DOI: 10.1590/2317-4889201530192

ARTICLE

The Cogollo Group and the oceanic anoxic events 1a and 1b, Maracaibo basin, Venezuela

El Grupo Cogollo y los eventos oceánicos anóxicos 1a y 1b, Cuenca de Maracaibo, Venezuela

José Alejandro Méndez Dot[1]*, José Méndez Baamonde[2], Dayana Reyes[3], Rommel Whilchy[3]

ABSTRACT: Carbonates of Cogollo Group (Apón, Lisure and Maraca formations) constitute the broader calcareous platform system originated during Aptian and Albian of Cretaceous in north-western South America, Maracaibo Basin, Venezuela. On the shallow shelf, a variety of calcareous sedimentary facies were deposited during marine transgressive and regressive cycles. Some of them developed porosity and constitute important hydrocarbon reservoirs. Due to some major marine transgressions, from early Aptian, the anoxic environment and characteristic facies of a pelagic environment moved from the outer slope and basin to the shallow shelf, during specific time intervals, favouring the sedimentation of organic matter-rich facies, which correspond to the oceanic anoxic events (OAEs) 1a and 1b. The source rock of Machiques Member (Apón Formation) was deposited during early Aptian OAE 1a (~ 120 Ma). The source rock of Piché Member, located at the top of the Apón Formation, was deposited during late Aptian OAE 1b (~ 113 Ma). Finally, La Luna Formation, from Cenomanian, that covers the OAE 2 (~ 93 Ma), represents the most important source rock in the Maracaibo Basin. In this way and based on sedimentological and organic geochemistry results from the determinations performed on 247 samples belonging to six cores in the Maracaibo Basin, we propose these two organic-rich levels, deposited on the shallow shelf of the Cogollo Group, as "effective source rocks", additional to La Luna Formation, with oil migration in relatively small distances to the porosity facies.

KEYWORDS: Cogollo Group; Maracaibo Basin; source rocks; oceanic anoxic events.

RESUMEN: *Los carbonatos del Grupo Cogollo (formaciones Apón, Lisure y Maraca) constituyen el sistema de plataforma calcárea más amplio originado durante el Aptiense y Albiense del Cretácico Inferior, en el noroeste de América del Sur, cuenca de Maracaibo, Venezuela. Sobre la plataforma somera se depositaron una amplia variedad de facies calcáreas en ciclos sedimentarios con secuencias regresivas y transgresivas, algunas con porosidad, constituyendo importantes yacimientos de hidrocarburos. Debido a algunas transgresiones marinas mayores, a partir del Aptiense temprano se trasladó, durante intervalos de tiempo puntuales, el ambiente anóxico y las facies características de un ambiente pelágico desde el talud externo y la cuenca hasta la plataforma somera, propiciando la sedimentación de facies ricas en materia orgánica, las cuales se corresponden con los Eventos Oceánicos Anóxicos (EOAs) 1a y 1b. La roca madre del Miembro Machiques (Formación Apón), se originó durante el EOA 1a del Aptiense temprano (~ 120 Ma). La roca madre del Miembro Piché, situada en la parte superior de la Formación Apón, se originó durante el OAE 1b de finales del Aptiense (~ 113 Ma). Finalmente, a partir del Cenomaniense, se depositó la Formación La Luna, la cual abarca el OAE 2 (~ 93 Ma) y representa la roca madre más importante en la cuenca de Maracaibo. De esta manera, sobre la plataforma somera del Grupo Cogollo se desarrollaron dos niveles de "rocas madre efectivas" adicionales a la Formación La Luna, con migraciones del petróleo en distancias relativamente pequeñas hasta las facies con porosidad.*

PALABRAS CLAVE: *Grupo Cogollo; cuenca de Maracaibo; rocas madre; eventos oceánicos anóxicos.*

[1]Facultad de Ingeniería, Universidad Central de Venezuela – UCV, Caracas, Venezuela. *E-mail: jose.a.mendez1@gmail.com*
[2]Facultad de Ciencias, Universidad Central de Venezuela – UCV, Caracas, Venezuela. *E-mail: jmgeologia@gmail.com*
[3]PDVSA Petroregional del Lago S.A., Caracas, Venezuela. *E-mail: reyesdjg@petroregional.pdvsa.com; whilchyr@pdvsa.com*
*Corresponding author.

Manuscript ID: 30192. **Received:** 10/30/2014. **Approved:** 04/08/2015.

INTRODUCTION

The Cogollo Group is a shallow carbonate platform composed by many sedimentological facies and depositional textures. The system was deposited during all the Aptian and Albian of Cretaceous Period, in the Maracaibo Basin, which is located in the North-West of Venezuela (Fig. 1). It is formed by Apón (Tibú, Machiques and Piché members), Lisure and Maraca formations (Renz 1977; Bartok *et al.* 1981; LEV 1970, 1997).

The variety of depositional textures and fossils includes mudstone, wackestone, packstone, dolomite and grainstone with bivalve, echinoderms, benthic foraminifera, red and green algae, oolites, among others (Ford & Houbolt 1963; LEV 1997). Between these shallow facies, two stratigraphic levels of organic rich pelagic and hemipelagic carbonate facies are found, with variable shale and silt content. These high total organic carbon (TOC) levels are the expression in the Maracaibo Basin sedimentary record of two oceanic anoxic events (OAEs): OAE 1a of the early Aptian (~ 120 Ma), represented by the Machiques Member, and the OAE 1b of the late Aptian (~ 113 Ma), represented by the Piché Member, both of them belong to the Apón Formation (Méndez *et al.* 2008). These two bituminous intervals, whose correlative sections have been studied in many sedimentary basins in Europe, the Mediterranean sea, Florida (USA), Gulf of Mexico, the Pacific and the Atlantic oceans (Sliter 1989; Bralower *et al.* 1993, 1994; Jenkyns & Wilson 1999; Leckie *et al.* 2002; Dumitrescu *et al.* 2006; Hofmann *et al.* 2008; Robinson *et al.* 2008), represent two effective source rock levels. This implies a new configuration of the Cogollo Group and Río Negro Formation petroleum system.

The oil contained in the production levels of the conglomerate and sandstone reservoir facies of the Río Negro Formation (Barremian), underlying the Gogollo Group and the Piché Member reservoir facies (Apón Formation), was generated by Machiques Member and Piché Member source rock levels, respectively. Therefore, La Luna Formation should not be considered the only source rock in the Maracaibo Basin.

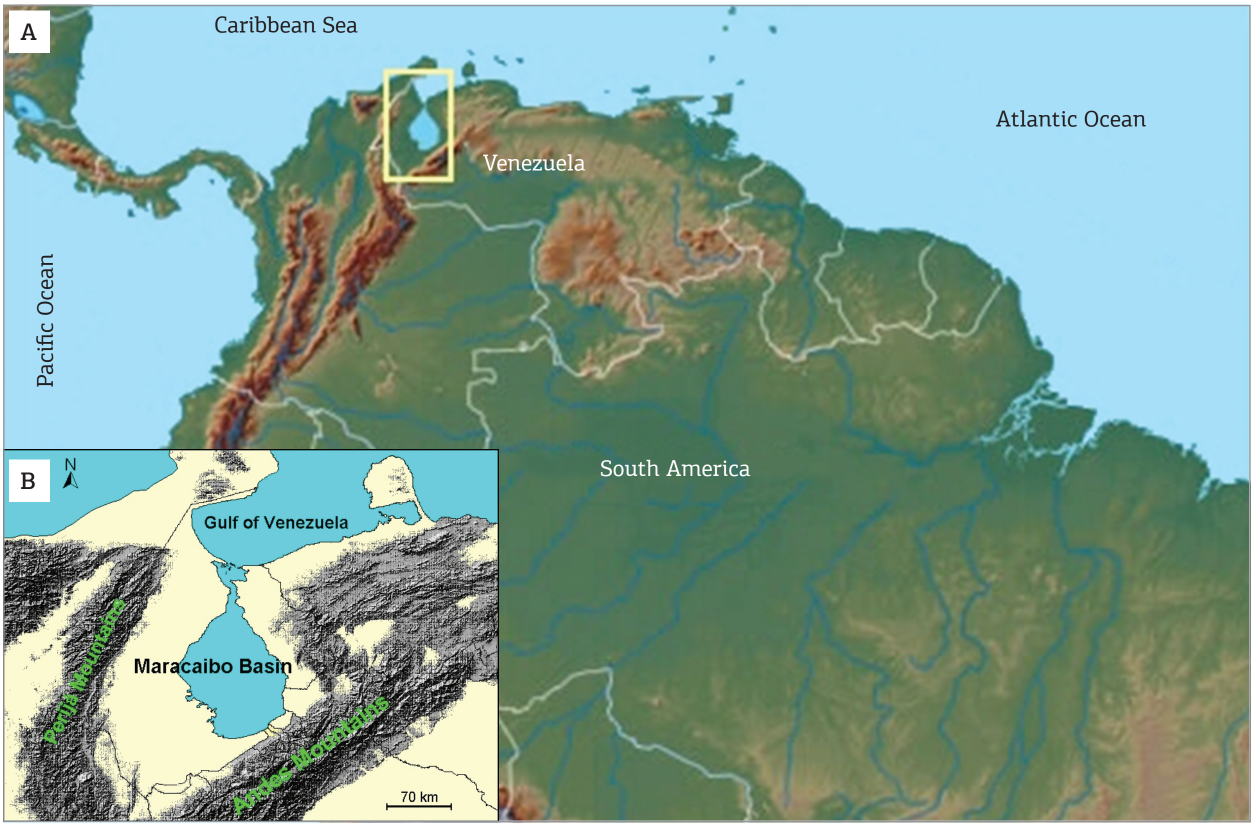

Figure 1. (A) Geographical position of the Maracaibo basin with respect to Venezuela and South America. (B) The deep of the Maracaibo Basin in the subsurface is ranged between 6,000 and 18,000 feet and is extended over the Zulia state and part of the Gulf of Venezuela. The most important outcrops with large thicknesses of Lower Cretaceous are in Perijá. In the Andes of Venezuela, the thicknesses are smaller but the changes in facies of ancient shorelines of the platform can be observed.

Detailed studies on sedimentation, transgressive and regressive stratigraphic cycles, porosity levels, diagenesis, organic and inorganic constituents were performed by macro descriptions of cores from several wells within the basin and a subsequently petrographic and petrological detailed study of thin sections. Once characterized the various sedimentary facies, porosity areas and possible source rock levels in the Cogollo Group platform system, the corresponding intervals to oceanic anoxic events 1a and 1b were correlated by their identification through the use of electrical gamma ray logs in several wells in the basin.

To determine the hydrocarbon generating potential of these two TOC rich stratigraphic levels, a set of samples was taken from the base to the top of these black sedimentary levels in several cores, with the aim of quantify and determine the thermal maturity, quality and source of the organic matter that forms the kerogen, and the redox conditions of the depositional environment. For this purpose, the following experimental methods and techniques were required: Rock-Eval pyrolysis 6, to determine the values of S1, S2, S3, T Max, building kerogen types and organic matter maturation state; Visual Kerogen Assessment, that includes a study of the kerogen macerals and the determination of the Thermal Alteration Index (TAI), the Vitrinite Reflectance and Liptinite Fluorescence. Eventually, a sedimentological model and paleoenvironmental implications for these facies are developed.

GEOLOGICAL SETTING

Before clastic sedimentation of the Río Negro Formation and subsequent Cogollo Group calcareous sediments, a system of grabens was developed in southwest-northeast direction, stretching from Ecuador to the current Gulf of Venezuela (Fig. 2). These grabens were located among the current Magdalena River valley, the valley of the Cesar and the Perija Mountains. Much of the Maracaibo Basin was included in this system, which included the Perijá-Machiques fossa, the Uribante fossa, the groove of the Guajira, the San Lázaro graben and the graben of Lake of Maracaibo (LEV 1970, 1997). The grabens represent a part of the tectonic

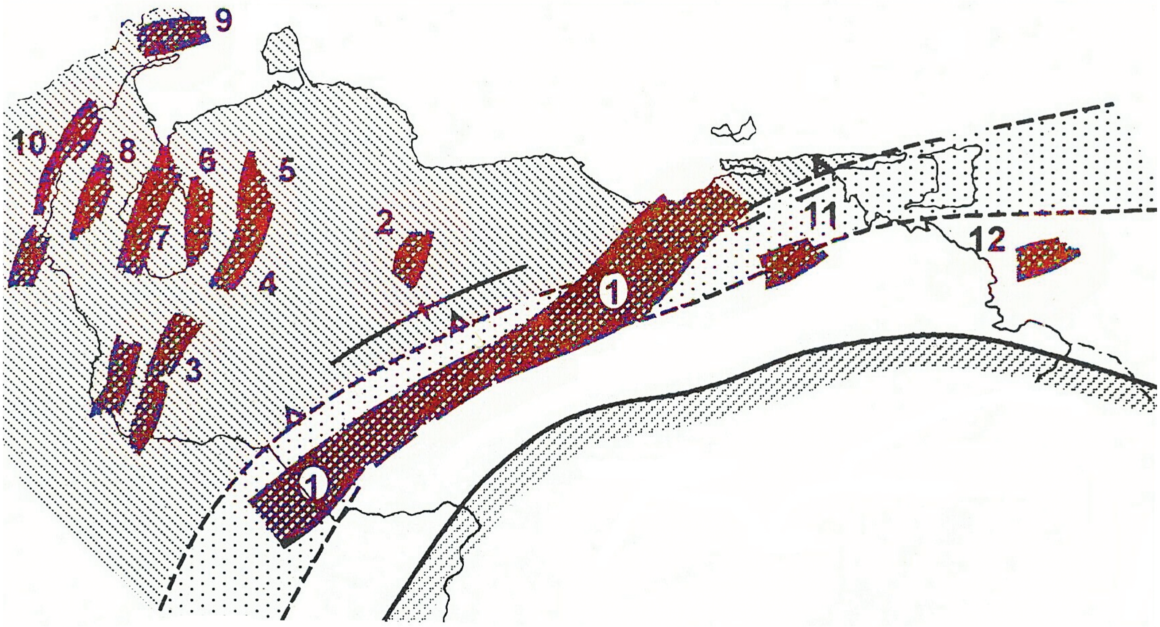

Figure 2. Position of different grabens formed during the early Jurassic as part of tectonic extension and breakup of Pangaea. This graben system and its sedimentary filling underlie the Cogollo Group (LEV 1997).

extension and partial rupture during the breakup of Pangea during early Jurassic and the beginning of the opening of the proto-Caribbean during early Cretaceous, when the volcanic activity ceased. A series of volcanic red beds, known as La Quinta Formation, was deposited inside the grabens. This process caused the partial fillings of the grabens. Later, during the Neocomian and Barremian, continental sedimentation and fluvial and alluvial environments dominated the sedimentary processes, and sandstones and conglomerates facies were deposited interbedded with siltstones and shales of the Río Negro Formation of Barremian age.

The sandstones and conglomerates facies overlying La Quinta Formation completed the filling of the grabens, shaping a plain physiographic system. The Río Negro Formation has highly variable thicknesses. In the grooves as Machiques, thicknesses may exceed 1,000 m, whereas on the peneplain and most of Lake of Maracaibo, it has only a few tens of meters (LEV 1997).

Carbonates of Cogollo Group have an origin and belong to the same derivative sedimentation of ancient Tethys Sea, in which calcareous sediments were deposited with similar characteristics and ages in the Gulf of Mexico (calcareous Cretaceous environments of Mexico and southern USA). The calcareous sedimentation took place on a passive margin platform, during the development of the proto-caribbean, as a consequence of the separation that the North American craton and the South American craton experienced by means of a mid-ocean ridge (Ross & Scotese 1988; Pindell & Kennan 2001; Bachmann 2001; Orihuela 2012). Passive margins corresponded to shelf seas. Once the transgression began, these shelf seas penetrated deep into the cratons, developing reef margins and calcareous sedimentary environments behind the margins (Fig. 3).

During the formation of the Gulf of Mexico, previous carbonate deposits, from late Jurassic, were developed on the coastal plains areas of Mississippi, Alabama and Florida (Manzini *et al.* 2001). Since the late Barremian and early Aptian, one active calcareous sedimentation began around the platforms bordering the Gulf of México as a consequence of an eustatic transgression (Vail *et al.* 1977; Méndez 1989a; Himes 2000; Lehmann *et al.* 2000), which was related to a large release of ocean basalts, which caused the development of a thick oceanic crust and the rising of the sea level during Aptian, Albian and most of late Cretaceous (Arthur

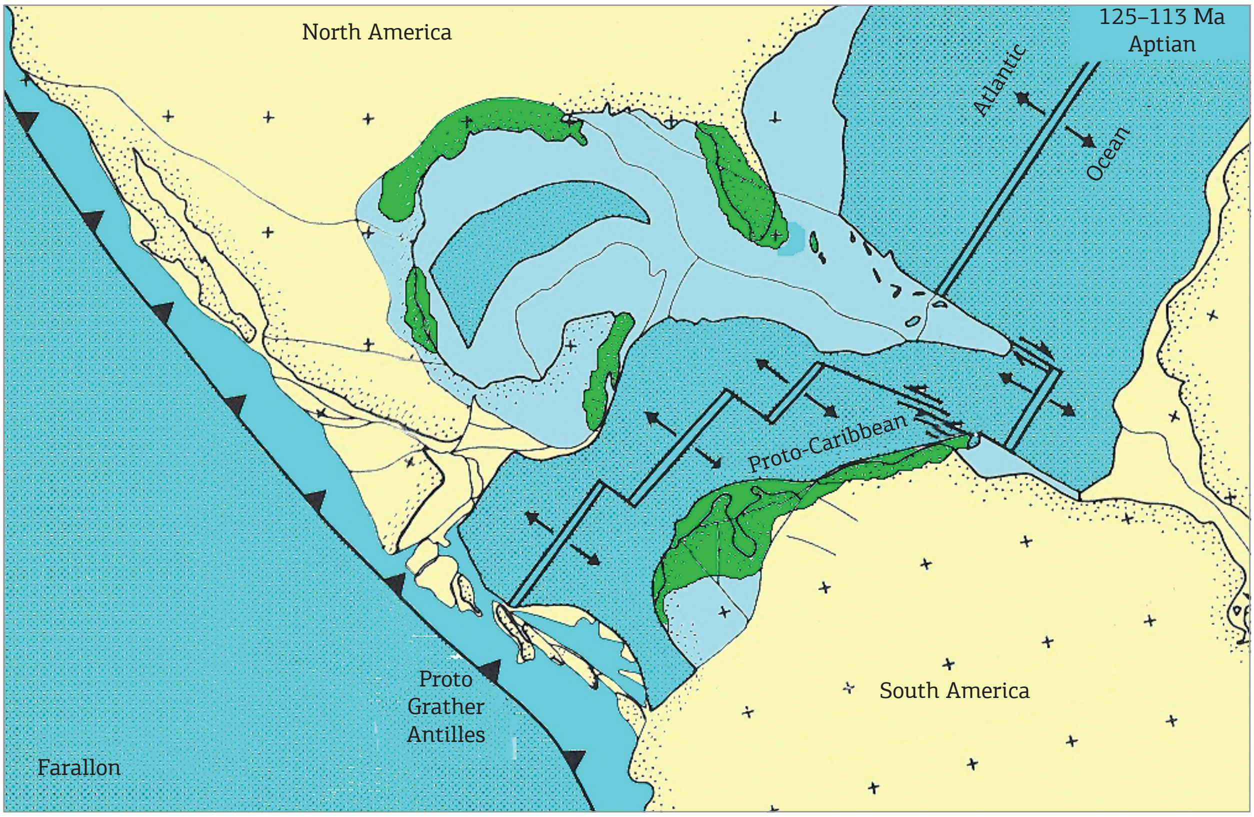

Figure 3. Areas of carbonate platforms during the early Aptian (in green). In Venezuela, these carbonate systems were developed in the Maracaibo and the Orient basins. Part of this system is also found in eastern Colombia in outcrops and the subsurface.

et al. 1985; Larson 1991; Berner 1992; Jones & Jenkyns 2001; Kuypers *et al.* 2002; Jahren 2002; Wagreich *et al.* 2011). From the Valanginian and Hauterivian, carbonates were developed on the shorelines of the northwest coast of South America (now Colombia).

STRATIGRAPHIC AND SEDIMENTOLOGICAL CHARACTERIZATION

The carbonates of Cogollo Group were deposited throughout the Aptian and Albian. This group is formed by three formations: Apón (Aptian), Lisure (Albian) and Maraca (late Albian). The Apón Formation is divided into three members: Tibú, Machiques and Piché. The carbonate sedimentation is interdigitaded with siliciclastic facies deposited mainly in shorelines to the east and south of the old carbonate platform. These carbonate and clastic sediments represent an initial ramp that evolved into a platform (Méndez 1989a, 1997). Sedimentation at the base of the Apón Formation (Tibú Member) was developed on a ramp and the transition to a platform is at the stratigraphic level that corresponds to the Machiques Member. The top of the Apón Formation (Piché Member), and the Lisure and Maraca Formation indicate that the sedimentation occurred in the platform, with regional extension for most facies. A good example is the oolites facies in Lisure Formation and Piché Member, which extend throughout the platform for a specific stratigraphic level and a geologic time. Maraca Formation has similar regional features, because the entire platform has a similar thickness and characteristics in terms of lithology, texture and porosity present (Fig. 4).

The calcareous sedimentation was developed at the beginning of Aptian in the north of South America craton and it overlies the conglomerates and sandstones of Río Negro Formation of late Barremian age. Overlying Cogollo Group is La Luna Formation, deposited since Cenomanian to Campanian, which is one of the most important oil source rocks in the world (Fig. 4). Today, among the subsurface and lifted areas in Perijá and Los Andes Mountains, the basin extends over many states from western Venezuela, covering Zulia, Táchira, Mérida and Lara states, western Falcón state and a part of the Gulf of Venezuela. From the beginning of the sedimentation, the basin covers over 100,000 km^2, between what is now Venezuela and Colombia. In Venezuela, it currently covers over 70,000 km^2. Most of the basin lies in the subsurface and partly as outcrops in the Andes and Perijá mountains. The stratigraphy and sedimentation were initially studied in outcrops of the Andes and Perijá (Renz 1977; García Jarpa *et al.* 1980; Macellari 1988), but in the last 30 years, researches have been focused mainly in core studies (Bartok *et al.* 1981; Chacartegui 1985; Méndez 1989a, 1997), and log analysis (Fig. 4). The Cogollo Group in the subsurface range from 17,000 to 14,000 feet deep, but in some areas it is deeper and shallower than it is in others, such as the La Paz field, where carbonates are found at 6,000 – 8,000 feet deep. Thicknesses range between 1,700 feet in the subsurface near the Perijá Mountains Piedmont (west of the basin) up to 900 feet in the central area of the basin. In the Andes (east) and the south of the basin, the thickness of the Cogollo Group decreases to 700 feet. This area represented the coast line with sandstone, siltstone and shale interdigitations. The thickness difference is related to a greater or lesser subsidence that allowed the variation in the sedimentation. In the west, a greater subsidence allowed more sediment accumulation, while in the center, east and south of the basin, the subsidence was lesser. This increased the accumulation of sediment in the Tibú member, which corresponds to the bottom of the Apón Formation, represents a ramp-type depositional environment that subsequently evolved to a platform of shallow depths. In the West, Tibú Member has 700 feet thickness, but in the center, east and south, it has only 40 – 30 feet.

The reservoirs facies of Río Negro, Apón, Lisure and Maraca formations are vertically separated by more than 400 feet between them, therefore, it is necessary to estimate more than one source rock, allowing the migration of hydrocarbons to nearby reservoirs. The oil stored in these reservoirs was generated by the anoxic and high TOC facies deposited during the oceanic anoxic events that occurred during the early Cretaceous (OAE 1a of early Aptian, ~ 120 Ma; and OAE 1b of late Aptian, ~ 113 Ma) and late Cretaceous (OAE 2 of Cenomanian-Turonian ~ 93 Ma). The OAEs 1a and 1b are represented in the stratigraphic record of the Cogollo Group by a black pelagic and hemipelagic levels which are present in the Machiques and the top of the Piché members respectively and both are part of the Apón Formation, while the OAE 2 is part of La Luna Formation.

Many controversies have arisen from various studies on porosities and main type facies that may consist in hydrocarbon reservoirs, their origin, main diagenesis related (surface or burial) and fractures as the porosity main forming element (Méndez 1989b, 1997, 2009; Kummerow & Pérez de Mejía 1989; Márquez 1997; Montoya & Méndez 2005; Nelson *et al.* 2000). Usually in the last decades of drilling for Cretaceous in the Maracaibo Basin, the wells were located near major faults and fracture systems looking porosity related to these (Fig. 4). The authors of this study estimate that the major chemical and diagenetic changes in dissolution and cementing carbonates occurred either on the surface or close

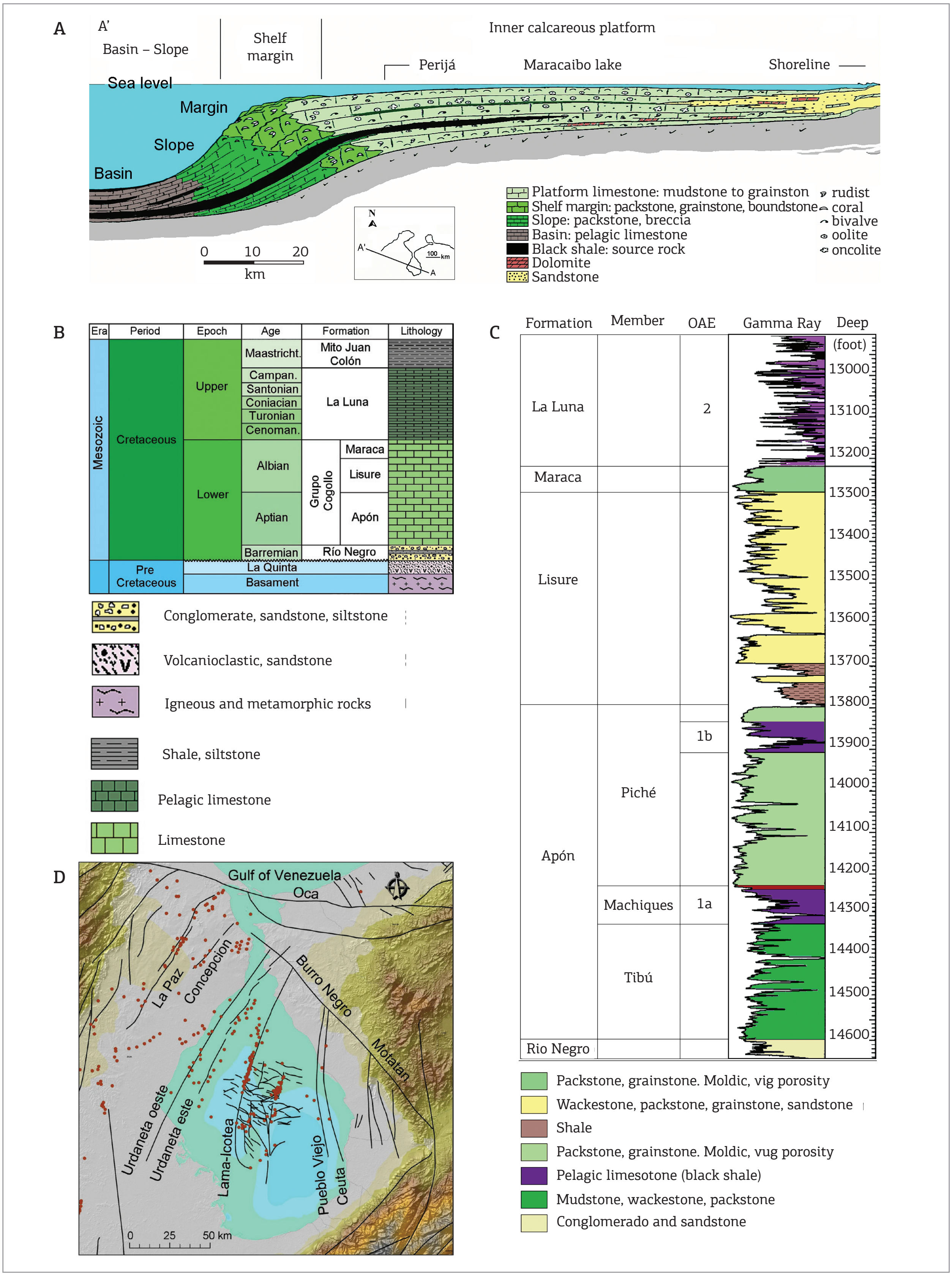

Figure 4. (A) Idealized model for the platform of the Cogollo Group. (B) Stratigraphic chart for the Cretaceous Period in the Maracaibo Basin. (C) Stratigraphic position of the formations, members and OAEs 1a and 1b in the Cogollo Group in a gamma ray well log (well TOT 3). (D) Alignment of several wells (red dots) in the Maracaibo basin, following the pattern of faulting at the large faults systems, looking for porous stratigraphic intervals developed by fractures.

to it, during primary diagenesis. However, this controversial and important topic is not covered in this article.

Apón Formation

The Apón Formation represents the onset of carbonate sedimentation overlaying Río Negro Formation. It indicates the gradual cessation of erosion and transport of siliciclastic positive areas in the craton and the onset of marine transgression on the platform. The sedimentation gradually changes, along the entire basin, from sandstones of Río Negro Formation to carbonates and calcareous facies with interdigitaded clastic sediments derived from an incipient ramp, which gradually changes to a shallower platform system. Apón Formation is formed by Tibú, Machiques and Piché members. The typical fauna described by Renz (1977) of Aptian age, consists of several bivalve genera: *Ostrea scyfax*, *Exogyra boussingaulti* and echinoids as *Toxaster sp*. The *Choffatella decipiens*, a benthic foraminifera that is found always at the base of the Apón Formation, is characteristic of Tibú Member as well as the green algae *Dinaric Salpingoporella* (Ford & Houbolt 1963).

Tibú Member

It represents the bottom of Apón Formation and it indicates the initial phase of a marine transgression on the platform, mainly forming a ramp as the sedimentation and the transgression progressed on ancient shorelines. All the transgressions (TST) moved the cost line from west to east, but always intercalated with a little regressions until the cost line was established at the actual position of the Andes of Venezuela. The texture of the sediments varies from mudstone to packstone. Wackestone and mudstone predominate with green algae, echinoderms, bivalves and miliolids fragments. Packstone facies are occasionally composed by caprinid fragments (rudist). The *Choffatella decipiens* is common at Tibú base along the basin. The porosity is too small to constitute reservoirs and it rarely exceeds 2%. The thicknesses are highly variable over 700 feet in the west of the basin to 30 feet near the ancient shorelines, which is typical of a ramp system.

Machiques Member

Machiques Member was formed by a great and fast transgression over the Tibú Member. The transgresion covered almost the entire basin and reached the coast line during previous sedimentation of Tibú Member. It was described as "a possible source rock" by Méndez (1989c) and Méndez *et al.* (1990). This was based on the observations and descriptions of many cores, which are located in different points of the Maracaibo Basin, and many examples for TOC analysis (2 – 5.6%) and Tmax (temperature at which the maximum release of hydrocarbons from cracking of kerogen occurs during pyrolysis at the top of S2 peak: 434 – 441°C). Alberdi-Genolet and Tocco (1999) proposed the Machiques Member as a "possible source rock" based on geochemical analysis performed on an outcrop in Perijá, Venezuela. With the increasing of depth and the rising in the organic matter content at the top of Tibú Member, a rapid transgression occurred during early Aptian, characterized by an oceanic anoxic event (OAE 1a). From the Cogollo Group platform margins, the transgression resulted in the sedimentation of a pelagic facies that covered most of the basin, which is present at Rosario, Aricuaisa, Machiques Alturitas, San Jose, Alpuf, La Villa, La Paz, Urdaneta West fields, among others (Méndez 2009). The designation of pelagic to this sedimentation does not necessarily indicate a great water depth, since the anoxic event source was determined by physicochemical characteristics of the waters transgression, being oxygenated at the surface and anoxic at the bottom, and these conditions were achieved at only few tens of meters deep. The Machiques Member in some sectors of the fields mentioned above it may reach 100 – 120 feet thick. In Perijá region, concretions contain abundant macrofossils, among them fish, molluscs, *Inoceramus* and *Douvilliceras*, *Drufencia*, *Deshayesites,* ammonites. After petrography studies of the thin sections, undeveloped pelagic foraminifera were identified (LEV 1997). Sutton (1946) describes the following ammonites: *Deshayesites colombianus*, *Chelonieras cornuelianum*, and *Parahoplites inconstants*. Renz (1977) reports *Engonoceras* genus ammonites at the top.

The top of Machiques is characterized by a massive dolomite facies, which appears on a regional scale to the north and west of the platform and gradually decreases towards the Lake of Maracaibo and the Andes. This dolomite facies presents, in some wells, intercrystalline and vugs porosity, and fractures on the top. These features indicate a rapid marine regression (LSW) that exposed the upper sediments deposited on the platform, which favored an intense evaporation and dolomitization processes. The black shale of Machiques indicates, by its stratigraphic position, a favorable migration to overlying porosity facies at the Piché Member.

Piché Member

When the Piché Member sedimentation started, all the carbonate system was represented by a shelf bordered by a margin (packstone and grainstone of bioclasts, oolite and isolated coral and rudist colonies) and not by a barrier reef. The inner shelf is represented by facies and environments we know today (lagoon, banks, cost line). The Piché Member represents shallow facies and several cycles of lagoon facies (TST) at the base with mudstone and wackestone mainly of green algae and peloids, and packstone and grainstone in banks and bars at the top of the sequence (HST), with progradation in the inner platform.

The facies are composed of fragments of bioclasts (green algae, pelecypods, gastropods, benthic foraminifera, echinoderms, bryozoans), and peloids, ooids, among others, and they formed a series of sequences of small marine transgressions and regressions that partially affected the platform. The Piché Member is represented by several depositional textures, among which mudstone, wackestone, packstone and grainstone are included. These facies indicate banks and bars of calcareous sediments at shallow depths, formed by currents and tidal systems. All of these facies and depositional environments were originated at shallow depths and the most important packstone and grainstone textures were formed during the progradation on the platform.

In the upper zone of Piché Member, the benthic foraminifera Orbitolina is found, which is considered as a biozone and its stratigraphic position is the same for the entire basin. At the top of Piché, organic matter-rich pelagic facies was deposited during a mayor transgression as a consequence of an oceanic anoxic event, corresponding to OAE 1b. These TOC rich sediments generated the oil stored in the middle and near the top of the Apón formation reservoirs. The Piché Member has similar thickness throughout the basin, about 400 feet. This indicates the subsidence along the platform did not vary.

Lisure Formation

The Lisure Formation presents a very similar thickness throughout the basin. The thickness is slightly larger to the east and north. This fact indicates a balance between subsidence and sedimentation rate, but with a small increasing of sedimentation mainly in packstone and grainstone of oolite and bioclasts facies. The deposition of this formation is typical of a progradational facies with the development of banks at shallow depths and prograding sedimentation toward the basin. At the base of Lisure, in the southern area of Lake of Maracaibo, there are two levels of quartz sandstones. These levels are separated by a limestone interval. This indicates two terrigenous events which probably represent a mouth bar sedimentation environment that belongs to Aguardiente Formation, but it is considered an interdigitation of carbonates and clastics that belongs to the base of Lisure (Azpiritxaga 1991). The most representative Lisure Formation limestone facies were developed as bioclasts bars, oolites, pellets and oncolites, among which we can find gap facies of green algae, benthic foraminifera (mainly miliolids) and partial dolomitization events of wackestone, packstone and occasionally grainstone on these platform and lagoon facies.

The Lisure Formation represents a transgressive facies sequences at the base and high levels at the top, with an active sedimentation at very shallow depths. Facies are mainly transgressive and they typically have large amounts of glauconite, which indicates a decrease in overall sedimentation and a partially reducing environment. The facies of oolites, intraclasts and bioclasts are regional and they indicate interdigitated bars mobilized by currents and tides. The oolites of Lisure Formation do not indicate the presence of a margin or close to it, as it is usually indicated in some facies distribution schemes (Wilson 1975). By the time of sedimentation, Lisure developed high levels of intergranular porosity in grainstone facies with oolites and bioclasts. However, the presence of sparite precipitated in pore spaces into many Lisure Formation facies indicates a high rainfall climate in the basin and in the area of terrigenous sediments sources. Sparite formed due to diagenesis in meteoric groundwater and freshwater environments destroyed much of the porosity. At the Urdaneta West field, the Lisure formation has a thickness that ranges from approximately 370 – 380 feet.

Maraca Formation

This formation marks the end filling carbonate platform, with extensive regional facies found throughout the basin, which were deposited in shallow depths, and probably never exceeded 3 or 4 feet deep. The Maraca Formation has a thickness that ranges from approximately 50 – 60 feet all over the basin, indicating a gradational system with progradation at the top of the sequence. At the top of the Maraca Formation, the facies are characterized by large colonies of pelecypods and often rudist mounds are present in the platform. Biostromes that prograded developed regionally at high sedimentation levels. The biostromes were exposed to subaerial diagenesis during a marine regional regression and moldic and vug porosities were developed, providing a level of bivalves with packstone porosities above, that characterizes this formation reservoir. At the top of Maraca Formation, the foraminifera biota is planktonic with pelecypods, indicating the first transgressive developments that eventually gave rise to La Luna Formation. The organisms' content of the facies at the bottom is more heterogeneous, as well as inorganic grains and authigenic minerals. The depositional textures are mainly packstone of bioclast and wackestone generally of ooids, intraclasts and bioclasts with varying proportions of glauconite, pyrite and quartz fragments.

Constituents, texture and porosity

The organic and inorganic constituents include green algae, planktonic and benthic foraminifera, bivalve, gastropod, oncolite, bryozoan, echinoderm, brachiopods, ostracod, pellets, oolite, dolomite, quartz, glauconite and pyrite. The best porosity values (moldic, vug interparticle) in the Piché Member and Maraca Formation are found in packstone and grainstone facies (Fig. 5).

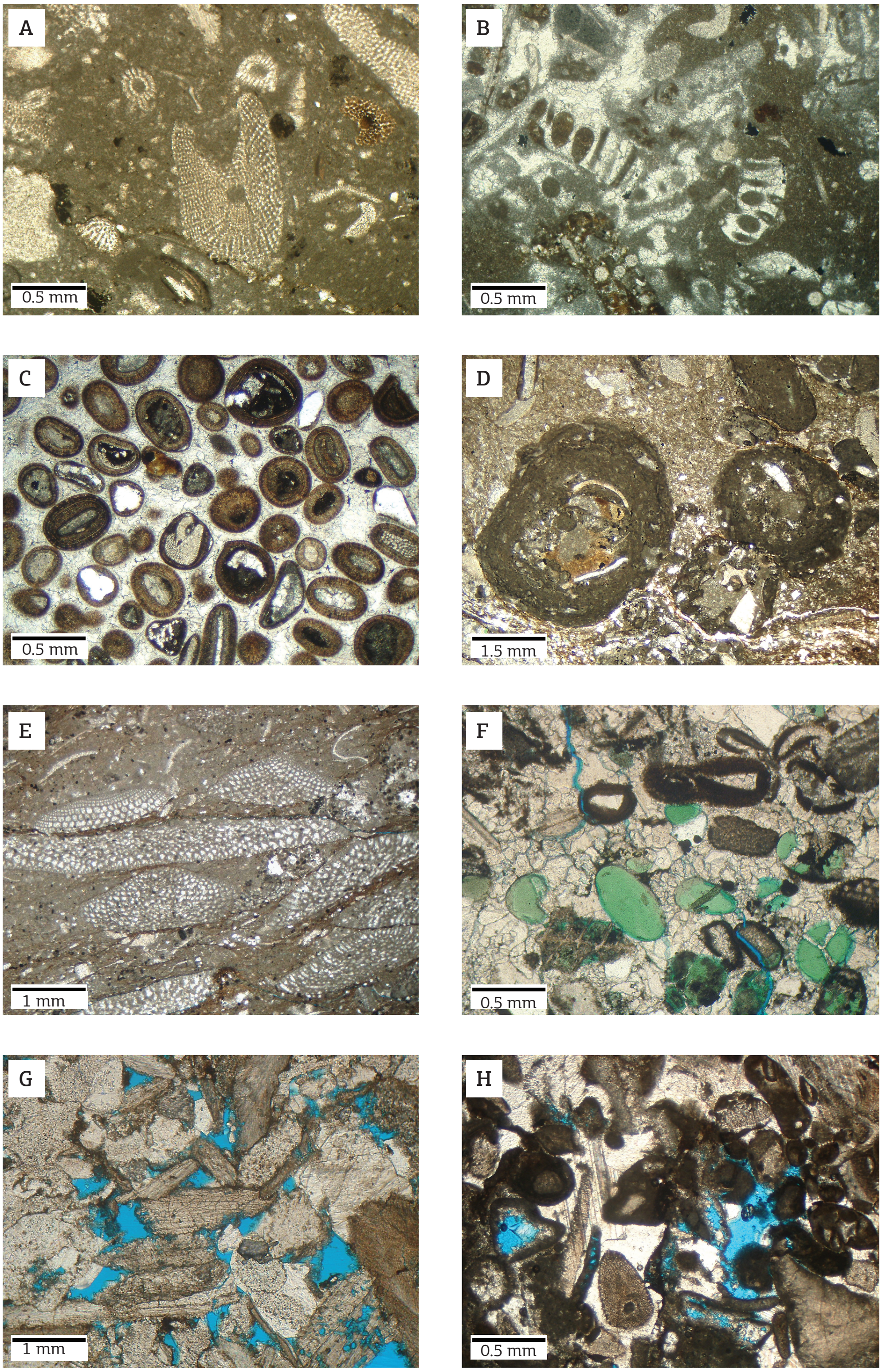

Figure 5. Some characteristic facies in the Cogollo Group. (A) Echinoderm wackestone, Apón Formation. (B) Green algae wackestone, Apón Formation. (C) Oolites grainstone without porosity, Lisure Formation. (D) Oncolites wackestone, Lisure Formation. (E) Orbitolina benthic foraminifera wackstone-packstone, Piché Member of the Apón Formation. (F) Oolites grainstone with glauconite peloid, Lisure Formation. (G) Bivalves fragment grainstone with intergranular porosity, Maraca Formation. (H) Oolites and bioclastic grainstone with intergranular porosity, Piché Member.

OCEANIC ANOXIC EVENTS

During the Phanerozoic, changes in sea level developed episodes with significant accumulations of organic carbon-rich sediments or source rocks. Hydrocarbon generators sediments are related to rising sea levels and marine transgressions, while coal deposits occurred during low sea levels and marine regressions. During the Middle and Late Cretaceous, globally transgressive events (Fig. 6) coupled with an increase in the organic matter productivity and the diversity of pelagic organisms led to the deposition of sedimentary facies, both carbonate and clastic, organic-rich, which represent the main source rocks worldwide. These events are characterized by a large burial of organic carbon during the Cretaceous and were the cause of isochronous cyclic perturbations of the global carbon cycle, which are known in the literature as the "oceanic anoxic events" (Schlanger & Jenkyns 1976; Baron *et al.* (1981); Jenkyns 1980, 2010). The causes that produced these oceanic anoxic events in a global scale were derived from a combination of several factors (Schlanger & Jenkyns 1976; Baron *et al.* (1981); Jenkyns 1980, 2003, 2010; Arthur *et al.* 1990; Bralower *et al.* 1994; Wignall 1994):

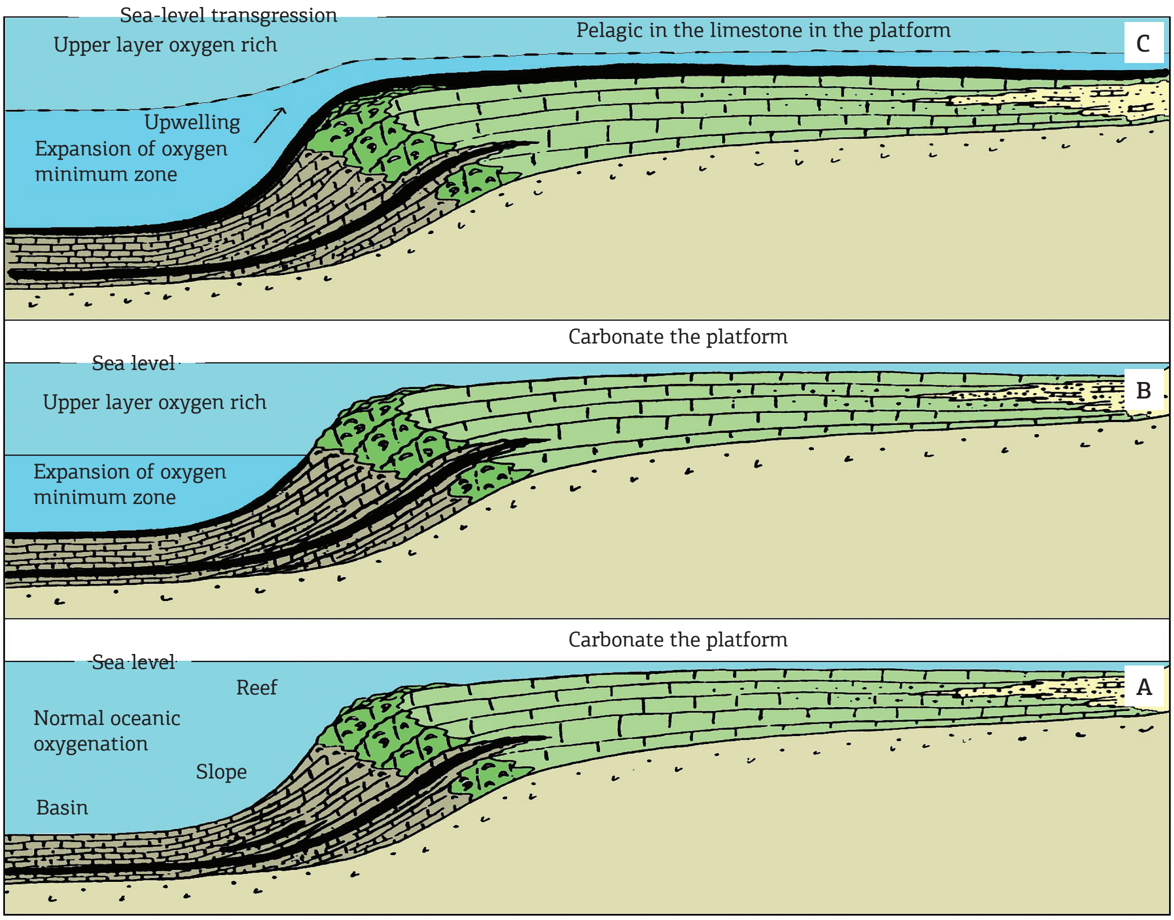

Figure 6. Diagram that illustrates the sedimentation of TOC-rich facies on the shallow shelf after a transgressive event due to the expansion of the oxygen minimum zone. (A) Normal oxygenation of the ocean waters in the basin, slope and shallow shelf. (B) Beginning of the expansion of the oxygen minimum zone in the basin and the slope due to the increase in the organic matter productivity and normal oxygenation in the shallow shelf. (C) Increase and rapid sea-level transgression on the shallow shelf; increase in the oxygen minimum zone in the basin and the platform margin; transfer of oxygen minimum zone and anoxic waters to the platform by the marine transgression; upwelling currents influence in the margins of the platform, whose wealth of nutrients was propitious for the development of the planktonic biota, contributing to anoxia at bottom waters. Thus, during the Cretaceous, several marine transgressions were able to move the anoxic environments to shallow shelf, causing various organic matter-rich sediment levels.

- Marine transgressions that covered large areas of the continental platforms, causing epeiric or epicontinental seas.
- Greater emission of basalts in ocean ridges and the formation of Large Igneous Provinces (LIP) in various parts of the world that increased the CO_2 concentration in the marine environment and the atmosphere.
- High productivity of organic matter derived from phytoplankton and zooplankton and organic matter developed in large coastal areas (deltas, lagoons), which were incorporated into the platforms and epeiric seas.
- Development of anoxic conditions at the bottom marine waters of the deep basin and the platform due to the consumption of dissolved oxygen in the water column as a consequence of a high primary productivity, which led to the deposition and preservation of large amounts of organic matter. This led to an increase in the concentration of CO_2 in marine environments.
- Expansion of oxygen minimum zone, poor circulation and vertical mixing of the water due to the stratification of the same, based on differences in density of water bodies according to depth.
- Influence of upwelling currents, which locally transported nutrients and led to an increase in the productivity of organic matter and the expansion of the oxygen minimum zone.
- Stagnation of water in enclosed marine basins.

PELAGIC LIMESTONE IN COGOLLO GROUP

During sedimentation Cogollo Group, which represents the facies situated only behind a platform margin, the inner shelf was subject to the normal cycles of transgressions and regressions. As the platform became shallower, a relatively small transgression partially or completely flooded this platform. Thus, the Cogollo Group carbonates are an interdigitation of transgressive and regressive stratigraphic sequences. The transgressive facies, as part of the petroleum system, act as seals, or in some cases, as source rock for porosity facies which were originated and preserved during the regressive events.

In front of the margin platform (slope and basin) an anoxic environment was developed in the background and it had periods of alternate anoxia-dysoxia events with higher and lower intensity.

During some major transgressions, the anoxic environment and characteristics facies of a pelagic environment moved from the slope to the platform, whereby organic matter was developed and preserved on an essentially shallow sedimentary system, interspersed between facies that indicate high sedimentation levels that in some cases developed porosity. Thus, the Cogollo Group platform was able to develop “source rock” levels that generated oil volumes in addition to those generated by La Luna Formation, with relatively small migrations to porosity facies at the same platform (Méndez 1989c, 2009).

These ideas have also been explored in the Persian Gulf, at the platforms of the Middle Cretaceous carbonates (Khatiyah and Mishrif formations), where it is estimated that a high organic matter content in mudstone and wackestone facies of the inner shelf act as the source rock and adjacent porosity level act as reservoir facies (Farzadi 2006). Therefore, the generation and storage of hydrocarbons occurred in adjacent facies.

Porosity zones and oil reservoirs in the Cogollo Group have three different source rocks originated during three oceanic anoxic events displaced from the margin to the inner platform:

1. the source rock of Machiques Member was deposited during the OAE 1a of the early Aptian (~ 120 Ma). Probably this source rock has generated the oil stored in Río Negro Formation reservoirs (Barremian sandstones and conglomerates underlying the Apón Formation) and Piché Member reservoirs, together with those arising from the OAE 1b (~ 113 Ma). It is located at the western areas of the basin, with a decreasing thickness in the area of Lake of Maracaibo;
2. the source rock of the Piché Member is located at the top of this member of the Apón Formation and was deposited during the OAE 1b (late Aptian, ~ 113 Ma). Probably the oil stored in the Piché porosity facies was generated by this source rock.
3. the La Luna Formation, which is deposited from the Cenomanian and is the most important source rock in the Maracaibo Basin, corresponds to OAE 2 (~ 93 Ma). The reservoirs in the Maraca Formation porosity facies throughout the basin contain the oil generated by the La Luna Formation.

Pelagic limestone in Apón Formation

The Apón Formation has two important pelagic limestones facies (black shale), representing two “effective source rocks”. The first, known as the Machiques Member, was deposited during early Aptian OAE 1a. The second one is virtually unknown, but reported as possible “source rock” and corresponds to OAE 1b (Méndez *et al.* 2008).

Pelagic limestone in Machiques Member – oceanic anoxic event 1a

The Machiques Member is an example of a pelagic limestone. It was deposited on a shallow shelf at the top of Tibú Member, displacing anoxic features from the outer edge of the platform and the basin to the inner shelf by a marine transgression. The Machiques Member is well represented in the western part of the basin, mainly in the Alpuf, Totumo, San Jose, Alturitas, San Julián, Machiques, La Paz, Urdaneta Oeste fields, among others.

In some of these areas, it may be up to 100 or more feet thick. Towards the middle and near the top, the facies are purely pelagic limestones with planktonic foraminifera and, especially toward the top, dolomite crystals are disseminated in the limestone matrix (Fig. 7). Therefore, the Machiques Member represents an oceanic anoxic event that was derived from a marine transgression that led to the deposition of a "source rock" that overlies the shallow shelf carbonates facies. This event corresponds to OAE 1a (Aptian, ~ 120 Ma).

The top of Machiques Member indicates a marine regression that affected most of the basin, mainly in the western areas. The marine regression affected the uppermost platform sediments and it caused a shallow sedimentary environment at the top of the pelagic limestones, increasing the evaporation rate and the Mg/Ca ratio, promoting regional dolomitization. The importance of the pelagic limestones and the Machiques Member "source rock" is the presence of an oceanic anoxic event on the shallow platform itself, which generated the hydrocarbons that migrated easily after its generation to these dolomite facies with intercrystalline porosity and other facies located in the Piché Member.

Pelagic limestone in Piché Member – oceanic anoxic event 1b

The Piché Member of the Apón Formation is a classic example of transgressive and regressive stratigraphic sequences. Some of these are regressive cycles in which moldic porosity and vugs were developed. These cycles are located between transgressive sequences that act as seals for porosity zones. On the top of Piché Member, there are two levels of pelagic limestone that indicate, as in the case of Machiques, an oceanic anoxic event which was displaced toward the internal platform by marine transgressions (Fig. 7).

These levels of high TOC values have generated the hydrocarbons stored into adjacent facies with porosity. Higher thicknesses are found on the top of the member, where the pelagic facies may submit up to 60 feet thick and lay between shallower levels of porosity facies that are often present. It is important to consider that the top of the Piché Member has the best Apón Formation reservoirs. The presence of pelagic limestones, interdigitated between porosity zones, suggests that Piché Member oil reservoirs were not necessarily generated by La Luna Formation, and a more logical view indicates that they were generated by a source rock near or adjacent to the reservoirs facies. We consider that this anoxic level of the late Aptian belongs to the OAE 1b (~ 113 Ma).

Oceanic anoxic event 1a and oceanic anoxic event 1b - black shales

The OAEs 1a and 1b were disturbances in the global carbon cycle. The early Aptian event (Selli event, OAE 1a) has its type locality in Italy, named "Livello Selli" (Coccioni *et al.* 1989; Baudin *et al.* 1998; Li *et al.* 2008; Blättler *et al.* 2011), and the event of early Albian (Paquier event, OAE 1b) was first recognized in the Vocontian basin in southeastern France (Bréhéret 1985, 1994; Herrle *et al.* 2003). Both events are well represented by organic rich black shales in the Alpine-Mediterranean region and anthers regions of the world (Sliter 1989; Bralower *et al.* 1993; Herrle *et al.* 2003; Tsikos *et al.* 2004; Robinson *et al.* 2008; Hofmann *et al.* 2008; Blättler *et al.* 2011; Nuñez-Useche *et al.* 2014).

The black shale term has been used in the literature for a wide variety of rocks, usually without a specific definition (Wignall 1994). Therefore, the use of this term is descriptive and does not include strictly the mineralogical composition of the rock and its petrological classification. Tyson (1987) defined black shales as a muddy fine-grained, dark colored rock which presents sedimentological, paleoecological and geochemical characteristics associated with sedimentation in anoxic environments. In this paper, the authors consider an organic matter-rich facies as black shale, regardless of the ratio between the content of carbonate and clastic sediments.

ORGANIC GEOCHEMISTRY RESULTS

Sampling covered the stratigraphic intervals of interest in six cores of six wells located at the Maracaibo Basin, and this was done based on the following criteria:

- Visual estimates as the colour of the rock, lamination degree, grain size and absence of bioturbation.
- Correlation between the depth of the rock intervals of interest in both electric logs and cores (Fig. 8).

A total of 254 samples were taken, that corresponds to the stratigraphic intervals of OAEs 1a (~ 120 Ma, Machiques Member) and 1b (~ 113 Ma, Piché Member). All samples were administered through the Rock-Eval 6 pyrolysis technique, in order to obtain the values of: TOC (% weight), S1 (mg HC/g rock; free hydrocarbons), S2 (mg HC/g rock; hydrocarbons generated from the thermal cracking of kerogen), S3 (mg HC/g rock; CO_2 generated during pyrolysis kerogen), and T Max (maximum temperature reached during the peak of S2; Celsius degrees). Some of the results are shown in Tabs. 1 to 3.

The percentage of TOC average for most the studied intervals is greater than 2% and maximum values that are greater than 7%, values for defining these intervals as a "very good"

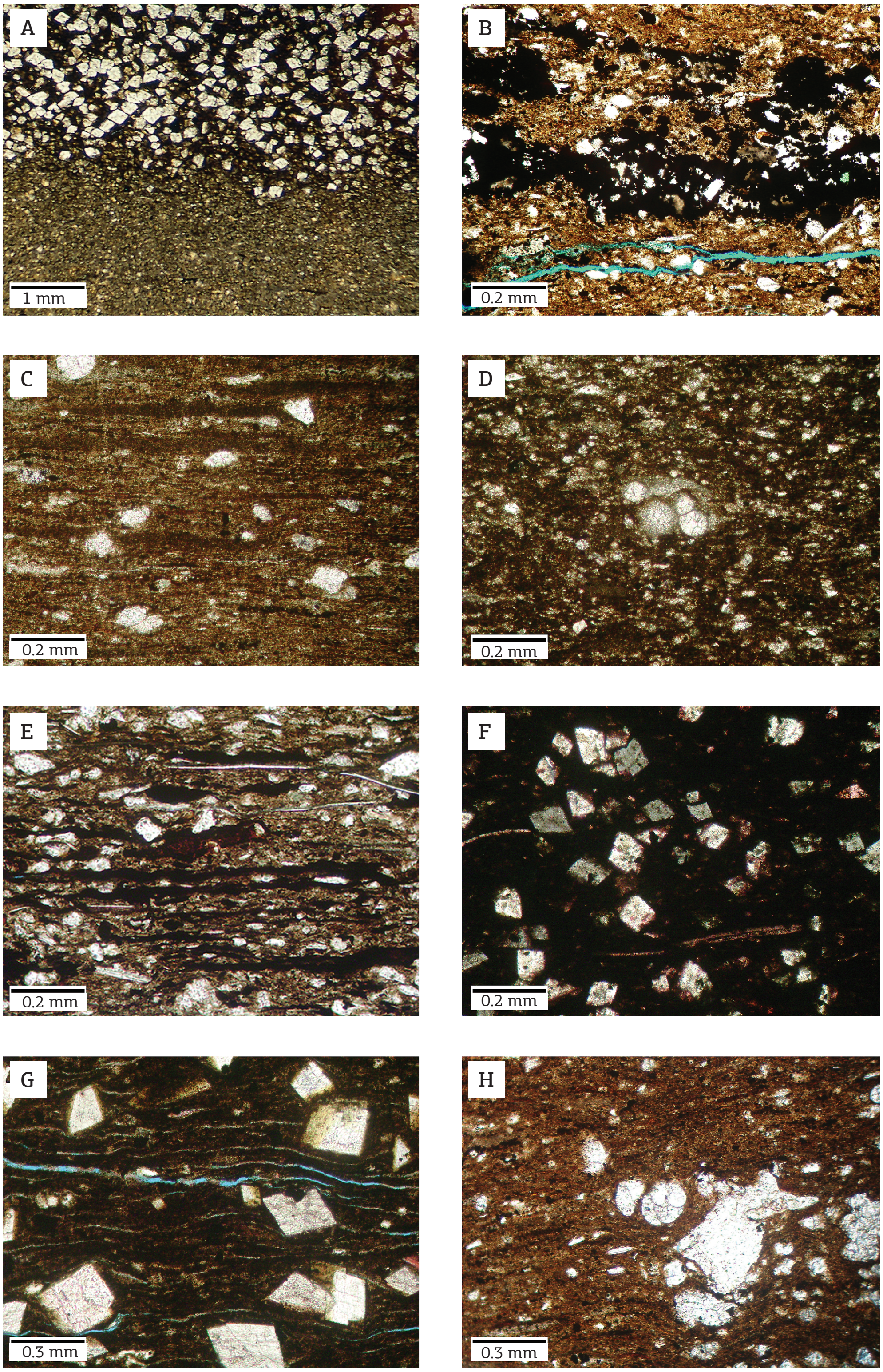

Figure 7. (A) Contact between the rich TOC mudstone facies and dolomite facies on top of the Machiques Member (OAE 1a). (B) Partially phosphatized mudstone with kerogen and bitumen accumulated in pore spaces (OAE 1a). (C) Laminated mudstone with isolated dolomite crystals and fragments of planktonic foraminifera (OAE 1a). (D) Similar to previous but with major planktonic foraminifera development (OAE 1a). (E, to G) Facies with isolated dolomite crystals and bioclasts fragments, kerogen and/or bitumen are oriented according to the rock lamination (OAE 1b). (H) Similar to the previous but more developed planktonic foraminifera (OAE 1b).

source rocks as to the amount of organic matter posing. S2 values are between 5 and 20 mg HC/g rock, representing source rocks values "good" to "very good". The maximum temperature (T Max) reached at the peak of generation S2 lies on an average between 435 and 445°C, which implies that these rock intervals reached the temperature required to cause the thermal cracking of the kerogen and form the bitumen (Tabs. 1 to 3). This allows to state that the source rock levels proposed in Machiques and Piché Members of Apón Formation should be considered as "effective source rocks" as they have generated and expelled hydrocarbons (Hunt 1995; Peters *et al.* 2005a).

For a total of 42 samples, it was performed a visual kerogen assessment, which was composed of the following studies (Figs. 9 to 16):

- Determination of the proportions of macerals in the samples, with a predominance of liptinite content (macerals abundant in source rocks composed of type II kerogen and oil generators) of about 80% and the identification of solid bitumen, which indicates *in situ* hydrocarbon generation and primary migration processes.
- Thermal alteration index (TAI), using a transmitted light microscopy, with results that, according to the colour scale used in this technique, yielded dark colours for the organic matter; that is indicative of a thermal maturity according to the generation of hydrocarbons.
- Vitrinite reflectance (%Ro), with average values between 0.6 and 1.1, that places most consistent samples within the thermal maturity hydrocarbon generation window.

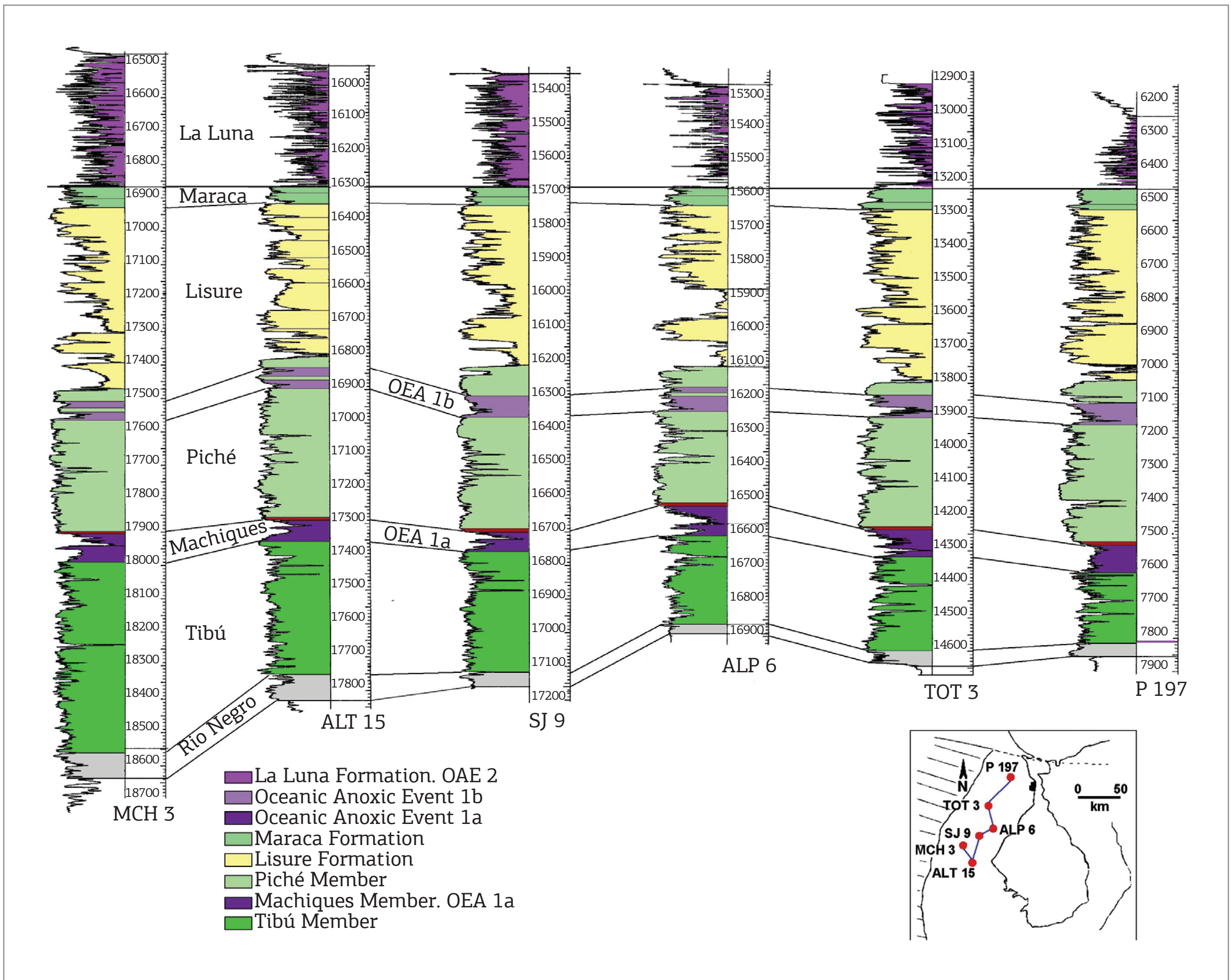

Figure 8. Correlation of wells with electric logs of gamma ray in western Maracaibo basin. The stratigraphic and sedimentological features observed in the cores are extrapolated to records which allows for an effective correlation throughout the basin. It can be seen that the greatest thickness in the Apón Formation is related to the Tibú Member and this occurs in the western areas, which may be associated with a subsidence increase during the deposition, while thicknesses of Piché Member and Lisure and Maraca formations are relatively constant, indicating similar subsidence for the basin. It was also observed that the OAE 1a was deposited in one period of time on the platform, while the OAE 1b can be divided into two levels of black shale facies, separated by a shallow carbonate facies with low organic matter content. Depth is presented in feet.

- Fluorescence liptinites, macerals that within the studied samples showed a low fluorescence intensity and indicative of thermal maturity commensurate with the oil generation window. In turn, the identification of organic material of amorphous structure in most samples under ultraviolet excitation of blue light is more indicative of the presence of organic material suited for generating oil (Hunt 1995; Peters *et al.* 2005a).

Visual kerogen assessments complement chemical assessments by recording information from the discrete particles (macerals) that make up the sedimentary organic matter. Vitrinite macerals are particles of sedimentary organic matter derived

Table 1. ALPUF 6 core samples. Total organic carbon, Rock-Eval pyrolysis, hydrogen index and vitrinite reflectance results.

ALPUF 6 Member / OAE	Sample	TOC	S1	S2	S3	HI	Tmax (°C)	%Ro (WR)	%Ro (I.Q)
Piché / 1b	16110’	1.61	1.06	3.58	0.62	222	438	0.82	–
Piché / 1b	16120’	1.28	0.53	3.49	0.2	273	443	0.80	–
Piché / 1b	16212’	2.82	1.2	8.57	0.36	304	443	0.78	
Piché / 1b	16223’	2.93	2.28	8.79	0.37	300	444	0.81	1.13
Piché / 1b	16230’	3.03	2.00	9.33	0.36	308	443	0.78	–
Piché / 1b	16232’	7.23	6.71	26.99	0.42	373	435	0.81	1.08
Machiques / 1a	16543’	2.35	0.74	7.08	0.39	301	444	0.82	–
Machiques / 1a	16545’	4.68	1.07	14.93	0.43	319	445	0.83	1.12
Machiques / 1a	16555’	2.59	2.16	6.4	0.57	247	439	0.84	–
Machiques / 1a	16565’	4.20	3.06	19.32	0.38	460	444	0.94	–
Machiques / 1a	16569’	5.25	2.78	19.37	0.32	369	439	0.89	1.19

TOC: total organic carbon; HI: hydrogen index; Tmax: temperature at which the maximum release of hydrocarbons from cracking of kerogen occurs during pyrolysis at the top of S2 peak; %Ro: vitrinite reflectance; WR: whole rock.

Table 2. Z26 D2 core samples. Total organic carbon, Rock-Eval pyrolysis, hydrogen index and vitrinite reflectance results.

Z26 D2 Member / OAE	Sample	TOC	S1	S2	S3	HI	Tmax (°C)	%Ro (WR)	%Ro (I.Q)
Piché / 1b	11209’	4.66	0.40	21.4	0.59	459	426	0.61	0.65
Piché / 1b	11230’	4.72	0.33	23.01	0.74	487	426	0.61	0.67
Piché / 1b	11262’	3.16	0.15	21.09	0.40	667	434	0.60	–
Piché / 1b	11278’	13.12	2.06	77.41	0.88	590	435	0.66	0.85
Piché / 1b	11283’	8.56	0.30	48.13	0.80	562	433	0.72	0.84
Piché / 1b	11331’	2.98	0.20	18.45	0.54	619	433	0.68	–
Machiques / 1a	11589’	2.25	0.37	9.14	0.88	376	436	0.80	–
Machiques / 1a	11598’	1.71	0.17	5.81	0.71	341	437	0.82	–
Machiques / 1a	11609’	4.09	0.43	20.04	0.62	490	441	0.52	0.92
Machiques / 1a	11632’	10.97	1.16	43.39	0.75	395	428	0.63	0.98
Machiques / 1a	11635’	9.19	0.98	46.72	1.11	508	435	0.68	0.76

TOC: total organic carbon; HI: hydrogen index; Tmax: temperature at which the maximum release of hydrocarbons from cracking of kerogen occurs during pyrolysis at the top of S2 peak; %Ro: vitrinite reflectance; WR: whole rock.

from wood, and their reflectance of incident light under oil immersion is used to assess the thermal maturity of a sample.

The core samples analyzed belong to Totumo 3, Alpuf 6 and Z26 D2 wells, and the obtained results indicate that the organic matter-rich facies under study (Machiques Member and the top of the Piché Member) are effective source rocks, since the thermal maturity of organic matter indicates that most samples are displayed within the oil

Table 3. Totumo 3 core samples. Total organic carbon, Rock-Eval pyrolysis, hydrogen index and vitrinite reflectance results.

TOTUMO 3 Member / OAE	Sample	TOC	S1	S2	S3	HI	Tmax (°C)	%Ro (WR)	%Ro (I.Q)
Piché / 1b	13782'	1.55	0.86	7.32	1.13	472	429	0.50	–
Piché / 1b	13841'	2.52	1.64	15.67	0.74	622	434	0.50	1.04
Piché / 1b	13852'	3.52	0.52	25.34	0.51	7,21	431	0.56	–
Piché / 1b	13856'	2.29	1.26	13.00	0.80	568	435	0.66	0.68
Piché / 1b	13866'	1.94	1.10	11.75	0.62	606	433	0.75	–
Machiques / 1a	14240'	2.14	1.34	4.64	0.80	217	431	0.75	–
Machiques / 1a	14248'	2.32	2.38	10.81	0.82	466	435	0.77	–
Machiques / 1a	14253'	3.34	2.56	25.28	0.66	756	437	0.75	–
Machiques / 1a	14262'	3.72	1.03	18.82	0.53	507	438	0.71	0.92
Machiques / 1a	14271'	2.59	1.25	11.49	0.63	444	438	0.78	1.02
Machiques / 1a	14300'	3.67	1.76	22.25	0.68	614	437	0.78	0.94

TOC: total organic carbon; HI: hydrogen index; Tmax: temperature at which the maximum release of hydrocarbons from cracking of kerogen occurs during pyrolysis at the top of S2 peak; %Ro: vitrinite reflectance; WR: whole rock.

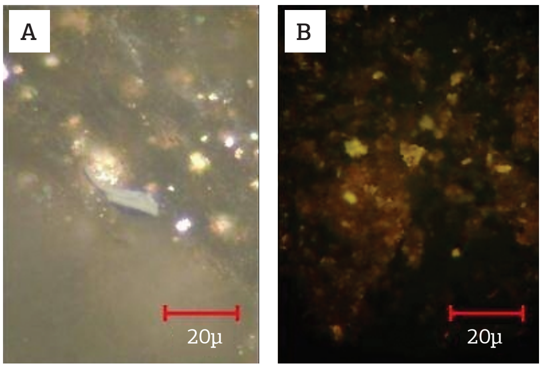

Figure 9. Visual kerogen assessment (isolated kerogen). Sample depth: 11230' (Z26 D2 core). Piché Member (oceanic anoxic event 1b). Kerogen is dominated by mild to dark orange fluorescing amorphous matter. Solid bitumen is present in modest to significant amounts. Kerogen is classed as type II. Vitrinite reflectance indicates kerogen is early oil window mature. Photomicrograhps: (A) incident white light; (B) incident blue light.

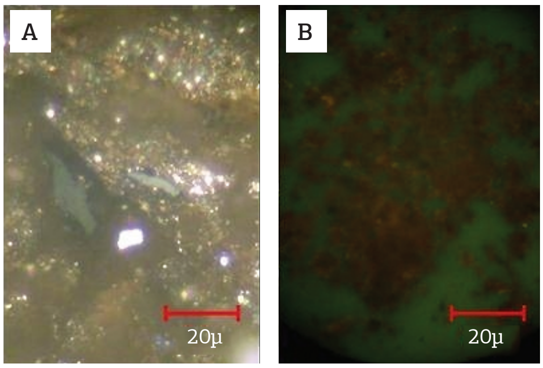

Figure 10. Visual kerogen assessment (isolated kerogen). Sample depth: 11278' (Z26 D2 core). Piché Member (oceanic anoxic event 1b). Kerogen is dominated by very weak fluorescing dark orange-red amorphous matter. Solid bitumen is present in minor amounts. Kerogen is classed as type II. Vitrinite reflectance indicates kerogen is early oil window mature. Photomicrographs: (A) incident white light; (B) incident blue light.

window maturity. We present two examples of the obtained results in Figs. 13 to 16.

The results shown in Tabs. 1 to 3 for 33 samples present TOC values above 1%, and 32 of them show values above 1.5%, indicating a high potential for hydrocarbon generation. Tmax values indicate that 22 of the 33 samples have a maturity in accordance with the oil generation window (early oil window between 435 – 445°C; peak oil window between 445 – 450°C). However, according to what is stated in the literature (Tissot & Welte 1978; Hunt 1995; Killops & Killops 2005; Peters *et al.* 2005a), the vitrinite reflectance (%Ro) is

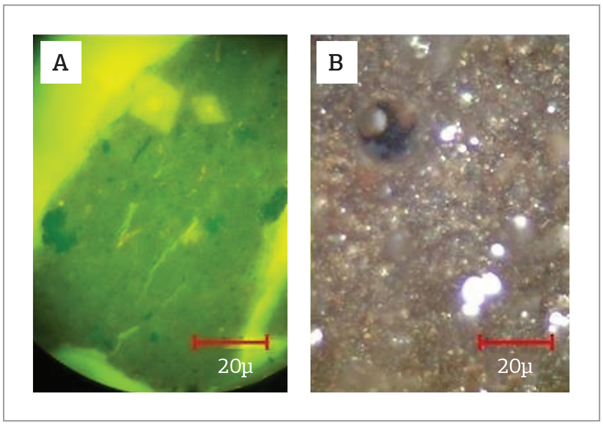

Figure 11. Visual kerogen assessment (whole rock). Sample depth: 14248' (Totumo 3 core). Machiques Member (oceanic anoxic event 1a). Calcareous shale has a moderate matrix bitumen stain. Foraminifera tests are infilled with amorphous matter, and solid bitumen is reasonably common. Vitrinite reflectance indicates shale is peak oil window mature. Photomicrographs: (A) incident blue light; (B) incident white light.

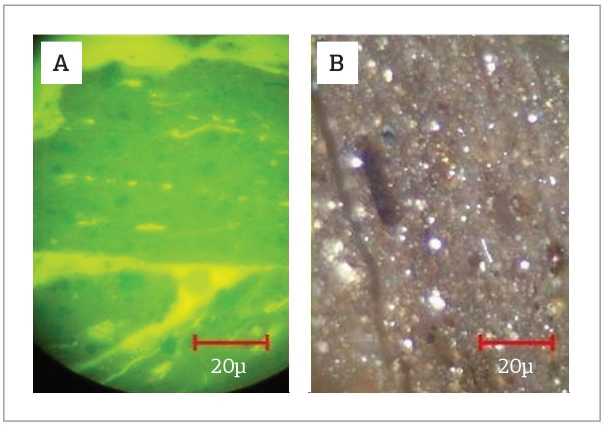

Figure 12. Visual kerogen assessment (whole rock). Sample depth: 14240' (Totumo 3 core). Machiques Member (oceanic anoxic event 1a). Mudstone is laminated with bitumen streaks, and matrix has moderately strong pervasive bitumen stain. Vitrinite and inertinite are present in minor abundance. There is low to moderately rich liptinite content. Vitrinite reflectance indicates shale is peak oil window mature. Photomicrographs: (A) incident blue light; (B) incident white light.

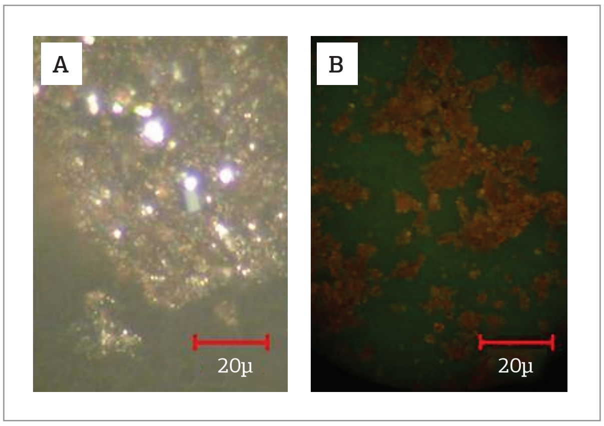

Figure 13. Visual kerogen assessment (isolated kerogen). Sample depth: 11278' (Z26D2 core). Piché Member (oceanic anoxic event 1b). Kerogen is dominated by mild to dark orange-red fluorescing amorphous matter. Solid bitumen is present in minor amounts. Thermal Alteration Index (2 to 2+) is based on trace spore and amorphous kerogen color. The proportion of macerals is dominated by liptinite (86%), followed by alginnite (20%), inertinite (10%) and vitrinite (4%). Kerogen is classed as type I/II with a good potential for the generation of oil hydrocarbons. Vitrinite reflectance (%Ro = 0.85) indicates kerogen is peak oil window mature. Photomicrographs: (A) incident white light; (B) incident blue light.

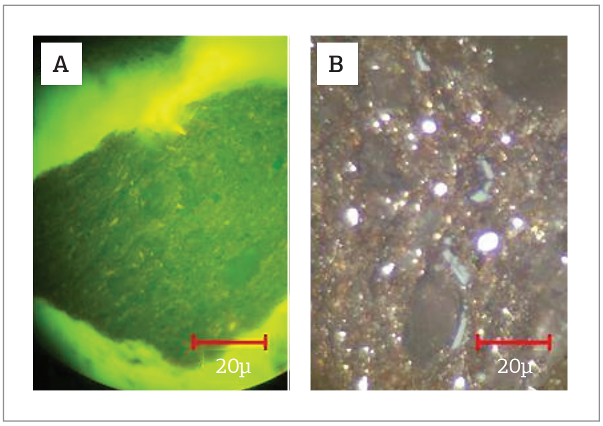

Figure 14. Visual kerogen assessment (whole rock). Sample depth: 11278' (Z26 D2 core). Piché Member (oceanic anoxic event 1b). Calcareous shale shows a great content of liptinite when it is viewed in incident white light. Solid bitumen appears to be dominant over minor inertinite. Vitrinite reflectance (%Ro = 0.66) indicates shale is early oil window mature. Photomicrographs: (A) incident blue light; (B) incident white light.

the most reliable parameter to determine the thermal maturity of the rock. This was determined for the 33 samples in whole rock (WR) and isolated kerogen (IK). The values obtained for %Ro (WR) indicate that 29 of the 33 samples have a maturity in accordance with the oil generation window (early oil window between 0.6 and 0.65, peak oil window between 0.65 and 0.90, generation wet gas zone between 0.90 and 1.35). The results for %Ro in isolated kerogen are higher than those obtained in the whole rock, since it eliminates the interference generated by mineral phases. These indicate that all the samples analyzed reached at least the peak oil window generation zone, and 10 samples reached the wet gas zone generation. Maturity ranges of all the maturity parameters shown in tables were taken from Peters *et al.* 2005a.

Soxhlet extraction

This technique was performed on a set of 11 core samples for the purposes of quantifying the amount of extractable organic matter (EOM or bitumen). The amount of bitumen obtained for each of the analyzed samples is greater than 2,000 ppm (very good), and in 7 samples it is greater than 4,000 ppm (excellent) (Peters *et al.* 2005a). Some of the results are shown in Tab. 4.

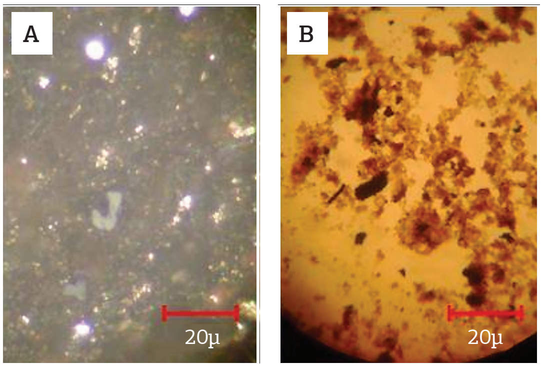

Figure 15. Visual kerogen assesment (isolated kerogen). Sample depth: 14271' (core Totumo 3). Machiques Member (OAE 1a). Kerogen is dominated by non-fluorescing amorphous matter, followed by a significant amount of terrestrially-derived organic matter. Solid bitumen is present in minor amounts while algal and spore debris are present at trace-level abundance. Organic matter fluorescence has extinguished. The proportion of macerals is dominated by liptinite (70 %), followed by inertinite (15 %), vitrinite (14 %) and alginite (6 %). TAI (3/3+) is based on red-brown to dark brown trace spores in conjunction with amorphous kerogen color. Kerogen is classed as type II. Vitrinite reflectance (% Ro = 1.02) indicates kerogen is late oil window mature. Photomicrographs. (A): incident white light; (B): transmitted white light.

Gas chromatography mass spectrometry biomarker analysis

Data obtained from the thermal maturity biomarker indicators are consistent with those obtained by Rock-Eval pyrolysis and visual kerogen assessment. The ratios of saturated compounds $C_{32}\beta\alpha/(\alpha\beta+\beta\alpha)$ Hopane; Ts/Ts+Tm; Tric./Tric.+17α Hopane; C_{29}20S/(20S+20R) Esterane; $C_{29}\beta\beta/(\beta\beta+\alpha\alpha)$ Esterane; and mono-aromatic and tri-aromatic compounds MA(I)/MA(I+II); TA(I)/TA(I+II); TA28/TA28+MA29 indicate that the thermal maturity of most samples analyzed are between early and peak oil window generation (Hunt 1995; Killops & Killops 2005; Peters *et al.* 2005b).

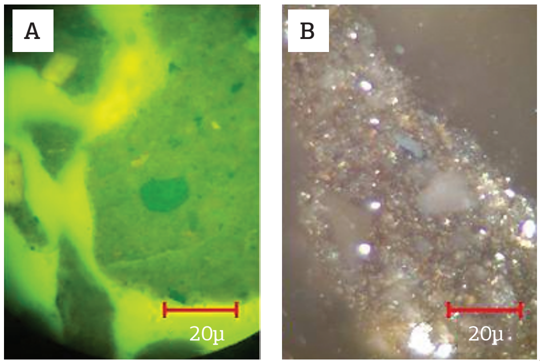

Figure 16. Visual kerogen assesment (whole rock). Sample depth: 14271' (Totumo 3 core). Calcareous shale has a moderately rich organic matter content that is comprised mostly of recycled vitrinite, inertinite and bituminite. Primary vitrinite is present in modest amounts. Matrix shows a strong bitumen stain. Vitrinite reflectance (%Ro = 0.82) indicates kerogen is peak oil window mature. Photomicrographs: (A) incident blue light; (B) incident white light.

Table 4. Soxhlet extraction (ppm = mg EOM / kg rock)

Core / depth (feet)	Member / OAE	EOM (ppm)
Alpuf 6 / 16.232'	Piché / 1b	19,539
Alpuf 6 / 16.545'	Machiques / 1a	4,472
Totumo 3 / 13.187'	Piché / 1b	4,821
Totumo 3 / 13.852'	Machiques 1a	6,670
Z26 D2 / 11.278'	Piché / 1b	14,347
Z26 D2 / 11.609'	Machiques / 1a	3,287

ppm = mg EOM/kg rock.
EOM: extractable organic matter.

CONCLUSIONS

The Cogollo Group in the Maracaibo Basin (Venezuela) is the largest system of shallow shelf carbonates deposited during the Aptian and Albian in north-western South America. It consists of the Apón Formation, with Tibú Machiques and Piché members, the Lisure Formation and Maraca Formation. This carbonate system underlies the La Luna Formation, which is one of the most important world source rocks deposited from Cenomanian to Campanian.

The calcareous sedimentation begins with the sea level rise in the late Barremian and early Aptian above the conglomerates and sandstones of the Río Negro Formation. In a similar way, most of the carbonate systems began as a carbonate ramp, which evolved to a platform system, gaining stability between regional subsidence and sedimentation.

The Cogollo Group has a wide variety of lithofacies, biofacies and porosity levels, and generally presents regional extension. Some of these facies present porosity and represent oil reservoirs in the Apón and Maraca formations, which have the largest carbonate reservoirs along the basin.

In reference to anoxic events with pelagic limestone sedimentation deposited in the Cogollo Group platform and prior to the massive event that gave rise to the La Luna Formation, we can consider the following:

- During the sedimentation of the Cogollo Group carbonates, some mayor transgressions were able to move the physicochemical and sedimentological characteristics to the inner shelf and the slope from outer margin and caused the deposition of anoxic pelagic and hemipelagic limestones with high organic matter content.
- The Machiques Member represents a regional event, characterized by a massive OAE with carbonate pelagic sedimentation on the shallow inner shelf. The thickness of this high TOC level is 80 feet or more in some western areas of the basin.
- Towards the top of the Piché Member, there is another high TOC level shifted to the inner shelf and divided by two intervals, the main of which is located closer to the top of the Piché Member and had a longer duration, with thicknesses of over 60 feet, on a regional basis, and it is located between hydrocarbon producing intervals.

According to this, there were two major OAEs derived from marine transgressions on the platform as well as other smaller events with similar characteristics. Major events correspond to Machiques Member (OAE 1a) and the top of Piché Member (OAE 1b).

According to sedimentological, petrographical and organic geochemistry results, the organic matter-rich facies in Machiques (OAE 1a) and Piché (OAE 1b) members should be considered as "effective source rocks". Rock-Eval pyrolysis, visual kerogen assessment, soxhlet extraction, gas chromatography mass spectrometry saturated and aromatic biomarkers results indicate that the thermal maturity of the kerogen in the analyzed samples is in the range between early window and peak oil window generation.

ACKNOWLEDGEMENTS

The authors wish to thank PDVSA-Exploration and PDVSA-Petroregional del Lago and the PDVSA-Nucleoteca staff at La Concepción, Zulia state, Venezuela, besides to Professor Patricia Lugo, from Faculty of Sciences of the Central University of Venezuela, for her interesting comments related to organic geochemistry, and to colleagues and BJG editors for the opportunity to consider the publication of this work.

REFERENCES

Alberdi-Genolet M. & Tocco R. 1999. Trace metals and organic geochemestry of the Machiques Member (Aptian-Albian) and La Luna Formation (Cenomanian-Campanian), Venezuela. *Chemical Geology*, **160**:19-38.

Arthur M.A., Dean W.E., Schlanger S.O. 1985. Variations in the global carbon cycle during the Cretaceous related to climate, volcanism, and changes in atmospheric CO_2. *American Geophysical Union Monograph*, **32**:504-529.

Arthur M.A., Jenkyns H.C., Brumsack H.J., Schlanger S.O. 1990. Stratighraphy, geochemestry, and paleoceanography of organic-rich Cretaceous sequences. *In*: Ginsburg R. N. & Beaudoin B. (eds.) *Cretaceous resources, events and rhythms*. NATO ASI Ser., 304. Dordrecht, Kluwer Academy, p. 75-119.

Barron, E.J., Thompson, S.L., Schneider, S.H. (1981): Cretaceous'oceanic events' as casual factors in development of reef-reservoired giant oil fields. - Amer. Ass. Petrol. Geol. Bull., 63, 870-875

Azpiritxaga I. 1991. Carbonate depositional styles controlled by siliciclastic influx and relative sea level changes, Coger Cretaceous, Central Lake Maracaibo, Venezuela. MS Dissertation, University of Texas, Austin.

Bachmann R. 2001. The Caribbean plate and the question of its formation. Freiberg, Institute of Geology, Department of Tectonophysics, Freiberg University of Mining and Technology.

Bartok P., Reijers T.J.A., Juhasz I. 1981. Lower Cretaceous Cogollo Group, Maracaibo Basin, Venezuela-sedimentology, diagenesis and petrophisics. *American Association of Petroleoum Geologists Bulletin*, **65**(6):1110-1134.

Baudin F., Fiet N., Coccioni R., Galeotti S. 1998. Organic matter characterisation of the Selli Level (Umbria-Marche Basin, central Italy). *Cretaceous Research*, **19**(6):701-714.

Berner R.A. 1992. Palaeo-CO_2 and climate. *Nature*, **358**:114.

Blättler C.L., Jenkyns H.C., Reynard L.M., Henderson G.M. 2011. Significant increases in global weathering during Oceanic Anoxic Events 1a and 2 indicated by calcium isotopes. *Earth and Planetary Science Letters*, **309**:77-88.

Bralower T.J., Arthur M.A., Leckie R.M., Sliter W.V., Allard D., Schlanger S.O. 1994. Timing and paleoceanography of oceanic dysoxia/anoxia in the late Barremian to early Aptian. *Palaios*, **9**:335-369.

Bralower T.J., Sliter W., Arthur M.A., Leckie R.M., Allard D.J., Schlanger S.O. 1993. Dysoxic/anoxic episodes in the Aptian-lbian (Early Cretaceous). *In*: Pringle M.S., Sager W.W., Sliter W.V., Stein S. (eds.) The Mesozoic Pacific: geology, tectonics, and volcanism. Geophys. Monograph Ser., 77, Washington, American Geophysical Union, p. 5-37.

Bréhéret J.G. 1985. Indices d'un événement anoxique étendu à la Téthys alpine, à l'Albien inférieur (événement Paquier). *Comptes-rendus des Séances de l'Académie des Sciences. Série 2*, **300**(8):355-358.

Bréhéret J.G. 1994. The mid-Cretaceous organic-rich sediments from the Vocontian zone of the French South-East Basin. *In*: Mascle A. (ed.) *Hydrocarbon and petroleum geology of France*. The European Association of Petroleum Geoscientists Special Publication, 4. Berlin, Springer-Verlag, p. 295-320.

Chacartegui F.J. 1985. Estudio Sedimentológico en el Grupo Cogollo del Cretáceo Inferior. *In*: VI Congreso Geológico de Venezuela. Caracas, *Tomo I*, p. 278-304.

Coccioni R., Franchi R., Nesci O., Wezel F.C., Battistini F., Pallecchi P. 1989. Stratigraphy and mineralogy of the Selli Level (Early Aptian) at the base of the Marne a Fucoidi in the Umbro–Marchean Apennines, Italy. *In*: Wiedmann J. (ed.) *Cretaceous of the Western Tethys*. *In*: 3rd International Cretaceous Symposium, Tübingen. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart. 1987, p. 563-584.

Dumitrescu M., Brassell S.C., Schouten S., Hopmans E.C., Sinninghe Damsté J.S. 2006. Instability in tropical Pacific sea-surface temperatures during the early Aptian. *Geology*, **34**:833-836.

Farzadi P. 2006. The development of Middle Cretaceous carbonate plataforms, Persian Gulf, Iran: constraints from seismic stratigraphy, well and bioestratigraphy. *Petroleoum Geoscience*, **12**:59-68.

Ford A. & Houbolt, J.J.H.C. 1963. Las microfacies del Cretáceo de Venezuela Occidental. In: International Sedimentary Petrographical Series by Cuvillier J. & Schürman H.M.E.,VI. Leiden, E. J.Brill. 170 p.

García Jarpa F., Ghosh S., Rondon F., Fierro I., Sampol M., Benedetto G., Medina C., Odreman O., Sanchez T., Useche A. 1980. Correlación Estratigráfica y Síntesis Paleoambiental del Cretáceo de los Andes venezolanos. *Boletín Geológico*, **14**(26):3-88.

Herrle J.O., Pross J., Friedrich O., Kößller P., Hemleben C. 2003. Forcing mechanisms for mid-Cretaceous black shale formation: evidence from the Upper Aptian and Lower Albian of the Vocontian Basin (SE France). *Palaeogeography, Palaeoclimatology, Palaeoeco*logy, **190**:399-426.

Himes B.T. 2000. *The lower Cretaceous James Lime Play of the Northeast Gulf of Mexico*: a new trend discovery made on the mature Gulf of Mexico shelf. Tulsa, SEPM, Society for Sedimentary Geology.

Hofmann P., Stüsser I., Wagner T., Schouten S., Sinninghe Damsté J.S. 2008. Climate-ocean coupling off North-West Africa during the Lower Albian; The Oceanic Anoxic Event 1b. *Palaeography, Palaeoclimatology, Palaeoecology*, **262**:157-165.

Hunt J.M. 1995. Petroleum Geochemestry and Geology. 2nd edition. New York, W. H. Freeman, 743p.

Jahren A.H. 2002. The biochemical consequences of the mid-Cretaceous superplume. *Journal of Geodynamics*, **34**:177-191.

Jenkyns H.C. 1980. Cretaceous anoxic oceanic events: from continents to oceans. *Journal of Geological Society*, **137**:171-188.

Jenkyns H.C. 2003. Evidence for rapid climate change in the Mosozoic-Paleogene greenhouse world. *Philosophical Transactions of the Royal Society A*, **361**:1885-1916.

Jenkyns H.C. 2010. Geochemistry of oceanic anoxic event. *Geochemestry, Geophysics, Geosystems*, **11**(3):30.

Jenkyns H.C. & Wilson P.A. 1999. Stratigraphy, paleoceanography, and evolution of Cretaceous Pacific guyots: relics from a greenhouse Earth. *American Journal of Science*, **299**:341-392.

Jones C.E. & Jenkyns H.C. 2001. Seawater strontium isotopes, oceanic anoxic events, and sea floor hydrothermal, activity in the Jurassic and Cretaceous. *American Journal of Science*, **301**:112-140.

Killops S. & Killops V. 2005. Introduction to Organic Geochemistry. USA, Blackwell Publishing, 393 p.

Kummerow E.C. & Pérez de Mejía D. 1989. Evolución diagenética de los carbonatos del Grupo Cogollo, Cuenca del lago de Maracaibo. *In*: VII Congreso Geológico Venezolano. Barquisimeto. Tomo II, p. 746-769.

Kuypers M.M.M., Blokker P., Hopmans E.C., Kinkel H., Pancost R.D., Schouten S., Sinninghe Damsté J.S. 2002. Archaeal remains dominate marine organic matter from the early Albian oceanic anoxic event 1b. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **185**:211-234.

Larson R.L. 1991. Geological consequences of superplumes. *Geology*, **19**:963-966.

Leckie R.M., Bralower T.J., Cashman R. 2002. Oceanic anoxic events and plankton evolution: biotic response to tectonic forcing during the mid-Cretaceous. *Paleoceanography*, **17**:623-642.

Lehmann C., Osleger D.A., Montañez I. 2000. Sequence stratigraphy of Lower Cretaceous (Barremian-Albian) carbonate platforms of northeastern Mexico: regional and global correlations. *Journal of Sedimentary Research*, **70**(2):373-391.

Ministerio de Minas e Hidrocarburos, 1970. Léxico Estratigráfico de Venezuela, 2a Edición, *Boletín de Geología*, Publicación Especial No. 4, Caracas, 756 p.

Léxico Estratigráfico de Venezuela - LEV. 1997. 3rd edition. Tomos I – II. Caracas, Ministerio de Energía y Minas, Dirección de Geología, 828 p.

Li Y.-X., Bralower T.J., Montañez I.P., Osleger D.A., Arthur M.A., Bice D.M., Herbert T.D., Erba E., Premoli Silva I. 2008. Toward an orbital chronology for the early Aptian oceanic anoxic event (OAE 1a, ~ 120 M.a). *Earth and Planetary Science Letters*, **271**:88-100.

Macellari C.E. 1988. *Cretaceous paleogeography and depositional cycles of western South America*. Columbia, Earth Sciences and Resources Institute of South Carolina.

Manzini E., Badali M., Puckett T.M., Parcell W.C. 2001. Mesozoic carbonate petroleoum in the northeastern Gulf of Mexico area. Tuscaloosa, Center for Sedimentary Basin Studies and Department of Geological Sciences, University of Alabama, GCSSEPM Foundation.

Márquez X. 1997. Porosidad efectiva en carbonatos en el oeste de la Cuenca del lago de Maracaibo: posibles causas. *In*: VIII Congreso Geológico de Venezuela and I Congreso Latinoamericano de Sedimentología. Caracas, Sociedad Venezolana de Geología. Tomo II, p. 29-36.

Méndez B.J. 1989a. Modelo depositacional del Grupo Cogollo. Talud externo, márgenes y plataforma interna. *In*: VII Congreso Geológico Venezolano. Barquisimeto. Memorias, Tomo II, p. 827-851.

Méndez B.J. 1989b. Porosidades en el Grupo Cogollo y su relación con los ambientes depositacionales. *In*: VII Congreso Geológico Venezolano. Barquisimeto. Memorias, Tomo II, p. 868-889.

Méndez B.J. 1989c. La Formación La Luna. Características de una cuenca anóxica en una plataforma de aguas someras. *In*: VII Congreso Geológico Venezolano. Barquisimeto. Memorias, Tomo II, p. 851-866.

Méndez B.J. 1997. Sedimentación y porosidad en el Grupo Cogollo. Ambientes diagenéticos Someros y su relación con las porosidades. *In*: VIII Congreso Geológico de Venezuela and I Congreso Latinoamericano de Sedimentología. Caracas. Tomo II, p. 81-86.

Méndez B.J. 2009. Carbonatos. Origen y sedimentación. Caracas, Instituto de Ciencias de la Tierra, Facultad de Ciencias, Universidad Central de Venezuela, 300 p.

Méndez B.J., Baquero M., Méndez Dot J.A. 2008. Calizas pelágicas derivadas de eventos oceánicos anóxicos en la Formación Apón del Grupo Cogollo. Cuenca de Maracaibo. Venezuela. *In*: II ALAGO. Congreso Latinoamericano de Geoquímica Orgánica. Caracas. p. 6-18.

Méndez B.J., Escandon M., Lagazzi R. 1990. Sedimentos ricos en carbono orgánico en el Grupo Cogollo. El Miembro Machiques como resultado de eventos transgresivos de carácter anóxico. *In*: II Congreso Latinoamericano de Geoquímica Orgánica. Caracas.

Montoya N. & Méndez B.J. 2005. *NMR Applications of the determination of sedimentary facies and porosity systems on carbonate core plug samples*. Aberdeen, Society of Petroleum Engineers.

Nelson R.A., Moldovanyi E.P., Matcek C.C. Azpiritxaga I., Bueno E. 2000. Production characteristics of the fractured reservoirs of the La Paz Field, Maracaibo Basin, Venezuela. *American Association of Petroleum Geologists Bulletin*, **84**(11):1791-1809.

Nuñez-Useche F., Barragan R., Moreno-Bedmar J.A. Canet C. 2014. Mexican archives for the major Cretaceous Oceanic Anoxic Events. *Boletín de la Sociedad Geológica Mexicana*, **66**(3):491-505.

Orihuela N. 2012. *Análisis de la placa caribe a partir de modelos integrados de anomalías de campos potenciales*. PhD Thesis, Facultad de Ingeniería, Universidad Central de Venezuela, Caracas, 101 p.

Peters K., Walters C., Moldowan J. 2005a. The biomarker guide. Biomarkers and isotopes in the environmental and human history. v. I, 2nd edition. Cambridge, Cambridge University Press, 471 p.

Peters K., Walters C., Moldowan J. 2005b. The biomarker guide. Biomarkers and isotopes in petroleum systems and Earth history. v. II, 2nd edition. Cambridge, Cambridge University Press, 1155 p.

Pindell J. & Kennan L. 2001. Kinematic evolution of the Gulf of Mexico and Caribbean. *In*: GCSSEPM Foundation, 21st Annual Research Conference Transactions, Petroleum Systems of Deep-Water Basins, p. 193-220.

Renz O. 1977. The lithologic units of the Cretaceous of western Venezuela. *In*: V Cong. Geol. Venez. Caracas. Memories, 1, p. 45-58.

Robinson S.A., Clarke L., Nederbragt A., Wood I.G. 2008. Mid-Cretaceous oceanic anoxic events in the Pacific revealed by carbon-isotope stratigraphy of the La Calera Limestone, California, USA. *Geological Society of America Bulletin*, **120**:1416-1427.

Ross M. & Scotese C. 1988. A hierarchical tectonic model of the Gulf of México and Caribbean region. *Tectonophysics*, **155**:139-168.

Schlanger S.O. & Jenkyns H.C. 1976. Cretaceous oceanic anoxic events: causes and consequences. *Geologie en Mijnbouw*, **55**:179-184.

Sliter W.V. 1989. Aptian anoxia in the Pacific Basin. *Geology*, **17**:909-912.

Sutton F.A. 1946. Geology of Maracaibo Basin, Venezuela. *Bulletin of The American Association of Petroleum Geologists*, **30**(10):1621-1646.

Tissot B.P. & Welte D.H. 1978. Petroleum formation and ocurrence. A new approach to oil and gas exploration. Berlin-Heidelberg, Springer-Verlag, 538 p.

Tsikos H., Karakitsios V., van Breugel Y., Walsworth-Bell B., Bombardiere L., Petrizzo M.R., Sinninghe Damsté J.S., Schouten S., Erba E., Premoli Silva I., Farrimond P., Tyson R.V., Jenkins H.C. 2004. Organic carbon-deposition in the Cretaceous of the Ionian Basin, NW Greece: the Paquier event (OAE 1b) revisited. Geological Magazine, **141**:401-416.

Tyson R.V. 1987. The genesis and palynofacies trends, Piper and Kimmeridge Clay Formations, UK onshore and northern North Sea. In: Batten D.J. & Keen M.C. (eds.) *European Micropaleontology and Palynology*, Chichester, Ellis Horwood Ltd, p. 136-171.

Vail P.R., Mitchell R.M.S., Thompson S. 1977. Seismic stratigraphy and global changes of sea level, Part 4. Global cycles of relative changes of sea level. *In*: Payton C.E. (ed.) *Seismic stratigraphy applications to hydrocarbon exploration*. Memoir 26. Tulsa, American Association of Petroleum Geologists, p. 83-97.

Wagreich M., Hu X., Sageman B. 2011. Causes of oxic-anoxic changes in Cretaceous marine environments and their implications for Earth systems: an introduction. *Sedimentary Geology*, **235**:1-4.

Wignall P.B. 1994. Black shales. Oxford; New York, Claredon Press, 127 p.

Wilson J.L. 1975. *Carbonates facies in Geologic History*. Berlin, Springer-Verlag, 471 p.