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(Sub)regional Hydrocarbon Potential in the Valanginian Mulichinco Formation in the North-Eastern Part of the Neuquén Basin

by

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Abstract

Since the beginning of the 20^{th} century, the Neuquén Basin has been the most important hydrocarbon producer in Argentina. Many different conventional plays have been explored and exploited, while, the unconventional exploitation in the Neuquén Basin is relatively recent and underdeveloped. The Valanginian Mulichinco Fm, known as a reservoir within the basin has been historically approached as a conventional reservoir. In more recent years it has also been exploited as an unconventional reservoir by deploying horizontal production wells and modern completion and fracking technology. The reservoir quality of the Mulichinco Fm varies throughout the Basin, which makes both production techniques relevant.

The general facies variability of the Mulichinco Fm is understood at a basin-wide scale, mainly from outcrop studies and well data, which are then used to understand the formation at the subsurface. However, the facies variation in the subsurface, especially towards the basin edges, is understudied. The purpose of this study is to understand the facies distribution of the Mulichinco Fm, how the facies variation affects the reservoir quality of the formation, and to understand the petroleum system including the Mulichinco Fm as the reservoir in the Northeastern region of the Neuquén Basin. This is done by correlating wells and seismic using key stratigraphy, interpreting the sequence boundaries containing the Mulichinco Fm, and interpreting the internal facies of the formation.

The study identifies two tectono-sequences containing the petroleum system that consists of the Vaca Muerta Fm source rock, the Mulichinco Fm reservoir and the Agrio Fm seal. The stratigraphy is interpreted with the seismic and wells to produce structure, thickness, attribute, and petrophysical maps. A lower order sequence is identified for the Mulichinco Fm as well.

This is done by interpreting internal facies within the Mulichinco Fm using cutting descriptions, well logs, and seismic, which are then used to make facies maps. The reservoir properties are then studied through the various maps made. Further understanding of the facies distribution and reservoir properties within the region may be used for ongoing future conventional and unconventional exploration within the Mulichinco Fm.

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Lastly, I want to thank my family for supporting me every step of the way.

1 Introduction

1.1 Geologic Problem

The Neuquén Basin, located in the Western part of Argentina, is bordered by the Andean Cordillera and the North Patagonian massif (figure 1). It initially formed roughly 220 m.a. in the Triassic, and has created up to 7000m of accommodation space filled with sediment (Vergani et al., 1995). The shape of the basin was created by multiple phases of extension and compaction/inversion mainly caused by the Pacific Plate subducting beneath the South American Plate.

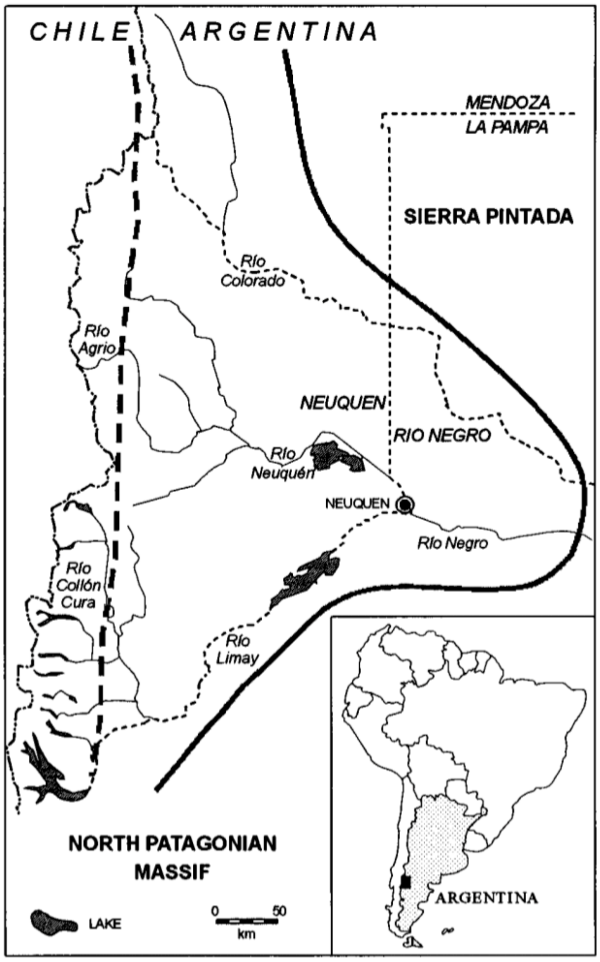
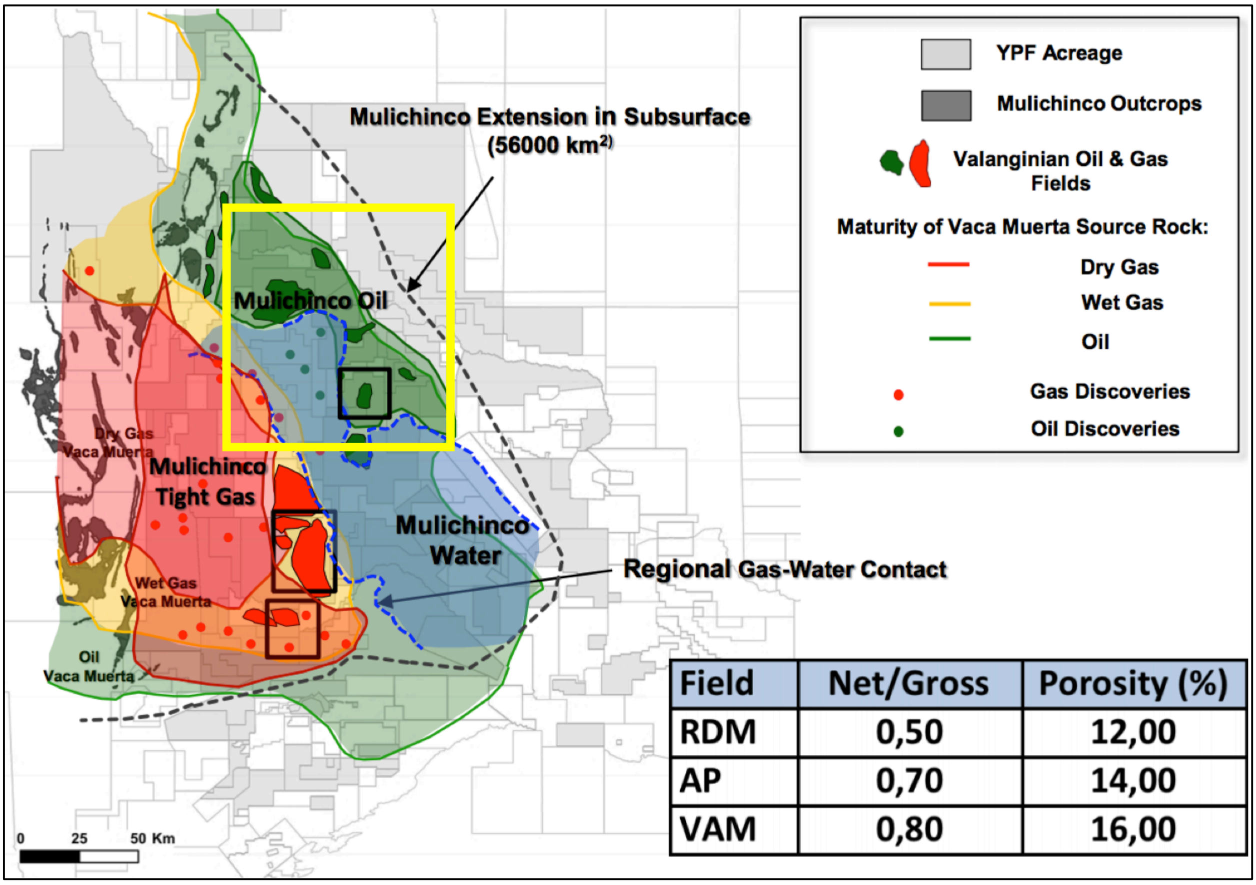


Figure 1. Location of the Neuquén Basin in Western Argentina. Taken from Vergani et al., 1995.

Due to the alternation between extensional and compressional forces, several flooding events are linked to subsidence phases that produce excellent conditions for the deposition of source rocks, such as the Los Molles, Vaca Muerta and Agrio Fms. Regressive events formed conventional reservoir deposits in the basin, including the Tordillo and the Mulichinco Fms. These events cause variability in facies and quality that also allow for new and different opportunities, such as unconventional exploration.

Conventional and unconventional hydrocarbon exploration are two different methods of extracting hydrocarbon used in the basin depending on the reservoir quality. Conventional drilling targets reservoirs with higher porosity and permeability reservoir properties, while unconventional methods are used when the permeability values are too low to support commercial hydrocarbon flow in the reservoir towards the wellbore without extensive stimulation. Conventional drilling techniques are used on reservoirs with generally 5-30% porosity or higher, and permeability values over tens of millidarcys. Unconventional methods are typically required where the permeability is in the range of nanodarcys to microdarcys. Due to the different reservoir properties, different drilling techniques are used. Unconventional drilling requires mainly horizontal wells and extensive stimulation of the reservoir by fracking, increasing the permeability, and allowing the hydrocarbons to move throughout the reservoir rock.

The Neuquén Basin has been the most important hydrocarbon producer in Argentina since the beginning of the 20th century. Many different plays have been established and are already being produced from. However, the unconventional aspect in the Neuquén Basin is relatively recent and underdeveloped. Although the Mulichinco Fm has been historically approached as a conventional reservoir, it has been in more recent years also exploited as an unconventional reservoir by deploying horizontal production wells and modern completion and fracking technology. In figure 2, the different qualities and distribution of the Mulichinco Fm are observed, as well as the areas where the reservoir is conventional or unconventional, where there are hydrocarbons and different fluid phases. Although this figure indicates a general overview of the formation, the exact extent of the conventional or unconventional reservoir potential is relatively unknown and may vary locally both vertically and sub regionally



Field	Net/Gross	Porosity (%)
RDM	0,50	12,00
AP	0,70	14,00
VAM	0,80	16,00

Figure 2. Modified from Arismendi et al., 2016. The Mulichinco Fm has a lateral variation which characterizes the type of reservoir it may be (conventional/unconventional). The distribution of different fluid phase within the reservoir in the Neuquén Basin is illustrated. The yellow square indicates the study area.

As mentioned in Arismendi et al. (2016), the sand distribution in the Mulichinco Fm is poorly understood. This means that the formation as a reservoir needs further research. Hence, the objective of this work is to map the reservoir properties and the hydrocarbon potential locally within the basin, i.e. the Northeastern area near Equinor's assets, and to describe factors controlling reservoir properties and hydrocarbon potential.

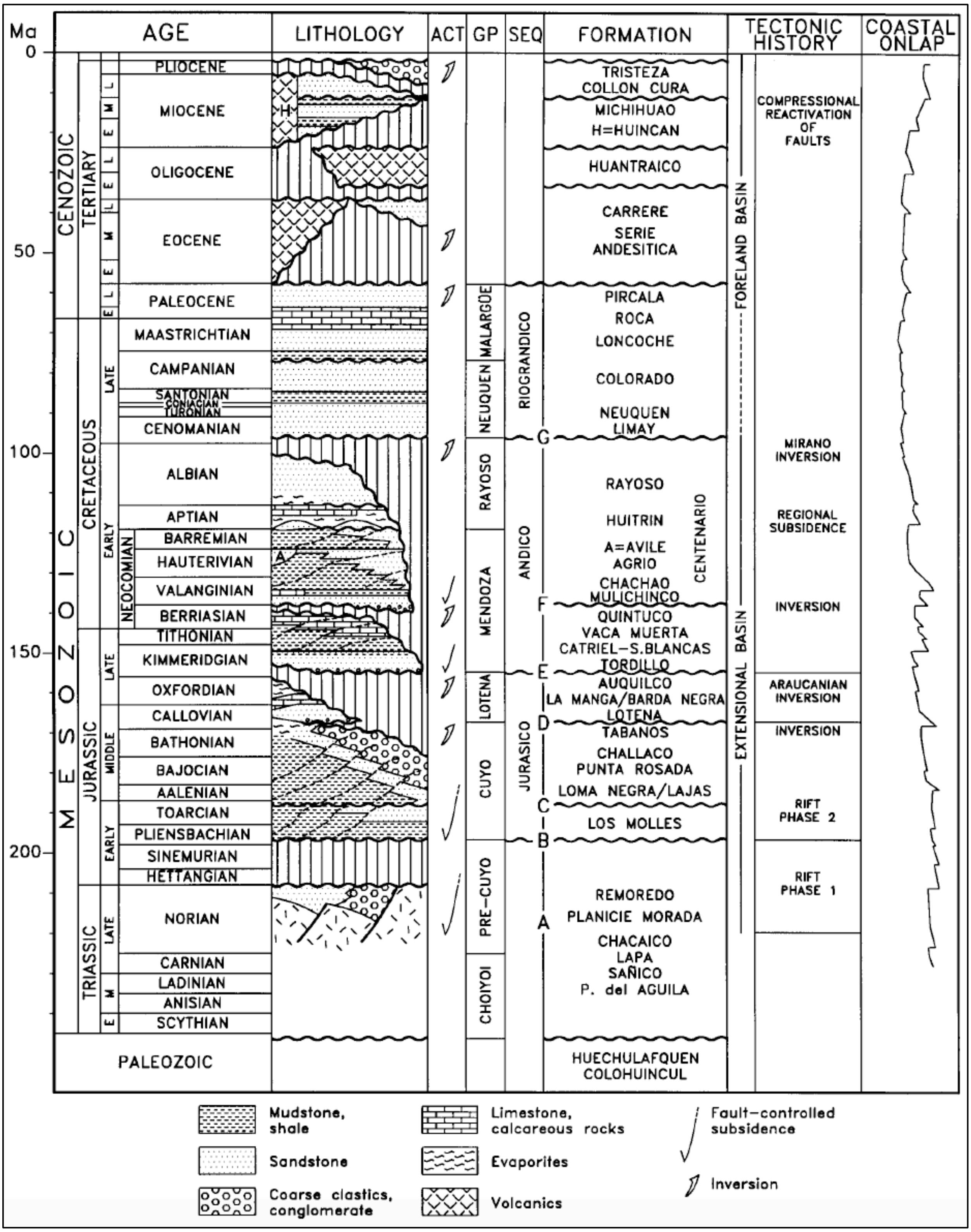


Figure 3. Stratigraphic chart of the Neuquén Basin taken from Vergani et al. (1995).

1.2 Previous Work

Being one of the most important conventional reservoir rocks, the Mulichinco Fm has been studied as a part of the Neuquén Basin for many years. Many authors such as Schwarz (Schwarz, 1999, 2011) (Schwarz and Howell 2005) (Schwarz et al., 2006) research the formation's structural and sedimentary complexities. Other authors observe the Mulichinco Fm as a reservoir unit and its hydrocarbon potential (Hogg, 1993) (Zapata et al., 2001) (Arismendi et al., 2016) (Pascariello et al., 2018).

The literature of Arismendi et al. (2016), Pascariello et al. (2018), and Liberman et al. (2014) focus on the facies distribution of the Mulichinco Fm throughout the basin, and use it to discuss the petroleum systems. This is done by analyzing both subsurface and outcrop studies. Papers such as Schwarz and Howell (2005) and Schwarz et al. (2006) also focus on the facies variation in the Mulichinco Fm, as well as the internal structure, mainly using outcrops from the Neuquén Basin. Studies from Hogg (1993) focus on the petroleum systems within the Neuquén Basin that also includes the Mulichinco Fm, but does not focus on that reservoir. Many other works that are useful for this study, such as Vergani et al. (1995), focus on the Neuquén basin with no specific emphasis on the Mulichinco Fm, but rather a regional study on the whole basin.

1.3 Objectives

The Neuquén Basin has been explored for its hydrocarbon potential, proving that various plays are present and are already being produced from. The extent of the hydrocarbon potential within the Mulichinco Fm, however, is general and is observed as a basin wide formation. Building on previous work, the formation is studied in the Northeast region of the basin using new data (wells and seismic).

The aim of this study is to understand the facies variation of the Mulichinco Fm and their effects on the reservoir quality, the characterization of the depositional environment, and the hydrocarbon potential within a study area in the Northeastern region of the Neuquén Basin. Studying the depositional system, reservoir qualities, trap types, and observed fluid phases in the hydrocarbon accumulations in the Neuquén Basin is done to understand:

- How does the facies distribution change laterally and vertically throughout the study area in the NE region of the Neuquén Basin?
    - How does this affect the reservoir quality?
    - What are the control mechanisms for the facies distribution?
- How does the petroleum system including the Mulichinco Fm work?
    - Source rock quality.
    - Trapping mechanisms.
    - Seal presence and quality.

Understanding the facies distribution throughout the Mulichinco Fm in the study area allows for a more detailed overview of the variation of reservoir quality. Where larger quantities of sand deposition provide a higher porous and permeable reservoir, and areas with less sand and more carbonates will lead to low porosity and permeability reservoir qualities.

Production of the Mulichinco Fm is currently being done, and the general fluid phase within the reservoir has been mapped (figure 2). The objective of this study is to map the potential and the fluid phase more accurately rather than a general overview. By interpreting the subsurface structures of the formation and the variation of reservoir quality, it is possible to have a better understanding of the hydrocarbon potential within the study area (figure 8C).

Furthermore, with the interpreted structures, it is possible to understand the trapping mechanisms of the Mulichinco Fm. Whether the mechanism is fault based, anticlinal features, due to intrusions or other structural styles. By doing so, zones of oil and/or gas accumulations provide information on the potential within the Mulichinco Fm.

Since the oil to gas mature source rock within the Vaca Muerta Fm is found beneath the reservoir within the AOI, the final key element of the play is the Agrio Fm seal. Understanding the presence and quality of the seal is significant to figure out whether hydrocarbons may accumulate in certain areas or not.

1.4 Challenges

Due to the changes in quality and facies within the reservoir, the Mulichinco Fm should be handled differently depending on the location of the basin it is encountered. The Mulichinco Fm is explored as a conventional reservoir in certain areas, but may change properties to an unconventional reservoir nearby due to the lateral and horizontal variability within the reservoir. The formation in the Northeast region is affect by faults and intrusions. Although most major faults are found deeper in the basin (e.g. inverse faults formed in the Triassic-Jurassic rifting phase), there are faults which displace the Mulichinco Fm. Many faults that displace formations in the Mendoza Gp (including the Mulichinco Fm) are related to the salt movement in the Auquilco Fm. This formation, composed mainly of evaporites, impact the region stress distribution and thereby the deformation and the faults in the units superimposing it. The challenges related to the faults are that many are below seismic resolution and are not visible in the dataset. Intrusions are more common in different formations, such as the Vaca Muerta Fm, but may also perturb the Mulichinco Fm in certain areas. This will affect the Mulichinco Fm in terms of reservoir qualities. In terms of data, the study zone is extensive and the seismic is composed of several merged 3D seismic cubes. Tying multiple cubes together cause artifacts in the seismic, leading to displacements which are not geological but rather geophysical. Another challenge is the lack of data that is needed to complete certain tasks. For example, many wells do not contain logs or have missing sections within the log. Final Well Reports (FWRs) are also inconsistent. Some FWRs do not have lithology descriptions i.e. from cutting descriptions) for the well. This is particularly challenging when interpreting the facies distribution within the Mulichinco Fm. A key challenge that is faced when only using the lithology reports, well logs and seismic is that there are scarce available cores to observe.

2 Regional

2.1 Tectonostratigraphic Evolution

The Neuquén Basin is an area which has undergone several tectonic events which developed the basin into what it is today. The The first recordable even in the Neuquén Basin started roughly in the Triassic-Late Jurassic, 220 m.a., with rifting causing subsidence and sediments were initially deposited. Towards the edges of the basin sediments thin out, while in the center of the basin there is over 7000 meters of sediments (Vergani et L., 1995). Although there are many groups and formations, the three-phase subdivision of the basin include:

1) The Choiyoi, Pre-Cuyo and Cuyo Gps of the Triassic-Jurassic extensional phase (figure 4A)
2) The Lotena, Mendoza, Rayoso and Neuquén Gps of the Late Jurassic-Cretaceous subsidence phase (figure 4B)
3) The Malargüe Gp together with the remaining formations and intrusions in the Tertiary of the compressional Tertiary/ Sub-Andean Foreland Basin phase (figure 4C) (Vergani et L., 1995) (Ponce et al., 2015) (Schwarz et at., 2005).

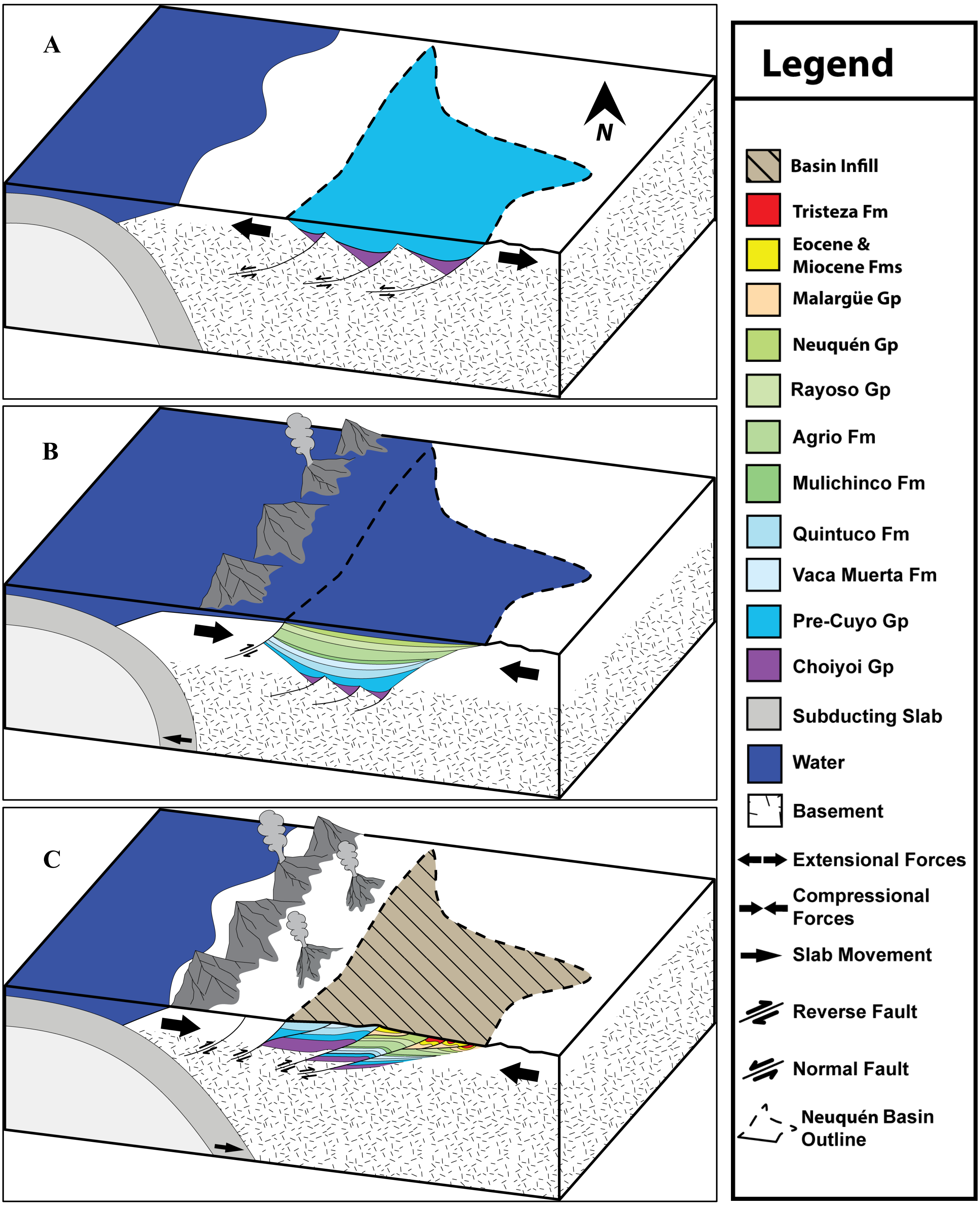


Figure 4. Formation of the Neuquén Basin divided into three main Phases. A) Top left figure representing the initial opening of the basin during the Triassic-Jurassic extensional phase. B) Figure in the middle left illustrating the Late Jurassic-Cretaceous subsidence phase. C) Bottom left figure showing the compressional Tertiary/ Sub-Andean Foreland Basin. The figures are influenced by Vergani et al., 1995, Ponce et al., 2015, and Horton et al., 2015.

During these different basinal evolution settings, changes in the deposition caused sediments to vary from marine to terestrial deposits. There are multiple reservoirs and source rocks within the basin. The main conventional reservoirs explored in the basin are:

1) The basement of the Choiyoi Gp and the Lajas and Challacó Fms of the Cuyo Gp
2) The Lotena Fm of the Lotena Gp
3) The Tordillo, Quintuco, Mulichinco, Avile and Centenarío Fms of the Mendoza Gp
4) The Troncoso Clástico, La Tosca, and Rayoso Clástico Fms of the Rayoso Gp
5) The Huincul Fm of the Neuquén Gp

Some formations have been explored more recently as unconventional reservoirs, such as the Vaca Muerta Fm and the Mulichinco Fm. The Mulichinco Fm has been explored as both a conventional and unconventional reservoir due to the variation in quality, where the porosity and permeability alters from high to low values. The main source rocks present in the basin are:

1) Los Molles Fm of the Cuyo Gp
2) The Vaca Muerta and Agrio Fms of the Mendoza Gp
3) The Troncoso Eváporitico and Rayoso Eváporitico Fms of the Rayoso Gp
4) The Huincul and Lisandro Fms of the Neuquén Gp

The Vaca Muerta Fm being the most prolific source rock in the area, having Total Organic Carbon (TOC) content around 1-10% and producing a large amount of the hydrocarbons in the basin (Ponce et al., 2015).

Overall, the tectonostratigraphic record of the basin may be divided into three main phases:

1) Extension during the Triassic-Jurassic
2) Subsidence of the Late Jurassic-Cretaceous
3) Compression of the Tertiary/ Sub-Andean Foreland Basin (Vergani et al., 1995) (Ponce et al., 2015) (Schwarz et at., 2005).

The following description of the tectonostratigraphic record of the Neuquén Basin may be observed in further detail in Vergani et al. (1995), Hogg (1993), Digregorio and Uliana (1980), Schwarz and Howell (2005), and Schwarz et al. (2006).

2.1.1 Late Triassic to Early Jurassic

Regional extensional forces (NE-SW) formed normal faults striking N-S/NW-SE leading to the development of the Pre-Cuyo Fm (basement) half-grabens (figure 5) (Tankard et al., 1995). Uliana and Biddle (1988) argue that the extensional forces during this time is likely due to a buildup of heat in the lithosphere prior to the break-up of Gondwana that lead to the thermal subsidence. Rifting during this period caused normal faulting of the basement, located beneath the Choiyoi Gp that is mainly composed of andesitic and rhyolitic flows. Extension provided accommodation space that deposited the sediments forming the remainder of the Choiyoi Gp (Hogg, 1993). Within the Choiyoi Gp, hydrocarbon exploration focusing the basement has been sought out where fracturing and weathering allowed for reservoir qualities to develop (Hogg, 1993).

As extension continued providing further accommodation space, the Late Triassic-Early Jurassic Pre-Cuyo Gp filled the basin. This group is composed mainly of coarse continental sediments (Vergani et al., 1995). These sediments were deposited during a transgressional period due to tectonic subsidence. The transgression continued, depositing the marine sediments of the Jurassic Cuyo Gp, overlaying the Pre-Cuyo Gp (Digregorio & Uliana, 1980).

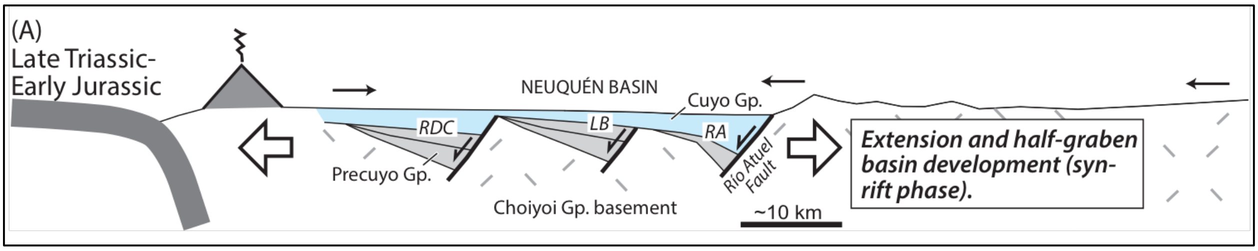


Figure 5. Overview of the tectonostratigraphic setting of the basin during the Late Triassic-Early Jurassic. Image taken from Horton et al., 2016.

2.1.2 Late Jurassic to Cretaceous

Late Jurassic tectonic inversion caused uplift and erosion (Vergani et L., 1995) (figure 6). This ended the transgression during the Middle Jurassic, where the Callovian-Oxfordian Lotena Gp was deposited above the Cuyo Gp, separated by an unconformity. Shallow marine sandstones dominate the base of the Lotena Gp in the Western-Central part of the basin, while fluvial conglomeratic sandstones are present towards the East (Hogg, 1993). The middle to upper units of the Lotena Gp is composed of micrite carbonates in the middle and the evaporitic Auquilo Fm on top in the center of the basin due to the depositional environment altering from open to restricted marine (Hogg, 1993). The Auquilo Fm caused much of the deformation in the Late Jurassic to Early Cretaceous due to the mobility of the evaporites.

After the temporary compression, relaxation allowed for a continuation of subsidence within the basin (Vergani et L., 1995). At the same time, subduction of the Nazca plate beneath the South American plate allowed the formation of a magmatic arc (Ponce et al., 2015). The subduction also caused extension to the East of the magmatic arc, turning the Neuquén Basin into an extensional backarc basin (Uliana et al., 1989). The extension lead to subsidence that caused a basin-wide major transgression to occur, depositing the Late Jurassic-Early Cretaceous Mendoza Gp. At the base of the group is the Tordillo Fm comprised of inter-sand dune and eolean brachan facies, which varies in thickness between roughly 600-100m from the center of the basin towards the East, respectively (Hogg, 1993). The Vaca Muerta Fm superimposes the previous formation, and is composed mainly of a thick layer of organic-rich shales. An initial major flooding event occurred due to the initial opening of open ocean to the basin, followed by the deposition of the Vaca Muerta Fm in anoxic to restricted marine conditions. The basin filled from the Southeast forming various sets of clinoforms while the organic rich facies continued to be deposited at the toe of the slopes. This provided the conditions to form the source rock. The sediments shallow upwards until the Quintuco Fm was deposited, representing the ultimate filling of the basin. Hence, the transituion from Vaca Muerta to Quintucu is diacroneous beeing older in the south east, and younger in the northwest.

The overall trend of subsidence was interrupted during the Early Cretaceous by compression and uplift causing tectonic inversion of older faults (Vergani et L., 1995). The basin entered a regression phase due to inversion, depositing the Quintuco Fm, composed mainly of carbonates. The Valanginian Mulichinco Fm superimposes the Quintuco Fm and was also deposited during the same regression phase. The Mulichinco Fm is composed mainly of fluvial calcareous sandstones interbedded with shales towards the East, and marine shales interfingering with carbonates towards the North (Vergani et al., 1995). The Neuquén Basin returns to a phase of subsidence in the Hauterivian. Basin-wide subsidence triggers a transgressional period which deposits a thick package of marine shales known as the Agrio Fm (Hogg, 1993).

Several unconformities are located between the the Mendoza and Rayoso Gp (Vergani et al., 1995). The Rayoso Gp is mainly composed of evaporites, anhydrites and carbonates deposited in marine settings (Hogg, 1993). The top of this group is eroded due to a small pulse of inversion starting in the Albian.

The short inversion phase allowed for the basin to enter a regressive period. During this period, the Cenomanian to Campanian Neuquén Gp was deposited, composed of mainly fluvial red-bed sandstones and lacustrine shales.

The Malargüe Gp is characterized by another subsidence phase that followed the inversion of the Neuquén Gp. Both marine and continental sandstones and marine carbonate deposits dominate the group.

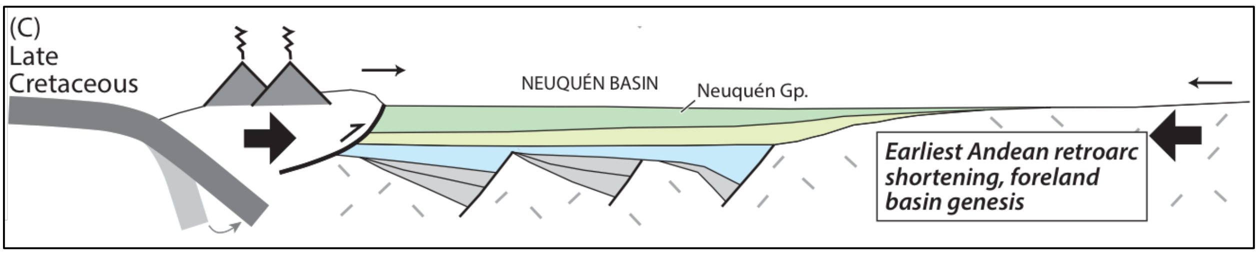


Figure 6. Overview of the tectonostratigraphic setting of the basin during the Late Cretaceous. Image taken from Horton et al., 2016

2.1.3 Tertiary/ Sub-Andean Foreland Basin

Following the Late Cretaceous, there was a continuation of regional compression which lead to basin wide deformation during the Tertiary (Vergani et L., 1995). Towards the West there was thick-skinned deformation which involved inversion of the normal faults that first formed in the Triassic-Jurassic which have controlled the basin structure, observed in figure 7 (Vergani et L., 1995). The crustal thickening towards the West caused the basin to undergo subduction, changing the nature of the Neuquén Basin to progress from a back-arc basin in the Jurassic-Cretaceous to a foreland basin in the Tertiary. The thickening caused the lithosphere to bend leading to the further subduction of the basin. Towards the East, there was thin-skinned deformation which was mainly determined by the Jurassic-Cretaceous sediments (Vergani et L., 1995). During this time frame, the fill of the Neuquén Basin consists of sediment deposits with volcanic intrusions. From the Eocene until the present, sandstones and shales filled the basin, with pulses of volcanic intrusions present.

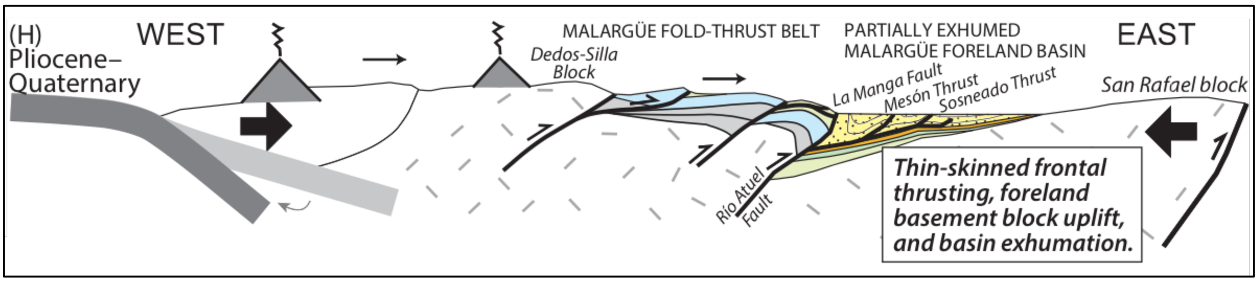


Figure 7. Overview of the tectonostratigraphic setting of the basin during the Pliocene-Quaternary. Image taken from Horton et al., 2016.

3 Data & Methods

3.1 Data

A dataset was provided by Equinor to complete the research needed to achieve the previously acclaimed objectives. The overall data used is composed of:

1) Merge of various 3D seismic cubes which cover approximately 4000 km^2 (figure 8C)
2) Various wells throughout the study area, comprising:
    a. Well logs including GR, density, sonic, and other logs
    b. FWRs
    c. Cutting descriptions

Interpretations of the seismic and wells were mainly conducted using Petrel.

3.1.1 Seismic

Reflection seismic is collected by recording reflected sound pulses induced into the subsurface from energy sources at the surface. The sound waves are reflected when reaching lithology boundaries having velocity and/or density (impedance) contrasts. By analyzing the data, it is possible to map geological structures under the Earth's surface before drilling, and between existing wells. By using various techniques of seismic acquisition, a 3D seismic cube is made that may be linked to other seismic cubes to produce a merger, such as the data set used for the study area. The area includes three of Equinor's assets: Bajo del Toro, Bajo del Toro Este, and Aguila Mora Noreste (figure 8C).

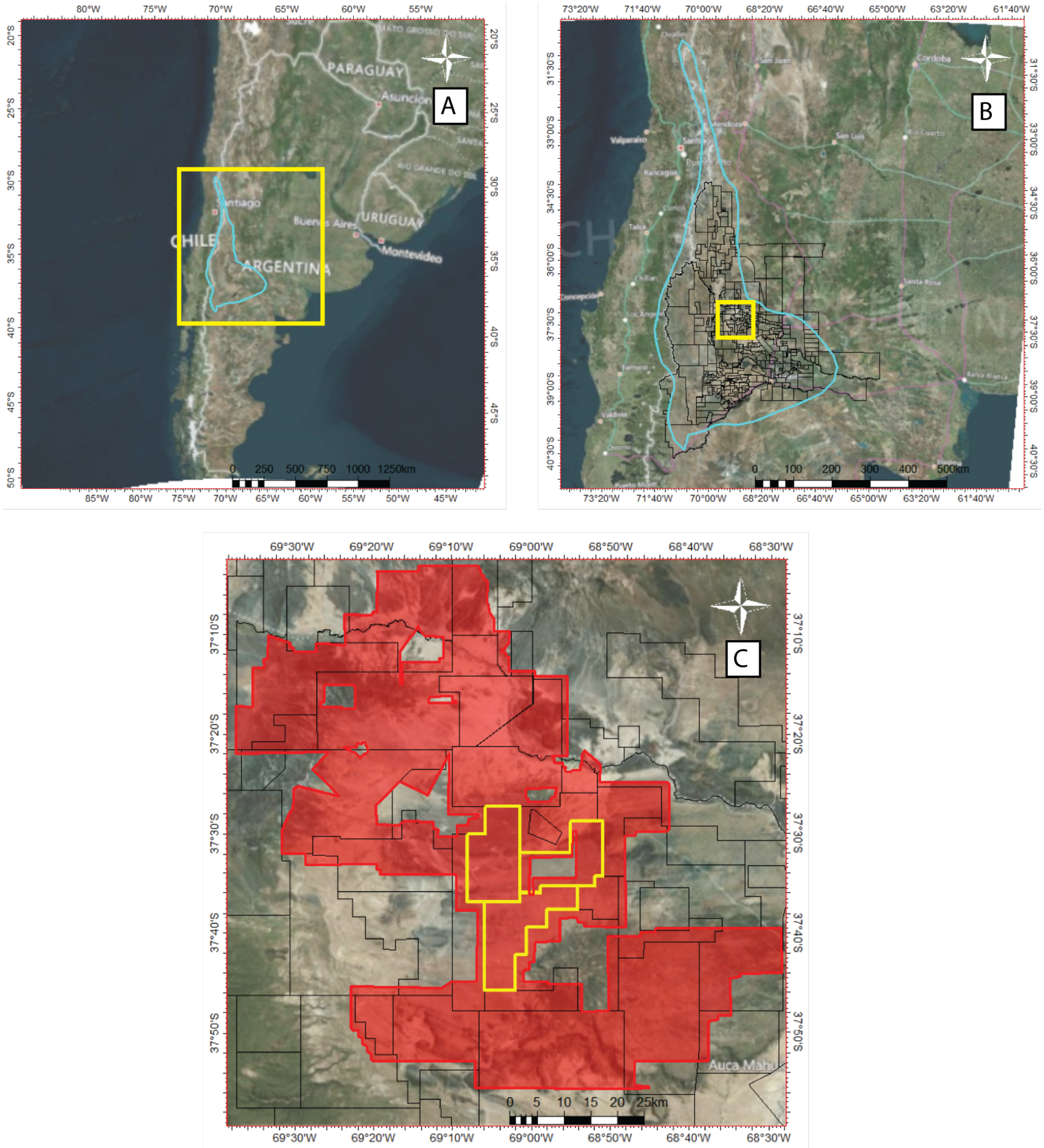


Figure 8. A) Location of the Neuquén Basin in Western Argentina. B) The basin is outlined in orange with the licenses outlined in white. C) Top view of the AOI with the given seismic on top. The licenses highlighted in yellow are Equinor's assets: Bajo del Toro (BdT), Bajo del Toro Este (BdTE), and Aguila Mora Noreste (AMNE).

The seismic merger has a positive polarity, which means that peaks represent an increase in acoustic impedance (overlaying rocks are less dense and/or have lower velocity than the underlying rock) are blue, and the troughs represent a decrease in acoustic impedance (overlaying rocks are denser and/or have higher velocity than the underlying rock), which are red. The seismic is measured in time, and depth maps are generated by time depth conversions as described in chapter 3.2.6. Therefore, a time-depth conversion will be necessary for observing the horizons in depth.

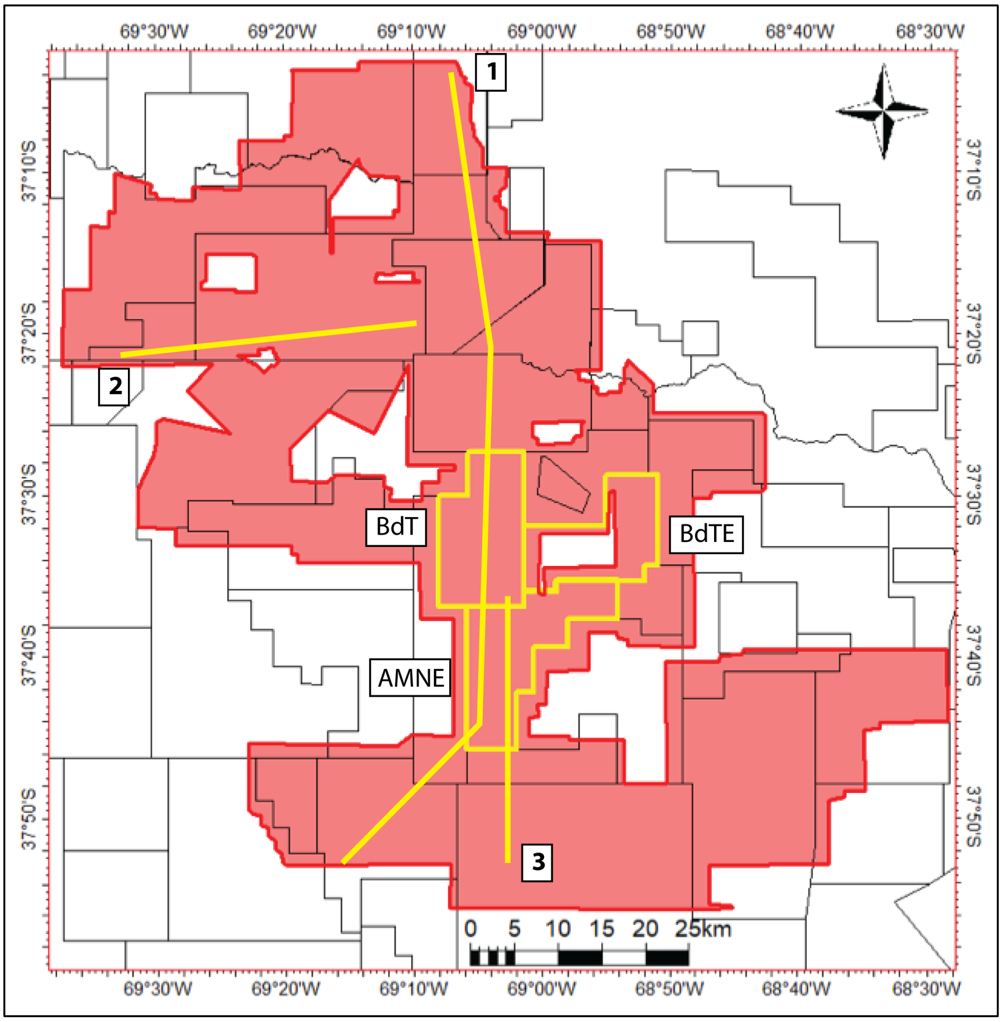


Figure 9. Map with cross sections to exemplify the seismic quality. The three highlighted areas are Equinor assets Bajo del Toro (BdT), Bajo del Toro Este (BdTE), and Aguila Mora Noreste (AMNE). Yellow lines are the cross sections 1-3. Red area shows extent of 3D seismic merger

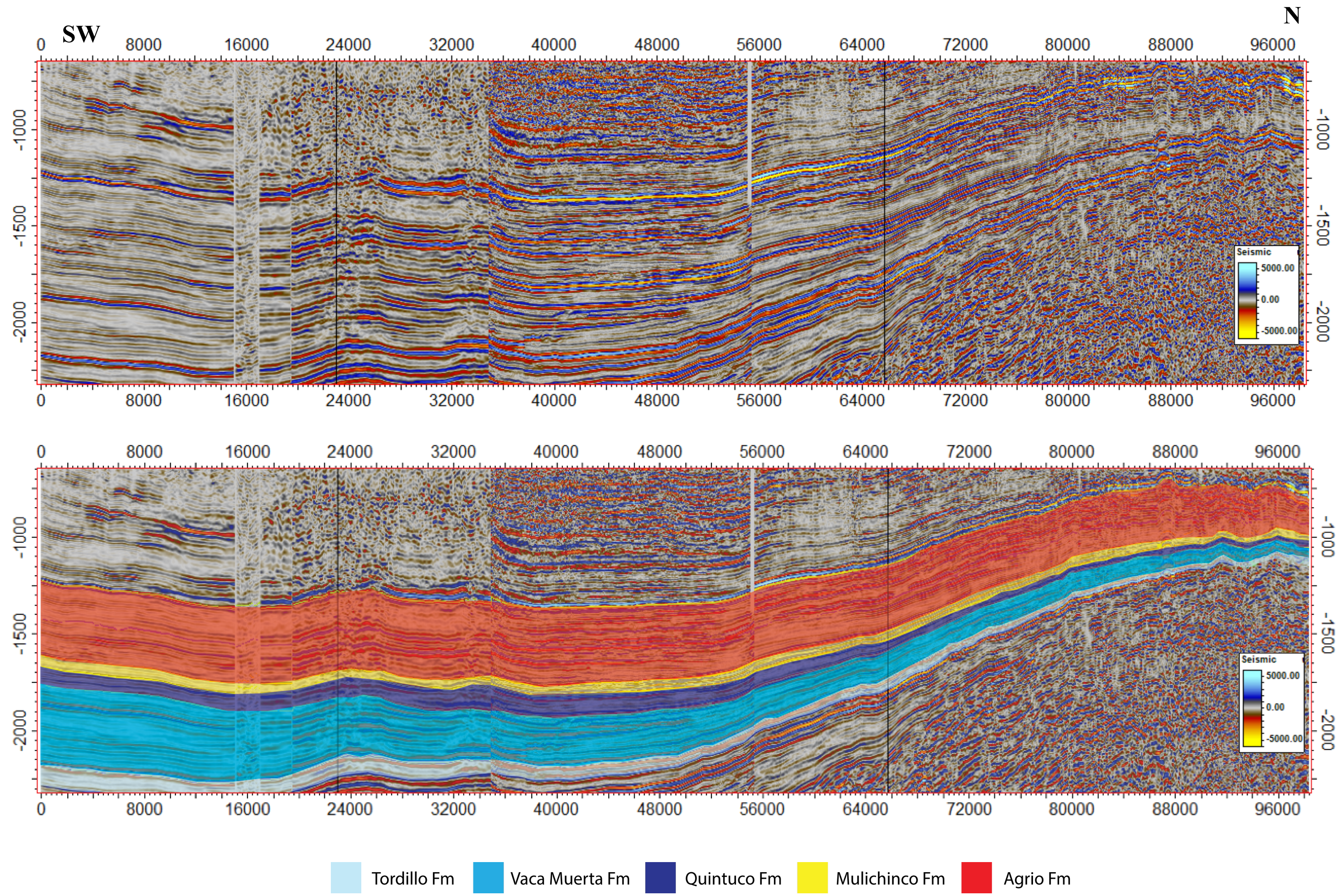


Figure 10. Regional cross sections. Top figure shows seismic without interpretation of key formations. Bottom figure has the key formations interpreted. Location of cross sections marked as cross section 1 in figure 9. The Y axis is depth in milliseconds. The X axis is horizontal distance in meters.

3.1.1.1 Seismic Quality

The quality of the seismic cube in the area is variable. In some areas, there are clear imaging and in others it becomes more complicated to observe the subsurface. These poor quality areas have been displayed in figures 11 A and B.

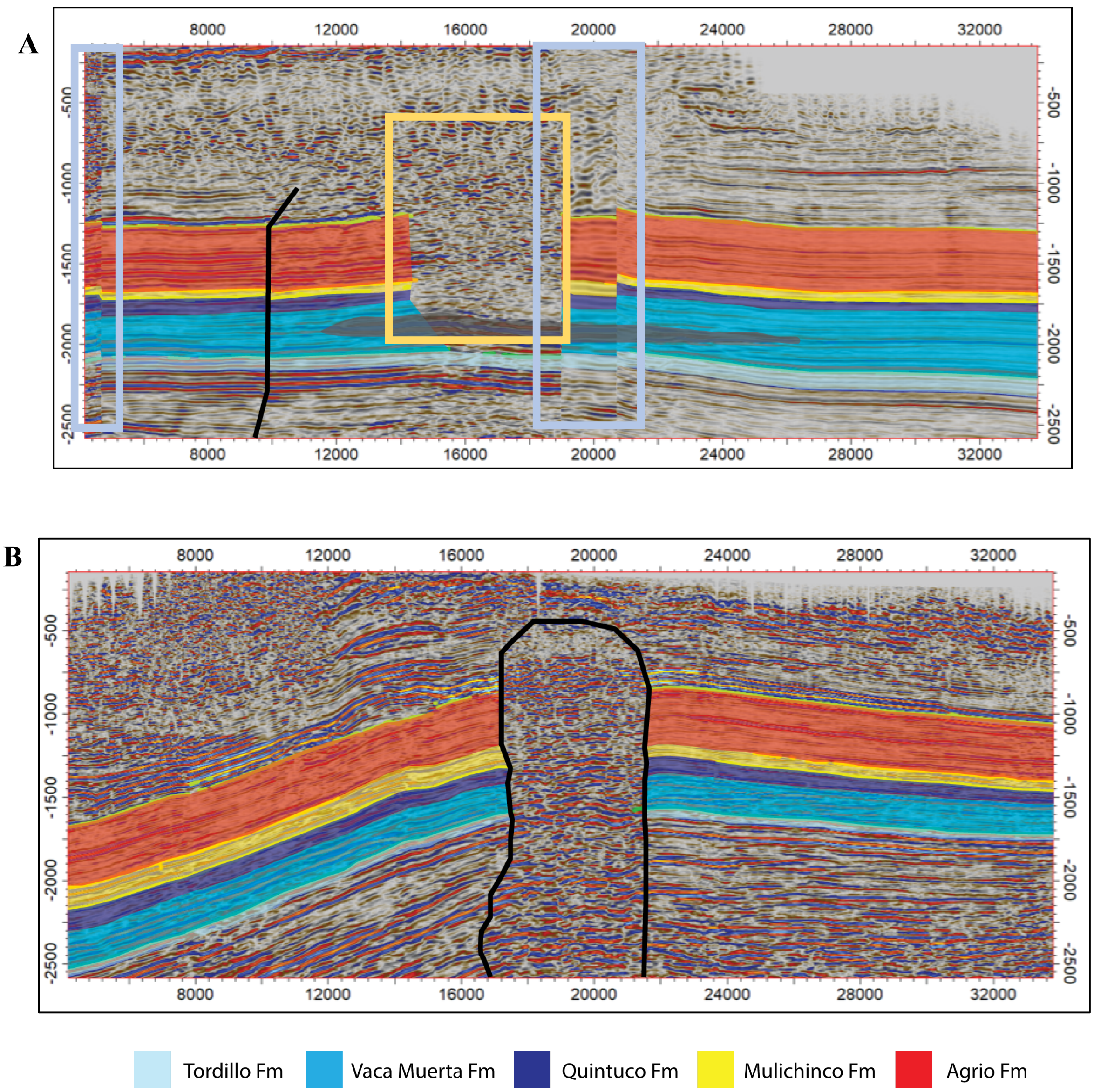


Figure 11. Cross sections showing example of poor seismic. A) Cross section 3 from. The yellow box indicates areas where horizons cannot be interpreted. The boxes in blue indicates displacement due to seismic merger. B) Cross section 2. The black line outlines volcanism that does not allow further interpretation of horizons. Location of both cross sections are in figure 8. The Y axis is depth in milliseconds. The X axis is horizontal distance in meters.

3.1.2 Wells

Equinor provided wells that covered a large area of the basin. However, of those wells, 45 were used in this study, shown in figure 12. Some wells observed in this figure contain well logs such as GR, sonic, density, and more, while other wells may provide only the well location. The 45 wells used were chosen due to their location and quantity/quality of the logs they contained (Table of wells and well logs found in appendix, Table 1). Those wells also contained FWRs. The well logs and FWRs are used to conduct seismic well ties, time depth conversion, interpret facies, and to make facies distribution maps.

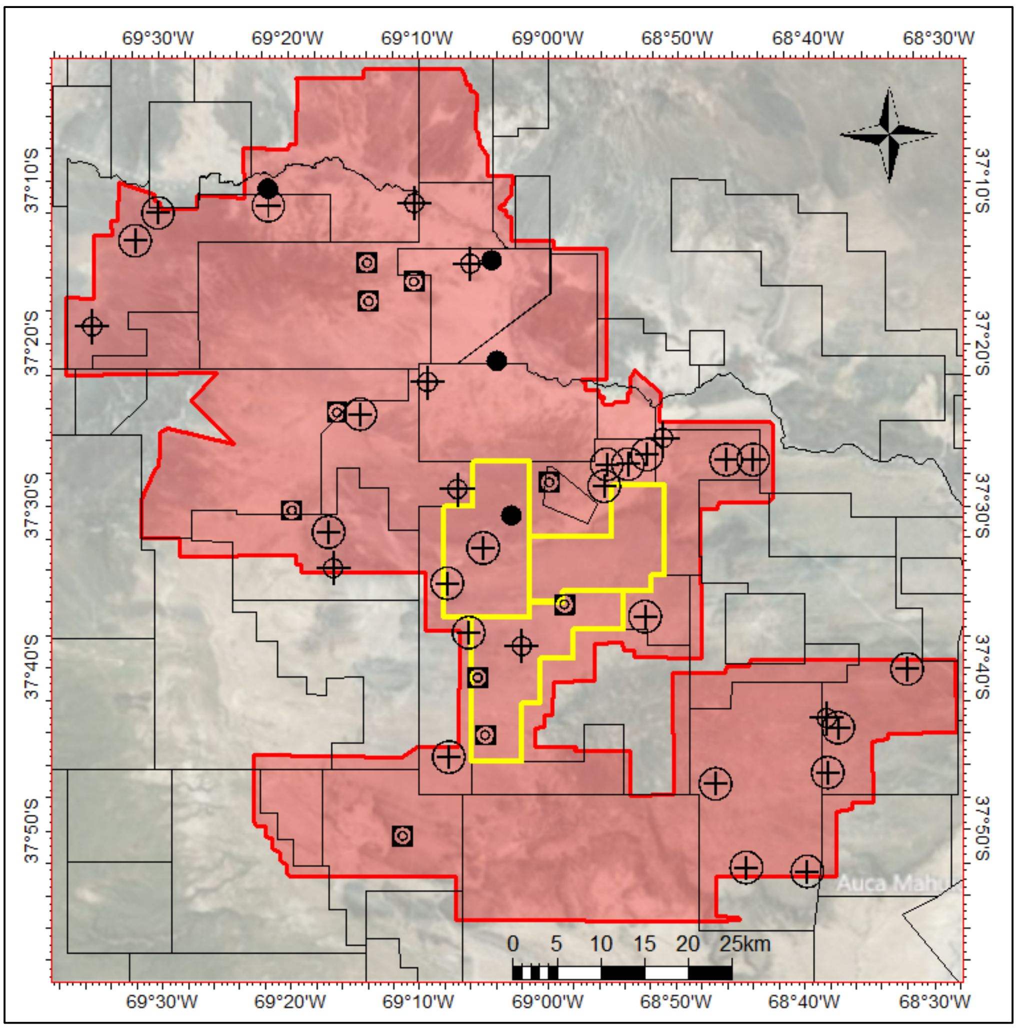


Figure 12. Location of the wells used in the study. All of which have different quantity and qualities of logs.

The well logs used to conduct the study were the GR, density, sonic, resistivity, and acoustic impedance logs, which vary in quality and quantity from well to well. Figure 13 displays three wells with their logs. As observed in the left well (Aguada del Chivato Oeste x-1), there are many logs that cover the basin from top to bottom. Other wells, such as La Tropilla x-1 and Aguada Bocarey 4, have less logs. Some of which (Sonic and Caliper logs) only cover small intervals of the well.

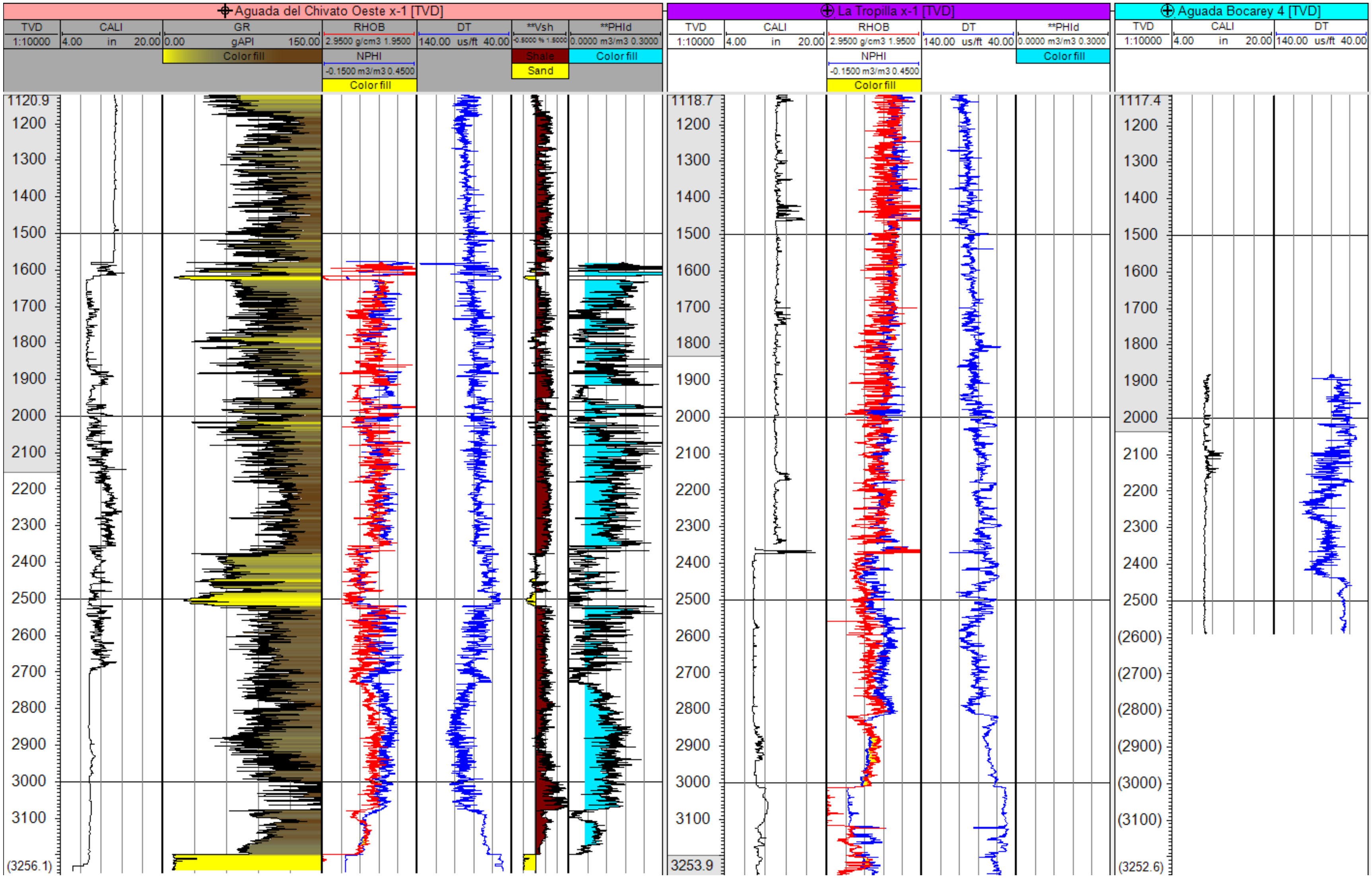


Figure 13. Three wells with their different logs displaying the variation in quality and quantity of logs. Wells from left to right: Aguada del Chivato Oeste x-1, La Tropilla x-1, and Aguada Bocarey 4.

3.2 Methods

By correlating the wells, it is possible to understand the signature of each key horizon within the basin. In turn, this will help to interpret the horizons within the seismic. The seismic interpretation is used to produce structure maps in time. Seismic well ties are essential to linking geology to seismic horizons. The seismic well ties are also used to produce velocity intervals to convert the time maps into depth maps. Attribute maps extract properties of a selected interval. Facies distribution maps will provide insight on the facies variability of the Mulichinco Fm as a reservoir both laterally and horizontally.

3.2.1 Well Correlations

Wells containing GR, density, and sonic logs of good quality were selected for the well correlation. The wells in the area were correlated by interpreting the key stratigraphy. The Agrio, Mulichinco, Quintuco, Vaca Muerta and Tordillo Fms were interpreted throughout the study area. Furthermore, the same sections were interpreted into a sequences stratigraphic framework.

The internal units within the Mulichinco Fm were also interpreted within the wells to observe the facies variation within formation (Appendix figures 48). This well correlation was done by selecting five wells that are located along the depositional trend of the Mulichinco Fm (Appendix figure 49) and interpreting the facies variation using cutting descriptions. The five wells being Bajo Batra 1, Loma del Barril x-1, Bajo del Toro 5, Filomena x-1, and Loma Partida Este 2.

3.2.2 Seismic Well Tie

Connecting the seismic and wells is essential to understand the geologic variation between wells and in the seismic. It also serves as a quality control (QC) to ensure that the interpretations of both the wells and the seismic are consistent.

By using the sonic and density logs of the wells, synthetic seismograms are made. Wavelets for each well were applied to best fit the data, generally being a zero phase 22 Hz positive polarity. Four horizons were used as reference picks to align the synthetic seismic to the seismic, the top Agrio, Mulichinco, Quintuco and Vaca Muerta Fms.

3.2.3 Seismic interpretation

Important structural elements, formation thickness variation and unit terminations are recognizing in the seismic once the key horizons are interpreted. By recognizing the top and base of the Mulichinco Fm and the top of the Agrio Fm (the seal), it is possible to visualize potential structural traps.

The horizons of the key formations are interpreted in Petrel. Seeded 3D autotracking is used to interpret the horizons within the seismic. The horizons are then extended using the Paintbrush Autotracking tool in 2D. Errors that occur using the autotracking tools are evident, therefore quality checks of the interpretations were continuously done by correcting the horizon interpretation in seismic.

3.2.4 Sequences Stratigraphic Interpretation

The stratigraphy containing the key formations is divided into two tectono-sequences, Tectono-Sequence 1 (TS1) and Tectono-Sequence 2 (TS2). Formations may change in facies and nomenclature depending on the location of the basin, such as the Quintuco Fm in the center and East of the basin being the Picun Leufu Fm in the far West, or as the Mulichinco Fm being fluvial calcareous sandstones in the Southeast and marine carbonates in the North (Vergani et al., 1995). The tectono-sequences are seperated by sequence bounderies. TS1 covering the Late Kimmeridgian to Late Beriasian, containing the Tordillo, Vaca Muerta and Quintuco Fms. TS2 is defined by the Early Valanginian to late Barremian that contains the Mulichinco and Agrio Fms. The tectono-sequences are similar to Hogg (1993), but using different sequence bounderies.

The sequence stratigraphy for the Mulichinco Fm is interpreted as well, but at a lower order. Similar to how the tectono-sequences are interpreted, the sequence bounderies comprising the Mulichinco Fm are also interpreted. The sequence bounderies are identified to establish the system tracts of the formation using techniques from Embry (2009), which is done on both scales: tectono-sequence scale and at the sequence scale of the Mulichinco Fm.

3.2.5 Gridding of time maps

Time surface maps are created from the interpreted formations. These are made to observe structures and the trends that formations may have in terms of thickening and elevation changes (shallowing/deepening). These time maps are made by extending the seismic interpretation of the horizons in 2D to cover as much of the study area as possible. The parameters depend on the formations. If there are formation terminations, or areas that interpretation is not possible, then the surface will not cover those areas. Once the maps are created, they may be used to produce thickness and attribute maps, as well as convert them to depth structure maps.

3.2.6 Time-Depth Conversion

Various steps are necessary prior to converting time to depth. Since there are changes in ground level, a standard Reference Datum (SRD) is set to an elevation of 1200m. By doing this, all wells can be set to the same starting height. The velocity used from the SRD to ground level is set to an interval velocity of 2400m/s. With the seismic-well tie, it is possible to extract thickness points of the interpreted formations. By taking the thickness points in Two Way Time (TWT) and True Vertical Depth (TVD), interval velocities for each formation can be made. These thickness points are introduced in the equation:

$$Interval\ Velocity = \frac{TVD}{TWT/2000}$$

A quality check of the interval velocities maps was done to correct for velocity anomalies within formations. The internal velocities allow the time-depth conversion to be made, producing a velocity model.

3.2.7 Attribute Maps

Using seismic data, various rock and fluid properties may be extracted with attribute maps. This method helps to recognize changes in facies, fluid presence, and various anomalies. Although there are numerous different attributes that could be applied to the seismic, the ones used in this study include maximum amplitude, interval average, and root mean square (RMS) attributes.

The amplitude of a given seismic reflection indicates the contrast between two rocks with impedance. It is common to find strong amplitudes between two formations with different impedances, or even the same formation that has a large enough change in impedance within. This change in impedance is caused by facies variations and/or variance in pore fluids within the formation. The presence of gas produces an abrupt decrease in velocity. Oil and gas saturations decrease the overall formation density. Hence, contrasting impedance may produce seismic patterns known as DHIs (Direct Hydrocarbon Indicators). The <u>maximum amplitude</u> attribute highlights areas where the maximum positive amplitudes increase within an interval in the seismic. The <u>interval average</u> attribute will highlight areas where there is an increase of all positive amplitudes within a specified interval. The <u>RMS</u> attribute is calculated by squaring the amplitudes, summing them up, dividing them by the number of samples within a given window and then taking the square root of that value. Overall, the reflectivity within the seismic may be measured using this method, highlighting areas of high reflectivity. The downside of this method is that noise in the seismic will also be squared, amplifying these non-geologic anomalies.

All attribute maps were created by applying the selected attribute to a given interval. The interval being from the top Mulichinco Fm to 10ms above top Quintuco Fm. This ensures that Quintuco Fm properties are not included within the Mulichinco Fm interval.

3.2.8 Thickness maps

Using the key horizons tracked in the seismic, thickness maps are produced. Time surface maps are created once the horizons are interpreted in seismic. The time thickness maps are then made by calculating the isochore between any two given surfaces. Depth surface maps are also produced once the time-depth conversion is complete. Those surfaces are used to calculate the isochore of formations, creating a depth thickness map. The thickness maps created were of the Agrio, Mulichinco and Vaca Muerta Fm, as well as the thickness maps for TS1 and TS2.

3.2.9 Facies Distribution Maps

The facies distribution maps are made from the facies determined from the well correlation of the internal sequences of the Mulichinco Fm, as well as the Mulichinco Fm thickness map. Together, the lateral extent of the different facies within the Mulichinco Fm may be visualized in map view by extending the interpreted facies along thickness trends. Areas where there are no wells nor seismic are influenced by interpretations in this study and by the work of Pascariello et al. (2018).

3.2.10 Volume Shale

The volume shale (Vsh) is calculated for 21 individual well with good quality GR logs. The Vsh is calculated from the GR log, using the equation:

$$Vsh = \frac{GR - GR_{Sa}}{GR_{Sh} - GR_{sa}}$$

Where GR is the GR log for the individual well, GR_{sa} is the GR value for clean sands and GR_{sh} is the value for pure shales. A cutoff for the Vsh is made at 0.4, where values over 40% shale within the Mulichinco Fm are not shown. A map with the average Vsh with the cut off at 0.4 is made for the Mulichinco Fm interval.

3.2.11 Porosity

Porosity logs are made for 28 individual wells containing good quality density logs. The porosity logs are calculated through the density log, while using two constants:

$$\Phi_{den} = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

Where $\boldsymbol{\rho_{ma}}$ is the matrix density (the value used is 2.65), $\boldsymbol{\rho_b}$ is the density log for the specific well, and $\boldsymbol{\rho_f}$ is the density of the fluid that saturates the rock (the value used is 0.8).

It is important to remember that the Porosity logs are produced from the density logs, therefore carbonates will appear to have low porosity values due to their higher density, but this is not guaranteed. Carbonates may have a higher density than sands, yet both rock types may be porous.

4 Observations

4.1 Stratigraphic Framework

Correlating the wells and seismic is the basis for the stratigraphy framework of this study. The terminology and stratigraphy used throughout this study are widely accepted through the literature, such as Vergani et al. (1995), Hogg (1993), Schwarz and Howell (2005). The key stratigraphic tops are interpreted for the wells together with the horizons in the seismic. The seismic-well tie is then used to make time-depth conversions to produce maps in depth. Other maps, such as the facies distribution map, are made by interpreting the Mulichinco Fm facies within the wells and correlating the facies to thickness trends.

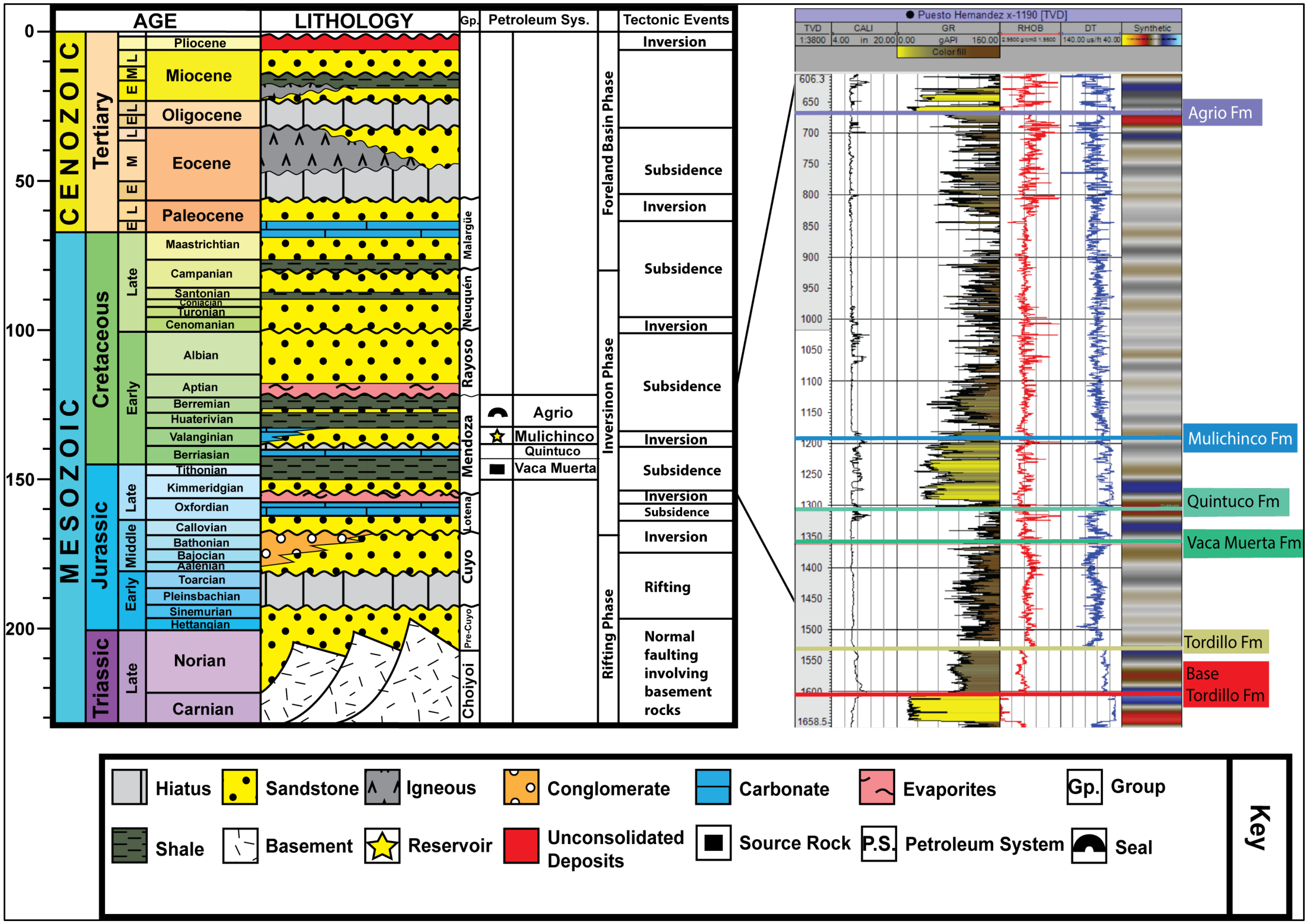


Figure 14. Stratigraphic chart of the Neuquén Basin together with depth, caliper, GR, density, and sonic logs from Puesto Hernandez x-1190 well. Also with seismic. Influenced by Vergani et al., 1995 and Ponce et al., 2015.

4.1.1 Well Response

4.1.1.1 TS1

The carbonate rich composition of the Quintuco Fm at the top of TS1 produces an evident GR log reading when compared to the base TS2 Mulichinco Fm. The GR and sonic log values decrease from TS1 to TS2 (figure 15). The contact between the base Quintuco Fm and top Vaca Muerta Fm representing a diachronous boundary is not as easily recognized. The Quintuco Fm has a lower GR value at the base than the top Vaca Muerta Fm (figure 15). The top Vaca Muerta Fm also has lower sonic values compared to the Quintuco Fm. The contact between the base Vaca Muerta Fm and the underlying Tordillo Fm representing a rapid flooding event is easier to recognize. The Vaca Muerta Fm in the study area has a very high GR log value at the base (figure 15). The GR and sonic log values for the Tordillo Fm is lower, which provides a strong contrast at the contact. The sequence boundary at the base of the TS1 is also very evident. The GR log values are much lower and the sonic and density log values are much larger beneath the TS1 than at the base of the TS1 (figure 15).

4.1.1.2 TS2

Top tectono-sequence two is recognizable in various logs, due to the contrast of the top TS2 being the shale rich Agrio Fm, and the overlying evaporite Huitrin Fm. The GR value decreases and the sonic and density values increase significantly from top TS2 to the Huitrin Fm (figure 15). Within TS2, The Mulichinco Fm varies throughout the area, having more sand to calcite rich sand packages with interbedded shales in the South-Southeast, and more carbonate rich layers with sand beds and few shale layers towards the North. This is observed in the lithology reports from the cutting descriptions. Overall the Mulichinco Fm is more sand rich than under and over laying sequences and is easily recognized between the overlying shale rich Agrio Fm and the underlying Quintuco Fm in TS1 composed mainly of carbonates. Within the Mulichinco Fm, the GR values are mostly low, although containing some internal high GR intervals (figure 15). Both the sonic and density logs are variable throughout the formation. However, the sonic log generally has lower values within the Mulichinco Fm than both Agrio and Quintuco Fm. The Mulichinco Fm also has larger density values than the overlying and underlying formations.

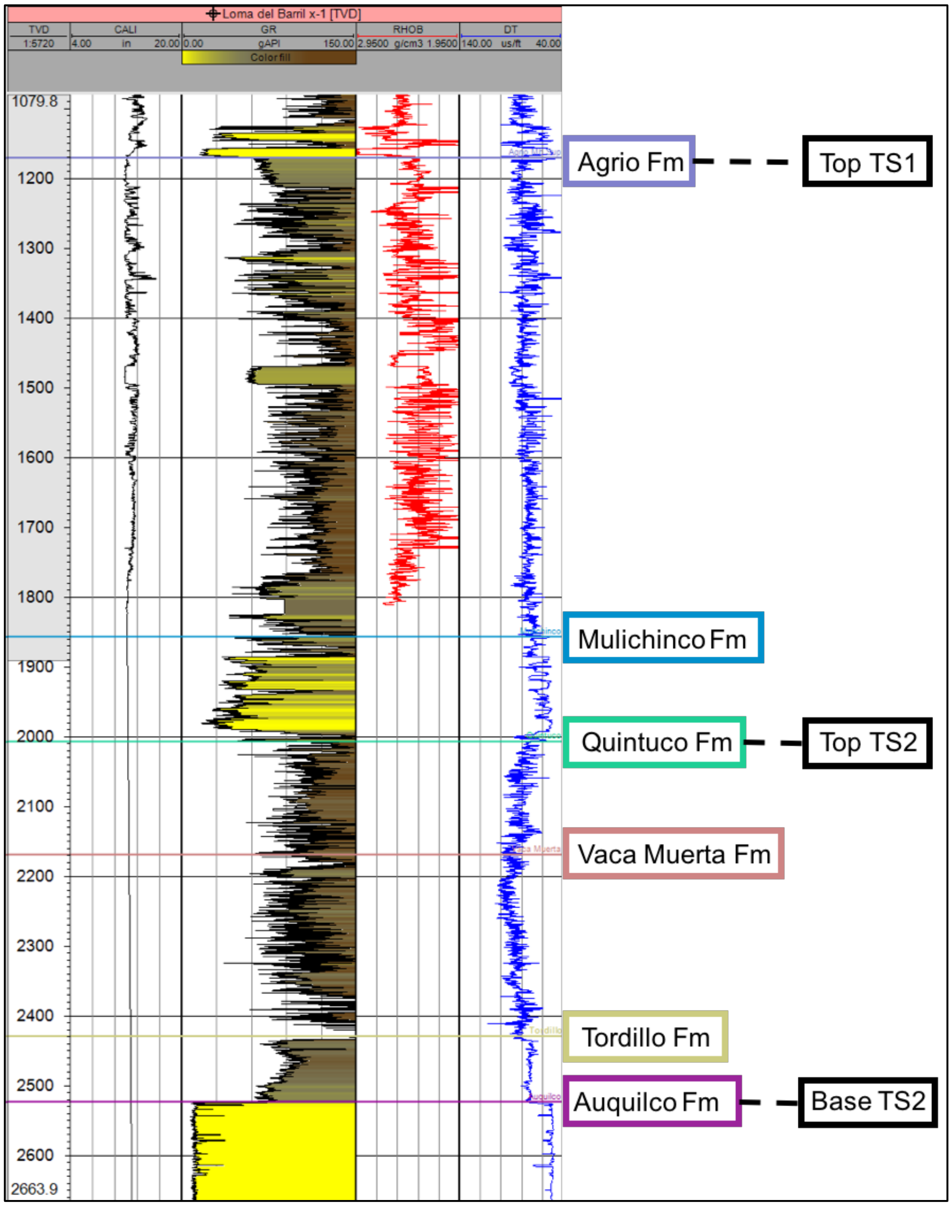


Figure 15. Loma de Barril x-1 well with the key stratigraphic horizons and the tectono-stratigraphic tops interpreted. The logs shown are the caliper, GR, density and sonic logs (left to right). The yellow color in the GR log represents low values and the brown represents high GR values.

4.1.1.3 Mulichinco Fm Interval

Variation in lithology through cutting descriptions, as well as variations in log readings from the **Bajo Batra 1** well (figure 16) are observed. At the base, there is a sharp contact between the Quintuco Fm and the base Mulichinco Fm (at 2858 m). The lowest unit (Unit 1) comprises carbonates and fine grained calcite cemented sandstones. The next unit (Unit 2) contains carbonates from micrite to limestone with overall low GR signals. Unit 3 is composed of a mixture of sands, carbonates, and shale, however it is separated into two. Unit 3A contains more shale and carbonates and has repetitive fining upwards trend. Unit 3B contains more calcite cemented sands mixed with less carbonates and shales. Overall, within Units 3A and 3B, the lithology coarsens upwards with rounded to sub-rounded sand grains at the base and sub-angular grains together with bivalves at the top. Unit 4, representing the uppermost section of the Mulichinco Fm comprises a coarsens upwards section, containing carbonates rich deposits at the base and a mixture of carbonate and calcite cemented sands towards the top. Top Mulichinco Fm is identified at 2592m.

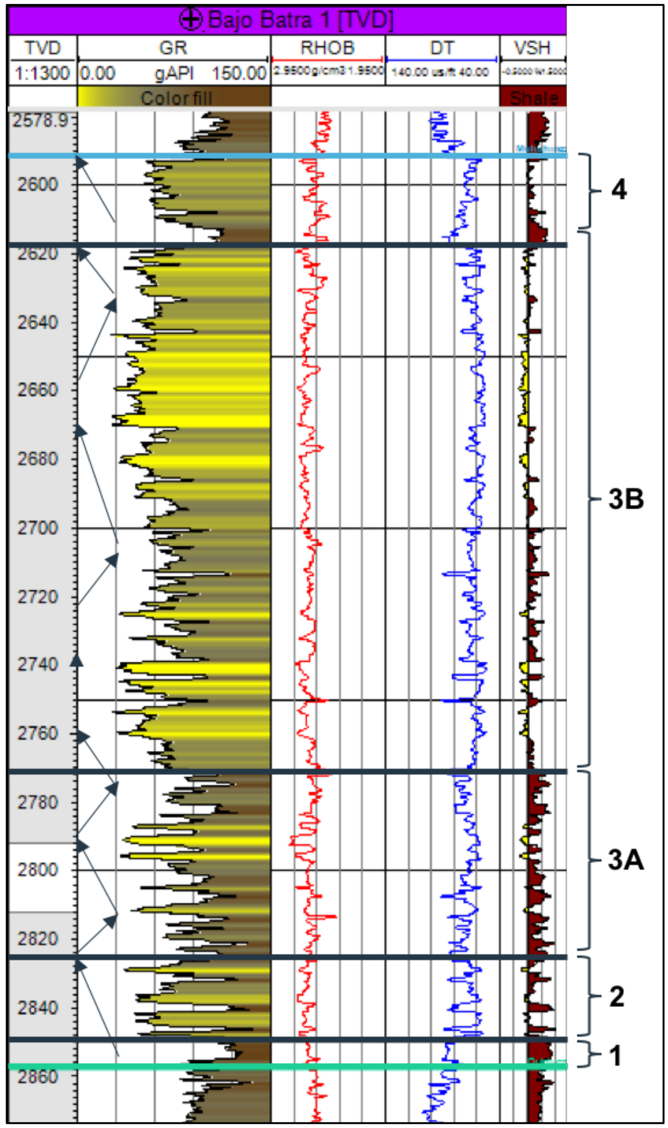


Figure 2. Bajo Bartra 1 well. Base (green) and top (blue) Mulichinco Fm are interpreted along with units within the formation. GR, density, sonic, and Vsh logs are provided in the figure (from left to right). The arrows on the left indicate coarsening upwards and fining upwards trends observed.

In the **Loma del Barril x-1** well (figure 17), four units are also observed. The base of the Mulichinco Fm is interpreted at 2008m. Unit 1 consists mainly of sand-rich packages with a clay matrix interbedded with shales and carbonates, both having high GR values. Unit 2 is composed mainly of carbonates of low GR readings with some minor sand content. Unit 3A contains more sand content than the underlying unit, and is composed of a mixture of carbonates and calcite cemented sands that fines upwards. Unit 3B is similar to the underlying interval but has more sand content and less carbonates. At the top of the Mulichinco Fm is Unit 4, comprised of a mixture of carbonate and calcite cemented sands that are sub rounded to rounded, medium to fine grained. The top of the Mulichinco Fm is identified at 1857m.

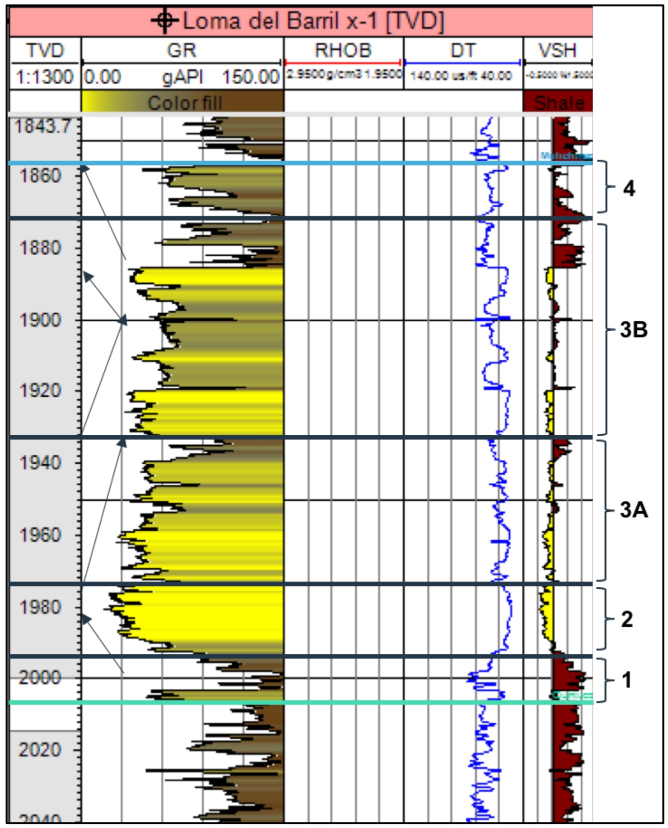


Figure 3. Loma del Barril x-1 well. Base (green) and top (blue) Mulichinco Fm are interpreted along with units within the formation. GR, density, sonic, and Vsh logs are provided in the figure (from left to right). The arrows on the left indicate coarsening upwards and fining upwards trends observed.

The **Bajo del Toro 5** well in figure 18 shows the well logs of the Mulichinco Fm. Four units are observed in this well. The Mulichinco Fm is identified at 2509m. The first unit (Unit 1) is composed of a coarsening upwards silty sandstone and sandstone with clay matrices. The silty sand being very fine to fine grained and the clay matrices sandstone is fine to medium grained. Both are made of sub-angular grains and are regular to well sorted. Unit 2 coarsens upwards and is composed mainly of carbonates with low GR readings and some calcite cemented sand content. Unit 3A is composed of carbonates, calcite cemented sandstone, and shale. The unit has more sand than carbonates. Unit 3B has a similar composition as Unit 3A, but the content of calcite cemented sandstone increases and the concentration of carbonates decreases. Unit 4 consists mainly of sandstone with clay matrices and some carbonates. The carbonates in this unit vary from wackstone at the bottom to limestone at the top. Top Mulichinco Fm is interpreted at 2357m.

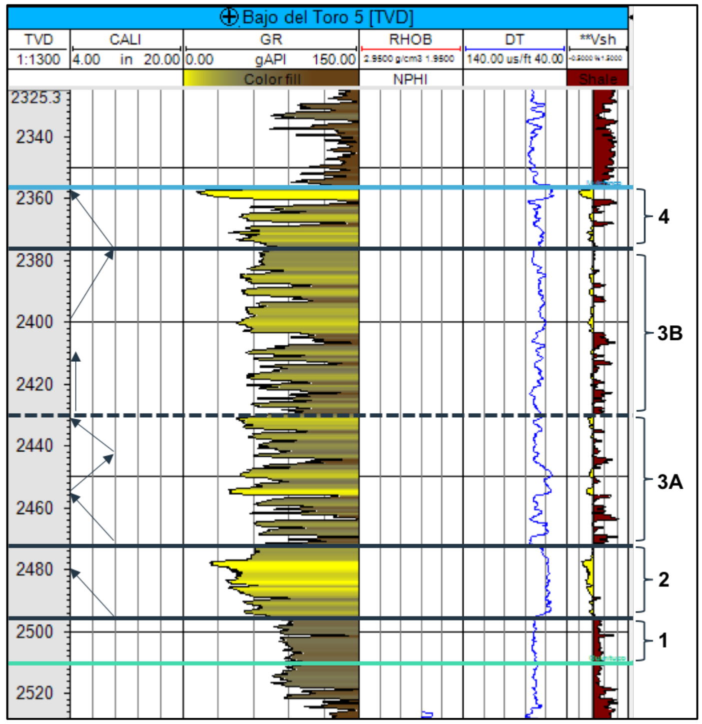


Figure 4. Bajo del Toro 5 well. Base (green) and top (blue) Mulichinco Fm are interpreted along with units within the formation. GR, sonic and Vsh logs are provided in the figure. The caliper and density logs do not exist for the Mulichinco Fm interval. The arrows on the left indicate coarsening upwards and fining upwards trends observed.

Figure 19 shows the well logs of the **Filomena x-1** well at the depth of the Mulichinco Fm. The base of the Mulichinco Fm is identified at 2512m. Four units are recognized within the formation. The first unit (Unit 1) is composed of silty sandstone at the base coarsening to sandstone with clay matrices at the top, both lithologies with high GR values. The silty sandstone is fine to medium grained while the sandstone is medium to coarse grained. Both have sub-rounded to sub-angular grains and are regular to poorly sorted. Unit 2 is composed of calcite cemented sandstone and carbonates with interbedded ash layers. The ash layers have calcite content within. Unit 3A is a mixture of calcite cemented sandstones with interbedded shales. The sandstones are regularly sorted and have sub-rounded grains. This interval coarsens upwards, eventually consisting of calcite cemented sand with clay matrices and no shale layers. Unit 3B is similar to Unit 3A, containing calcite cemented sandstone with interbedded shales that coarsens upwards to mainly calcite cemented sandstone with clay matrices and no shale layers at the top. The grains progress from sub-rounded to sub-angular from base to top. Unit 4 consists of shale and sandstone with clay matrices layers at the base, with carbonate content increasing upwards in the interval. The sandstone grains are regular to well sorted with fine, sub-angular grains. The top Mulichinco Fm is interpreted at 2373m.

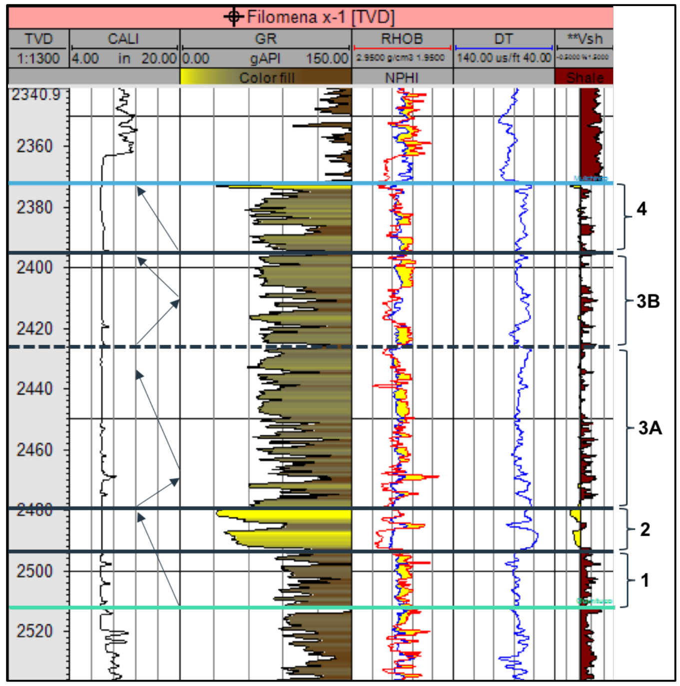


Figure 5. Filomena x-1 well. Base (green) and top (blue) Mulichinco Fm are interpreted along with units within the formation. Caliper, GR, density, sonic and Vsh logs are provided in the figure. The arrows on the left indicate coarsening upwards and fining upwards trends observed.

The **Loma Partida Este 2** well in figure 20 presents the GR and sonic logs for the Mulichinco Fm. The base of the formation is identified at 1908m. Two units are recognized in figure 20. The first unit (Unit 3) is composed of fine, sub angular sandstones with clay matrix and low amounts of carbonates. Unit 4 is composed of sands intercalated with pelites and having wave bedding structures. There are more shale layers at the base with increasing sand content towards the top. The top of the Mulichinco Fm is interpreted at 1859m.

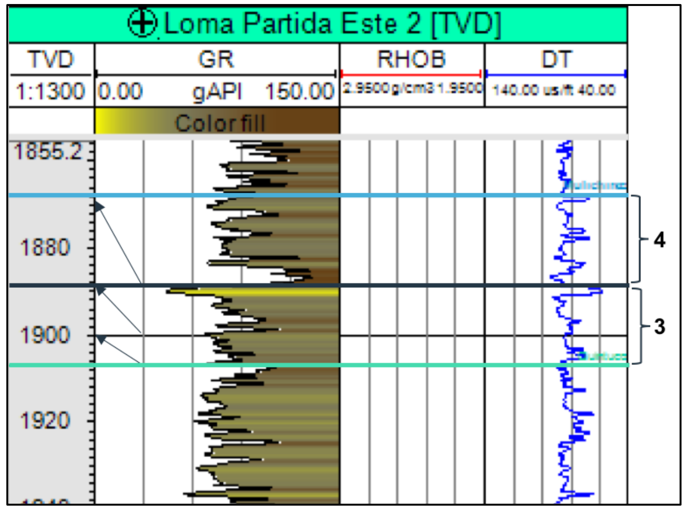


Figure 6. Loma Partida Este 2 well. Base (green) and top (blue) Mulichinco Fm are interpreted along with units within the formation. GR and sonic logs are provided in the figure. The caliper, density and Vsh logs do not exist for the Mulichinco Fm interval. The arrows on the left indicate coarsening upwards and fining upwards trends observed.

4.1.2 Seismic Response

4.1.2.1 TS1

The sequence boundary between TS1 and TS2 at the top of the Quintuco Fm, observed in the seismic as a trough (figure 14). This is due to the decrease in acoustic impedance across the sequence boundary. This seismic response is consistently recognized across the area. The base Quintuco Fm and top Vaca Muerta Fm is recognized as a red reflector (figure 14) that is easily tracked throughout the region. The base Vaca Muerta Fm, top Tordillo Fm contact is observed as a trough (figure 14) that is consistent throughout the area. The base of TS1 sequence boundary is a strong trough (figure 14) that indicates the contact between the Tordillo and the underlying Auquilco Fm.

4.1.2.2 TS2

At the sequenced boundary of the top TS2 and the overlying Huitrin Fm, there is a high density and velocity contrast. The top TS2, Agrio Fm, is recognized as a trough (figure 14). The seismic reflector of the top of the sequence is continuous throughout most of the area, with some areas where the amplitude slightly dims, and other areas where it is not present. Within TS2, the top Mulichinco Fm reflector is observed as a trough (figure 14) with a generally high amplitude throughout most of the region. In certain areas, the reflector is not present.

4.2 Thickness Maps

4.2.1 TS1

TS1 is between roughly 200m to 1500m thick (figure 21). The trend of the sequence is thickening towards the Southwest and thinning towards the Northeast. The thickest interval is located to the Southwest, while the thinnest interval is located along the Northeast-Eastern extent of the region. The circled areas are inconsistent due to poor seismic quality, therefore horizons were not interpreted.

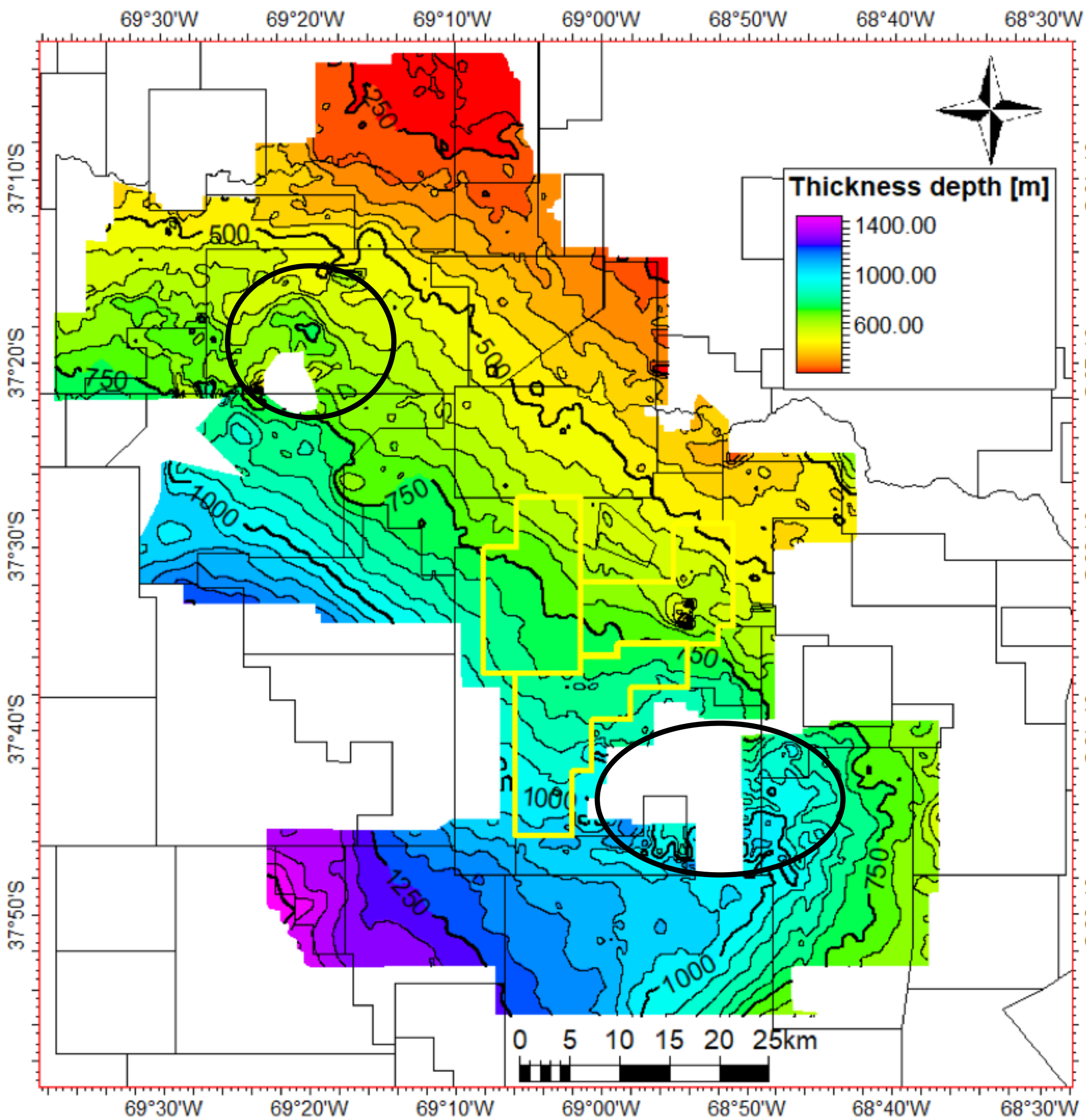


Figure 21. Thickness map of TS1. This includes the Tordillo, Vaca Muerta, and Quintuco Fms.

4.2.2 TS2

The thickness of TS2 ranges roughly between 400 and 1200 m (figure 22). The tectono-sequence is thickest in the Southwest, while the thinnest is towards the North-Northeast. The circled areas in figure 22 are inaccurate due to lack of seismic interpretation within those areas.

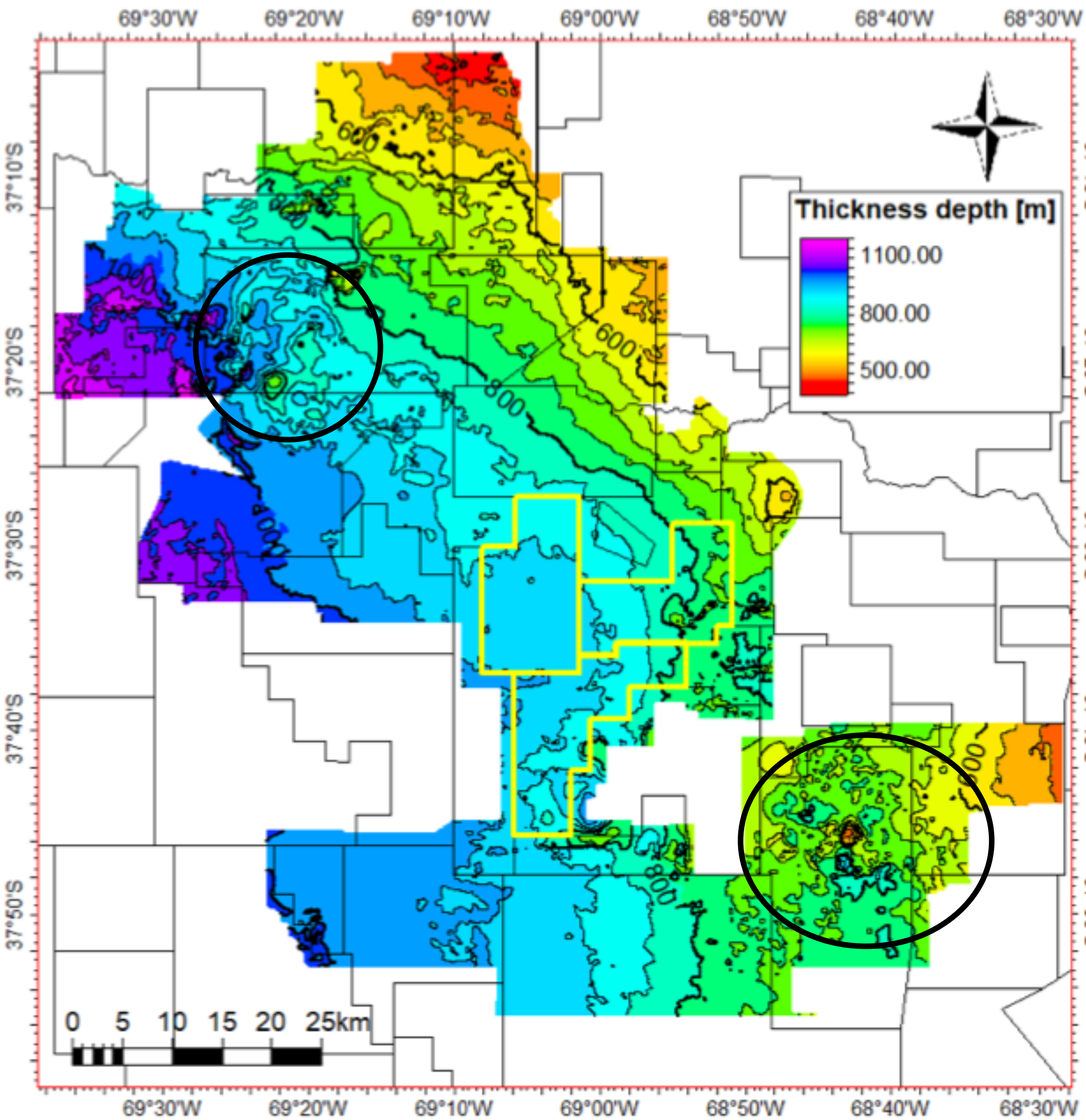


Figure 22. Thickness map of the TS2. This contains the Mulichinco and Agrio Fms.

4.2.3 Mulichinco Fm

TS2 contains the primary target, the Mulichinco Fm. Figure 23 shows the depth thickness map of the formation. The trend varies from the overall TS2, where the thinnest interval is located along the East of the region, thinning out fully in the Southeast, and is thickest towards the Northwest. The circle in the Northwest is the area where seismic quality is too poor to track the

Mulichinco Fm reflectors, therefore producing inaccurate thicknesses. The circled area in the Southeast represents the area that the top and base Mulichinco Fm is difficult to track due to the thinning of the interval.

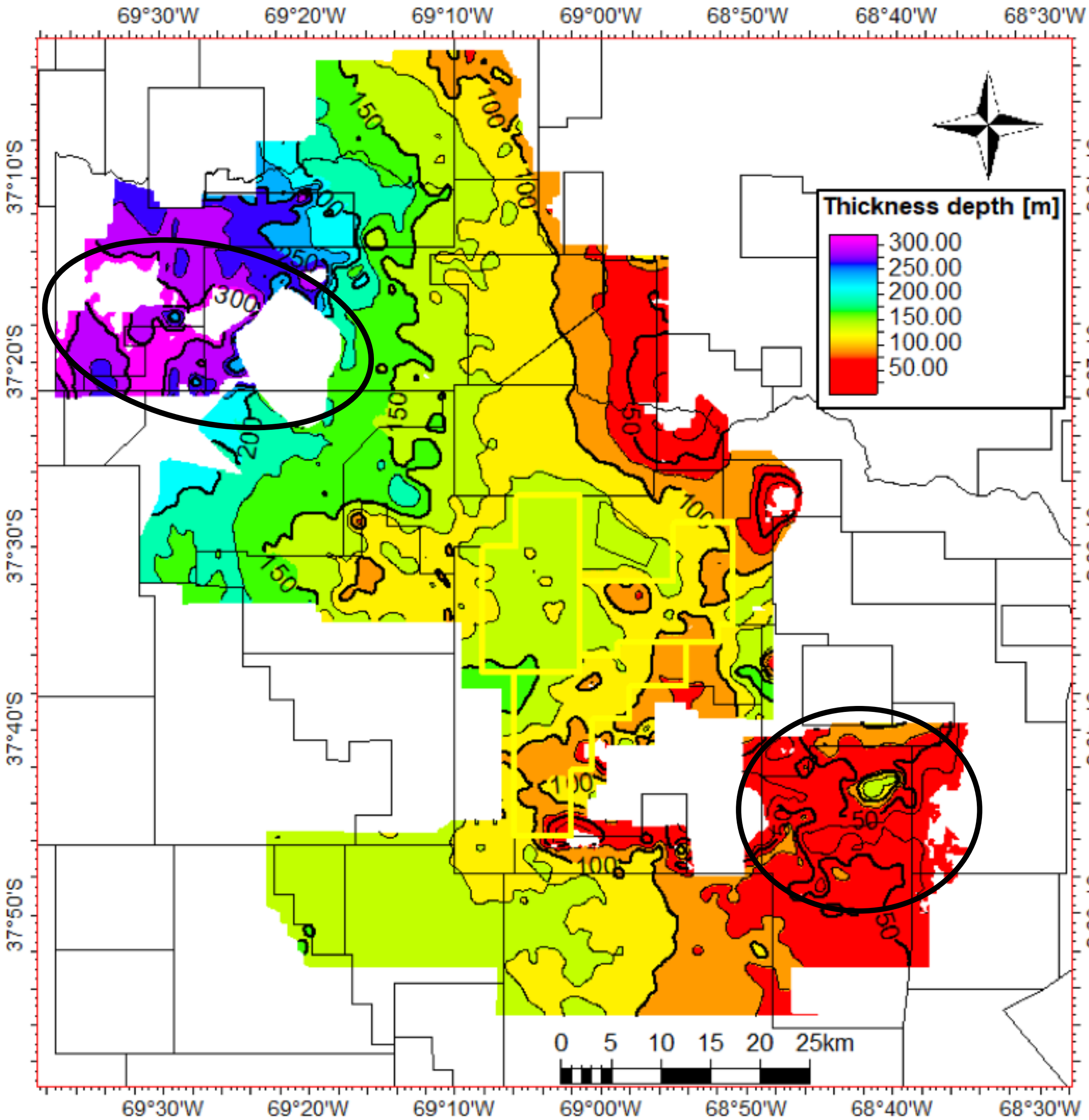


Figure 23. Thickness map of the Mulichinco Fm.

4.3 Well-Seismic Response

4.3.1 TS1

Overall, the stratigraphic horizons dip towards the West-Southwest. The key horizons interpreted are consistent throughout the region in the seismic. However, internal reflectors within formations tend to terminate from West to East/Southwest to Northeast, towards the shallower parts of the basin. Internal structures are interpreted within the Vaca Muerta Fm. The formation has internal reflector terminations both up dip and down dip, especially in the far South-Southeast of the region, forming clinoforms trending East to West. The Quintuco and Auquilco Fm have much less reflectors in-between and internal structures are not interpreted. In the well logs, the Vaca Muerta is interpreted in having more TOC% at the base than at the top. This is recognized with the high GR log values, especially at the GR log spike at the base of the formation, while the resistivity log also increases.

4.3.2 TS2

The stratigraphy of the tectono-sequence dips towards the West-Southwest. Internal reflectors within the formations in the seismic are interpreted, however, the Mulichinco Fm is much thinner than the overlying Agrio Fm so internal structures are difficult to recognize. The internal reflectors of both the Agrio Fm and Mulichinco Fm tend to terminate towards the East. In the Southeast, the Mulichinco Fm was not deposited. This is interpreted from the top and base Mulichinco Fm reflectors merging together until it is no longer present. The same interpretation is made through the wells, where the Mulichinco Fm thins towards the East until it is no longer present in the Cerro Avispa Este 1 well.

4.3.3 Thickness Interpretation

4.3.3.1 TS1

Since the tectono-sequence is deposited on a time span of more than 10 m.y., the basin edge and depo-center varied slightly between each formation deposition. As interpreted from figure 21, the thinnest interval of the TS1, towards the North-Northeast, is where the basin edge is located at the time of deposition due to the low accommodation space. The thickest interval is located towards the South-Southwest, towards the depo-center of the basin where there was greater accommodation space at the time of deposition.

4.3.3.2 TS2

The depo-center and basin edge varies within the TS1. However, the overall trend interpreted from figure 22 is the depo-center being located towards the South-Southwest, and the basin edge located towards the East-Northeast of the region. Towards the basin edge, having the lower accommodation space, the thinnest interval of the TS2 is present. While the depo-center, towards the Southwest, has a greater accommodation space, where the TS2 is the thickest.

4.3.3.3 Mulichinco Fm

The deposition of the Mulichinco Fm is different from the other key formations. The thinnest interval observed in figure 23 is to the Southeast and along the Eastern edge of the region, which is in the direction of the basin edge during the time of Valanginian. The thickest interval is towards the Northwest, towards the depo-center of the basin where there is more accommodation space. The change in location of basin edge and depo-center of the basin is due to the tectonic activity during the Valanginian.

4.3.4 Sequence Stratigraphy Mulichinco Fm

The first unit (Unit 1) of the Mulichinco Fm, recognized in figure 24, overlays the Sequence Boundary (SB) Valanginian Unconformity. The unit is interpreted as a Lowstand System Tract (LST) consisting of deep marine mixed carbonate/clastic in the Northwest, shallow marine mixed carbonate/clastic centrally in the basin, and fluvial/terrestrial facies in the Southeast. The basin edge is interpreted to the far Southeast of the study area during the time of deposition, therefore there was no accommodation space available for Unit 1 to be deposited. The end of the regression is marked by the Maximum Regressive Surface (MRS) located at the top of Unit 1.

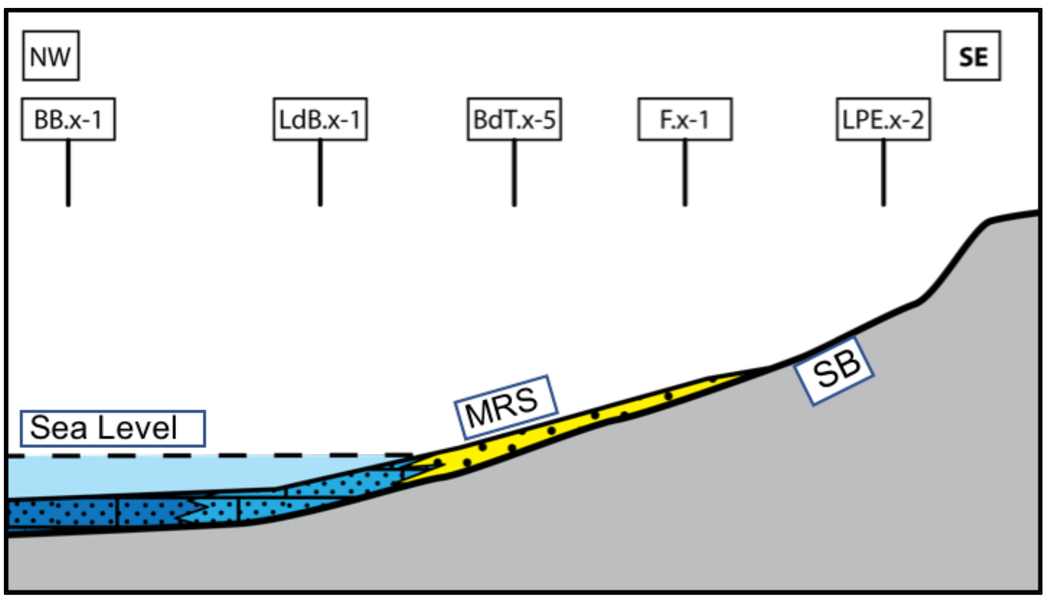


Figure 24. Cross section of the deposition of the Mulichinco Fm Unit 1 with the Valanginian Unconformity beneath. The vertical scale is exaggerated. Key for this figure is in figure 27.

Subsidence dominates the basin again, causing a relative sea level rise. An overall transgression within the area leads to the deposition of the Transgressive System Tract of the deep marine facies of Unit 2, progressing from deep marine carbonate facies towards the Northeast to deep marine mixed carbonate/clastic towards the Southwest, shown in figure 25. Accommodation space is still not present farther towards the Southeast during the deposition of Unit 2, therefore the unit is not present. The top of the second unit is interpreted as a Maximum Transgressive Surface (MTS).

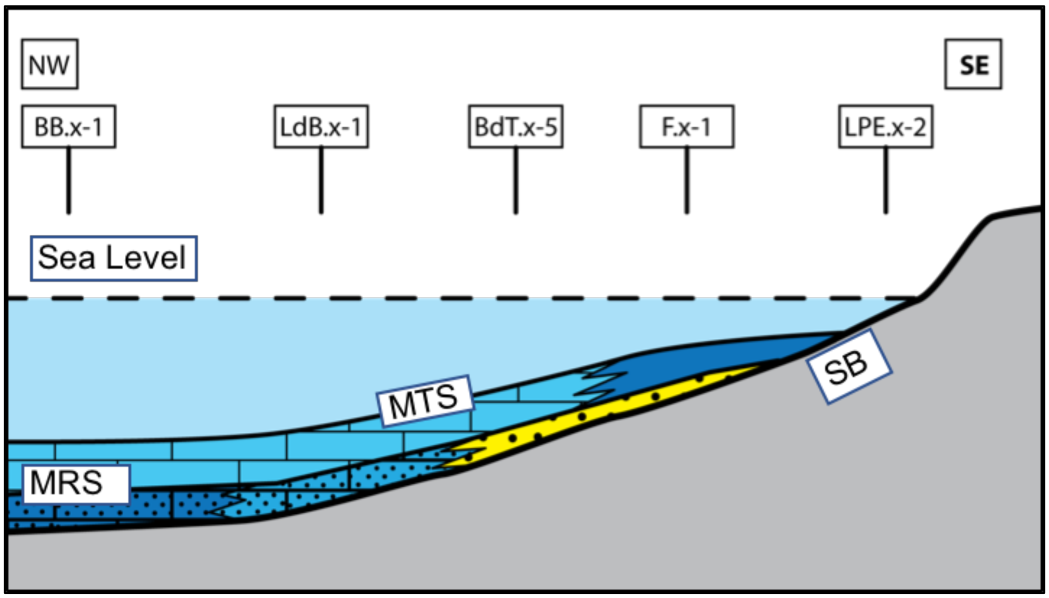


Figure 25. Cross section of the deposition of the Mulichinco Fm Units 1 and 2. The vertical scale is exaggerated. Key for figure is in figure 27.

Tectonic quiescence following the second unit allows for the Unit 3 Highstand System Tract to deposit, as observed in all wells in figure 26. This unit is divided in two, a lower agradational interval and an upper progradational interval, i.e. the Falling System Tract. The lower interval being composed of coastal deltaic facies towards the Southeast, shallow marine deltaic facies towards the center of the study area, and delta front deep marine turbidite facies towards the Northwest. The delta front turbidites are not present in Unit 3B, but may be present farther towards the Northwest, outside of the area of study. At the top of Unit 3 represents a MRS, and a new sequence boundary completing the main Mulichinco depositional sequence.

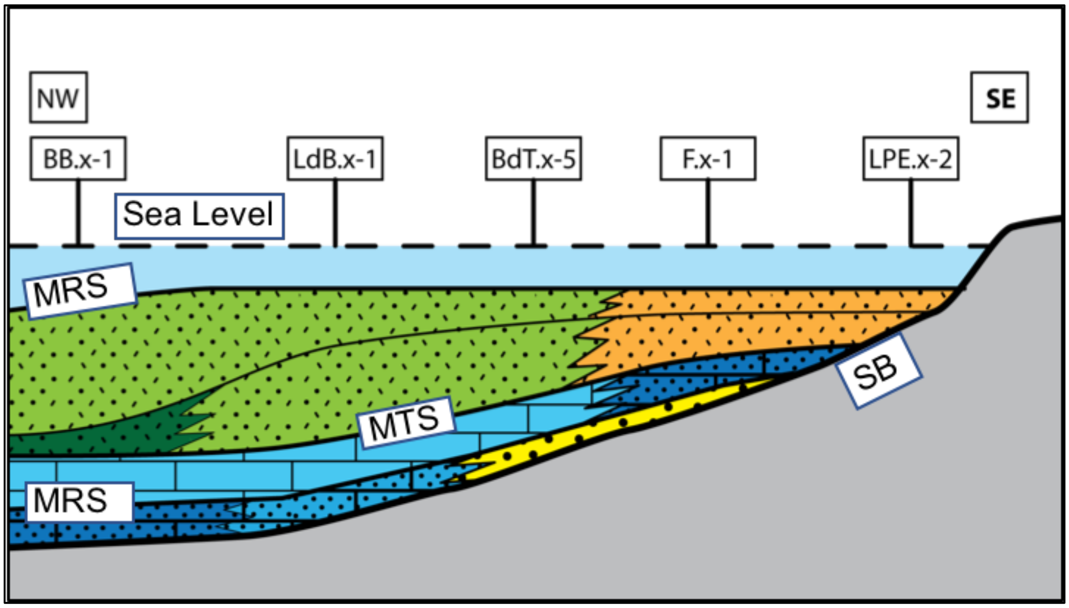


Figure 26. Cross section of the deposition of the Mulichinco Fm including Units 1, 2, 3A and 3B. The vertical scale is exaggerated. Key for figure is in figure 27.

Unit 4, shown in figure 27, represents a subsequent LST deposited at the end of the Valanginian. This unit consists of estuary deposits towards the Southeast, and shallow mixed carbonate/clastic marine facies towards the center of the study area, and deep mixed marine carbonate/clastic marine facies towards the Northwest. The estuary facies are deposited from the Southeast to the Northwest, having the bay head with greater terrestrial content towards the Southeast, and the estuary inlet with more carbonate content towards the center of the area of study. Tectonic subsidence increases within the Neuquén Basin, triggering the deposition of the subsequent TST during a large flooding event, the marine shales of the Agrio Fm.

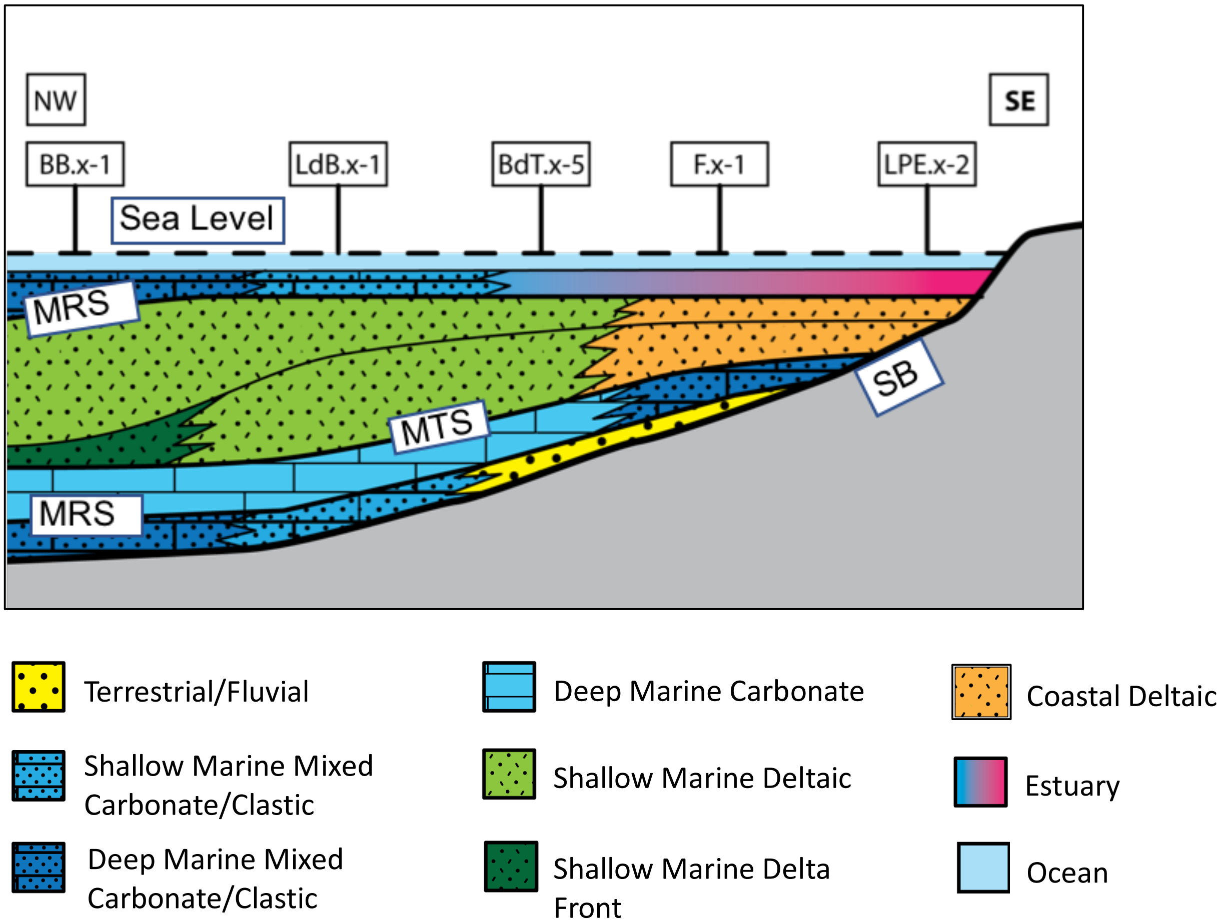


Figure 27. Cross section of the deposition of the Mulichinco Fm including all units. The vertical scale is exaggerated. Key is for this figure and figures 24, 25 and 26.

The vertical facies interpretations are extended to 2D horizontal maps (Figures 28-31). The extent of the facies was interpreted with the vertical facies interpretations together with the thickness map trends.

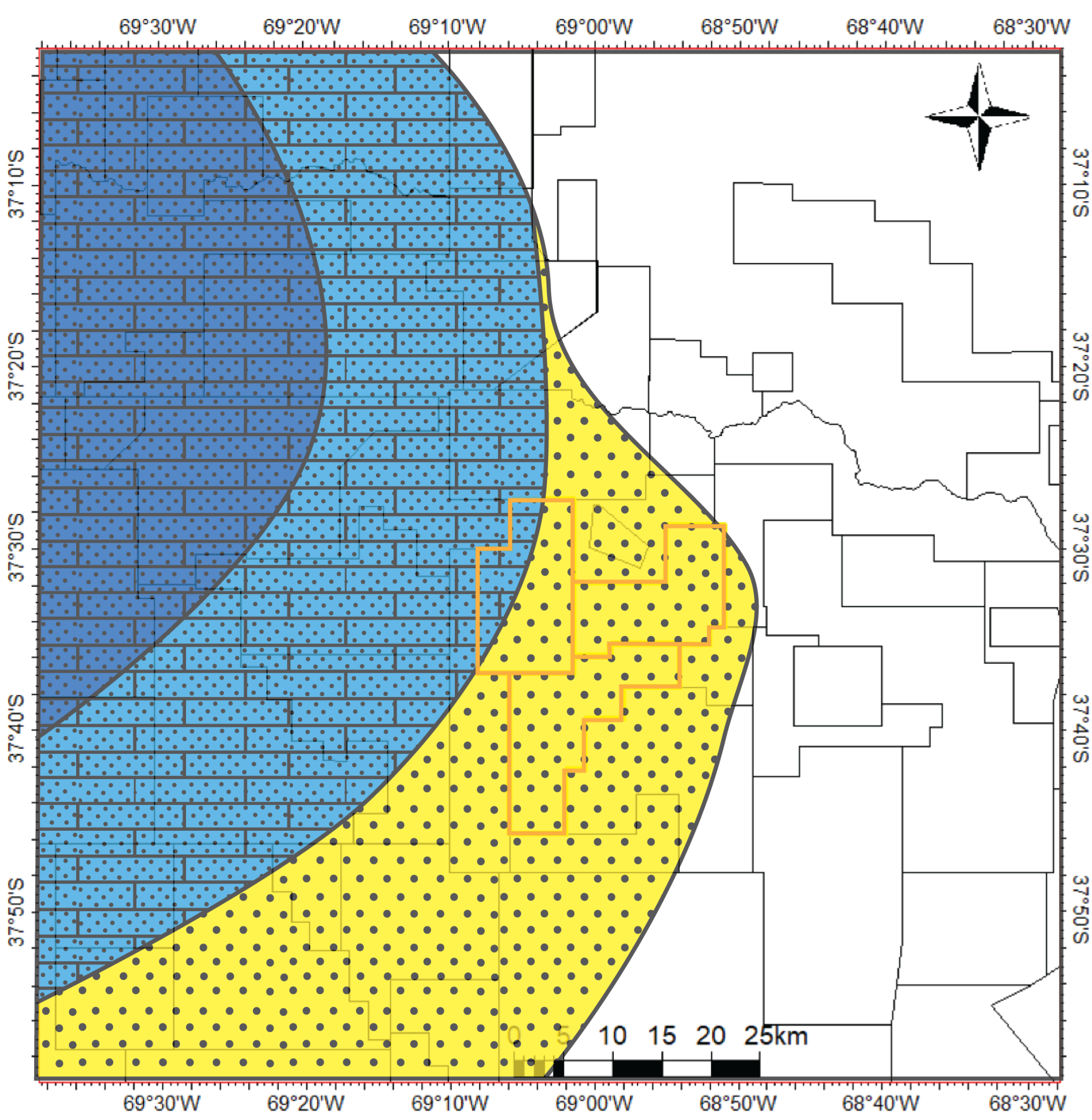


Figure 28. Facies distribution map of Unit 1. The deep mixed marine carbonate/clastic facies are deposited where the Mulichinco Fm thickness is around 200m or thicker. The shallow mixed marine carbonate/clastic facies are deposited where the Mulichinco Fm thickness is around 200m to 150m thick. The fluvial facies are deposited where the thickness is around 150 to 100m thick. No deposition of Unit 1 is observed where the Mulichinco Fm is less than 100m thick. Same key used in figure 27 applies for this figure.

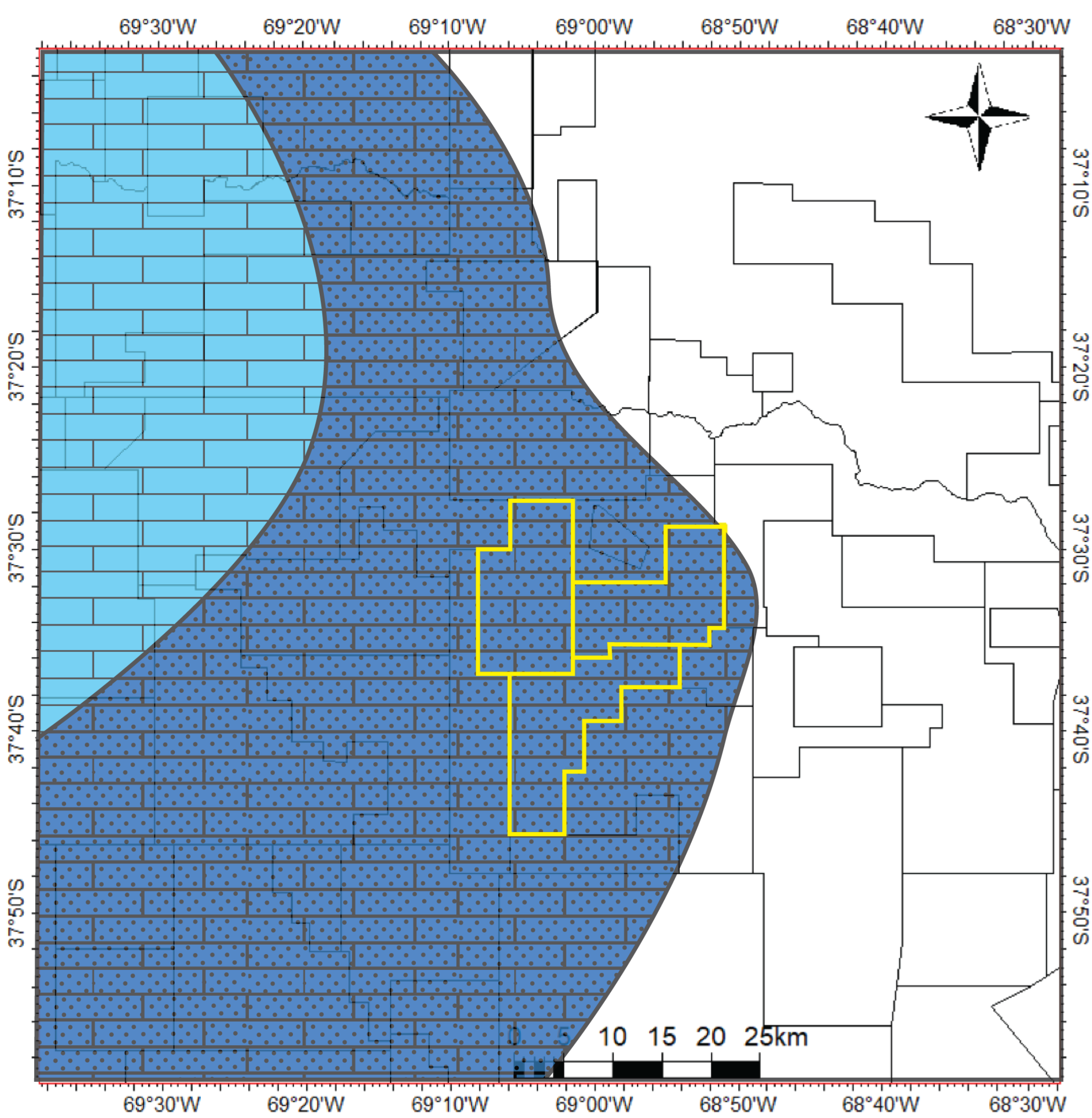


Figure 29. Facies distribution map of Unit 2. The deep marine carbonate facies are deposited where the Mulichinco Fm thickness is around 200m or thicker. The deep marine carbonate facies are deposited where the Mulichinco Fm thickness is around 200m to 100m thick. No deposition of Unit 2 is observed where the Mulichinco Fm is less than 100m thick. Same key used in figure 27 applies for this figure.

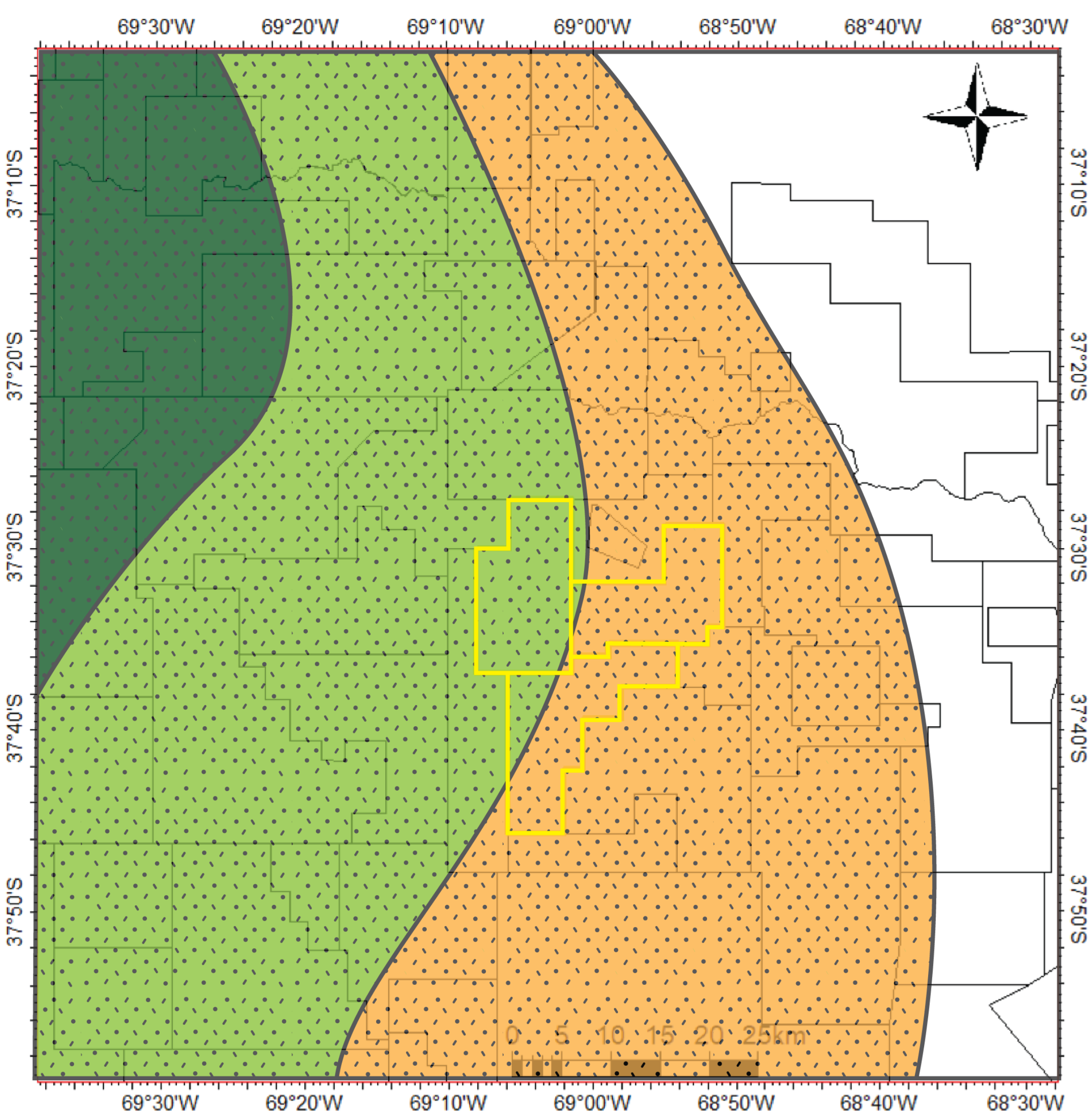


Figure 30. Facies distribution map of Unit 3. The delta front deep marine turbidite facies are deposited where the Mulichinco Fm thickness is around 200m or thicker. The shallow marine deltaic facies are deposited where the Mulichinco Fm thickness is around 200m to 125m thick. The coastal deltaic facies are deposited where the thickness is around 125m thick or less. Same key used in figure 27 applies for this figure.

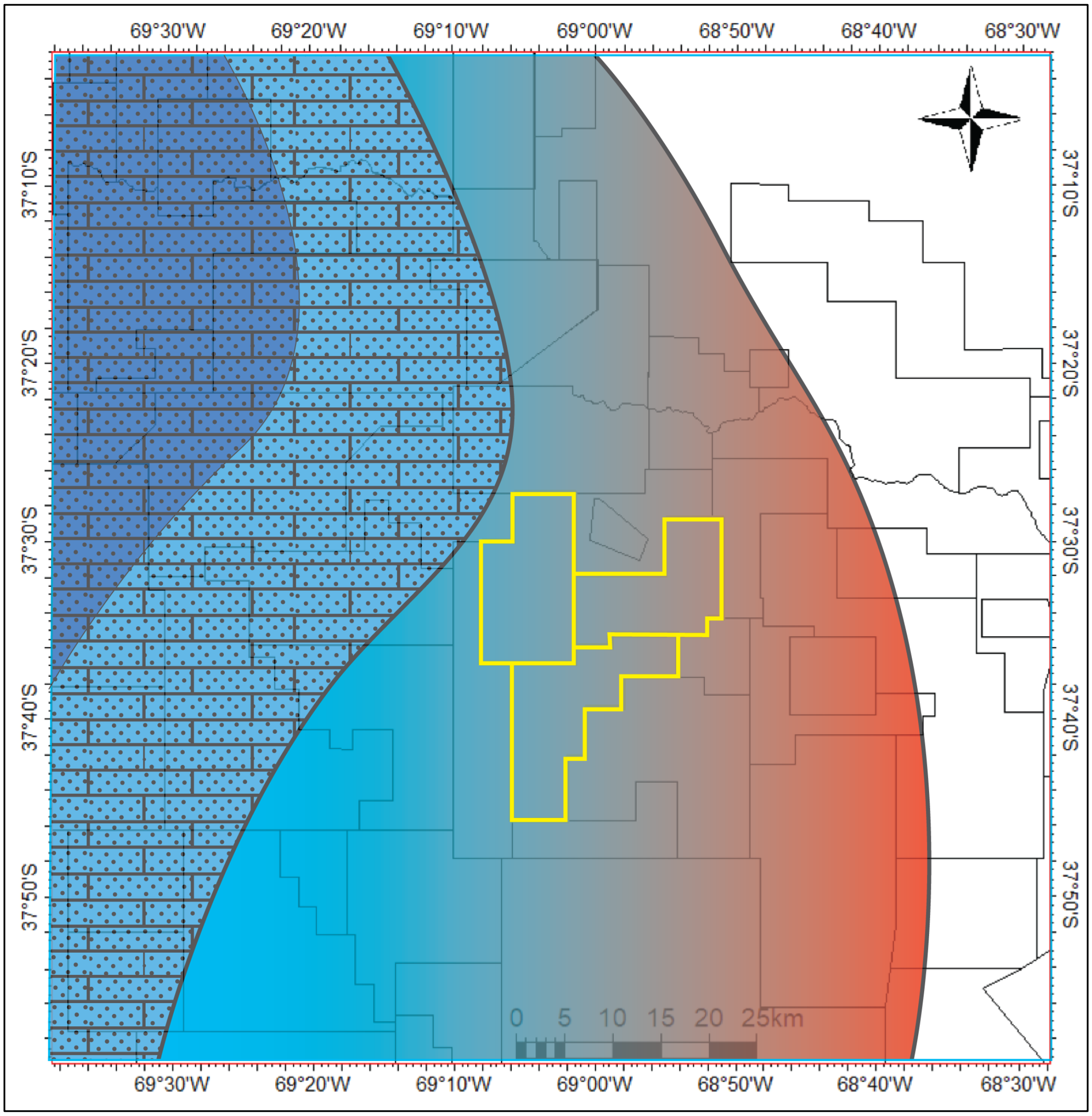


Figure 31. Facies distribution map of Unit 4. The deep mixed marine carbonate/clastic marine facies are deposited where the Mulichinco Fm thickness is around 150m or thicker. The shallow mixed carbonate/clastic marine facies are deposited where the Mulichinco Fm thickness is around 150m to 100m thick. The estuary facies are deposited where the thickness is around 100m thick or less. Same key used in figure 27 applies for this figure.

5 Petroleum System Elements

The trapping mechanism, as well as the quality of the source rock, reservoir, and seal are observed to better understand the petroleum system. In addition to the facies distribution interpreted for the Mulichinco Fm, an in-depth analysis of the reservoir quality is necessary. Further evaluation of key formations within the tectono-sequences is also necessary to understand the properties of the petroleum system within the region.

5.1 Observations

5.1.1 Mulichinco Fm Structure Map

The overall trend observed in the Mulichinco Fm is that the formation shallows towards the North-Northeast and deepens towards the West-Southwest. Faults interpreted in the seismic are not visible on the structure map. However, several structures are interpreted. A dome style structure is observed in the central Northwest area in the Mulichinco Fm, indicated by the first circle in figure 32. An anticline found towards the Northeast that trends Southeast-Northwest is also present, with a syncline beside it to its East (circle 2 in figure 32). The third structure is not as evident in figure 32 as the other structures. However, a smaller structure is observed in the circled area.

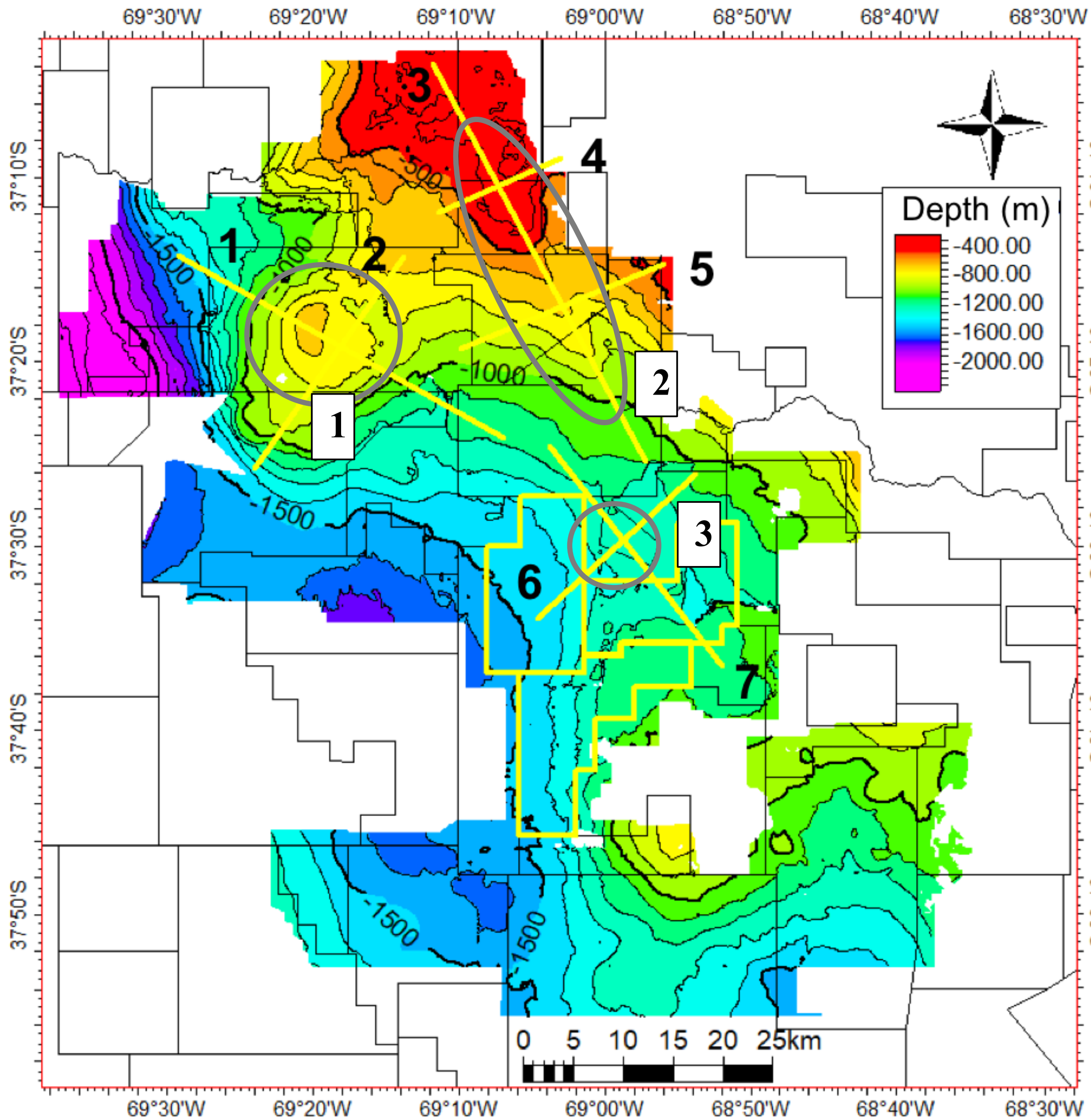


Figure 32. Depth map of top Mulichinco Fm. Grey circles numbered 1-3 indicate structural highs. Yellow lines indicate the location of cross sections 1-3.

5.1.2 Petrophysics

As observed in the Vsh logs of the Mulichinco Fm in figure 33, the intervals with Vsh values under 0.4 are located more towards the base, while values over 0.4 are present in the middle and upper sections of the well. Vsh values under 0.4 at the base of the Mulichinco Fm are associated to carbonates with low GR values. Values under 0.4 in the middle and upper section of the well are associated with sand intervals within the Mulichinco Fm. The porosity logs have lower values at the base of the Mulichinco Fm compared to the middle and top sections of the formation. The low porosity values are located at the interval at the base of the well, where the low Vsh values are also present.

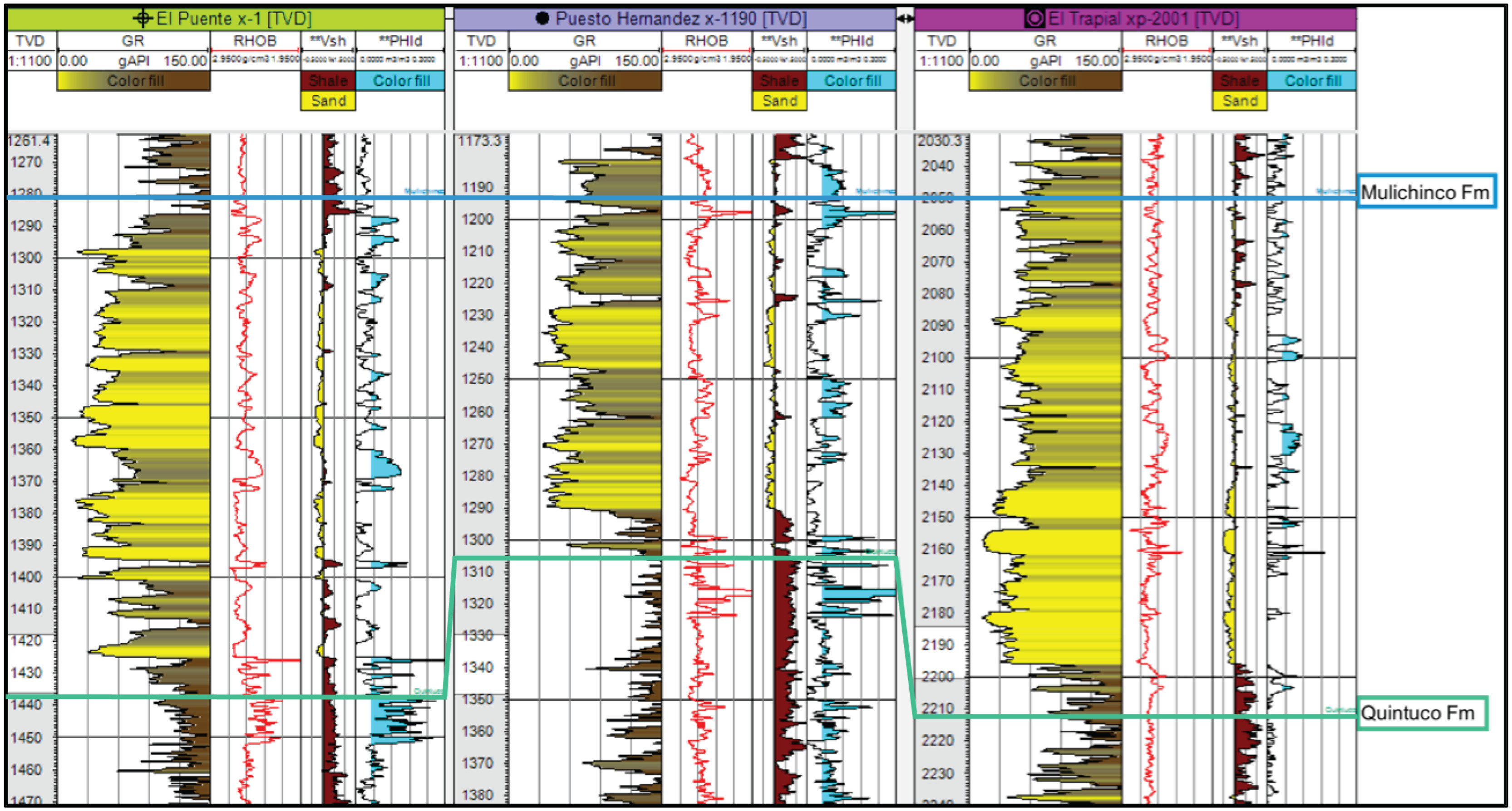


Figure 33. Three wells with their logs, including the calculated Vsh and porosity logs. Wells flattened to the top Mulichinco Fm. The top Mulichinco Fm and top Quintuco Fms are interpreted. The Vsh log is colored yellow where Vsh values are under 0.4 and brown where values are over 0.4. The porosity logs are colored blue where values are over 0.1 and white where values are under 0.1.

5.1.3 Attributes

Three attribute maps created for the Mulichinco Fm interval, maximum amplitude, average interval, and RMS attribute maps, have similar trends and anomalies in similar areas. Although the maximum amplitude and average interval attribute maps vary slightly in areas with high values, the RMS attribute maps present a combination of the two. Therefore, only the RMS attribute map is presented in figure 34.

The RMS attribute map highlights areas where the root mean squared amplitudes produced high values. The orange circle marks the location where the Mulichinco Fm thins out, producing irregular high values.

The main anomalies observed in the attribute map are those in the areas circled in yellow. The anomaly covering the largest area is highlighted in the Northern most circle, covering several licenses. The rest of the anomalies highlighted cover smaller areas but are observed as high RMS values. The anomalies that are not highlighted are interpreted as noise or inconsistent tracking of the Mulichinco Fm top and base, where the seismic is poor.

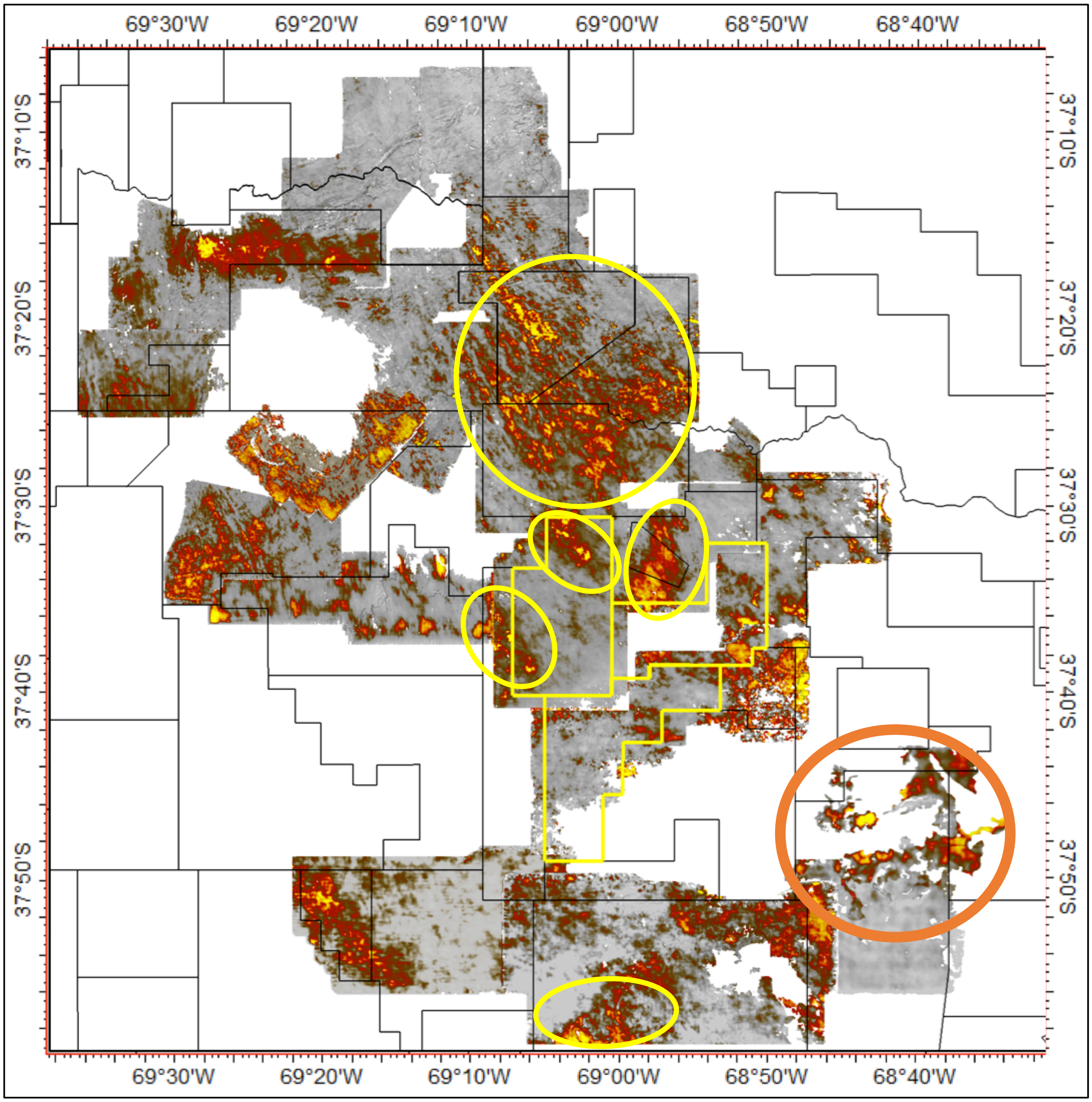


Figure 34. RMS attribute on Mulichinco Fm. The grey color on the map indicate low attribute values. While the areas in red have above average values, and the yellow colors indicate high attribute values.

Proven and producing oil fields having reservoirs in the Mulichinco Fm are overlain on top of the RMS attribute map to observe if there are any trends. Two areas are focused, illustrated in figures 35 and 36. Figure 35 illustrates the area covering the Aguada del Chivato and Aguada

Bocarey fields, and figure 36 covers the Northeast area that includes several fields, such as the Puesto Hernandez and Chihuido de la Sierra Negra fields.

Figure 35 has the Aguada del Chivato and Aguada Bocarey fields overlaying the RMS attribute map. It is observed that the Aguada del Chivato field has high RMS values, producing the yellow and red colors. However, the bright area does not follow the field outline. The Aguada Bocarey field is grey on the RMS map, meaning that the root mean squared values are low.

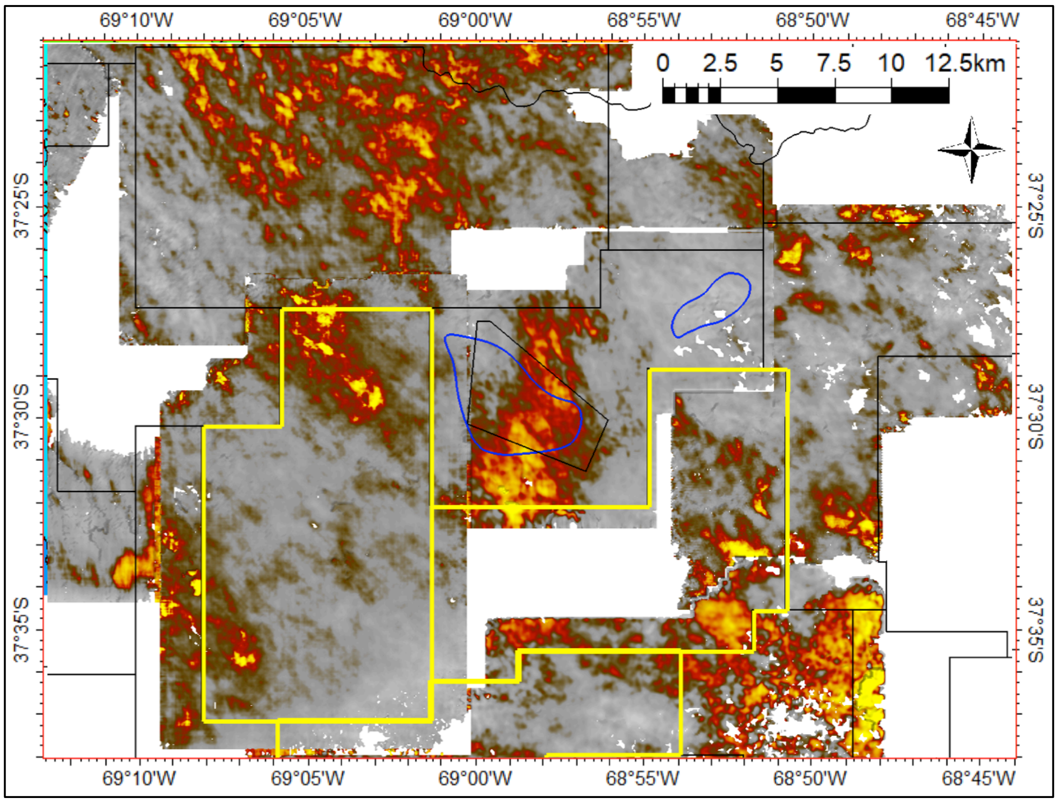


Figure 35. RMS attribute on the Mulichinco Fm. The blue polygon on the left is the Aguada del Chivato field, and the one to the right is the Aguada Bocarey field.

Focusing on the Eastern side of figure 36, a large area of the RMS attribute map is covered in anomalies. The large field within the Puesto Hernandez license is the Puesto Hernandez field, highlighted in the yellow box. Most of the field is observed as yellow or red, with some areas in grey. However, the yellow and red anomalies extend further towards the South and Southeast, outside of the field. There are also fields in the Northern most area of figure 36 that are mainly grey, or contain some red at most.

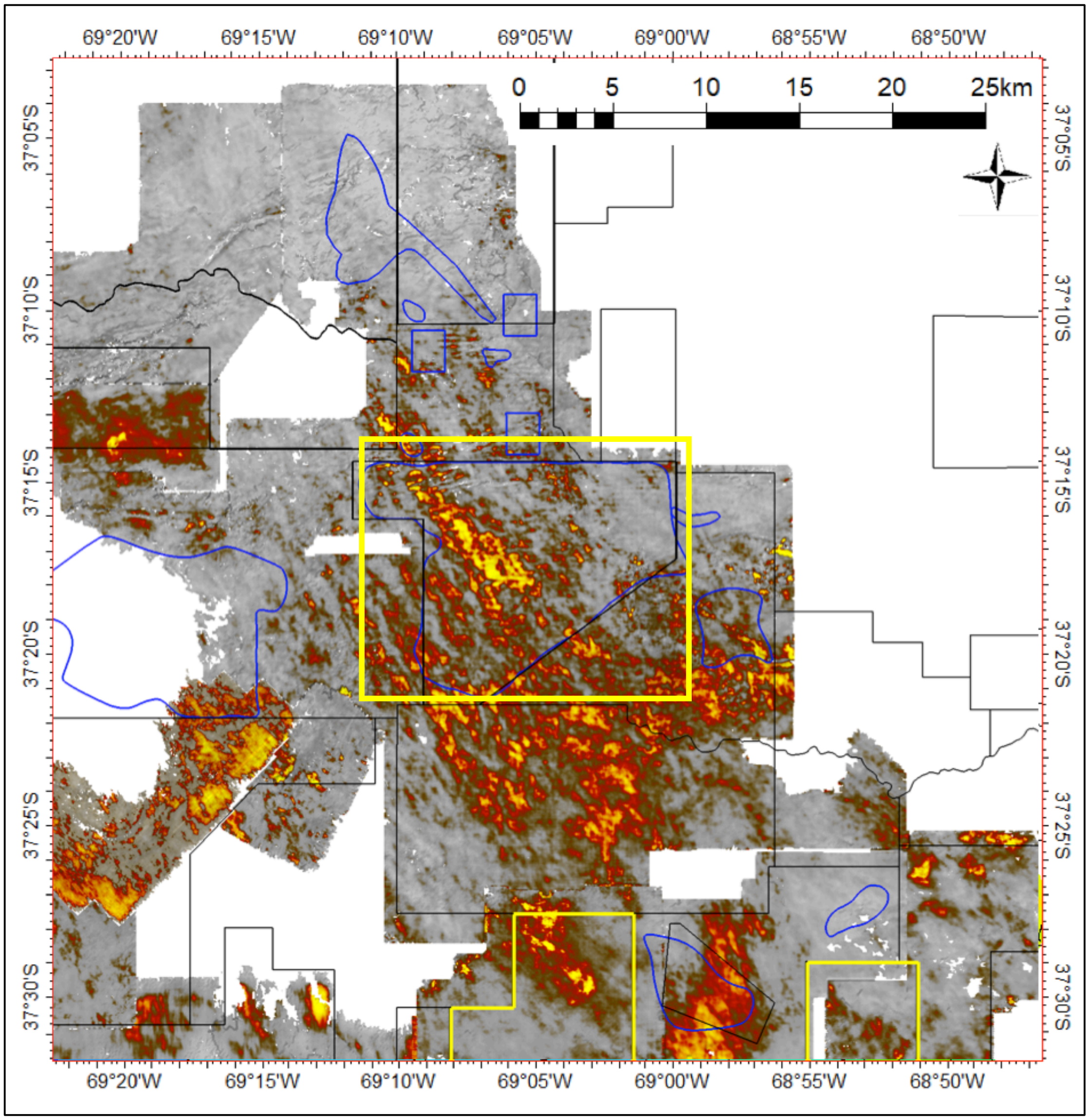


Figure 7. RMS attribute on the Mulichinco Fm. The blue polygons indicate the fields present in the Mulichinco Fm. The large field in the yellow square is the Puesto Hernandez field.

5.1.4 Thickness Source Rock

The thickness of the Vaca Muerta Fm is observed in figure 37, ranging from roughly 150 to 1000m. The formation thins from Southwest to Northeast. The thickest interval of the Vaca Muerta Fm is located towards in the South-Southwest, while the thinnest interval is located along the Northeastern edge of the study area. The areas circled in grey marks the zone that have poor seismic quality, affecting the seismic interpretation of the Vaca Muerta Fm reflectors, therefore resulting in inaccurate thickness values.

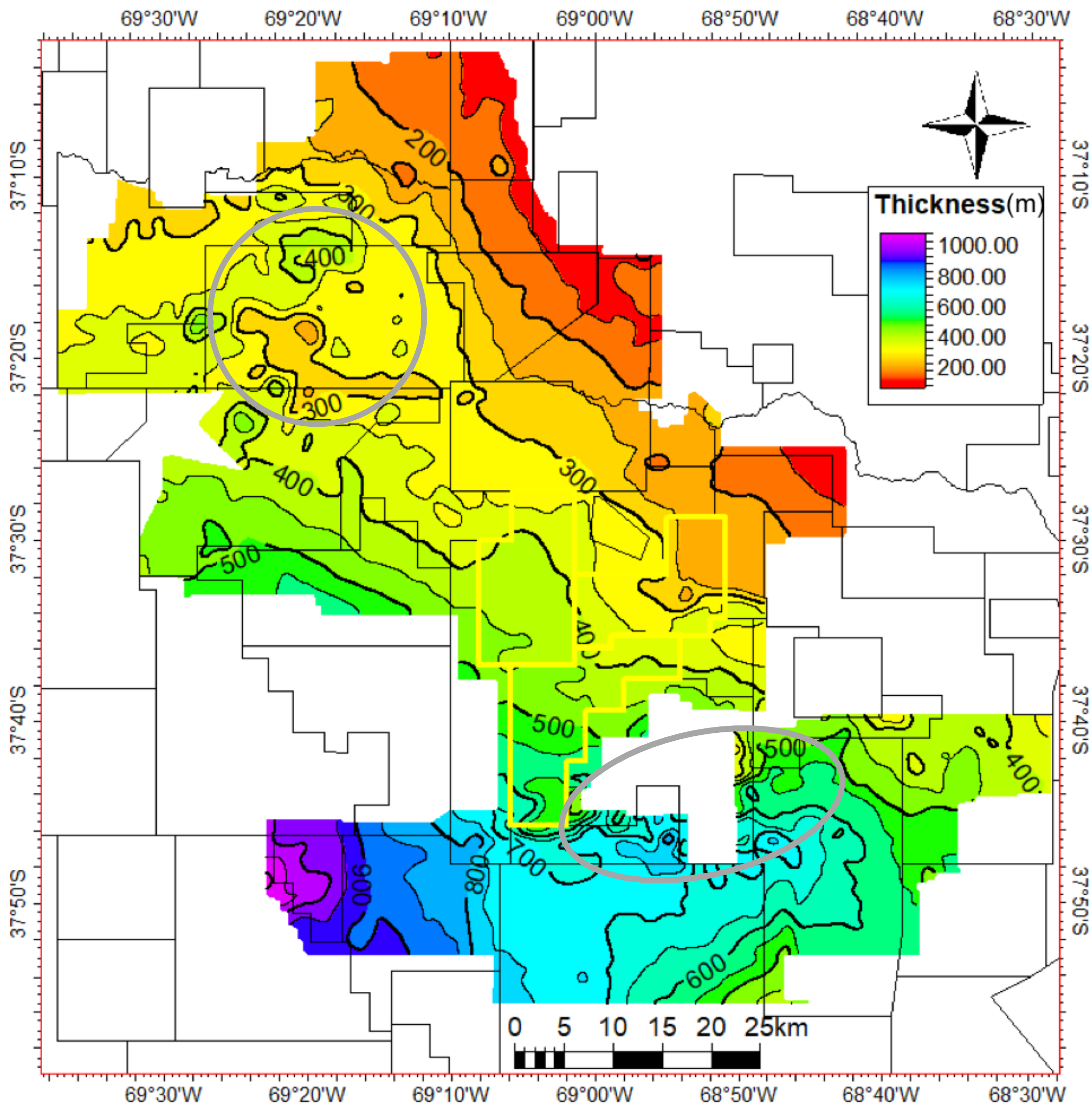


Figure 8. Thickness of the Vaca Muerta Fm. The circled areas are areas of poor tracking of seismic horizons.

5.1.5 Thickness Seal

Figure 38 illustrates the Agrio Fm thickness, ranging from roughly 350 to 850m. The formation thins towards the Northern and Eastern areas of the region, while it thickens towards the West-Southwest. The thickest intervals being in the West and South, while the thinnest is located in the North.

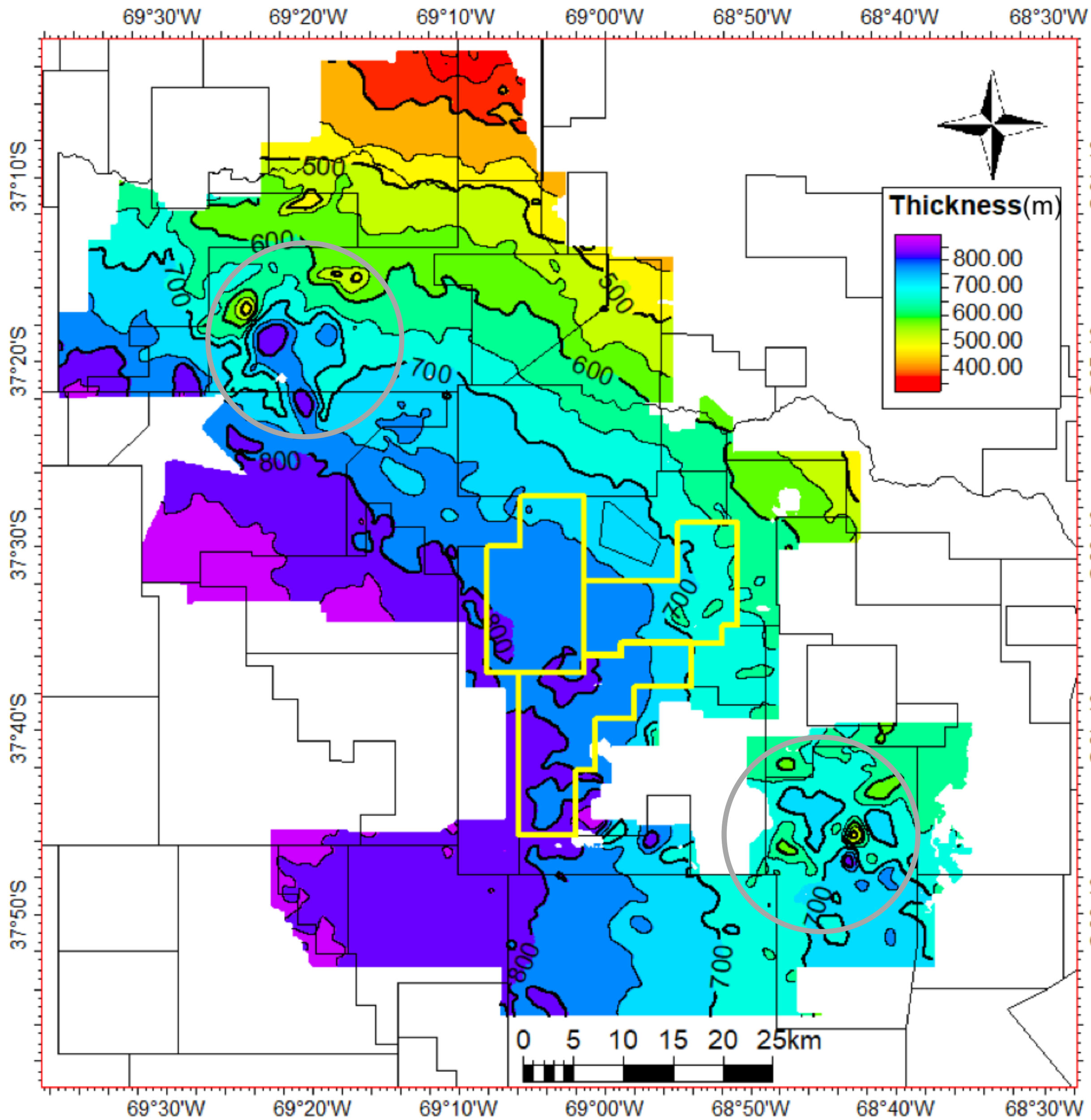


Figure 9. Thickness map of the Agrio Fm. The circled areas are areas of poor tracking of seismic horizons.

5.2 Petroleum System (Interpretation)

5.2.1 Traps

The large dome structure from figure 32 is the Chihuido de la Sierra Negra field, circled in the Northwest interval. This structure is created by a laccolith which elevates both tectono-sequences. Figures 39 A and B illustrates both cross-sections 1 and 2, respectively.

The intrusion is more noticeable in the seismic of the figure 39B, which has a column of chaotic, unorganized seismic reflections. In the same figure, there are noticeable sills which mainly perturb the surrounding stratigraphy, including the Mulichinco Fm. There is full closure surrounding the intrusion, providing the functional trapping mechanism of the Chihuido de la Sierra Negra field.

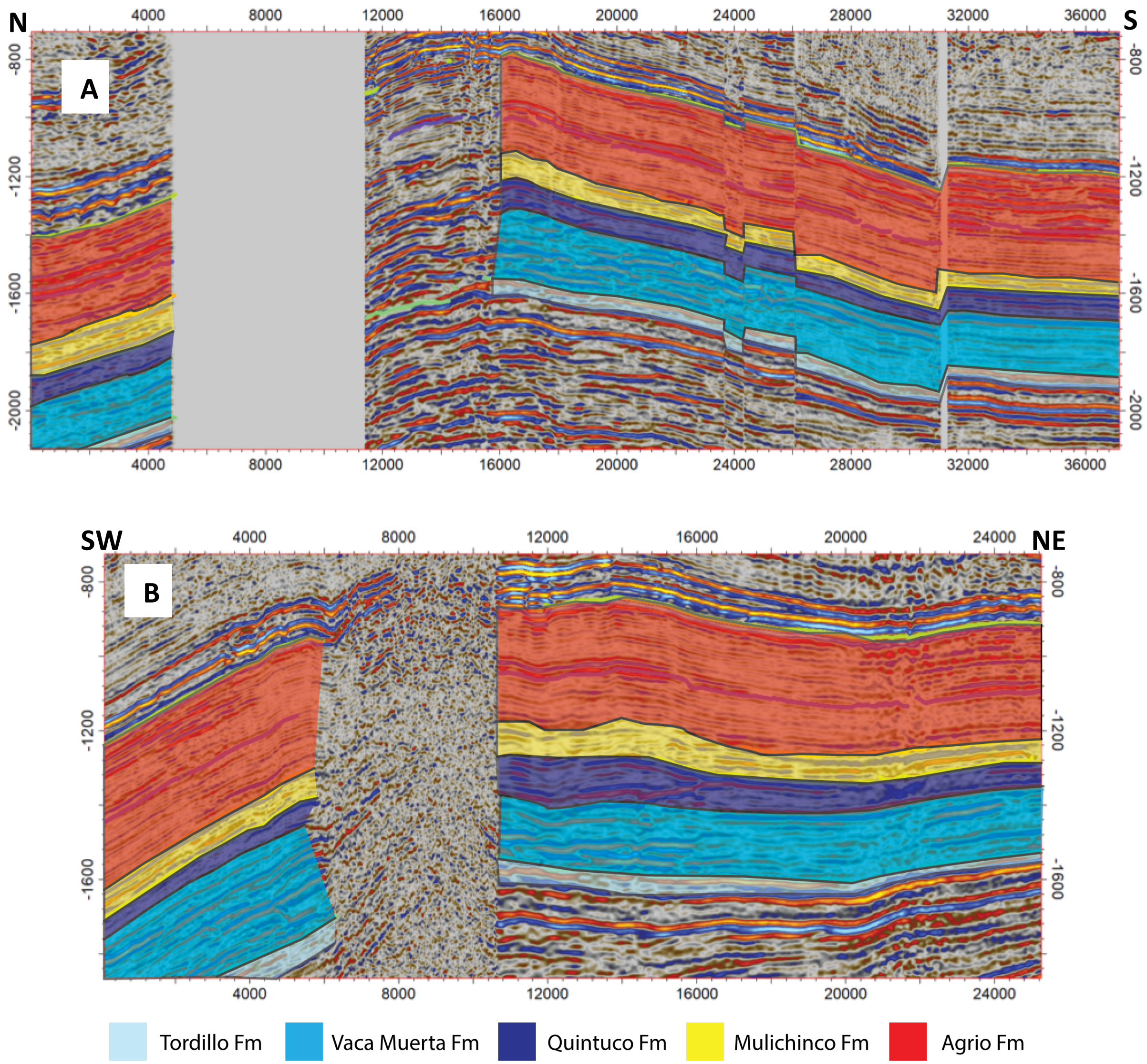


Figure 10.A) Cross section 1 from figure 32. B) Cross section 2 from figure 32. Both images represent the Chihuido de la Sierra Negra field.

Figures 40 (A and B) and 41 illustrate the anticline structure in the Northeastern section of the study area. Figure 40A, goes along the trend of the anticline Northwest to Southeast, while figures 40B and 41 are perpendicular to the anticline. Both cross sections that are perpendicular to the anticline show closure on either side of the anticline, however there needs to be closure up-dip along the axis of the anticline to form a trap. Along the axis, figure 40A, there is closer at the Northwestern end of the anticline, where the dip angle of the axis changes. Various fields are located around the Northwestern end of the anticline where there are traps with full closer.

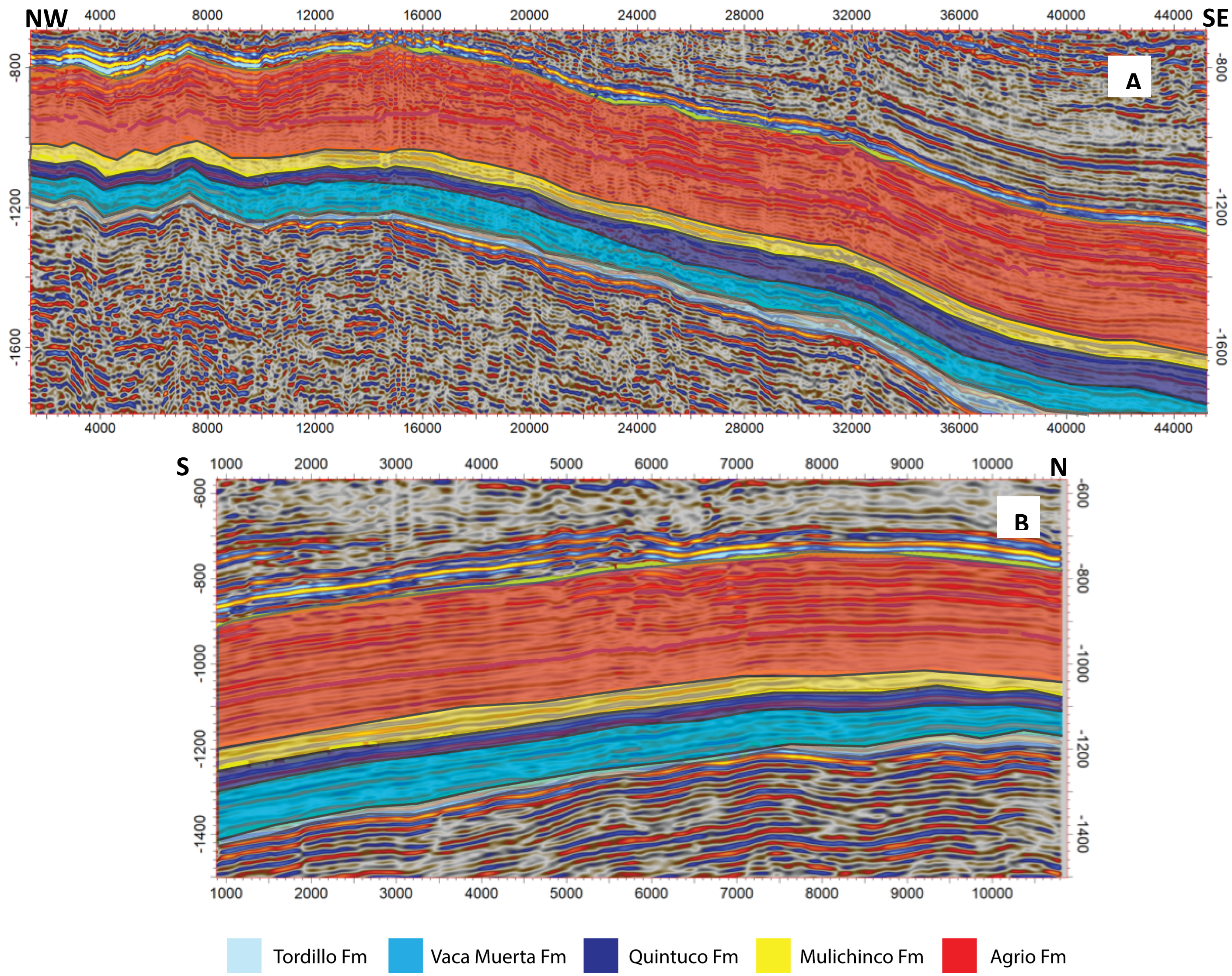


Figure 11. The two images represent cross sections from figure 32. A) Cross section 3. B) Cross section 4. The key formations are interpreted in both images.

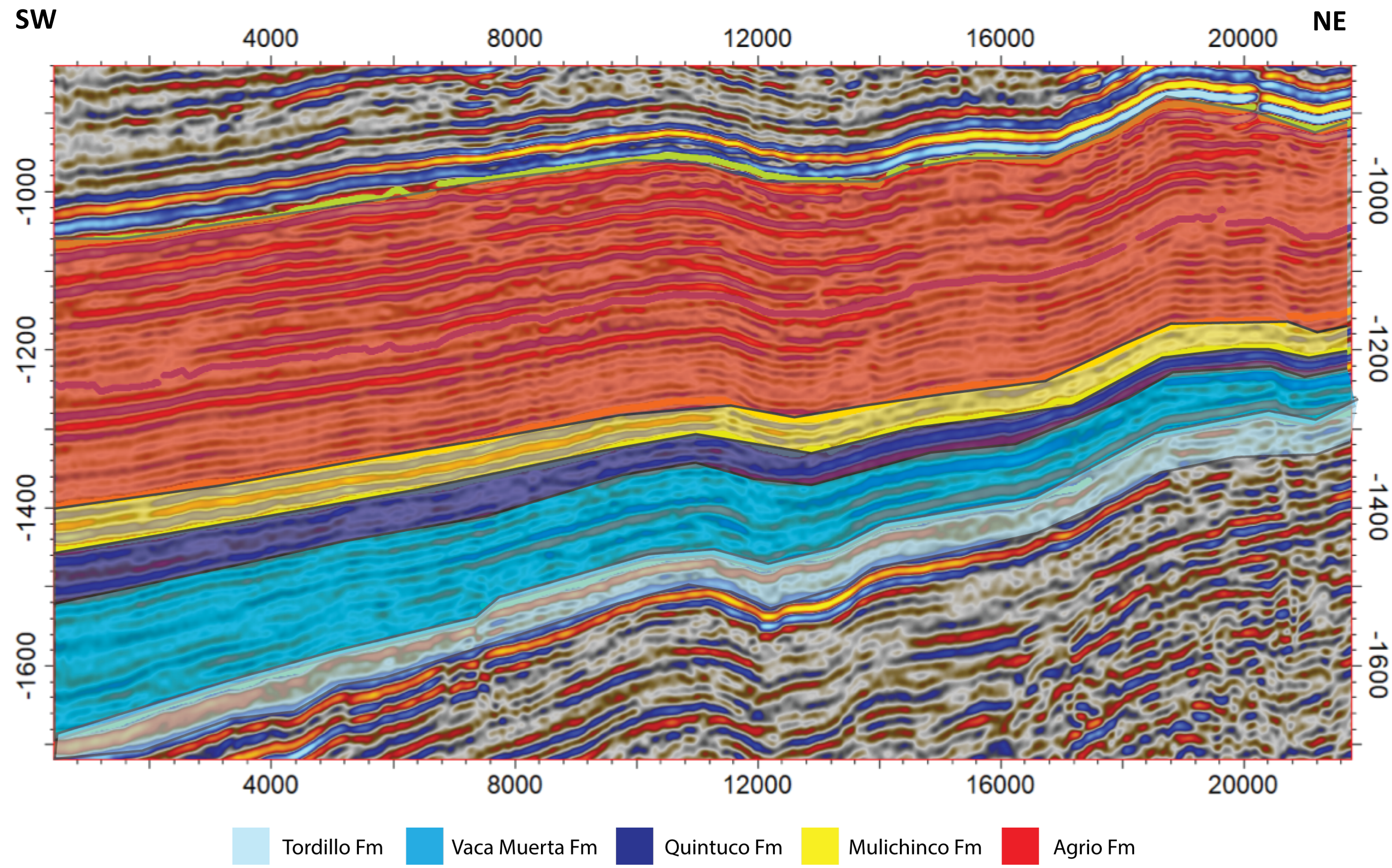


Figure 12. Cross sections 5 from figure 32. The figure has the key formation interpreted.

Another structural trap circled in figure 32 is that of the Aguada del Chivato field, located at the intersection of cross sections 6 and 7. The full closure is not apparent in the depth map of figure 32, nor is it recognized in the seismic. Cross section 6 (figure 42) illustrates an anticline that forms a trap, however, full closure is not recognized in cross section 7 (figure 43). This is due to the seismic resolution that makes it difficult to recognize the fault towards the north which allows for full closer.

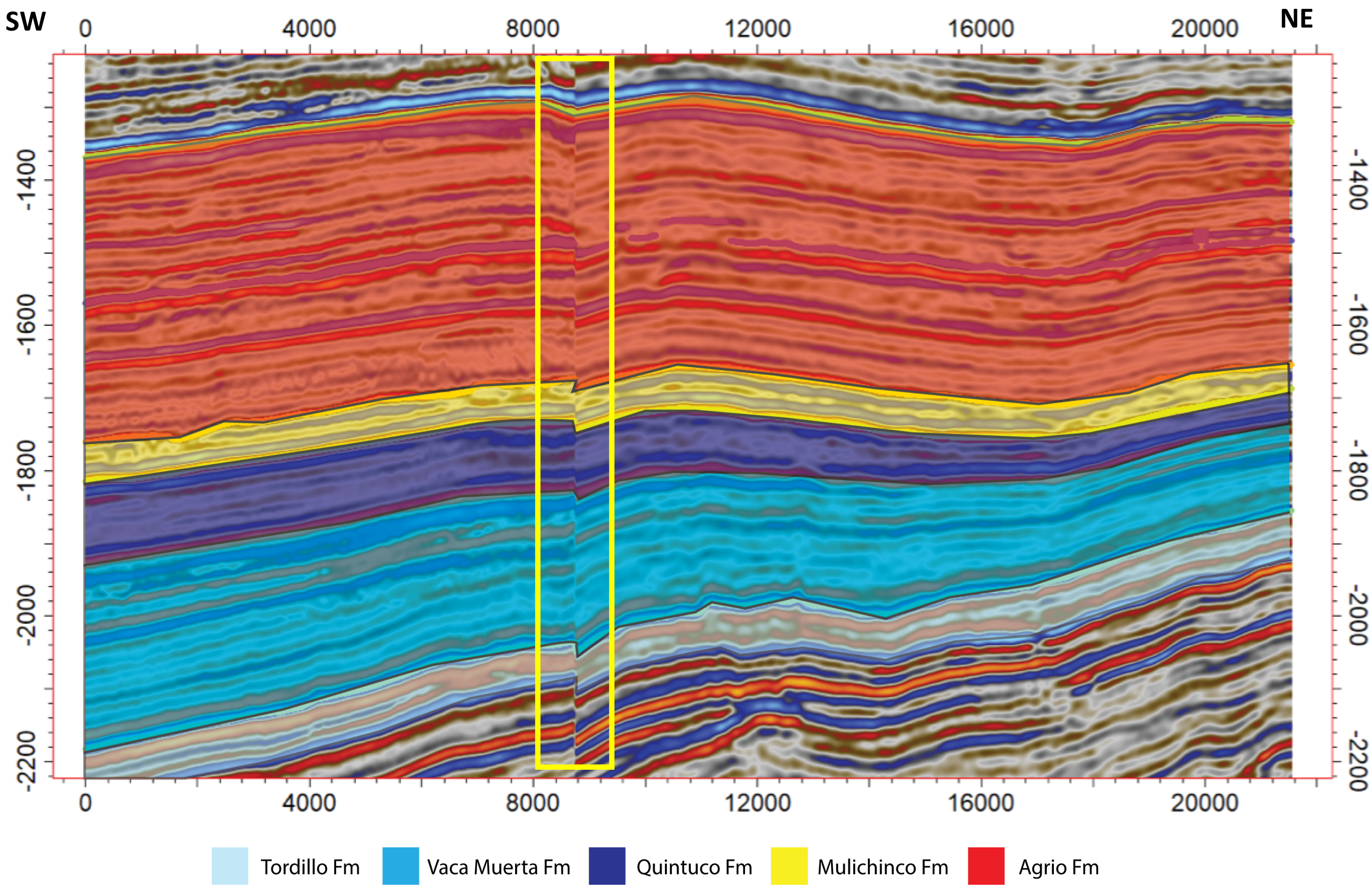


Figure 42. Cross sections 6 from figure 32 displaying the structure of the Aguada del Chivato field. The figure has the key formations interpreted. The yellow boxes indicate displacement in the seismic due to the merger of two individual 3D seismic cubes.

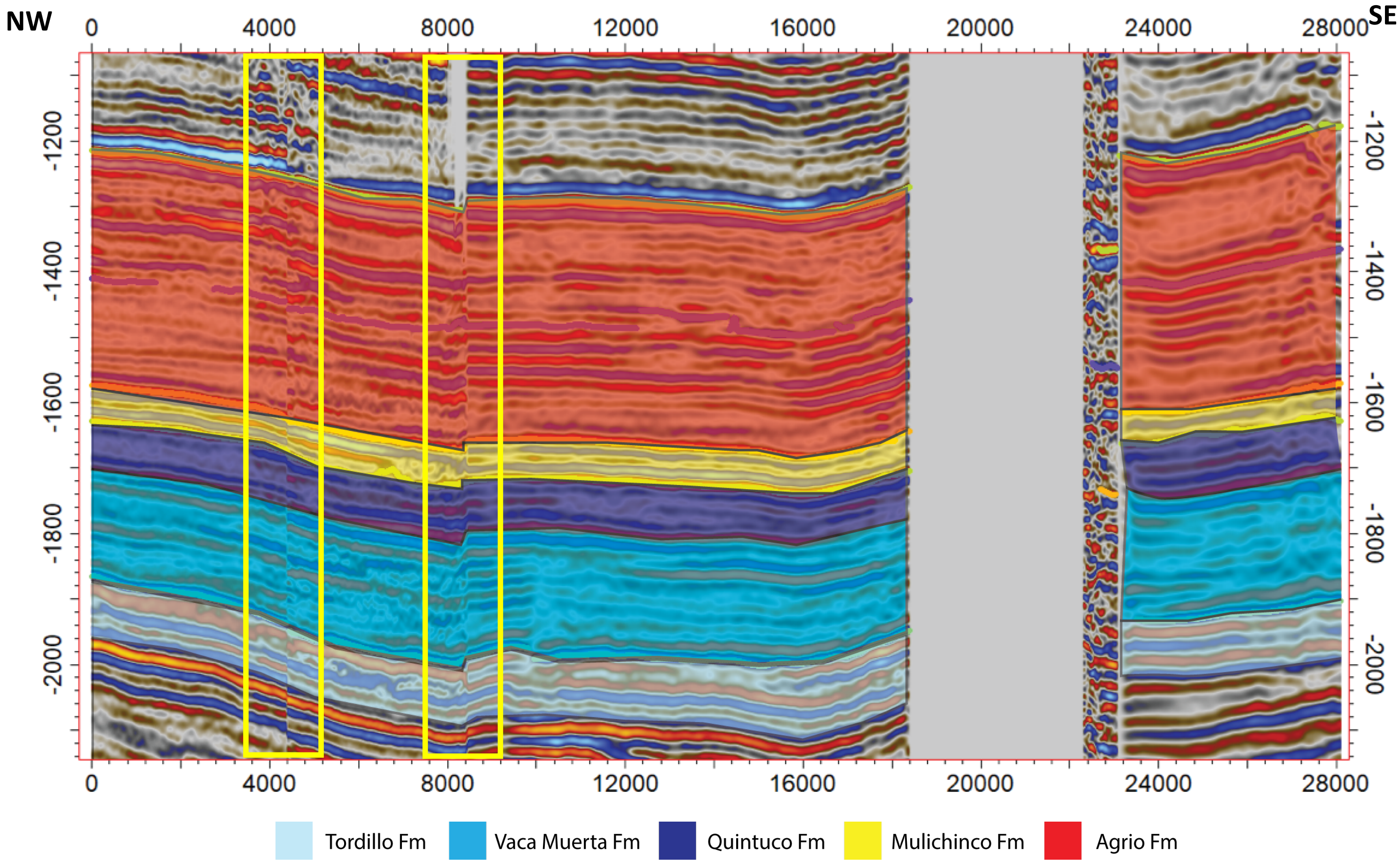


Figure 43. Cross sections 7 from figure 32 displaying the structure of the Aguada del Chivato field. The key formations have been interpreted in the figure. The yellow boxes indicate displacement in the seismic due to the merger of two individual 3D seismic cubes.

5.2.2 Reservoir Quality

5.2.2.1 Petrophysical Analysis

Figure 44 and 45 illustrates both the Vsh (44) and porosity (45) maps, indicating variations of reservoir qualities for the Mulichinco Fm. A concentration of porous sands is recognized in both figures towards the basin edge in the Southeast and East are recognized due to the low Vsh and high porosity values. An increase in carbonates is interpreted towards the North-Northwest, especially in the area that is circled in figure 44. This is interpreted as carbonate rich and not sand rich due to the porosity values in the area. Carbonates and sands have similar Vsh readings, however the density of the carbonates is much larger within the Mulichinco Fm, resulting in lower porosity values. However, carbonates may contain higher porosity values than observed from the porosity logs derived from density logs. Overall, the best reservoir properties are observed where the Vsh values are low and the porosity values are high throughout the Mulichinco Fm interval.

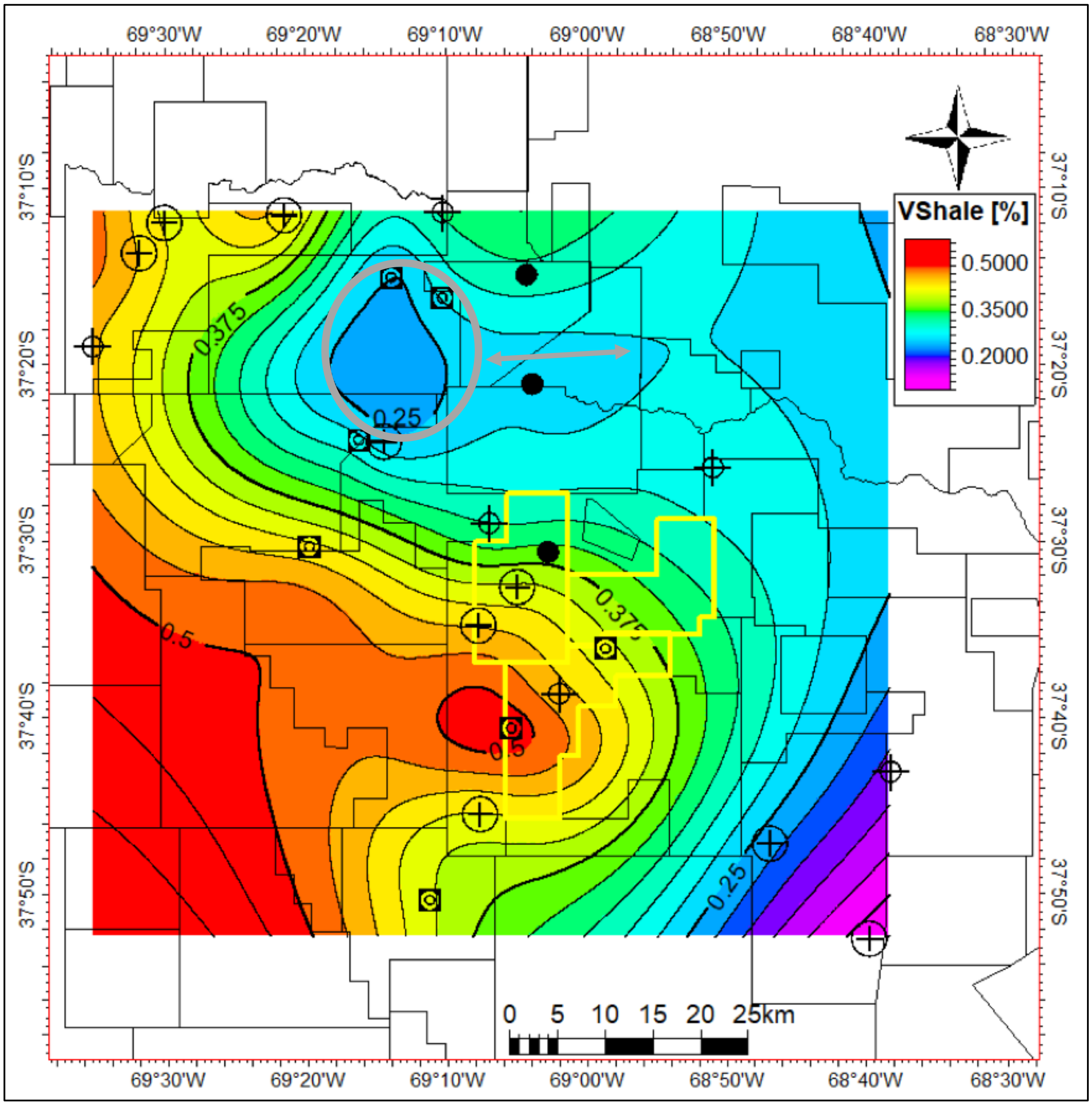


Figure 13. Map of the volume shale within the Mulichinco Fm from the calculated Vsh logs. Both the circle and the arrow indicate values that do not follow the general trend.

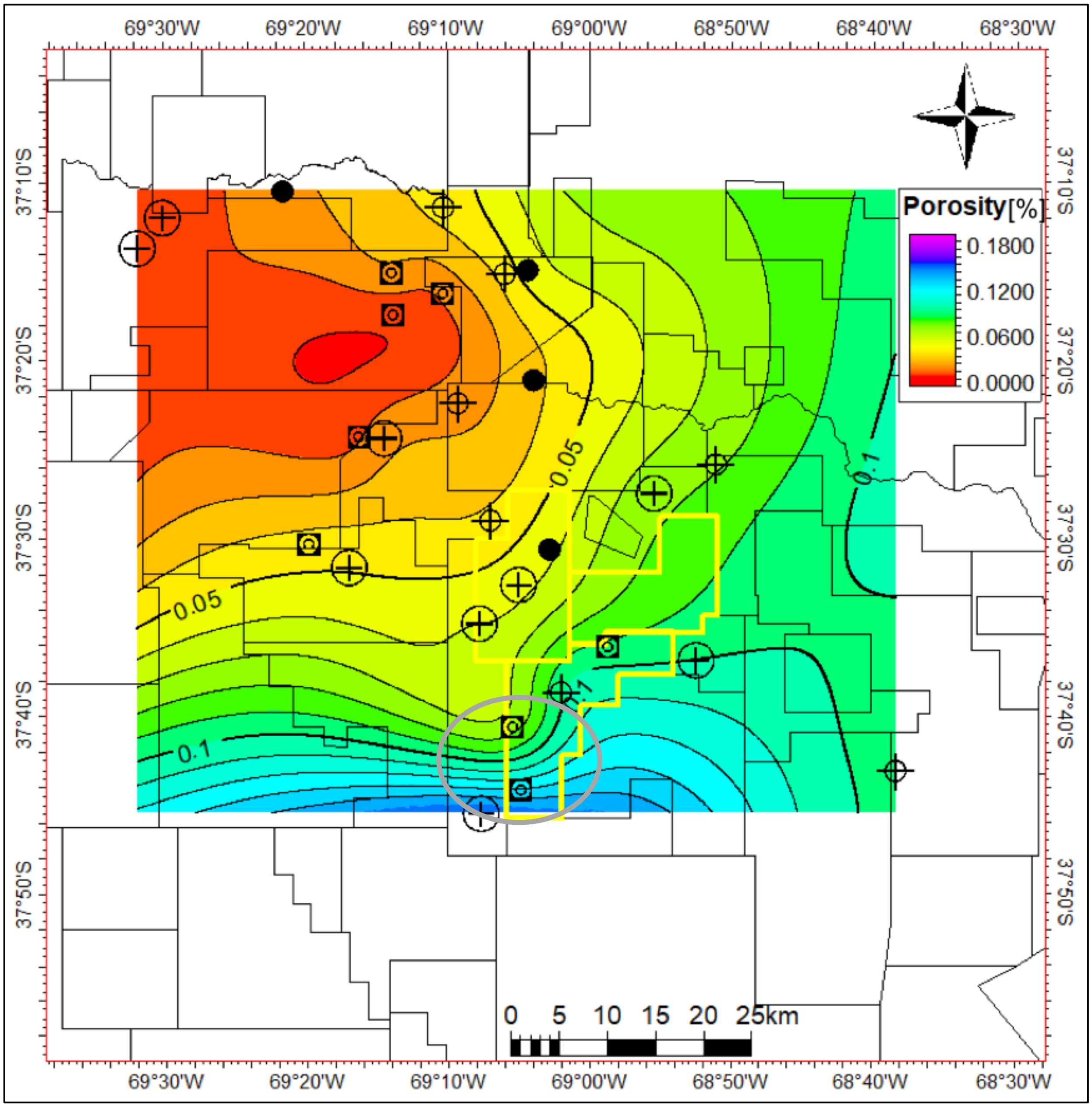


Figure 14. Porosity map of the Mulichinco Fm interval made from the calculated porosity logs. The area circled in grey has a rapid change in porosity over a short distance.

The facies variation of the Mulichinco Fm is observed both vertically and horizontally through the facies distribution. Vertically, four main units were identified containing various facies. The fluvial/terrestrial facies of Unit 1 contain some sand intervals but mainly have high Vsh values and porosity values under 5%. The Unit 2 deep marine carbonate facies have much lower Vsh values, but also have low porosity values. The deep marine delta front facies of Unit 3 mainly have high Vsh and porosity values under 5%, however, the sand packages within the facies has porosity values near 10% or higher. This facies transitions to shallow marine delta facies to the East-Southeast, which consists of less shale and more sand, increasing the thickness of porous intervals and lowering the average Vsh values. Further towards East-Southeast, the facies transitions to coastal delta facies, containing porosity values reaching 10% or higher. In Unit 4, shallow mixed carbonate/clastic marine facies transitions to estuary facies from West to East. The shallow marine facies contain low Vsh values and porosity values roughly around 3-7%, while estuary facies increase the clastic supply, increasing both the Vsh values and having porosity values up to 15% or higher. Overall, the upper sections of the Mulichinco Fm have much better reservoir qualities than the bottom sections. There are some intervals with good reservoir properties in the Northwest-West, however, the reservoir quality increases towards the East-Southeast.

5.2.2.2 Attributes

The attributes maps made are interpreted together with the traps. Most of the traps containing the current fields within the Mulichinco Fm in the study area are not recognized in the structural maps, such as the Aguada del Chivato field, due to the low seismic resolution. Internal structures, as well as most faults, within the Mulichinco Fm are not large enough to interpret in the seismic as the formation interval, therefore the attribute maps may indicate zones of hydrocarbon accumulation within traps that are below seismic resolution.

For example, full closure of the Aguada del Chivato field is not recognized in the seismic because the fault providing the closure to the North-Northeast is below seismic resolution.

However, the field is apparent in the RMS attribute map. Anomalies within the field, which also extend further out, are observed in the RMS map. The Aguada del Chivato Field contains some gas. Formations that are gas bearing rather than water or oil bearing are expected to stand out with higher amplitude patterns. The complete absence of RMS amplitudes at the neighboring Aguada Bocarey field may reflect less gas and heavier oil in this field than in the Aguada del Chivato field. Wells located within the anomaly but outside of the Aguada del Chivato field outline (i.e. Aguada del Chivato x-2) encounter non-economic amounts of gas in the lower levels of the Mulichinco Fm. This may explain the RMS anomaly extending outside of the field boundary, although no depth consistent trends are seen in the amplitude pattern and it is likely the amplitudes are as much related to lithology as to fluid composition. Two examples of anomalies are highlighted in figure 46.

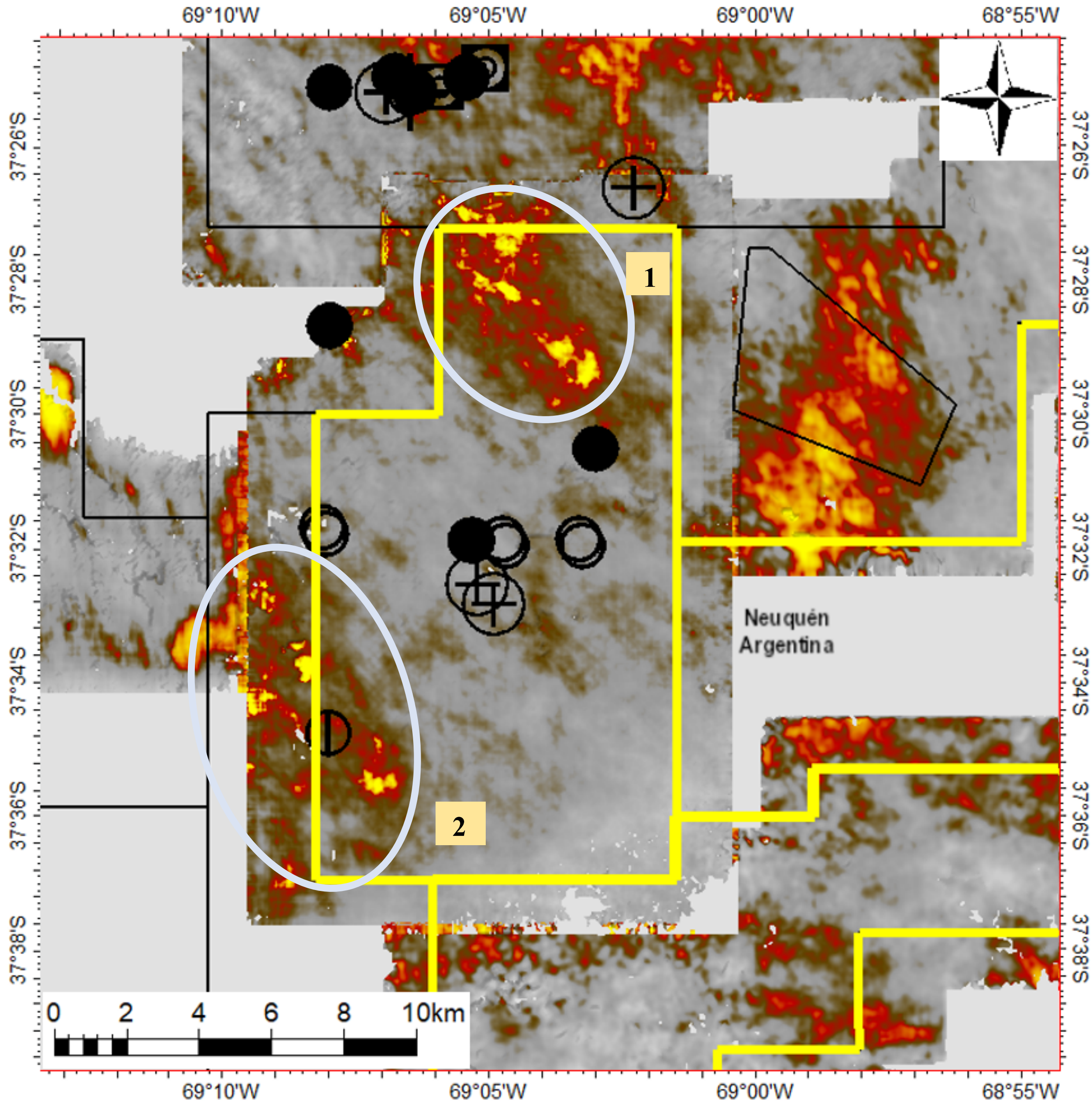


Figure 15. RMS attribute map of the Mulichinco Fm interval. Blue circles 1 and 2 are two areas where anomalies in the RMS map are present.

Circles 1 and 2 are in the Bajo del Toro license (figure 46) and indicate areas with high RMS attribute values. The Bajo del Toro 7v well is located in the second circle. The FWRs record gas at the base of the Mulichinco Fm. The well logs indicate three intervals at the base/middle of the Mulichinco Fm where the density and neutron logs cross over, which may be an indication of gas (figure 47). Circle 1, however, does not have wells within the anomaly. The Mulichinco Fm structure map and the seismic do not indicate structural traps in this area. This may be due to gas trapped within layers in the Mulichinco Fm that are too tight for gas to flow through. Again, no depth consistent trends are seen in the amplitude pattern, therefore it is likely the amplitudes are as much related to lithology as to fluid composition.

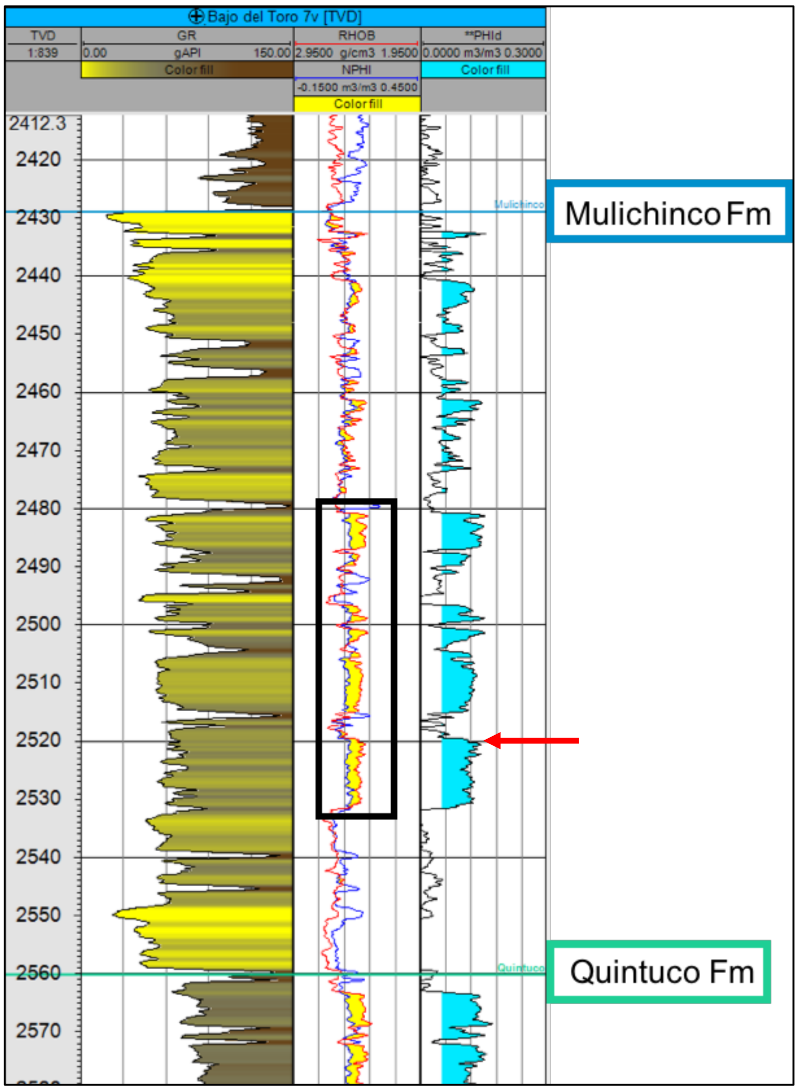


Figure 16. Bajo del Toro 7v well. The GR, density, neutron, and porosity logs may be observed in the well. Tops Mulichinco and Quintuco are labeled. The black box highlights the areas where the density and neutron logs cross over. The red arrow is the depth where gas is recorded within the FWRs. Gas spike is 3 times higher than the background gas at that interval.

5.2.3 Quality Source Rock

The basin edge during the time of deposition of the Vaca Muerta Fm was towards the Northeast where there was less accommodation space for the formation to deposit, therefore being thinner. The depo-center was located towards the Southwest, allowing more sediments to deposit, due to the higher accommodation space within the basin, therefore being thicker. Hydrocarbon production is less probable towards the basin edge, where the formation is thinner and shallower. However, the Vaca Muerta Fm is located deeper in the basin and is thicker towards the Southwest, allowing more layers containing high TOC% to produce and expel hydrocarbons. The formation proves its high potential, filling every Mulichinco Fm field within the study region with oil, gas, or both.

5.2.4 Quality Seal

The basin edge was located towards the North of the region during the time of deposition of the Agrio Fm, while the depo-center of the basin was towards the South-Southwest. The lower accommodation space of the basin edge is interpreted from the thinner intervals of the Agrio Fm, while basinward there was more accommodation space, depositing thicker intervals of the Agrio Fm. Overall, the Agrio Fm is composed of over 300 meters of mainly shales, that have much lower pore space than the underlying Mulichinco Fm, providing an excellent seal. Few faults are observed throughout the Agrio Fm, however, the integrity of the seal may be at risk at the anticline-syncline structure trending Northwest-Southeast in the Northeast of the region. The formation is thinner than average in this area, and the underlying faults may cause faulting beneath seismic resolution that affect the Agrio Fm.

6 Discussion

Many of the observations presented here have been previously studied to a basin-wide scale, while the focus in this study is the Northeastern region of the Neuquén basin. The key points discussed that go against previous literature are mainly due to the observations and interpretations done on a more local scale in this study compared to previous work done. However, the conclusions from this study agree with most of the literature on the Mulichinco Fm.

6.1 Tectono-Sequences

The tectono-sequences interpreted vary from previous literature. The selected time intervals were the Late Kimmeridgian to Late Berriasian, forming the TS1 that contains the Tordillo, Vaca Muerta and Quintuco Fms and the intervals Early Valanginian to late Barremian forming the TS2, containing the Mulichinco and Agrio Fms. This differs from liturature such as Hogg (1993). Hogg (1993) devided the sections into three different as mega-sequences or cycles which are selected from Toarcian to Oxfordian (cycle 1), Kimmeridgian to the Late Valanginian (cycle 2), and Huatervian to the Aptian-Albian (cycle 3).

The first cycle from Hogg (1993) is not interpreted in this study since the focus of this study is of the Mendoza Group. Cycle two of the Hogg (1993) study is similar to the TS1 of this study, where the sequence/cycle starts at the Kimmeridgian after a period of basin-wide erosion forming the unconformity between the Oxfordian and Kimmeridgian. However, Hogg (1993) includes the Valanginian Mulichinco Fm to the top of this sequence. In this study, the sequence boundary between TS1 and TS2 is located beneath the Mulichinco Fm, therefore including the

Mulichinco Fm into the second tectono-sequence (cycle 2). Tectonic induced inversion reactivated several faults within the basin which lead to a period of erosion and hiatus which forms the Valanginian Unconformity (Vergani et al. 1995) (Schwarz and Howell, 2005). The third cycle from Hogg (1993) does not contain the Mulichinco Fm, but the Agrio Fm and the Rayoso Gp. Contrary to that study, this study includes the Mulichinco and Agrio Fm within the TS2, with the unconformity between the Mendoza and Rayoso Gps being the sequence boundary rather than the unconformity between the Rayoso and Neuquén Gps.

6.2 Mulichinco Facies distribution

The Mulichinco Fm is a lowstand wedge at the tectono-stratigraphic scale, as recognized in literature such as Schwarz and Howell (2005), Liberman et al. (2014) and Pascariello et al. (2018). However, the formation also comprises system tracts, creating a lower order sequence within the Mulichinco Fm. The sequence consists of various facies that were deposited throughout the Neuquén basin, forming the Mulichinco Fm. The vertical and horizontal deposition of the facies is discussed in the literature, identifying the lateral extent of the facies and the variation of facies through time. Many of the studies being compared to this study approach the Mulichinco Fm on a basin-wide scale. This study focuses the Mulichinco Fm in the Northeastern region of the Neuquén Basin.

6.2.1 Unit 1 LST

Pascariello et al. (2018) and Liberman et al. (2014) made similar interpretations as this study mainly using cores and other subsurface data. The research conducted by Schwarz and Howell (2005) uses outcrop and surface data to interpret the Mulichinco Fm, therefore having variable interpretations in the Northeastern region of the Neuquén Basin due to lack of surface exposure of the formation. Liberman et al. (2014) recognizes Unit 1 as fluvial deltaic deposits. However, the study is focusing the Aguada del Chivato license, therefore the facies transitions interpreted towards the Northeast are not recognized in Liberman et al. (2014) study. Similarly, Pascariello et al. (2018) interprets the facies distribution of the Mulichinco Fm, with overlapping areas of study as this study. Pascariello et al. (2018) interprets the three main facies of Unit 1 and similar transitional zone locations. Schwarz and Howell (2005) interpret the Mulichinco Fm throughout the whole of the Neuquén Basin but has areas without interpretation, such as the Northeastern area of the basin due to lack of outcrops. The interpretation of Unit 1 towards the North is characterized as wave and storm dominated deposits. Schwarz and Howell (2005) mention that fluvial deposits are likely towards the Northeast, where there is no interpretation. This coincides with the interpretations made with the Northeastern dataset.

6.2.2 Unit 2 TST

The Unit 2 interpreted in this study correlates with Liberman et al. (2014), Pascariello et al. (2018) and Schwarz and Howell (2005), where it is composed mainly of marine facies. Liberman et al. (2014) interprets a facies variation from carbonate rich marine facies to mixed carbonate/clastic marine facies, however, the variation is a vertical change in facies. That study is different from this study that recognized a horizontal transition of facies but not a vertical change for Unit 2. Schwarz and Howell (2005) also interpret a vertical transition from marine carbonate facies to mixed carbonate/clastic marine facies in the North of their study. Pascariello et al. (2018) interprets the mixed marine and carbonate rich marine facies, as well as coastal plain and fluvial facies farther South. There are overlapping areas between that study and this study which differ. A transition from mixed marine to coastal plain and further South to fluvial facies is interpreted in the Pascariello et al. (2018) that is not recognized in this study.

6.2.3 Unit 3 HST

Liberman et al. (2014), Pascariello et al. (2018) and Schwarz and Howell (2005) have similar interpretations for Unit 3 as in this study. Liberman et al. (2014) recognizes deltaic facies but divides it into prodelta, deltafront, distributary channel, interdistributary plain, and abandoned channel facies. The detailed interpretation of Unit 3 is due to core data analysis. However, the same overall coarsening upwards trend is present in both Liberman et al. (2014) and this study. The Schwarz and Howell (2005) study also agrees with this study, where a coarsening upwards trend is recognized in Unit 3, indicating initial aggradation to progradation. Pascariello et al. (2018) interprets shallow marine delta, shallow marine shoreface, deep marine facies, coastal plain and fluvial facies in the region where both that study and this study overlap. The deep marine, shallow marine and coastal plain facies coincide with the interpretations from this study, where the deeper depositional systems are located towards the Northwest and the shallower facies are located towards the Southeast. However, Pascariello et al. (2018) interprets fluvial facies towards the Southeast where both study areas overlap. The Mulichinco Fm thins towards the East-Southeast, where the farthest well (Cerro Avispa Este 1) to the Southeast in the dataset provided does not encounter the Mulichinco Fm. This goes against the interpretation of Pascariello et al. (2018), where fluvial deposits are interpreted farther East than where the Mulichinco Fm terminates. Schwarz and Howell (2005) also disagree with the Pascariello et al. (2018) study by stating that there was not enough progradation to develop fluvial facies in the Eastern and Northern regions of their study area.

6.2.4 Unit 4 LST

Liberman et al. (2014), Pascariello et al. (2018) and Schwarz and Howell (2005) recognize the Unit 4 as a transgression. Liberman et al. (2014) interprets Unit 4 as estuary facies, both internal (clastic rich) and external (mixed clastic and carbonates). Since these interpretations are located in the Aguada del Chivato license, it coincides with the interpretations made in this study. Where the estuary inlet is interpreted a towards the West of Aguada del Chivato, and the estuary bay head is interpreted towards the Southeast of the license. Schwarz and Howell (2005) interpret shoreface deposits towards the Northeast of their study area. Since the interpretations for that study are mainly done through outcrops, estuary deposits are not interpreted in the subsurface farther towards the Northeast, in this study area. Pascariello et al. (2018) interprets various facies forming Unit 4 in the overlapping Northeast region: deep marine, shallow marine shoreface, coastal plain, and fluvial facies. The shallow marine shoreface facies interpreted in that study coincides with the estuary facies in this study. However, coastal plain and fluvial facies are not interpreted in this study in the area that overlaps with the study of Pascariello et al. (2018).

6.3 Petroleum System

The petroleum system within the Northeastern region of the Neuquén Basin for the Mulichinco Fm include the Vaca Muerta Fm source rock, the Mulichinco Fm reservoir, and the Agrio Fm seal. The Mulichinco Fm may also function as a seal with the internal shale layers that are buffers within the reservoir. Although various studies expand on different petroleum systems within the Neuquén Basin, this specific petroleum system is widely accepted. Literature, such as Vergani et al. (1995), Ponce et al. (2015), Arismendi et al. (2016), and Pascariello et al. (2018) study various petroleum system, including the one focused in this study.

6.3.1 Reservoir Quality

The study of the reservoir quality of the Mulichinco Fm recognizes that the reservoir varies both vertically and horizontally in quality. The reservoir properties encountered within the study are recognized through both the facies distribution and petrophysical analysis. The Vsh and porosity maps indicate good reservoir qualities towards the Southeast of the study area. While further to the Northeast, the reservoir quality decreases. Vertically, the Vsh and porosity logs indicate higher clastic content towards the top of the Mulichinco Fm, increasing both the Vsh and porosity values, which indicating good reservoir qualities. The lower section of the formation decreases in Vsh due less sand content and more carbonate content, which also decreases the porosity values. This indicates poor reservoir qualities. This coincides with the facies distribution maps, where Unit 1 has high shale content within the fluvial/terrestrial and shallow marine mixed carbonate/clastic facies, and Unit 2 has deep marine carbonates. While the two upper Units increase in sand content, and decrease in carbonate supply. Therefore, through the facies distribution maps, the same trend is present. Where the base of the formation has poor reservoir qualities and the upper section has good reservoir properties.

This leads to the potential of unconventional production, where reservoir stimulation is necessary to allow hydrocarbons to flow in intervals where there are poor reservoir qualities. Throughout the literature, there is scarcely any discussion on the unconventional aspect of the Mulichinco Fm. However, this study highlights areas where unconventional drilling may be a viable alternative. Although oil is not evident through petrophysical analysis, such as attribute maps in figure 34, oil may be present in these areas, where hydrocarbon migration is not possible in the areas with tight reservoir properties.

6.3.2 Traps

As mentioned throughout the study, most fields composed of structural trap are not recognized through structure maps, especially ones with 3-way closure due to many faults being below seismic resolution within the Mulichinco Fm. The major stratigraphic traps that produce fields, such as the Chihuido de la Sierra Negra field, are recognized. However, better seismic resolution targeting the Mulichinco Fm is necessary to improve structural recognition within the Northeast region of the Neuquén Basin.

6.3.3 Source Rock

As mentioned in the literature, the Vaca Muerta Fm is the most prolific source rock in the Neuquén Basin due to its high organic carbon content. This is recognized in the Northeastern region of the Neuquén Basin. The Vaca Muerta is present throughout the region, ranging in thickness between roughly 150 to 1000m. The TOC% values of the source rock range between 1 and 10% within this study, which is also recognized in the literature González et al. (2016) in the areas that overlap with this study. All Mulichinco Fm fields within this region are sourced from the Vaca Muerta Fm. As recognized in both this study and in literature, the quality of the source rock varies both vertically and horizontally. Vertically, there are intervals within the Vaca Muerta Fm with different source rock qualities. The base Vaca Muerta Fm has much larger TOC content, than at the top, also recognized in González et al. (2016).

6.3.4 Seal

The main seal interpreted in this study is the Agrio Fm, however, the Mulichinco Fm may provide internal seals due to the facies variation and shale content. The thick Agrio Fm is present throughout this region as well as most of the Neuquén basin, as recognized in the literature. It provides a functional seal due to its high shale composition. Through the observations made, the seal integrity is considered intact. Most faulting in the basin does not reach the Agrio Fm and there is little reactivation of faults post Agrio Fm deposition. This observation is widely agreed upon throughout the literature.

7 Conclusions

The study focuses on the Mulichinco Fm as a reservoir within the Northeastern region of the Neuquén Basin. This was done through the correlation of well and seismic correlation using key stratigraphy, interpreting the sequence stratigraphy of the section containing the Mulichinco Fm, and interpreting the internal facies of the formation. Subsurface data is used to interpret the variation of deposition, reservoir quality, and the petroleum system including the Mulichinco Fm as the reservoir. With this study, various conclusions are made:

1) The facies distribution and the distribution controls of the Mulichinco Fm in the Neuquén Basin varies from previous literature. This study focuses on the Northeastern region of the basin rather than most previous studies that approach the facies distribution of the Mulichinco Fm for the whole Neuquén Basin. The main discussion is the lateral extent of the facies composing the formation. However, a combination of the facies distribution interpretations from other literature may be combined with the interpretations made throughout this study to expand the Mulichinco Fm distribution map. Overall, the facies distribution of the Mulichinco Fm was sourced from the Southeast, and was deposited towards the Northwest, towards the depo-center. Tectonic events caused sea level fall and rise, which changed the accumulation space for sediment deposition.

2) The reservoir quality of the Mulichinco Fm varies both vertically and horizontally. The base of the Mulichinco Fm contains lower porosity values, which requires for the lower section of the formation to be targeted as an unconventional reservoir. The top section of the reservoir contains better porosity values, which results in better reservoir properties that are currently targeted as conventional reservoirs. Towards the West, there are higher concentrations of shale, while the

North and central areas containing higher carbonate content, and the East-Southeast composed of higher amounts of sand. The porosity values are higher towards the Southern and Eastern edges of the region, while the central North area of the region decreases in porosity. The best reservoir qualities for the Mulichinco Fm are located towards the central and Southeastern areas of the Northeastern region of the Neuquén Basin.

3) The petroleum system for the Mulichinco Fm as a reservoir is proven to function. Various fields are present in the Mulichinco Fm contain oil, gas or both, all sourced from the Vaca Muerta Fm in this region. The Vaca Muerta Fm is thick and abundant and within the oil to early gas window within the study area. The Agrio Fm is also thick and found throughout the whole study area with excellent seal qualities, composed of shale and maintaining good seal integrity. Structural traps, with either 4-way or 3-way closures, allowing hydrocarbon accumulation are also recognized throughout the region.

8 Reference

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9 Appendix

9.1 Tables

Wells	Seismic well tie	Sonic	Density	GR	Porosity
Aguila Mora x-2h	y	y	y	y	-
Aguila Mora x-3h	y	y	y	y	y
Anticlinal Del Este x-1	Y	y	y	y	y
Bajo del Toro 3	-	MS	MS	y	-
Bajo Los Barreales x-1	Y	MS	MS	MS	-
Cerro Avispa Este 1	Y	y	y	y	y
El Trapial xp-2001	Y	y	y	y	y
Loma Pedregosa x-2	-	y	-	y	-
Aguada Bocarey Este x-1	Y	y	y	y	-
Avutarda x-1	Y	y	y	y	-
Puesto Hernandez x-1190	Y	y	y	y	-
Rincon La Ceniza x-1	Y	y	y	y	-
Aguada Bocarey 3	-	y	-	-	y
Aguada Bocarey 4	-	MS	-	-	MS
Aguada Bocarey 5	D/S	y	-	-	y
Aguada del Chivato x-1	-	y	-	-	y
Aguila Mora x-1h	Y	y	y	y	y
Amancay 1	-	-	y	y	y
Bajo Batra 1	Y	y	y	y	y
Bajo del Toro 5	-	y	-	y	-
Bajo del Toro 7v	-	y	y	y	-
Barda de los Sauces 1	D/S	y	-	-	y
Barda de los Sauces 2	D/S	y	-	-	y
Cerrito el Indio x-3	Y	y	y	y	y
El Alpataco 1	D/S	y	Poor	-	y
El Humo 1	D/S	y	-	y	y
El Trapial 1	Y	y	y	y	y
Filomena x-1	D/S	y	MS	y	MS
La Invernada x-3h	Y	y	y	y	y
La Tropilla x-1	Y	y	y	-	MS
Loma Amarilla 1	Y	y	-	y	y

Loma del Barril x-1	-	y	MS	y	-
Loma Partida Este 2	D/S	y	Poor	y	y
Lomita Norte x-10	Y	y	y	y	y
Paso de Las Bardas 2	Y	y	MS	MS	-
Sierra Auca Mahuida 1	D/S	y	-	-	y
Sierra Auca Mahuida 2	Y	y	y	y	-
Tinudo 1	MS	MS	MS	MS	MS
Aguada Bocarey 11	Y	y	y	y	-
Aguada del Chivato Oeste x-1	Y	y	y	y	-
Chihuido de La Sierra Negra xp-623	Y	y	y	y	-
El Puente x-1	Y	y	y	y	-
La Ramada x-1	Y	y	y	y	-
Lomita x-30	Y	y	y	y	-
Puesto Hernandez xp-242	Y	y	y	y	-

Table 1. Wells used located in the study area. Logs presence and quality are indicated. Y= log is present. - = log is not present. MS = missing section in the log. D/S = density log derived from sonic log. Poor = log quality is poor or inconsistent.

9.2 Figures

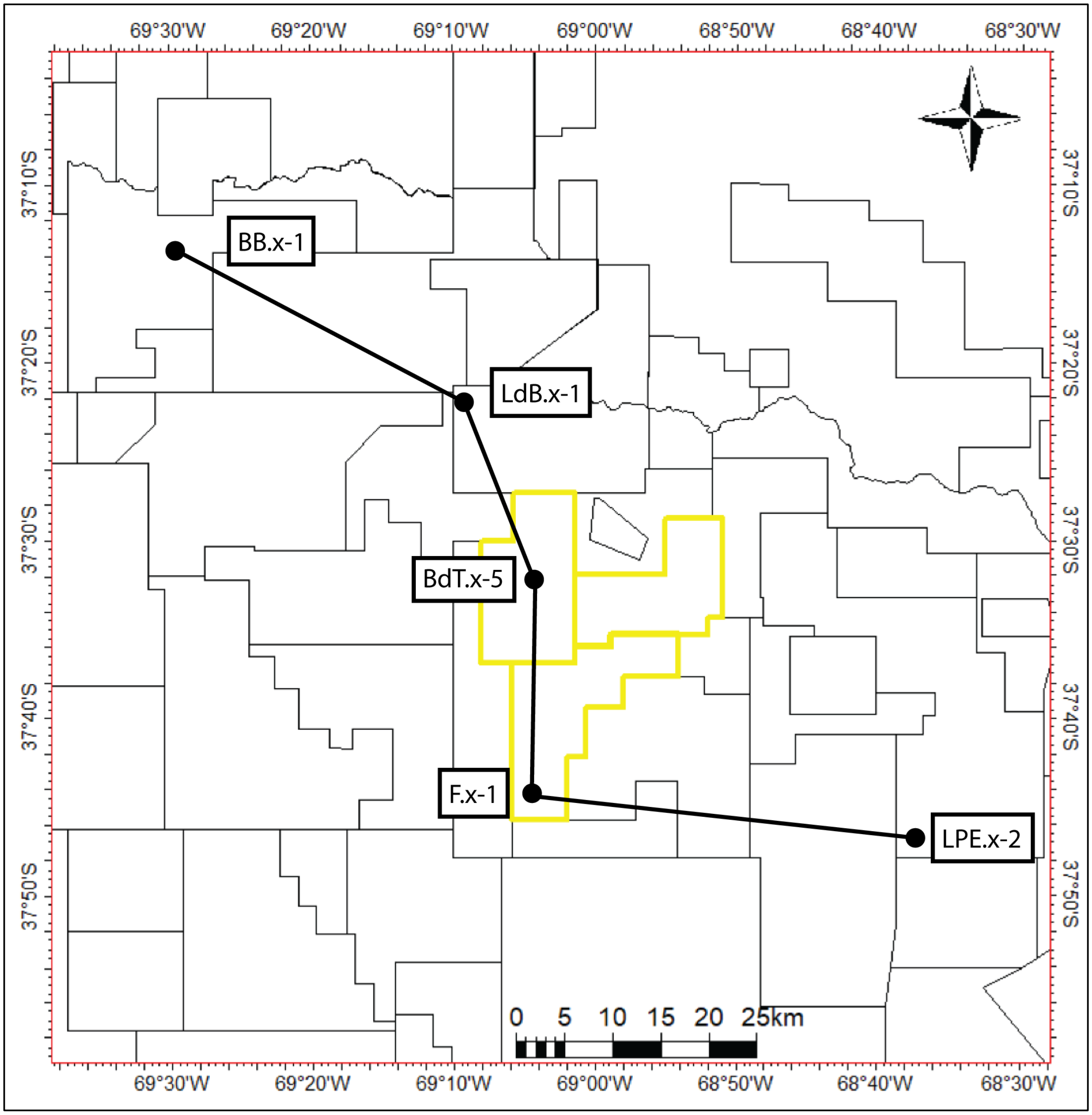

Figure 17. Location of wells used for facies interpretation within the Mulichinco Fm.

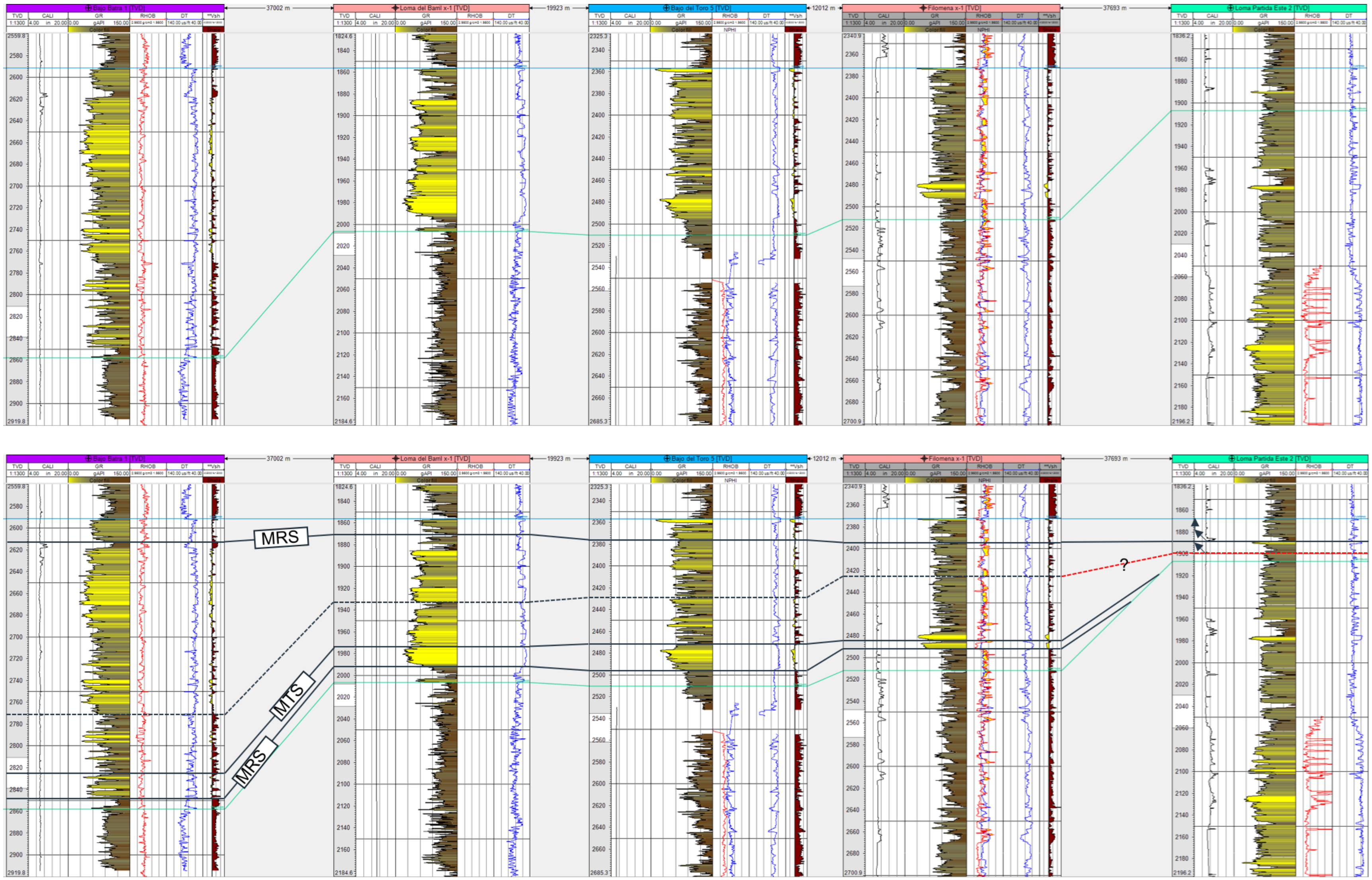

Figure 18. Both figures show the five wells selected for the Mulichinco Fm correlation. The figure on top indicates the top and base Mulichinco Fm. The image on the bottom includes the interpreted surfaces.