ELECTROFACIES, ELEMENTAL COMPOSITION, AND SOURCE ROCK CHARACTERISTICS ALONG SEISMIC REFLECTORS OF THE VACA MUERTA FORMATION IN THE LOMA LA LATA AREA, NEUQUEN BASIN, ARGENTINA

by

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ABSTRACT

The Vaca Muerta Formation is a fine-grained marine lithostratigraphic unit that was deposited during the Late Jurassic and Early Cretaceous in the Neuquén Basin of Argentina. Accommodation space was generated by back-arc subsidence of the crust as the Pacific Plate subducted beneath the South American Plate during and after the break-up of the Gondwana supercontinent. The Vaca Muerta was recognized and named in early stratigraphic studies of the basin in the 1930s. The production of hydrocarbons in the basin led to subsequent detailed studies of the formation, primarily as an important source rock. Currently, however, the mineralogy, thickness, organic content, and maturity of the Vaca Muerta have highlighted it as a prospective resource play, comparable to plays in the United States such as the Eagle Ford.

This study integrated well log, cuttings, and seismic data in the Loma La Lata area of the basin. Electrofacies were generated using well log data, with five electrofacies defined. Cuttings were analyzed for elemental composition, mineralogical makeup, and source rock characteristics. Cuttings at the base of the section proved to be good source rock and enriched in trace metals, with declining quantities up-hole. Seismic data was interpreted to highlight three major clinoform surfaces, one progradational and two aggradational.

Electrofacies were related to both the results from cuttings and seismic reflector patterns. A relationship exists between the well-log values, source rock characteristics, mineralogy, and seismic patterns. Facies can be shown to vary along seismic reflectors between wells. The methodology and results presented here could help in high-grading current and future data for exploring and exploiting the Vaca Muerta Formation.
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CHAPTER 1
PURPOSE AND OBJECTIVES

This study focused on describing geologic properties of the Vaca Muerta Formation in the Neuquén Basin, Argentina. Various datasets were integrated, including well cuttings, samples from core, well log analysis, and outcrop measurements. The study focused on a pre-defined Consortium Area of Interest in the south-east portion of the basin.

1.1 Introduction

The Neuquén Basin is located in the provinces of Neuquén, Rio Negro, and Mendoza in western Argentina (Figure 0.1). The majority of the sedimentary record was deposited during the Paleozoic by transgressions due to the encroachment of the proto-Pacific Ocean through openings in the magmatic arc to the west. The Late Jurassic to Early Cretaceous Vaca Muerta Formation, which is the focus of this study, constitutes the most extensive areal and landward deep marine deposition in the Neuquén Basin.

The Vaca Muerta Formation is part of the Lower Mendoza Group. The group is bounded by two unconformities and is made up of lithostratigraphic units that are often time-equivalent. Lithologies in the Vaca Muerta Formation include alternating shale, marl, chalk, and limestone beds. The basal Vaca Muerta is an excellent oil-prone generating interval that has been recognized as one of the main source rock of the Neuquén Basin (Leanza et al., 2011).

The immense thickness of the formation (100 to 1,000 meters), its favorable mineralogy, and high kerogen content indicate it has potential for being a self-sourcing reservoir comparable to current unconventional plays in the United States. The purpose of this study is to describe the different facies and facies associations present in the formation, and characterize their reservoir
quality in light of new geological concepts. The data available for this study are seismic, well logs, well cuttings, core, and outcrop work.

Seismic data are available as 2D lines throughout the basin and three 3D cubes on the eastern side of the basin covering three blocks. Well logs are available throughout the basin, although the log suites run through the Vaca Muerta can be limited in certain locations. Well cuttings are available for five wells near 2D seismic lines, but there are no wells inside the 3D cube limits. Core is available for the basal 12 meters of the Vaca Muerta in one well within one of the 3D seismic cubes. Outcrops are present on the western margin of the basin, with variable exposure and quality. Figure 0.3 shows the location of the data used in this study.

The results of this study will provide value to the consortium companies by integrating datasets donated by individual companies. It will also provide a methodology for looking at international unconventional resources plays that rely on limited historical data. The identification of the most promising reservoir facies in the data will aid in selecting targets to land horizontal wells and hydraulically stimulate production.

1.2 Motivation/Significance of Project

The objective of this investigation is to integrate various datasets for an international resource play in order to characterize it geologically. The focus is the Vaca Muerta Formation in the Neuquén Basin of Argentina. This will help the consortium member companies in the exploration and production of hydrocarbons from the Vaca Muerta. The focus area was defined by the companies as their primary drilling blocks in the eastern portion of the Neuquén Basin and the Vaca Muerta outcrops located in the fold belt to the west of these blocks (Figure 0.3).
The Vaca Muerta has long been identified as a very important formation to the petroleum system in the Neuquén Basin (Uliana and Legarreta, 1993). It was identified early on as one of the primary source rocks of the basin (Leanza et al., 2011). Only recently, however, has the Vaca Muerta started to be considered a prospect target in its own right. Detailed descriptions that have been undertaken focused on the expulsion potential of the Vaca Muerta. This project will contribute to the understanding of the Vaca Muerta mineralogy and facies stacking patterns from a reservoir perspective.

This project will address issues that are important to the exploration and development of the Vaca Muerta Formation. As with any emerging play, the most common data available are historic well logs. Well logs alone, however, do not fully define an unconventional play. A key question for the Vaca Muerta is whether log response can predict elemental composition, source rock characteristics, and the seismic reflector patterns that define a clinoform.

In addition to this question, developing a methodology for integrating limited and historic datasets in an underexplored basin is also important. Drilling in the Neuquén Basin is extremely expensive given the remoteness of the location and the business climate in Argentina. Maximizing the meaning of available data and the value of new data is therefore of great economic importance to companies. This study will provide a methodology for interpreting the existing suite of logs through the Vaca Muerta. It will also contribute to increasing the confidence of interpretations from measurements, such as hand-held x-ray fluorescence (XRF), which can be used to determine mineralogy. Overall the goal of this study is to provide value to the consortium companies at the current exploration stage of the Vaca Muerta play.
Figure 0.1 Location of the Neuquén Basin in Argentina. This study focused on the center of the basin, outlined by the green box (see Figure 0.2).
Figure 0.2 Location map of data presented in this study within the Neuquén Basin. The hydrocarbon blocks are shown, with the consortium companies’ blocks colored. The consortium’s focus area is outlined by the green box (see Figure 0.3).
Figure 0.3 A close-up of the consortium’s focus area in the eastern Neuquén Basin.
CHAPTER 2
GEOLOGIC OVERVIEW

The Neuquén Basin formed at the edge of Gondwana as the supper continent broke up. There are different accreted terrains in the basement, which introduce some variability into the flexure caused by the rise of the proto Andean magmatic arc. The Vaca Muerta and Quintuco formations make up the thickest portion of the Lower Mendoza Group, which represents the greatest marine encroachment in the basin. They are deposited as clinoforms prograding from east to west, and bound by two unconformities.

2.1 Basin History and General Stratigraphy

The Neuquén Basin was formed on the western margin of Gondwana by a series of tectonic events that occurred mostly during the Mesozoic Era (Howell et al., 2005). The initial stage was a synrift phase that produced narrow half-grabens filled by clastic and volcaniclastic deposits, followed by a post-rift phase dominated by back-arc subsidence (Howell et al., 2005). This stage, spanning from the Early Jurassic to Early Cretaceous, deposited the greatest thickness of sedimentary strata in the basin.

The basement under the basin is comprised of three major accreted terrains (Pangaro et al., 2011) formed during the Gondwana cycle. The Cuyania terrain, which lies against the Gondwanan continental crust in the eastern portion of the basin, was accreted in the Middle to Late Ordovician (Astini, 1996). During Late Devonian the Chilenia terrain was accreted against the Cuyania terrain and forms the basement in the west of the basin (Ramos et al., 1986). Patagonia collided to the south in Late Carboniferous to Early Permian (Ramos et al., 2011), and its boundary is marked by the Dorsal (arch) de Huincul. The configuration of these terrains is presented in Figure 2.1. At the end of the Patagonian Orogeny, a metasilicate to silicate
magnatic province, known as Choiyoi, intruded into the basement underlying the Neuquén Basin. The end of the Gondwana cycle is marked by a slowdown in the subduction of the Pacific plate. The subsequent magnetism helps form semigrabens which are the depocenters for the oldest sedimentary formations in the basin.

The first thick sedimentary infill in the Neuquén Basin is grouped under the Andean cycle (Pangaro et al., 2011). The cycle is characterized by the development of a volcanic arc oriented north-south that extends towards southern Peru. This arc induces the development of the Neuquén Basin as a backarc basin, along with a family of basins formed during this episode that extend as far north as the Oriente basin of Ecuador. The presence of a heterolithic basement composition affected the response of the crust to flexure induced by the rise of the proto-Andean arc. The area underlain by the Patagonian terrain, to the south of the Dorsal de Huincul, recorded a large amount of proximal Cuyo Group sediment deposition of early Middle Jurassic age, which did not prograde into the northern portion of the basin (underlain by the Chilenian terrain) until the late Middle Jurassic. The sediments deposited in the area of Picún Leufú, slightly to the north of the Dorsal de Huincul, have at least three tectonic reactivations (Freije et al., 2002). The next group of sedimentary deposits is the Lotena Group, which records a limited marine excursion into the basin followed by platform carbonates when sedimentary input is limited. There is widespread development of thick evaporate packages, suggesting restricted access to the proto-Pacific and a positive balance between accommodation space and sedimentary rates. The Lotena group is recognized by many authors as the final expression of the Andean cycle.

Groeber (1946) named the increased and expansive continental sedimentation, followed by the largest marine transgression in the basin’s history, as the Andico cycle. The Andico cycle is made up of the Mendoza Group and the Bajada del Agrio Group (Figure 2.2). Marine
sedimentation extends much further than the earlier Pliensbachian-Toarcian Cuyo Group (Figure 2.3). The Vaca Muerta is the lithostratigraphic name for the Tithonian-Berrasian marine transgression that forms the thickest sequence of the Lower Mendoza Group. The Upper Mendoza contains the Agrio Formation, which is less extensive. The Bajada del Agrio Group records a definite drying of the basin and includes evaporites and red beds. The end of the Bajada del Agrio Group marks the closing of the access to the proto-Pacific and the continental sedimentation of the Neuquén Basin during the Late Cretaceous.

Deposition in the basin is relatively quiescent during the Late Cretaceous (Cenomanian to Maastrichtian). With the aperture of the Atlantic Ocean and the separation of South America from Africa an eastern transgressive event flooded the basin. Deposition and tectonic activity in the Cenozoic is dominated by the development of the Andean Cordillera. The current outcrops in the fold belt at the foothills of the Andes, as well as, the subsurface folding identified in seismic data, developed during the three stages of deformation of the Andes.

2.1 Lower Mendoza Group

The Lower Mendoza Group was deposited during the Early Cretaceous. Figure 2.4 shows the paleogeography of the Neuquén Basin during this time, and the generalized deposition of lithologies. The Lower Mendoza Group is bounded by the Araucanica Unconformity at its base (155.6 Ma, Kimmeridgian) and the Huncalica Unconformity at its top (~138 Ma, Valanginian). The isopach for this Tithonian-Valgarian section is shown in Figure 2.5. The Araucanica Unconformity is formed by the fluvial base of the Tordillo Formation over the Lotena Group. The Tordillo is overlain by the deep marine Vaca Muerta Formation, whose lower section is a transgressive marine flooding over the entire basin. The
Quintuco Formation is the shelf and near shore expression of the prograding Vaca Muerta/Quintuco clinoform system (Figure 2.6). The edges of the basin hold time-equivalent named formations, most notably the carbonate platform Picún Leufú and clastic Bajada Colorada in the southern part of the basin (Picún Leufú sub basin), the marginal marine and evaporite Loma Montosa Formation in the eastern edge, and the turbidic Huncal and Rahueco Members in the north-western edge (Leanza et al., 2011; Figure 2.7 and Figure 2.8). The Huncalica Unconformity is formed by the fluvial Mulichinco Formation, which is part of the Upper Mendoza Group. The Vaca Muerta Formation makes up the greatest thickness of the Lower Mendoza Group and is its most distinctive feature.

2.2 Vaca Muerta and Quintuco Formations

The most important relationship in the Lower Mendoza Group is between the Vaca Muerta and Quintuco Formations. These formations are the largest components of the prominent prograding clinoform packages that identify the Lower Mendoza Group. The Vaca Muerta is the distal, deep marine black shale and deep water carbonate facies of the clinoforms, while the Quintuco is a grey shale to siltstone/sandstone interbedded with carbonate slope and proximal facies. Other formations of the Lower Mendoza Group are locally present as shallow marine to fluvial and sabkha facies.

The Vaca Muerta Formation was recognized by one of the first workers in the Neuquén Basin, Charles Weaver, who explored the area on horseback in 1931. It is a lithostratigraphic term assigned to interbedded black shales and carbonates overlying the Tordillo sandstone. These black shales grade into grey shales and silts, a lithology that is often ascribed to the Quintuco Formation, although differences in what constitutes the “Quintuco” do exist (Leanza et al., 2011). The top of the Vaca Muerta gets younger towards the center of the basin. Together the
Vaca Muerta and Quintuco are the predominant formations that make up the Lower Mendoza Group, especially in subsurface interpretation, and represent a catastrophic flooding event (Transgressive Surface of Erosion), followed by a shallowing upward infilling of the accommodation space (Highstand Systems Track). All of the other formations and members that are time-equivalent to the Vaca Muerta (between the Araucanica and Huncalica unconformities) are shallower facies related to processes active at the basin margins.

2.3 Vaca Muerta Facies and Mineralogy

The Vaca Muerta Formation is often referred to as a shale or black shale (Nawratil et al., 2012). A significant portion of the Vaca Muerta has been recognized as carbonate, especially in the eastern portion of the basin (Nawratil et al., 2012). As a litho-stratigraphic term, Vaca Muerta is often described as calcareous benches encased in black shales.

The term “shale” has increased in usage because of the proliferation of fine-grained oil and gas plays. The term “shale gas” and “shale oil” are often used as catch-all labels for hydrocarbons recovered from reservoirs that require stimulation; yet a great quantity of these reserves are in rocks with neither a fine-grained texture nor significant clay mineralogy. The Vaca Muerta is comprised primarily of rocks with a shale texture, with some carbonate wackestones and a few silt- to sandstone bodies. Compositionally, the formation has only a small percentage of clay minerals, especially compared to formations in the United States commonly referred to as “shale”.

Kietzmann (2007) described in detail an outcrop in the northern portion of the basin, near the Loncoche Creek in Mendoza Province. He presents scanning electron microscorpe (SEM) images and secondary electron data for 11 samples throughout the outcrop focused on the
identification of clay minerals. Illite is consistently present throughout the section, with higher intensity peaks in the bottom half of the samples. Illite/smectite peaks are present at discrete intervals, but absent in others. Kaolinite is present only in trace amounts in the bottom of the section, but increases in abundance until it dominates the top of the section. Chlorite is present in trace amounts throughout all the samples. Kietzmann (2007) does not find significant differences in the appearance of clay minerals between sedimentary facies, or between fine-grained lithologies (marls or shales). He suggests that the clay minerals found in the samples are therefore detrital in origin and sourced from erosion of the surrounding landmass, primarily the proto-Andean volcanic arc to the West. Weaver (1989) proposes that illite would dominate in arid to semiarid conditions, and illite and illite/smectite in semiarid conditions. An increase in rainfall to near 50 cm/year would increase the conversion of illite to illite/smectite. Above 50 cm/year of rainfall kaolinite would predominate. Kietzmann (2007) proposes a tentative link between the abundance of the relative clay minerals and the prevalent weathering patterns at the time of deposition.

Kietzmann et al., (2008) identify 12 lithofacies and 8 microfacies based on the same section as Kietzmann (2007) in Mendoza. They group facies into associations interpreted as basin, outer ramp (distal and proximal), and middle ramp depositional settings. Most of the facies presented by Kietzmann et al., (2008) are carbonates, with definitions based on lamination vs. massive, and bioclastic versus nonbioclastic deposition.

2.4 Vaca Muerta Chemosтратigraphy

With the advent of hand-held x-ray fluorescence technology it has become relatively simple to analyze samples for elemental composition. Nawratil et al. (2012) performed a chemical element analysis using X-Ray Fluorescence (HHXRF) on 4,300 Vaca Muerta cutting
samples from 58 wells in the Agua del Cajon block in the southern margin of the Neuquen Basin. In addition, they analyzed 80 samples for total organic content (Rock Eval TOC) and mineralogical X-Ray Diffraction (XRD). Nawratil et al. (2012) relate the amount of Zr identified through the XRF tool as an indicator of the siliciclastic vs. chemical (Ca precipitate) sedimentary input into the system and suggest that the Lower Vaca Muerta, which shows an increase of Zr relative to the Upper Vaca Muerta, is dominated by clastic sedimentation. Their results are shown in Figure 2.9.

2.5 Vaca Muerta – Quintuco Seismic Clinoforms

The Vaca Muerta – Quintuco lithostratigraphic units have been recognized as a clinoform system since their description by the first workers in the Neuquén Basin. With the advent of seismic data, however, the clinoforms came into distinct focus. Mitchum and Uliana (1985) and Mitchum and Uliana (1987) wrote a definitive study on the shape, depositional style, and progradational nature of the Vaca Muerta – Quintuco system based on 2D seismic lines stretching from east to west across the basin. One of their most significant conclusions was the identification of eight major clinoform surfaces, labeled A to H (Figure 2.10). As the clinoforms get younger the depositional axes progrades into the basin from east to west (Figure 2.11). Mitchum and Uliana (1985) grouped the eight clinoforms into three depositional styles (Figure 2.12). The Early–Mid Tithonian section (surfaces A-C) is low-relief progradational with an ill-defined shelf break. The Berriasian–Late Tithonian section (surfaces D-F) is aggradational with complex oblique clinoforms and toplap terminations. The Valanginian section (surfaces G-J) has a constrained geometry but continues to be aggradational with thick packages.

The Michum and Uliana (1985) study is a seminal work that integrates sea-level curves, well log observations, and seismic data. The current study is focused on examining a smaller
area of the Vaca Muerta – Quintuco system, but uses many of the conclusions from Michum and Uliana (1985) as a basis.

2.6 La Lata Anticline

This study focuses on subsurface interpretation of the Loma La Lata area, which is the largest hydrocarbons accumulations in the basin (Hechem, 2010). It is a large anticline discovered by well YPF.Nq.LLL.x-1 in 1977 (Hechem, 2010). The anticline is located in the basin center near the Bajo (low) de Añelo axis of deposition (Pangaro et al., 2011). The main conventional reservoir Loma unit is the Sierras Blancas Formation, which is reported as having an estimated ultimate recovery (EUR) of 28,000 million cubic meters (10 TCF) of gas and more than 20 million cubic meters of condensate (Hechem, 2010).

The structural history of the basin is divided into three phases (Pangaro et al., 2011; Dean, 1987). Compressional events occurred in two of the phases. First, during the end of Phase II (late Cretaceous to Cenozoic) the rate of subduction to the west slowed down, causing the Neuquén region to become a retro-arc foreland basin and induced significant shortening (Howell et al., 2005). Major folding and uplift also occurred during the Tertiary Phase III, which was dominated by the Andean Orogeny (Pangaro et al., 2011). The Loma La Lata structure is associated with both these events.
Figure 2.1 Location and provenance of basement underneath the Neuquén Basin, and their relationship with the western margin of Gondwana. Modified from Mosquera et al., 2011.
Figure 2.2 Stratigraphic chart for the Neuquén Basin with relative lithologic composition and named unconformities. Modified from Arregui et al., 2011.
Figure 2.3 Maximum extent of marine flooding during the major transgressions in the basin. The Tithonian-Berasian flooding surface, of which the Vaca Muerta is the deep marine facies, reached further landward and was of a greater extent than the older Pliensbachian-Toarcian. Modified from Arregui et al., 2011.
Figure 2.4 A schematic of the paleogeography of the Neuquén Basin during the Early Cretaceous, showing general lithologic deposition. Modified from Spalletti et al., 2008.
Figure 2.5 An isopach map of the Tithonian-Valgarian cycle, of which the Vaca Muerta is the thickest lithostratigraphic unit. From Leanza et al., (2011).
Figure 2.6 Stratigraphic column for the Lower Mendoza Group showing the time-transgressive nature of the lithostratigraphic units. The Vaca Muerta and Quintuco are the thickest formations in the Lower Mendoza Group. Modified from Leanza et al., 2011.

Figure 2.7 Schematic depositional relationship between all the lithostratigraphic units of the Lower Mendoza Group. The Vaca Muerta is the distal expression of prograding clinoform. Modified from Leanza et al., 2011.
Figure 2.8 Schematic relationship between the different lithostratigraphic units of the Lower Mendoza Group. Modified from Leanza et al., 2011.
Figure 2.9 Individual (colored) and average (black) element curves for samples in the Agua del Cajon block, 75 km south of the Puesto Sin Nombre X1 well (used for this study). From Nawratil et al., 2012.
Figure 2.10 Regional geologic cross section from Mitchum and Uliana (1985) showing seismic clinoform horizons and well ties with interpreted lithology. Cross section location is shown as A-A' in Figure 2.11.
Figure 2.11 Shelf breaks for the clinoforms identified by Michum and Uliana (1985).

Figure 2.12 Major grouping of clinoform surfaces in Michum and Uliana (1985). Early – Mid Tithonian (A-C) is low-relief progradational. Berriasian – Late Tithonian (D-F) is aggradational. Valanginian (G-J) is constrained aggradational.
CHAPTER 3
METHODOLOGY

The methodologies used in this research included outcrop work, x-ray diffraction (XRD), x-ray fluorescence (XRF), source rock pyrolysis, well log interpretation, and seismic interpretation. The goal of using different datasets was to integrate results and high-grade the significance of each measurement.

3.1 Outcrop Work

Two field seasons were conducted in Neuquén in order to measure outcrops of Vaca Muerta along the fold belt at the foothills of the Andes on the western edge of the Neuquén Basin. The purpose of the field studies was to walk out and sample the entire Vaca Muerta section. The thickness of the Vaca Muerta suggests that few, if any, company will ever core the entire interval, so outcrops provide invaluable insight into bed boundaries and facies. Additionally, at the time of outcrop section measurement, there were no rock samples available to the consortium, so outcrops samples were very important. Table 3.1 gives the location of the outcrops and some key observations. Figures 3.1, 3.2, 3.3, 3.4, 3.5, and 3.6 shows the general and detailed location of the outcrop with satellite images.

The first field season was conducted in December 2012 with help from Pluspetrol. It focused on measuring the outcrop at Puerta Curaco near Chos Malal. Multiple studies and discussions with Argentinian companies have established that this outcrop is the best exposed full section of the Vaca Muerta. The facies present at Puerta Curaco are deeper water than many of the facies found in the subsurface to the east, but it nonetheless provides a unique opportunity to see the entire Vaca Muerta. The measured section focused on identifying the lithology (mostly based on weathering pattern) of beds within the Vaca Muerta and sampling at key intervals. The
samples brought back from Puerta Curaco were made into petrographic thin sections and analyzed for mineralogy and source rock properties.

The second field season was conducted in May 2013 to measure the type locality of the Vaca Muerta Formation at the Sierra de la Vaca Muerta outcrop near Zapala. This outcrop is directly east of the blocks with seismic data, and so provides a more direct opportunity for correlation, although the full section is not visible. The same criteria for the lithology/weathering profile, was followed as at Puerta Curaco. In addition to Sierra de la Vaca Muerta, other outcrops were visited and sampled at the contact between the Vaca Muerta and the Tordillo.

3.2 Well Cuttings

Well cuttings were provided by Shell, who arranged to have them collected and shipped from the repository in Neuquén City. The locations of wells with cuttings are shown in Figure 3.8. The wells with cuttings that were received at the Colorado School of Mines are Jaguel del Rosauros 1, Bajada del Palo X-3, Puesto Sin Nombre X-1, Medano de la Mora X-1, and Bajada Colorada 1. Additionally, Sierras Blancas Oeste X-1 (SBOX-1) had cuttings that were analyzed for total organic content (TOC) weight percent directly by Shell. All the cuttings were examined and evaluated for quality. Table 3.2 lists the logs available and the observations made on the cuttings that were received at the Colorado School of Mines. Puesto Opazo 1 and Bajada del Palo X-3 must have experienced uncontrolled mud loss because their cuttings for the Vaca Muerta section were full of walnut shells (lost circulation material). The well chosen for this study, Puesto Sin Nombre X-1 (PSNOX1), had a lot of cuttings material, no walnut or other additive in the cuttings, and a good depth match to the logs.
PSNOX1 cuttings were ground up using a mechanical mill provided by Professor Richard Wendlandt. Samples were only milled for about 1 minute to minimize heat and the deterioration of kerogen. About half the available cutting sample was milled in order to provide future researchers with raw material. Cuttings and cutting powder were analyzed through x-ray diffraction mineralogy, x-ray fluorescence elemental composition, and source rock analysis.

### 3.3 X-Ray Diffraction Mineralogy

X-Ray Diffraction (XRD) analysis is a technique in which the counts of x-ray diffraction are recorded at various angles. Minerals have well-defined angles of diffraction which form peaks that can be recognized and interpreted semi-quantitatively. Two different processes were applied to collecting XRD data. One was using the department’s XRD machine under the guidance of Professor Richard Wendlandt. Outcrop samples were analyzed both for whole-rock analysis and clay-size fraction. Cuttings samples were analyzed only for whole-rock mineralogy because of the lack of material. The raw data and two-theta plots generated for each sample are included in the data DVD attached in Appendix A. Some samples were run from 5 to 60 two-theta. The majority of cuttings samples were run from 24 to 32 two-theta because the minerals of interest were quartz and calcite, which have their most recognizable peaks at 26.7 and 29.4 two-theta respectively. Other minerals of interest and their major peaks (two-theta) were dolomite (30.98), gypsum (31.2), feldspar (27.5-28), and the kaolinite 002 peak (24.9). Due to the inherent uncertainty in absolute intensity of peaks, samples were compared using a ratio of two mineral peaks. The most important ratio was that between quartz and calcite because they were the major peaks. Logs shown in Chapter 5 were derived from the ratio of these peaks.

The other method employed for mineralogical data was sending samples to an outside vendor, The Mineral Lab in Golden, Colorado. Outcrop and cuttings samples were sent to The
Mineral Lab in order to receive calibrated, semi-quantitative results of the whole rock mineralogy. Since XRD results are heavily reliant on individual labs’ interpretation and calibration, it is useful to have multiple XRD interpretations. The Mineral Lab has been used for other fine-grained mudrock research conducted at CSM (Niobrara Consortium and Bakken Consortium). The samples analyzed by The Mineral Lab were used to calibrate the samples run on the department’s XRD machine by comparing the mineral percentage reported by The Mineral Lab with the peak ratio observed on the same sample run in-house.

In order to roughly quantify the results from the department’s XRD, an equation was derived from points plotted on calcite/quartz peak ratio vs lab reported calcite percent graph, shown in Figure 3.7.

3.4 X-Ray Fluorescence Elemental Composition

X-ray fluorescence (XRF) analysis is a technique in which secondary x-rays from a material are generated and counted. Cuttings were analyzed with a handheld Bruker T4S2572 tool. For each sample, at least 5 mm of sample material was placed on a clear plastic film above the aperture. A major and a trace elements assay was conducted for 90 seconds each, and results captured in weight percent. An Excel macro was used to convert weight percent of each element into parts per million (ppm). Elements that were important to this study are Aluminum (Al), Titanium (Ti), Niobium (Nb), Thorium (Th), Cerium (Ce), Hafnium (Hf), Lanthanum (La), Sulfur (S), Iron (Fe), Rhenium (Re), Molybdenum (Mo), Uranium (U), Vanadium (V), Calcium (Ca), Silica (Si), Zinc (Zn), Copper (Cu), Zirconium (Zr), and Nickel (Ni).
3.5 Source Rock Analysis

Cutting samples for the PSNOX1 well were evaluated for source rock characteristics using a Source Rock Analyzer (SRA) in Dr. Steve Sonnenberg’s lab by one of his students. Between 60-100 mg of the powdered sample were analyzed with a pyrolysis process that yielded S1, S2, and maximum temperatures (Tmax), as well as, estimated total organic content (TOC) percent. These values indicate the maturity of the rock and generation capability. Source rock characteristics for cuttings from the SBOX1 well were provided by Shell. The data were integrated with well logs, XRD, and XRF analysis and are presented in the Chapter 5 Results.

3.6 Well Log Interpretation

Well logs were one of three main components for this study. Consortium companies provided historical logs for the entire Neuquén Basin in “.las” format. No proprietary logs were provided, which is one potential area of future research. All the logs were screened for data through the focus section from the Mulichinco-Quintuco contact to the top few meters of the Tordillo below the Vaca Muerta. Unfortunately due to the cost drilling in Argentina, many companies have historically decided not to log the Vaca Muerta when targeting deeper sections, or have only run limited suites. A basin-wide log study was out-of-the-scope of this study given the available data.

The Vaca Muerta – Quintuco section was picked in each log where it was possible to do so. The Top Quintuco and Base Vaca Muerta are sharp lithologic contacts and represent unconformities. The boundary between these two lithologic units, however, is much more difficult to pick and has been a source of uncertainty in the basin. It is usually located where carbonate and mudrock intervals become more siliceous and darker in color in the cuttings. The log response ascribed to this lithologic change is a gamma ray reading that stays roughly below
80 API units and a slower sheer compressional speed. It is, however, a tentative boundary that varies in description by interpreter and in different areas of the basin.

Fourteen wells were selected as the primary wells for this study. Their locations are shown in Figure 3.8. These wells were selected because they went through the Loma La Lata seismic cube and/or had cuttings available. Table 3.3 shows the logs for each well that were run through the Vaca Muerta – Quintuco section.

An important tool in this study was the use of Schlumberger’s Techlog software, specifically its Unconventionals HRA Clustering and HRA Tagging modules. These tools perform a statistical least-means analysis on a given interval and group log responses into a predetermined number of “electrofacies”. Multiple iterations and comparison to the available rock samples help establish the number of groupings that best represent the number of reservoir facies in each section. Once a pattern is established in one well, it can be applied to other wells and its results validated or modified.

The Anelo Neuquén X-1 (ANNX1) well was used as the principal electrofacies well to which all the rest were tagged. This well was chosen because it had a complete suite of logs (RHOB, DTCO, and GR) and it is located in the center of the clinoform packages seen in the Loma La Lata seismic data. It is important to choose the principal well with care because it is not possible to add or modify facies definitions when tagging other wells. This means that if a facies is missing in the principal well but present in a tagged well, it will not be recognized. The ANNX1 well was chosen in the middle of the seismic data in order to minimize this type of error.
The gamma ray curve was normalized in all the wells that were used for electrofacies analysis. Figure 3.9 shows an example of the results of normalization for two wells. Quantile normalization was used because it provided the best-looking shift in the data.

3.7 Seismic Interpretation

The consortium had three 3D seismic cubes donated by companies. The one used for this study was the Loma La Lata, which was purchased from the Neuquén government by Shell. It is a composite of five 3D surveys and therefore has a non-polygonal shape (Figure 3.8). Seismic horizons for the Vaca Muerta Base (Tordillo) and Quintuco Top were identified with the help of geologists from Shell, who had also worked on the same seismic cube. Due to the vintage of the wells that penetrate the seismic it was not possible to acquire any check shots that may have been collected, and hence a synthetic well tie was not constructed. The Vaca Muerta Base and Quintuco Top are major unconformities, however, and are therefore easily distinguishable as high amplitude reflections that were tied to well horizons.

Within the Vaca Muerta – Quintuco section, clinoforms were identified. Major clinoform surfaces were identified through the onlap and downlap of minor surfaces. The model proposed by Mitchum and Uliana (1985; 1987) was used as a basis for the seismic interpretation. The defining surfaces between the progradational and two aggradational sets were identified first. Internal clinoforms were then interpreted, although not every reflector was traced to its full extent.
Figure 3.1 Map showing the location of all the outcrops visited for this study.
Figure 3.2 The Picun Lefu outcrops, which are part of an anticline. The Picun Lefu South outcrop contains many ammonites.

Figure 3.3 The Mallin Quemado and Mallin de los Caballos outcrops exposed along gullies. The Vaca Muerta outcrops along the entire ridge, which is held up by the Tordillo Formation. The Los Catutos member outcrops at the base of the slope.
Figure 3.4 The outcrops near Cerro Mulichinco. Cerro Mulichinco South contains many examples of calcite beef, and is exposed along a deep gully.

Figure 3.5 The Chacay Mehue outcrop, which has many large concretions.
Figure 3.6 The Puerta Curaco and Yesera del Tronel outcrops. These are the best exposure of the full Vaca Muerta system.

Table 3.1 Location and some key observations of the outcrops visited as part of this study.

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerro Mulichinco South</td>
<td>-38.046</td>
<td>-70.43484</td>
<td>Abundant calcite beef (bedding-parallel veins of fibrous calcite)</td>
</tr>
<tr>
<td>Arroyo Mulichinco</td>
<td>-38.0224</td>
<td>-70.47329</td>
<td>Concretion beds</td>
</tr>
<tr>
<td>Mallin de los Caballos</td>
<td>-38.6702</td>
<td>-70.19213</td>
<td>Has a fold and Los Catutos member</td>
</tr>
<tr>
<td>Mallin Quemado South</td>
<td>-38.6097</td>
<td>-70.15213</td>
<td>Los Catutos member at the base of the ridge</td>
</tr>
<tr>
<td>Mallin Quemado North</td>
<td>-38.5745</td>
<td>-70.1132</td>
<td>Less exposed than South</td>
</tr>
<tr>
<td>Picun Lefu Bridge</td>
<td>-39.212</td>
<td>-70.05497</td>
<td>Silt and sandstone facies</td>
</tr>
<tr>
<td>Picun Lefu South</td>
<td>-39.2133</td>
<td>-70.07394</td>
<td>Amonites in sandstone</td>
</tr>
<tr>
<td>Puerta Curaco</td>
<td>-37.3807</td>
<td>-69.94497</td>
<td>Best exposure of entire system</td>
</tr>
<tr>
<td>Chacay Mehue</td>
<td>-37.2593</td>
<td>-70.46416</td>
<td>Many large concretions, eroded</td>
</tr>
<tr>
<td>Yesera del Tronel</td>
<td>-37.2218</td>
<td>-69.80705</td>
<td>Good exposure, concretions</td>
</tr>
</tbody>
</table>
Table 3.2 Available logs and observations of cuttings received at Colorado School of Mines. Puesto Sin Nombre X-1 was chosen for this study.

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Available Logs</th>
<th>Cuttings Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaguel de Rosauros 1</td>
<td>GR, DT, RHOB</td>
<td>No visible walnut shells. Good quality cuttings with good transition from shale to silt.</td>
</tr>
<tr>
<td>Bajada del Palo X-3</td>
<td>GR, DT</td>
<td>Very large pieces towards bottom of section. Good amount of sample in most bags, good color transition.</td>
</tr>
<tr>
<td>Puesto Sin Nombre X-1</td>
<td>GR, DT</td>
<td>No visible additives or major cavings, good amount of sample in each bag, good color transition.</td>
</tr>
<tr>
<td>Puesto Opazo 1</td>
<td>GR, DT, RHOB</td>
<td>From 288-2948 the bags are all walnut shells. From 2249-2825 there is a large amount of sample with good transition from shale to silt.</td>
</tr>
<tr>
<td>Medano de la Mora X-1</td>
<td>DR, DT</td>
<td>Very powdered cuttings in downhole samples. Good transition from shale to silt.</td>
</tr>
<tr>
<td>Bajada Colorada 1</td>
<td>GR, DT, RHOB</td>
<td>Walnut shells in Vaca Muerta section. Good amount of sample in Quintuco section.</td>
</tr>
</tbody>
</table>

![Calcite Calibration](image)

Figure 3.7 Plot showing the ratio of calcite/quartz two-theta peaks for XRD done in the department vs reported calcite percentage from The Mineral Lab. The equation was used to roughly quantify the XRD results from the department’s machine.
Figure 3.8 Location of wells and seismic data in the area of study. The Loma La Lata seismic cube is a composite of five different surveys, hence its shape.
Table 3.3 Logs available through the Vaca Muerta – Quintuco section for the wells used to calculate electrofacies in this study. The location of these wells is shown in Figure 3.8.

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Short Name</th>
<th>GR</th>
<th>SP</th>
<th>DT</th>
<th>RES</th>
<th>RHOB</th>
<th>NPHI</th>
<th>NEU</th>
<th>PEF</th>
<th>Cuttings</th>
<th>Core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berreales Colorado 2</td>
<td>Bec.X2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sierras Blancas Oeste X1</td>
<td>SBO.X1</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Chihuidos Colorados X1</td>
<td>ChCo.X1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Loma La Lata E5</td>
<td>LLL.E5</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Loma La Lata a342</td>
<td>LLLa342</td>
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Figure 3.9 An example of gamma ray normalization carried out on all the wells that were used for electrofacies analysis. The quantile normalization was used because it provided the best-looking shift.
CHAPTER 4
RESULTS

Various types of analysis were carried out as part of this study, and each reached results independently of the others. The figures presented in this chapter capture some of the observations for each individual methodology. Raw data is included in the attached CD.

4.1 Outcrop Observations

Outcrop work was conducted before subsurface data was available. It focused on understanding the different lithologies present in the Vaca Muerta section and their vertical and lateral heterogeneity. Although outcrop results were not primary to the conclusions reached by this study, they are presented below for possible future follow-up by subsequent researchers.

4.1.1 Measured Sections

Outcrops of Vaca Muerta were only available in the western portion of the basin adjacent to the Andean uplift. Although the facies in these outcrop are different from those found in the subsurface to the east (and where the majority of this study was focused), fieldwork was still invaluable in understanding the Vaca Muerta – Quintuco system. The section is so thick at even its thinnest in the subsurface (100 meters) that a full core is not a cost-effective way of characterizing the rocks in the subsurface.

The Puerta Curaco outcrop was measured and sampled in detail because it is the best exposure of the Vaca Muerta in the basin (see Figure 3.1 for location). The outcrop is part of the limb of an anticline that dips 42-47 degrees (Figure 4.1). The Vaca Muerta – Tordillo contact was identified as the first occurrence of ammonites above silt beds (Figure 4.2). The outcrop is made up of resistive limestone beds surrounded by shale. Exposure quality varies, but in certain places is very good (Figure 4.3). The Vaca Muerta – Quintuco contact is transitional and was set
where silt and grey shales supplanted black shale (Figure 4.4), although some workers have described the entire Puerta Curaco outcrop as part of the Vaca Muerta lithostratigraphic unit.

A detailed measured section with source rock and mineralogical analysis was completed at this outcrop (Figure 4.5). The focus of the measured section was to identify erosional resistant units (high calcite content) versus slope formers (siliceous mudrocks). Moderately eroded units were classified as marls. The calcareous units increase in abundance up the section. Towards the top of the section siltstone units were identified. Figure 4.6 shows the estimated percentage of each lithology in the outcrop. Throughout the section there are bentonite beds that record the high level of volcanic activity in the basin during the deposition of the Vaca Muerta.

Thirty-two samples were collected from intervals that looked interesting and/or representative of the section at that depth. All the samples were analyzed for source rock characteristics and ten samples were analyzed for mineralogy using XRD. Figure 4.5 shows the TOC values colored by lithology throughout the outcrop, as well as, the mineral percentages from the XRD. Figure 4.7, Figure 4.8, Figure 4.9 show TOC and mineralogy results and illustrate what the samples looked like in outcrop. Figure 4.10 shows the distribution of TOC values by lithology. Table 4.1 presents the average TOC values by lithology, as well as, an absolute and weighted (by lithology) average TOC.

4.1.2 Vaca Muerta – Tordillo Contacts

Although the Vaca Muerta can have a large surface expression in the western Neuquén Basin, it is difficult to find good outcrop exposures. One surface that is easy to identify is the Vaca Muerta – Tordillo contact because it is a clear unconformity and transgressive surface of erosion where deep-marine shales overlie sand and silt (which are sometimes aeolian). All the
Vaca Muerta – Tordillo contacts that were examined during fieldwork for this study are shown below

### 4.1.3 Calcite-filled Fractures

Fractures have been recognized as important in the producibility of tight reservoirs. The Vaca Muerta is known to have distinctive fractures filled bedding-parallel veins of fibrous calcite, commonly referred to as calcite beef (Rodrigues et al., 2009). Future studies could further the understanding of how these fractures formed and how they affect reservoir characteristics. The Cerro Mulichinco South outcrop in particular had a tremendous amount of calcite-filled horizontal fractures. It is located in a remote area, so it is worth documenting its location and appearance. Figure 4.14 and Figure 4.15 show the calcite beef at this outcrop.

### 4.1.4 Concretions

Calcite concretions are a distinctive feature of the Vaca Muerta section. They range in size from 0.1 m – 1 m in diameter (Figure 4.16, Figure 4.17, and Figure 4.18). Concretions often occur along an entire bed spaced out by a pure shale interval (Figure 4.19). Their occurrence to a particular stratigraphic level has not been determined in this preliminary analysis. Future work could focus on studying the concretions more closely. They have become of interest in unconventional plays in the United States like the Bakken and Eagleford as drilling hazards, sources of fractures, and baffles to stimulation and production.

### 4.1.5 Los Catutos Member

Los Catutos Member is a limestone-rich interval of the Vaca Muerta identified primarily in the eastern portion of the basin. It was identified in outcrop along the Mallin Quemado – Mallin de los Caballos ridge (Figure 3.3). No definite analysis was performed on any of the samples.
collected from Los Catutos. It could, however, be of interest to future studies as a brittle interval in the subsurface that could be more susceptible to hydraulic fracturing. Figure 4.20 and Figure 4.21 show the Los Catutos member in outcrop, with its characteristic layering of thick limestone beds and marls. Future workers could propose to sample the fine-grained beds in the Los Catutos member and describe their source rock characteristics, as well as, the reservoir characteristics of the limestone beds.

4.2 X-Ray Diffraction Mineralogy

Mineralogical percentages were collected using x-ray diffraction (XRD). Mineral percentages for individual outcrop samples are presented above under heading 4.1.1 Measured Sections. Based on the average mineralogy weighted by lithology the Vaca Muerta can be described as a siliceous marlstone (Figure 4.22). X-ray diffraction was also performed on the cuttings for the PSNOX1 well. The 2-Theta plots for each sample are stored in the accompanying DVD (Appendix A). The results obtained from XRD were quantified using the relationship presented in Figure 3.7. The results of this qualitative analysis are shown in Figure 4.23. The ratio of quartz peak to calcite peak increased in the cuttings up the section, which is congruent with the system becoming more carbonate rich as it transitions from the Vaca Muerta to the Quintuco.

4.3 X-Ray Fluorescence Elemental Composition

Measuring major and trace element composition in fine-grained rocks is a long established practice dating from the early 1900s, and solidified during the 1980s as an oil-industry tool for studying source rocks (Sageman et al., 2003). Certain elements have been established as detrital-proxy indicators, the most common of which are: Ti, Nb, Th, Ce, Hf, and La (Ross and Bustin, 2009). Redox-proxy indicator elements are: C, S, Fe, Re, Mo, U, and V (Ross and Bustin, 2009).
There have been instances, however, where Mo, U, and V have proven poor paleoredox proxies under certain sedimentary conditions, for example in the Upper Besa River Shale of the Western Canadian Basin (Ross and Bustin, 2009).

The XRF results for the PSNOX1 cuttings show some very interesting trends. Figure 2.24 shows the concentrations for major elements in the cuttings by depth. The silica (Si) concentration is highest at the base of the section, decreasing up section. Conversely, the calcium (Ca) concentration is lowest at the base and increases up section. These results are in line with the transition from the Vaca Muerta Formation into the Quintuco Formation, which is much more calcareous.

Another trend is the increase of Ti/Al in the section. The ratio is high at the base, then decreases dramatically and slowly increases towards the top. Ti/Al has been suggested as a proxy for detrital input (Sageman et al., 2003). For the section above the base, increases in detrital input are in line with a progradational and aggradational model of deposition. The bulge at the base is located in the Transgressive Systems Track below the maximum flooding surface. An increase in Ti/Al could be explained by reworking of underlying continental sediments of the Tordillo formation.

Figure 4.25 shows the results of trace elements from XRF of the PSNOX1 cuttings. The major visible trend is a high concentration of trace metals (Mo, V, Ni, Cu, Mo) in the base section. These metals are indicative of anoxic conditions (Sageman et al., 2003). Other metal concentrations stay somewhat constant within the section.

XRF results for this study were preliminary within the wider study that is currently being conducted at the Colorado School of Mines Vaca Muerta consortium. Elemental composition is
shown to vary within the Vaca Muerta section by depth and log response, which has implications for environment of deposition interpretations and exploration. Further analysis of elemental composition will be presented by future workers.

### 4.4 Source Rock Characteristics

Source rock data was available from cuttings, core, and outcrop samples. Outcrop data relies on random sampling of the entire interval and was collected at the Colorado School of Mines lab. PSNOX1 cuttings represented samples every 3 meters throughout the entire interval and was also collected at CSM. Source rock analysis for cuttings from SBOX1 was provided by Shell. Sampling intervals for this well varied from 4 to 20 meters. Data was also available from the core supplied by Pluspetrol and analyzed at Terratek, but represented only the bottom 12 meters of the Vaca Muerta section.

Each data type supplies a different type of information; core shows the best source rock interval in great detail, cuttings are an average of the subsurface, and outcrop samples are weathered. Though direct comparison of the different data types is difficult, using different types provides a broader understanding of how the Vaca Muerta could be characterized for source rock potential.

A maturity window plot is shown in Figure 4.26. Cuttings and core data all fall within the oil window. Outcrop data is unreliable in this plot because it is overmature, and most of the data plots off the Tmax limits of the chart. Cuttings show a range of maturities, but mostly plot in the oil window.

A source rock potential plot is shown in Figure 4.27. Outcrop data is unreliable because it is overmature. Core data has the highest resolution of the best (base) source rock section of the
Vaca Muerta. Cuttings plot along a range of generation potential, with some samples showing intervals of source rock that are as good as individual beds in the core.

A modified van Krevelen diagram is shown in Figure 4.28. The outcrop samples are unreliable because they are overmature. The core samples are clustered at the Type II line. Cuttings samples are spread between Type II and Type III curves.

4.5 Defining Electrofacies

The purpose of electrofacies interpretation is to group log responses in a statistically significant and reproducible manner. Different interpreters may have different ideas on what a “hot” or “very hot” gamma ray is, and it is notoriously difficult for people to generate accurate statistics simply from observations. Electrofacies analysis is a more sophisticated way of log interpretation, but it still requires inputs and understanding from an interpreter.

The Anelo Neuquén X1 (ANNX1) well was used as the master well for electrofacies generation. The rest of the wells were tagged using the ANNX1 as a template. Through an iterative process, it was established that five electrofacies provided a good description of the Vaca Muerta – Quintuco section. Each facies has a range of gamma ray, density, and compressional sonic responses, which are shown in Figure 4.30 as box-and-whisker plots. Figure 4.31 shows some of the outputs from Techlog regarding the principal components of the statistical computation done by Techlog. An in-depth discussion of the statistics involved in principal component analysis is beyond the scope of this study. It is sufficient to say that Techlog was used as a tool to provide statistically significant, reproducible groupings of log response. Figure 4.32 shows a cross section with the results for electrofacies with all the wells that were tagged.
Well Puesto Sin Nombre X-1 (PSNOX1) was tagged with the electrofacies master from ANNX1. PSNOX1 does not have a density curve through the Vaca Muerta section, so this curve was not an input in electrofacies tagging. This adds uncertainty to the electrofacies generated for PSNOX1, although analysis showed that the gamma ray and sonic curves could still provide statistically repeatable electrofacies results. PSNOX1 was very important to this study because it had good-quality cuttings throughout the Vaca Muerta – Quintuco section. An electrofacies probability curve, which shows the likelihood of any given facies being assigned to an interval, is provided in order to characterize the uncertainty associated with the tagging. The electrofacies for PSNOX1 was also resampled to match the cuttings resolution. This was done by taking the mode electrofacies value between cuttings sample points (spaced 3 meters). The electrofacies results for PSNOX1 are shown in Figure 4.33.

When comparing the electrofacies results, the LLLa342 well did not appear correct in light of the wells around it. Further investigation showed that the electrofacies result varied greatly when the RHOB curve was excluded, as shown in Figure 4.34. The RHOB values for well LLLa342 are much higher than the wells around it. It also looks like the RHOB curve tracks the DTCO curve too well for it to be a measured property instead of a derived curve. Well LLLa342 was therefore excluded from the results.

An additional approach was also tried, where the elemental curves were used as an input into the electrofacies analysis, so that they would influence the facies definitions. The issue with this approach was that the resulting electrofacies definitions did not reflect any additional data from the elemental curves. It also complicated the tagging of additional wells (none of which had cuttings). It was therefore established that the relationship between electrofacies and the cuttings’ properties should be evaluated independently.
4.6 Seismic Surfaces

This study focused on interpreting the Loma La Lata 3D seismic cube using Schlumberger’s Petrel software. The Vaca Muerta Base, Quintuco Top were interpreted throughout the entire cube. Figure 4.35 shows the time-structure map of the base of the Vaca Muerta and illustrates how Loma La Lata field is a large anticline. Figure 4.36 is a time-structure map of the top of the Quintuco, which is identified by a high amplitude reflector because of the change of lithology from sandstone (Mulichinco Formation) to carbonates. Figure 4.37 is an isochron map of the Vaca Muerta and Quintuco Formations. The system thickens towards the north and west because that is the direction of the basin’s depocenter.

Current structure is dipping to the east, away from the Andes uplift, as shown in Figure 4.38. When the seismic is flattened on the Quintuco Top surface the characteristic clinoform surfaces are more easily identified (Figure 4.39). The major clinoform packages represent prograding and then aggrading packages similar to those described by Mitchum and Uliana (1984).

Major clinoform surfaces were interpreted in the northern half of the seismic cube. Major clinoforms were identified as dipping reflectors that had minor downlapping and truncating reflectors. Figure 4.40 shows the time-structure map of the major clinoform surfaces and illustrates how the shelf break progrades west into the basin.
Figure 4.1 A view of the Puerta Curaco outcrop. This outcrop is the best complete exposure of the Vaca Muerta, although the facies present are more distal than the facies under the consortium blocks to the east. A measured section was completed of this outcrop.
Figure 4.2 The Vaca Muerta – Tordillo contact at the Puerta Curaco outcrop. The contact was identified at the first occurrence of ammonites above sandstone.

Figure 4.3 A gully in the Puerta Curaco outcrop with an extensive shale lithology. It occurred between meters 300-350. A person is circled in red for scale.
Figure 4.4 The top of the measured section for this study. The literature disagrees on whether the Quintuco is truly found this far west in the basin.
Figure 4.5 Measured section of the Puerta Curaco outcrop divided into lithologies. TOC analysis is also presented, with circles color-coded by lithology. XRD of certain samples is also presented, which shows an abundance of calcite and quartz.
Figure 4.6 Estimated lithologic percentages in the Puerta Curaco outcrop.

Figure 4.7 TOC and mineralogy (XRD) values of a shale sample in the Puerta Curaco outcrop.
Figure 4.8 TOC and mineralogy (XRD) values of a marl sample in the Puerta Curaco outcrop. Notice the high silica value.

Figure 4.9 TOC and mineralogy (XRD) of three samples within 1 meter of each other in the Puerta Curaco outcrop. Notice the variation of TOC weight percent between lithologies, and the high feldspar content in the shale sample.
Figure 4.10 Distribution of TOC weight percent values by lithology. “Marl” lithology was difficult to define in outcrop, which is one reason for its’ larger range.

Table 4.1 Average TOC values with standard deviation (SD) and number of samples. The weighted average total was calculated using the lithology percentages in Figure 4.6.

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Figure 4.11 Vaca Muerta – Tordillo contact at the Picun Lefu outcrop.

Figure 4.12 Vaca Muerta – Tordillo contact at the Mallin Quemado Norte outcrop.
Figure 4.13 Vaca Muerta – Tordillo contact at the Mallin Quemado South outcrop.

Figure 4.14 A gully in the Cerro Mulichinco outcrop. The resistive white beds are bedding parallel horizontal fractures filled with calcite beef, shown in more detail in Figure 4.15
Figure 4.15 A detailed look at bedding parallel horizontal fractures with calcite beef in the Cerro Mulichinco outcrop.

Figure 4.16 An example of a large concretion resistive to erosion at the Chacay Mehue outcrop.
Figure 4.17 An example of a medium concretion at the Mallin Quemado South outcrop. Notice the fold induced by the growth of the concretion.

Figure 4.18 An example of a small concretion at the Mallin Quemado North outcrop.
Figure 4.19 A section along the Mulichinco river (Arroyo Mulichinco outcrop) with concretion beds.

Figure 4.20 Carbonate bed in the Los Catutos member at the Mallin Quemado South outcrop.
Figure 4.21 Los Catutos member at the Mallin de los Caballos outcrop, characterized by alternating thick limestone beds and black marls.

Figure 4.22 Ternary diagram showing the clay, carbonate, and siliciclastic mineralogy of the Vaca Muerta compared to major unconventional plays in the United States. Modified from Sonnenberg (2013).
Figure 4.23 Plot showing GR (normalized), DTCO, and percent calcite from XRD on cuttings for well PSNOX1. The calcite percent is qualitative only, but does show an increase in calcite content towards the top of the section.
Figure 4.24 Major elements found through XRF analysis of the cuttings in well PSNOX1. Cuttings are spaced every 3 meters.
Figure 4.25 Elemental composition from XRF analysis of cuttings for well PSNOX1. Cuttings are spaced every 3 meters.
Figure 4.26 Source rock maturity plot from production index (PI) versus Tmax. Core (PPL1010), cuttings (PSNOX1 and SBOX1), and outcrop (Puerta Curaco) data are all plotted, although most of the outcrop data plot off the chart because it is overmature (high Tmax, >480°C).
Figure 4.27 Source rock potential plot from TOC versus S1+S2 peaks. Outcrop (Puerta Curaco) data is unreliable because it is overmature. Core data (PPL1010) represents the highest resolution of the best (base) source rock section of the Vaca Muerta. Cuttings (PSNOX1 and SBOX1) are an averaged over many meters, but still show intervals of good source rock.
Figure 4.28 Modified van Kreveln diagram with oxygen index (OI) versus hydrogen index (HI) for Vaca Muerta samples in outcrop (Puerta Curaco), core (PPL1010), and cuttings (PSNOX1 and SBOX1). Outcrop samples are overmature.
Figure 4.29 The Anelo Neuquén X-1 (ANNX1) well RHOB, DTco, GR (normalized) and electrofacies curves. This well was used as the main electrofacies definition to which all the
rest were tagged because it is located in roughly the center of the clinoforms seen in the Loma La Lata 3D seismic.

Figure 4.30 Box and whisker plots showing the distribution of density, sonic, and gamma ray values for each cluster
Figure 4.31 Principle components and silhouette plot for the electrofacies
Figure 4.32 A cross section of the wells inside the Loma La Lata seismic and the results of electrofacies tagging. Loma La Lata is an anticline and the wells are shown in measured depth, which accounts for some of the variation in section thickness. The top of the section analyzed for electrofacies was picked on seismic time.
Figure 4.33 Electrofacies tagging of the Puesto Sin Nombre X-1 (PSNX1) well, which does not have a RHOB curve. Both an electrofacies with a sampling rate of 0.1 meters (same as the well-logs) and an up-scaled 3.0 meters sampling rate (calculated from the mode over the interval) are shown, as well as an electrofacies probability curve. A percent mode (count of mode facies over total samples) curve is shown to qualify the uncertainty in the electrofacies up-scaling, with 1 representing full confidence.
Figure 4.34 GR, DTCO, RHOB, and electrofacies logs for well LLL a-342. This well’s tagged electrofacies changed drastically when the RHOB curve was excluded. The RHOB did not match values from neighboring wells. It may be a logging issue, or a calculated RHOB curve (from sonic; notice the exact tracking of the logs). Due to these issues the well was excluded from the final analysis.
Figure 4.35 Time structure map of the Vaca Muerta Base horizon in the composite Loma La Lata 3D seismic cube.
Figure 4.36 Time structure map of the Quintuco Top horizon in the composite Loma La Lata 3D seismic cube.
Figure 4.37 Isochron of the Vaca Muerta – Quintuco surfaces. The surface was smoothed with 1 iteration and 1 filter width using Petrel operations. Notice the thickening section to the west as the system progrades into the basin. The thinning to the south could be accounted for both by seismic edge artifacts and proximity to the Dorsal (arch) de Huincul.
Figure 4.38 Seismic line through the Loma La Lata composite 3D cube. The location map is a time structure map on the Vaca Muerta horizon. Current structure is dipping to the east, away from the Andes uplift. Notice the 30x vertical exaggeration.
Figure 4.39 Seismic line through Loma La Lata, flattened on the Quintuco Formation top. Interpretations show major clinoform surfaces.
Figure 4.40 Major clinoform surfaces in the Loma La Lata seismic cube with time-depth isochron maps of the difference between the clinoform surface and Quintuco Top that show prograding clinoform packages.
CHAPTER 5
DISCUSSION

The purpose of this study was to integrate various datasets in order to high-grade results and present a geologic overview from various perspectives. An issue with this approach is the compounding of errors. Results showed, however, that each analysis, though reached independently, supported the same geologic attributes. Figures in this chapter combine datasets to present a more complete geologic picture of the results presented earlier.

5.1 Purpose/Significance of Dataset Integration

Integrating multiple datasets is essential for a complete understanding of a geologic system, especially when considering the generation, migration, and entrapment of oil. Furthermore, our current knowledge on the exploration and production of unconventional oil and gas accumulations is evolving, so there is no set formula for fully characterizing these systems. The Vaca Muerta Formation has the added complication of being located in a basin that by United States standards is underexplored. There are many penetrations in the basin through the formation, but well-log data is limited due to the cost sensitivity of companies at the time of drilling. Physical properties of rocks, such as porosity, permeability, and mineralogical composition are even scarcer than electronic signatures. To further complicate any study, the term Vaca Muerta refers to rocks that at a minimum are 100 meters thick, and can reach 1,000 meters. It is therefore essential to take what little data is available and refine and high-grade it as much as possible.
This study presents results from Vaca Muerta Formation outcrop, cuttings, core, well log, and seismic datasets. Each dataset presents a portion of the geologic picture, but some datasets are more common and/or continuous than others. The most common and publically available dataset are well logs, therefore the main research question was whether well-log response can predict elemental composition, source rock characteristics, and the seismic reflector patterns that define a clinoform. The discussion below illustrates the possibilities and limitations of answering this question.

5.2 Integrating Electrofacies and Cuttings Analysis

Cuttings were available in 6 wells outside the seismic area (Figure 3.8). The cuttings from the well Puesto Sin Nombre X-1 were chosen for this study because of their quality (Table 3.2). This well does not lie within the Loma La Lata seismic, but 6 km to the north east of the edge of the seismic cube. Cuttings are an important part of studying the Vaca Muerta Formation because of the thickness of the interval. There will be few companies willing to spend the money necessary to core the entire Vaca Muerta – Quintuco system, so cuttings, whether historic or from new wells, will have to play a role in the geologic interpretation of the section. The cuttings were analyzed for mineralogical properties (XRD, Section 0), elemental composition (XRF, Section 4.3), and source rock characteristics (Section 4.4).

Cuttings were spaced every 3 meters. In order to correlate log response and the cuttings’ properties, the electrofacies generated in Schlumberger Techlog, which had a sampling rate of 0.1 meters (equal to that of the logs), were up-scaled to a sampling rate of 3 meters. This was done by taking the modal electrofacies for each 3 meter cuttings interval.
(Section 4.5). The cuttings’ source rock and elemental properties could then be compared more robustly with the electrofacies assigned to that interval.

The major element concentrations in the cuttings show some variations along electrofacies. Silica (Si), which can be used as a proxy for quartz, increases with depth, while calcium (Ca) conversely decreases. Aluminum (Al), which can be found mostly in clay minerals, increases with depth. This fits with the established Vaca Muerta depositional model where the base is silica- and clay-rich, grading into carbonates towards the top. Sulfur (S), which is mostly found in pyrite and is an indicator of anoxic conditions, decreases sharply from the base towards the top. Iron, which should track with sulfur if it is related to pyrite, does not change very much. It is possible that there are drill bit contaminants in the cuttings that make the iron readings unreliable. Figure 5.3 shows the gamma ray, modal electrofacies, and major elements by depth. The relationship between major elements and electrofacies suggests that the Red facies is rich in siliciclastics (both quartz and clays) and was deposited in anoxic conditions. The Yellow facies had more of a mixing environment, but is still silica rich. Green, Light Blue, and Dark Blue are carbonate rich. Figure 5.4 shows the distribution of major element concentrations.

Trace element concentrations also show a relationship with electrofacies, and therefore log response. Figure 5.5 shows the up-scaled electrofacies plotted against the trace metal concentrations in the cuttings. Facies patterns are apparent in certain trace metal concentrations. The strongest relationship is between the Red facies and concentrations of Zn, V, Ni, Cu, and Mo. The Yellow facies has higher concentrations of Cu than the other facies, but there are no other distinctive trace metal concentrations in the facies. Figure 5.6 shows the distribution of trace elements by facies.
Source rock characteristics can also be related to facies definitions. The Red facies has the highest TOC weight percentages, while Dark Blue has the least, as shown in Figure 5.1. This pattern is similar to the TOC results by lithology for the Puerta Curaco outcrop samples (Figure 4.10). Figure 5.2 shows the distribution of Tmax and S1/S1+S2 values, as well as TOC, by facies. The variations in source rock characteristics of the cuttings indicate a wide range of maturity, kerogen type, and generation potential in the samples, as mentioned previously in Section 4.4.

When separated by electrofacies the source rock characteristics fall into distinct groups of generation potential. The Red facies has mostly good generation potential given S1+S2 and TOC values. The Yellow facies has good intervals with mostly moderate results, and some samples showing poor results. The Green, Light Blue, and Dark Blue facies all have poor to very poor generation potential. Figure 5.7 shows the TOC versus S1+S2 results for the cuttings colored by facies, along with the 3.0 meter modal facies and GR and DTCO logs.

Results for maturity window show a similar trend. The Red and Yellow facies all fall within the oil window. Many of the Green facies results show high Production Index (PI), values, and are spread out towards the gas window. Light Blue and Dark Blue also show some values outside the oil window. Given that Green, Light Blue, and Dark Blue facies are all poor source rocks (TOC values below or close to 1%), these results could just be due to a lack of kerogen. Figure 5.8 shows a plot of PI versus Tmax results for the cuttings colored by facies, along with the 3.0 meter modal facies and GR and DTCO logs.
The kerogen type indicated by a modified van Kreveln diagram also shows variable results throughout the cuttings. The data are affected by the level of maturity of the samples. The Red facies shows a Type I to Type II kerogen clustering. Some values spread towards the Type III curve. The Yellow facies has values towards Type II but most results cluster in the mixed Type II-III area. Green, Light Blue, and Dark Blue facies plot towards the Type III and even Type IV curves. Two processes could explain these results. First, Type I kerogen is found only in the bottom of the section, and corresponds with the results obtained from core (Section 4.4). As the system changed from the Transgressive Systems Track to a Highstand Systems Track the kerogen source could have changed from purely marine to more terrestrial input (Type II & III). In addition, however, the quality of the source rock must be considered. Given that the Green, Light Blue, and Dark Blue facies have been shown to be poor to very poor source rocks, the oxygen index (OI) and hydrogen index (HI) (on which the van Kreveln diagram curves rely) could be suspect. What remains clear is that the different electrofacies have vastly different source rock characteristics. Figure 5.9 shows the OI versus HI van Kreveln plot colored by facies, along with the 3.0 meter modal facies and GR and DTCO logs.

5.3 Integrating Electrofacies and Seismic Data

Seismic data is very useful in characterizing a reservoir because it provides continuous information about the subsurface. It can be essential in systems such as the Vaca Muerta where lithologic and stratigraphic terms intermix, and facies change both laterally and vertically. The Loma La Lata seismic cube is of great interest because not only does it encompass a very large structure that hosted a conventional field, it also shows very clearly the prograding clinoforms that characterize the Vaca Muerta-Quintuco system.
(Section 4.6). One of the stated purposes of this investigation was to determine if log response can predict elemental composition, source rock characteristics, and the seismic reflector patterns that define a clinoform. As discussed above, log patterns (grouped into electrofacies) do correlate with source rock and elemental analysis from cuttings. This section will discuss whether electrofacies can be related to seismic reflector patterns.

Major clinoform surfaces were interpreted and their shelf breaks mapped (Section 4.6). The wells were then tied to the seismic data and the electrofacies response plotted along the well bore. Although the seismic data is in time and the well bore is in measured depth, it is still possible to see the relative positions of the electrofacies patterns and seismic reflectors.

The electrofacies have a distinct vertical pattern in each of the wells. The Red facies is present in all the wells and is represented in the seismic data by a high amplitude reflector that marks the base of the section. This reflector represents the Transgressive Systems Track and is interpreted by the reflectors downlapping onto it. The Yellow facies is always present above the Red, and it increases in abundance in the wells located towards the depocenter of the basin to the west, specifically in wells VXX1, ANAX1 and BCOX2. The Yellow facies is associated with minor clinoform reflectors truncating against the major clinoform surfaces. The Green facies is interspersed throughout the wells. It represents a lower density reading (Figure 4.30) that could be diagenetic porosity or a tool issue. Given that it does not represent a large part of any of the wells, it bears further investigation in a future study. The Light Blue facies is present above the Yellow facies in most wells and is represented in the seismic data as lower amplitude reflectors. It is abundant near the shelf break of the clinoforms. The Dark Blue facies is present at the top
It is also possible to see a change in electrofacies while following the major clinoform surfaces between wells. Figure 5.10, Figure 5.11, and Figure 5.12 are the best examples of this change along the major clinoform surfaces. A reflector starts in the Dark Blue facies and changes to Light Blue, Yellow, and finally Red at the toe of the clinoform. The changes are more apparent in the progradational (Green) clinoform than in the stratigraphically higher clinoform packages. The changes are predictive given each facies’ source rock properties, mineralogy, and elemental composition suggested by the cuttings.

Wells roughly along strike of the shelf break show similar facies patterns. Figure 5.13 is a composite seismic line oriented north to south. The major clinoform surface reflectors stay at a constant time depth and do not change electrofacies between wells. The consistency of the electrofacies patterns in wells located in similar positions along clinoform packages further reinforces the relationship between the electrofacies predictions and seismic reflector patterns.

5.4 Sources of Uncertainty in Dataset Integration

Besides the usual calibration and error bars associated with the data collection, there are various sources of uncertainty in the integration of the well log, cuttings, and seismic datasets. This study has focused on presenting the best results given the current dataset, but future work could add robustness to the conclusions.

One source of uncertainty is the lack of cuttings from wells within the area with seismic data. The PSNOX1 well, from which the cuttings were collected, is a few
kilometers to the east of the Loma La Lata seismic cube boundaries. This means that the facies found in the PSNOX1 cuttings may not be representative of the facies captured by the seismic data.

Another source of uncertainty is the lack of check shots in the wells within the seismic data. Wells were tied to time depth by looking at the major unconformities that bound the Vaca Muerta – Quintuco system. A recent well with quality check shots and calibrated sonic and density logs could dispel a considerable amount of the uncertainty about the time-depth relationship between well and seismic data.

Well log quality is another source of uncertainty. The well logs used in this study were supplied by the consortium companies in .las format. This type of data is notorious for hiding inaccuracies in the well log measurements. As shown in Section 4.5 for well LLLa342, some curves are very suspect. Original raster images and well files for these wells would increase the confidence in the measurements that are being used in the analysis. Despite these sources of uncertainty, the results presented in this study are still strong enough to provide value in understanding the Vaca Muerta – Quintuco system.
Figure 5.1 Frequency histogram of TOC weight percent values by electrofacies for cuttings in the PSNOX1 well.
Figure 5.2 Distribution of source rock characteristics by facies for cuttings in the PSNOX1 well.
Figure 5.3 Plot showing depth versus gamma ray, sonic, and electrofacies logs with XRF major element results for cuttings and TOC for cuttings.
Figure 5.4 The distribution of major element concentrations by facies.
Figure 5.5 Plot showing depth versus gamma ray, sonic, and electrofacies logs with XRF element results for cuttings and TOC for cuttings. The Red facies which represents the transgressive surface of erosion has a high concentration of elements that indicate redox conditions.
Figure 5.6 Trace metal concentrations by facies. The Red facies holds the highest trace metal concentrations.
Figure 5.7 Generation potential for cuttings in the PSNOX1 well grouped by electrofacies. Results show that log response (electrofacies) can help predict generation potential.
Figure 5.8 Maturity window for cuttings in the PSNOX1 well grouped by electrofacies. Results show that log response (electrofacies) can help predict maturity window.
Figure 5.9 Kerogen type for cuttings in the PSNOX1 well grouped by electrofacies. Results show that log response (electrofacies) can help predict kerogen type.
Figure 5.10 Electrofacies and gamma ray plotted along well bores and tied to seismic. The major clinoform surfaces are shown in green, purple, and orange. It is possible to see a change in electrofacies along the clinoform seismic reflectors. These changes follow vertical stacking patterns (i.e. Red to Yellow to Light Blue to Dark Blue).
Figure 5.11 Electrofacies and gamma ray plotted along well bores and tied to seismic. The major clinoform surfaces are shown in green, purple, and orange. It is possible to see a change in electrofacies along the clinoform seismic reflectors. These changes follow vertical stacking patterns (i.e. Red to Yellow to Light Blue to Dark Blue)
Figure 5.12 Electrofacies and gamma ray plotted along well bores and tied to seismic. The major clinoform surfaces are shown in green, purple, and orange. It is possible to see a change in electrofacies along the clinoform seismic reflectors. These changes follow vertical stacking patterns (i.e. Red to Yellow to Light Blue to Dark Blue)
Figure 5.13 Composite seismic line going roughly north to south, along strike of the shelf break. The gamma ray and electrofacies logs are plotted along the well bore. Electrofacies change along seismic reflectors, indicating different lithologies time-equivalent clinoform deposition.
Conclusions reached by this study integrated results from seismic, electrofacies, and cuttings analysis. Each dataset provided part of an integrated geological picture. Electrofacies could be used to predict the position of a well in relation to the Vaca Muerta – Quintuco clinoforms identified in seismic, and vice versa.

6.1 Conclusions from Seismic, Electrofacies, and Cuttings Integration

This study integrated available seismic, well log, and cuttings data for the Vaca Muerta – Quintuco system in the Loma La Lata area. The purpose of the study was to establish a relationship between log response (electrofacies), elemental composition, mineralogy, source rock characteristics, and seismic reflectors. Although there are sources of uncertainty with integrating these different datasets (Section 5.4), a relationship was identified. Electrofacies have a distinctive set of characteristics, presented in Table 6.1, that suggest they could be predictive of the characteristics listed above.

Previous studies have described the lithologic changes along clinoform reflectors in the Vaca Muerta – Quintuco system (Mitchum and Uliana, 1987 and Mitchum and Uliana, 1985) but have done so with a limited log suite and no statistical analysis of the different logs. It is now possible to look at the changes along seismic reflectors in the Vaca Muerta using additional logs and statistical analysis. The electrofacies defined in this study showed that the petrophysical response changed along seismic reflectors. The cuttings data suggests that the different electrofacies had variations in trace metal concentrations indicating changes in the depositional environment. Critically, the trace metal concentration,
mineralogy, and source rock characteristics distinctive to each electrofacies are in agreement with the expected outcome given the seismic reflector pattern. The Red facies shows an anoxic depositional environment and increased organic content, which is predictive given its association with the transgressive systems tract in the seismic data. The Yellow facies is a moderate to good source rock with decreased trace metal concentrations; it is abundant towards the progradational direction of the clinoforms and is associated with reflector downlaps. The Light Blue and Dark Blue facies are rich in calcium and low in organic content, which is consistent with their appearance near to or behind the shelf break of the major clinoform surfaces.

Overall this study has shown it is possible to find a relationship within datasets of varying quality, sampling distance, and measurements. This type of data integration is invaluable in targeting the Vaca Muerta as an unconventional reservoir target in the most efficient and economic manne

6.2 Recommendation for Future Work

This study has relied on the best data available at the time and given the agreements with consortium companies. There remains much to be done in order to solve pressing questions about the Vaca Muerta – Quintuco system.

A major issue is the quality and accessibility of data. The major operator in the Neuquén Basin in general and in the Loma La Lata area, in particular, is the National Oil Company, Yacimientos Petrolíferos Fiscales (YPF). Access to the logs, cuttings, tests, and core that YPF have acquired from current and future drilling is critical. The integration of new, as simple as, several additional wells or core could add significant robustness to the
conclusions presented in this study. Increasing access to this data is necessary in the name of science.

Even without involving YPF, there still remains much that could be done with the data currently available to the Vaca Muerta CSM Consortium and its member companies. Figure 6.1 Map of the consortium area of interest with suggestions for future work. Figure 6.1 shows a map of the companies’ acreage and the data at the Colorado School of Mines. First, additional well cuttings are available from wells near the Loma La Lata area. Analyzing the cuttings for source rock characteristics, XRF elements, and XRD mineralogy and integrating the results with well log response would add to the electrofacies characterization presented in this study. In addition, two more seismic cubes, Loma Jarillosa Este and Cinco Saltos, are available for interpretation. Some work has already been done by other students in the consortium on these additional seismic cubes. The consortium also has access to several hundred well logs throughout the basin. At least a few tens of these wells have logs through the Vaca Muerta section in the deeper sections of the basin. Finally, Chevron and Shell have drilled wells in their blocks to the north of the current area of interest that have encountered volcanic sills through the Vaca Muerta. Given this data, the consortium could serve as a medium to facilitate investigation into this phenomena.

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<table>
<thead>
<tr>
<th>Facies</th>
<th>GR (api)</th>
<th>RHOB (g/cm³)</th>
<th>DTCO (us/ft)</th>
<th>Well Bore Pattern</th>
<th>Clinoform Stacking Pattern</th>
<th>Source Rock Characteristics</th>
<th>Elemental Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Blue</td>
<td>41-66</td>
<td>2.53-2.65</td>
<td>57-70</td>
<td>Present at the top of all wells</td>
<td>Present behind shelf break where reflectors have a railroad pattern</td>
<td>Not a source rock</td>
<td>High Ca content with lower Si</td>
</tr>
<tr>
<td>Light Blue</td>
<td>60-96</td>
<td>2.47-2.55</td>
<td>69-82</td>
<td>Above and interspersed with Yellow. Not abundant in PSNOX1</td>
<td>Near shelf break of clinoform</td>
<td>Not a source rock</td>
<td>Low concentration of metals, low Si and high Ca</td>
</tr>
<tr>
<td>Green</td>
<td>55-81</td>
<td>2.28-2.47</td>
<td>61-75</td>
<td>Low density, diagentic porosity? Interspersed throughout upper portions of well</td>
<td>No section in seismic wells is thick enough to associate with reflectors, but present in PSNOX1</td>
<td>Not a source rock</td>
<td>Low trace metals, high Si and lower Ca</td>
</tr>
<tr>
<td>Yellow</td>
<td>94-128</td>
<td>2.38-2.48</td>
<td>78-89</td>
<td>Above Red, wells towards the basin have more than those to the east</td>
<td>Lower slope to tow of clinoforms, associated with stacking clinoforms</td>
<td>Poor to moderate, oil window, type I-II kerogen</td>
<td>Some high V, Cr, Ni, and Cu, high Si and Ca</td>
</tr>
<tr>
<td>Red</td>
<td>135-190</td>
<td>2.31-2.42</td>
<td>83-93</td>
<td>Present in all wells at base.</td>
<td>High amplitude reflector, transgressive systems track</td>
<td>Good source, oil window, type I-II kerogen</td>
<td>Enriched in trace metals, especially V, Ni, Cu, and Mo, high Si content, high S</td>
</tr>
</tbody>
</table>
Figure 6.1 Map of the consortium area of interest with suggestions for future work.
REFERENCES CITED


