–8380 ft intervals), as well as by non-biogenic silica, pyrite, and black amorphous marine organic matter which increases from the middle part up. This record discloses an anoxic event in the transit of the Coniacian/Santonian boundary, probably related with OAE3 (sensu Jenkyns 1980). The latest Early Santonian to Late Santonian show a fall in the abundance of planktonic and benthonic foraminifera. A shallowing-up pattern is notable, sedimentation occurred in shallow marine, from middle to inner shelf (Ecozone 2 to Ecozone 1, Figs. 8 and 9a, b). Sedimentation ends at the beginning of the Late Santonian.

The Campanian stage is similar to the base of the Lower part of the Umir formation in MMVB (Navarrete-Parra et al. 2016b, c). Planktonic foraminifera in the Umir Formation range in age from latest Early Campanian, *Globotruncanita elevata* Zone, to Late Santonian, *Radotruncana* (*Globotruncanita*) *calcarata* Zone. Its transgressive base in Chuira-2 and Chuira-2ST consists of a calcareous mudstone (intra-biomicrite), with extraclasts of foraminiferic spate-micrite, black and dark brown colored, rich in mature glauconite, and rich in reworked blackish dark green glauconite, just in Chuira-2ST (7920–7910 ft). The base of the Umir Formation yields an abundant assemblage of benthonic foraminifera with allochthones from shallowest shelf; presence of phosphatic pellets, fish remains and echinoderm and bivalve fragments. Micro-bioturbation is common. It contains autogenic acicular and euhedral pyrite. Thus, the base of the Umir Formation is interpreted as a flysch-type sedimentation. It always reveals keeled planktonic foraminifera, tied with median and big size benthonic foraminifera (infaunal and epifaunal), which suggests stratified, oligotrophic surface waters and some dysaerobic conditions with intervals characterized by high-stress ecologic conditions.

A shallow marine environment with unstable (depth, salinity, oxygen, and nutrients) bottom waters is evident by the alternation of levels with greater and lesser abundance of shallow bottom benthonic foraminifera and proliferation of opportunistic planktonic species. Although with few variations, a general depth between 100–200 m in the middle shelf (Ecozone 2, Figs. 8 and 9a, b), with high organic productivity is interpreted.

7 Conclusions

Planktonic foraminifera from Chuira-2ST, Upper Cretaceous La Luna, and Lower Umir Formations in the Middle Magdalena Valley Basin were analyzed. A detailed planktonic foraminiferal study allowed the identification of a Turonian to Santonian age for the La Luna Formation and a Campanian age to the lower part of the Umir Formation. The La Luna Formation in Chuira-2ST was reached at the Early Turonian at Terminal depth of 9365 ft, but the drilling did not reach its lower contact. In the Aguablanca and El Salto streams and Cuesta El Diablo section, the base of the La Luna Formation is Late Cenomanian to earliest Turonian. The base of the Umir Formation is Campanian.

The La Luna Formation in Chuira-2ST revealed planktonic foraminifera *Whiteinella archaeocretacea*, *Helvetoglobotruncana helvetica*, and *Marginotruncana sigali* zones from the Turonian stage. The Coniacian stage corresponds with planktonic foraminifera *Dicarinella primitiva* Zone, and *Dicarinella concavata* sub-zone into the *D. concavata* Zone. The upper part of the La Luna Formation discloses the *Dicarinella concavata–Costellagerina* (*Rugoglobigerina*) *pilula* association sub-zone into the *D. concavata* Zone of Early Santonian age. At the top of the La Luna Formation, *Dicarinella asymetrica* Zone was identified.

The Campanian was recognized with planktonic foraminifera *Globotruncanita elevata* zone (upper part), *Globotruncana elevata* and *Radotruncana* (*Globotruncanita*) *calcarata* zones, which occurs at the base of the Umir Formation in MMVB.

La Luna and Umir Formations are separated by a hiatus that comprises at least 4.4 Ma. It is associated with a turnover of diverse planktonic foraminifera as *Planoheterohelix* (*Heterohelix*) *reussi*, *Whiteinella archaeocretacea* and *W. baltica*, whose vertical distribution are truncated before reach their extinction levels. It discloses also the first record of *Globotruncanita elevata*, *Rugoglobigerina rugosa*, and *Planoheterohelix* (*Heterohelix*) *striata*. There is neither record of the upper part of *Dicarinella asymetrica* Zone, nor of the lower part of *Globotruncanita elevata* Zone. Sedimentary features reveal important presence of glauconitic grains exhibiting high maturity and hardground surfaces with phosphatic intraclasts and bioturbation.

Chuira-2ST reveals an unconformable relationship between the La Luna and Umir contact. This contact discloses two special events: the Santonian-Campanian hiatus and a Campanian condensed sedimentation. The base of the Umir Formation postdates the hiatus; its base corresponds to condensed sedimentation, 10 m spans (80.3–75.4 Ma), and the deposits are flysch type.

Environments with oxygen-depleted waters and episodic blackish marine organic matter deposits because of anoxic events and upwellings with nutrient input from the offshore characterizes the La Luna Formation. Foraminifera, dinocysts, and calcareous

nannofossils assemblages indicate shallowing-up paleoenvironment from an outer shelf to marine littoral (transitional marine) setting. The Early Turonian disclose anoxic conditions linked with the OAE2. The Middle Turonian shows a deepest and sudden anoxic peak, probably an anoxic local event. The Coniacian/Santonian boundary also shows a peak of depth, corresponding to an outer-shelf environment with sedimentation associated with the OAE3. The sediments of the studied section were deposited during the late stage of the upper Cretaceous Turonian–Santonian relative sea-level rise in the Colombian Cretaceous Basin and a drop in the sea level is revealed at the end of the Santonian, at the La Luna and Umir Formations contact.

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