STRUCTURAL ANALYSIS OF AN AREA IN THE NORTHERN CENTRAL PART
OF THE MIDDLE MAGDALENA VALLEY BASIN, COLOMBIA

by
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ABSTRACT

The area of study is located in the northern sector of the Middle Magdalena Valley Basin in the north central part of Colombia. Most of the discovered oil fields in the Middle Magdalena Valley Basin correspond to hydrocarbon accumulations in structural traps in Tertiary siliciclastic reservoirs.

The main aim of this project is to undertake a structural restoration of the present day geometry of the study area, which will validate the proposed structural interpretation and test current structural models for the tectonic evolution of the study area. The main data used in this research are 2D and 3D seismic profiles. The interpretation focused mainly on a 3D volume due to its good seismic resolution as well as well information. The workflow for this study was 1) 2D/3D seismic interpretation, 2) depth conversion of horizons and faults, 3) 3D structural model construction, and 4) 2D structural restorations.

The main structural feature of the area is the Cagui Fault and its associated half graben, which is interpreted as an ancient (Jurassic age) listric normal fault that was inverted to its present configuration as a reverse fault. The main evidence for this includes: 1) reflectors diverging toward the Cagui Fault, indicating activity as a normal fault during the Jurassic, 2) the syn-rift package is located in the hanging wall of the Cagui Fault, 3) the structure shows typical minor faulting related to tectonic inversion such as a) footwall and hanging wall shortcuts, b) back thrusts and c) an anticline fold on the hanging wall. The extensional phase corresponds to Jurassic rifting proposed for the
central part of Colombia. The Maastrichtian-Paleocene compressional phase is related to subduction located along the western border of the South American continent.

The tectonic inversion is an important factor since it can significantly modify the burial history, the porosity (secondary) of uplifted sediments, modify the directions of fluid migration, and change the sealing properties of reactivated faults.

A possible new hydrocarbon exploratory play is proposed for the intra-Jurassic syn-rift units in the hanging wall of the Cagui Fault, depending on the possibility of having an intra-Jurassic source rock, or a hydrocarbon migration from the footwall of this fault where the main source rocks are located.
TABLE OF CONTENTS

ABSTRACT .......................................................................................................................... iii
LIST OF FIGURES ........................................................................................................... viii
LIST OF TABLES ............................................................................................................. xi
ACKNOWLEDGMENTS ................................................................................................ xii
CHAPTER 1: INTRODUCTION ..................................................................................... 1
  1.1 Research Objectives ........................................................................................ 4
  1.2 Review on Inversion Tectonics ..................................................................... 5
    1.2.1 Definition of Inversion ..................................................................... 5
    1.2.2 Origins of Inversion ...................................................................... 5
    1.2.3 Degree of Inversion ....................................................................... 7
    1.2.4 Theoretical Model .......................................................................... 8
    1.2.5 How to Recognize Inversion............................................................ 10
    1.2.6 Fault Sequences ............................................................................... 11
    1.2.7 Examples .......................................................................................... 12
    1.2.8 The Importance of Inversion Tectonics ........................................... 14
  1.3 Study Area ...................................................................................................... 14
  1.4 Data Set ........................................................................................................... 15
  1.5 Previous Studies in the MMV Basin ............................................................... 19
CHAPTER 2: GEOLOGIC FRAMEWORK ................................................................... 26
  2.1 Structural Setting and Basin Evolution........................................................... 26
  2.2 Stratigraphy ..................................................................................................... 31
    2.2.1 Jurassic: Sequence A ........................................................................ 31
    2.2.2 Cretaceous-Paleocene: Sequence B .................................................. 34
      2.2.2.1 Tambor Formation .................................................................. 34
      2.2.2.2 Los Santos Formation .............................................................. 35
      2.2.2.3 Cumbre Formation ................................................................. 35
      2.2.2.4 Rosablanca Formation ............................................................ 35
      2.2.2.5 Paja, Tablazo, Simití, La Luna Formations ................................. 35
      2.2.2.6 Umir Formation ..................................................................... 36


2.2.2.7 Lisama Formation ................................................................. 36
2.2.3 Middle Eocene-Quaternary: Sequence C .................................. 37
  2.2.3.1 La Paz Formation .......................................................... 37
  2.2.3.2 Esmeraldas Formation ............................................... 37
  2.2.3.3 Mugrosa Formation ..................................................... 37
  2.2.3.4 Colorado Formation .................................................... 38
  2.2.3.5 Real Group .................................................................. 38

CHAPTER 3: METHODOLOGY ........................................................................... 39
  3.1 Previous Studies of the Area of Study ........................................... 39
  3.2 Well – Seismic Tie .................................................................... 41
  3.3 Seismic Interpretation ............................................................... 41
  3.4 Time Depth Conversion ........................................................... 42
  3.5 3D Structural Model Construction ............................................. 45
  3.6 2D Structural Restoration ......................................................... 46
    3.6.1 Decompaction ............................................................... 47
    3.6.2 Isostatic Correction ........................................................ 49
    3.6.3 Structural Restoration ..................................................... 49

CHAPTER 4: RESULTS ....................................................................................... 52
  4.1 Seismic Interpretation ............................................................... 52
  4.2 Structural Restorations ............................................................. 60
    4.2.1 Potential Sources of Error ............................................... 65
    4.2.2 Section 2 (Seismic Merge M-76-04/IL140) ......................... 66
      4.2.2.1 Jurassic-Cretaceous Unconformity ............................... 66
      4.2.2.2 Cretaceous .............................................................. 67
      4.2.2.3 Eocene Unconformity ............................................. 70
      4.2.2.4 Tertiary Units-Current Stage .................................... 71
    4.2.3 Section 1 (Seismic Line IL40) ........................................... 75
    4.2.4 Section 4 (Seismic Line IL440) ........................................... 79

CHAPTER 5: DISCUSSION ................................................................................. 82
  5.1 Inversion Tectonics in the Study Area .......................................... 82
    5.1.1 Definition of Inversion ..................................................... 82
LIST OF FIGURES

Figure 1.1 - Location of the Middle Magdalena Valley Basin (MMVB) .................. 2
Figure 1.2 - Main structures of the MMVB .............................................................. 3
Figure 1.3 - Laboratory experiment for inversion of a normal fault .................... 6
Figure 1.4 - Sequential diagrams showing the contractional inversion of an extensional fault .................................................................................. 8
Figure 1.5 - Conceptual models for thrust faults developed by the dip-slip inversion of a listric fault system .............................................................. 9
Figure 1.6 - Schematic diagram of a positive inversion structure ......................... 11
Figure 1.7 - The development of a footwall shortcut fault with a shallower dip during inversion of a steeply dipping extension fault ........................................ 12
Figure 1.8 - Seismic line of the Missour Basin showing the reactivated listric normal fault and the synrift and postrift sequences ............................................ 13
Figure 1.9 - Restoration of migrated and depth converted seismic line of the Missour Basin) ............................................................................................. 13
Figure 1.10 - Northern MMVB and general location of the Study Area ............... 16
Figure 1.11 – Map of seismic and well data available for this study .................... 17
Figure 1.12 – Comparison between old 2D seismic and new 3D seismic data ....... 18
Figure 1.13 - Traverse section through the Arcabuco-Guantiva and Floresta rift structures, as restored to a post-rift stage ..................................................... 21
Figure 1.14 - Structural cross sections of the MMV Basin ..................................... 22
Figure 2.1 - Location of the Upper Magdalena and Middle Magdalena Valley Basin... 27
Figure 2.2 - Tectonical boundaries of the northern part MMVB .......................... 28
Figure 2.3 - Generalized structural cross section of the northern part MMVB ....... 29
Figure 2.4 - Tectonic history of the MMVB ............................................................ 32
Figure 2.5 - Generalized stratigraphic column of the MMVB ............................... 33
Figure 2.6 - Two lithologic profiles of the Floresta rift structure .................................. 34
Figure 2.7 - Thin sections of two of the Cretaceous formations .................................... 36
Figure 2.8 - Thin sections of two of the Tertiary formations ........................................... 38
Figure 3.1 - Methodology followed in this study for developing the structural analysis . 40
Figure 3.2 – Synthetic seismogram of Cagui-1 well ....................................................... 43
Figure 3.3 – Stratigraphic column with the seismic horizons interpreted ....................... 44
Figure 3.4 – Location of the 2D cross sections and seismic lines ................................... 47
Figure 4.1 – Dip Seismic Profile IL 40 ........................................................................... 53
Figure 4.2 – Dip Seismic Profile IL 40 ........................................................................... 55
Figure 4.3 – Dip Seismic Profile IL 140 ........................................................................... 57
Figure 4.4 – Dip Seismic Profile merge M-76-04/IL40 .................................................. 58
Figure 4.5 - Dip Seismic Profile IL 440 ........................................................................... 61
Figure 4.6 - Strike Seismic Profile XL 340 ..................................................................... 62
Figure 4.7 - Strike Seismic Profile XL 500 ..................................................................... 63
Figure 4.8 - 3D structural image for the Jurassic-Cretaceous Unconformity .................... 64
Figure 4.9 - Time slice at 3000 ms showing the Cagui Fault and seismic character of Jurassic and Cretaceous rocks ........................................................................... 65
Figure 4.10 - Structural restoration of section 2 ............................................................... 72
Figure 4.11 - Structural restoration of section 1 ............................................................... 76
Figure 4.12 - Structural restoration of section 4 ............................................................... 80
Figure 5.1 – Seismic line showing the thickness of the Jurassic units increasing toward the Cagui Fault .................................................................................................... 83
Figure 5.2 – Isopach thickness in TWT of the J2 unit ...................................................... 83
Figure 5.3 – Degree of inversion of the Cagui structure .................................................. 85
Figure 5.4 – Comparison of theoretical models vs. Cagui structure................................. 86

Figure 5.5 – Dip Seismic Profile merge M-76-04/IL40. Distinctive characteristics of inversion............................................................................................................................ 88

Figure 5.6 – Comparison of example of inversion from Missour Basin vs. Cagui structure........................................................................................................................................ 90

Figure 5.7 – Decision workflow chart in the structural restoration of Section 2 .......... 92

Figure 5.8 – Tectonics plate framework in the Paleocene time ............................................. 95
LIST OF TABLES

Table 1.1 - Seismic acquisition parameters .............................................................. 15
Table 3.1 - Horizons interpreted and their pick confidence................................. 45
Table 3.2 - Values used in decompaction steps ...................................................... 48
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CHAPTER 1
INTRODUCTION

The Middle Magdalena Valley Basin (MMVB) of Colombia is located in the north central part of the country between the Central and Eastern Cordillera of the Colombian Andes (Figure 1.1). The MMVB is one of the most prolific petroleum basins in Colombia. Most of the discovered oil fields correspond to hydrocarbon accumulations in structural traps in Tertiary siliciclastic reservoirs.

The MMVB has a complex history of deformation and formed as a result of a series of tectonic events in the northwest corner of South America. During the Triassic to Early Cretaceous time, the basin was a rift basin, which evolved in the Cretaceous to a back-arc basin, east of the Andean subduction zone (Cooper et al., 1995). During the Maastrichtian-Paleocene time, the basin developed into a foreland basin, related to the uplift of the Central Cordillera. During the Middle Miocene the basin became an intermontane basin due to the uplift of the Eastern Cordillera (Cooper et al., 1995). As a result, the MMVB has a complex history of extension, transpression, compression, and tectonic inversion.

The study area is located in the northern sector of the MMVB. The western boundary of the basin is defined by the Central Cordillera, highlighted by the Palestina Fault, a dextral strike-slip fault system. The eastern boundary corresponds to the Bucaramanga Fault, a sinistral strike-slip fault system that juxtaposes the basin against
the Santander Massif (Figure 1.2). Toward the north, the basin becomes thins and terminates against a paleohigh (Suárez, 1997).

Figure 1.1: Location of the Middle Magdalena Valley Basin (MMVB), from Córdoba et al., 2001.
Figure 1.2: Main Structural Features of the MMVB, from Schamel (1991).
Given this complex tectonic history, it is not surprising that the current geometry of the basin is characterized by a complex structural style. For this reason, in order to constrain the structural interpretation and restoration of a study area, it is important to have a good understanding of inversion structures that have been active during the basin shortening phases that followed the early rifting events.

Therefore, section 1.2 reviews structural inversion styles, based on previous studies of inverted basins from around the world.

1.1 Research Objectives

The main goal of this project is to undertake a structural restoration of the present day geometry of the study area in the MMVB, which will validate the structural interpretation obtained and test current models for the tectonic evolution of the area. This will also comprise the interpretation and delimitation of a half graben of the Jurassic-Triassic rift and its control on the structural inversion and present day structural configuration of this part of the basin. Other secondary goals of the study are:

- To test theoretical models, or examples of inversion tectonic from other basins apply, in the study area.
- To determine the position of detachments, ramps and flats for the different faults in the study area.
- To establish the relationship between the geometry of the faults and the geometry of the structures that affects the reservoirs.
- To identify potential new exploratory plays for petroleum reserves, particularly in the unexplored Jurassic rift section.
1.2 Review of Inversion Tectonics

In this part, a review about structural inversion styles will be discussed, based on previous studies of inverted basins from around the world.

1.2.1 Definition of Inversion

Cooper et al. (1989) recommended restricting the terms “inverted basin” and ‘inversion tectonics’ to the intra-plate compressional-transpressional deformation of basins, which developed earlier a largely tensional-transtensional setting. It is also possible to define an inversion structure or an inversion as: “a pre-existing extensional-transtensional fault controlling a hanging wall basin containing a syn-rift or passive fill sequence that has subsequently undergone compression-transpression producing uplift and partial extrusion of the basin” (Coward, 1994). These definitions can be classified as positive inversion. However, there can also be negative inversion when an area of uplift subsequently subsides. The most common type of inversion structure is however positive inversion (Holdsworth et al., 1997), and the term “inversion” is commonly used when discussing structures generated by positive inversion as defined above.

1.2.2 Origins of Inversion

Laboratory experiments and field observations show that faults develop at an angle of 30° to the greatest stress direction (σ1). Accordingly, extensional faults commonly dip at 60° and contractional faults at 30°. As a consequence of this, once formed, steep normal faults tend to be reactivated as steep reverse faults instead of low angle reverse faults, when there is a reverse change in the regional stress field (Figure
1.3). The key factor is that a 60° dip of the fault plane is not optimal for reactivation unless the slip is more oblique or the normal faults are listric. If the faults are too steep then footwall shortcuts develop.

Plate collision, especially oblique plate collision, is one of the most common causes of tectonic inversion. Numerous zones of continental collision show some
evidence of collision-related inversion tectonics as well as thin-skinned thrusting (Coward, 1994). Nevertheless, inversion related to changes of relative plate motion is not confined to areas of continent/continent collision. Large-scale inversion structures occur along most of the NW Pacific margin, related to closure of Paleogene back-arc basins (Coward, 1994).

Major crustal shortening of the Eastern Cordillera of Colombia and Llanos Foothills began at approximately 10.5 Ma and resulted from Panamá’s collision with South America. Pre-existing extensional faults were inverted into compressional structures (Cooper et al., 1995).

On a broad scale, it is possible to distinguish between weakly and strongly inverted basins, where the strongly inverted basins may develop a thickened crust and mountain belt and generally, but not always, occur at the sites of continental collision. The French Alps are examples of strong inversion associated with collision (Gillcrist et al., 1987).

1.2.3 Degree of Inversion

The degree of inversion can be indicated by the inclusion of a descriptor such as 1) **mild**, 2) **moderate** or 3) **strong** depending on the location of the null point or 4) **total** when no null point exist due to complete extrusion of basin-fill sediments (Cooper et al., 1989).

The null point is defined as a point along the fault with no apparent displacement. That is, rocks dropped below their regional elevation by extension are elevated back just to their regional elevation by later shortening. Progressive contractional inversion of an
extensional syn-rift sequence causes the null point to move down the fault during the inversion process (Figure 1.4).

Figure 1.4: Sequential diagrams to show the contractional inversion of an extensional fault (Williams et al., 1989).

1.2.4 Theoretical Models

Conceptual models for inversion of extensional faults systems may be constructed based upon experimental models and natural examples. A series of schematic models for possible geometries that could arise upon the inversion of a simple listric fault system, are shown on Figure 1.5 (McClay and Buchanan, 1992). These models include 1) inversion on the main fault, 2) footwall shortcut thrusts, 3) hanging wall bypass thrust, 4) back thrusts and 5) combination of these possibilities. Footwall short cut faults and back thrusts are common features of both the experimental models and are also found in nature (McClay and Buchanan, 1992). Experimental work of inversion structures shows that
thrust and reverse faults commonly use pre-existing extensional structures (McClay and Buchanan, 1992).

Figure 1.5: Conceptual models for thrust faults developed by the dip-slip inversion of a listric fault system (McClay and Buchanan, 1992).

FW = footwall short cut    HW = hanging wall bypass thrust
BT = Back Thrust

Figure 1.5: Conceptual models for thrust faults developed by the dip-slip inversion of a listric fault system (McClay and Buchanan, 1992).
Inversion of extensional fault systems are characterized by high-angle thrust systems that may be convex upwards, steepen downwards and join pre-existing extensional detachments (McClay and Buchanan, 1992).

### 1.2.5 How to Recognize Inversion

Distinctive characteristics of positive inversion geometries are anomalic variations of fault-throw with depth, thicker strata on the hanging wall of thrusts faults and footwall shortcut thrusts (Cooper et al., 1989). It is possible to recognize inversion when two marker horizons display different elevation above and/or below their respective regionals across a controlling fault (Cooper et al., 1989) (Figure 1.6).

One key feature of a positive inverted structure is that it must be possible to identify a syn-rift (or passive infill) sequence in all inversion structures. If the syn-rift package cannot be positively identified then inversion cannot be unequivocally interpreted (Cooper et al., 1989) (Figure 1.6). These authors use the term “syn-rift” to describe sedimentation synchronous with extension, which may not necessarily be the result of a rifting event.

When an extensional half-graben is inverted, footwall shortcut faults (Figure 1.7) will commonly be produced in order to generate a more gently inclined fault trajectory favorable to a sub-horizontal compression stress (Cooper et al., 1989). Listric faults will reactivate easily at depth, but the steeper parts of the faults may not reactivate leading to the development of folds on the hanging wall and shortcut faults on the hanging wall or footwall (Coward, 1994).
1.2.6 Fault Sequence

Sequential deformation documented in experiments on tectonic inversion is discussed by McClay and Buchanan (1992). The sequence of thrust development observed in the models is as follows: the main extensional detachment is the first fault to reactivate followed closely by the development of footwall short cut thrust. After appreciable contractional deformation (approximately 25%) forward-breaking, hanging wall-vergent back thrusts develop.

Figure 1.6: Schematic diagram of a classical positive inversion structure. A, B and C are stratigraphic sequences. A, prerift; B, synrift; C, postrift sequence (Williams et al., 1989).
1.2.7 Examples

An example of intracontinental rifting and inversion in the Missour Basin and Atlas Mountains, Morocco, is presented by Beauchamp et al. (1996).

Figure 1.8 shows a migrated seismic line depth converted to enable the modeling of the reactivated listric normal fault dipping to the southeast. Thickening of the synrift sedimentary sequences is evident from the southeast to the northwest toward the listric fault. Figure 1.9 shows the restoration steps for this seismic line. Reactivation of the syn-rift listric fault occurs until the fault steepens, and the syn-rift fault is bypassed. Shortening is then accommodated by a thrust that cuts the footwall at a lower angle (C). A fault-bend fold forms over the new footwall ramp (B), and this is later faulted along the fore limb by reactivation of the original syn-rift normal fault (A).
Figure 1.8: Seismic line of the Missour Basin showing the reactivated listric normal fault, the synrift and postrift sequences (Beauchamp et al., 1996).

Figure 1.9: Restoration of migrated and depth converted seismic line of the Missour Basin (Beauchamp et al., 1996).
1.2.8 The Importance of Inversion Tectonics

Identification of thrusting related to thin-skin or inversion is an important aspect of structural interpretation. The misinterpretation of thrusting related to single event compressive thin-skinned rather than inversion tectonics, leads to the following possible mistakes in structural interpretation: a) use of wrong methods and assumptions in section construction, b) incorrect calculations of the amount of shortening and c) incorrect assumptions and interpretations about the nature of structure at depth, both directly beneath the fold/thrust belt and further back within the hinterland of the mountain belt (Coward, 1994).

The recognition of inversion tectonics is important in the oil industry because inversion can: a) modify the burial history of a sedimentary basin, b) uplift sediments above sea level generating secondary porosity, c) modify the tilt of the sedimentary package, allowing different directions of fluid migration with time, d) reactivate older faults, changing their sealing properties and e) form complex structures at depth and care needs to be taken to differentiate these from single event compressive thin-skinned thrust structures (Coward, 1994).

1.3 Study Area

The area of study is located in the northern sector of the Middle Magdalena Valley Basin in the north central part of Colombia (Figure 1.10). The MMVB is an intermontane basin (Cooper et al., 1995), developed between the Central Cordillera to the west and the Eastern Cordillera to the east. The area of study is located in the valley of the Magdalena River, which is covered by Quaternary sediments.
1.4 Data Set

The data sets used in this research comprise 2D and 3D seismic and well data.

Seismic data

A 3D seismic volume of 200 Km$^2$ was acquired in 2005 and processed in 2006 by Geotrace Technologies. This volume was acquired for planning the development of an oil field discovered in Lower Cretaceous limestones. Acquisition parameters for the survey are shown in Table 1, while the areal extent of the survey is shown on the base map in Figure 1.11.

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</table>

Table 1.1: Seismic Acquisition Parameters.

Twenty eight 2D seismic lines were acquired in the 1970’s (400 Km) and reprocessed recently (Figure 1.11).
Figure 1.12 shows a comparison between an old 2D seismic line and the new 3D seismic data. It is possible to see the improved quality of the 3D seismic data and the benefit to the present research in terms of structural imaging.

Figure 1.10: Northern MMVB and general location of the study area. Modified from Suárez et al., 1998.
Figure 1.11: Data base map of seismic and well data available for this study.

Well data

A set of eight wells are used. Five of them are located within the 3D seismic survey (Figure 1.11) (Cagui-1, Cachira-1A, Gironda-1, Puntapiedra-1, Puntapiedra-2). Most of the wells in the area were drilled down into the Tertiary sequence, which has the main hydrocarbon reservoirs of the basin located. Three wells (Gironda-1, Puntapiedra-1, Puntapiedra-2) were drilled into the Middle to Lower Cretaceous units and only one well reached the Jurassic-Cretaceous unconformity (Cagui-1). The sedimentology and
stratigraphy of the Jurassic section in this area is therefore interpreted from regional data (Kammer and Sanchez, 2006).

Figure 1.12: Comparison between old 2D seismic and new 3D seismic data.

Figure 1.12: Comparison between old 2D seismic and new 3D seismic data.
**Softwares**

The seismic interpretation was carried out on Landmark (Openworks). 3DMove and 2DMove (Midland Valley) were used for structural restorations.

1.5 **Previous Studies in the MMV Basin**

Several regional studies on the MMV Basin provided an understanding of one of the most productive and complex basins of Colombia. Some of the most important results are as follows:

Etayo et al. (1969), described and mapped the advance of the Cretaceous sea.

Cáceres et al. (1991), evaluated the Tertiary sequence in the region to define the remaining petroleum prospectivity.

Cáceres, C. H. and Rubio, R. (1994), evaluated the generation potential, accumulation and hydrocarbon productivity in the Pre-Eocene sedimentary sequence.

Cooper et al. (1995), presented the basin development and tectonic evolution of Llanos Basin, Eastern Cordillera and Middle Magdalena Valley, which constituted a major regional sedimentary basin from Triassic to Middle Miocene.

Ecopetrol (1996), defined the petroleum systems of the MMV Basin.

Ecopetrol (1998), carried out a stratigraphic and structural characterization of the basin for the Cretaceous rocks.

Córdoba et al. (2001), conducted a regional evaluation of the basin focused on the Cretaceous sequence and integrated all the topics of the petroleum geology. They also compiled structural sections throughout the basin constructed by different companies and
presented one section for the sector of the present study that covers the entire basin from west to east.

In the sector of the present research, Suárez, 1998, studied the Tertiary sequence, analyzing the properties of the reservoirs and the remaining exploratory potential. Suárez et al., 1998, also carried out a structural interpretation of the Cretaceous sequence and proposed three prospects.

Kammer and Sánchez (2006) interpret two normal faults located about 200 Km to the south-southeast of the present study area, in the Eastern Cordillera, where the location of the deepest part of the Jurassic rift has been interpreted (Cooper et al., 1995). Faults bound rift basins are filled with 1) conglomerates for the Soapaga Fault and 2) lacustrine-fluvial sequences for the Boyacá Fault. These basins display wedge-like geometry of rift-related depositional systems (Figure 1.13). The basin-fill of the relatively narrow basin associated with the Soapaga Fault is dominated by fanglomeratic successions organized in two coarsening-upward cycles. In the larger basin linked to the Boyacá Fault, the sedimentary fill consists of two coarsening-upward sequences that, when fully developed, vary from floodplain to alluvial fan deposits (Kammer and Sánchez, 2006).
Figure 1.13: Traverse section through the Arcabuco-Guantiva and Floresta rift structures, as restored to a post-rift stage (Kammer and Sánchez, 2006). Location on figure 1.2.

Figure 1.14 shows a series of cross sections of the basin interpreted by Ecopetrol S.A. (Córdoba et al. 2001). In the cross sections located within the MMV Basin no evidences of intra-Jurassic syn-rift sequence (eg. cross section B, area of study) are shown. This differs from the proposed results of the present research. In cross sections located in the southern part of the basin (eg. cross section K) the authors interpreted inversion structures to the east that corresponds to the western foothills of the Eastern Cordillera. This is indicated by the inversion of normal faults located in the border of the “pre-cordillera” location that represent the main faults of the Jurassic-Early Cretaceous
rift (Cooper et al., 1995). Additionally, this event of tectonic inversion is proposed as Middle Miocene in age and caused the uplift of the Eastern Cordillera.

Figure 1.14: Structural cross sections of the MMV Basin (Córdoba et al., 2001).
Figure 1.14: Continued.
Figure 1.14: Continued.
2.1 Structural Setting and Basin Evolution

The Colombian Andes consist of three separate, north-south trending ranges (Figure 2.1): (1) the Western Cordillera, composed of accreted oceanic rocks, (2) the Central Cordillera, composed of Phanerozoic igneous and metamorphic rocks including an active volcanic arc, and (3) the Eastern Cordillera, most of which is underlain by uplifted Jurassic through Tertiary sedimentary rocks and their Precambrian through Mesozoic basement. The MMV Basin is located between the Central and Eastern Cordillera.

The western boundary of the Middle Magdalena Valley Basin is defined by the Central Cordillera. The Palestina fault, a dextral strike-slip system, represents the main tectonic element active during the uplift of this Cordillera (Figure 2.2). The eastern boundary of the basin is formed by the Eastern Cordillera and corresponds to the Bucaramanga fault, a sinistral strike-slip system that juxtaposes the basin against the Santander Massif (Figure 2.2). Toward the north, the thins and terminates against a paleohigh (Suárez, 1997).

Three different structural styles characterize the northern Middle Magdalena Valley Basin. The western margin consists of high-angle reverse faults while the central part is mainly deformed by lower angle east directed reverse faults that intercept the basement and mainly affects the pre-upper Eocene section (Figure 2.3). The central sector
is the location of the study area. The eastern margin of the basin is characterized by a zone of thrust faults to a sinistral strike slip system that involve the basement and corresponds to the western foothills of the Eastern Cordillera (Suárez, 1997).

Figure 2.1: Location of the Upper Magdalena and Middle Magdalena Valley Basin, from Bowen, 2005.
Figure 2.2: Tectonical boundaries of the northern part MMVB, modified from Schamel (1991)
Figure 2.3: Generalized structural cross section of the northern part MMVB (Córdoba et al., 2001). Location of the section is on Figure 2.2.
The Middle Magdalena Valley Basin is the result of a complex geological evolution that has occurred through different tectonic events that include 1) rifting, 2) oblique collision, 3) accretion, 4) transpression, and 5) inversion. These different phases of tectonic events resulted in the superposition of different structural styles.

1) Rifting: During the Jurassic period, the rift system formed a complex geometry of horst and grabens. The grabens were infilled by syn-rift sequences of Upper Jurassic Lower Cretaceous strata (Etayo et al, 1985) (Figure 2.4, Stage 1).

2) Back arc: Cretaceous strata are predominately marine and represent a transgressive-regressive cycle that covered an area much larger than the MMV B. Sedimentation occurred in a back-arc basin setting, east of the Andean subduction zone. This interpretation is based on the fact that basic intrusions were emplaced during the Jurassic-Cretaceous time in the west part of the basin (Figure 2.4, Stage 2).

3) Accretion: During the Maastrichtian to Paleocene, an accretion of the Western Cordillera produced the deformation and uplift of the Paleo Central Cordillera and created the early pre-Andean foreland basin (Dengo and Covey, 1993 and Cooper et al, 1995). The uplift of the Central Cordillera caused marine deposition to be abruptly terminated during the Paleocene. This period is completed with an intense erosion during the Early Eocene that is represented by a regional unconformity that is easily identified within the MMVB (Figure 2.4, Stage 3).

4) Foreland basin: Sedimentation from the Eocene to Miocene occurred in a foreland basin related to the deformation and erosion of the Central Cordillera (Dengo and Covey, 1993 and Cooper et al, 1995). The main fluvial clastic reservoirs in the basin were deposited during this time (Figure 2.4, Stage 4).
5) Intermontane basin: Finally, during the uplift of the Eastern Cordillera (Andean orogeny, Middle Miocene), the MMVB developed into its present form as an intermontane basin (Dengo and Covey, 1993 and Cooper et al, 1995) (Figure 2.4, Stage 5).

2.2 Stratigraphy

Three first order sedimentary sequences (Etayo et al., 1985) have been identified in the basin, from Jurassic to Quaternary. They were deposited unconformably on the crystalline basement, which is composed of metamorphic and igneous pre-Jurassic rocks (Figure 2.5).

2.2.1 Jurassic: Sequence A

The Girón Group (Late Jurassic in age). Lies unconformably on the crystalline basement. These strata are deposited within the Jurassic rift that developed in the location of the present MMVB and Eastern Cordillera. This group is composed of red siltstones interbedded with rhyolitic, rhyodacitic flows and tuffs (Etayo et al., 1983). López and Mesa (1997) present lithologic columns of this group that are located within the Floresta rift structure, 200 Km to the south-southeast of the present study area, within the Eastern Cordillera (Figure 2.6, Figure 1.14). This sequence is composed of massive cobble-pebble conglomerate at the base, overlain by coarsening- and thickening-upward packages of conglomeratic lenses embedded in a sandy matrix and that grade at the top into thick-bedded cobble conglomerates.
Figure 2.4: Tectonic history of the MMVB (Cooper et al., 1995).
Figure 2.5: Generalized stratigraphic column of the MMVB (Modified from Rolón, 2000)
2.2.2  Cretaceous-Paleocene: Sequence B

This sequence is bounded at the bottom by the Jurassic-Cretaceous unconformity and at the top by the middle Eocene unconformity. The Cretaceous sea invaded the basin from north to south.

2.2.2.1 Tambor Formation

The Tambor Formation is Berriasian in age and rests unconformably on the Jurassic Girón Group and it is composed of medium-grained, cemented sandstones, deposited in a continental environment (Rolón and Numpaque, 1997).
2.2.2.2 Los Santos Formation

Los Santos Formation is Berriasian in age and is composed of fine-grained to conglomeratic sandstones deposited in fluvial environments (Rolón and Numpaque, 1997).

2.2.2.3 Cumbre Formation

The Cumbre Formation is Early Valanginian in age and corresponds to the first marine invasion during the Cretaceous. This formation is composed of sandstones, green siltstones and black shales, deposited in a shallow marine environment (Rolón and Numpaque, 1997).

2.2.2.4 Rosablanca Formation

The Rosablanca Formation is Valanginian to Hauterivian in age and is composed of calcareous mudstone, wackestone and bioclastic packestones deposited in intratidal to subtidal environments (Rolón and Numpaque, 1997) (Figure 2.7).

2.2.2.5 Paja, Tablazo, Simití, El Salto, La Luna Formations

These formations are Hauterivian to Santonian in age and were deposited in a marine environment (Morales et al, 1958). The Paja Formation consists of black shales deposited on the shelf. The Tablazo Formation is composed of limestones, sometimes fossiliferous, with interbedded black shales and fine-grained sandstones (Rolón and Numpaque, 1997) (Figure 2.7). The Simití Formation is composed of black shales with interbedded sandstones, deposited in transitional to internal shelf (Rolón and Numpaque,
La Luna Formation is the most important source rock in the basin and is composed of limestone, cherts, and calcareous shales.

Figure 2.7: Thin sections of two of the Cretaceous formations. A) Rosablanca Formation: bioclastic wackestone. B) Tablazo Formation: recrystalized mudstone.

### 2.2.2.6 Umir Formation

The Umir Formation is Campanian to Maastrichtian in age and overlies the La Luna Formation. This unit is mainly composed of shallow marine to lagoonal gray shales with interbedded coals and sandstones (Morales et al, 1958).

### 2.2.2.7 Lisama Formation

The Lisama Formation is Paleocene in age and overlies the Umir Formation. It represents a transition from marine to deltaic deposition. This mainly consists of vari-colored mudstones and coals with interbeds of medium to fine-grained, locally cross-bedded sandstones (Morales et al, 1958).
2.2.3 Middle Eocene-Quaternary: Sequence C

This sequence is bounded at the bottom by the middle Eocene unconformity.

2.2.3.1 La Paz Formation

The La Paz Formation is Middle Eocene in age. This formation was deposited above the middle Eocene unconformity and consists of alternating coarse-grained sandstones and claystones overlain by massive coarse-grained to conglomeratic sandstones with thin interlayers of gray claystones (Morales et al., 1958). This unit was deposited as alluvial fans in the western part of the basin (Medina et al., 1992) and as fluvial braided systems in the eastern part of the basin.

2.2.3.2 Esmeraldas Formation

The Esmeraldas Formation is Late Eocene in age and consists primarily of thick intervals of mudstones and siltstones deposited as floodplains of meandering rivers (Rubiano, 1995).

2.2.3.3 Mugrosa Formation

The Mugrosa Formation is Oligocene to Lower Miocene in age and unconformably overlies the Esmeraldas Formation. This formation was deposited in meandering fluvial systems and consist of interbedded sandstones and mudstone (Rubiano, 1995) (Figure 2.8).
2.2.3.4 Colorado Formation

The Colorado Formation is Lower Miocene to Lower middle Miocene in age and unconformably overlies the Mugrosa Formation. This is predominantly composed of massive, light-gray to purple-red shales, interbedded with fine to coarse-grained, well-sorted sandstones (Morales et al., 1958). This formation is interpreted being deposited in fluvial setting illustrated by presence of point and longitudinal bars (De la Cruz, 1988) (Figure 2.8).

![Figure 2.8: Thin sections of two of the Tertiary formations. A) Colorado Formation. B) Mugrosa Formation (F: feldspars and L: lithics).](Image)

2.2.3.5 Real Group

The Real Group is Middle to Uppermost Miocene in age and unconformably overlies the Colorado Formation. This is mainly composed of conglomerates, conglomeratic sandstones, and gray claystones deposited in fluvial settings (Rubiano, 1995).
CHAPTER 3

METHODOLOGY

This study was conducted using available seismic data and well data information. A 3D seismic volume of 200 Km², 400 Km of 2D seismic lines, and eight wells were included in this structural analysis.

This study was carried out based on the following workflow:

- Previous studies and cross sections analyzed
- Well-seismic tie
- 2D-3D seismic interpretation
- Time to depth conversion
- 3D structural model construction and editing
- 2D structural restorations

Figure 3.1 shows a chart summarizing the methodology followed in this study.

3.1 Previous Studies of the Area of Study

Previous studies in the area have focused on the Tertiary and Cretaceous sequences with the aim at looking for hydrocarbon traps and principally the structural traps in the Cretaceous units. These studies focus mainly on the structural interpretation of the seismic data for the Cretaceous and Tertiary sequences, with little attention to the pre-Cretaceous sequence because of the poor quality of the seismic data, the great depth
of the potential reservoirs, and the lack of interest in petroleum prospectivity in these more unknown units.

Figure 3.1: Chart showing the methodology followed in this study for developing the structural analysis.
Structures have previously been seismically interpreted without attention to detailed geometry of the fault’s detachment and their relationship with inversion structures. In similar manners, there is little understanding of the exact structural evolution of the area.

Córdoba et al. (2001), compiled structural cross sections built throughout the basin by different oil companies. These sections include the Simití-Cáchira, made by Ecopetrol S.A. that covers the area of the present study (Figure 2.3). The location of the section is shown in Figure 2.2. This cross section covers almost the entire MMV Basin from west to east and is 50 Km long. In the study area, basement was interpreted below the Cretaceous units, because of the poor quality of the 2D seismic data.

3.2 Well - Seismic Tie

Two wells with check shot data, Cagui-1 and Gironda-1, were used to tie horizon tops to the seismic. For the wells without check shot data, the depth-time table of Cagui-1 was applied. The deepest well in the area is Cagui-1 (12.711’ TD), which was drilled down to the Jurassic-Cretaceous unconformity. A synthetic seismogram was constructed for this well and is shown tied to the seismic data in Figure 3.2.

3.3 Seismic Interpretation

A 2D/3D merge of seismic data was performed for the interpretation of the area, although 3D seismic has a much better resolution than the 2D seismic profiles, especially in the deeper zones. Seismic interpretation focused on the 3D volume. 2D lines were interpreted in sectors located outside of the 3D seismic survey, in order to have some
longer 2D/3D seismic sections. The 3D seismic volume was interpreted every 10 inlines (IL) and every 20 crosslines (XL).

Eight seismic horizons were tied to well information and are listed here, corresponding to: 1) Jurassic-Cretaceous unconformity, 2) top Rosablanca Formation, 3) top Tablazo Formation, 4) top Simití Formation, 5) Eocene unconformity, 6) top Esmeraldas Formation, 7) top Mugrosa Formation and 8) top Colorado Formation. Three horizons were interpreted in the Cretaceous sequence (eroded in the sector of the wells) in the western part of the study area. These horizons were interpreted using regional thickness measurements from other parts of the basin (top Luna Formation, top Umir Formation, and top Lisama Formation). Three horizons in the Jurassic Sequence that have not been drilled were interpreted using seismic character to complete the structural model and are referred as: top J1, top J2, and top J3 (Figure 3.3). Table 3.1 shows the horizons interpreted on seismic and the relative confidence in picking each horizon across the data set.

3.4 Time-Depth Conversion

Horizons and faults interpreted in the seismic data were depth converted using the TDQ module of Openworks (Landmark). The software does a horizontal interpolation of velocity between wells to cover the area of the seismic interpretation and a linear extrapolation of velocity to deeper zones. This is due to the fact that only two wells have a depth-time table, that the depth of the wells reached only the Cretaceous units, and that no data exist for the Jurassic Sequence. Despite the limitations there is a good match between horizons in depth and well tops.
Figure 3.2: Synthetic seismogram of Cagui-1 well.
Figure 3.3: Stratigraphic column with the seismic horizons interpreted (Modified from Rolón, 2000)
<table>
<thead>
<tr>
<th>Horizon</th>
<th>Age</th>
<th>Confidence of the pick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Colorado Formation</td>
<td>Miocene</td>
<td>High</td>
</tr>
<tr>
<td>Top Mugrosa Formation</td>
<td>Oligocene</td>
<td>High</td>
</tr>
<tr>
<td>Top Esmeraldas Formation</td>
<td>Eocene</td>
<td>High</td>
</tr>
<tr>
<td>Eocene Unconformity</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Top Lisama Formation</td>
<td>Paleocene</td>
<td>Moderate</td>
</tr>
<tr>
<td>Top Umir Formation</td>
<td>Campanian-Maastrichtian</td>
<td>Moderate</td>
</tr>
<tr>
<td>Top La Luna Formation</td>
<td>Cenomanian-Santonian</td>
<td>Moderate</td>
</tr>
<tr>
<td>Top Simiti Formation</td>
<td>Albian</td>
<td>High</td>
</tr>
<tr>
<td>Top Tablazo Formation</td>
<td>Albian</td>
<td>High</td>
</tr>
<tr>
<td>Top Rosablanca Formation</td>
<td>Valanginian</td>
<td>High</td>
</tr>
<tr>
<td>Jurassic-Cretaceous Unconformity</td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Top J3 Unit</td>
<td>Jurassic</td>
<td>Low</td>
</tr>
<tr>
<td>Top J2 Unit</td>
<td>Jurassic</td>
<td>Low</td>
</tr>
<tr>
<td>Top J1 Unit</td>
<td>Jurassic</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 3.1: Horizons interpreted and their pick confidence.

3.5 3D Structural Model Construction

The 3DMove is a Midland Valley software package used for visualization and structural restoration. Horizons and faults depth converted were imported to 3DMove, where they were used to create and edit horizon and fault surfaces. In this way the 3D structural model can be visualized and used for restoration purposes.
The interpretation of one of the 2D seismic line was depth converted and integrated to the 3D model in order to have the longest section to the west available for restoration.

From the structural model constructed in 3DMove it was possible to select the best 2D sections to be restored in 2DMove. Four 2D sections were chosen to be restored, based on their location in the different structural zones and the need to provide a regular pattern covering all the area of study (Figure 3.4).

3.6 2D Structural Restoration

For the structural restoration 2DMove software was used. 2DMove is also a Midland Valley software package. The 2D cross sections chosen and created in 3DMove were imported to 2DMove. The first step was to edit the sections, which consisted mainly of joining horizons to faults when necessary and to create polygons for each of the geological units.

The general process to restore sections involves three procedures: decompaction, isostasy correction and structural restoration.
3.6.1 Decompaction

This process corrects the effect of rock volume change due to porosity loss with burial, assuming an exponential porosity decreasing with increasing depth. When a restored layer is removed from the model, the underlying units are decompacted, producing a subtle increase in their thickness. This can be represented by:

\[ f = f_0 \left( e^{-cy} \right) \]

where:

- \( f \): final thickness
- \( f_0 \): initial thickness
- \( c \): a constant
- \( y \): depth
\( f \) is the present-day porosity at depth

\( f_0 \) is the porosity at surface

\( c \) is the porosity-depth coefficient (Km\(^{-1}\))

\( y \) is depth (m)

For the study area, \( f \) and \( y \) values were taken from wells and regional studies. The \( f_0 \) value is given in 2DMove Online Manual for each rock type. The \( c \) value is calculated using the above equation (Table 3.2).

<table>
<thead>
<tr>
<th>Formation and Sequence</th>
<th>Lithology</th>
<th>( f ) (%)</th>
<th>( f_0 ) (%)</th>
<th>( y ) - Depth (m)</th>
<th>( c ) (Km(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real</td>
<td>Shaley sandstone</td>
<td>0.18</td>
<td>0.56</td>
<td>308</td>
<td>3.68</td>
</tr>
<tr>
<td>Colorado</td>
<td>Sandstone</td>
<td>0.14</td>
<td>0.49</td>
<td>2275</td>
<td>0.55</td>
</tr>
<tr>
<td>Mugrosa</td>
<td>Sandstone</td>
<td>0.14</td>
<td>0.49</td>
<td>2929</td>
<td>0.43</td>
</tr>
<tr>
<td>Esmeraldas</td>
<td>Sandstone</td>
<td>0.13</td>
<td>0.49</td>
<td>3189</td>
<td>0.42</td>
</tr>
<tr>
<td>Lisama</td>
<td>Sandstone</td>
<td>0.12</td>
<td>0.49</td>
<td>3200</td>
<td>0.44</td>
</tr>
<tr>
<td>Umir</td>
<td>Shale</td>
<td>0.02</td>
<td>0.63</td>
<td>3200</td>
<td>1.08</td>
</tr>
<tr>
<td>La Luna</td>
<td>Limestone</td>
<td>0.03</td>
<td>0.40</td>
<td>3200</td>
<td>0.81</td>
</tr>
<tr>
<td>Simití</td>
<td>Shale</td>
<td>0.02</td>
<td>0.63</td>
<td>3214</td>
<td>1.07</td>
</tr>
<tr>
<td>Tablazo</td>
<td>Limestone</td>
<td>0.03</td>
<td>0.40</td>
<td>3514</td>
<td>0.74</td>
</tr>
<tr>
<td>Rosablanca</td>
<td>Limestone</td>
<td>0.03</td>
<td>0.40</td>
<td>3726</td>
<td>0.70</td>
</tr>
<tr>
<td>Jurassic</td>
<td>Shaley sandstone</td>
<td>0.08</td>
<td>0.56</td>
<td>3860</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 3.2: Values used in Decompaction steps.
3.6.2 Isostasy

The 2DMove isostatic correction is applied in the same step as the decompaction. This process models the rebound of the crust as if a stratigraphic unit was removed. The flexural isostasy was used in this study for the longest section (Section 2, 18 Km). The 2DMove manual recommends use of flexural isostasy in sections of tens of kilometers or longer with laterally variable loads.

The Central and Eastern Cordillera are located 40 and 20 Km from the study area, respectively. The section elevation varies between 200 to 300 m. After application of flexural isostasy, very subtle changes are seen in the section. Only small changes occur in the form of the basement, compared to the section without this correction. The reason for these subtle changes is due to the absence of great differences in topography and the absence of a structural load in the length of the restored profile.

The values used in 2DMove isostatic adjustment are:

* Density of the load= 2800 Kg/m$^3$
* Density of the mantle= 3300 Kg/m$^3$
** Effective elastic thickness (Te)= 45 Km
* Young’s module (E)= 7 * 10$^{10}$

* default values of the software

** value given by the software for Andes Cordillera

3.6.3 Structural Restoration

Midland Valley structural restoration software implements general rules that are applied to all tectonic settings:
- Rock volume is conserved during deformation
- Rock volume is only altered by erosion and sediment compaction
- Dominant deformation mode is brittle faulting
- Volume losses attributed to pressure solution and tectonic compaction are assumed to be minimal

The techniques used in kinematic structural restorations can be categorized into two groups:
- Unfolding restorations: fault geometries are ignored
- Move–on–Fault restorations: effects of fault geometry on hanging wall deformation are considered.

The Cagui Fault and the Splay Fault in the model were restored using the Inclined Shear algorithm, which is suggested by the 2DMove manual for restoring listric faults, inverted basins, and growth faults.

The other faults in the model were restored using the Fault Parallel Flow algorithm. This is designed for kinematically modeled geological structures in the hanging wall where deformation is accommodated by fault parallel shear. This also assumes that particles flow parallel to the fault surface and parallel to the plane of the cross section (2DMove Manual).

The general workflow applied for restoring was:
- Strip off Tertiary units (2 steps)
- Complete eroded Cretaceous horizons, creating parallel tops
- Restore the faults cutting the Cretaceous units
- Strip off Cretaceous units (6 steps, restoration and decompaction of each Cretaceous formation).
- Complete eroded Jurassic horizons, preserving their thinning tendency
- Restore the faults cutting the Jurassic units
CHAPTER 4
RESULTS

4.1 Seismic Interpretation

Three first order sedimentary sequences, that are unconformity-bounded, have been identified in the basin, corresponding to Sequence A (Triassic-Jurassic), Sequence B (Cretaceous-Paleocene) and Sequence C (Late Eocene-Quaternary). Each sequence is characterized by the following seismic facies: Sequence A corresponds to divergent reflectors increasing their thickness towards the southeast, with medium to high amplitude and moderate continuity; sequence B is composed of parallel reflectors with high amplitude and good continuity; and sequence C corresponds to sub parallel to parallel reflectors with medium amplitude and moderate continuity (Figures 3.4, 4.1).

Each of these seismic facies has a correlative relationship with the sedimentary environment in which it was deposited: Sequence A was deposited in a continental environment with active normal faults that explain the divergent character of the reflectors; Sequence B was deposited in a marine environment and is composed of limestones units that form the parallel, high amplitude and good continuity reflectors; and Sequence C was deposited in a fluvial environment in a foreland to intermontane basin, which explains the moderate continuity of the reflectors.

In the following paragraphs, the geological structure present in the study area will be described, from south to north, highlighting important variations. The most important fault in the area is the Cagui Fault (Figure 4.1), which cuts all the Pre-Eocene units with a
Figure 4.1: Dip Seismic Profile IL 40. Horizontal scale in meters, vertical scale in milliseconds (TWTT). Location on Figure 3.4
slip of 2800 m for the Jurassic-Cretaceous unconformity in the southern part. In the hanging wall of this fault, the Jurassic, Cretaceous and the basement units are present, while in the footwall only the Cretaceous and the basement are found (Figures 3.4, 4.2).

The angular Jurassic-Cretaceous unconformity is observed in the hanging wall of the Cagui Fault, and is not evident in the footwall. This fact and the lack of well data at depth, drove the interpretation of a basement directly beneath the Cretaceous on the footwall side. This indicates that the Cagui Fault was a normal fault during the Jurassic. A period of erosion resulted in the truncation of 1) the Jurassic units in the hanging wall of the Cagui Fault and 2) the basement in the footwall. However there is no evidence of a regional compressional event during this period.

In the present day structural configuration, the Jurassic-Cretaceous unconformity is present in the hanging wall of the Cagui Fault (Figures 3.4, 4.2). This Fault is interpreted as an ancient half graben that was part of the Jurassic-Triassic rift that produced the breakup of Pangea and the separation of North America from South America. The evidence that this fault was an ancient normal fault is also supported by the fact that the Jurassic units increase their thickness toward the fault (Figures 3.4, 4.4). This evidence supports the interpretation of the Cagui Fault as an ancient active growth fault. Taking into account that the Cagui Fault is the most important structural feature in the study area, we will discuss this result in more detail in the next chapter.

In the footwall of the Cagui Fault, the complete Cretaceous sequence is proven by the seismic character and the fact that some wells intercept the Upper Cretaceous formations below the Eocene unconformity. In the Cagui Fault’s hanging wall almost all of the Upper Cretaceous units were eroded prior to deposition of the Tertiary.
Figure 4.2: Dip Seismic Profile II 40. Horizontal scale in meters, vertical scale in milliseconds (TWTT). Location on Figure 3.4.
The strike of the Cagui Fault is 030 (Figure 3.4). The compressional dominant transport direction is close to west to east and is related to the subduction zone in the west border of the South American continent.

We interpret the Back 1 Fault as corresponding to a back thrust of the inverted Cagui Fault. A footwall short cut fault (fwsc) was also interpreted and is related to the inversion event of the Cagui Fault (Figures 3.4, 4.2, 4.3).

The Eocene unconformity juxtaposes strata from the Lower Cretaceous to Paleocene with Upper Eocene units. The Tertiary sequence shows very subtle folding in this sector, which is possibly related to some small reactivation during the post-Eocene time.

Moving toward the northern part of the study area, the geometry is similar with the difference that a splay fault is developed (splay). This fault is classified as a hanging wall short cut of the Cagui Fault (Figures 3.4, 4.3).

Figure 4.4 is a 2D/3D seismic merged profile, which is key to the present interpretation because it is the longest seismic section available. It is possible to interpret another back thrust (back2) in the west part of the section, related to the inversion of the Cagui Fault. Additionally, to the west, it is possible to interpret the complete Cretaceous Sequence under the Eocene Unconformity, and to have on both sides of the section the regional level of the Cretaceous Sequence, which is an important fact for the structural restoration of the section.
Figure 4.3: Dip Seismic Profile IL 140. Horizontal scale in meters, vertical scale in milliseconds (TWTT). Location on Figure 3.4.
Figure 4.4: Dip Seismic Profile merge M-76-04/IL40. Horizontal scale in meters, vertical scale in milliseconds (TWTT). Location on Figure 3.4.
In the northern sector of the study area, the splay fault disappears, and instead two new back thrust faults appear (back3 and back4), which are genetically related to the inversion of the Cagui Fault (Figures 3.4, 4.5). In this seismic line, the Jurassic subcrops the Eocene Unconformity in the hanging wall of the Cagui Fault. In the footwall of the Cagui Fault, the Jurassic sequence is underlying the Lower Cretaceous units. In this part of the study area occurred a greater deformation of the structure, which produced that the formations got to a higher structural position.

Figure 4.6 shows a strike line (cross line 340, Figure 3.4), where the closure of the Cagui structure can be seen. This cross line is interesting because it is possible to see the Cretaceous units in the hanging wall and footwall of the Cagui Fault, with their very characteristic strong seismic reflectors, contrasting with the less coherent reflectors of the Jurassic Sequence. Additionally, this crossline shows the Cretaceous units in the hanging wall rising to the north. Figure 4.7 shows another crossline (XL 500) (Figure 3.4), located in the footwall of the Cagui Fault, which illustrates how the Pre-Eocene structure is rising to the north. The basement-Jurassic boundary is interpreted to the north and the Cretaceous units overlie the basement to the southeast and Jurassic to the northeast. Figure 4.8 shows a 3D structural image for the Jurassic-Cretaceous Unconformity and the faults cutting this horizon, where is possible to see that the general structure has a shallower position to the north of the study area and a deeper position to the south.

Figure 4.9 is a time slice of the 3D seismic volume. The location of the Cagui Fault can be observed. This figure shows the boundary of the half graben and the contrasting seismic character of the Jurassic in the hanging wall against the Cretaceous in the footwall. Cretaceous reflectors are parallel with high amplitude and good continuity.
representing the marine environment of deposition with limestones, while the Jurassic reflectors have medium amplitude and moderate continuity representing the continental environment of deposition.

### 4.2 Structural Restorations

Four palinspastic restorations were constructed from the seismic interpretation. The dominant direction of movement during the Maastrichtian-Paleocene was close to west to east. The strike of the Cagui Fault is 030. Therefore, the location of the restored cross sections was chosen perpendicular to the Cagui Fault. This direction is parallel to the orientation of the inlines in the 3D volume (Figure 3.4). The analysis of the restored sections focus on the seismic profiles IL40, merge M-76-04/IL140 and IL440. This analysis can be applied to the other seismic lines according to their location in the 3D volume. Ten to twelve restoration stages are shown for each section and are described from oldest to youngest. Plates A to E include all the structural restorations constructed in this study.
Figure 4.5: Dip Seismic Profile IL 440. Horizontal scale in meters, vertical scale in milliseconds (TWTT). Location on Figure 3.4.
Figure 4.6: Strike Seismic Profile XL 340. Horizontal scale in meters, vertical scale in milliseconds (TWTT). Location on Figure 3.4.
Cretaceous, Paleocene

Figure 4.7: Strike Seismic Profile XL 500. Horizontal scale in meters, vertical scale in milliseconds (TWTT). Location on Figure 3.4.
Figure 4.8: 3D structural image for the Jurassic-Cretaceous Unconformity.
Figure 4.9: Time slice at 3000 ms. The Cagui Fault and seismic character of Jurassic and Cretaceous strata can be observed.

4.2.1 Potential Sources of Error

The depth conversion of the seismic interpretation was performed using the only two wells with depth-time tables. Furthermore, the Jurassic Sequence has not been drilled, and this is an important part of the present structural modeling. The footwall of
the Cagui Fault that corresponds to Cretaceous units has been interpreted only by the seismic character, because it lacks a well tie.

In general, the 3D seismic data quality is good, although the quality becomes critical below the Cagui Fault. Also, the cross sections were chosen based on the dominant direction of transport and the fault boundaries map for the Jurassic-Cretaceous Unconformity. Nevertheless, this direction could possibly not be optimal to avoid movement out of the plane. An inverted listric normal fault is difficult to restore to the exact geometry prior to the inversion, possibly due to slip out of the plane of the section (Beauchamp et al., 1996).

4.2.2 Section 2 (Seismic Merge M-76-04 / IL 140, Figures 3.4, 4.4)

Figure 4.10 shows the restoration steps for Section 2. In the following paragraphs, we describe each of the restoration steps and discuss the assumptions and choices made for this section, which in general can be applied to the other sections. This section is considered the key one because of its length (longest with 20 Km) and seismic data quality.

4.2.2.1 Jurassic - Cretaceous Unconformity (Stages A, B, C, D; Figure 4.10)

The assumptions made to restore these events are discussed in the following paragraphs.

- The Jurassic-Cretaceous Unconformity was restored to a horizontal position (300m) above the sea level because it represents a surface of erosion (Figure 4.10, Stage D).
- Jurassic units were added above the unconformity to preserve the strata thinning tendency to the west.

- Because the Jurassic-Cretaceous unconformity intercept the Jurassic units in the hanging wall of the Cagui Fault and the basement in the footwall, it was assumed that the Jurassic units had an elevation in the hanging wall equivalent to the elevation of the basement in the footwall prior to the erosion event. It is assumed that the level of deposition of the Jurassic units was controlled by the elevation of the basement to the east. Each of the Jurassic units was restored to the elevation of the basement in the footwall and then decompressed. The algorithm used to restore the Jurassic was Fault Parallel Flow, with a shear angle of -30°, which is essential to achieve line length and area balance in the deformed/undeformed model.

Geological evolution: In the Jurassic time, the MMV Basin was part of the rift related to the breakup of Pangea. As part of this rifting structure, the Cagui Fault was an active normal fault and defined a half graben where the Jurassic units were deposited thickening toward this fault (Stages A, B, C). After deposition of the Jurassic strata, an erosive event occurred that truncated these deposits and the basement to the east (Stage D).

### 4.2.2.2 Cretaceous (Stages E, F, G, H, I; Figure 4.10)

Five faults cut the Cretaceous units. They were restored from the youngest to the oldest in this order: 1) back thrust located to the west of the section (Back2) (Stage H), 2) back thrust located to the east of the last one (Back1) (Stage H), 3) the splay fault (Stage G), 4) the footwall short cut (Stage F) and 5) the Cagui Fault (Stage E).
The assumptions made to restore these faults are discussed in the following paragraphs.

- The paleo-structures above the Eocene Unconformity were extended using thickness of the same units observed in other parts in the basin. The extended tops were completed parallel to horizons located below the unconformity, taking into account that there is no evidence of changes in thickness.

- In order to restore the back thrusts we faced a challenge since 2DMove applies a constant slip which creates a blank space in the footwall of the restored fault. One explanation is that faults movement is associated with internal rotation of the hanging wall block, forming the back thrusts (Kluth, pers. commun.). For that reason, the back thrusts were restored manually.

- To restore the splay fault (Stage G), which is a splay of the inverted Cagui Fault, we created a single fault plane that joined the splay and the Cagui Fault. It is important to restore the movement along both faults to avoid that the splay fault cutting the main fault.

- To restore the footwall short cut fault (fwsc, Stage F), the position of this fault in the deeper part was subtly adjusted to make the restoration possible, which is not a problem because seismic data allows this.

- The next step was to restore the Cagui Fault, which corresponds to the inverted listric normal fault (Stage E). The ramp fault pick is well controlled (good the seismic resolution), but the detachment is located in the deeper part of the seismic line where resolution is poor. Also, we don’t know the basement lithology at that depth. For this reason, the detachment position was adjusted until we found one that was realistic for the fault restoration. The algorithm used to restore this fault was \textit{inclined shear}, which can be
applied to the restoration or forward modeling of inverted basins, growth faults and non planar normal faults. A shear angle of -30° was applied. This angle is parallel to the axial plane of the hanging wall fold, an option indicated in the 2DMove manual.

- After restoration of the faults that intercept the Cretaceous formations, the next step was to restore each of the Cretaceous formations to their depositional level and to apply decompaction for each of them (six steps of restoration and decompaction). The restoration of each of these units was done to a horizontal position below sea level, taking into account its depositional environments. It was carried out to remove the units and to have the Jurassic unconformity as a sub-aerial surface. The depositional environments and depositional depths considered of each formation are:

<table>
<thead>
<tr>
<th>Formation</th>
<th>Environment</th>
<th>Depositional depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lisama</td>
<td>Litoral</td>
<td>-30</td>
</tr>
<tr>
<td>Umir</td>
<td>Litoral</td>
<td>-50</td>
</tr>
<tr>
<td>La Luna</td>
<td>External Platform</td>
<td>-200</td>
</tr>
<tr>
<td>Simití</td>
<td>External Platform</td>
<td>-200</td>
</tr>
<tr>
<td>Tablazo</td>
<td>Internal Platform</td>
<td>-100</td>
</tr>
<tr>
<td>Rosablanca</td>
<td>Internal Platform</td>
<td>-100</td>
</tr>
</tbody>
</table>

Geological evolution: Cretaceous-Paleocene formations (Rosablanca, Paja, Tablazo, Simití, La Luna, Umir and Lisama) were deposited in a marine environment in the study area. Cretaceous to Paleocene deposition represents a great period of transgression-regression, where the sea invaded Colombia from north to south. The
Rosablanca Formation overlies unconformably the Jurassic sequence in the hanging wall of the Cagui Fault and the basement in the footwall (Stage F). The structural deformation of the Cretaceous formations took place in the Maastrichtian-Paleocene compressional event related to the uplift of the Central Cordillera (Cooper et al., 1995). In the study area, this tectonic event produced the structural inversion of the Cagui listric normal fault.

4.2.2.3 Eocene Unconformity (Stage J, Figure 4.10)

The Eocene unconformity was located above sea level after the Lower Tertiary was restored and removed. This unconformity is a surface of erosion that created an angular unconformity with the underlying Cretaceous units. This unconformity was related to the compressional tectonic events that affected the Cretaceous units. The geometry of the unconformity represents the final geometry of the eroded paleotopography. This is indicated by the onlaps of Eocene strata above the unconformity (Figure 4.1). The sediments eroded have been transported away from the study area with no evidence of Pre-Eocene reworked clastics in the sector. Having into account the form of the paleotopography, dipping to the south (Figure 4.6, 4.7); it is possible postulate that the Cretaceous sediments eroded were transported to the south, out of the study area. Erosion was more intense at the north sector, where truncated Lower Cretaceous formations and in some places pre-Cretaceous rocks, due that the structural uplift was greater in this part of the study area (Figure 4.6, 4.7). Above the Eocene unconformity, the siliciclastic strata (sandstones) correspond to sediments eroded from the Central Cordillera where granitic rocks outcrop, forming sandstones accumulations in the MMV.
Basin. The three oldest tectonosequences (Upper Eocene-lower to middle Miocene) were deposited in a foreland basin with sediment supply from the Central Cordillera and partially from the Santander massif (Suárez, 1997).

4.2.2.4 Tertiary Units - Current Stage (Stage K, Figure 4.10)

These units were grouped into two units. The first step of the restoration was to apply decompaction to the upper unit, then restore and decompact the lower unit. Tertiary units were restored to 700 m above sea level because they were deposited in continental environments. With this elevation, it is possible to have the Eocene unconformity above sea level.

These strata were deposited in a continental environment within a foreland basin (Middle Eocene to Middle Miocene) to an intermontane basin (middle Miocene to Pliocene).
Figure 4.10: Continued.
Figure 4.10: Continued.
4.2.3 Section 1 (Seismic Line IL40, Figures 3.4, 4.2)

Figure 4.11 shows the restoration steps for Section 1 (12 Km length).

This section is similar and equivalent to Section 2. The restoration steps of the Jurassic (stages A, B, C, D), Cretaceous (stages F, G, H, I, J) and Tertiary units (stage L), and Jurassic-Cretaceous (stage E) and Eocene (stage K) unconformities follow the same ideas and assumptions than Section 2.

Three faults intercept the Cretaceous units. This cross section, located to the south of the Section 2, doesn’t show the splay fault. The section is not enough long toward the west to intercept the second back thrust. The faults in this cross section were restored from the youngest to the oldest, in this order: 1) the back thrust (back1, Stage I), 2) the footwall shortcut (Stage H) and 3) the main fault (Stages G).
Figure 4.11: Continued.
4.2.4  Section 4 (Seismic Line IL 440, Figures 3.4, 4.5)

Figure 4.12 shows the restoration steps for section 4 (12 Km in length).

In this cross section, the Jurassic sequence on the hanging wall of the Cagui Fault has poor seismic resolution. For this reason, no intra-Jurassic units were interpreted (stage A).

The footwall of the Cagui Fault, has an important difference with the previous two cross sections discussed: the Lower Cretaceous overlies Jurassic units instead of basement as is shown on Figures 4.5 and 4.7 and explained in page 55.

The restoration workflow is similar to the one used for Section 2.

Four faults cut the Cretaceous units. In this section, located to the north of the Section 2, two other back thrusts closer the Cagui Fault developed (back3 and back4). These faults were restored from the youngest to the oldest, in this order: 1) back thrusts, starting from west to east (back1, back4, back3) and 2) the main fault (Stages C, D, E).
Figure 4.12: Continued.
CHAPTER 5
DISCUSSION

5.1 Inversion Tectonics in the Study Area

In this part, evidences of inversion tectonics in the study area will be discussed.

5.1.1 Definition of Inversion

According to the definitions of inversion tectonics given by Cooper et al. (1989), and Coward (1994) (section 1.2.1), it is possible to propose this structural style in the study area where extensional tectonics is seismically recognized due to intra-Jurassic units increasing their thickness toward the Cagui Fault, indicating that this was an active normal fault during the Jurassic (Figures 5.1 and 5.2). We postulate an inversion of this fault during the Maastrichtian to Paleocene indicated by the presence of a Jurassic synrift sequence in the hanging wall of the Cagui Fault, which is a reverse fault in the present configuration (Figure 4.3).

5.1.2 Origin of the Inversion

The Maastrichtian to Paleocene tectonic inversion proposed in the area of study is related to the compressive event associated with the subduction zone and collision of an island arc in the western part of the continent (Figure 2.4 - Cooper et al., 1995). This origin for inversion tectonics in the area of study is in accord with the suggestion that plate collision is one of the most common causes of tectonic inversion (Coward, 1994) (section 1.2.2).
Figure 5.1: Seismic line showing the thickness of the Jurassic units increasing toward the Cagui Fault.

Figure 5.2: Isopach thickness in TWT of the J2 unit (see Figure 5.1).
5.1.3 Degree of Inversion

The degree of inversion is classified as strong inversion (after Cooper et al., 1989) because the fault has an apparent normal displacement still at depth (Figure 5.3).

5.1.4 Theoretical Model – Possibilities for Inversion

According to the conceptual models of inversion of a listric normal fault presented by McClay and Buchanan (1992) (section 1.2.4), the model H (Figure 5.4) is similar to the studied structure. It is a combination of both back thrusts and footwall short cut thrusts that produce a characteristic fan structure and “pop-up” feature.

This model is similar to the inversion geometry of the present study area, with an inverted listric normal fault (Cagui Fault), a footwall short cut (fwsc) and back thrusts (back 1 and back 2). Additionally, in Section 2 (Figure 4.10, stage H) we interpreted a splay fault that corresponds to a hanging wall bypass thrust (model D, Figure 5.4); indicating a combination of the theoretical models (Figure 5.4).

5.1.5 How to Recognize Inversion

Inversion tectonics can be recognized in the study area based on the following criteria:

- In the hanging wall, two horizons display different elevations above their respective regional levels. The Lower Cretaceous units (e.g., Rosablanca Formation) in the hanging wall have higher elevation than these units in the footwall, while the basement of the
Degrees of inversion of a half-graben

From Cooper et al., 1989

Figure 5.3: Degree of inversion of the Cagui Structure.
Conceptual models for thrust faults developed by the dip-slip inversion of a listric fault system

From McClay et al., 1992

Figure 5.4: Comparison of theoretical models vs. Cagui Structure.
hanging wall is lower than this in the footwall (The Rosablanca Formation above regional level and basement below regional level) (Figure 4.10, stage K).

- The syn-rift package in the hanging wall of the Cagui Fault is clearly defined in the seismic lines, where reflectors are divergent, increasing their thickness toward the fault (Figure 5.1), indicating activity of the normal fault, with rotational kinematics during the accumulation of the syn-rift sequence.

- The structure of the Cagui sector clearly shows faults typical of an inversion history. It is possible to interpret a footwall shortcut fault (fwsc fault), a hanging wall shortcut fault (splay fault), back thrusts and a hanging wall anticline fold (Figure 5.5). Footwall shortcut faults form a more gently inclined trajectory than the main inverted normal fault (Cooper et al., 1989). Folds in the hanging wall and shortcut faults in the hanging wall or footwall occur when steep parts of the main fault do not reactivate (Coward, 1994).

- Features generated by extension, such as half grabens, are uplifted to form positive anticline structures (Beauchamp et al., 1996). That is the case of the area of study, where the original half graben has formed a roll-over structure above the main fault, after inversion has occurred (Figure 5.5).

- The reactivation of normal syn-rift faults inverts previous half grabens into anticline structures, with the axis of the half graben centered below the axis of the inversion anticline (Beauchamp et al., 1996). This feature is present in the area of study (Figure 5.5).
Figure 5. Dip Seismic Profile merge M-76-04/IL-40. Distinctive characteristics of inversion.
5.1.6 Faulting Sequence

Taking into account the theoretical model for faulting sequence in tectonic inversion proposed by McClay and Buchanan, 1992 (section 1.2.6), the order of restoration for the faults in the structure of Cagui, from younger to older, was as follows: back thrust (back 2, back 1), hanging wall short cut (splay fault), footwall short cut (fwsc fault) and the main fault (the Cagui Fault) (Figure 4.10).

5.1.7 Comparative Examples of Inversion Tectonics

An example of inversion tectonics similar to the studied case is presented by Beauchamp et al. (1996) (Figure 5.6, section 1.2.7). In the interpreted seismic section, the syn-rift sequence increases thickness toward the inverted listric normal fault as is the case of the Cagui Fault. Also, a footwall shortcut fault is interpreted in the case of the Cagui structure. In the Missour Basin case, this shortcut fault is more important than in the case of Cagui structure because it bypasses the main fault which does not reactivate due to the high angle. It forms a fault-bend fold structure, while in the case of the Cagui structure, the footwall short cuts only intercept the deeper part of the footwall block. Instead, the Cagui structure presents a hanging wall shortcut and back thrust that are not present in the comparative example (Figure 5.6).
Figure 5.6: Comparison of example of inversion from Missour Basin vs. Cagui Structure.
5.2 Decision Workflow in the Structural Restoration

A decision workflow chart was constructed to explain the steps made in the structural restoration of Section 2 and the probabilistic scenarios at each decision point (Figure 5.7).

On the left side of the graph is the restoration step and in the decision chart the possibilities for each step is presented as well as the probabilistic percentage of occurrence.

In the following paragraphs we explain the steps in more detail.

Step 1: Decompaction and restoration of the Tertiary units. After applying these processes, the Eocene Unconformity is located above the sea level.

Step 2: Creation of the structure above the Eocene Unconformity. The most probable option is that the structure had periods of growth and subsequent erosion, instead of total uplift being followed by erosion or erosion and uplift occurring at exactly the same time without creating a topographic expression.

Step 3: Restoration of the back thrusts. The way to restore these faults is by assuming an internal rotation of the block and by restoring these manually. It is not possible to restore these faults using the software because blank spaces are created.

Step 4: Restoration of the splay fault. It is not possible to restore this fault individually. It is necessary to join the splay fault to the main fault and in this way the movement along both faults can be restored.

Step 5: Restoration of the footwall shortcut fault. To restore this fault, it was necessary to do iterations by adjusting the form of the detachment.
Figure 5.7: Decision workflow chart in the structural restoration of Section 2.
Step 6: Restoration of the Cagui Fault. To restore this fault, it was necessary to do a number of iterations by adjusting the form of the detachment.

Step 7: Decompaction and restoration of the Cretaceous formations. Each of these was restored to a position below sea level because these were deposited in a marine environment.

Step 8: Restoration of Jurassic-Cretaceous Unconformity. This was restored to a position above sea level because this represents a surface of erosion.
Step 9: Creation of the structure above the Jurassic-Cretaceous Unconformity. The Jurassic units were completed by keeping their thinning tendency toward the west. The highest elevation of the Jurassic units is considered to be equivalent to the elevation of the basement in the footwall, which is controlling the Jurassic deposition.

5.3 Potential Strike-Slip in the Structural Cross Sections

From the Late Cretaceous to Early Paleocene, there is general agreement for the subduction of a south-western portion of a Caribbean or proto-Caribbean oceanic plate west of the Central Cordillera and obduction-accretion of oceanic terranes to form the Western Cordillera (McCourt et al., 1984) (Figure 5.8). Caribbean collision with north-western South America was diachronous, becoming younger northward and eastward: Cenomanian-Campanian in Ecuador and Campanian-Maastrichtian in Colombia (Pindell and Erikson, 1993; Pindell and Tabut, 1995). Therefore, plate-tectonic history suggests that Paleogene basin inversion and upthrust of basement blocks were collision related, probably involving right-lateral transpressional deformation, and led to pre-Andean orogeny in the Central Cordillera during Paleogene. It is probable that some right-lateral strike-slip faults (e.g., the Palestina Fault) were active during the Paleogene (Sarmiento, 2001).

Structural cross sections that cover both the MMVB and the Eastern Cordillera presented by different authors (Colleta et al., 1990; Dengo et al., 1993; Cooper et al., 1995; Córdoba et al., 2001; Toro et al., 2004) are oriented generally NW-SE and no discussion is presented about out of plane movement. All of these cross sections are located perpendicular to the present day strike of the major structures.
Figure 5.8: Tectonics plate framework at the Paleocene time for the northwestern corner of South America (Pindell et al., 1998).
Taking into account that the strike of the structures in the study area is close to 030 and the tectonic compressive event related to the subduction zone on the western border of the South American Continent was approximately west to east in the Maastrichtian-Paleocene time, it is possible that a strike-slip component would create out of the plane movement in the structural cross sections. However, with this shortening direction, the most likely direction of tectonic inversion of the Cagui Fault was approximately perpendicular to the strike of the fault. Additionally, in the study area, the stresses were more compressive than transpressive, as there was less influence of the Palestina Fault, a dextral strike-slip fault system located in the Central Cordillera.

### 5.4 Geological Evolution and Exploration Implications

During Jurassic time, the study area was part of the rift interpreted by Cooper et al. (1995), with its deepest part in the present location of the Eastern Cordillera (Figure 4.10, stages A, B, C). Taking into account that there is no evidence of a compressional tectonic event in the Late Jurassic time, I interpret the Jurassic-Cretaceous Unconformity to represent a period of intense regional erosion (Figure 4.10, stage D), probably related to the fact that the subduction zone on the western border of the continent is believed to have intensified in the Late Jurassic and Berriasian, based on the presence of calc-alkaline plutons of this age in the eastern part of the Central Cordillera (McCourt et al. 1984).

There is a clear angular Jurassic-Cretaceous Unconformity in the Cagui sector. This is interpreted as a syn-rift/post-rift boundary unconformity, since the units below the
unconformity change thickness toward the main normal fault while units above the unconformity show constant thickness (Figure 4.10, stage E).

Overlying the Jurassic-Cretaceous Unconformity is the Cretaceous-Paleocene sequence that was deposited during a period of tectonic quiescence (Figure 4.10, stage E). The Maastichtian-Paleocene compressional event related to the subduction zone on the western border of the continent (Figure 2.4, Cooper et al., 1995) produced the uplift of the Central Cordillera and the inversion of the Jurassic extensional system (Figure 4.10, stage F, G, H, I). As a result of this compressional event, a period of significant erosion took place, with truncation of the structures formed prior to this event (Figure 4.10, stage J). This was followed by the deposition of the middle Eocene units, that highlight the Eocene Unconformity (Figure 4.10, stage K).

In the southern part of the study area, I interpret the basement being present in the footwall of the Cagui Fault (Figures 4.2, 4.3 and 4.7), while in the northern part a Jurassic sequence is interpreted (Figures 4.5 and 4.7). Based on this interpretation, I postulate in the southern part of the study area a basement paleo-high, limited at the western side by the Cagui Fault, which controlled the deposition of the Jurassic sequence. To the north, the paleo-high was not present, or diminished, causing the deposition of the Jurassic sequence to cover the sector from west to east.

The petroleum exploration implications of the geological evolution proposed are discussed in the following paragraphs:

- In the southern part of the study area, where there is good seismic resolution of the Cagui Fault, the potential Jurassic reservoirs are limited to the hanging wall block.
- Although there is no evidence of a source rock in the Jurassic sequence, any hydrocarbons generated during Jurassic time would have most likely escaped to the surface since these units were cropping out. Additionally, the Jurassic sequences probably did not have enough burial depth to reach the oil window.

- Any potential Jurassic source rocks could have reached the oil window in the Cretaceous or Tertiary times, because of the lithostatic load of these sequences.

- Any oil trap in the Jurassic units requires that the Jurassic-Cretaceous Unconformity be a seal, due to the fact that the intra-Jurassic packages are cut by the unconformity.

- Traps formed during the Maastrichtian-Paleocene tectonic event were breached during the Eocene erosion event. A pulse of generation from the Cretaceous source rocks in the Paleocene time has been proposed in the basin (Ramón et al. 1997).

- As a result of the lithostatic load caused by the deposition of the Tertiary units, a second pulse of hydrocarbon generation from the Cretaceous source rocks has been proposed in the Middle Miocene time (Suarez, 1997). This is the most important hydrocarbon generation event in the basin that caused the filling of the traps in the Tertiary formations.

- Jurassic units in the hanging wall of the Cagui Fault could be a potential exploratory play if it is possible to have migration from the Cretaceous source rocks in the footwall, which can be risky since oil generated could migrate up dip in the footwall to the east.

- It is important to distinguish between a structure that is an inversion feature or a newly generated compressional structure, because reactivated rift structures may have prospective stratigraphic relationships (Beauchamp et al, 1996).

- In the Jurassic sequence, syndepositional strata are very thick and can be coarse-grained siliciclastics related to the erosion in the uplifted neighboring blocks.
CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

The main aims of this research are to validate the structural interpretation of the seismic data and to better understand the tectonic evolution of the area by using structural restorations. The key point of discussion is the inversion tectonic event in the area, which played an important role and lead to the present day structural configuration. This is an important factor because this event has influenced some petroleum system parameters such as burial history, fluids migration, faults seal properties and the possibility of new hydrocarbon exploratory plays.

6.1 Conclusions

- The Cagui Fault bounded a half-graben that was part of the Jurassic rift, with the deepest part in the present position of the Eastern Cordillera.

- The Cagui Fault is an inverted listric normal fault, classified as positive inversion. This is related to an extensional half graben that is inverted as a result of a compressional tectonic event.

- As a result of the inversion of the main listric normal fault, associated structures developed include footwall and hanging wall shortcuts, back thrusts and hanging wall folds. The combination of these structures formed a complex structure and created the potential for different trap styles.
- The inverted structure has several similarities with theoretical models and examples from other basins, which gives confidence in the proposed model.

- Tectonic inversion in the area of study occurred during Maastrichtian to Paleocene times, related to a compressional tectonic event caused by the subduction zone along the western part of the South American continent that also produced the uplift of the Central Cordillera. Additionally, the age of the tectonic inversion is constrained by the fact that the inverted structures are buried by the Eocene Unconformity.

- Taking into account that the direction of the compressional event (west to east) that produced the tectonic inversion was not perpendicular to the strike of the normal Cagui fault (030), implies that there is movement out of the plane of the section complicating the restorations.

- In the Middle Magdalena Valley Basin, petroleum exploration has focused on the mid-Cretaceous to Tertiary rocks. However, it is possible to have a potential for hydrocarbon plays in the Jurassic syn-rift sequence. Understanding the geometry of the syn-rift and the infill cycles, will provide insights about the generation, migration and trapping in this sequence.

- An understanding of the Jurassic structures leads to a better understanding of the geometry and genesis of the Cretaceous traps and possibly the Tertiary traps in other sectors of the basin.

- With the quality of resolution of the 3D seismic volume, it is possible to propose exploratory plays in the Jurassic syn-rift sequence, which was not possible with the old 2D seismic data.
- A potential oil exploratory play is the intra-Jurassic syn-rift units in the hanging wall of the Cagui Fault. Its presence depends on the possibility of having migration from the footwall of this fault, where the main source rocks are located.

6.2 Recommendations

- If the 3D seismic volume could be reprocessed it should focus on the Jurassic units. The resolution can be improved, making the interpretation of this sequence easier and allowing better definition of traps.

- An attempt should be made to identify the same play in a shallow depth in the basin, where good seismic quality is available.
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105