Petroleum System Analysis:
Middle Magdalena Valley Basin, Colombia, South America

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A report prepared in partial fulfillment of
the requirements for the degree of

Master of Science
Earth and Space Sciences: Applied Geosciences

University of Washington

December 2014

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MESSAGe Technical Report Number: 011

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Executive Summary

The purpose of this study is to create a petroleum system model and to assess whether or not the La Luna Formation has potential for unconventional exploration and production in the Middle Magdalena Valley Basin (MMVB), Colombia. Today, the Magdalena River valley is an intermontane valley located between the Central and Eastern Cordillera of Colombia. The underlying basin, however, represents a major regional sedimentary basin that received deposits from the Triassic through the Cenozoic.

In recent years Colombia has been of great exploration interest because of its potentially vast hydrocarbon resources, existing petroleum infrastructure, and skilled workforce. Since the early 1900s when the MMVB began producing, it has led to discoveries of 1.9 billion barrels of oil (BBO) and 2.5 trillion cubic feet (Tcf) of gas (Willatt et al., 2012). Colombia is already the third largest producer of oil in South America, and there is good potential for additional unconventional exploration and production in the Cretaceous source rocks (Willatt et al., 2012). Garcia Gonzalez et al. (2009) estimate the potential remaining hydrocarbons in the La Luna Formation in the MMVB to be between 1.15 and 10.33 billion barrels of oil equivalent (BBOE; P90 and P10 respectively), with 2.02 BBOE cumulative production to date.

Throughout the 1900s and early 2000s, Cenozoic continental and transitional clastic reservoirs were the primary exploration interest in the MMVB (Dickey, 1992). The Cretaceous source rocks, such as the La Luna Formation, are now the target for unconventional exploration and production. In the MMVB, the La Luna formation is characterized by relatively high total organic carbon (TOC) values, moderate maturity, and adequate thickness and depth (Veigal and Dzelalijal, 2014). The La Luna Formation is composed of Cenomanian-Santonian aged shales, marls, and limestones (Veigal and Dzelalijal, 2014). In addition to the in-situ hydrocarbons, the fractured limestones in the La Luna formation act as secondary reservoirs for light oil from other formations (Veigal and Dzelalijal, 2014). Thus the system can be considered more of a hybrid play, rather than a pure unconventional play.

The Cretaceous source rocks of the MMVB exhibit excellent potential for unconventional exploration and production. Due to the complex structural nature of the MMVB, an understanding of the distribution of rocks and variations in rock qualities is essential for reducing risk in this play.

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Glossary
(In order of appearance; Definitions from PRA proprietary employee training manual)

PRA – Platte River Associates, Inc.
MMVB – Middle Magdalena Valley Basin
BBO – Billion barrels of oil
Tcf – Trillion cubic feet (used to describe volumes of natural gas)
BBOE – Billion barrels of oil equivalent (used to describe combined volumes of oil and gas)
Highstand systems tract – Sequence stratigraphy designation for units accumulated when sea level is highest
Transgressive systems tract – Sequence stratigraphy designation for units accumulated during a sea level transgression
TOC – Total organic carbon (usually given in weight percent)
MMBo – Million barrels of oil
HI – Hydrogen index (used to characterize the hydrogen richness of the source rock, kerogen type, and estimate thermal maturity; HI = [100*S2]/TOC)
S2 (mg HC/g rock) – Amount of hydrocarbons created during rock eval pyrolysis laboratory test (milligrams of hydrocarbons per gram rock)
Hydrocarbon richness (MMBOE/km^2) – Billions of barrels of oil equivalent per area of basin
Kerogen – Remnant organic matter in a rock that is insoluble in organic solvents
Type II kerogen – Planktonic/bacterial (often restricted marine), oil prone
Vitrinite reflectance (%Ro) – Lab measurement of source rock maturity (0.2-0.6% = immature, 0.6-1.35% = mature, >1.35% = postmature)
Type I kerogen – Saprogenic/algal (often lacustrine), oil prone
Remnant generation potential – The potential to generate hydrocarbons from organic carbon remaining in the rock after previous periods of generation
GDE – Gross depositional environment
Cumulative hydrocarbons – Hydrocarbons generated and expelled in a source rock (mg/g TOC)
Type IIs kerogen – Sulfur-rich Type II kerogen
VMM – Alternate acronym for Middle Magdalena Valley Basin (used in Spanish-speaking countries)

1.0 Introduction

A petroleum system for a given sedimentary basin is defined by a set of hydrocarbon source, reservoir, and seal rocks. Models for petroleum systems are digital frameworks in which geological, geochemical, and geographical information can be compiled and used to calculate and estimate key parameters for extracting oil and gas. The resulting maps, graphics, and calculations are essential for making educated decisions regarding a particular resource. Platte River Associates, Inc. (PRA) has created a suite of products for developing petroleum system models that begins with a 1-D model in BasinMod® 1-D. BasinMod® 1-D is a modeling tool that can be used to assess the presence and effectiveness of a potential hydrocarbon resource using the stratigraphy and basic geochemical information from a single well or multiple wells. This report outlines a 1-D model, composed of a single well, which is used as a jumping point for the analysis of oil shale potential in the Middle Magdalena Valley Basin (MMVB), Colombia (Figure 1). A 1-D model is a valuable first approach because it can provide answers to the most basic of questions when developing a hydrocarbon resource. Are the geology and geological history conducive for hydrocarbon generation in this basin? The purpose of this paper is to answer this question and create a preliminary unconventional resource assessment model for the La Luna Formation in the MMVB.

The context of this assessment revolves around the creation of a new PRA product called BasinData. The purpose of BasinData is to provide basic geologic information about a user-selected area to aid in creating models with PRA software (BasinMod® projects, BasinMod® 2-D cross-sections, BasinView® - BasinFlow® maps, and/or PetroAnalyst® Play Fairway Analysis projects). The BasinData information is stored in a BasinMod® 1-D project to which the user can add wells and data. The intention of BasinData is to reduce the amount of research necessary before a user begins the modeling process in a new location, as this information has already been compiled into the starter model. This document is meant to provide context for the BasinData model in addition to assessing the La Luna Formation in the MMVB.

In recent years Colombia has been of much exploration interest because of its potentially vast hydrocarbon resources, existing petroleum infrastructure (Figure 2), and skilled workforce. Oil seeps were well documented as far back as the late 1700s, and commercial production began in the 1910s and was widespread by the middle of the 20th century (Jimenez, 2012). Exploration to date in the MMVB has resulted in a number of actively producing oil and gas fields (Figure 3), and has led to discoveries of 1.9 billion barrels of oil (BBO) and 2.5 trillion cubic feet (Tcf) of gas (Willatt et al., 2012). Colombia is already the third largest producer of oil in South America, and there is good potential for additional unconventional exploration and production in the Cretaceous source rocks (Willatt et al., 2012). Garcia Gonzalez et al. (2009) estimate the potential remaining hydrocarbons in the La Luna Formation in the

MMVB to be between 1.15 and 10.33 billion barrels of oil equivalent (BBOE; P90 and P10[1] respectively), with 2.02 BBOE cumulative production to date. The yet-to-find oil reserves of Colombia as a whole are between 20 and 430.4 billion barrels of petroleum liquids (BBL; P90 and P10, respectively; Table 1), and the associated gas reserves are between 0.409 and 260.924 Tcf (P90 and P10, respectively; Table 2; Jimenez, 2012).

2.0 Methods

The information contained in this BasinData collection was obtained primarily through literature searches as referenced in the text below. The data in the BasinMod® 1-D project and in this document are non-proprietary and should be supplemented with user data prior to use in a professional setting. Because data were found through many different resources, this supplementary document was written to provide context and extra information, as well as clarify the decisions that were made while creating the model. Additional data, such as ESRI shapefiles, were created and/or modified using QGIS[2].

BasinMod® 1-D is an all-inclusive piece of software for petroleum system analysis. It provides a framework to compile geological and geochemical information from a single well or multiple wells, and utilizes this information to make calculations pertinent to developing a hydrocarbon resource. The data in the BasinMod® 1-D project described in this paper were compiled using the stratigraphy encountered in the Infantas-1613 well. This well was used because it has been extensively studied since it was drilled in 1953. Additionally, Infantas-1613 is located in the La Cira-Infantas oil field near the center of the basin where the stratigraphy is most complete and well understood. Additional basin-wide data and information are used to extrapolate interpretations made at the Infantas-1613 well.

3.0 Middle Magdalena Valley Basin Background

3.1 Basin Development and Structural Setting

The Andes Mountains of South America consist of three distinct ranges in Colombia: the Western, Central, and Eastern Cordilleras. Each represents an accretionary and/or deformational event resulting from various instances of rifting, oblique collisions, and transpressional/transtensional tectonics (Barrero et al., 2007). The modern Magdalena Valley now separates the Central and Eastern Cordillera; however,

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[1] P90 and P10 correspond to a statistical confidence level of an estimate. P90, in this case, means that 90% of total BBOE estimates exceed the P90 amount, while P10 means that only 10% of total BBOE estimates exceed the P10 amount (www.cooperenergy.com.au).

[2] QGIS is an open-source GIS program available for both Mac OSX and Windows. The version used in this paper is version 2.4 Chugiak (available free at www.qgis.org).

the underlying basin represents a major regional sedimentary basin (Figure 4) that received sediment from the Triassic through the Cenozoic.

The separation of North and South America during the Triassic and early Cretaceous created a large synrift basin in the proto-Caribbean (Figure 5 - frame 1; Cooper et al., 1995). This marked the beginning of epicontinental transgression and deposition into what became the sedimentary basins of Colombia (Cediel et al., 2011). The resulting synrift megasequence is composed of continental deposition that grades into paralic and shallow marine deposits into the early Cretaceous (Cooper et al., 1995). As the Andes developed throughout the Cretaceous, deposition continued in a back-arc setting, east of the rising mountains (Figure 5 - frame 2). The final accretion of the Western Cordillera temporarily terminated deposition in the basin, but not before the basin's shallow-marine source rocks were deposited during the Turonian-Coniacian (Cooper et al., 1995). During this time, mafic magnetism associated with the accretion of the Western Cordillera overheated the middle and outer-shelf shales (Cediel et al., 2011).

Deposition re-established in the early pre-Andean foreland basin after the accretion of the Western Cordillera in the late Maastrichtian (Figure 5 - frame 3; Cooper et al., 1995). These deposits consist of coal-rich alluvial plain, coastal plain, and estuarine deposits in the MMVB (Cooper et al., 1995). Eocene deformation, and the creation of the Central Cordillera, once again, temporarily interrupted deposition into the basin (Cooper et al., 1995). Subsidence and deformation eventually re-established the basin, into which late pre-Andean foreland basin sediments were deposited (Figure 5 - frame 4). These Tertiary 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).

By the middle Miocene, transpressional deformation of the Eastern Cordillera fully isolated the MMVB from adjacent basins (Figure 5 - frame 5; Cediel et al., 2011; Cooper et al., 1995). The resulting accommodation space was filled with the Andean foreland basin megasequence (Cooper et al., 1995). 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 (Cediel et al., 2011; Cooper et al., 1995).

The MMVB today is bound on the north and south by the Espíritu Santo fault system and the Girardot foldbelt, respectively (Figure 6; Barrero et al., 2007). The Bucaramanga-Santa Marta fault system marks the northeast boundary, and the Bituima and La Salina fault systems mark the southeast boundary (Barrero et al., 2007). The western limit is delineated by the contact between the sedimentary rocks and the Central Cordillera basement (Barrero et al., 2007).

3.2 Depositional Settings and Generalized Stratigraphy

The Early Cretaceous synrift megasequence sediments in the MMVB lie unconformably on Jurassic units. In the case of the Infantas-1613 well, this is the final unit in the succession of Triassic-Jurassic terrestrial red beds, referred to as the Giron Formation (Schamel, 1991). The basal Cretaceous units start as continental sands and conglomerates (Tambor Formation) that grade into shallow-marine sediments (Cumbre Formation; Schamel, 1991; Cooper et al., 1995). As the coarse clastic sediments ponded to the east, the future MMVB accumulated marginal marine mudstones (Rosablanca and Paja Formations) and subsequently more organic-rich marine mudstones that form the uppermost unit of the basal calcareous group (Tablazo Formation; Cooper et al., 1995).

Despite having similar depositional environments, the Cretaceous back-arc megasequence is distinguishable from the synrift megasequence because of substantial thickness changes across basin-controlling faults (Cooper et al., 1995). In the southern portions of the Magdalena basins, sediments are characterized as organic-rich marine mudstones with occasional thin limestones and sandstones (Simití Formation; Cooper et al., 1995). These could have either been deposited in deeper-marine environments or shallower restricted anoxic environments (Cediel et al., 2011). After continued basin subsidence and regional transgression, a shallow-marine siliciclastic shelf built out over a wide area, including the intrabasinal high spot, the Santander high (Cooper et al., 1995). A global sea level rise and anoxic upwelling in the Turonian-early Coniacian then resulted in the deposition of the La Luna Formation in the vicinity of the MMVB (Cooper et al., 1995). This oil-prone formation later became a major petroleum source rock throughout many Colombian basins. As sea level fell there was a westward shoreline progradation and aggradation of quartz-rich shoreface sandstones above the marine mudstones and limestones (Cooper et al., 1995). This regression was quickly reversed in the early Maastrichtian when the shoreface sands were replaced by transgressive sands that grade into shale in the MMVB (Umir Formation; Cooper et al., 1995).

The final episode of accretion in the Western Cordillera drastically changed the depositional environments in the MMVB. Nonmarine sediments dominate the resulting early pre-Andean foreland basin megasequence. In the MMVB these deposits are primarily coastal and alluvial-plain shales and occasional sands (Lisama Formation; Cooper et al., 1995). By 54 Ma, a major drop in sea level resulted in a depositional hiatus of approximately 15 m. y. (Cooper et al., 1995). During this time many of the MMVB's fold and thrust structures were created as a result of changes in subduction direction or rate (Cooper et al., 1995). This angular unconformity is the basis for separating the early pre-Andean foreland basin sediments from the late pre-Andean foreland basin sediments.

The late pre-Andean foreland basin megasequence in the MMVB begins with the Esmeraldas and La Paz Formations, which form the Chorro Group, and the Mugrosa and Colorado Formations, which form the Chuspas Group (Schamel, 1991). These groups consist primarily of feldspathic and lithic sandstones and shales with localized conglomerates (Schamel, 1991). These are the result of four cycles of marine-influenced coastal-plain deposition ranging in between 34-16.5 Ma (Cooper et al., 1995). Each cycle includes a mud-dominated highstand systems tract with a thin regression systems tract and ends with a sand-prone transgressive systems tract (Cooper et al., 1995).

The final sequence of sedimentation in the MMVB is the Andean foreland basin megasequence. Global sea level rise and significant deformation and uplift coincided with deposition of marine mudstones, shoreface sands, and marginal-marine facies rocks of the Real Group (Cooper et al., 1995). This sequence is dominated by volcaniclastic sediments derived from the Central Cordillera, and mark a period of andesitic volcanism in the area (Schamel, 1991). The upper portions of the sequence are defined by a color change in the mudstones from gray to red, indicating the end of marine influence in the system (Cooper et al., 1995). Rapid deposition of the upper Tertiary units caused a late-stage burial of the Cretaceous-early Tertiary units into the oil window at approximately 5 Ma (Cooper et al., 1995).

Figure 7 shows a complete generalized stratigraphic column for the MMVB and Figure 8 shows a seismic section near the Infantas-1613 well with stratigraphic tops and structures marked. Note that the middle Eocene unconformity lies directly on the upper member of the La Luna formation in the seismic section. In the Infantas-1613 well, both the Umir and Lisama Formations are missing.

3.3 Unconventional Petroleum System

Since conventional production began in the MMVB in the early 1900s, Cenozoic continental and transitional clastic reservoirs have been the primary exploration interest. The Cretaceous source rocks, on the other hand, are the new target for unconventional exploration and production. The main source/reservoir used in this model is the La Luna Formation; however, other organic rich horizons throughout the Cretaceous section show good potential for unconventional production (Ramon et al., 1997) and are discussed briefly below. The basic geochemical parameters for each potential source rock are tabulated in Table 3. The following sections outline the relevant petroleum system properties of each unit throughout the stratigraphy, beginning with the main formation of interest for this assessment; the La Luna Formation. The remaining Cretaceous source rocks are described in stratigraphic order, from the lowermost unit of interest (Cumbre Formation) to the top of the Cretaceous section.

3.3.1 La Luna Formation

In the MMVB, the La Luna formation is characterized by relatively high TOC values, moderate maturity, and adequate thickness and depth (Veigal and Dzelalijal, 2014). It is composed of Cenomanian-Santonian aged shales, marls, and limestones (Veigal and Dzelalijal, 2014). In addition to the in-situ hydrocarbons, the fractured limestones act as a secondary reservoir for light oil from other formations (Veigal and Dzelalijal, 2014).

The La Luna Formation has been divided into three members (from base to top): Salada, Pujamana, and Galembo (Reyes et al., 1998; Rangel et al., 2000a; Rangel et al., 2000b). The Salada member is composed of black shales, black mudstones, black calcareous claystones, black limestone layers, and concretions with pyrite (Torres et al., 2012). The Pujamana member is composed of claystone, mudstone, gray shale, and chert (Torres et al., 2012). And finally, the Galembo member is composed of calcareous shales with limestone layers and nodules (Torres et al., 2012). Average total organic carbon (TOC) varies from member to member. The Salada member averages approximately 4.5 wt% organic carbon, while the Pujamana and Galembo members average around 3.5% and 2.4%, respectively (Zumberge, 1984, Rangel, 2000b). Remaining reserves in many conventional fields throughout Colombia have been estimated at lower than 10 million barrels of oil (MMBo) per field; however, certain wells drilled into the La Luna Formation exhibit excellent oil-shale potential with Hydrogen Index (HI) values close to 302 mg HC/g TOC and S2 values ranging from 5-27 mg HC/g Rock (Veigal and Dzelalijal, 2014). These HI and S2 values indicate that there is significantly more than 10 MMBo remaining in this unconventional play in the MMVB.

Data from the Norean-1 and Morales-1 wells (Figure 3) at the northern end of the basin show immature to early mature source rock values for the La Luna Formation; however, 2D seismic lines indicate a deeper depocenter to the SE where the formation could be more mature (Veigal and Dzelalijal, 2014). Petrophysical analysis of the La Luna Formation in the Norean-1 well shows two progradational cycles in the upper portion with a net thickness of hydrocarbon producing units of 95 m, average porosity of approximately 10%, clay content approximately 40%, and hydrocarbon saturation of nearly 70% (Veigal and Dzelalijal, 2014). Richness was calculated to be between 4 MMBOE/km^2 and 41 MMBOE/km^2 (P90-P10, respectively) in the Norean-1 well, whereas richness is close to 100 MMBOE/km^2 in the Morales-1 well (Veigal and Dzelalijal, 2014). A conservative estimate of the total area where the La Luna Formation has potentially reached adequate maturity is 1,400 km^2 (P50=1,913 km^2 by Garcia Gonzalez et al., 2009; Veigal and Dzelalijal, 2014).

3.3.2 Cumbre Formation

The Cumbre Formation is a thin unit that marks the change from continental deposition to shallow marine deposition. It is composed of dark gray shales with good organic content (1.0-7.8 wt% TOC) with a type II kerogen with good maturity (1.1-1.2% Ro; Ramon et al., 1997). Due to inadequate thicknesses throughout much of the MMVB it is often overlooked for unconventional production.

3.3.3 Rosablanca Formation

The Rosablanca Formation is at the bottom of the Basal Calcareous Group, which includes the Rosablanca, Paja, and Tablazo Formations. Analysis of the shallow-marine and intertidal marine limestones and micrites in several wells has shown fair to good organic content (0.3-5.4 wt% TOC) and maturity ranging from 0.75% Ro to 2.0% Ro depending on the well (Sarmiento, 2011). The amount of solid bitumen present in the formation is also highly variable from very low amounts (<5%) up to 20%, and the composition is indicative of a mixture of type I and II kerogens (Ramon et al., 1997; Sarmiento, 2011). HI values of 104 to 136 mg HC/g TOC and S2 values between 0.54 and 0.9 mg HC/g Rock show that the Rosablanca Formation likely suggests poor remnant generation potential (Sarmiento, 2011). Overall, the organic richness of the unit increases towards the E and SE of the basin (Sarmiento, 2011).

3.3.4 Paja Formation

The Paja Formation, in the center of the basal calcareous group, is composed of calcareous mudstones and shales with limestone interbeds and concretions (Sarmiento, 2011). It contains good amounts of TOC (0.74 - 8.95% with an average around 2-3%) of type I/II mixed kerogen with maturity ranging from 1.1-1.38% Ro (Sarmiento, 2011; Ramon et al., 1997). This indicates that this formation is in the gas zone in parts of the MMVB (Ramon et al., 1997). Large variations in geochemical attributes are mostly due to intra-formation facies changes throughout the basin. High maturity in most wells indicates that the formation has at least gone through to the end of the oil generation window in most of the MMVB (Ramon et al., 1997).

3.3.5 Tablazo Formation

The Tablazo Formation is the uppermost unit in the basal calcareous group. It is composed mostly of biomicrites, fossiliferous sandstones, and calcareous shales with generally good TOC values (0.48-4.78 wt%) and maturity ranging from 1.1-1.3% Ro (Ramon et al., 1997; Sarmiento, 2011). The organic poor regions tend to be in the northeast portion of the basin, and the rest of the basin has between 1 and 4.78 wt% TOC (Sarmiento, 2011). Prior studies have shown that 80% of the organic matter is composed of lipids, but the composition of the other 20% of the material indicates that the rock contains a mixture of type I and II kerogens (Ramon et al., 1997). Areas in the southern portion of the basin have wells that show over-maturity of the organic matter in the Tablazo Formation (Sarmiento, 2011). Because of the variations in presence and effectiveness of the formations in the basal calcareous group, the group is often considered as a single unit with organic rich zones that vary in depth, thickness, and quality from well to well.

3.3.6 Simití Formation

The Simití Formation is located just below the La Luna Formation and has long been considered to be one of the main source rocks in the MMVB (Barrero et al., 2007). It is composed of dark gray shales, deposited on an outer marine shelf, with fair to very good TOC values (0.55-12.8 wt% with an average of 2.6%) and maturity ranging from 0.71-0.95% Ro (Ramon et al., 1997). Most of the organic matter is composed of lipids, however, some wells show increasing amounts of terrestrial organic carbon input (Ramon et al., 1997). Thermal maturity is greatest in the southwest portion of the basin and the least in the northern and northwestern portions of the basin (Sarmiento, 2011).

3.3.7 Umir Formation

The Umir Formation lies just above the La Luna Formation near the top of the Cretaceous section. It is composed of gray mudstones with siltstone interbeds, sandstone interbeds, and some coal layers. The depositional environments consist of inner marine shelves to lakes to coastal plains. The uppermost portion is highly variable in its source potential (Ramon et al., 1997). In the Lisama area (eastern margin), it is organic lean and immature (Ramon et al., 1997). Sixty km to the north-northeast, Ecopetrol has found it to be a fair-to-good source with TOC >3% of a type II/III mixed kerogen, but it is also generally immature (0.6% Ro; Ramon et al., 1997). The lower portion of the formation has TOC values around 1.8-2.0 wt% of type II kerogen with greater maturity and with a HI between 340-420 mg HC/g rock/TOC (Ramon et al., 1997). Overall the maturity of the Umir Formation tends to increase to the south and southeast in the MMVB (Sarmiento, 2011).

The formations discussed above have the potential for unconventional production, but are highly variable in presence and effectiveness throughout the MMVB. Additionally, it has been shown that, in places, hydrocarbons from the Basal Calcareous Group have migrated into the fractured limestone reservoirs of the La Luna Formation, and thus the lower stratigraphic units might not be as rich as expected everywhere in the basin (Ramon et al., 1997).

The reservoir qualities of the above-described formations are also highly variable throughout the MMVB. The more calcareous units with limestone interbeds have high potential for hydrocarbon storage depending on the degree of fracturing. Due to the complex structural nature of the basin, it is relatively difficult to determine where natural fracturing is most prevalent in each of the units. Additionally, some wells show high clay content in the shale-dominated units, while others report very little clay in the correlative units. These factors will ultimately be important in determining which formation to target for unconventional or hybrid production in a given area within the MMVB.

4.0 Results

4.1 Model Inputs

4.1.1 Stratigraphic Events

The Infantas-1613 well has some of the most complete stratigraphy of any well in the MMVB. The only inputs required to create the stratigraphic units in BasinMod® 1-D are the top and bottom depth, or thickness, and the age that sedimentation ended for a given formation. The stratigraphic events used in the model are tabulated in Table 4 and is shown in graphic form in Figure 9.

4.1.2 Non-formation Events

Because the depositional environments and lithologies are discussed separately, this section will focus on the depositional events, erosional events, hiatus events, and missing units in the model.

4.1.2.i Jurassic Hiatus

At the end of the Jurassic, Cooper et al. (1995) describe a hiatus that occurred for only a few million years before deposition of the Tambor Formation began. This event is described as a hiatus, rather than erosion, because there is no evidence of missing deposits at this unconformity, and no evidence suggesting that the Giron Formation was uplifted and eroded significantly during this period of time.

4.1.2.ii Cumbre Formation pinch out

In the Petroleum System section of this report, the Cumbre Formation is mentioned as a potential source rock in the MMVB. In the chronostratigraphy diagrams from Cooper et al. (1995) and Sarmiento (2011), the Cumbre pinches out towards the north, and is not present in the Infantas-1613 well. The formation likely plays a more important role in the southern portions of the basin.

4.1.2.iii Umir-Lisama deposit

The Umir and Lisama Formations are not present in the Infantas-1613 well. Elsewhere in the MMVB the Umir can play an important role as a potential source rock and the Lisama can be an important reservoir rock; however, due to the uplift and erosion caused by the formation of the Central Cordillera both are missing in many areas of the basin.

4.1.2.iv Central and Eastern Cordillera uplifts

The creation of the Central and Eastern Cordillera resulted in widespread Tertiary-aged unconformities throughout the MMVB. The precise amount of erosion resulting from these uplifts is still somewhat poorly understood. Sanchez (2011) used low-temperature thermochronological and sandstone petrographic data to estimate that as much as 11,500 feet was eroded during these events. Because only the total amount of erosion is estimated, it was divided equally between the two events. The amount and timing of the erosions has implications for how long the source rocks were at generation depths; however, there is insufficient evidence to weight one event more than the other.

4.1.2.v Tertiary groups

The Tertiary formations have been the primary interest for hydrocarbon production since it began in the early 1900s (Dickey, 1992). Because this is an unconventional system model they have been placed in their respective groups rather than separated into individual formations. This was done to simplify the model and to focus primarily on the Cretaceous units.

4.1.2.vi Tertiary hiatus

Prior to the deposition of the Pliocene-Quaternary Mesa Group, there was one last hiatus in the MMVB. This hiatus is attributed to a slight tectonic stagnation following rapid crustal shortening during the late Miocene to the Pliocene (Sanchez, 2011). It occurred during the late-stage burial of the source rocks.

4.1.3 Gross Depositional Environments

In lieu of assigning specific lithologies or lithology mixes to the stratigraphic units in the model, gross depositional environments (GDE) were used. GDEs represent a mix of lithologies based on modern depositional analogues and were developed for use in BasinMod® 1-D by PRA through years of research. The GDE assignments in BasinMod® 1-D contain default values for porosity, permeability, and other estimated characteristics that can be used in calculations if down-hole or core analysis data is not available. The gross depositional environments assigned to each of the events in the model (Table 5) were determined using a combination of shapefiles and unit descriptions from the literature. The shapefiles for GDEs were digitized using paleo-environment maps created by Cooper et al. (1995; Figure 10). The collection of shapefiles for a particular time period represents a map of gross depositional environments within a highstand systems tract.

4.1.4 Source Rock Geochemistry: La Luna Formation

As stated previously, the La Luna Formation is the formation of interest for this model. Each of the members has been assigned a type IIs kerogen as described by Tissot et al. (1987). This kerogen type shows generation timing and kinetics windows similar to those inferred by Dickey (1992) for the La Cira-Infantas Field. The type IIs kerogen was chosen because of the high sulfur content typically found in marine carbonate derived oils (Ramon et al., 1997). The type IIs kerogen will generate slightly sooner than a type II, but the two are similar in many other characteristics.

A series of shapefiles for geochemical parameters of the La Luna Formation in the MMVB was digitized using maps from ANH (2012). The TOC shapefiles show locations where the measured TOC values are expected to fall between 1-2 wt% and 2-4 wt% (Figure 11). The % Ro shapefiles show locations where measured maturity values are <0.6, between 1.0 and 1.3, 1.3 and 2.0, or 2.0 and 3.0% Ro (Figure 12). According to ANH (2012), these shapefiles cover all areas in the basin where the La Luna is known to be present at depth.

4.1.5 Thermal History

The thermal history of the nearby Catatumbo Subbasin (Rangel and Hernández, 2007) is applied to the MMVB in this model. Because only the Eastern Cordillera separates the Catatumbo Subbasin from the MMVB, the two basins have experienced the same or similar events at roughly the same time. Thus the thermal history developed by Rangel and Hernández for the Catatumbo Subbasin should be applicable to the MMVB. The Rangel and Hernández (2007) study used one pseudo-well and five representative wells from the subbasin to constrain the history of heat flow for the region. The resulting heat flow graph (Figure 13) reflects the main tectonic events during the development of the Maracaibo Basin: rift stage, passive margin stage, foreland basin transitional stage, and foreland basin stage (Rangel and Hernández, 2007).

4.1.6 Compaction

The reciprocal mechanical compaction method, developed by Falvey and Middleton (1981), was chosen for this model because it is most applicable for carbonate rocks, which dominate much of the Cretaceous stratigraphy. The continental and transitional formations have been separately assigned the effective stress compaction method, because of their coarse grain-dominated lithologies. Figure 14 illustrates the level of compaction, as calculated using these input compaction methods, of the rocks in the Infantas-1613 well using porosity as a proxy parameter.

4.1.7 Sea Level Curve

BasinMod 1-D includes a sea level curve input and is important for creating the most complete geological history possible. Sea level was used as an aid for determining which GDEs to use for this model. The sea level curve was created for the Infantas-1613 well using data from the GSA data repository item number 2005148, from Gómez et al. (2004; Figure 15; Table 6). These values for sea level were determined just north of the Infantas-1613 well in the northern MMVB. Sea depth through time is given in Table 6 as well; however, it has not been used in the model due to uncertainty in the values.

4.2 Model Outputs

4.2.1 Burial History

One of the primary outputs of BasinMod 1-D is the burial history graph. The burial history is created based on the input stratigraphy and geological events, and is essential for visualizing the geological history of the rocks encountered in the well of interest.

As shown on the burial history graph (Figure 16), the maximum burial depth for the La Luna Formation in the Infantas-1613 well is roughly 7,500 to 10,000 feet (formation top and bottom), which is adequate depth for hydrocarbon generating temperatures and pressures. The multi-stage deposition and exhumation allowed for nearly continuous hydrocarbon generation from the Cretaceous through the Cenozoic because the La Luna Formation was already deeply buried by the late Cretaceous.

4.2.2 Hydrocarbon Generation

The La Luna formation began generating hydrocarbons in the late Cretaceous as it was buried to depths nearing 8,000 feet. Accumulation of hydrocarbons at this time, however, was minimal. The model shows the most significant phase of generation beginning during the early Cenozoic (Figures 17, 18, and 19) as a result of increased heat flow during the uplift of the Central Cordillera. The model also shows that hydrocarbons were being expelled from the Salada and Pujamana Members during this time of rapid generation (Figures 18 and 19). To this day, the La Luna Formation appears to be capable of additional generation in the vicinity of the Infantas-1613 well because the majority of the formation only went through the early and main phase generation (Figure 20). The Salada and Pujamana Members have generated significant amounts of hydrocarbons, however much of the organic carbon in the Galembo member is has not transformed from kerogen to hydrocarbons. This will have implications for how the La Luna can be developed as an unconventional resource.

4.3 ANH Ronda Colombia 2014 MMVB Assessment

Ronda Colombia is an event organized by Colombia's regulatory agency (ANH) every two years, where companies can come to the country to bid on land for oil and gas development. In the 2014 round, the ANH has designated two blocks of land (VMM 9 and VMM 40) in the MMVB to be developed for unconventional resources and one (VMM 38) for conventional resources (Figure 21). VMM 9 and VMM

40 are adjacent to each other in the south-central MMVB while the VMM 38 block is in the northern MMVB. Two additional unconventional blocks (one in the southernmost portion of the basin and one along the eastern edge of the basin between VMM 38 and VMM 40) are designated for coal bed methane production and are shown in the ANH (2014) documents. Because this model does not include coal bed methane assessments, the following discussion will focus on the three other blocks.

The map of La Luna TOC distribution overlain on the ANH Ronda Colombia 2014 MMVB blocks shows that both the VMM 40 and VMM 38 significantly overlap with the mapped TOC contents between 2 and 4 wt% (Figure 22). VMM 9 likely does not have the La Luna formation present, so alternative source rocks will need to be considered at this location. The VMM 40 block also appears to have good maturity levels in the La Luna formation (1.3-3.0% Ro), while the VM 39 block has lower maturity (<0.6 to 1% Ro; Figure 23). Determining sweet spots for these parameters within the blocks will require additional wells and higher resolution data than that presented in the shapefiles.

Overall, the MMVB appears to have the most potential along the eastern margin and in the southern portions of the basin. The ANH (2014) multivariate analysis map shows good TOC and oil potential for the VMM 38 block, and good TOC, oil, and gas in the VMM 40 block (Figure 24). VMM 9 overlaps slightly with good TOC potential, but because the La Luna is not present it might present a slightly higher risk than the other blocks. Areas just south of the unconventional blocks show the highest potential for gas production in the entire basin, but the potential for oil production is significant throughout. The areas outside of the ANH (2014) sweet spot polygons aren't necessarily poor prospects, but rather there is insufficient data for a complete analysis.

5.0 Discussion

The results of this model are constrained by the fact that it only contains one well with limited information for calibration. Even so, the Infantas-1613 well provides an adequate beginning point for model expansion. The burial history and geological story created by this model are commensurate with burial graphs published in literature, with the addition of separated uplift events in the Central and Eastern Cordillera. Although it is un-calibrated, estimates of cumulative hydrocarbon generation in the Infantas-1613 well, as shown in Figures 17-19, is equivalent to other areas in northern South America where La Luna analogues are currently being produced (Fernando Marcano (PRA), verbal communication, 2014).

Outputs, such as compaction, also remain un-calibrated due to the lack of published down-hole porosity data. The modeled porosity is a good first approximation, however, development decisions should not be made without calibration and additional wells. Unconventional resources are extremely spatially variable, and in most cases many wells are needed for complete analysis. For the purposes of this paper, the Infantas-1613 well and default values for calculations are adequate for a preliminary assessment of the viability of the La Luna Formation.

6.0 Conclusions

The MMVB houses some of the largest and most productive oil fields in Colombia. Many of the fields, such as the La Cira-Infantas, have a long production history with great potential for future production. Since most of the producing fields target structural traps in the Tertiary units, there is potential for new exploration in stratigraphic traps, unconventional reservoirs, and underexplored areas. To revisit the question posed for 1-D modeling, the La Luna Formation exhibits qualities of an exceptional oil shale with potential for unconventional production in the MMVB. The system also has potential for hybrid production where La Luna Formation carbonate interbeds are present and naturally fractured.

The other Cretaceous units also show promising potential for future discoveries throughout the basin because of their excellent source rock qualities and internal or nearby reservoirs. According to Sarmiento (2011) the main concern is the reservoir rock properties since hydrocarbon generation and maturity have already proven to be of adequate quality. Most of the known Cretaceous reservoirs are fractured limestones, but more studies are needed to determine the oil-shale potential of the less carbonate-rich interbeds, in addition to determining the extent of natural fractures in the system.

7.0 Recommendations and Limitations

It is recommended that a user of the BasinData project add wells, data, and shapefiles to specific areas of interest within the MMVB for use in a professional setting. The data provided using the Infantas-1613 well might not be applicable elsewhere in the basin due to the highly variable nature of geology and petroleum resources. Additionally, petroleum system models give no single solution to a given problem. Reasonable quantities and qualities of data are needed to create and calibrate a model. Information for this BasinData project comes from a wide variety of sources but it is not necessarily complete. The conclusions stated in this paper are based on information from a single well and extrapolated using geological information from literature. As unconventional exploration continues in the MMVB, the true potential of the La Luna Formation will be revealed.

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9.0 Figures

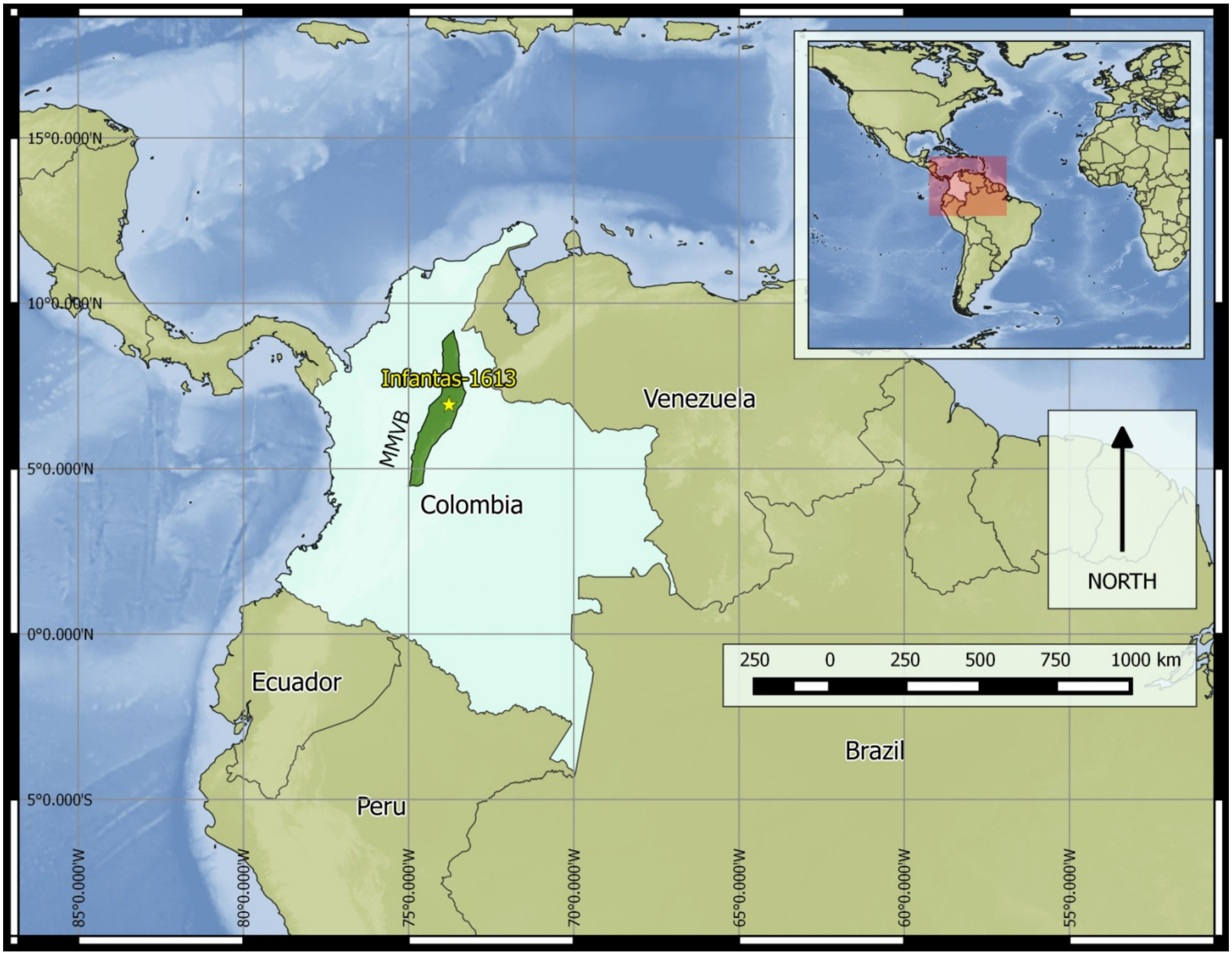

Figure 1. Location map of Colombia and Middle Magdalena Valley Basin (MMVB). The well used in the BasinMod® 1-D project, Infantas-1613, is marked by the yellow star (geographic information from: North American Cartographic Information Society—www.nacis.org; ANH—www.anh.gov.co; NOAA—www.noaa.gov).

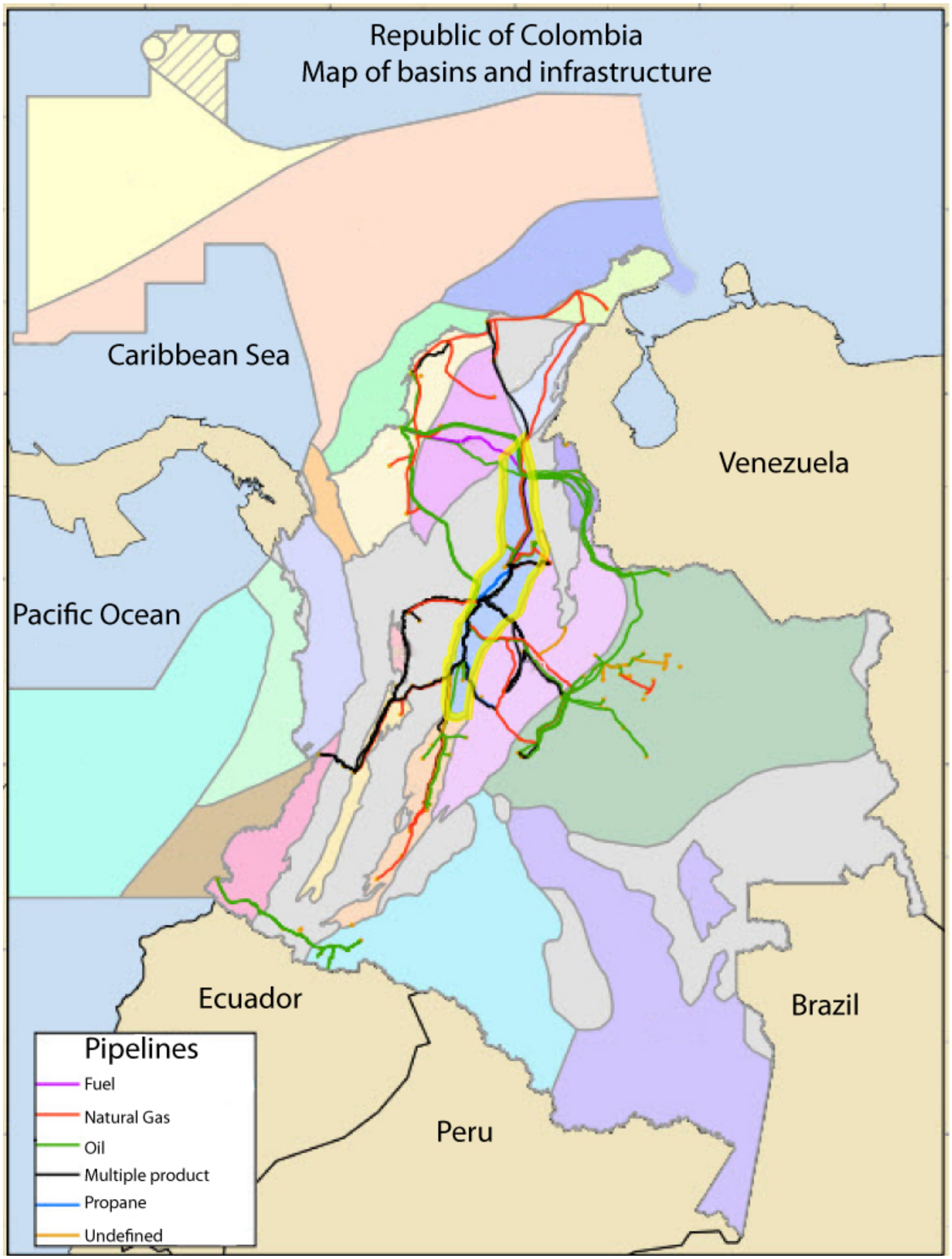

Figure 2. Map of petroleum infrastructure and sedimentary basins for Colombia. The MMVB, outlined in yellow, has been in production longer than most other basins in Colombia, so the petroleum infrastructure is well established (modified from ANH, 2014).

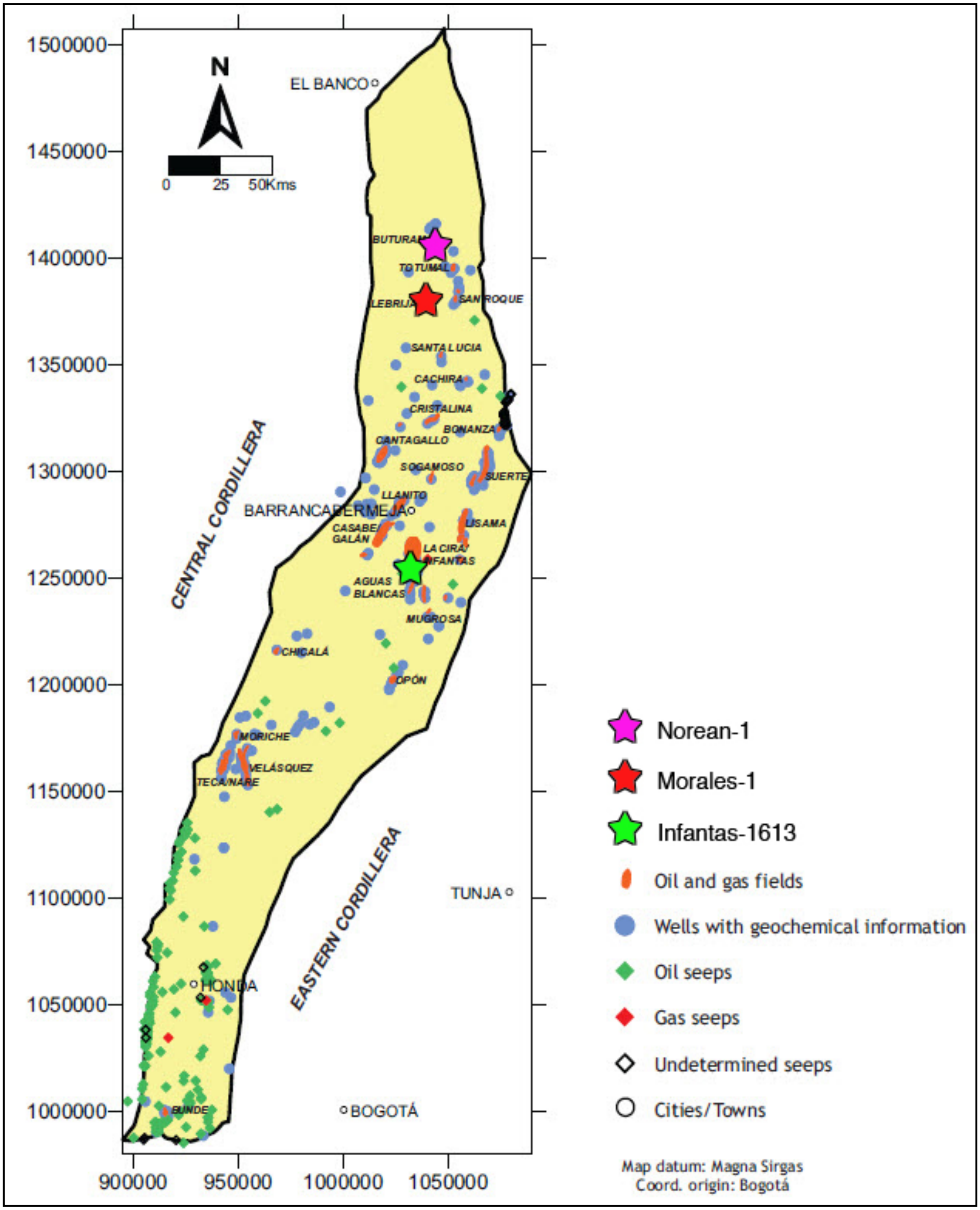

Figure 3. Map of oil fields, oil seeps, gas seeps, and wells in the Middle Magdalena Valley Basin. Additional wells of interest marked by colored stars (from Montes, 2010).

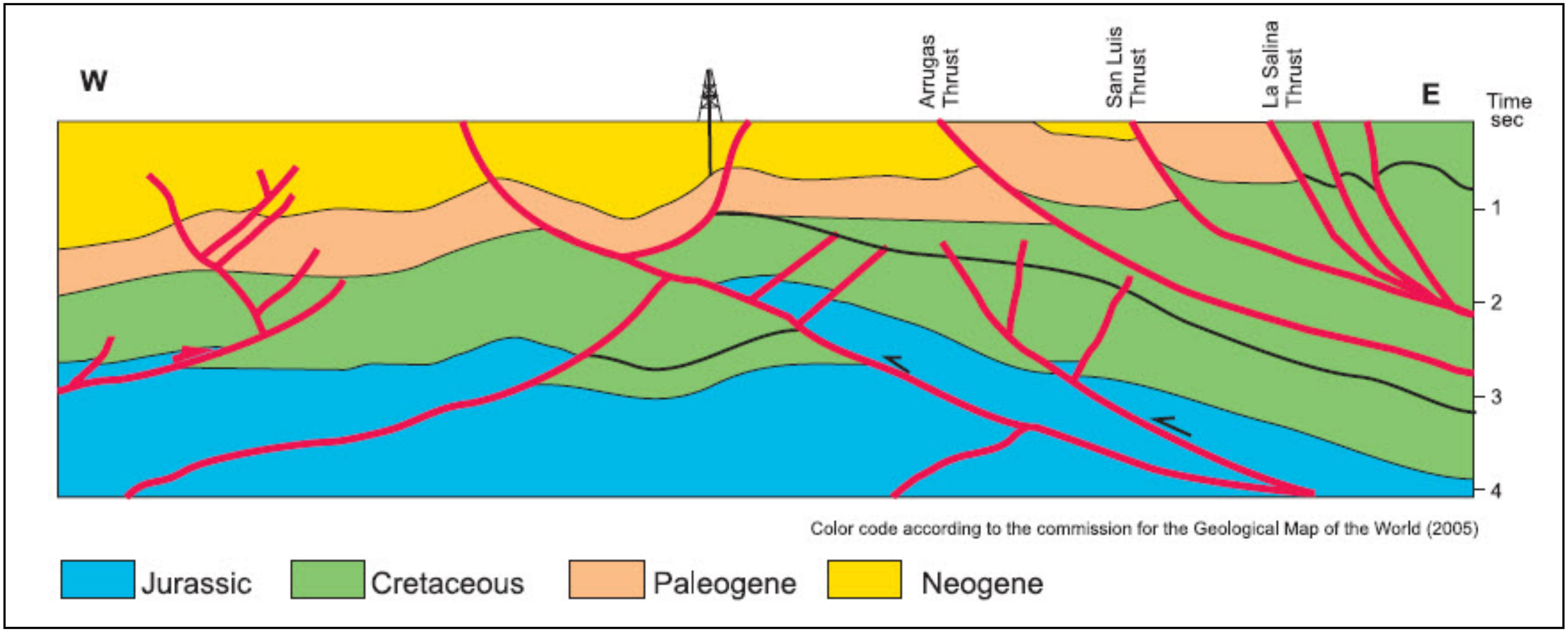

Figure 4. Schematic cross-section (two-way travel time) of the Middle Magdalena Valley Basin. The MMVB is highly faulted in the Jurassic and Cretaceous units with younger thrusts extending through to the surface. The well shown in the figure is not representative of the Infantas-1613 well. It is shown to demonstrate a typical structural play found in the basin (from Barrero et al., 2007).

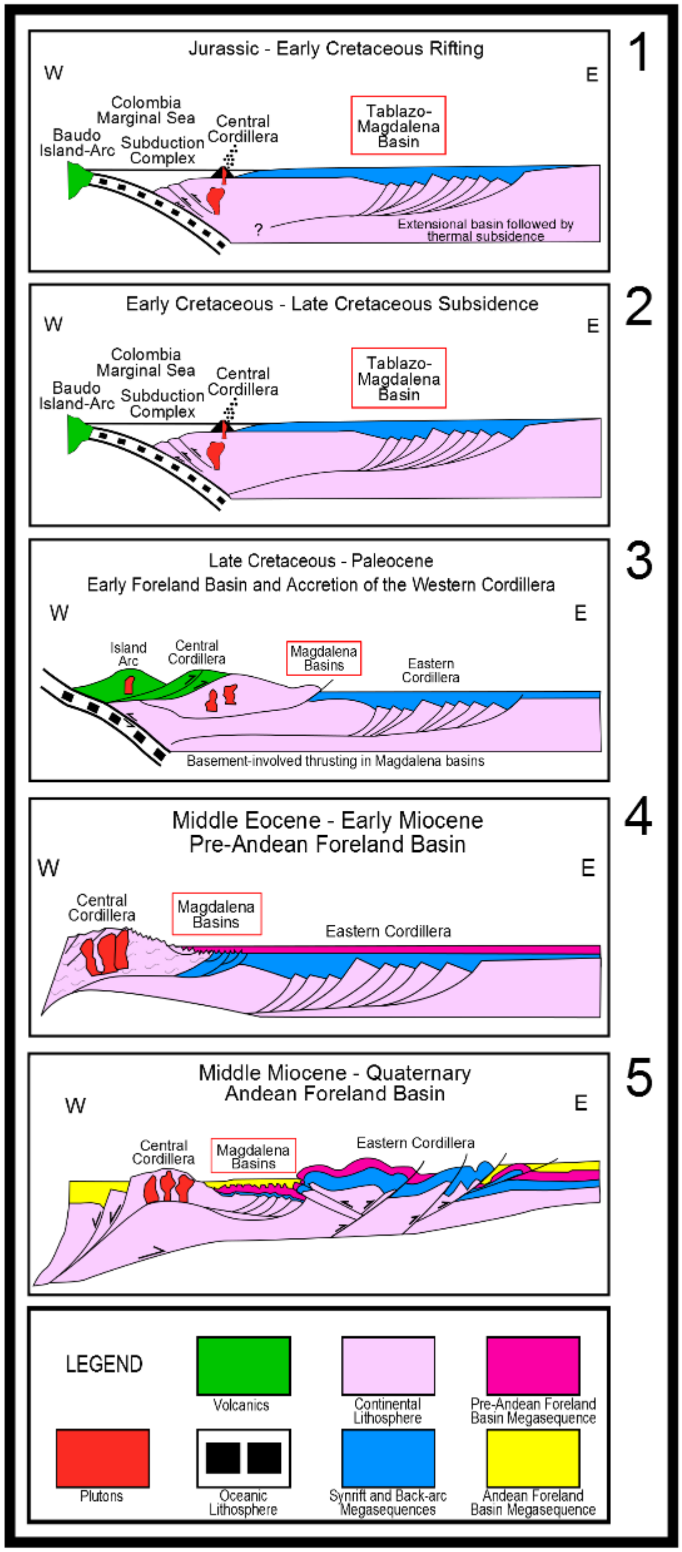

Figure 5. Basin development sequence. This diagram shows the development of several of Colombia's highlands and basins. The cross-section is oriented W-E, and the frame numbers correspond to those mentioned in text (modified from Cooper, et al., 1995).

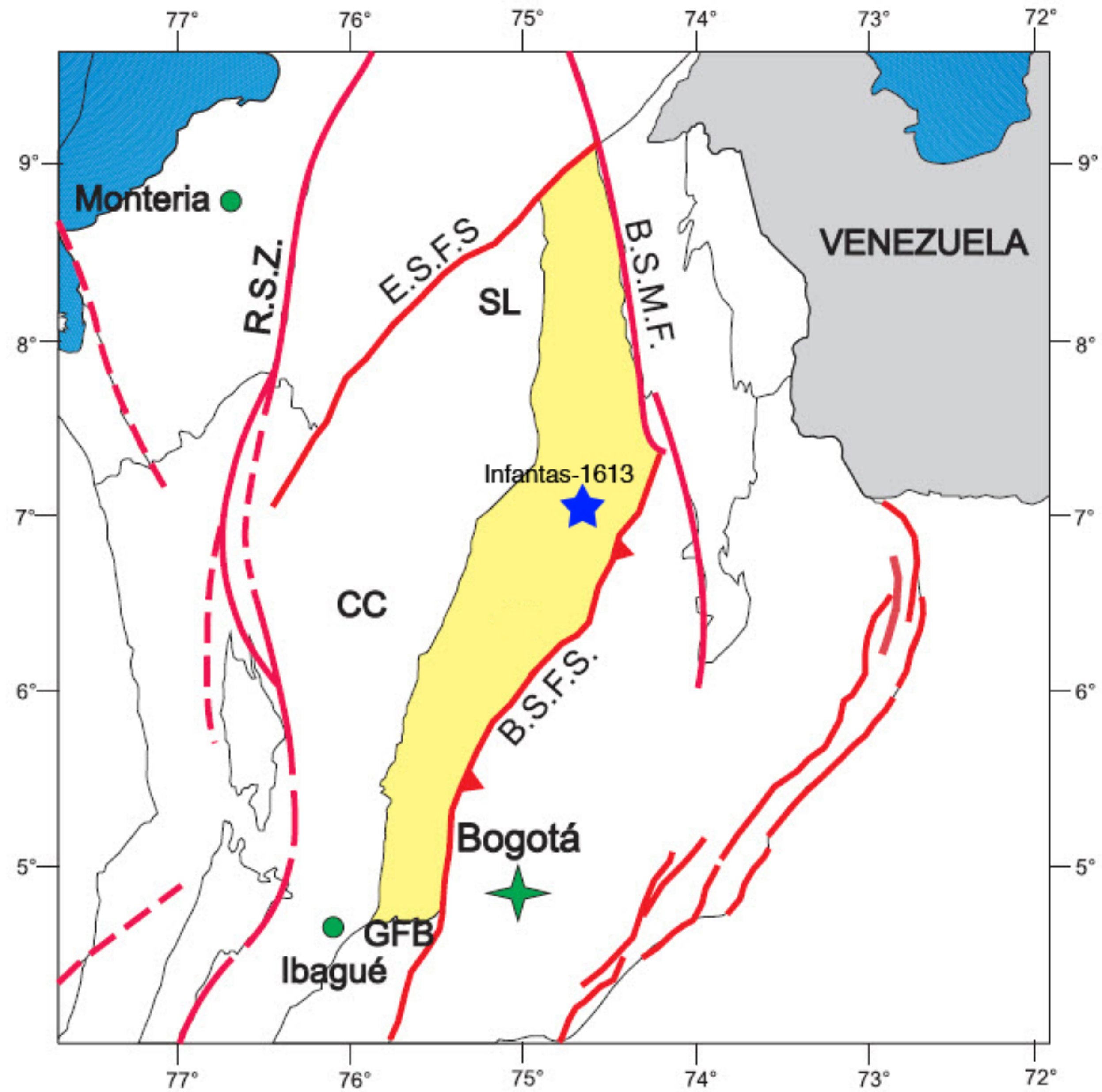

Figure 6. Middle Magdalena Valley Basin with fault zone boundaries. The MMVB is mostly fault bound with the western boundary marked by the onlap of sediments onto the Central Cordillera basement. Abbreviation key: B.S.F.S. = Bituima and La Salina fault systems; E.S.F.S = Espiritú Santo fault system; SL = Serranía de San Lucas basement; CC = Central Cordillera basement; GFB = Girardot fold belt; B.S.M.F. = Bucaramanga-Santa Marta fault system. Blue star indicates the approximate location of the Infantas-1613 well in relation to the faults (from Barrero, et al., 2007).

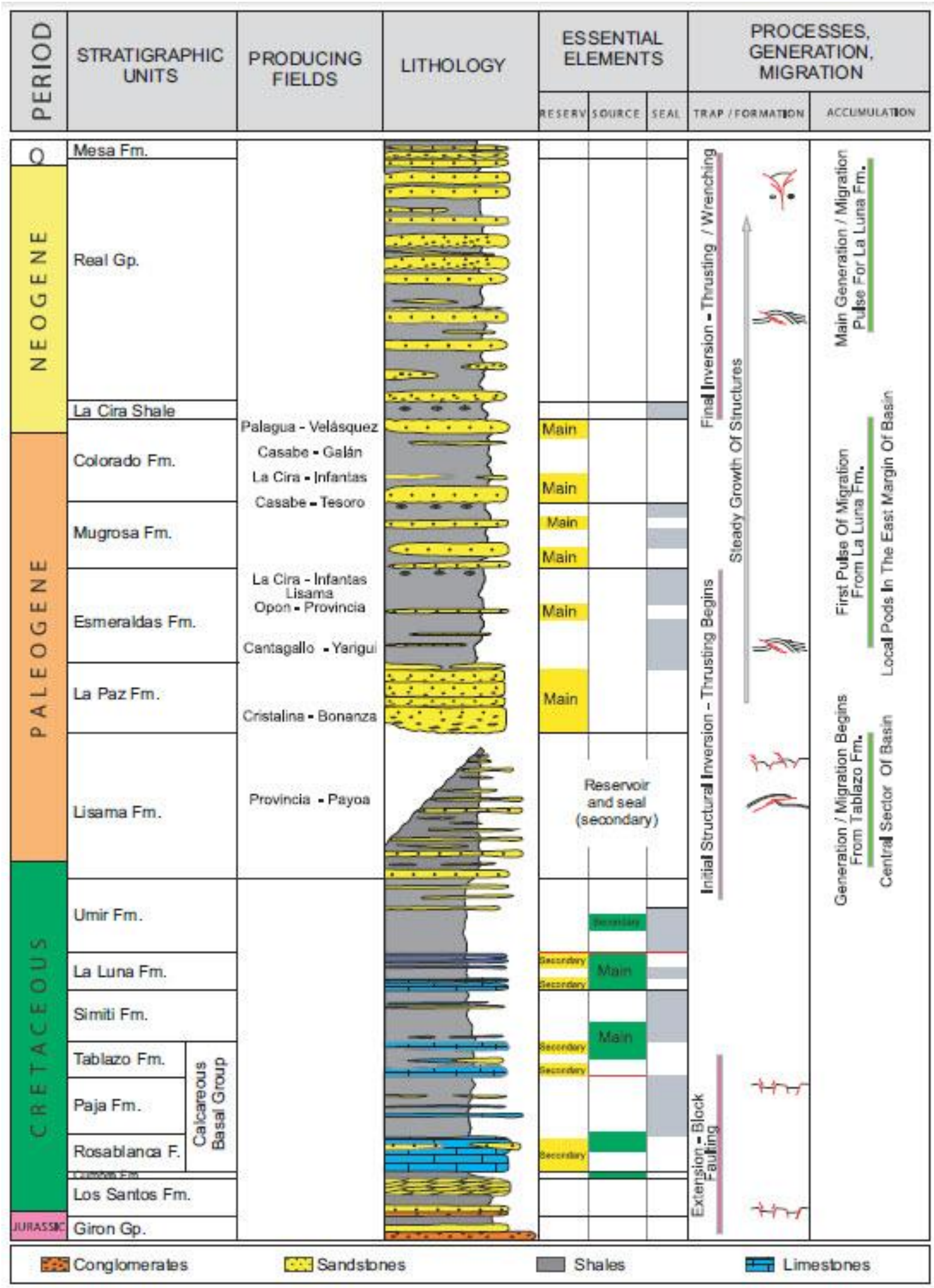

Figure 7. Generalized stratigraphic column for Middle Magdalena Valley Basin. Diagram also shows elements of the petroleum system and stratigraphic locations of the producing conventional oil fields (from Barrero, et al., 2007).

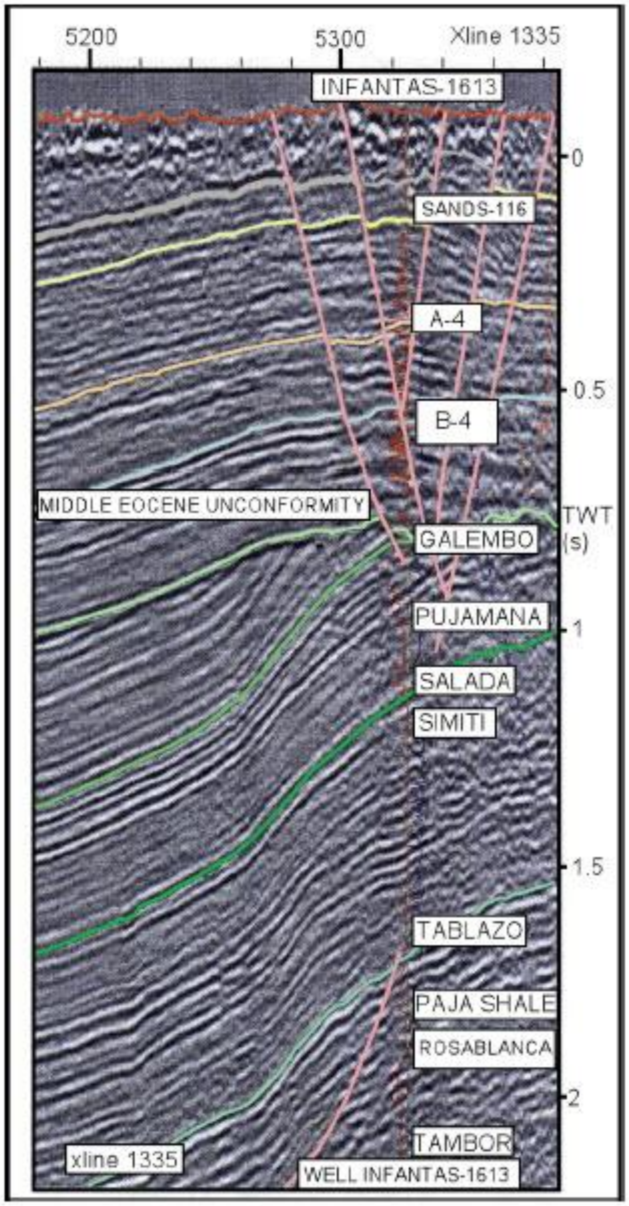

Figure 8. Seismic line (showing two-way travel time) near Infantas-1613 well with stratigraphic tops and structures interpreted. The Middle Eocene unconformity marks a major angular unconformity between the Cretaceous units and the overlying Tertiary units (labeled B-4, A-4 and SANDS-116). The La Luna Formation is labeled with the individual member names; Salada, Pujamana, and Galembo (from Gutierrez, 2001).

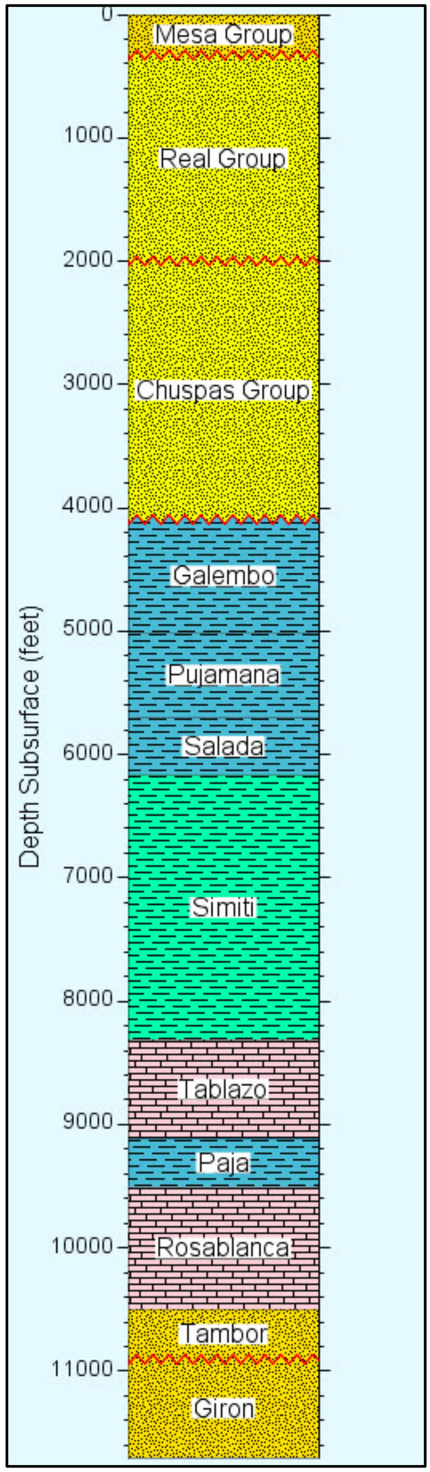

Figure 9. Stratigraphic column for the Infantas-1613 well in BasinMod® 1-D project. Colors and patterns correspond to gross depositional environments (GDEs) assigned in the project. Irregular red lines mark both the erosion and hiatus events. Patterns: Dots on yellow = mostly sand, continental; Lines on blue = carbonate-rich shale, marine; Lines on Green = shale, marine; Brick on pink = mostly carbonates, marine.

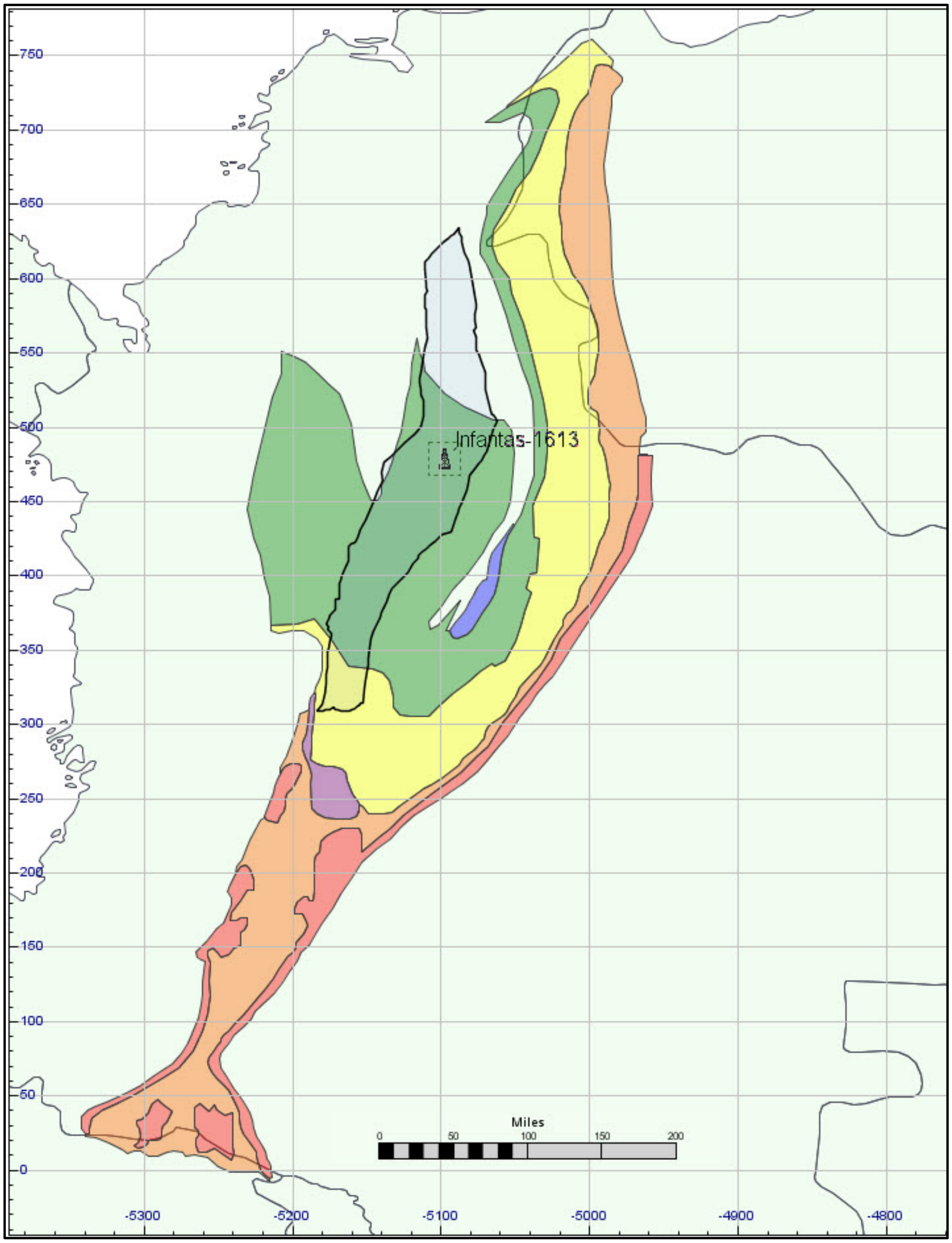

Figure 10. Example GDE map created with the 125 Ma GDE shapefiles in BasinMod® 1-D project. These GDE shapefiles can be used to spatially display the distribution of various depositional environments at a given time period. Color key: Red = Nonmarine SS and MS; Orange = Coastal Plain SS; Purple = Coastal Plain MS; Yellow = Shallow-marine SS; Green = Shallow-marine MS and SLT; Blue = Shallow Carbonate (shapefiles digitized from Cooper et al., 1995).

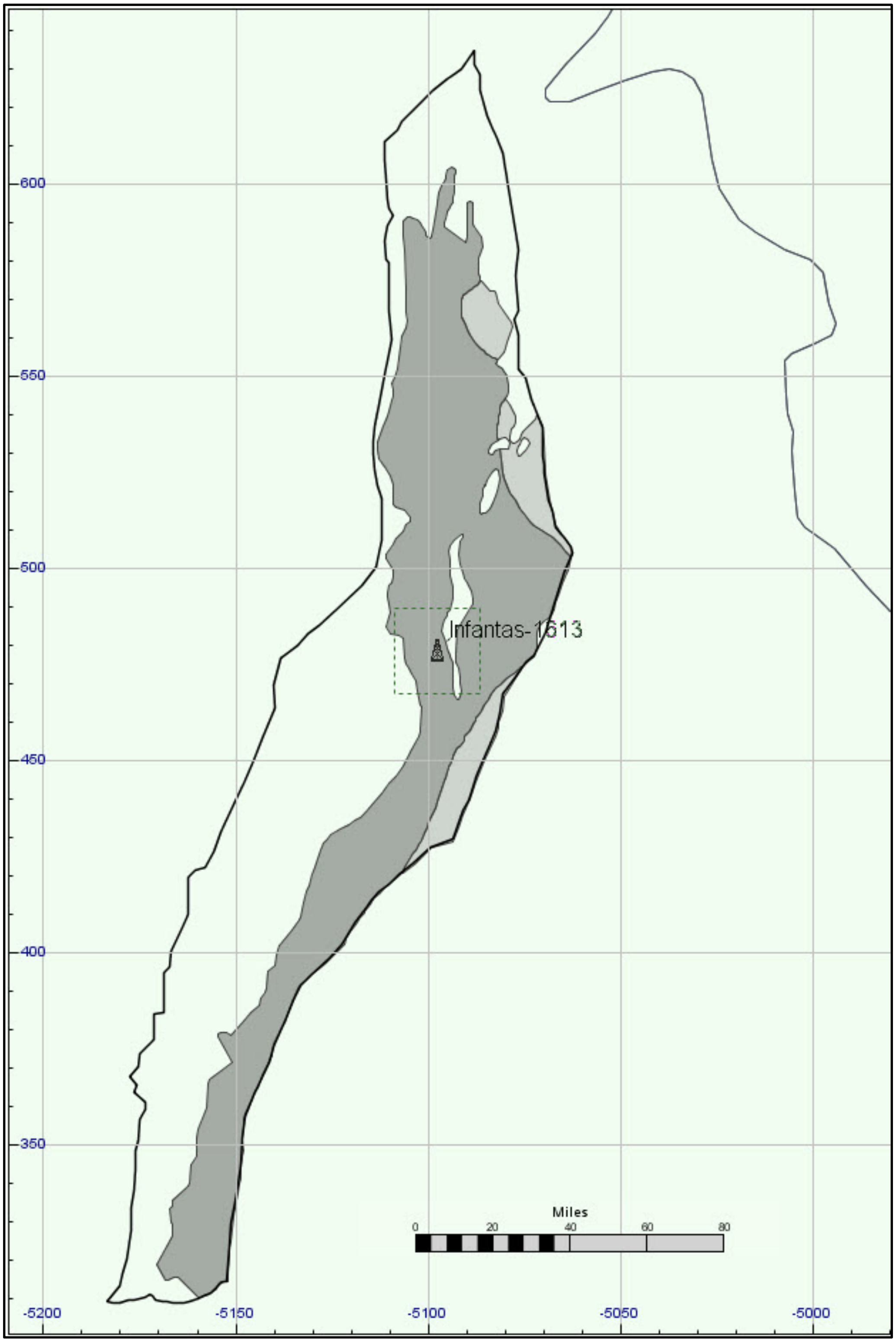

Figure 11. Map of La Luna total organic carbon (TOC) distribution created using TOC shapefiles in BasinMod® 1-D project. Color key: Light gray = 1-2 wt%; Dark gray = 2-4 wt% (shapefiles digitized from ANH, 2012).

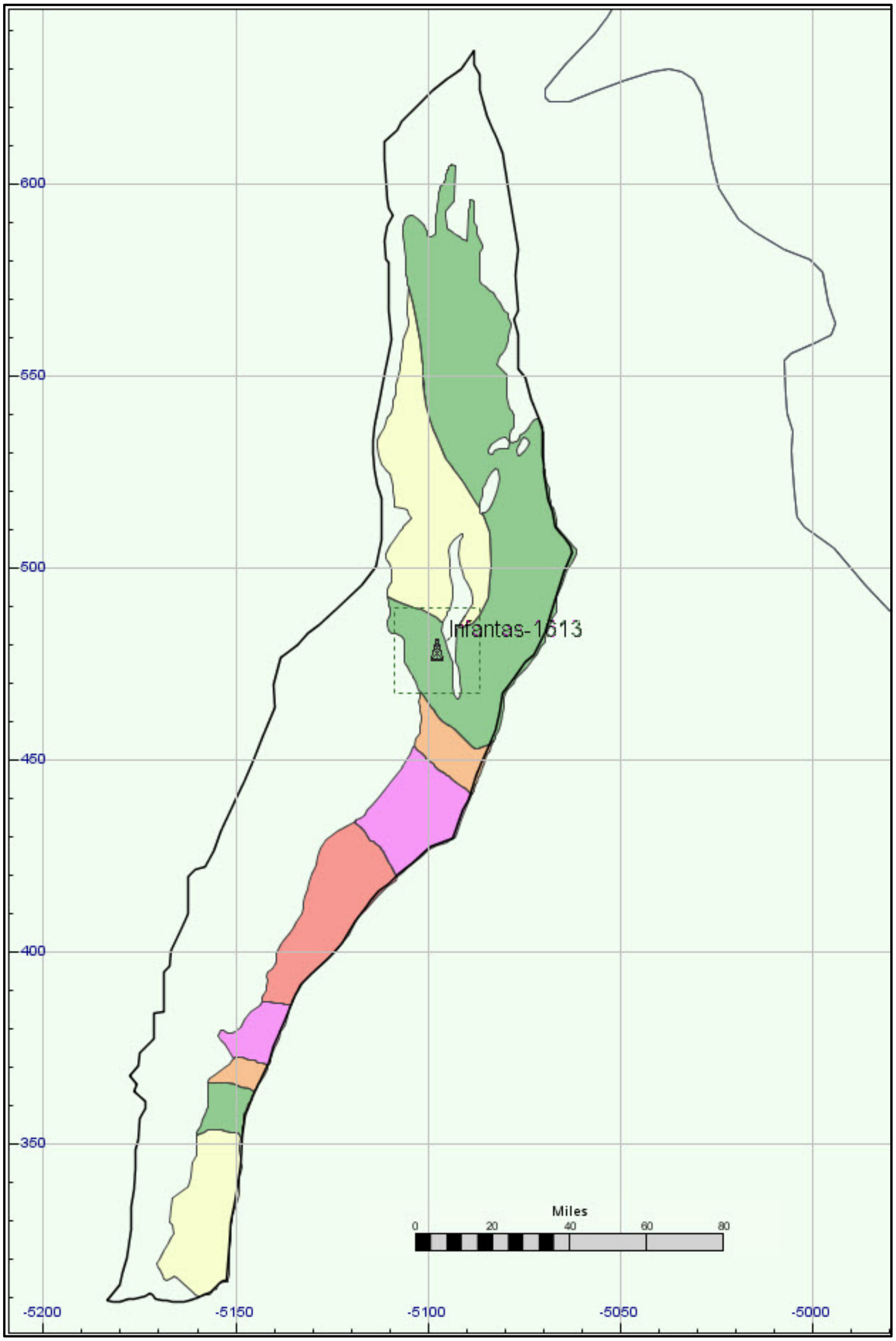

Figure 12. Map of La Luna maturity distribution created using vitrinite reflectance (%Ro) shapefiles in BasinMod® 1-D project. Color key: Tan = <0.6% Ro; Green = 0.6-1.0% Ro; Orange = 1.0-1.3% Ro; Pink = 1.3-2.0% Ro; Red = 2.0-3.0% Ro (shapefiles digitized from ANH, 2012).

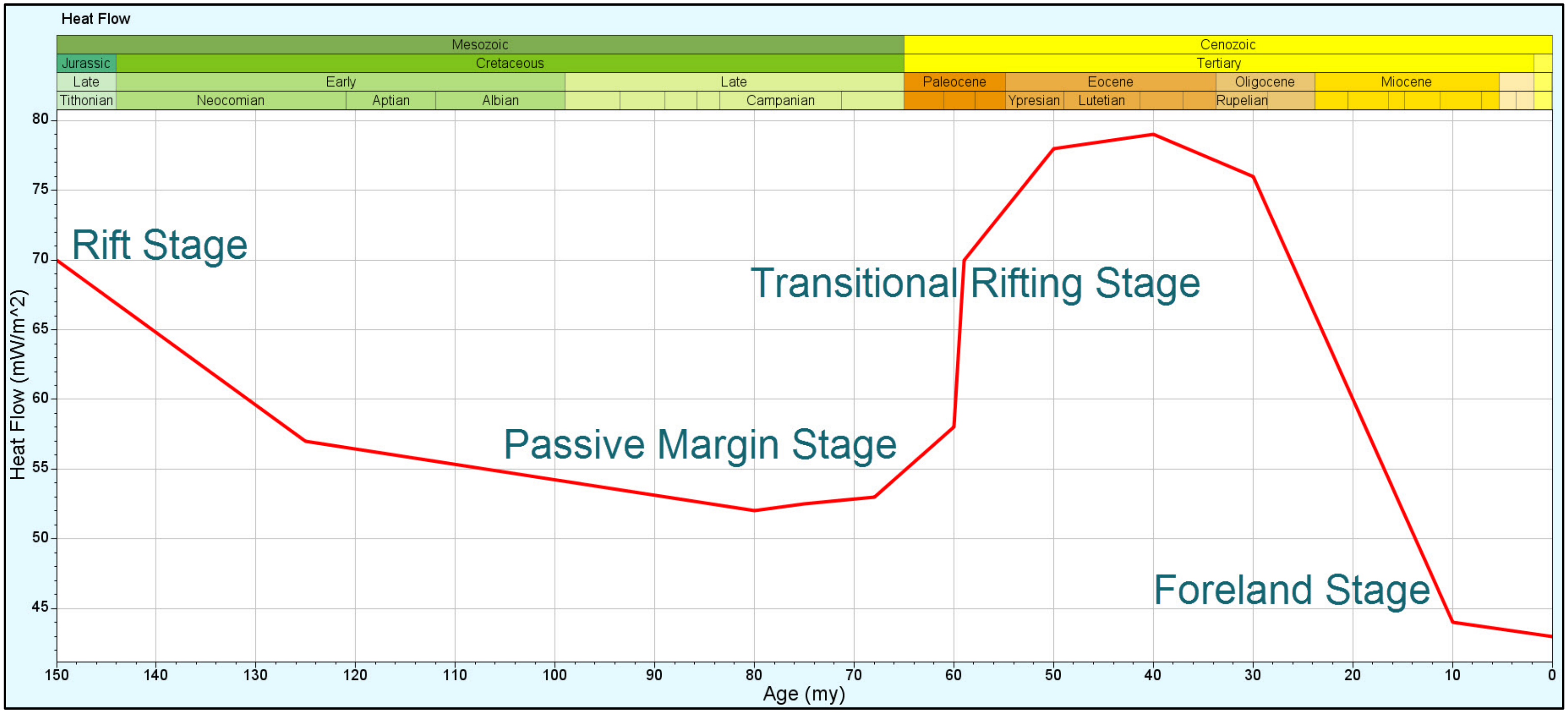

Figure 13. Heat flow graph from Catatumbo Subbasin used in BasinMod® 1-D project. Annotations correspond to the timing of tectonic stages as described by Rangel and Hernández (2007). The initial cooling takes place as the rift margin converts to a passive margin (Rangel and Hernández, 2007). The sharp increase in heat flow in the Tertiary occurs during the transition from passive margin to collision margin where there was a period of slight rifting with extensional movement concentrated on the preexisting Cretaceous faults (Rangel and Hernández, 2007). The subsequent cooling occurs during a period of crustal shortening as a result of the collision margin (Rangel and Hernández, 2007)

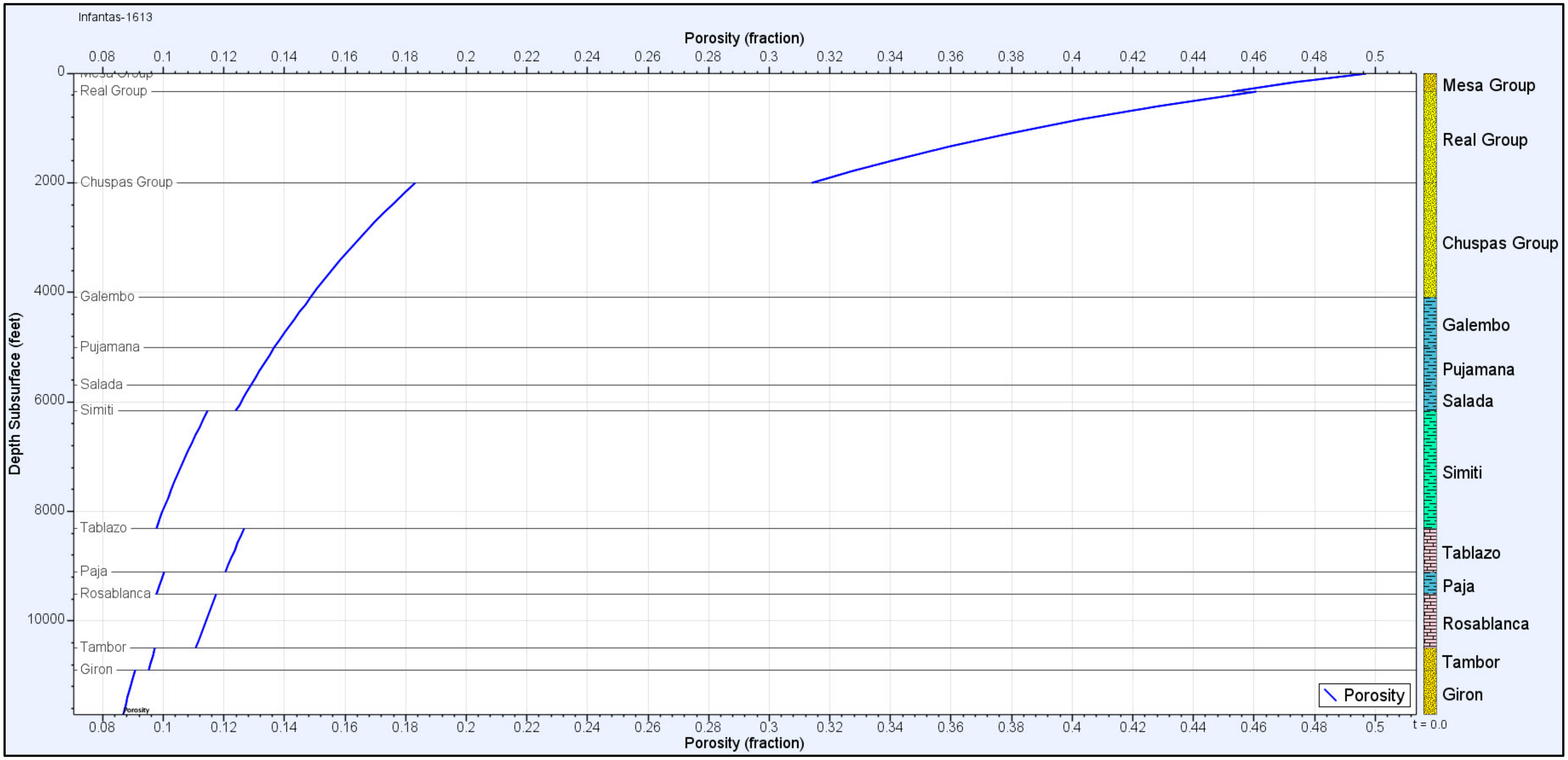

Figure 14. Graph of porosity with depth output from BasinMod® 1-D project. Mechanical-reciprocal compaction method used for the Rosablanca Formation through the La Luna Formation. Effective stress compaction was used for the Giron Formation, Tambor Formation, and Cenozoic groups. The uppermost groups are composed of continentally derived lithic sandstones and conglomerates, and so the porosity is very high. The Chuspas group has been compacted by the upper units, thus resulting in a lower porosity despite lithologies similar to the overlying sediment. The Cretaceous units have lower porosity due to the nature of the lithologies in addition to being deeper in the stratigraphy. These curves have not been calibrated due to lack of available measured porosity data for the Infantas-1613 well.

Figure 15. Paleo sea level curve used in BasinMod® 1-D project. Sea level was relatively high throughout the depositional periods for the source rocks (Cretaceous and early Cenozoic). The continentally-derived sediments were deposited in the late Jurassic and middle to late Cenozoic when sea level was the lowest (curve adapted from Gómez et al., 2005).

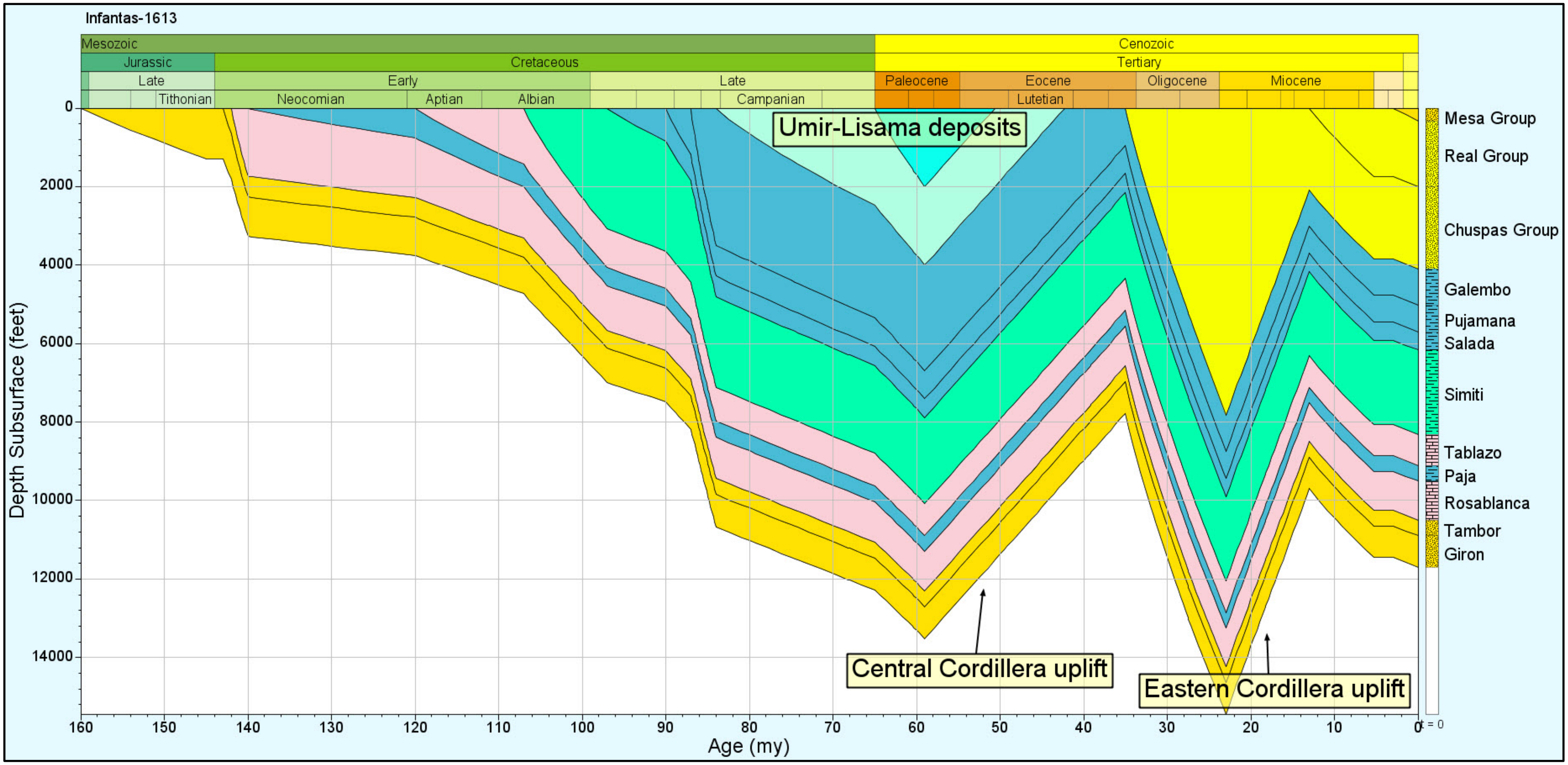

Figure 16. Burial history graph with the Cordillera uplifts/exhumations and the Umir-Lisama depositional event annotated.

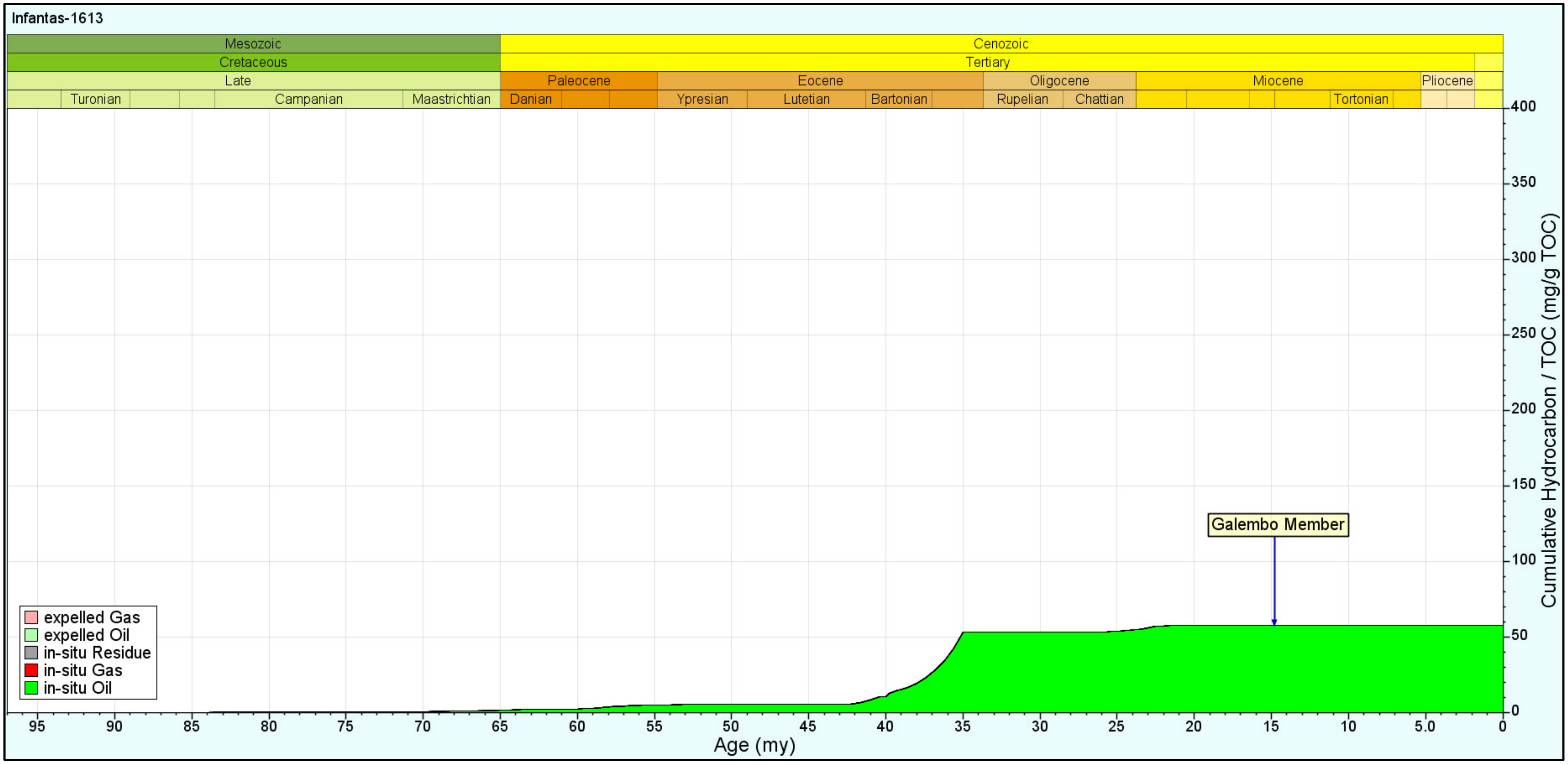

Figure 17. Modeled cumulative hydrocarbon per gram of TOC graph for the Galembo Member (uppermost) of the La Luna Formation. The model shows that the Galembo Member, in the vicinity of the Infantas-1613 well, has generated significantly less oil than the other two members of the formation. The Galembo Member has not reached the gas window yet, so it is only generating oil.

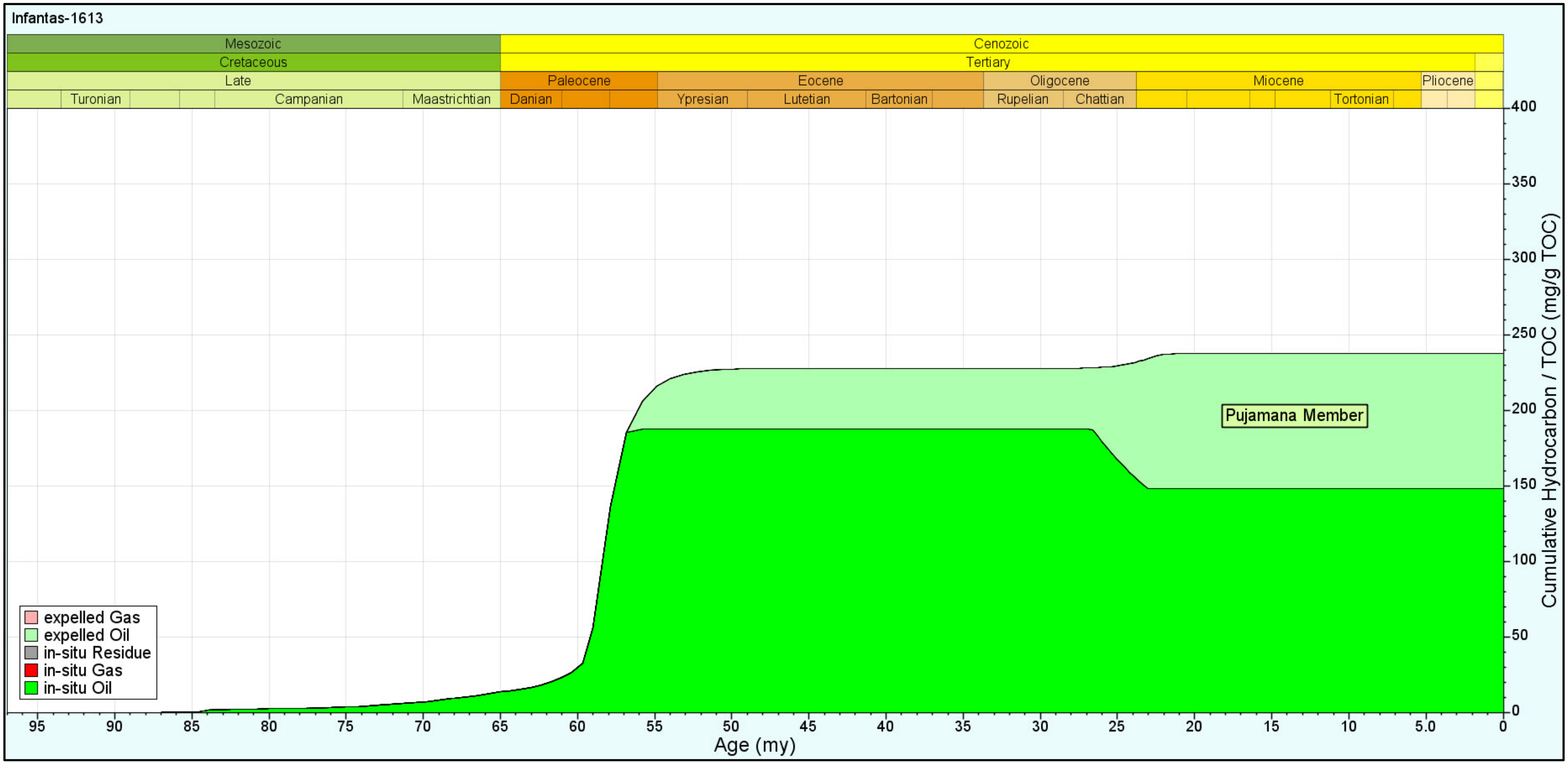

Figure 18. Modeled cumulative hydrocarbon per gram of TOC graph for the Pujamana Member (middle) of the La Luna Formation. The model shows that the Pujamana has not only accumulated a significant amount of oil, but it has also been expelling since the late Paleocene. Like the Galembo Member, the Pujamana Member has not reached the gas window in this location.

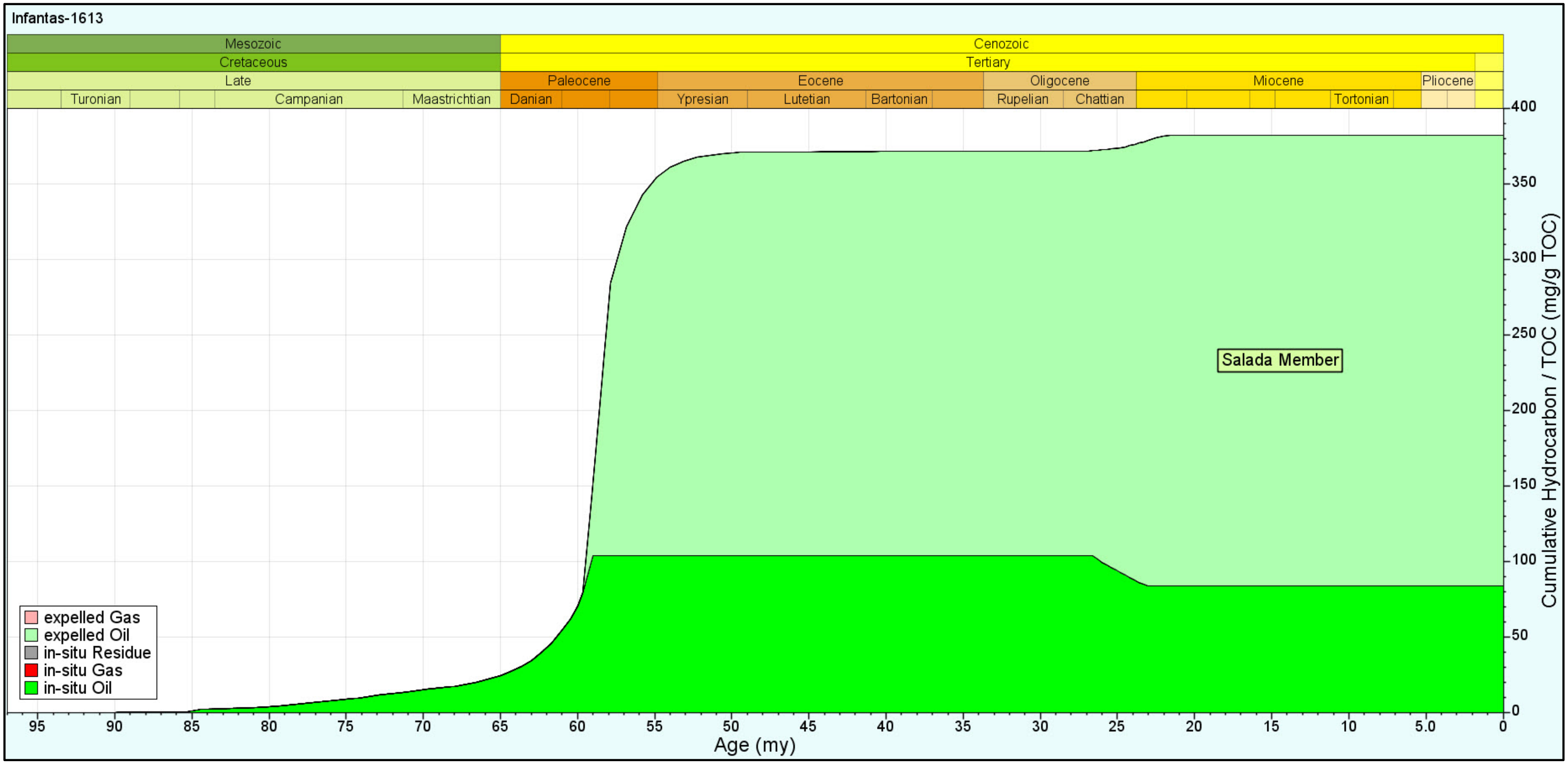

Figure 19. Modeled cumulative hydrocarbon per gram of TOC graph for the Salada Member (lowermost) of the La Luna Formation. The model shows that the Salada has generated the most oil out of the three members, but it has expelled much of what it has generated. Like the other two, the Salada Member has not reached the gas window in this location.

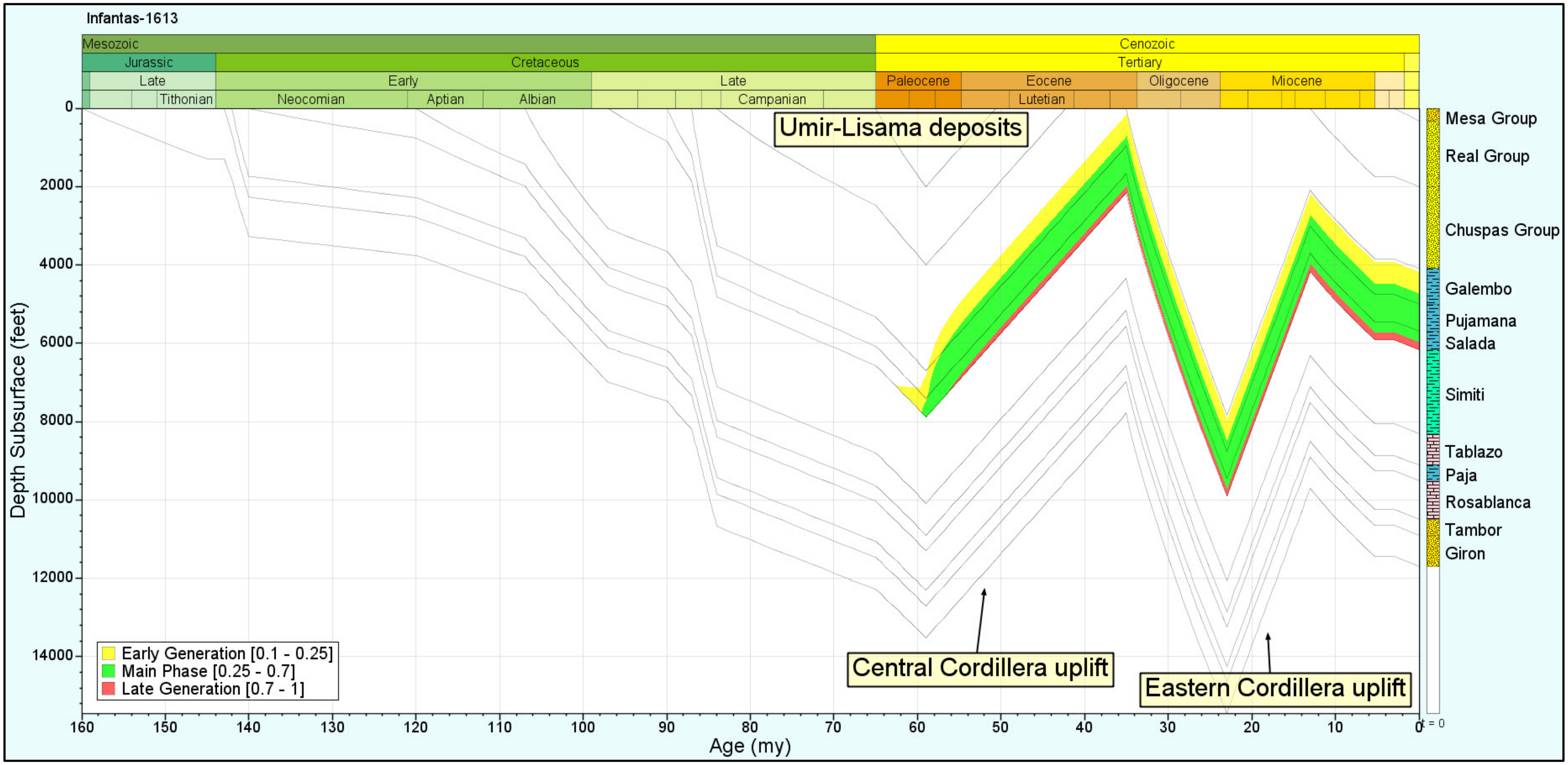

Figure 20. Kinetics windows (kerogen: type IIs, Tissot '87, Monterey) for La Luna Formation on burial history graph in BasinMod® 1-D project. The kinetics windows correspond to the percentage of kerogen that is transformed into hydrocarbon (transformation ratio) and are only pertinent for the source rocks.

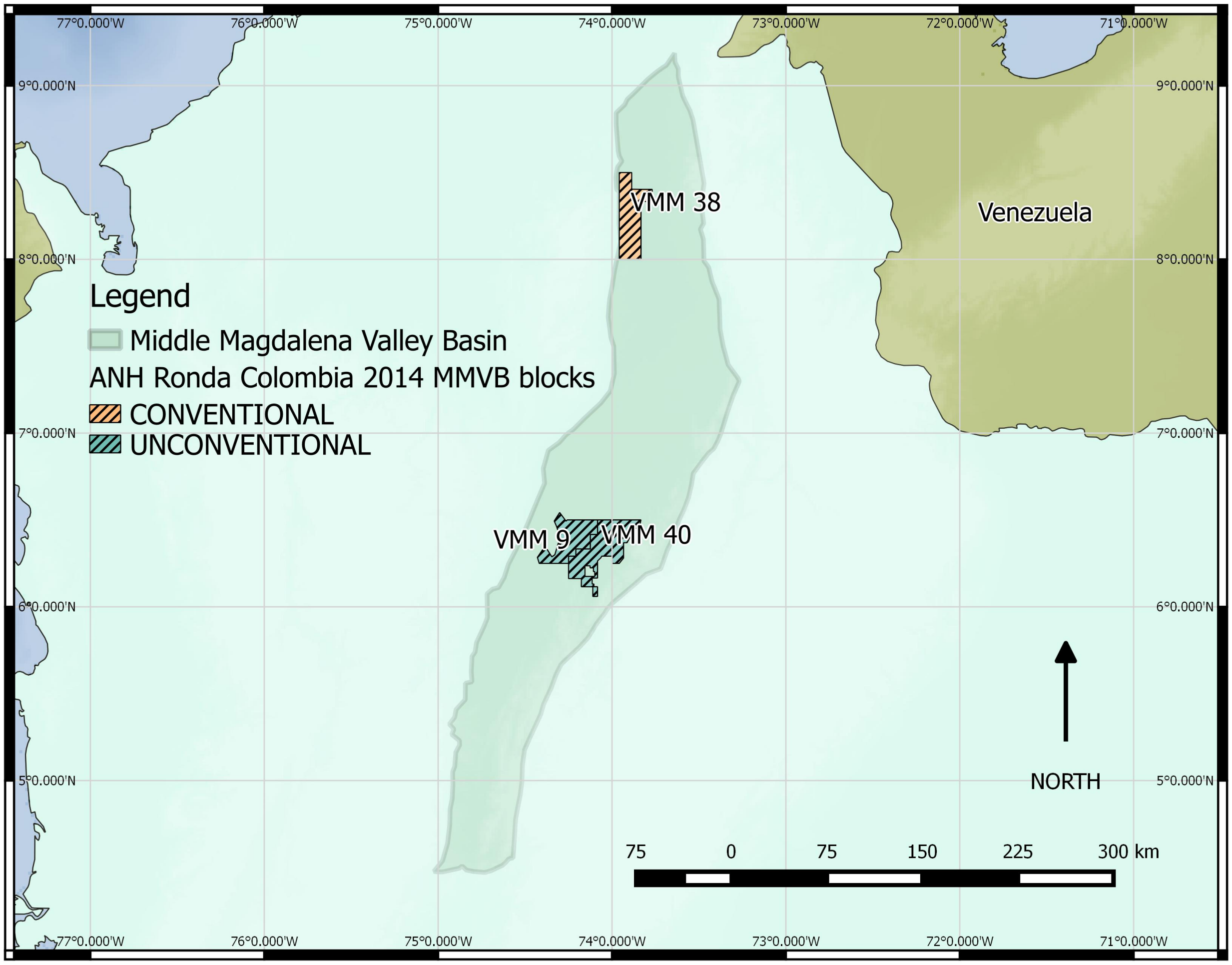

Figure 21. Map of ANH Ronda Colombia 2014 Middle Magdalena Valley Basin blocks. VMM 9 and VMM 40 are adjacent pieces of land designated for unconventional resources in the central-southern MMVB. VMM 38 is in the northern MMVB and is designated for conventional resources. Two additional unconventional blocks (one in the southernmost portion of the basin and one along the eastern edge of the basin between VMM 38 and VMM 40) are designated for coal bed methane production and are shown in the ANH (2014) documents. They are not shown on this figure because they are not included in the analysis (geographic information from: North American Cartographic Information Society—www.nacis.org; ANH—www.anh.gov.co; NOAA—www.noaa.gov).

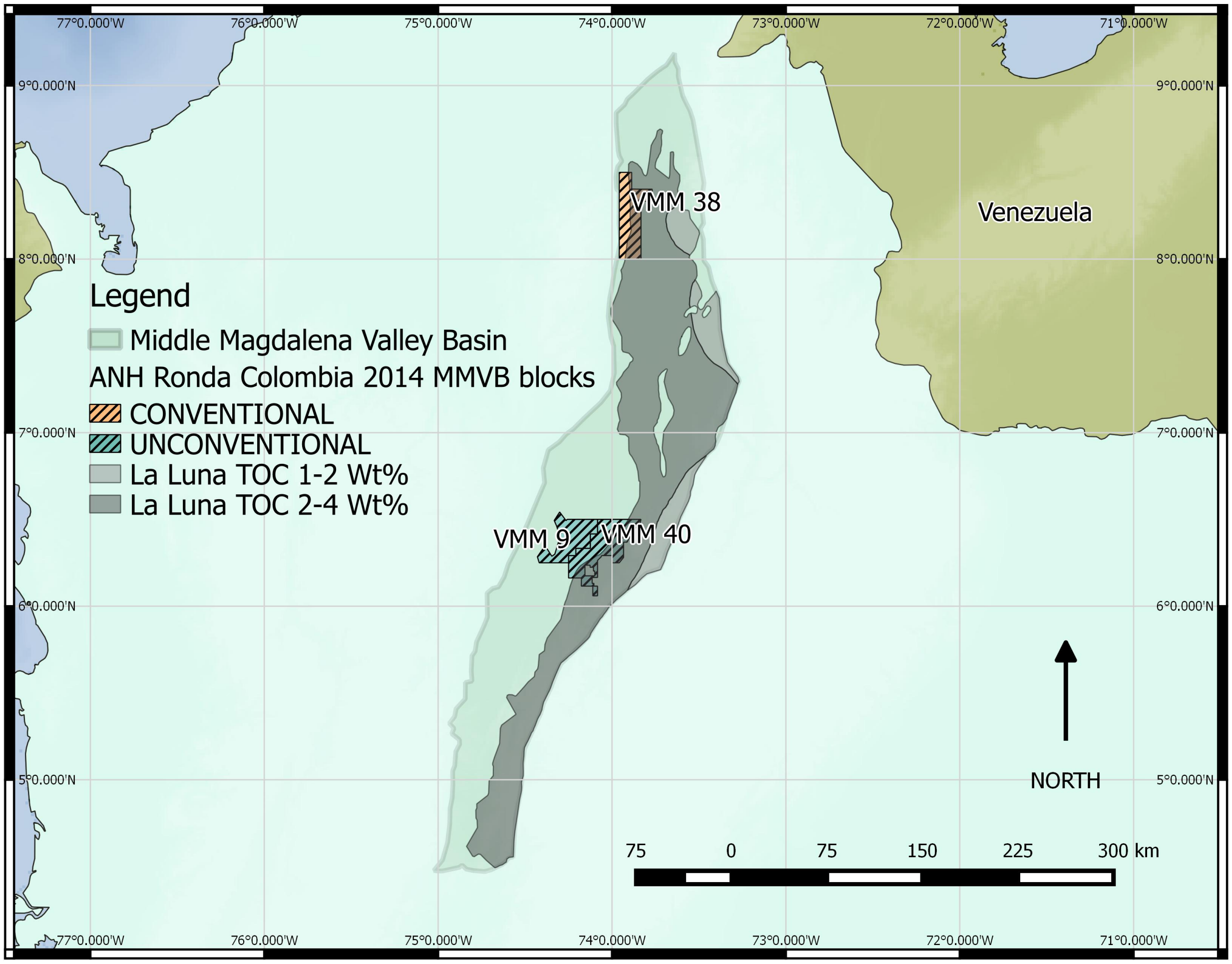

Figure 22. Map of La Luna TOC in relation to Ronda Colombia 2014 MMVB blocks. Both the VMM 40 and VMM 38 significantly overlap with the mapped TOC contents between 2 and 4 wt%. VMM 9 likely does not have the La Luna formation present, thus the alternative source rocks will need to be considered (geographic information from: North American Cartographic Information Society—www.nacis.org; ANH—www.anh.gov.co; NOAA—www.noaa.gov. La Luna TOC shapefiles digitized from ANH, 2012).

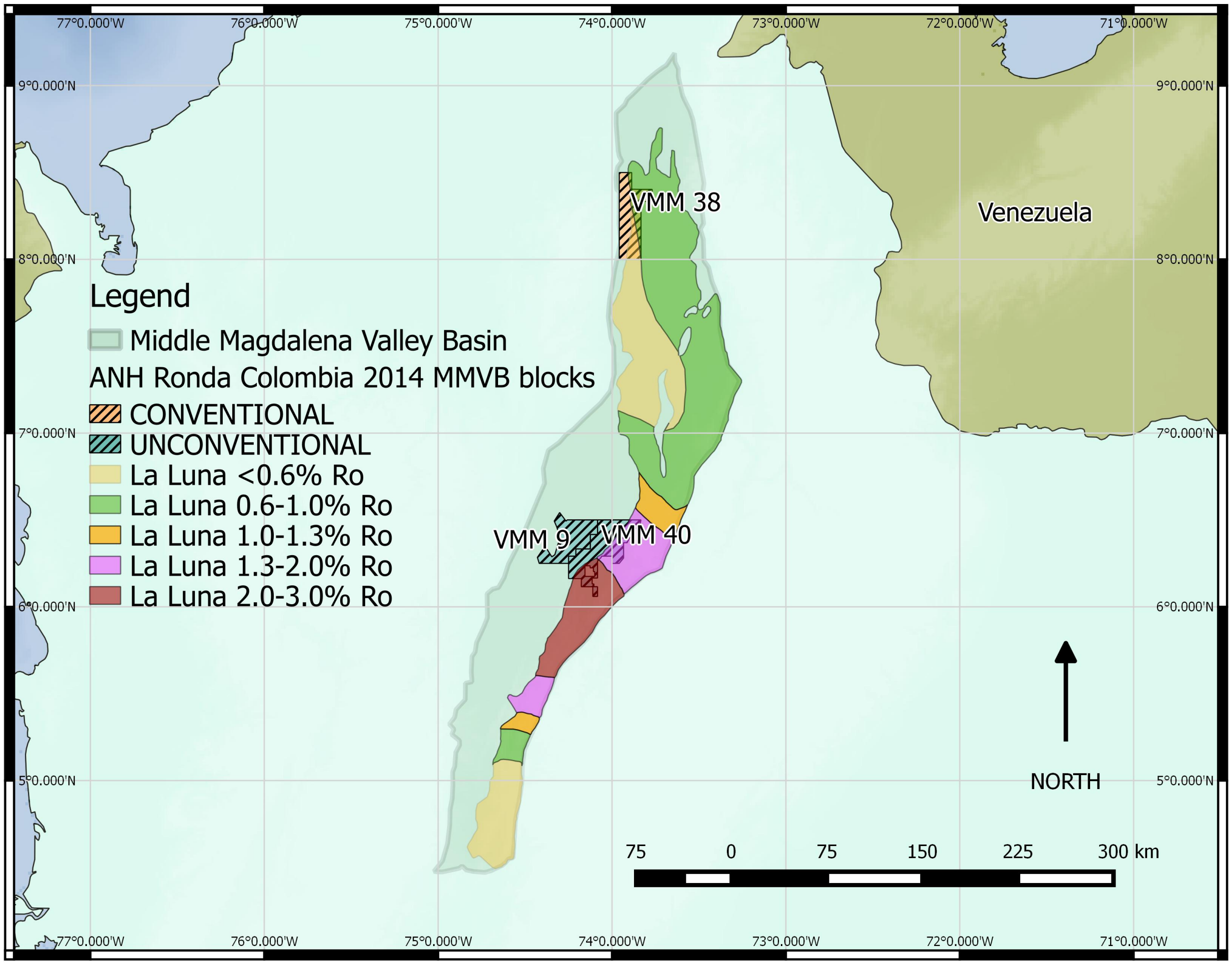

Figure 23. Map of La Luna vitrinite reflectance (Ro) in relation to Ronda Colombia 2014 MMVB blocks. In the VMM 38 land block, the La Luna formation appears to have maturity measurements on the lower end of the mapped scale (<0.6 to 1% Ro). Land block VMM 40, on the other hand, overlaps with measured maturities ranging from 1.3-3.0% Ro. No maturity overlaps in the VMM 9 block because the La Luna is not present (geographic information from: North American Cartographic Information Society—www.nacis.org; ANH—www.anh.gov.co; NOAA—www.noaa.gov. La Luna maturity shapefiles digitized from ANH 2012).

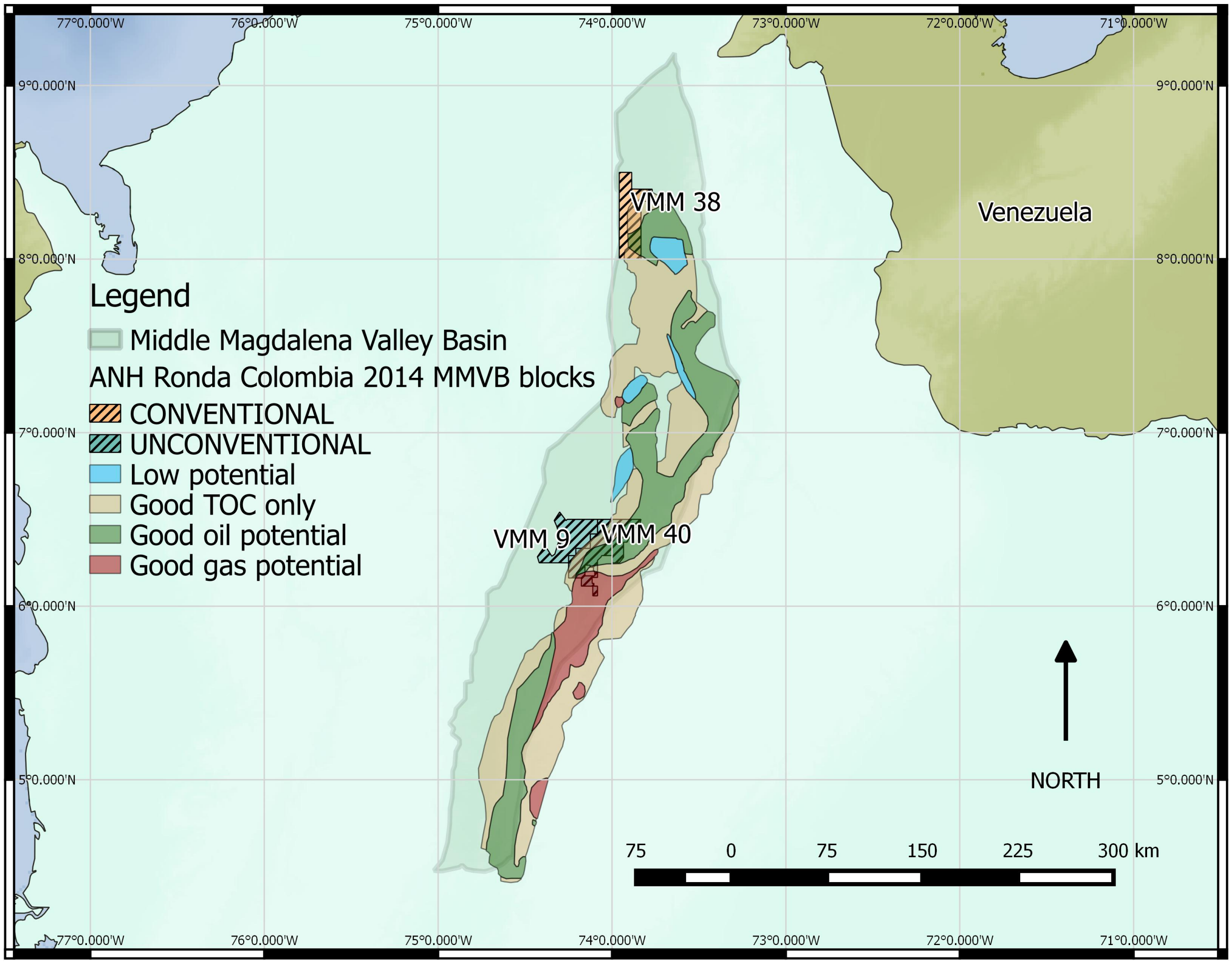

Figure 24. ANH (2014) sweet spot (multivariate analysis) map with Ronda Colombia 2014 MMVB blocks. VMM 38 appears to overlap with mapped zones of good TOC only and good oil potential. The VMM 40 block shows good potential for oil and gas with zones of high TOC. VMM 9 overlaps with good TOC potential. Areas to the south of the unconventional blocks show the highest potential for gas production in the basin (geographic information from: North American Cartographic Information Society—www.nacis.org; ANH—www.anh.gov.co; NOAA—www.noaa.gov. Multivariate analysis shapefiles digitized from ANH, 2014).

10.0 Tables

Table 1. Yet-to-find oil reserves in Colombia (Middle Magdalena Valley Basin values highlighted with red box; from Jimenez, 2012).

Basin	P_{10}	P_{50}	P_{90}
	(MMbbl)		
Total OFFSHORE	276,413	75,815	12,570
Los Cayos	43,050	11,774	1,950
Chocó offshore	12,589	3,453	575
Colombia	90,992	24,923	4,138
Guajira offshore	18,721	5,131	855
Deep Pacífic	92,961	25,566	4,224
Sinú offshore	8,182	2,248	377
Tumaco offshore	9,918	2,720	451
Total ONSHORE	153,952	42,148	7,436
Amagá	804	233	75
Caguán - Putumayo	419	137	34
Catatumbo	213	59	17
Cauca-Patía	4,553	1,247	208
Cesar - Ranchería	4,137	1,135	189
Chocó	13,444	3,682	607
The Eastern Cordillera	22,653	6,221	1,030
The Guajira	4,777	1,307	218
The Eastern Llanos	3,250	892	148
Sinú - San Jacinto	13,469	3,697	614
Tumaco	4,486	1,651	611
Urabá	4,413	710	159
The Lower Magdalena Valley	13,177	3,609	602
The Middle Magdalena Valley	11,885	3,252	539
The Upper Magdalena Valley	999	274	45
Vaupés - Amazonas	51,273	14,042	2,340
TOTAL	430,365	117,963	20,006

Table 2. Yet-to-find gas reserves in Colombia, associated with the oil reserves above (Middle Magdalena Valley Basin values highlighted with red box; from Jimenez, 2012).

Basin	P_{10}	P_{50}	P_{90}
	(Tcf)		
Total OFFSHORE	83.111	6.076	0.166
Los Cayos	0.183	0.02	0.002
Chocó offshore	53.389	3.756	0.065
Colombia	1.604	0.305	0.061
Guajira offshore	2.156	0.15	0.002
Colombian Deep Pacific	0.302	0.059	0.012
Sinú offshore	5.136	0.365	0.000
Tumaco offshore	20.341	1.421	0.024
Total ONSHORE	177.813	12.415	0.242
Amagá	2.842	0.203	0.004
Choco	8.607	0.609	0.020
Caguán - Putumayo	0.570	0.041	0.002
Catatumbo	7.755	0.548	0.010
Cauca-Patía	58.586	4.107	0.071
Cesar -Ranchería	7.937	0.558	0.010
The Eastern Cordillera	35.281	2.477	0.043
The Guajira	15.408	1.076	0.018
The Eastern Llanos	7.105	0.491	0.008
Sinú - San Jacinto	11.287	0.79	0.014
Tumaco	3.130	0.219	0.004
Urabá	2.558	0.179	0.004
The Lower Magdalena Valley	6.658	0.467	0.008
The Middle Magdalena Valley	2.253	0.041	0.002
The Upper Magdalena Valley	7.531	0.528	0.008
Vaupés - Amazonas	0.305	0.081	0.016
TOTAL	260.924	18.5491	0.409

Table 3. Geochemical parameters for potential Cretaceous-age source rocks (Sources: Ramon et al, 1997; Sarmiento, 2011; Veigal and Dzelalijal, 2014; – = no data).

Formation	Kerogen Type	TOC wt%	% Ro	HI (mg HC/g TOC)	S-2 (mg HC/g Rock)
Cumbre	Type II	1.0 - 7.8	1.1 - 1.2	-	-
Rosablanca	Type II	0.3 - 5.4	0.75 - 2.0	104 - 136	0.54 - 0.9
Paja	Type I/II mix	0.74 - 8.95 (avg. 2 - 3)	1.1 - 1.38	120	0.68
Tablazo	Type I/II mix	0.48 - 4.74 (avg. 2 - 3.5)	1.1 - 1.3	100 - 600	2.18 - 5.97
Simití	Type II	0.55 - 12.08 (avg. 2.6)	0.71-0.95	100 - 600	0.42 - 6.21
La Luna	Type IIs	2.4 - 4.5	0.49 - 2.5	302	5.0 - 27.0
Umir	Type II/III mix	0.67 - 6.72	0.6	173 - 420	-

Table 4. Stratigraphic events used in the Infantas-1613 well in the BasinMod 1-D® project (Sources: ANH, 2012; Cooper et al., 1995; Garcia Gonzalez et al., 2009; Olivella, 1972; Rangel et al., 2002; Rolon, 2004; Sánchez, 2011; Schamel, 1991; Toro, 1990; Torres et al., 2012; Walls, 2013; – = N/A).

Event	Type	End Age (Ma)	Top Depth (ft.)	Thickness (ft.)	Eroded Thickness (ft.)
Mesa Group	Formation	0	0	330	-
Tertiary hiatus	Hiatus	3	-	-	-
Real Group	Formation	5.3	330	1,670	-
East. Cord. uplift	Erosion	13	-	-	-5,740 (estimate)
Chuspas Group	Formation	23	2000	2,240	-
Cen. Cord. uplift	Erosion	35	-	-	-5,740 (estimate)
Lisama-Umir	Deposit	59	-	-	3,000 (average)
Galembo	Formation	84	4,094	918	-
Pujamana	Formation	87	5,012	688	-
Salada	Formation	90	5,700	467	-
Simití	Formation	97	6,167	2,147	-
Tablazo	Formation	107	8,314	798	-
Paja	Formation	120	9,112	395	-
Rosablanca	Formation	140	9,507	993	-
Tambor	Formation	142	10,500	400	-
Jurassic hiatus	Hiatus	143	-	-	-
Giron	Formation	145	10,900	800	-

Table 5. Gross depositional environment (GDE) designations for stratigraphic events in the Infantas-1613 well in the BasinMod® 1-D project. GDEs were assigned using the GDE maps digitized from Cooper et al. (1995) and lithological descriptions from the literature.

Event	Assigned GDE (in BasinMod® 1-D Project)
Mesa Group	Continental: Fluvial: Anastomosing Stream: Coarse to sand grained clastics dominated
Real Group	Transitional: Siliciclastic shoreline: Backshore/foreshore: Undifferentiated
Chuspas Group	Transitional: Siliciclastic shoreline: Backshore/foreshore: Undifferentiated
Lisama/Umir	Transitional: Shelf shoreline: Transition zone: Coastal sands - shelf muds
Galembo	Marine: Carbonate ramp: Deep ramp: Cherty bearing, shaley fossiliferous
Pujamana	Marine: Carbonate ramp: Deep ramp: Cherty bearing, shaley fossiliferous
Salada	Marine: Carbonate ramp: Deep ramp: Cherty bearing, shaley fossiliferous
Simití	Marine: Basin slope: Mud rich: Debris flows, slumps
Tablazo	Marine: Carbonate platform: Undifferentiated: Undifferentiated
Paja	Marine: Carbonate ramp: Deep ramp: Cherty bearing, shaley fossiliferous
Rosablanca	Marine: Carbonate platform: Undifferentiated: Undifferentiated
Tambor	Continental: Fluvial: Meandering stream: Sand-rich higher energy
Giron	Continental: Fluvial: Meandering stream: Channel fill

Table 6. Sea level data and other information from the northern Middle Magdalena Valley Basin. Values for sea level converted from meters to feet in Microsoft Excel prior to entry in the BasinMod® 1-D project (from Gómez et al., 2004).

TABLE DR1. INPUT PARAMETERS FOR BACKSTRIPPING AND GEOHISTORY ANALYSIS OF THE MESOZOIC TO CENOZOIC SEDIMENTARY SECTION OF THE NORTHERN MIDDLE MAGDALENA VALLEY BASIN*

Stratigraphic unit	Lithology†	Depth interval (m)	Age (Ma)	Grain density (kg/m3)	C (1/km)	Initial porosity	Water depth (m)	Absolute sea level (m)
Real	ss, ms, cg	0-2000	5.4-12.7	2679	0.37	0.55	-250±250	140
Colorado	ss, ms	2000-3150	12.7-23.8	2678	0.37	0.55	-250±250	135
Mugrosa	ss, ms	3150-4150	23.8-31.1	2685	0.39	0.56	-250±250	180
Esmeraldas	ss, ms	4150-4750	31.1-35.3	2685	0.39	0.56	-250±250	200
La Paz	ss, ms	4750-5719	35.3-43	2669	0.34	0.53	-250±250	205
LKCU		5719-5719	43-56				-1500±1500	200
Lisama	ms, ss	5719-6944	56-65	2692	0.41	0.57	0±5	210
Umir	ms, ss	6944-8019	65-83.5	2709	0.47	0.61	5±5	230
La Luna	ls, ms	8019-8319	83.5-93.5	2713	0.65	0.68	30±15	250
Salto	ls	8319-8444	93.5-98.9	2710	0.71	0.70	10±5	230
Simití	ms	8444-9211	98.9-110	2720	0.51	0.63	30±10	160
Tablazo	ls	9211-9461	110-112.2	2710	0.71	0.70	15±10	170
Paja	ms	9461-10086	112.2-127	2720	0.51	0.63	15±15	100
Rosa Blanca	ls	10086-10514	127-137	2710	0.71	0.70	5±5	165
Los Santos	ss	10514-10819	137-142	2650	0.27	0.49	-5±5	150
Girón-Jordán	cg, ss, ms	10819-16126	142-176.5	2671	0.34	0.53	-5±5	35
Bocas	ms, ls	16126-16709	176.5-193	2715	0.61	0.67	5±5	40

* Data sources: Etayo-Serna (pers.comm., 2000), Etayo-Serna et al (1983), Gómez (2001), Morales et al (1958), Ramírez (1988)
† ss (sandstone), ms (mudstone), cg (conglomerate)