A PETROLEUM SYSTEMS ANALYSIS OF THE SOUTHERN ESPAŃOLA BASIN OF THE RIO GRANDE RIFT, NEW MEXICO

A Thesis Presented to the Faculty of the

Department of Earth and Atmospheric Sciences

University of
Houston

In Partial Fulfillment

of the Requirements for the
Degree

Master of Science

By

Colby Patrick Record

August 2013

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ABSTRACT

The Española Basin of north-central New Mexico is an asymmetric half graben of the Rio Grande Rift. The Rio Grande Rift is Cenozoic in age with initial extension beginning at approximately 27 Ma. This extension immediately followed the compressional Laramide Orogeny and the rift is still active today, although it has become nearly dormant. The Española Basin is one of several NS-oriented narrow basins located in the central Rio Grande Rift, bordered by the San Luis Basin to the north and the Santo Domingo and Albuquerque Basins to the south. The Española Basin is dipping westward, bounded by the Pajarito master fault, with a maximum sediment thickness of approximately 3 km. The basin has undergone a small amount of petroleum exploration over the past century but this has been sporadic and sparse.

A petroleum system in this basin has been detected by oil and/or gas shows in exploratory wells and sampling of a Pennsylvanian source rock. In this study, numerous one-dimensional models were created to model basin characteristics as well as petroleum system elements at individual well locations throughout the basin. This process was used to model different reservoir/seal pairs as well other characteristics such as deeper burial depth of the source horizon not seen in all well bores. Two-dimensional models were also created for complete basin modeling of the southern Española Basin and to fully analyze the petroleum system present. Through basin modeling techniques it can be shown that this portion of the Española Basin has all of the necessary elements of a petroleum system including source, reservoirs, seals and migration pathways. The modeling also shows that despite the basin being relatively shallow high heat flow and other factors allowed for the source rock to mature and petroleum generation to occur.

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CHAPTER 1: INTRODUCTION

The Española Basin of New Mexico is one of several north-south trending basins of the Central Rio Grande rift. From south to north, the basins step en echelon to the right with the Albuquerque Basin to the south, Española Basin in the central region and the San Luis Basin to the north (Figure 1). The Rio Grande rift is a late Cenozoic continental rift that began to form approximately 27 Ma (Cavazza, 1989) and extends from the central Colorado region to southern New Mexico. The rift formed through passive rifting that now separates the Colorado Plateau from the Great Plains. The Española Basin began to form in late Oligocene time, around 26 Ma, and is an asymmetric basin with sediment thicknesses ranging from 2 to 3 km of sediments near the center. The basin consists of a series of asymmetric grabens and is approximately 70 km long and 60 km wide (Golombek et al., 1983). The Tertiary Santa Fe Group makes up most of the syn-rift basin-fill sediments with the Tesuque Formation of the Santa Fe group being the dominant unit within the southern Española Basin that this study focuses on.

The Española Basin represents an under-explored basin in which there are a low number of wells, and very few of these have been spudded since the 1980's. Of the wildcat wells drilled in the southern section of the Española Basin to date, however, most have reported the presence of a source rock in the pre-rift sediments. The Española Basin is thus an attractive target to perform a Petroleum Systems Analysis for several reasons, including the reported results from wildcat wells in the southern portion of the basin, and the similarity of the pre-Tertiary strata present in the Española Basin to the very productive section in the nearby San Juan Basin just to the northwest (Black, 1984).

The presence of these pre-rift source rocks combined with the occurrence of numerous possible reservoir rocks makes the possibility of trapped hydrocarbons realistic. In addition, heat flow throughout the basins of the central Rio Grande rift is relatively high (Russell and Snelson, 1994), despite the overall shallow depth of the basin, as a result of the large intrusive magma bodies and overall thinning of the lithosphere in this region. These high heat flow values and the numerous samples from exploration wells suggest that the source rock in this region reached maturity (Molenaar, 1988).

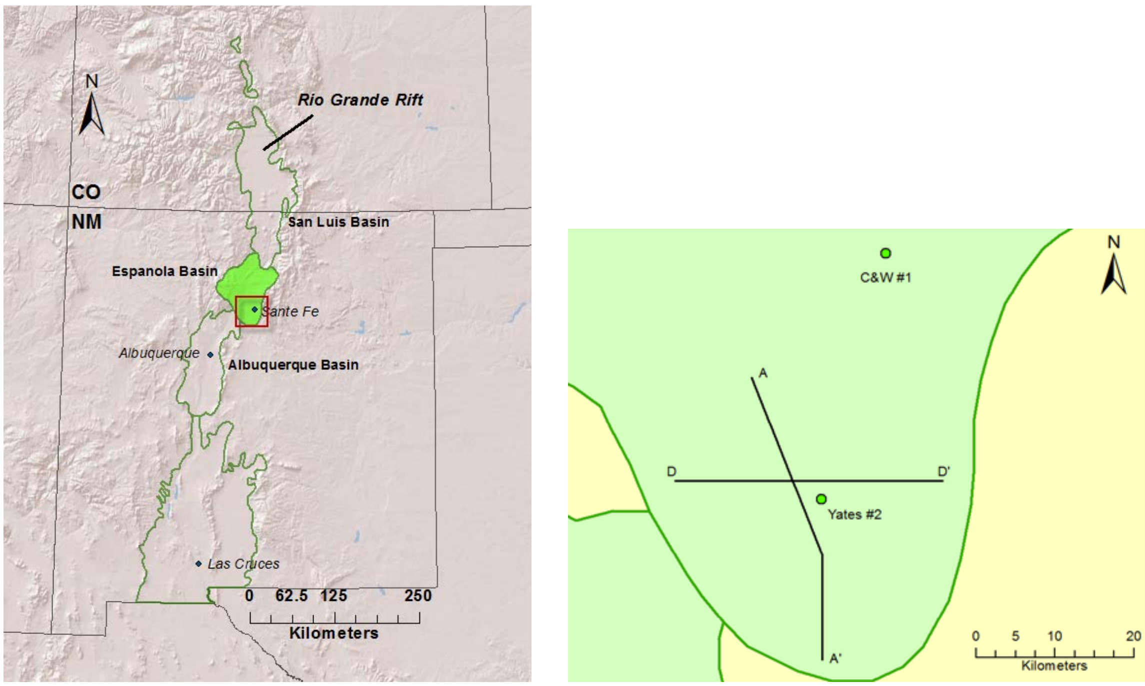

Figure 1. ***Left panel: The Rio Grande rift (outlined in green) in the southwestern U.S. Right panel: Close up of study area, southern Española Basin.***

In this study a Petroleum Systems Analysis was performed on a southern section of the Española Basin. Using tectonic history, heat flow diagrams, and burial history curves to set up a reliable model, cross sections of the basin and several exploration wells were used to evaluate hydrocarbon generation, migration, and entrapment possibilities. Specific data was input into the model, such as identified source and reservoir horizons, TOC (Total Organic Carbon) values, and kerogen types. The goal of the study was to develop a reliable model of the petroleum system present in the Española Basin in order to accurately assess the petroleum potential of the area as well as add to the understanding of the structural evolution of the Española Basin.

CHAPTER 2: GEOLOGIC SETTING OF THE ESPAŃOLA BASIN

The Rio Grande rift is located between Laramide uplifts, the Great Plains region to the east, and the Colorado Plateau to the west, with the rift extending over a distance of hundreds of kilometers (Biehler et al., 1991) and is bounded to the east and west by fault systems dominated by normal faulting (Figure 1, 3, 4). The rift is a Cenozoic feature that represented a change to an extensional regime from the compressional regime of the Laramide Orogeny that lasted from the Cretaceous to the early Tertiary (Golombek et al., 1983). During this period of time, the Laramide compression was thickening the crust, however at the same time magma intrusions intruded the crust and weakened the lithosphere. As the region transferred from a compressional to an extensional regime, crustal thinning occurred as tectonic forces pulled the plates apart and the asthenosphere rose to relatively shallow depths (Ingersoll, 2001). Crustal extension began in the region approximately 30 Ma and the rift is still active. The extension was highest in the early Cenozoic and has become nearly stagnant currently. The Rio Grande Rift however still represents a geologically active rift, shown by (sparse) seismic events, magmatic activity, and recent movement along faults (Gornitz, 1982).

There were two separate phases of extension that took place in forming the rift (Ingersoll, 2001). The first phase of extension was in the late Oligocene, resulting in the formation of broad, shallow basins and low-angle faulting. The low-angle faulting created the broad basins and was followed by a period of sediment infill (Large and Ingersoll, 1997). The second and most recent major phase of rifting began mid to late Miocene and lasted until the Holocene. The phase involved much higher angle faults which formed deep and thin grabens, ultimately forming the narrow, north-south-trending basins seen in the central Rio Grande Rift (Biehler et al., 1991; Ingersoll, 2001).

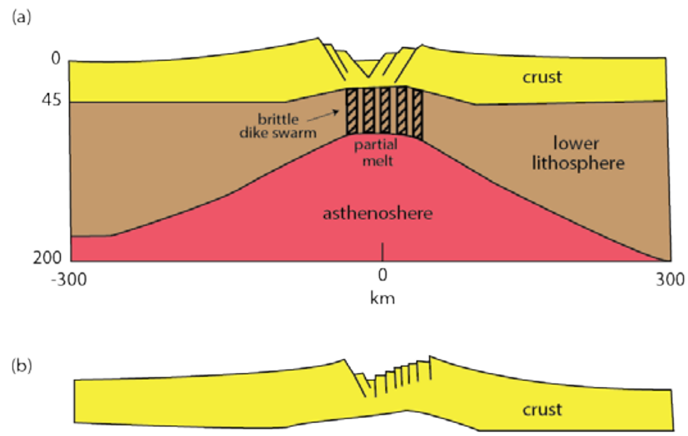

Figure 2. ***Model of narrow rifting of the Rio Grande rift and style of crustal deformation. Modified from Davis (1991).***

During continental rifting, the crust and mantle parts of the lithosphere thin (Figure 2). The Moho is uplifted, and the upper mantle and asthenosphere are found at very shallow levels. This results in decompression melting, magma intrusions, and volcanic activity in the rift zone (Russell and Snelson, 1994). Directly below the rift, the intrusion of magma occurs through a series of dikes that allow partial melt from the asthenosphere and lower lithosphere to reach crustal depths. This activity along with the partial melting of the lower crust

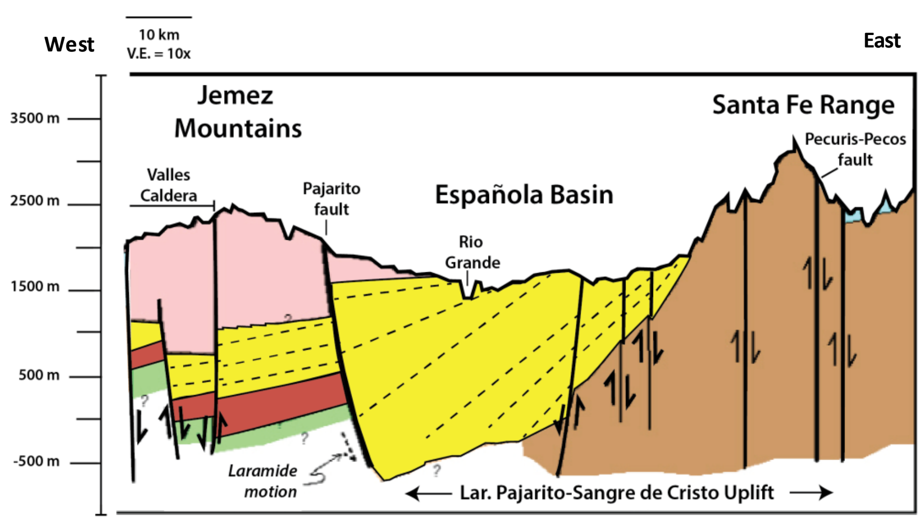

Figure 3. ***Simplified cross section of the Española Basin showing westward dipping strata.***

contributes the basaltic magmas and magmas with other compositions found in the Española Basin (Davis, 1991). The asymmetric north-south-striking basins of the Rio Grande rift (Figure 3) become larger as you move from the north to the south down the rift. These basins were all created by block faulting of the previously discussed broad basins (Cavazza, 1989). The crustal thickness in the Rio Grande Rift is approximately 35 kilometers thick, which is much thinner than that of the Colorado Plateau and Great Plains region which are located the west and east of the rift respectively. The Rio Grande Rift, as with many rift basins, has the characteristic of high heat flow (Figure 4). This high heat flow can generally be explained by the thinning of the crust during extensional tectonics, which involves hot mantle to warp upwards and closer to the surface. Throughout the rift numerous shallow magma bodies and intrusions also contribute to the high heat flow within the rift. To a lesser extent groundwater movement, especially in close proximity to magmatic intrusions, can also contribute to higher heat flow within the basins of the Rio Grande Rift (Clarkson and Reiter, 1984).

The Española Basin is one of these tilted asymmetrical basins found in north-central New Mexico (Figure 3). Characteristically it is a basin consisting of asymmetric half grabens with sediment tilting to the west, which is opposite of the Albuquerque and San Luis Basins to the south and north in which the sediments tilt east (Biehler et al., 1991). The basin, which represents a significant right step in the Rio Grande Rift, is bounded by the Pajarito Fault system to the west, in which the Jemez volcanic province is part of the footwall. The northern boundary of the Española Basin is formed by the Embudo Fault zone. Nearly all of the faults in this basin strike in a north to northwest direction and can dip either to the east or west (Pantea et al., 2011). The basin began to fill with sediments derived from the volcanic higher elevation areas to the north during the Early Tertiary. Soon afterwards, deposition of the Santa Fe Group began. These formations were deposited from the Miocene to the early Pliocene and consisted of

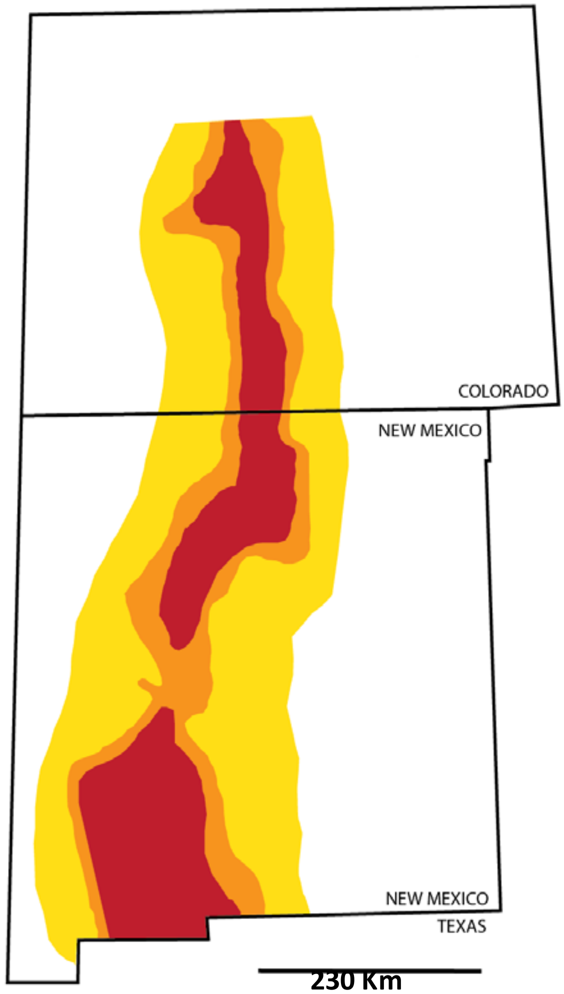

Figure 4. ***General heat flow map of the Rio Grande rift. Modified from Russel and Snelson (1994).***

conglomerates, terrestrial sandstones with minor limestones, and some basalt (Biehler et al., 1991). The La Bajada Fault system forms a partial southern boundary for the Española Basin and separates it from the Santo Domingo Basin. The Santo Domingo Basin is a smaller, symmetric basin in the northern section of the larger Albuquerque Basin. It shows subdued topography and has eastward dipping strata. This basin shows the same stratigraphy as the Española Basin, and rotation along bounding faults that have created the basin to have more of a northeast trending axis (Minor et al., 2006). In the southern portion of the Española Basin, which is the focus of this study, the underlying Paleozoic stratigraphy was not eroded as it was in some of the northern areas of the basin. These pre-rift strata along with several Mesozoic units are still present in the project area (Pantea et al., 2011). As with other areas of the Rio Grande Rift, the Española Basin exhibits high heat flow. The high heat flow in this basin is most likely explained by a combination of factors, most importantly crustal thinning and therefore migration of the upper mantle to shallow depths. Another factor is the emplacement of magmatic intrusions in the crust, crustal magma bodies and volcanic activity (Clarkson and Reiter, 1984). The Jemez Volcanic Field is located along the western margin of the southern Española Basin and numerous basalt layers are present in the stratigraphy of the basin. Along with these major factors, groundwater movement throughout the basin and its interaction with these magmatic and volcanic features attributes to the high heat flows in the basin (Johnson and Koning, 2013).

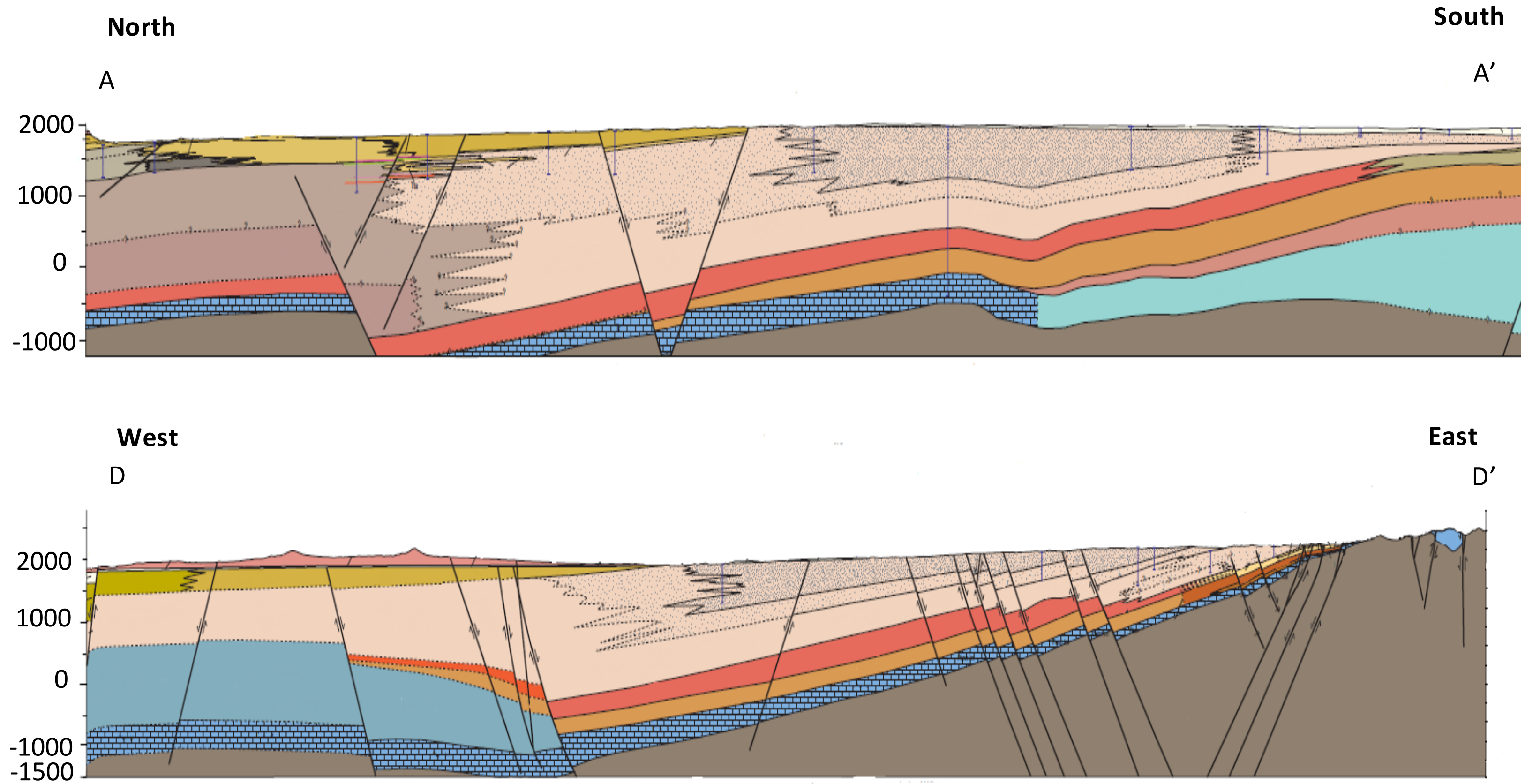

Figure 5. *Sketch of geologic cross section lines A-A’ (top) and D-D’ (bottom) crossing the southern Española Basin. Modified from Koning and Read (2010). Depth units in meters, 0 at MSL.*

CHAPTER 3: STRATIGRAPHY OF THE SOUTHERN ESPAŃOLA BASIN

This study focuses on the southern portion of the Española Basin which exhibits much of the same rift stratigraphy as the rest of the Rio Grande rift basins. The syn-rift sediments are completely contained within the Santa Fe Group (Figure 5) and volcanic deposits, while the pre-rift sediments of the Mesozoic and Pennsylvanian can be found above Precambrian basement. The Yates La Mesa #2 exploration well was used as an analog to the stratigraphy of the southern section of the basin.

3.1 RIFT STRATA

The Tesuque Formation of the Santa Fe Group makes up the majority of the rift sediments in the Española Basin but other Santa Fe Group formations are present in the section along with volcanic rocks that are considered to be in the group. The units above the Tesuque Formation in this area of the basin are generally the Ancha Formation or the Santa Fe Group and volcanic rocks associated with the Cerros del Rio volcanic field. The volcanic rocks that deposited in the Cerros del Rio field are late Pliocene to early Pleistocene in age and include basalt and andesite lava flow deposits. Due to the composition of the erupted lava flows the basalt deposits and andesite deposits cover a much different radius and vary greatly in thickness. The basalt flows are generally 3 to 4 meters in thickness and cover a broad area of the Cerros del Rio volcanic field. The andesite or basaltic andesite deposits cover a much smaller area of the volcanic field but area thicker and can reach around 30 meters in thickness. These volcanic rocks were deposits by broad shield volcanoes and small but steep vents. Dating of these rocks shows us they are between 2.7 and 1 Ma with most of the extrusion occurring before 2 Ma (Koning and Read, 2010). The Ancha Formation represents the youngest member of the Santa Fe Group in the

Española Basin and is late Pliocene to early Pleistocene in age. The Ancha Formation generally lies on top of the Tesuque Formation but can overlie older Santa Fe Group sediments where the Tesuque pinches out in the southern most area of the basin. In this study are the Ancha Formation is generally 5 to 35 meters thick and consists of alluvial fan deposits as well as deposits of the ancestral Santa Fe River. The formation consists of broad, tabular sand and silty sand layers along with coarse channel-fill sediments. Where the formation contains ancestral Santa Fe River deposits, it consists of sand and gravel interbedded with silty sand layers. The Ancha unconformably lies on top of the Tesuque Formation, usually with an angular unconformity (Koning and Read, 2010).

The Tesuque Formation makes up the majority of the rift sediments found in the Española Basin and in parts reaches thicknesses greater than 2000 meters (Figure 6). The characteristic sediments of the Tesuque Formation are sandstones, mudstones, and conglomerates (Cavazza, 1989). The Tesuque Formation consists of many distinct members and lithosomes in the Española Basin. The uppermost member of the Tesuque seen in the area of this study is the upper middle to late Miocene Cuarteles Member. The Cuarteles Member is a very fine-to medium-grained alluvial fan sandstones with minor interbedded mudstones deposited as discontinuous channels that can reach over 300 meters in thickness (Koning and Read, 2010). The remainder of the Tesuque Formation has been subdivided in this basin into four separate lithosomes, those being lithosome A, B, S and E. Furthermore, in cross sections of this study area as well as in the Yates La Mesa #2 control well lithosome S has been broken down into three distinct units based on grain size that scales from coarse to fine grained with increasing depth. Lithosome A of the Tesuque is interpreted as alluvial fan deposits that are early to middle Miocene in age with provenance from erosion of the Sangre de Cristo Mountains (Cavazza, 1989). Lithosome B of the Tesuque Formation is also lower to mid Miocene in age and interpreted as floodplain deposits with minor channel-fill sediments. It is dominated by mudstones, very fine-to medium-grained sandstones, and coarse sandstone in channel-fill sequences. Both the A and B lithosomes deposited between 26 and 13 Ma and grade laterally into lithosome S of the Tesuque Formation. Lithosome S is early to middle Miocene in age and was deposited as large floodplain deposits. Lithosome S has been subdivided based on grain size and this distinction is recognizable in cross section and well data. This lithosome makes up the majority of the basin fill in the middle of the southern Española Basin and can reach thicknesses of more than 2000 meters. All of the deposits in lithosome S are interpreted to be fluvial (Koning and Read, 2010). Lithosome E is the bottom unit of the Tesuque Formation and the basal sedimentary unit of the Santa Fe Group. While the underlying Cieneguilla Formation is generally considered part of the Santa Fe Group, it is a volcanic deposit. Throughout much of the study area lithosome E is interbedded with the uppermost fragments of the Cieneguilla Formation. Lithosome E is late Oligocene to early Miocene in age and much like the rest of the Tesuque Formation is dominated by fine to medium grained sandstones. The Cieneguilla Basanite lies directly below lithosome E and is upper Oligocene in age. The formation consists of mafic basanite and basalt which are dark gray to black in color (Koning and Read, 2010). The Cieneguilla was deposited approximately between 26 and 25 Ma and overlies the Espinaso Formation. As stated before, the Cieneguilla Basanite grades upwards into the lower lithosomes of the Tesuque Formation. This demonstrates that it is older than the Tesuque Formation and younger than the Espinaso Formation. Locally in the southern Española Basin the basanite can be over 300 meters in thickness (Baldridge et al., 2013). The Espinaso Formation is late Eocene to late Oligocene in age depositing between 36 – 29 Ma and generally interpreted as alluvial fan deposits shed from volcanic centers in close proximity to the southern Española Basin. The formation consists of sandstones and conglomerates with minor silt and volcaniclastic breccias (Koning and Read, 2010). All of these sediments and volcanics represent the rocks deposited during the rifting phase of the Rio Grande rift which began approximately 27 Ma and continues today.

3.2 PRE-RIFT STRATA

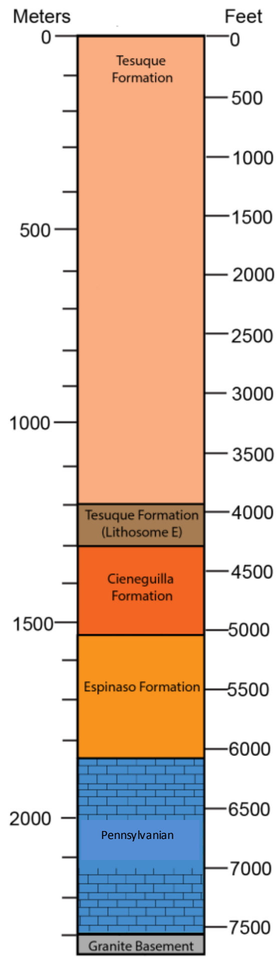

Figure 6. ***Stratigraphy of the Yates #2 La Mesa well. Figure modified from original by Daniel Koning and David Sawyer, U.S. Geologic Survey.***

The pre-rift sediments in the Española Basin vary greatly in age and thickness throughout the basin. There is also a degree of uncertainty concerning sediments from late Paleozoic through Mesozoic in age. Due to lack of well data and varying degrees of erosion that took place during the Laramide Orogeny little work has been done to understand the stratigraphy of these units in the Española Basin. This unit is generally just described as the undivided Mesozoic section which lies below the syn-rift sediments and volcanic rocks deposited in the Eocene and above the much more defined Pennsylvanian limestones. While in other parts of the basin this unit might reach large thicknesses, it does not appear in the Yates La Mesa #2 well. This undivided section could include Permian through Cretaceous sandstones and siltstones with minor limestones (Hudson et al., 2011). The Paleozoic section of pre-rift sediments consists of Pennsylvanian aged limestones with shale layers and minor siltstones. The Pennsylvanian is distinguishable in the subsurface through seismic imaging and cross section mapping and lies directly on top of Precambrian basement. This unit varies in thickness from 150 meters to over 300 meters in the Yates La Mesa #2 exploration well (Hudson et al., 2011). The Pennsylvanian is dominated in this study area by the Madera Group, which consists of limestones and shales that represent basin to continental shelf deposits. The deep-sea basin deposits are dominated by limestones interbedded with marine shales, while the shelf deposits consist of carbonates and minor shales assemblages (Kues, 2001). The Proterozoic section of the study area consists of Precambrian granite and crystalline rocks. These rocks form the geologic basement of the Española Basin and are congruent with the Proterozoic rocks of the Sangre de Cristo and Santa Fe Mountains (Hudson et al., 2011).

CHAPTER 4: PETROLEUM SYSTEM ELEMENTS

A detailed petroleum system analysis of the southern portion of the Española Basin has not been published to date. The petroleum system elements identified in this study have been determined from sparse exploration well data, cross section stratigraphy, New Mexico source rock studies, and observations noted during previous studies of the basin.

4.1: SOURCE

The source rock considered in this area of the Española Basin is found in the pre-rift Pennsylvanian rocks. Numerous shales within the Mesozoic section are potential source rock horizons and several more have been considered potential source horizons in other basins in New Mexico such as the Raton, San Luis, and Albuquerque Basins (Broadhead, 2008). These Mesozoic sources were not considered as potential sources in this petroleum systems analysis of the southern Española Basin, however, due to lack of control data and discontinuity throughout the study area. The Mesozoic section, as discussed earlier, has not been penetrated by deep exploration wells and has not been divided into formal stratigraphic units in this region. The

Pennsylvanian starta, namely the Madera Group, which is considered a potential source rock in the other basins of the Rio Grande rift in New Mexico, is present throughout the study area and has been penetrated by wells. The Pennsylvanian Madera Formation was pierced by the Yates La Mesa #2 and C&W Kelly Federal #1 wells used in this study. The Madera Formation consists of limestones and shales interpreted to be deposited as deep-sea basin and shelf deposits. The deep-sea basin deposits are dominated by limestones and marine shales, while the shelf deposits are dominated by carbonates and shales (Kues, 2001). The shales and limestones are considered to be organic rich, according to data collected in the New Mexico Petroleum Source Rock Database 1998. The database concludes that the TOC's of the Madera Formation in the Yates and C&W exploration wells range from 0.35 to 0.82 percent. These are lower than the average good source rock values, but still high enough of a percentage to generate hydrocarbons, i.e. above the 0.5% cutoff considered necessary for carbonate sources (Hunt, 1996). Lower TOC values are generally more acceptable if the source rock is limestone as opposed to the more common shale. The kerogen type identified in the samples is that of Type II to Type III kerogen with percentages ranging from 0-15% amorphous, 33-56% herbaceous and 22-33% woody with varying levels of inertinite. The mixture of algal/amorphous and herbaceous/woody gives the Type II distinction. Type II kerogen generally results in oil and gas while Type III kerogen generally results in gas generation. The kerogen type was also reported to be moderately mature to mature. The Madera Formation source rock also suggests that the limestone and shale layers are both organic rich with sample ranging from 20-100% limestone and 0-70% shale.

4.2 POTENTIAL RESERVOIRS

There has been very little exploration in the Española Basin, and as a result only a small amount of data exists. Of the wells drilled in the nearby area, there has been some variance in the reservoir units in which the hydrocarbon shows were found. One of the potential reservoir units, as in the rest of the rift basin in New Mexico, can be found in the Mesozoic section. Oil and gas shows have been reported in the Cretaceous units of the Niobrara Shale and the Gallup Sandstone. These specific units have not been distinguished in this particular study area but similar horizons most likely exist in the preserved Mesozoic section seen in the geologic cross sections assembled by Koning and Read (Broadhead, 1987). While the continuity of the Mesozoic section across the southern portion of the Española Basin is questioned, the presence of the Mesozoic strata insists that we should classify it as a potential reservoir. Another obvious potential reservoir rock is the Espinaso Formation. The Espinaso Formation lies directly above the Pennsylvanian Madera Group that is classified as the source rock in this section of the basin. The Espinaso Formation has good reservoir characteristics as it contains alluvial fan deposits which consist of a good amount of sand. The Espinaso is generally sandstones and conglomerates derived from weathering volcanic rocks in the surrounding areas and shows good porosity and permeability (Koning and Read, 2010). Another potential reservoir in this area of the Española Basin is the Pennsylvanian section itself, which also serves as the source rock. The Madera Group of the Pennsylvanian is composed of limestone carbonates and shales that are organic rich and interbedded with each other. The unit becomes an attractive reservoir target if the shales dispel hydrocarbons into nearby carbonate structures or if the shales and limestones themselves are permeable enough for movement of hydrocarbons. This potential reservoir is a very interesting target because of the advances of current unconventional hydrocarbon production. When the exploration wells within this area of the Española Basin were drilled, hydraulic fracturing was not a common practice in shale and limestone reservoirs. This could be a case of the source rock acting as the source and the reservoir. This means that potential conventional and unconventional resources exist in the Pennsylvanian units in the southern Española Basin.

4.3 MIGRATION ROUTES

The possible migration routes are very much related to the different potential reservoir rocks. In the case of the Pennsylvanian unit as the source and the reservoir, migration pathways are not necessary for hydrocarbon entrapment. In the case of unconventional reservoirs the source horizons themselves act as reservoirs so there is no migration. In the case of Pennsylvanian organic shales and limestones dispelling hydrocarbons into surrounding Pennsylvanian carbonates, there again no migration pathways are necessary as this is direct migration laterally or vertically into an area with greater pore space and permeability. In the case of potential Mesozoic reservoirs there can be several types of hydrocarbon migration. Due to the Mesozoic section lying directly above the Pennsylvanian source rock there is possible direct upward vertical migration. Where the Mesozoic section is deposited in the basin, it lies unconformably on top of the Pennsylvanian so the hydrocarbons could simply migrate upwards. In the case of reservoir horizons un the upper part of the Mesozoic section, migration pathways could be made possible through extensive faulting of the southern Española Basin. The Laramide Orogeny followed by regional extension during the formation of the Rio Grande rift has resulted in numerous faults throughout the area. These faults are pathways for hydrocarbon migration. Similar to Mesozoic reservoir horizons, the Espinaso Formation is another potential reservoir that in areas of the basin lies unconformably on top of the Pennsylvanian source rock. In this case hydrocarbons could migrate vertically into the reservoir horizons with relative ease. Again, the extensive faulting allows for extra migration pathways for hydrocarbons into the Espinaso Formation from the Pennsylvanian source.

4.4 SEALS

As there are several available reservoir rocks in the southern Española Basin there are also several different seals present. One obvious seal is the Pennsylvanian section itself. In the case of unconventional resources, the source rock is not only the source and reservoir but the seal as well. There is also the potential for the potential hydrocarbons to migrate into carbonate reservoirs within the Pennsylvanian. In this case surrounding shales could serve as the seals. In the case of Mesozoic reservoirs, interbedded shales could serve as seals for the sandstone reservoir horizons. Where present in the geologic cross sections of the Española Basin the Mesozoic is undivided, but is most likely contains several layers of shales interbedded sandstones due to knowledge of these reservoir/seal pairs in surrounding basins (Broadhead, 1987). Another seal rock present in the strat column is the Cieneguilla Basanite. The Cieneguilla Basanite in certain parts of the southern Española Basin overlies the Pennsylvanian source, the Espinaso Formation and the Mesozoic section. Meaning the Cieneguilla Formation is potentially a seal for Pennsylvanian, Espinaso Formation and Mesozoic reservoirs. The Cieneguilla Formation consists dominantly of basanite and basalt. Basalt flows can act as an excellent seal and are generally impermeable (Fainstein et al., 2012) and the Cieneguilla Basanite is widespread across the southern Española Basin.

4.5 POTENTIAL HYDROCARBON TRAPS

Several trapping mechanism are present in the southern Española Basin; these include structural and stratigraphic traps. The most obvious trapping style is structural, as this portion of the rift basin has undergone extensive faulting and deformation (Figure 7). During the Laramide Orogeny faulting occurred during regional uplift, and extensive normal faulting followed during the opening of the Rio Grande rift (Koning et al., 2013). This faulting and regional deformation has created numerous fault traps, rollover anticline traps, and anticline traps. As there are numerous possibilities for structural traps, there are just as many opportunities for stratigraphic traps. The most common types of stratigraphic traps include updip changes in facies, pinchouts, sandstone lenses, and carbonates. All of these types of traps are present in the rock descriptions and cross sections of the southern Española Basin. Almost all of the sedimentary units in this area of the basin are tilted and contain interbedded layers of sand and shale (Grauch et al., 2011). This provided a great opportunity to find sandstone pinchouts and updip facies changes. These types of stratigraphic traps would be found in the Mesozoic section and the Espinaso Formation which both contain alternating shale and sandstone layers which are interbedded. Carbonate traps, or reef traps, could be present in the Pennsylvanian section where carbonates have been incased in shale. The interbedding of shale and carbonate deposits, and more specifically shelf deposits, creates good trapping potential if there are hydrocarbons present.

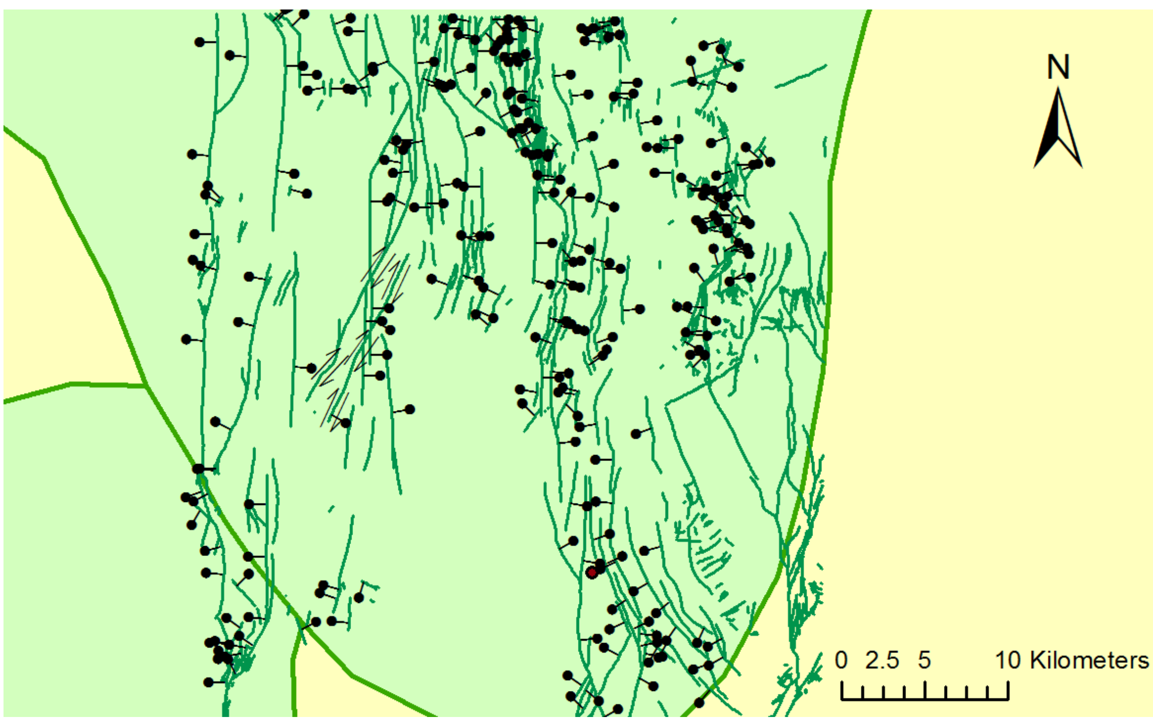

Figure 7. ***Map of extensive faulting in the southern Española Basin. Fault traces from Koning and Read (2010).***

CHAPTER 5: METHODS AND MODELING PROCEDURES

Basin modeling techniques are used to analyze the formation and development of sedimentary basins over geologic time. With a detailed tectonic history of the basin, along with sedimentary fill data, these models can reconstruct burial history in the basin as well as a more accurate thermal history in the basin. The tectonic and thermal history of a basin needs to be known for petroleum system modeling. Petroleum system modeling is the process of using basin modeling to predict and assess the availability of hydrocarbons in the basin of study. A petroleum system is a pod of active source rock and all of the genetically related oil and gas accumulations. The system includes all of the geologic elements and processes that are needed if oil and gas accumulations are to exist. The first step taken in the petroleum system analysis is defining the elements of the source, reservoir, seal and overburden rocks. These units are assessed by reviewing well data and well as detailed stratigraphic cross sections. Where possible, the rock types along with specific ages and rock properties were included in Petromod models in order to establish a correct burial and thermal history of the basin. The input of detailed rock properties and distribution of the source and reservoir units is necessary to establish a correct model. The detailed cross sections were used to incorporate the source, reservoir and seal distribution into the model. The timing aspects of a petroleum system are crucial in determining the critical moment of hydrocarbon generation and migration as well as deposition of source, reservoir, seal and trap. For this reason the maturity and heat profiles of this section of the basin are the main focus of the models. Basin modeling is the process of using geologic data to reconstruct the evolution of a sedimentary basin. One of the basic principles of this is backstripping, which involves the removal of the effects of sedimentation to get a clear analysis of tectonic subsidence of the basin. Backstripping involves corrections including decompaction to restore layer thickness at time of deposition, which can also be beneficial in determining porosities and permeabilities of units. Backstripping also creates a clearer picture of burial history and depth, both of which are crucial components in the generation and migration of hydrocarbons. The reconstruction of the evolution of a sedimentary basin is necessary in order to complete a petroleum systems analysis, particularly in regard to the prediction of charged reservoirs, hydrocarbon type, source and timing of hydrocarbon generation, entrapment, and migration routes throughout the basin.

In this study well data was combined with detailed geologic cross sections in order to build a Petromod basin model. The wells used were the only deep exploration wells drilled in the southern Española Basin that pierced the entire rift basin. The wells were the Yates La Mesa #2 (Figure 6) and the Castle and Wigzell #1 Kelly Federal (Figure 8). Both of these wells penetrated at least down to the Pennsylvanian and the Yates La Mesa #2 well actually goes down to the Proterozoic granite. The detailed geologic cross sections were created by Koning and Read (2010). To assemble a better understanding of the regional extent of basin processes pseudo-wells were created using the geologic cross sections to produce a more accurate model in Petromod. The pseudo-wells also helped to test multiple elements of the potential petroleum system in the southern Española Basin that had not been tested with the well bore. On top of this, the pseudo-wells helped to create multiple models in Petromod due to the discontinuity of some of the possible petroleum system elements. Due to uncertainty with some of the petroleum system elements, multiple models

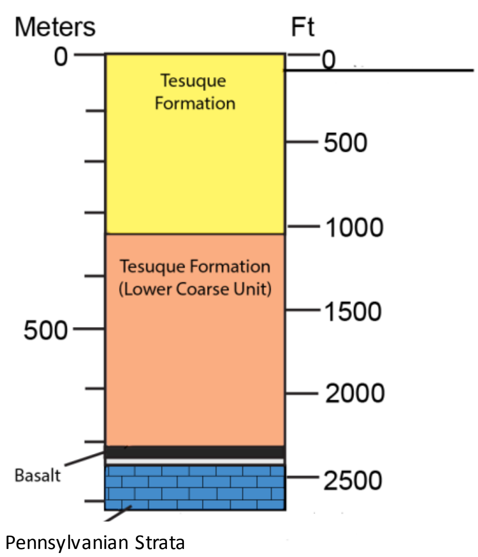

Figure 8. ***Stratigraphy in Castle & Wigzell #1 Kelly Federal Well. Modified from Koning et al (2013).***

were actually run changing the reservoir and seal properties in certain wells to test this portion of the basin for any petroleum system that might exist. An example of this was running two separate 1D models using the Yates La Mesa #2 well, but in one model using the standard source/reservoir/seal pairs and in another model modeling the Pennsylvanian as an unconventional reservoir. This is discussed in the results section. Another example of pseudo-well usage was modeling the Mesozoic section as a potential reservoir where the Mesozoic had not been tested previously with an actual exploration well.

Certain input parameters had to be adjusted to attempt to model this section of the Española Basin as accurately as possible. Mainly, heat flow properties had to be adjusted to demonstrate the higher than average heat flow in the basin. The beta-crust value (or thinning factor of the crust) was set at 1.95 to simulate higher heat flow trends to match the published data. The generated heat flow trends were also adjusted to simulate periods of volcanic activity in the basin to match what heat flow trends might have been at the time of the flows and intrusions. Another challenge was adapting the Petromod software to accommodate a possible unconventional reservoir. The software does not allow source and reservoir petroleum system elements to be assigned to one unit. This modification was made by separating the Madera Formation into two separate stratigraphic units. This allowed for one unit to be assigned the source and the other to be assigned the reservoir, while keeping all rock properties the same. As stated earlier, the Mesozoic section was not considered in this study to contain any source units. This decision was made based on a lack of data in this area. As the Mesozoic was mapped in the geologic cross sections, it was considered as a possible reservoir to examine all possible petroleum system elements the data in this region would allow. These are areas where more extensive data could provide a better understanding of the evolution of the Española Basin and model any potential petroleum systems.

LAYER	TOP	THICKNESS	ERODED	DEP FROM	DEP TO	ERODED FROM	ERODED TO	LITHOLOGY	PSE	TOC	KINETIC	HI
CDR VOLCANICS	0	152		2.7	1			Basalt (weathered)	Overburden Rock			
ANCHA FORMATION	152	27		3	2.7			SANDcongl	Overburden Rock			
TESUQUE-CUARTELES	179	296		13.2	3			SANDshaly	Overburden Rock			
TESUQUE-FINE	475	924		25	17			SANDsilty	Seal Rock			
MESOZOIC	1399	1344	50	227	90	85	45	SAND&SHALE	Reservoir Rock			
PENN (MADERA GR.)	2743	427		310	299			Limestone (organic rich - typical)	Source Rock	0.82	Tissot_in_Waples(1992)_TII_Crack	67

Table 1. ***Input parameters of the Mesozoic pseudo well showing petroleum system elements and depths of formations.***

Another issue faced in the modeling of the southern Española Basin was the erosional events and the amount of erosion that took place. The major erosional event that took place in this region was uplift and erosion associated with the Laramide Orogeny. The discontinuity of some of the units, namely the Mesozoic section, suggests that erosion took place but the amount and specific dating of these events was not detailed enough to be specific. This is another area where further study could be done in order to better model basin evolution and provide a better petroleum system analysis.

CHAPTER 6: RESULTS

The results are broken down by the exploration wells and test wells that were modeled for petroleum systems analysis. It should be noted that all depths shown in the results are based on surface elevation at 0 m. The depths are not meters below Sea Level but alternatively meters below the surface elevation.

6.1 C&W #1 KELLY (C&W) FEDERAL WELL

The C&W #1 well is located in the northern part of the southern Española Basin and is out of the area where geologic cross sections were available. The well, located at decimal degrees coordinates 35.978,-105.956 using a NAD27 UTM Zone 13N projection, was drilled to a total depth of 2,710 feet (826 meters) with the Pennsylvanian being the bottom hole formation. This well was chosen for a 1D model due to the fact that it penetrated the full rift basin and at the time of drilling reported minor oil shows in the Pennsylvanian.

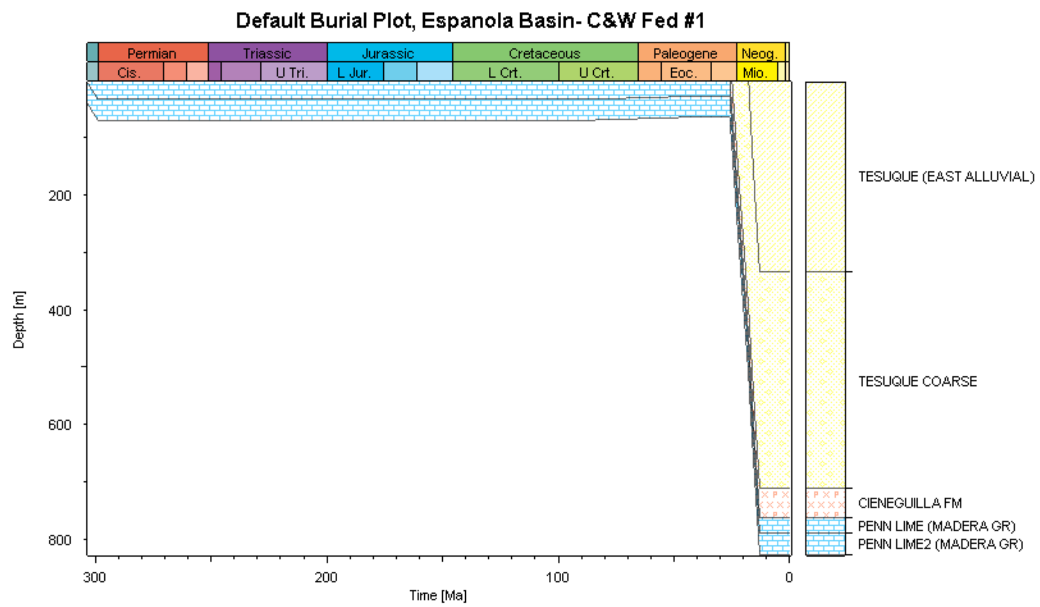

Figure 9. ***Burial history of the C&W Fed # 1 well.***

The burial diagrams for this section of the Española Basin (Figure 9), using the stratigraphy found in the C&W #1 well shows that there was not any deposition between the Pennsylvanian units and the beginning of the rifting phase at 27 Ma. This could also be interpreted as sediments were once there were eroded away. Once rifting began, significant deposition occurred as almost 800 meters of sediment and volcanic rocks fill the section. Mesozoic rocks are present in the surrounding areas of the basin but are absent in this well. It is possible that Laramide uplift eroded the Mesozoic layers away but at this time that is not clear. It is not believed that erosion greatly affected the Pennsylvanian section but a small amount of erosion was modeled as it is the only unit present in the section pre-rift. As discussed in the methods the Pennsylvanian was separated to accommodate the possibility of the source rock being a potential reservoir. The Tesuque Formation is this area of the basin has been separated into the East Alluvial facies (equivalent to the lower to middle Tesuque) and lower coarse unit of the Tesuque.

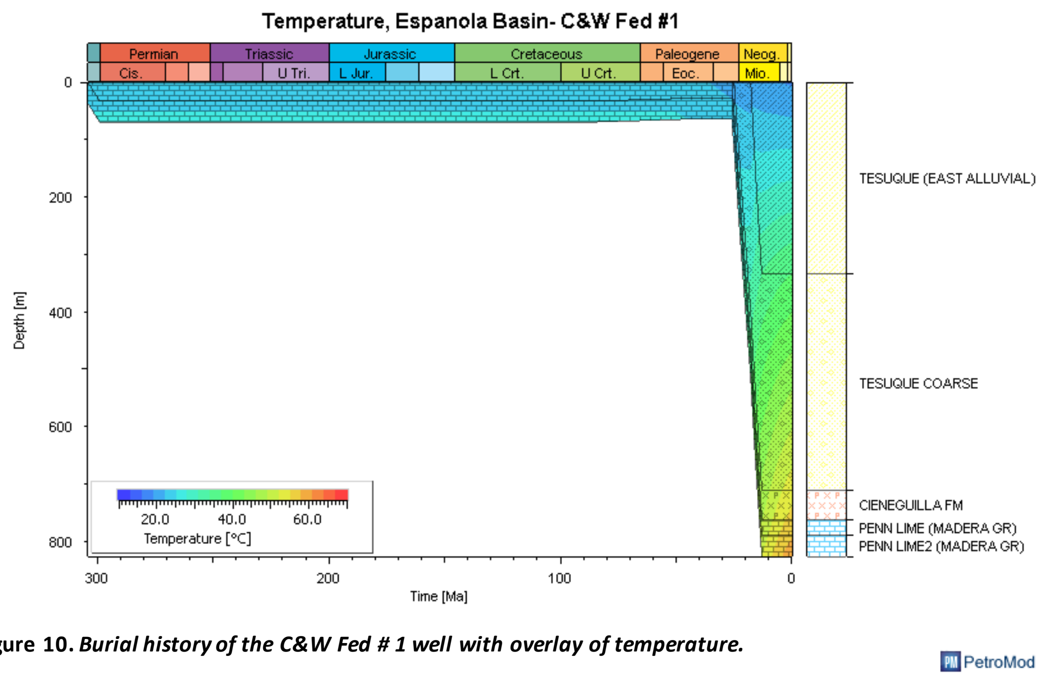

Figure 10. ***Burial history of the C&W Fed # 1 well with overlay of temperature.***

The temperature profile for the C&W #1 well (Figure 10) shows that the tempeatures reached just under 80°C at total depth of the well in the Pennsylvanian. The temperatures increase over time as the formations are buried deeper, and also as the heat flow into the basin increases when rifting progresses (Figure 11). This profile demonstrates that the basin was relatively cool until the onset of rifting.

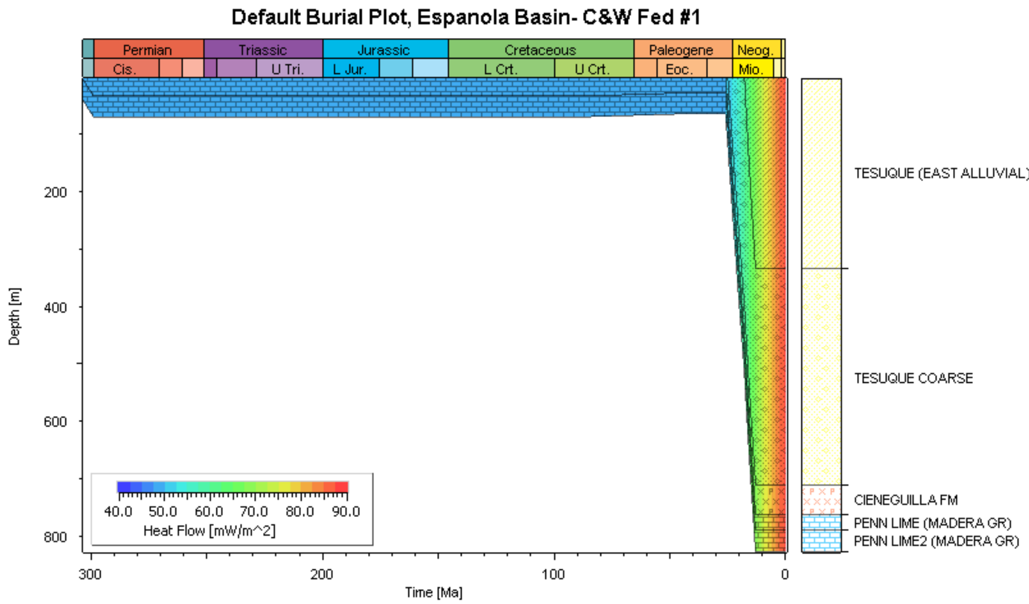

Figure 11. ***Burial history of the C&W Fed # 1 well with overlay of heat flow into the basin.***

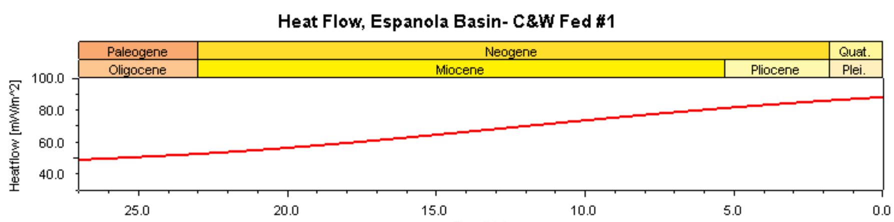

Figure 12. ***Heat flow into the Española Basin at the C&W Fed # 1 well.***

The temperature in the basin is related to the heat flow profiles modeled (Figure 12). The heat flow trend was adapted by first setting the geographic location and latitude to generate the SWIT profile. Then the rifting information was input in Petromod. The input values were adapted to create a viable model of the events that actually took place in the basin. The heat flow trend was created using a McKenzie stretching model with rifting beginning at 27 Ma and ending at 0 Ma, as rifting is still ongoing. The beta-crust value (this is the thinning factor of the crust) was set at 1.90 as this high value was needed to create a usable heat trend. From the burial plot with the heat flow overlay (Figure 11), it can easily be seen that the majority of the heat flow in the basin began at the time of rifting and is still very high in the basin.

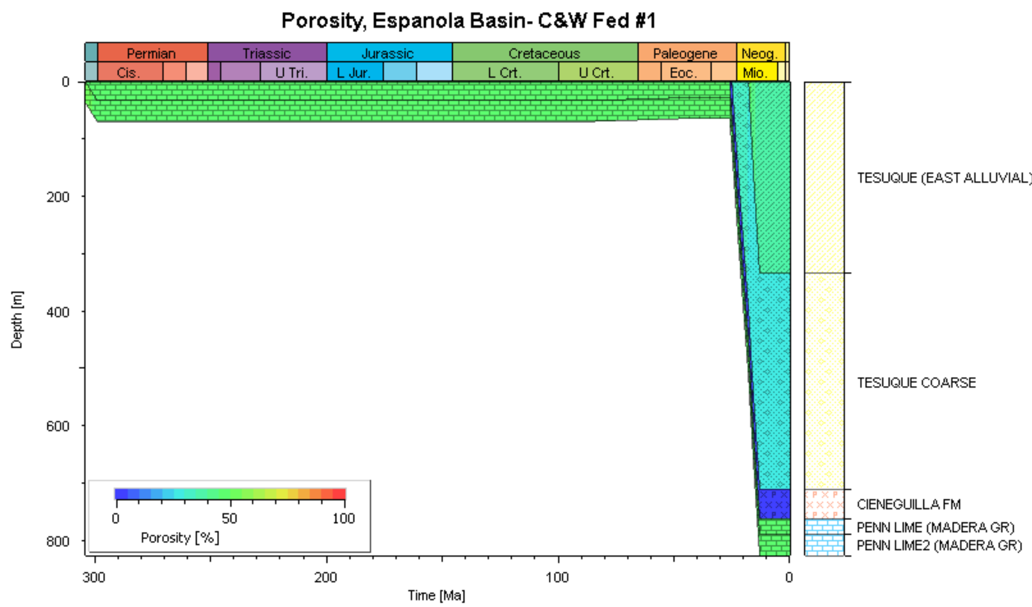

Figure 13. ***Burial history of the C&W Fed # 1 well with porosity overlay.***

The porosity profile of the basin at the well location takes into account the lithology and rock properties as well as compactions effect on porosity. The carbonates of the Pennsylvanian unit are rather porous, while the overlying Cieneguilla Basanite has very little to no porosity (Figure 13). This is the type of porosity and permeability that characterizes a good seal rock that could trap hydrocarbons in the Pennsylvanian carbonate structures. We also see less porosity in the coarse-grained Tesuque Formation as compared to the overlying alluvial facies of the Tesuque. This is a result of a combination of factors, which include greater stratigraphic depth and composition. The main lesson to take away from this porosity overlay is that the source/reservoir rock shows good porosity while the overlying seal rock shows very little to no porosity.

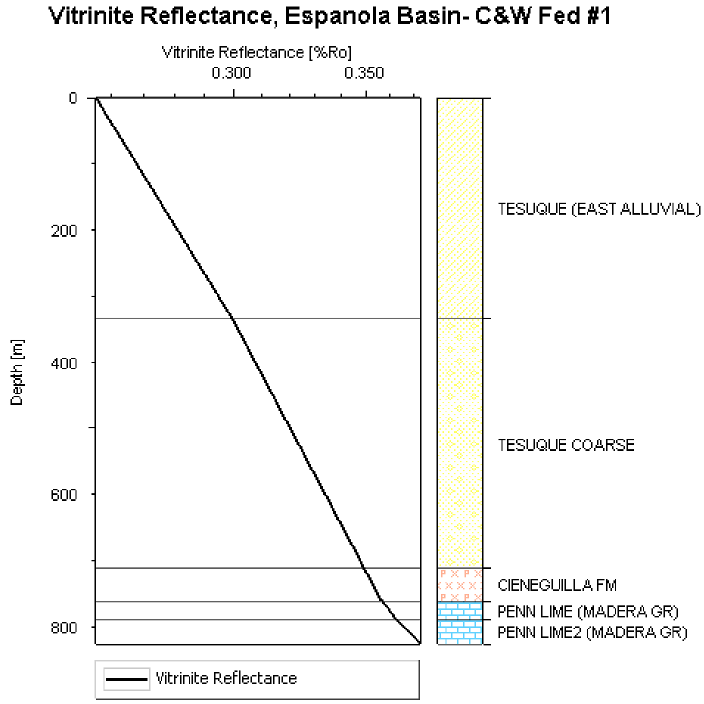

Figure 14. ***Vitrinite reflectance of the C&W Fed # 1 well.***

The vitrinite reflectance (%Ro) profile generated for the C&W #1 well (Figure 14, 15) shows that the Pennsylvanian unit only reached a maximum value of approximately 0.4%. This value is quite low in terms of maturity of hydrocarbons and not consistent with the generation of hydrocarbons. At this value of %Ro dry gas is the only possible hydrocarbon outcome and even that is a stretch. This value again might be affected by the lack of data regarding erosion and removal of Mesozoic sediments. Very minor hydrocarbon shows were reported in this well but the data did not mention the type of hydrocarbon show. This model suggests that the show was most likely a minor gas show. The C&W #1 well was a very shallow exploration well and in this area of the southern Española Basin the Pennsylvanian was quite shallow. These data show us that even with the higher heat flow in the basin there simply was not enough pressure and heat to reach mature vitrinite reflectance %Ro values.

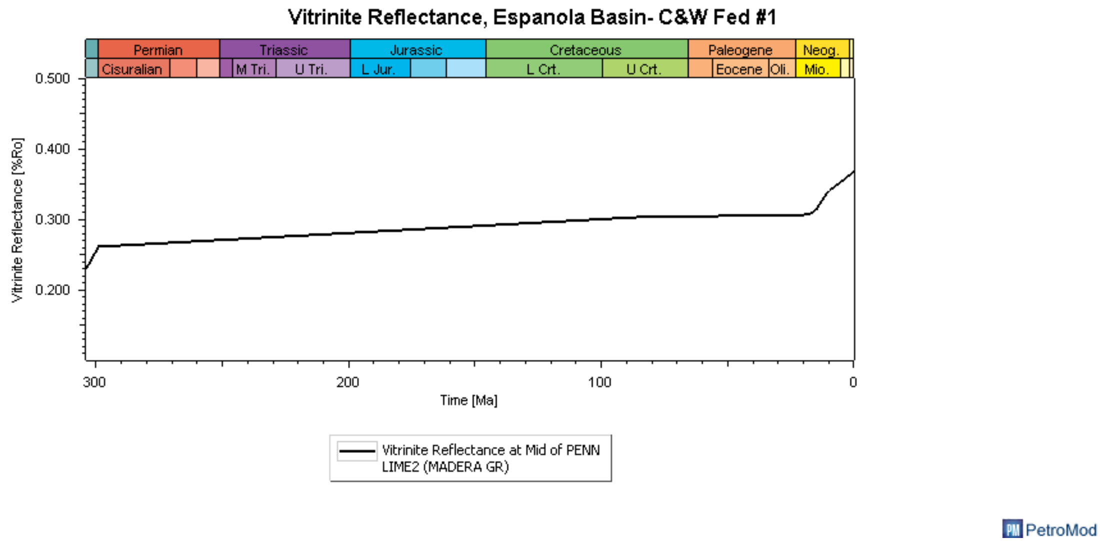

Figure 15. ***Vitrinite reflectance in the Madera Group of the C&W Fed # 1 well.***

The vitrinite reflectance values have been pretty steady over the history of the source rock (Figure 15) and only began to significantly increase when rifting began at approximately 27 Ma. Even with the increase in temperature during rifting the source rock is still not reaching the maturity levels needed to produce significant hydrocarbons. The possible addition of Mesozoic strata to this well could again provide the maturity needed but the data is not available.

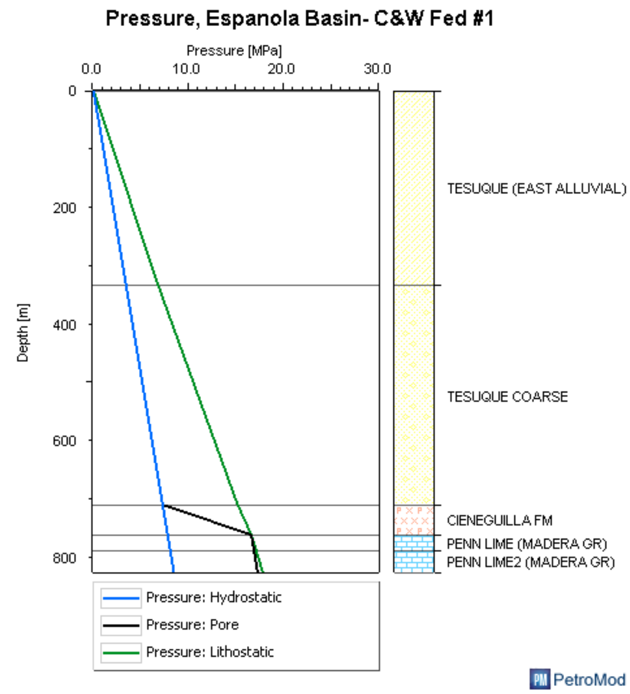

Figure 16. ***Pressure in the C&W Fed # 1 well.***

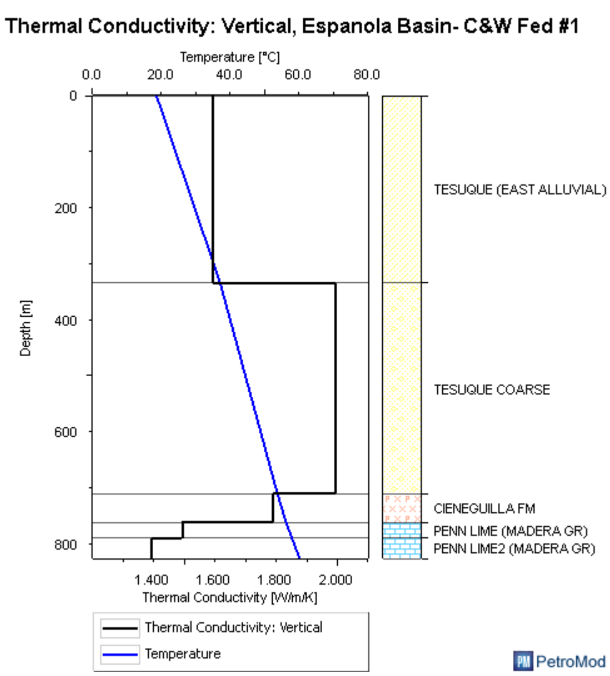

Figure 17. ***Thermal conductivity of the C&W Fed # 1 well.***

The pressure and thermal conductivity profiles (Figure 16 and 17) tell us a little more about the properties of the basin in the area. The lithostatic pressure increase with depth is expected and the bottom hole value of less than 20 MPa is a result of the shallow depth of the Pennsylvanian in this well. The thermal conductivity profile shows the modeled heat flow within each individual unit. The profile shows that there is good conductivity in the rift sediments but low values in the Pennsylvanian section. The low thermal conductivity values in the Pennsylvanian are believed to be a factor of increasing porosity and increasing temperature. As porosity increases in a stratigraphic unit, the thermal conductivity is decreasing (Ouali, 2009). While the values of 1.4 – 1.6 W/mK are low, they are within the general range for limestones and carbonates and considered normal. Errors in thermal conductivity are possible when composition of the formation does not exactly match the lithology used in the modeling program.

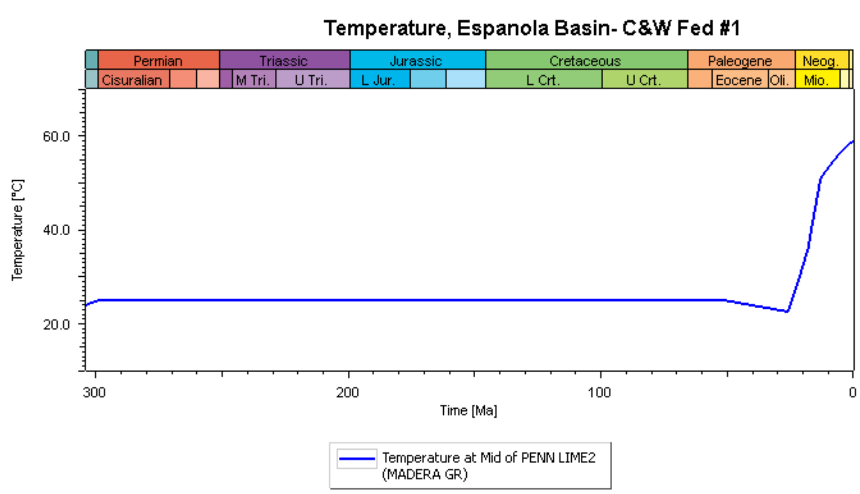

Figure 18. ***Temperature in the C&W Fed # 1 well, Madera Group.***

The temperature profile of the history of the basin, according to the model of the C&W #1 well, show us exactly when rifting began (Figure 18). The profile shows a steady basin temperature throughout the pre-rift era. The Pennsylvanian units maintained a steady temperature around approximately 25°C until the onset of rifting at approximately 27 Ma. As Rio Grande rifting began in the late Oligocene, a dramatic upturn in the temperature of the basin is observed and this trend continues today, as this is still an active rift. As the Rio Grande rift has slowed down, you can see this in the temperature profile as it is beginning to level off. The temperature in the basin was also moderately affected by volcanic flows and intrusions in the basin.

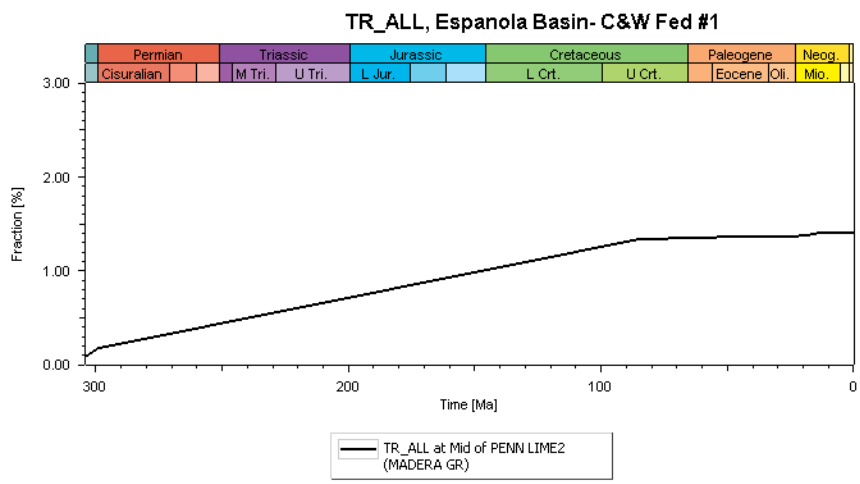

Figure 19. ***Transformation ratio for the C&W Fed # 1 well, Madera Group.***

The TR_ALL value (Figure 19) represents the Transformation Ratio, which is the in quantitative transformation of the original organic content based on the total organic carbon. The fraction percentage shows the percentage of the total organic carbon that was transformed into hydrocarbons. Based on the model of the C&W #1 well only 1% of the total organic carbon underwent transformation into hydrocarbons. Unfortunately this low percentage is not enough to supply an accumulation and a low mass of generation is likely. The amount of organic content in the Pennsylvanian Madera Limestone, that is the source rock present, is 0.82% TOC (Total

Organic Carbon). The source interval is less than 100 meters in this area of the basin and therefore a low TOC combined with a low transformation ratio shows that a very small amount of organic material reached the transformation stage.

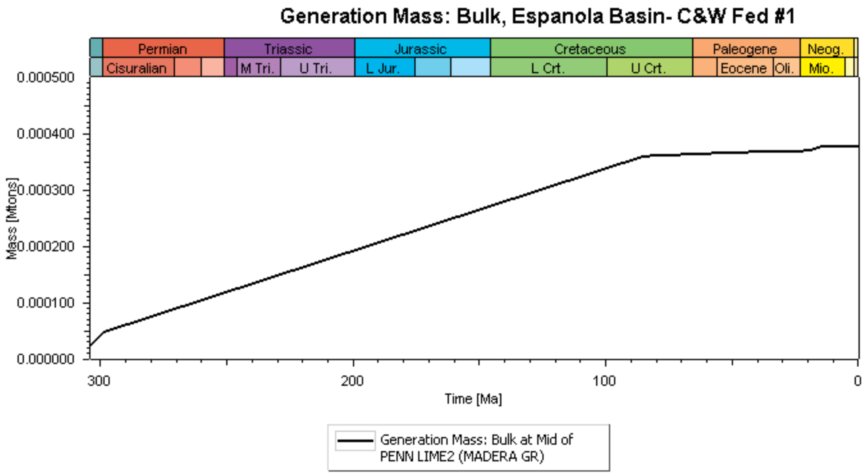

Figure 20. ***Generation mass for the C&W Fed # 1 well, Madera Group.***

As this is related to the transformation ratio, the total generated mass (Figure 20) is quite low in the model of this well. Far too low of a percentage of organic carbon in the source rock reached the transformation phase for there to be a significant mass of hydrocarbons generated. The maximum mass value of generated hydrocarbons was modeled at 0.00035 million tons which is a relatively small amount.

The C&W #1 well model was valuable in analyzing the entire sequence of units in the rift basin and in the pre-rift section. While some of the factors and input values of the model had to be assumed, the results of the model were consistent with the drilling results and gave a good test of the modeling input values. While temperature and maturity (%Ro) data suggest that the source rock did not reach the oil generation window, a very small amount of the total organic carbon did undergo transformation and resulted in a small mass of generated hydrocarbon products. This result is congruent with the drilling data that reported minor hydrocarbon shows in the Pennsylvanian strata. Any future work regarding this exploration well and petroleum system model should attempt to determine any layers, and to what extent, were eroded away from the section. If any considerable amount of rocks were in place, and then subsequently eroded during Laramide uplift, this could change the model dramatically. If a large amount of Mesozoic overburden was in place and remained in place until Laramide uplift, cooking of the hydrocarbons could have begun at a much early date.

6.2 YATES LA MESA #2 WELL – CONVENTIONAL MODEL

As stated in the Methods section, two types of models were run using the Yates #2 well. The first, described here modeled the Pennsylvanian Madera Formation as a conventional source rock. The meaning of conventional source is that the source rock generated and expelled hydrocarbons into a reservoir rock via migration pathways. The Yates #2 well was selected to be modeled due to it being geographically centered in the southern Española Basin and because this well reaches total depth in the Proterozoic granite basement, penetrating all rift sediment and all pre-rift sediments. The well is located at decimal degrees coordinates 35.689, -106.043 using the NAD27 UTM Zone 13N projection, and reached a total depth of 7,710 feet (2,350 meters).

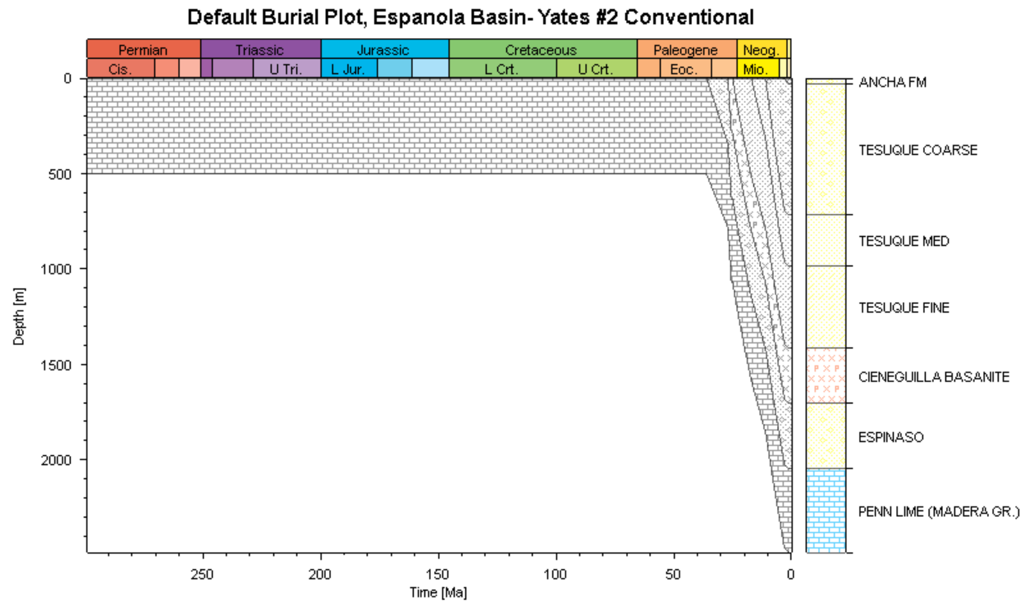

Figure 21. ***Burial history for the Yates #2 well.***

The burial history diagram for the Yates #2 well (Figure 21) shows much of the same deposition history as the C&W #1 well. For a long period of time the only units present in this area were the Proterozoic basement overlain by a Pennsylvanian unit. The end of Pennsylvanian deposition occurred at approximately 300 Ma and the next phase of deposition did not occur until the Espinaso Formation between 36 and 29 Ma. According to the stratigraphy penetrated by the well, roughly 260 million years pass by of which no sediments are present today. The presence of Mesozoic units elsewhere in the southern Española Basin suggests that at some point this unit laid unconformably on top of the Pennsylvanian and was eroded away during Laramide uplift. That being said, there is no published study or data to definitively prove this. There is also very little data regarding any erosion of the Pennsylvanian strata during Laramide uplift. The model burial history plot shows a thick Pennsylvanian section by itself until rifting began at approximately 27 Ma. From that point on deposition of several new units occurs in a relatively short period of time as Tertiary units fill the newly forming rift basin. The burial plot also shows the source/reservoir/seal sequence with the Pennsylvanian source rock being overlain by the reservoir Espinaso Formation, and the Espinaso in turn being overlain by the Cieneguilla Basanite seal rock.

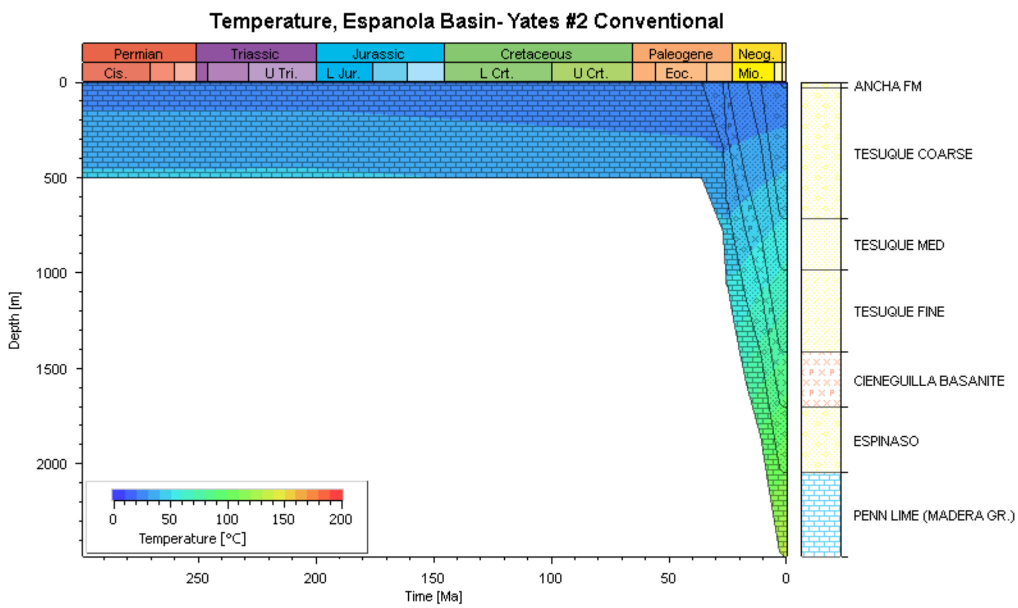

Figure 22. ***Burial history for the Yates #2 well with temperature overlay.***

The temperature overly of the burial history plot (Figure 22) shows that units in this portion of the basin reached greater temperatures than those in the C&W #1 well. This is due to the larger burial depths of the formation in the area of the southern Española Basin. The top of the Pennsylvanian section in this well is at approximately -2050 meters below the surface while it rests at approximately -750 meters below the surface in the C&W #1 well. That amount of depth and extra overburden rock increase temperatures by a significant margin. Temperatures in the Pennsylvanian strata are modeled at over 100°C in this well.

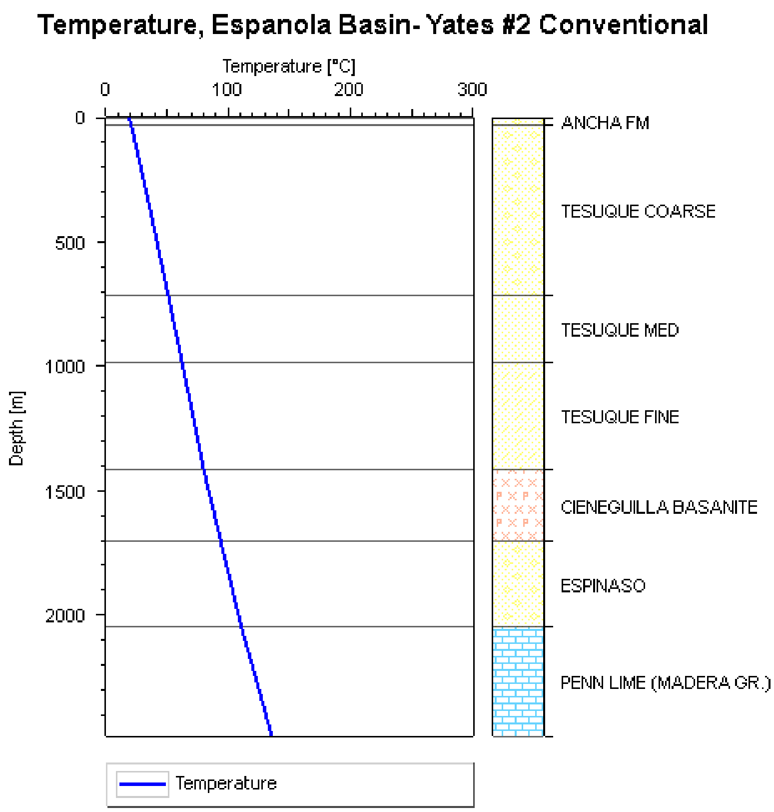

Figure 23. ***Present day temperature profile for the Yates #2 well.***

Higher temperatures at the depth of the source rock (Figure 23) should provide additional maturity and allow for a greater transformation ratios as compared to the C&W #1 well. The higher temperatures in the source provide a better opportunity for the source to be in the hydrocarbon window and stay in that window for a longer period of time, ultimately resulting in greater hydrocarbon generation potential.

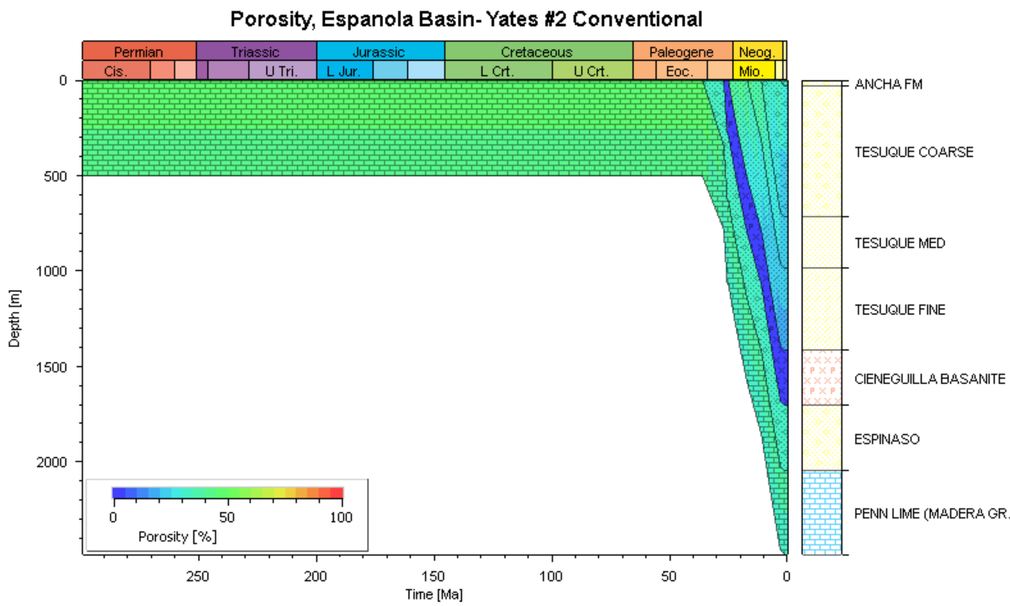

Figure 24. ***Burial history overlain by porosity for the Yates #2 well.***

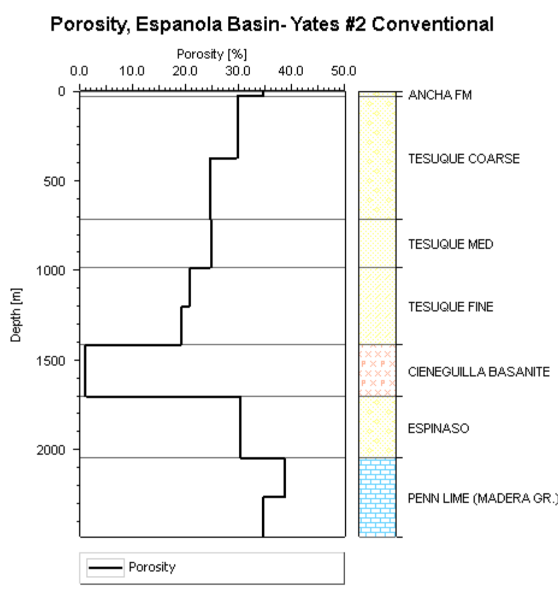

Figure 25. ***Present day porosity for the Yates #2 well.***

The porosity (Figure 24, 25) of the units is similar to what was seen in the C&W #1 well model. The Pennsylvanian aged carbonates and source rock show good porosity as well as the potential reservoir rock the Espinaso Formation. The Espinaso Formation is modeled to have porosities at just over 30% which is good for a reservoir horizon. Another important attribute to note is the dense and compact nature of the Cieneguilla Basanite, which is a seal rock in the section. The Cieneguilla is displaying porosities under 5% and this further proves the basanite and basalt as reliable seals.

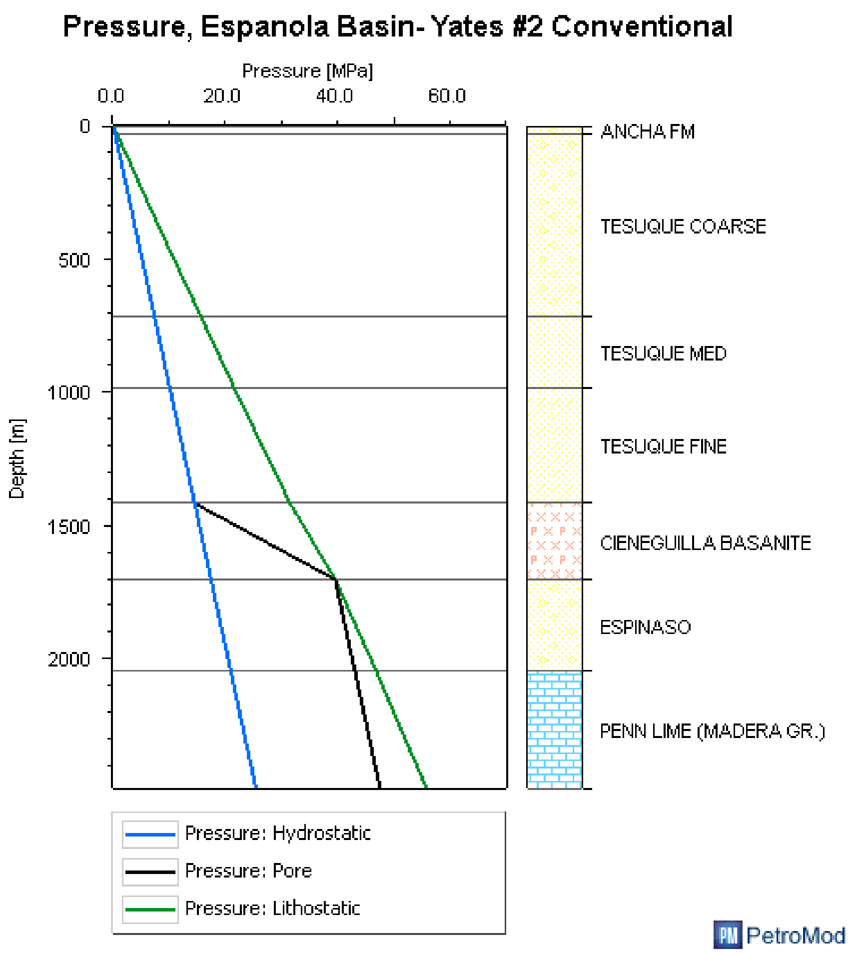

Figure 26. ***Pressure-depth profile for the Yates #2 well.***

The pressure diagram (Figure 26) shows that the lithostatic pressure on this stratigraphic column is much greater than predicted for the C&W #1 well and this further adds to the potential of the Pennsylvanian source to reach maturity; with more lithostatic pressure and heat the thermal maturity of the source is potentially larger. The lithostatic pressure reaches a maximum value of just under 60 MPa in the Pennsylvanian.

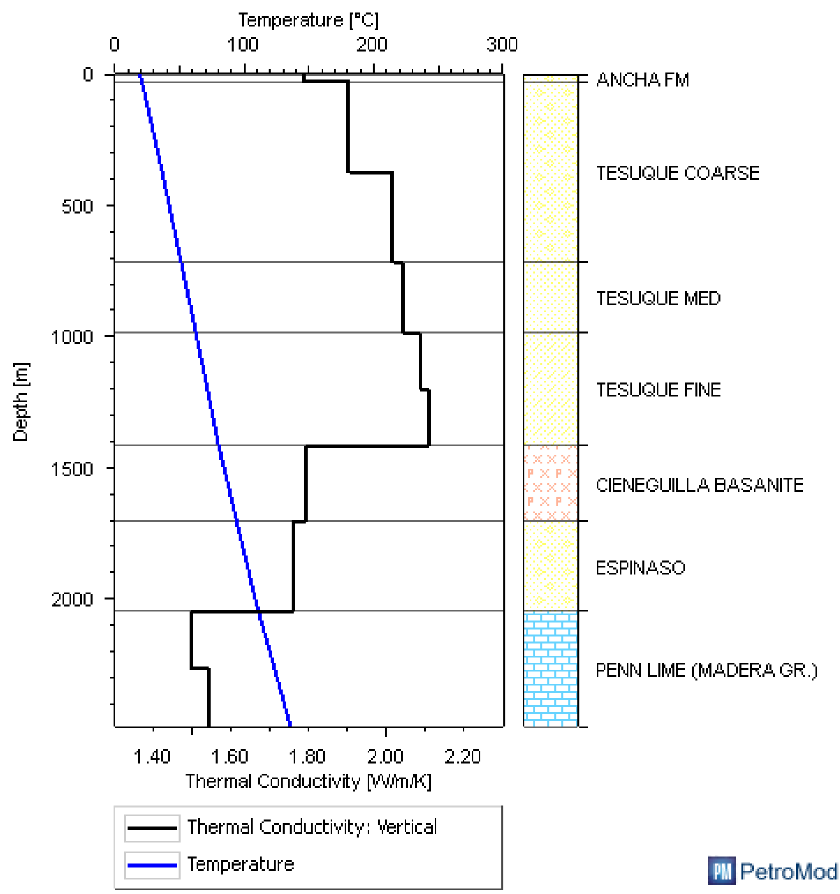

Figure 27. ***Thermal conductivity for the Yates #2 well.***

The thermal conductivity (Figure 27) is related to the heat flow and the geothermal gradient in this area of the southern Española Basin. The thermal conductivity values decrease with an increase in porosity and this is shown by the porous Pennsylvanian carbonates and the slightly less porous Espinaso Formation. Again the Pennsylvanian limstones have thermal conductivity values of 1.5 – 1.6 W/m°K and this is attributed to the high porosity of the formation. The thermal conductivity readings can be affected by errors in the composition of the unit. The Madera Group of the Pennsylvanian is shown to contain carbonates and marine to shelf shales but this composition is not included in the Petromod modeling software.

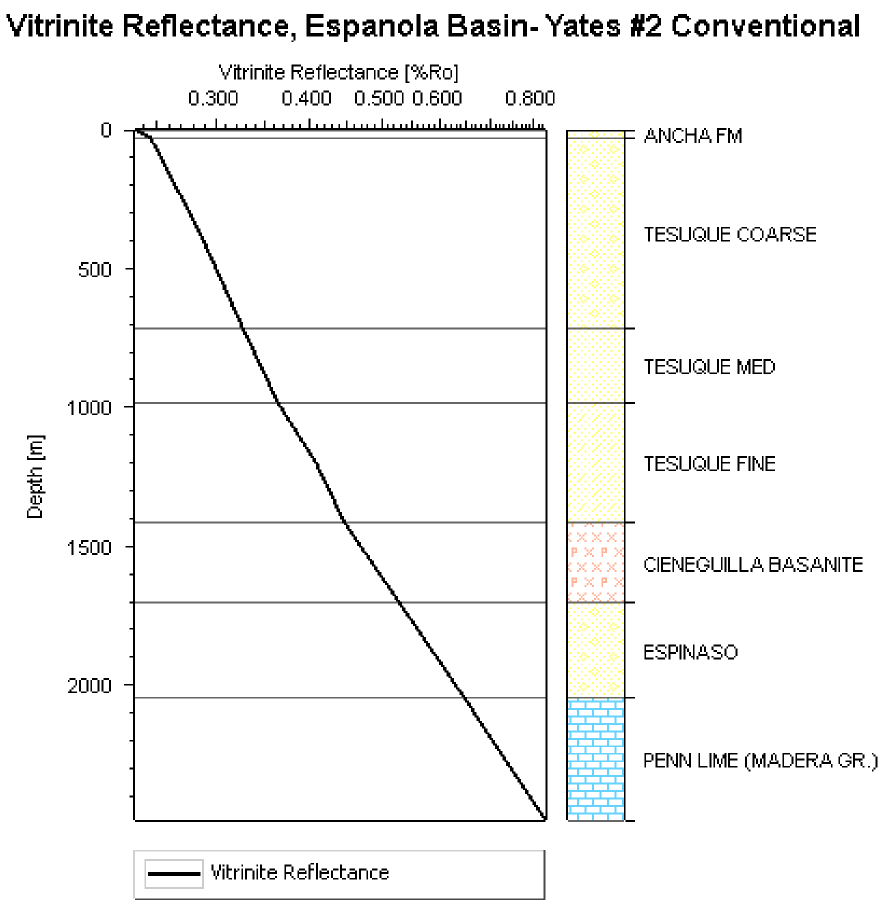

Figure 28. ***Vitrinite reflectance for the Yates #2 well.***

The modeled vitrinite reflectance %Ro (Figure 28) values of the Yates #2 well show greater thermal maturity of the source rock and show that the Pennsylvanian section did reach the maturity needed for hydrocarbon generation. Near the middle of the Pennsylvanian source unit the approximate %Ro is 0.75.

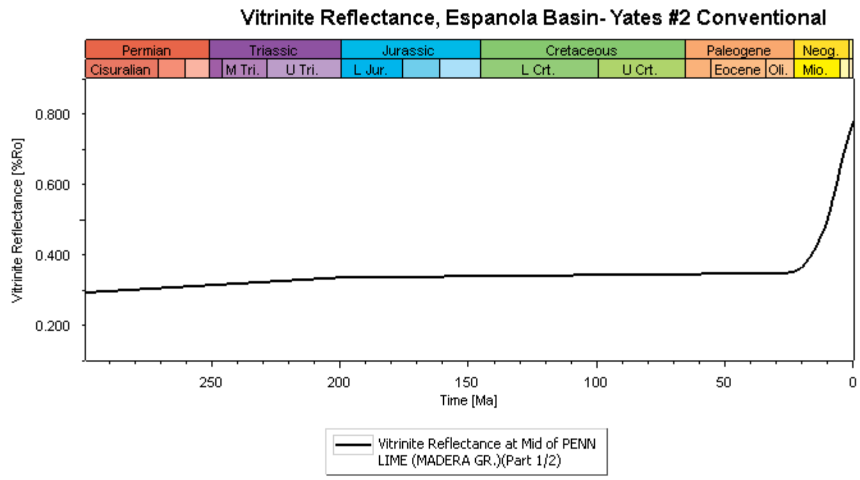

Figure 29. ***Vitrinite reflectance evolution for the Madera Group, the Yates #2 well.***

The vitrinite reflectance values were steady for most of the pre-rift phase (Figure 29) and then increased as rifting increased temperatures and heat flow in the basin. The diagram (Figure 29) shows the increase in %Ro maturity beginning at approximately 27 Ma, the same time frame that the Rio Grande rift was beginning to open the Española Basin. This plot shows that within the past 10 million years this section of the Española Basin reached the hydrocarbon generation window. The vitrinite reflectance maturity plot is directly related to the temperature history plot of this area of the basin (Figure 30).

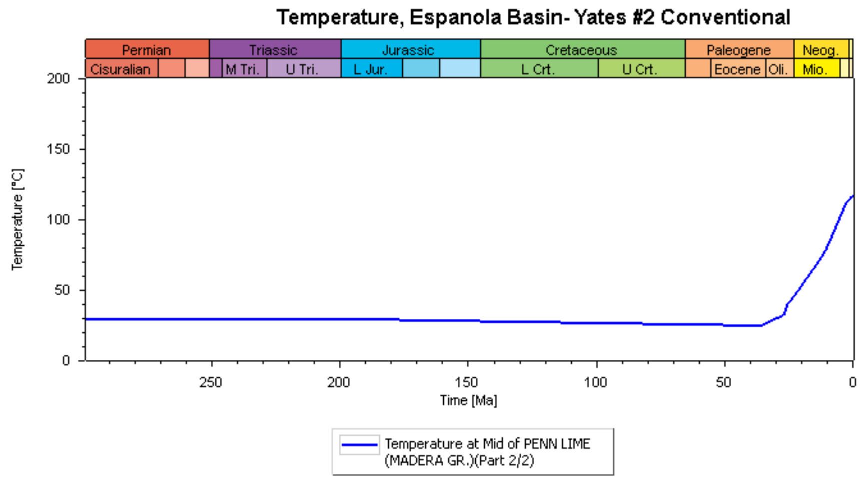

Figure 30. ***Temperature evolution for the Madera Group, the Yates #2 well.***

The model shows that temperatures started to increase with the onset of rifting and this in turn increased the thermal maturity of the source rock in the basin.

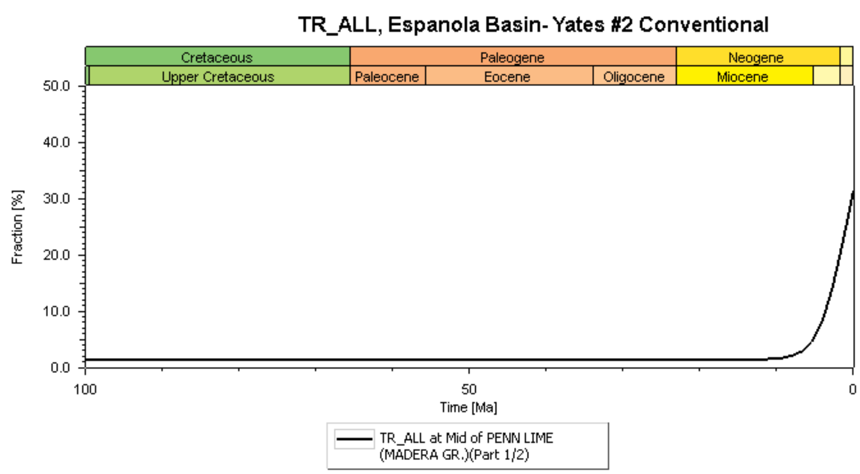

Figure 31. ***Transformation ratio for the Madera Group, the Yates #2 well.***

The transformation ratio, representing the quantitative transformation of original organic material based on the total organic carbon content is much higher (Figure 31) in the model of the Yates #2 well. The transformation ratio reaches just over 30% of the original organic material. With a source rock that has a TOC value of 0.82%, this higher transformation ratio provides a significant increase in potential generation of hydrocarbons.

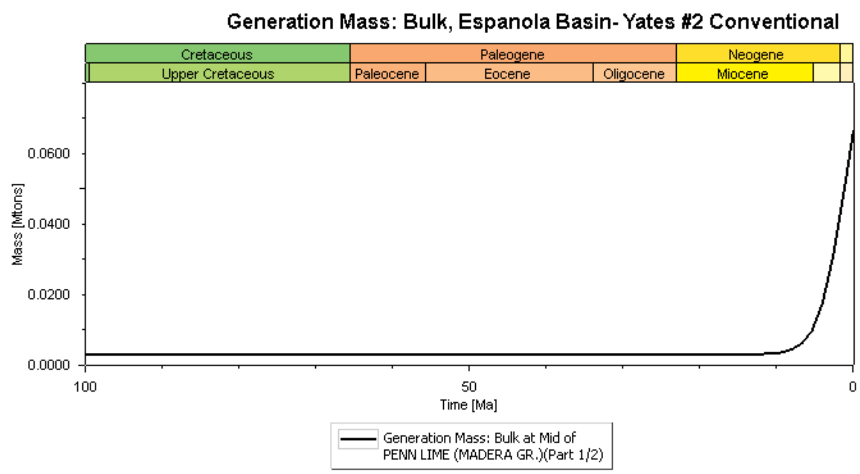

Figure 32. ***Generation mass for the Madera Group, the Yates #2 well.***

The greater depth, temperature and thermal maturity of the source rock in the Yates #2 model shows that a considerably larger mass of total hydrocarbons could be produced in this area of the southern Española Basin (Figure 32). The model shows that over 0.06 Mtons of bulk hydrocarbons could potentially be produced in the area. While this is still a lower value is prompts the argument that under the right conditions hydrocarbon accumulations could be found in the southern Española Basin. The model shows hydrocarbon being generated within the last 10 million years and most likely starting at about 7 Ma.

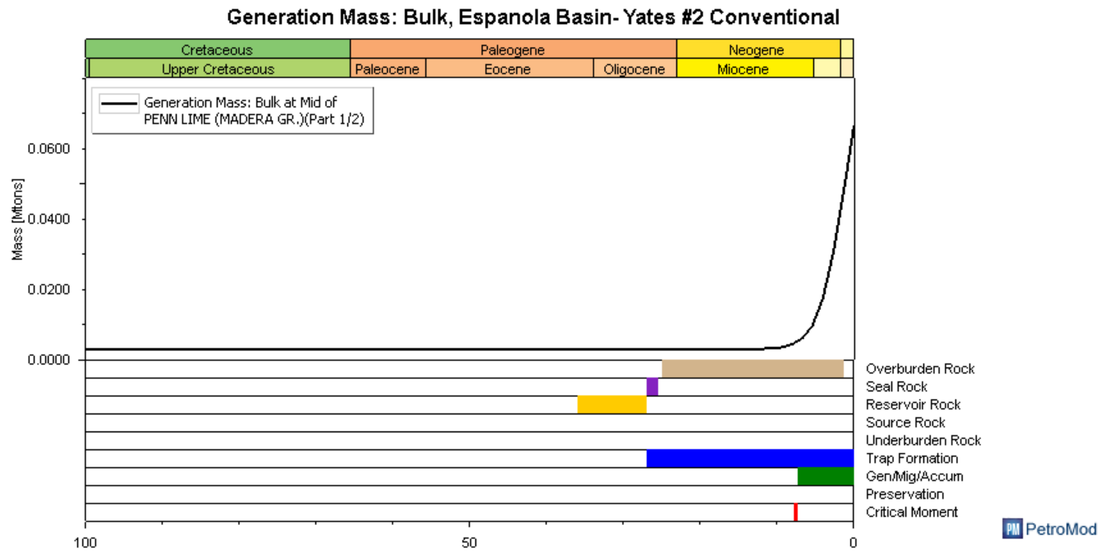

Figure 33. ***Generation mass with petroleum system elements for the Madera Group, the Yates #2 well.***

The bulk generation diagram with the petroleum system elements (Figure 33) shown gives reference to the formation of the potential petroleum system in the southern Española Basin. The source (not shown in the plot) is Pennsylvanian in age and dated between 310 and 300 Ma. The reservoir rock in this model is the Espinaso Formation which was deposited between 36 and 29 Ma with the Cieneguilla Basanite seal deposited right afterwards. One of the larger timing variables is hydrocarbon trap formation. Structural traps would have been created in the Espinaso Formation with the onset of faulting resulting from rifting. The entire region of the southern Española Basin is heavily faulted and these faults would create good structural traps. These traps would have been firmly in place by the time of hydrocarbon generation which potentially began at approximately 7-5 Ma.

The Yates La Mesa #2 well did not encounter any hydrocarbon shows during drilling but by modeling the petroleum system using the well stratigraphy it can be seen that there is some hydrocarbon potential in this area of the basin. The source rock in this area of the basin seems to have reached the necessary levels of thermal maturity for potential accumulations of hydrocarbons to exist.

6.3 YATES LA MESA #2 – UNCONVENTIONAL MODEL

In an effort to evaluate all possible potential petroleum systems present in the southern Española Basin, two types of models were created using the Yates #2 stratigraphy. The first, previously reviewed, was to test the Pennsylvanian Madera Group as a conventional oil and gas reservoir. This model takes the Pennsylvanian Madera Group and analyzes it as an unconventional reservoir. This theory of the Pennsylvanian being the source and reservoir was introduced by Molenaar (1988) in which it was suggested that the carbonates of the Pennsylvanian in the Española Basin be drilled and tested as the reservoirs. In order to do this a portion of the Pennsylvanian Madera Group had to be separated and categorized as the reservoir rock element.

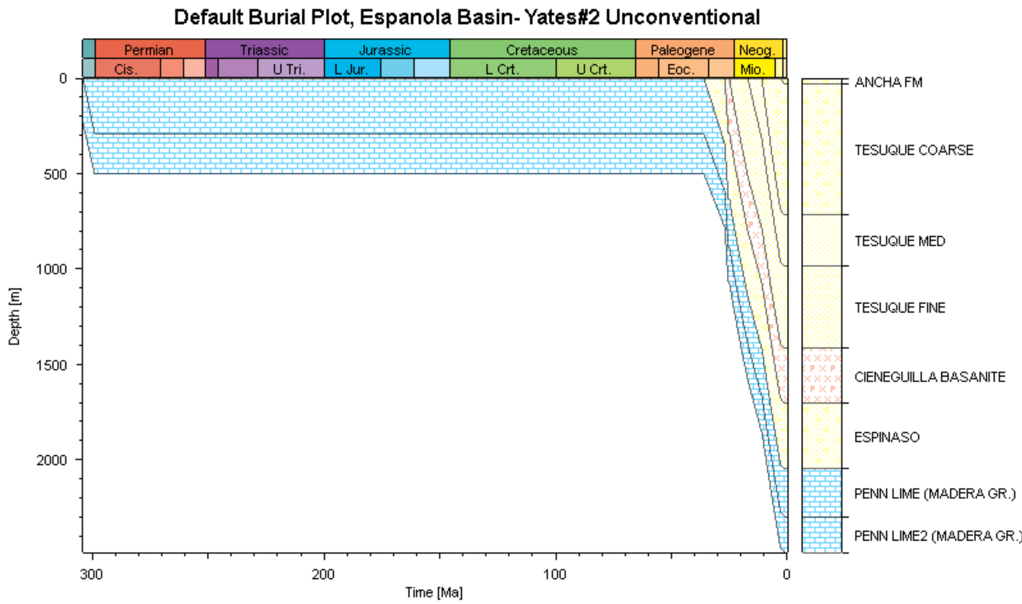

Figure 34. ***Burial plot for the Yates #2 well, unconventional.***

The burial history diagram for this model (Figure 34) is the same as the Yates #2 Conventional with the exception of the Pennsylvanian unit being separated into two distinct units in order to run a simulation. The burial history again shows the end of Pennsylvanian deposition occurred at approximately 300 Ma and the next phase of deposition did not occur until the Espinaso Formation between 36 and 29 Ma. The stratigraphy penetrated by the well shows that approximately 260 million years pass by without any deposition. Mesozoic units deposited in other regions of the basin suggests that at some point this unit lied unconformably on top of the Pennsylvanian and was eroded away during Laramide uplift. Again, this data is not available so the model had to be created assuming the stratigraphy of the well is the correct depositional history.

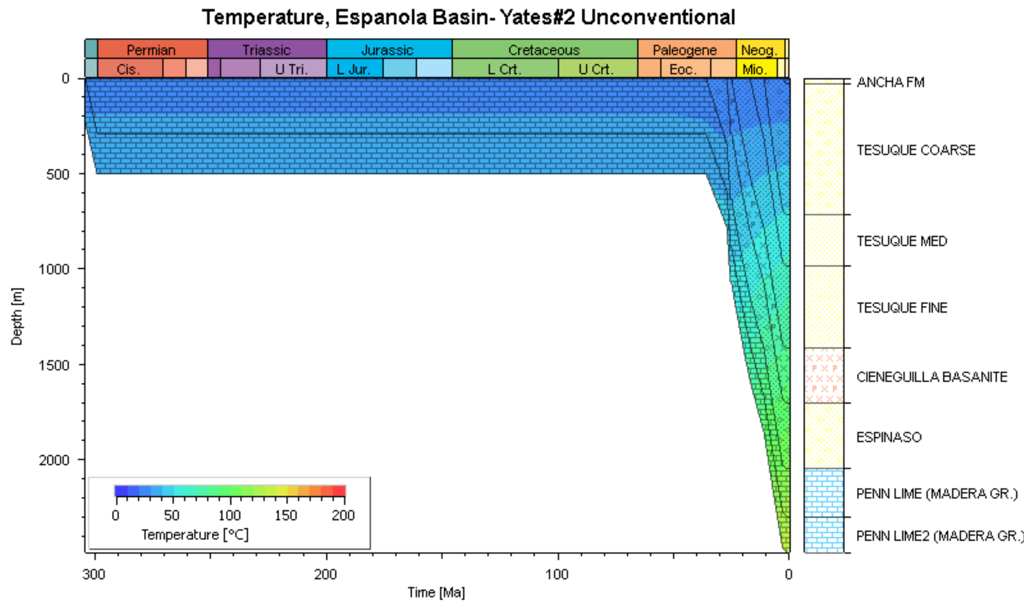

Figure 35. ***Burial plot for the Yates #2 well, unconventional, with temperature overlay.***

The temperature plot (Figure 35) for this model is identical to the temperature plot for the Yates #2 Conventional mode. This is due to all rock descriptions, depths and ages remaining exactly the same, with the exception of a section of the Pennsylvanian Madera Group being assigned the petroleum system element of a reservoir rock. As lithologies, rock characteristics, depths and ages stay the same, as should thermal properties of the units. The Pennsylvanian reaches temperatures of over 100°C in the subsurface in this model as with the Yates #2 Conventional model. The temperature plots for both the Yates well models show that this area of the southern Española Basin has just not been that hot for very long. Even with rifting beginning at approximately 27 Ma it appears it took the basin a little while to heat up. This lack of longer term heat in the basin good be an indicator of lackluster thermal maturity in the basin.

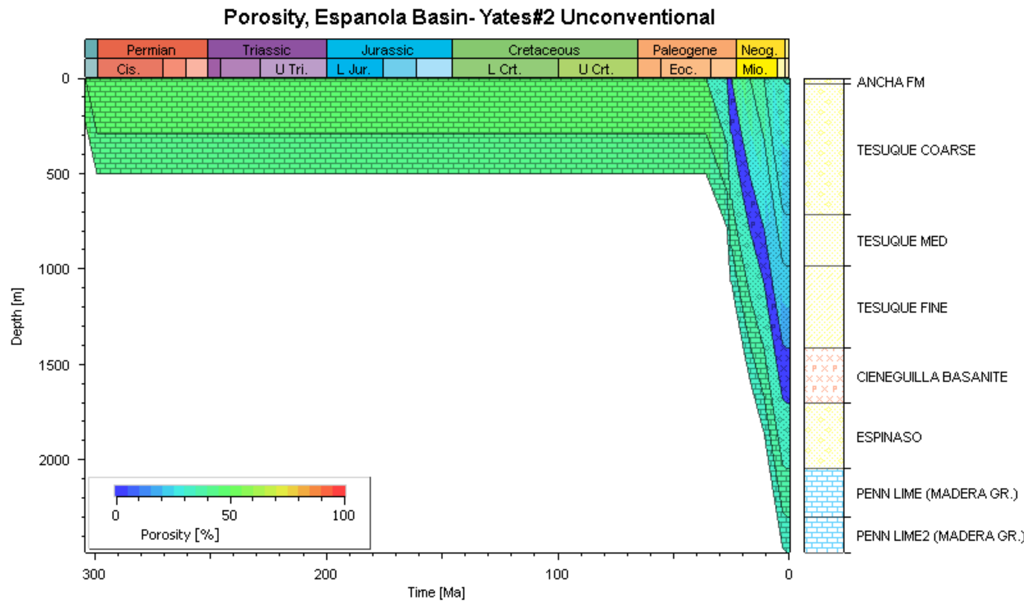

Figure 36. ***Burial plot for the Yates #2 well, unconventional, with porosity overlay.***

The porosity plot for the Yates #2 Unconventional model (Figure 36) is nearly exactly the same as the conventional model seen earlier. The two separate modeled Pennsylvanian units appear to have a varying degree of porosity. The interpretation here though is that the software is rounding units of porosity and therefore the upper Pennsylvanian unit shows greater porosity because it is only just slightly higher and under less sediment compaction than the lower Pennsylvanian unit. If studying closely, the gradual change in porosity of the Pennsylvanian unit can be seen in the Yates #2 Conventional model. This change is just highlighted with the source rock separated into source and reservoir.

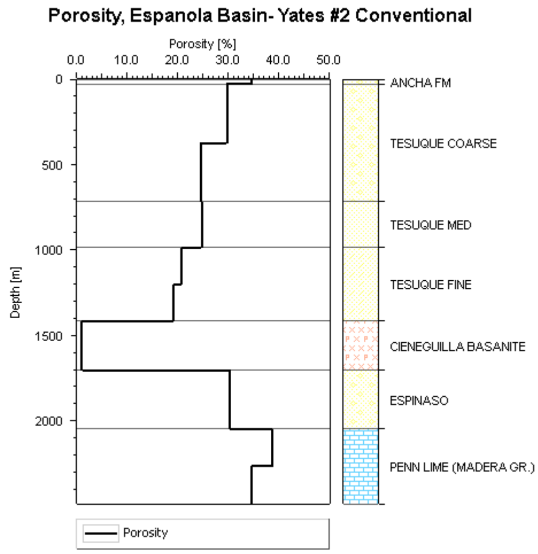

Figure 37. ***Porosity-depth profile for the Yates #2 well, unconventional.***

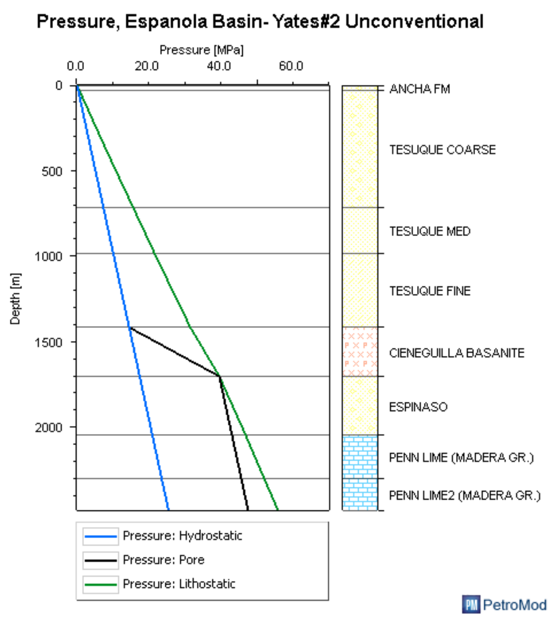

Figure 38. ***Pressure-depth profile for the Yates #2 well, unconventional.***

The porosity profile plot (Figure 37) shows that the porosity of the units in the section is exactly the same as it should be for both the Yates well models. This is also true for the lithostatic and hydrostatic pressure plots (Figure 38). The stratigraphic section remained the same with the exception of the defining one unit as a reservoir. Again, near the Pennsylvanian unit the lithostatic pressure is just below 60 MPa.

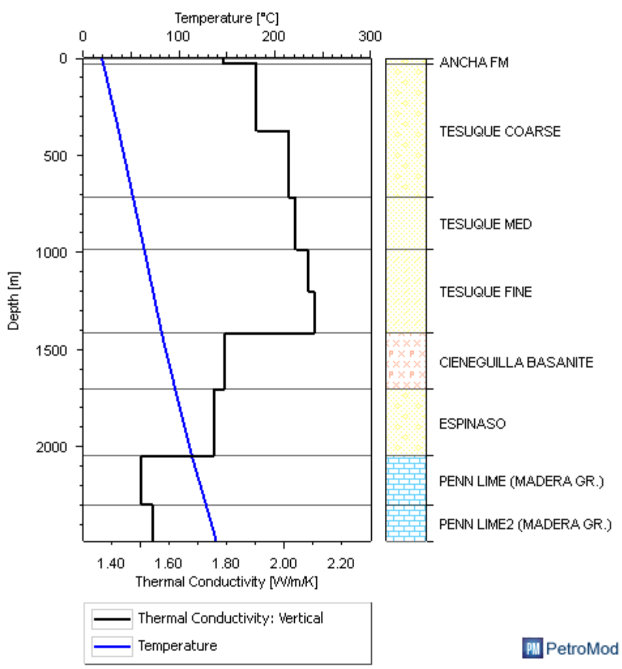

Figure 39. ***Thermal conductivity profile for the Yates #2 well, unconventional.***

The thermal conductivity plot (Figure 39) is as expected exactly the same as it was in the conventional test model. This is due to the rock properties, depths, and temperature in this area of the basin all remained the same. The porosities increased in the Pennsylvanian and as a result the thermal conductivity decreased proportionately.

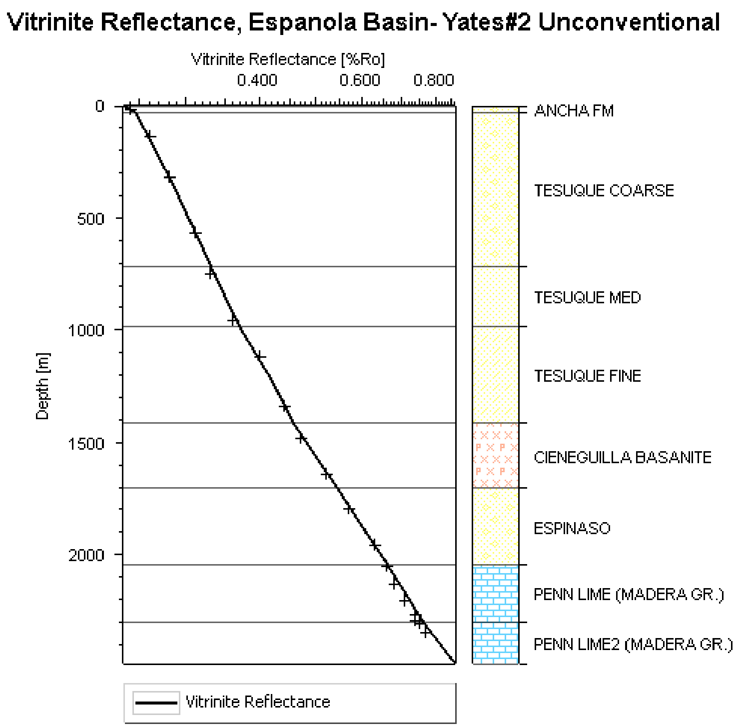

Figure 40. ***Vitrinite reflectance for the Yates #2 well, unconventional.***

The vitrinite reflectance plot (Figure 40), as with the thermal conductivity plot, stays exactly the same throughout the stratigraphic column. The temperature and thermal maturity of this area of the southern Española Basin did not change due to a change in petroleum systems elements.

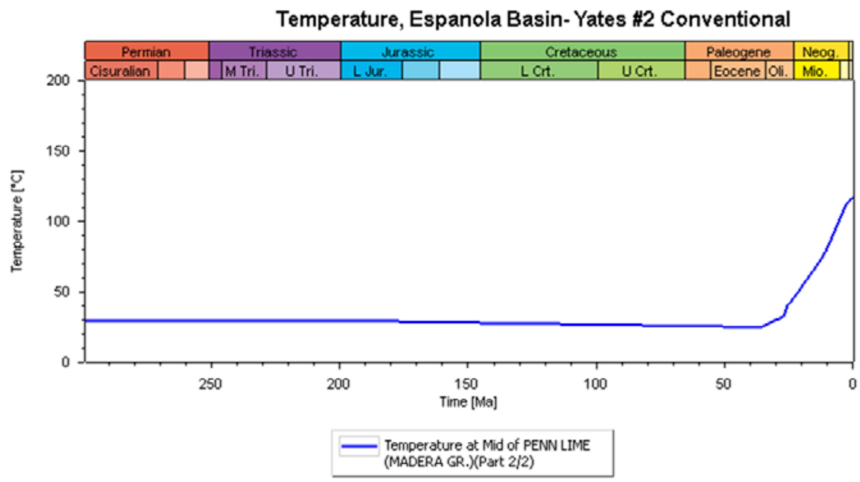

Figure 41. ***Temperature evolution for the Yates #2 well, unconventional, Madera Group.***

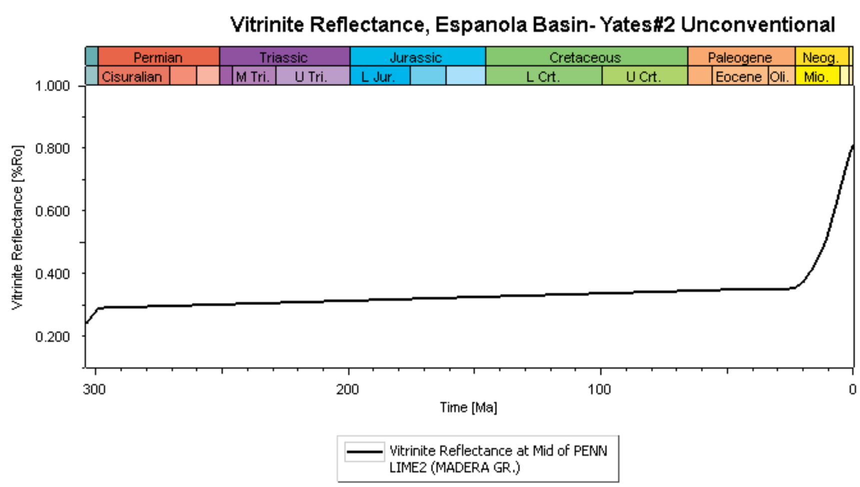

Figure 42. ***Vitrinite reflectance evolution for the Yates #2 well, unconventional, Madera Group.***

The temperature history of the basin (Figure 41) as well and the vitrinite reflectance plot (Figure 42) do not change from the conventional to the unconventional model. The thermal maturity of the basin is going to stay the same regardless of which unit is the source or reservoir. The true story of the difference in the models will be discovered in the generation/migration/yield categories of the petroleum system.

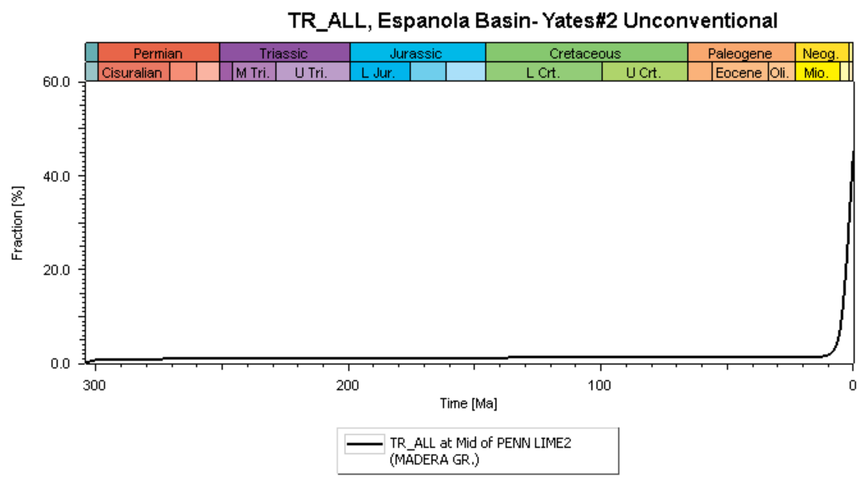

Figure 43. ***Transformation ratio for the Yates #2 well, unconventional, Madera Group.***

The transformation ratio of total organic carbon matter (Figure 43) is still set at in the 40% to 45% range that it was in the Yates #2 Conventional model. This figure means that 40% to 45% of the original organic carbon contained in the source rock reached the transformation phase of petroleum generation. This a good sign considering that only .82% of the source rock was TOC (Total Organic Carbon). When TOC values are low the transformation ratios need to be higher to balance out the amount of carbon potentially generated.

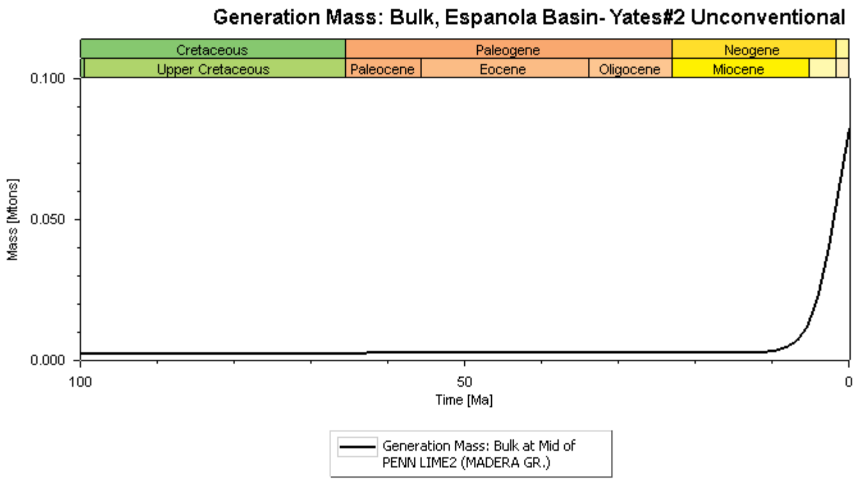

Figure 44. ***Generation mass for the Yates #2 well, unconventional, Madera Group.***

As opposed the conventional model, the Yates #2 Unconventional model only assumed the bottom two-thirds of the Pennsylvanian to be the source rock and the upper one-third to be the reservoir rock. From the model simulation the source rock portion of the Pennsylvanian Madera Group generated a bulk mass of 0.08 Mtons hydrocarbons (Figure 44). The 0.08 Mtons mass is comparable to the amount generated in the Yates #2 Conventional model and although 0.08 Mtons is not a significant bulk of hydrocarbons it does show that larger volumes of generation are possible in the southern Española Basin.

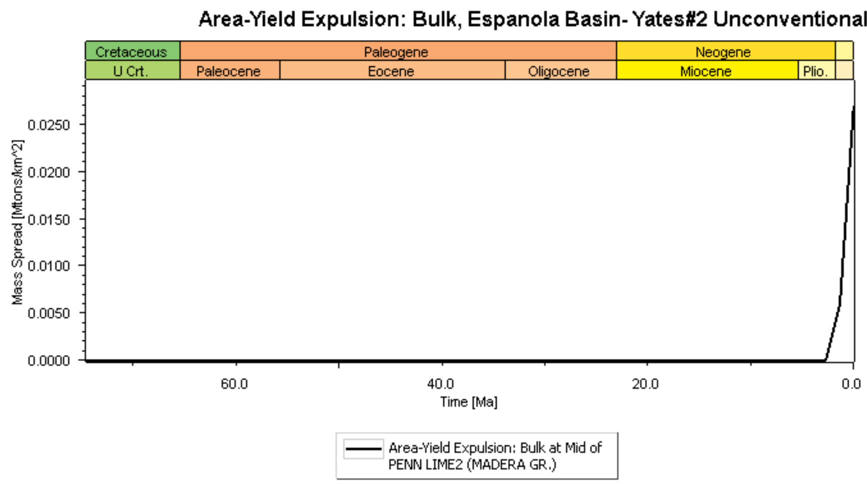

Figure 45. ***Expulsion for the Yates #2 well, unconventional, Madera Group.***

The Area-Yield Expulsion plot (Figure 45) is very important in the study of the petroleum systems analysis of the southern Española Basin for the simple reason that this is the first model in which the hydrocarbons reach the expulsion stage. At approximately 4 Ma this model showed bulk hydrocarbon expulsion from the source rock. While this bulk mass was very little it is still something and provides evidence that generation and expulsion of hydrocarbons can exist in the southern Española Basin. In order to simulate this generation and expulsion, the Pennsylvanian Madera Group source rock had to be split in order to be treated as an unconventional reservoir. In terms of expulsion and migration, this model is basically saying that the Pennsylvanian source rock is generating and expelling hydrocarbons into other sections of the carbonate source rock. In other words, the source is the reservoir and seal.

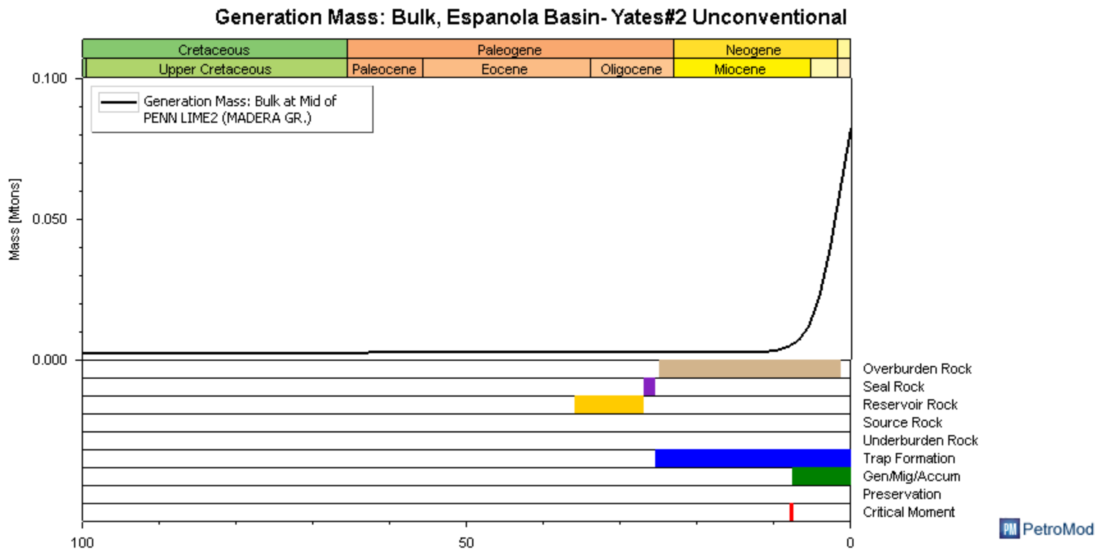

Figure 46. ***Generation mass for the Yates #2 well, unconventional, Madera Group.***

The plot above (Figure 46) shows the mass hydrocarbon generation curve along with the petroleum system elements underneath matching timing of events. Timing is one of the most important factors in studying petroleum systems. The first step is to have the source rock in place, which in this case is around 300 Ma. Then the reservoir rock deposition followed by the seal rock, which we have as the Pennsylvanian itself was considered a reservoir along with the Espinaso Formation. The seals would be the Pennsylvanian units sealing themselves and the Cieneguilla Basanite in the upper section. Trapping structures need to be in place before generation and expulsion. Structures created during Laramide uplift as well as the opening of the rift zone should provide adequate trapping possibilities throughout the southern Española Basin. The generation of hydrocarbons in this case begins at approximately 8-7 Ma. Generation, migration and accumulation follow a couple of million years later in this model. In this basin all the petroleum system elements would have been in place prior to the generation and expulsion of hydrocarbons making this simulation a valid petroleum system. The Yates #2 Unconventional model shows that the Paleozoic Pennsylvanian unit, if considered an exploration target, could prove to have hydrocarbon accumulations in place.

6.4 MESOZIOC TEST WELL MODEL

The deep Mesozoic section has never been tested with an exploration well in the southern Española Basin. Stratigraphic units in the Mesozoic are important oil reservoirs within other basins in the Rio Grande rift such as the San Luis and Albuquerque basins (Broadhead, 1987). Sections of Mesozoic rocks are present in the Española Basin and in some locations are relatively thick. However, the Mesozoic is not continuous across this portion of the basin and can disappear from one fault block to the next. Few data have been collected regarding the Mesozoic in the Española Basin and even less has been published regarding possible amounts of erosion that may have taken place. Early in this study it was assumed that the Mesozoic sediments did not deposit in the region of the exploration well. This step was taken because currently there is no data to prove otherwise, so the best course of action was to use the well bore stratigraphy. Because the Mesozoic could be very influential on the petroleum system analysis of the Española Basin it was considered as a possible exploration target of a pseudo-well generated using the detailed geologic cross sections. The pseudo well was located at the approximate location where the Green River Fault (under the Cerros del Rio volcanic field) crosses the D-D’ cross section line (Koning and Read, 2010), Figure 47. In this part of the Española Basin, beneath the Cerros del Rio volcanic field, the Mesozoic section reaches thicknesses of over 1000 meters.

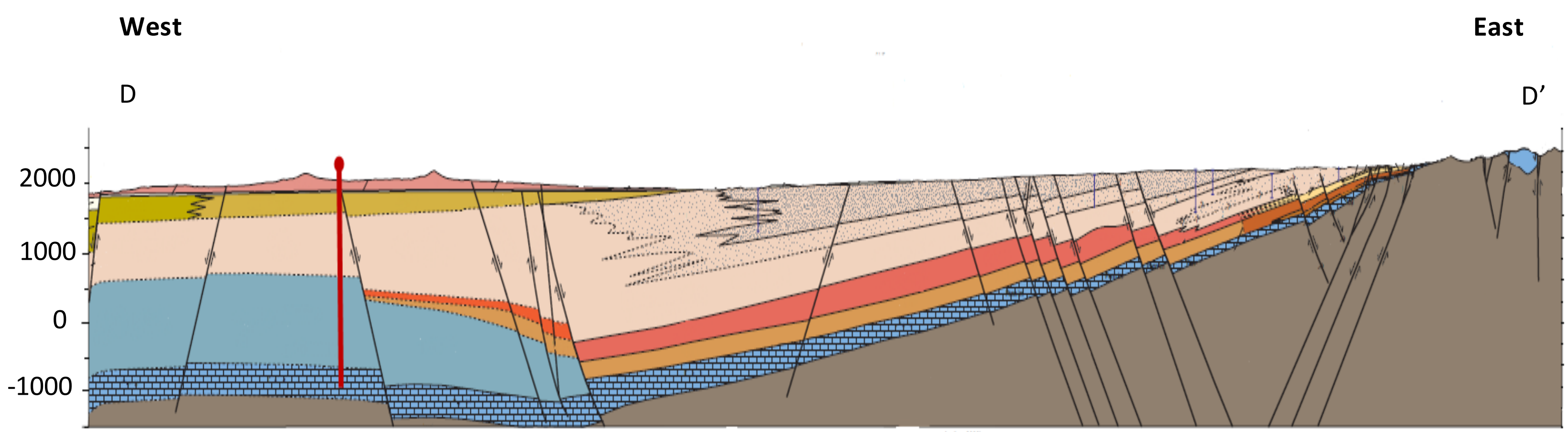

Figure 47. ***Cross section D-D showing approximate location of the pseudo well. Depth units in meters, 0 at MSL.***

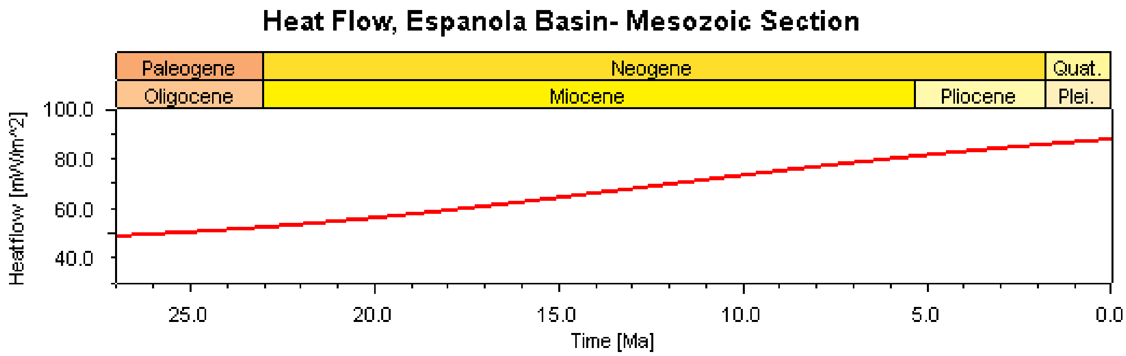

Figure 48. ***Heat flow evolution of the pseudo well.***

The generalized modeled heat flow trend for the Española Basin (Figure 48) shows that significant heat flow began in the basin at approximately 27 Ma, or the start time of Rio Grande rifting. This heat flow trend shows that temperatures and heat flow have in increased steadily over the past 25 Ma or so and this is representative of the opening of the Rio Grande Rift which is still active today. This heat flow trend is the same trend used in the other models and was put in place because there obviously is no data for a pseudo well.

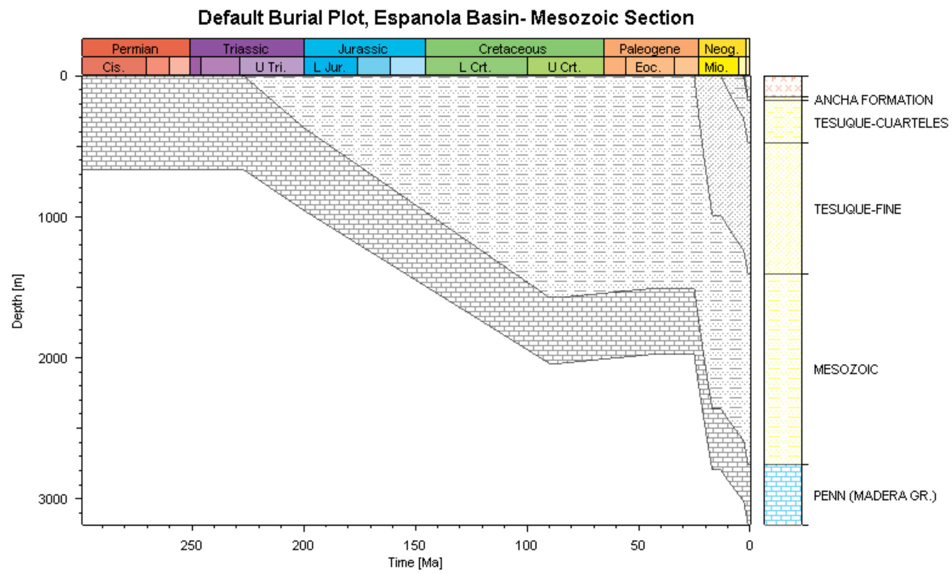

Figure 49. ***Burial history plot of the pseudo well.***

The burial history plot (Figure 49) shows a thick Mesozoic section overlying the Pennsylvanian Madera Group. The Mesozoic section was modeled to have experienced erosion between 85 and 45 Ma and this was due to Laramide uplift in the area. The decision was made to factor in this erosion as it was comparable to other erosional features of the Mesozoic section at other locations in the Española Basin and Rio Grande rift (Baldridge et al, 1994). This explains the slight upward trend in the depth of burial during that period. Like the other burial history plots modeled in this basin, deposition tends to be generally slow and steady until rifting begins which sparks a period of more rapid sedimentation. Another feature to note on this burial plot is that the top of the Pennsylvanian is at a significantly deeper depth than in previous models. The greater depth might lead to greater temperatures and therefore a higher thermal maturity.

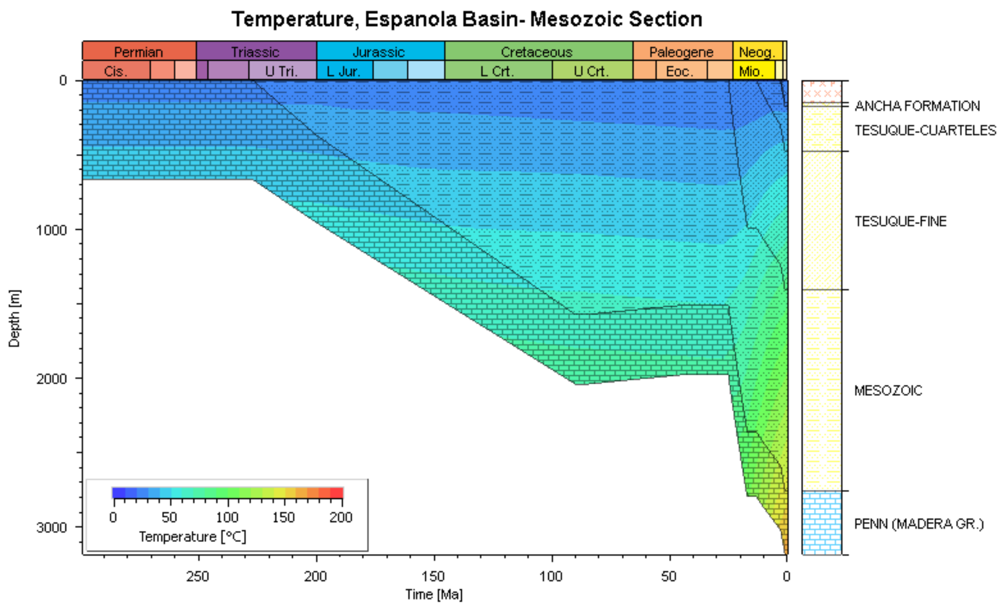

Figure 50. ***Burial history plot with overlay of temperature of the pseudo well.***

The temperature in the Pennsylvanian section of the basin is higher than in previous models (Figure 50) and that is most likely due to the larger burial depth. While it appears that temperatures increase with depth across the plot there is one important difference between this well and the other two wells. Higher temperatures in the lower units of the section began at an earlier date in time. The model display there is some heat in the Pennsylvanian pre-rift which was due to overburden pressure and this contributes to the thermal maturity of the source rock. This is important in the sense of petroleum generation and timing of petroleum system elements.

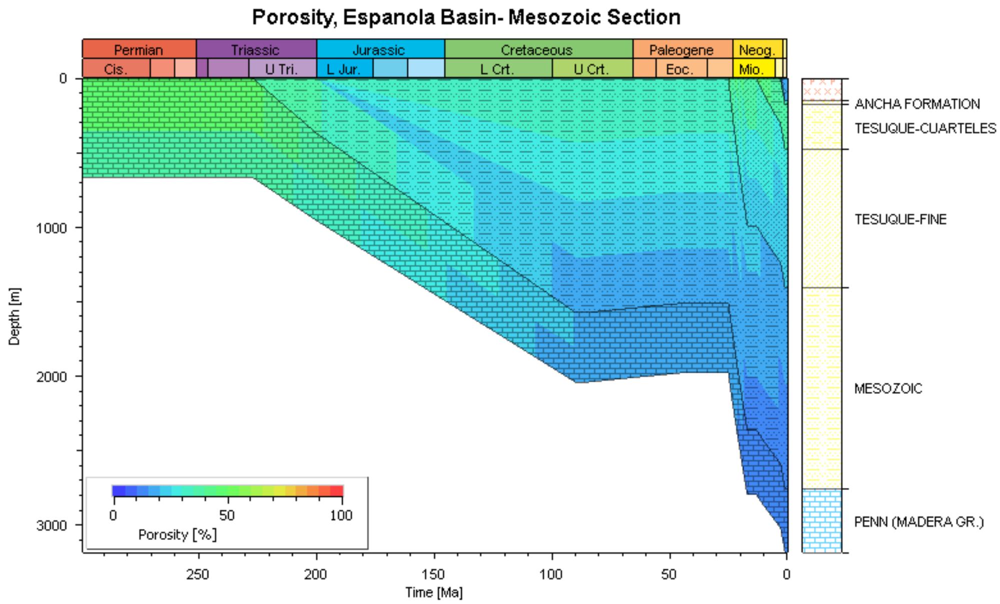

Figure 51. ***Burial history plot with overlay of porosity of the pseudo well.***

The porosity plot (Figure 51, 52) shows the decreasing porosity with depth with the porosity being at its lowest at the deeper part of the well. This is the first model simulation that actually modeled decreased porosity values in the Pennsylvanian units. The Mesozoic is considered to contain the reservoir horizons in this model, so the porosity range of 15-20% is adequate for reservoir sandstones. This model is the only simulation to show the Pennsylvanian Madera Group with little to no porosity at depth, showing the significant greater amount of depth the Mesozoic section has added to the strat column.

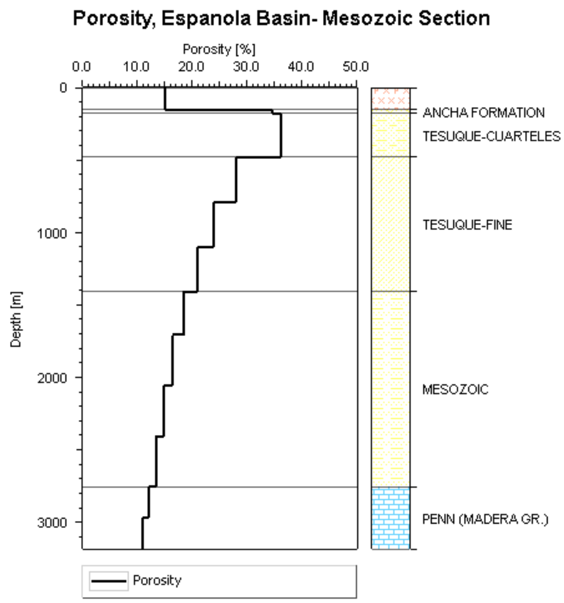

Figure 52. ***Porosity profile of the pseudo well.***

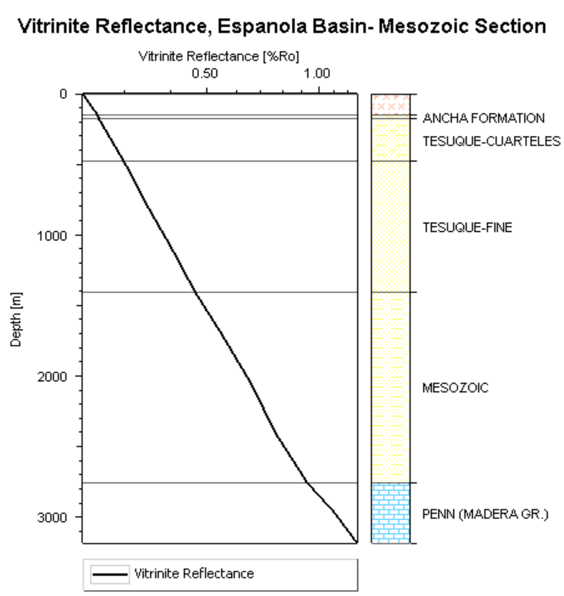

Figure 53. ***Vitrinite reflectance of the pseudo well.***

The vitrinite reflectance values (Figure 53) of the Pennsylvanian source rock are quite high in this model. At the top of the Pennsylvanian the %Ro values is approximately 0.85% and at the bottom it is over 1%. These values are a touch high for the hydrocarbon window and would be an indicator for gas as the hydrocarbons would undergo further cracking at these maturity levels. That being said, these values are present day and could have been lower, potentially in the oil window, at the time of first generation. This model shows that maximum of 150 mgHC per gTOC is possible out of the base of the source Pennsylvanian unit.

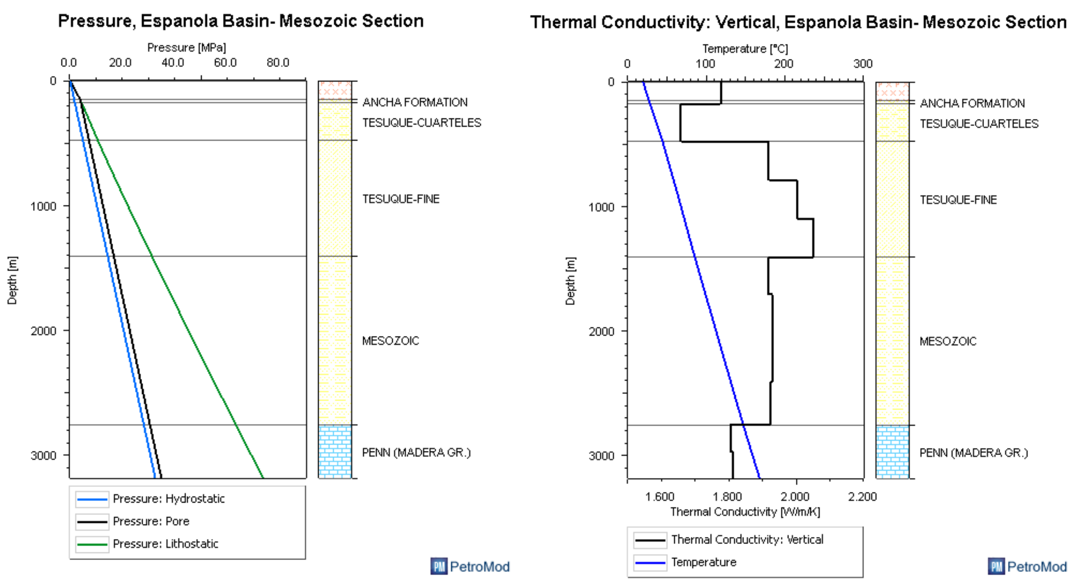

Figure 54. ***Pressure (left panel) and thermal conductivity (right panel) of the pseudo well.***

The model shows the high value of lithostatic pressure in the Mesozoic model (Figure 54) and reaches over 70 MPa in the Pennsylvanian Madera Formation. The high lithostatic pressure is contributing to the higher temperatures and thermal maturity in this model. The thermal conductivity plot for this model shows a function a temperatures and porosities (Figure 54). The thermal conductivities of the Pennsylvanian unit is higher due to a decrease in porosity and increase in formation temperature.

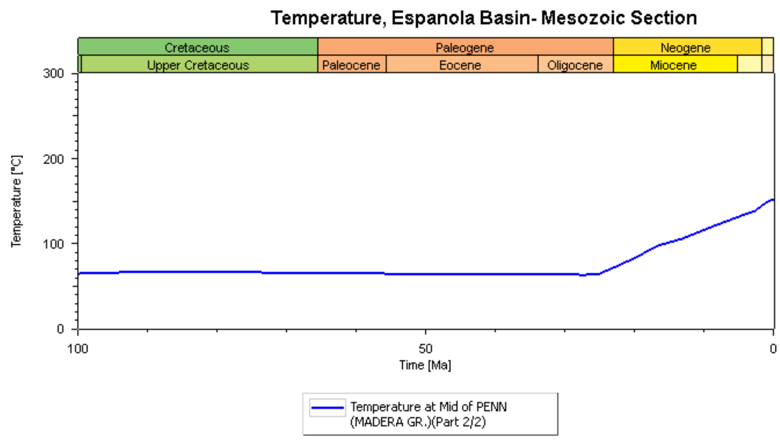

Figure 55. ***Temperature evolution of the pseudo well.***

The temperature evolution of the Mesozoic section model shows steady temperature before rifting (Figure 55) though slightly elevated as compared to the previous models. As rifting begins, the temperature in the deep sediments rises at a slow and linear pace. The shallow angle of temperature rise is due to the temperatures already being a little higher than in previous models and the fact that even during rifting it is hard to raise a unit over 75°C in temperature over that short of a period of time.

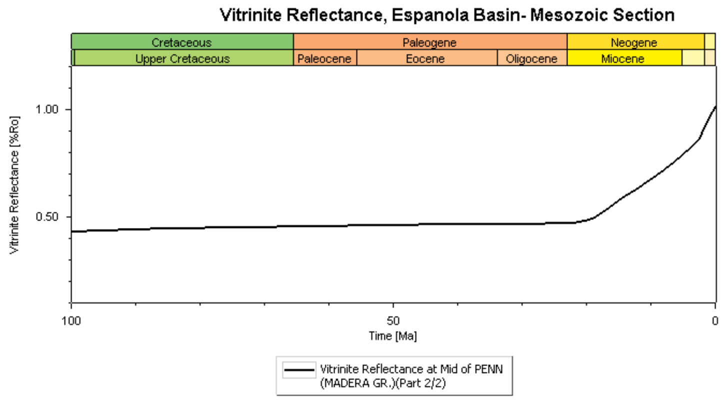

Figure 56. ***Vitrinite reflectance evolution of the pseudo well, Madera Group.***

The vitrinite profile over time for the Mesozoic section model (Figure 56) shows a steady %Ro of approximately 0.4% and at the onset of rifting begins an almost exponential curve upwards to approximately 1.00% from 27 Ma to present. These vitrinite reflectance values do demonstrate that the source rock passed through the hydrocarbon window in the model and generation is a possibility.

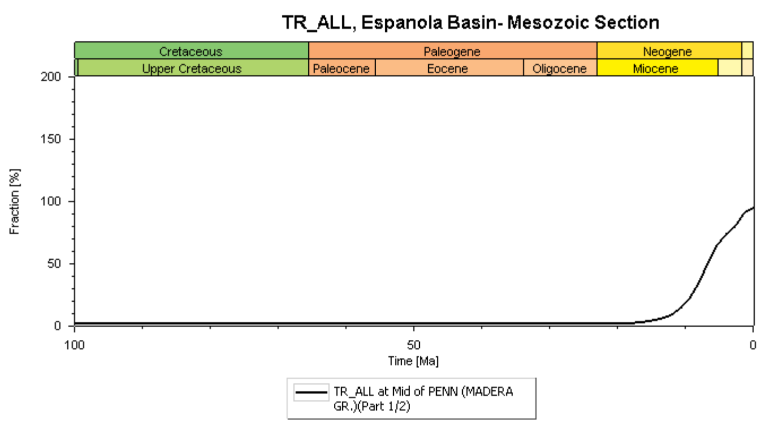

Figure 57. ***Transformation ratio of the pseudo well, Madera Group, part I.***

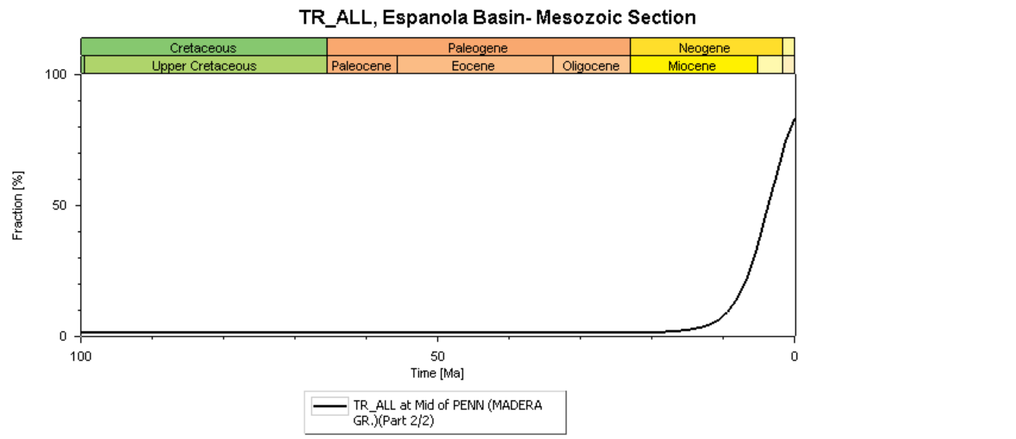

Figure 58. ***Transformation ratio of the pseudo well, Madera Group, part II.***

The transformation ratios (TR) for the Mesozoic section are relatively high (Figure 57, 58). The Pennsylvanian source rock TR data was displayed in two different graphs due to higher TR values at the base of the Pennsylvanian Madera Formation. The graphs clearly show that the transformation ratios are between 80 – 100%, which means much more original organic carbon is being transformed in this model as compared to the previously simulated wells in the southern Española Basin.

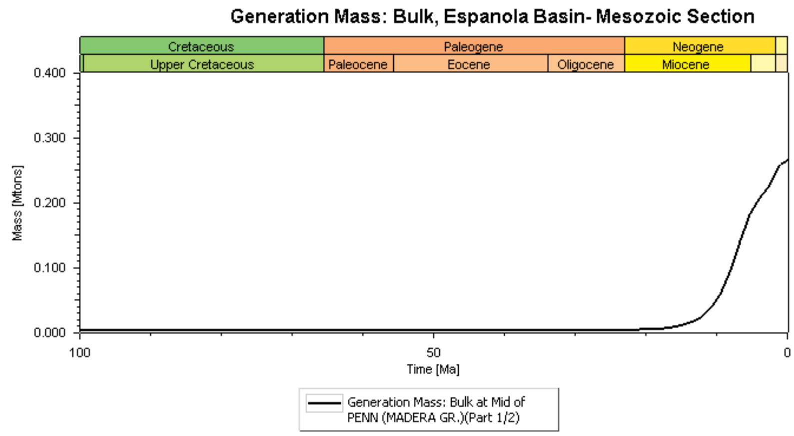

Figure 59. ***Generation mass of the pseudo well, Madera Group, part I.***

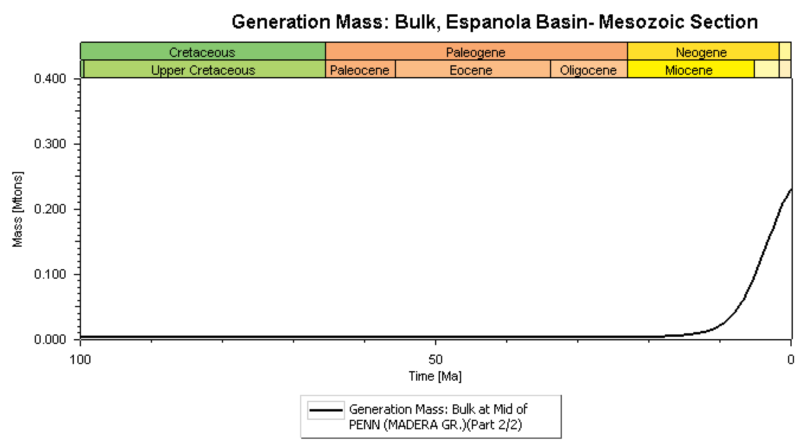

Figure 60. ***Generation mass of the pseudo well, Madera Group, part II.***

The mass generation values of the Mesozoic model show that the Pennsylvanian generates a bulk mass of approximately 0.25 Mtons (Figure 59, 60). This value is the greatest of any of the previous models and thus we can conclude that this model shows the greatest generation potential by simulated bulk mass generation. All of the generation begins at approximately 12-13 Ma in the model.

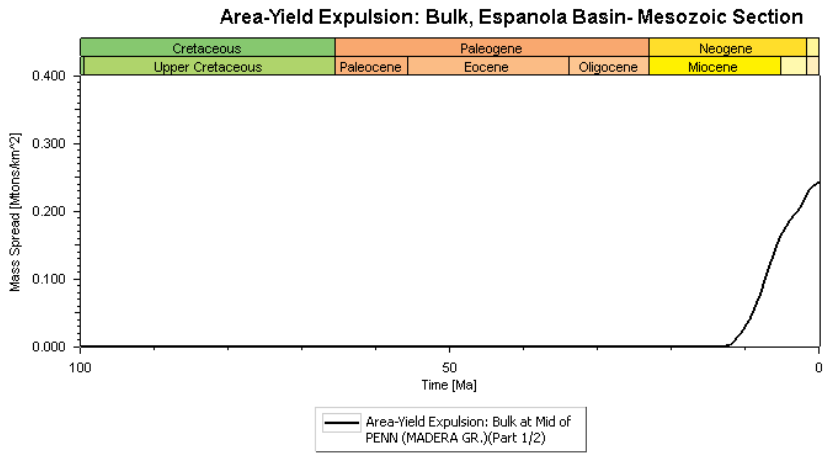

Figure 61. ***Expulsion of the pseudo well, Madera Group, part I.***

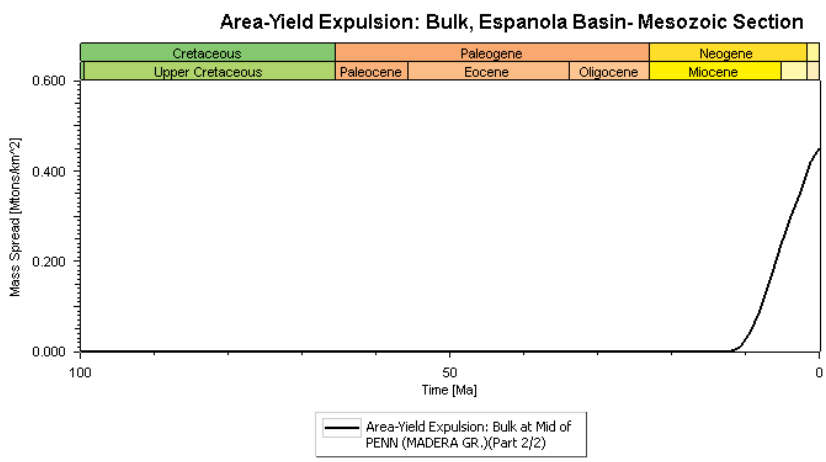

Figure 62. ***Expulsion of the pseudo well, Madera Group, part II.***

The Area-Yield plots for the Mesozoic model (Figure 61, 62) show that the Pennsylvanian Madera Formation is capable of yielding between 0.25 and 0.45 Mtons per square km. The theoretical area-yield expulsion begins at approximately 10 Ma in this model. These values of expulsion are the highest of any model run in this study of the southern Española Basin.

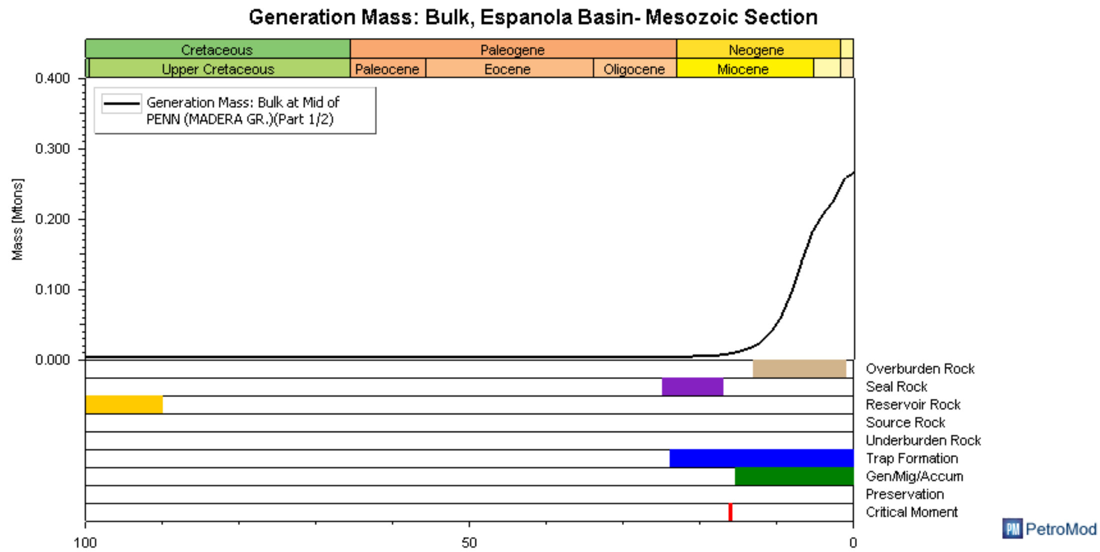

Figure 63. ***Generation mass of the pseudo well, Madera Group, part I, with petroleum system elements.***

The generation plot showing the petroleum system elements of the Mesozoic model (Figure 63) gives a synopsis of the potential petroleum system. The Pennsylvanian source deposited at approximately 300 Ma and was followed by the deposition of the Mesozoic reservoirs along with overburden rocks. Formation of the traps began with structural deformation during Laramide uplift and the beginning of rifting. Generation began in this model at approximately 12 Ma and was followed by a period of generation, migration, and accumulation that began around 12-10 Ma and continues to present.

The Mesozoic model represents the greatest probability of finding hydrocarbon accumulations according to the models run using Petromod. The main difference between this model and the other models run is that the Mesozoic section provided the overburden and depth the source rock needed to reach higher temperatures and therefore higher thermal maturity values. The Mesozoic section in the southern Española Basin is a bit of a mystery as it cannot be traced across the entire basin and at times is discontinuous across faults in the geologic cross sections assembled by Koning and Read (2010). More study of the Española Basin pre-rift stratigraphy is needed to determine the original depositional extent of Mesozoic strata; not only the original extent of the Mesozoic but also the amount of erosion that took place so that a correct reconstruction of the Española Basin can be carried out.

6.5 ESPAŃOLA BASIN 2D MODEL

The 2D Model of the southern Española Basin was created using pseudo-well formation tops, cross section facies changes and fault mapping provided in the D-D' geologic cross section compiled by Koning and Read (2010). This specific cross section was chosen due to its location in the center of the study area as it is a West to East trending line that depicts the subsurface from the Jemez Volcanic complex to the Sangre de Cristo Mountains in the East (Figure 1). The model was calibrated using vitrinite reflectance data from well bore data and modeled pseudo-well data. The 2D modeling effectively uses a backstripping process to gain a better grasp on burial history and depth in the southern Española Basin. In Figure 64, the process of establishing the correct formation tops as well as fault surfaces is shown. All of the fault locations as well as generalized angles were taken from geologic cross sections from Koning and Read (2010).

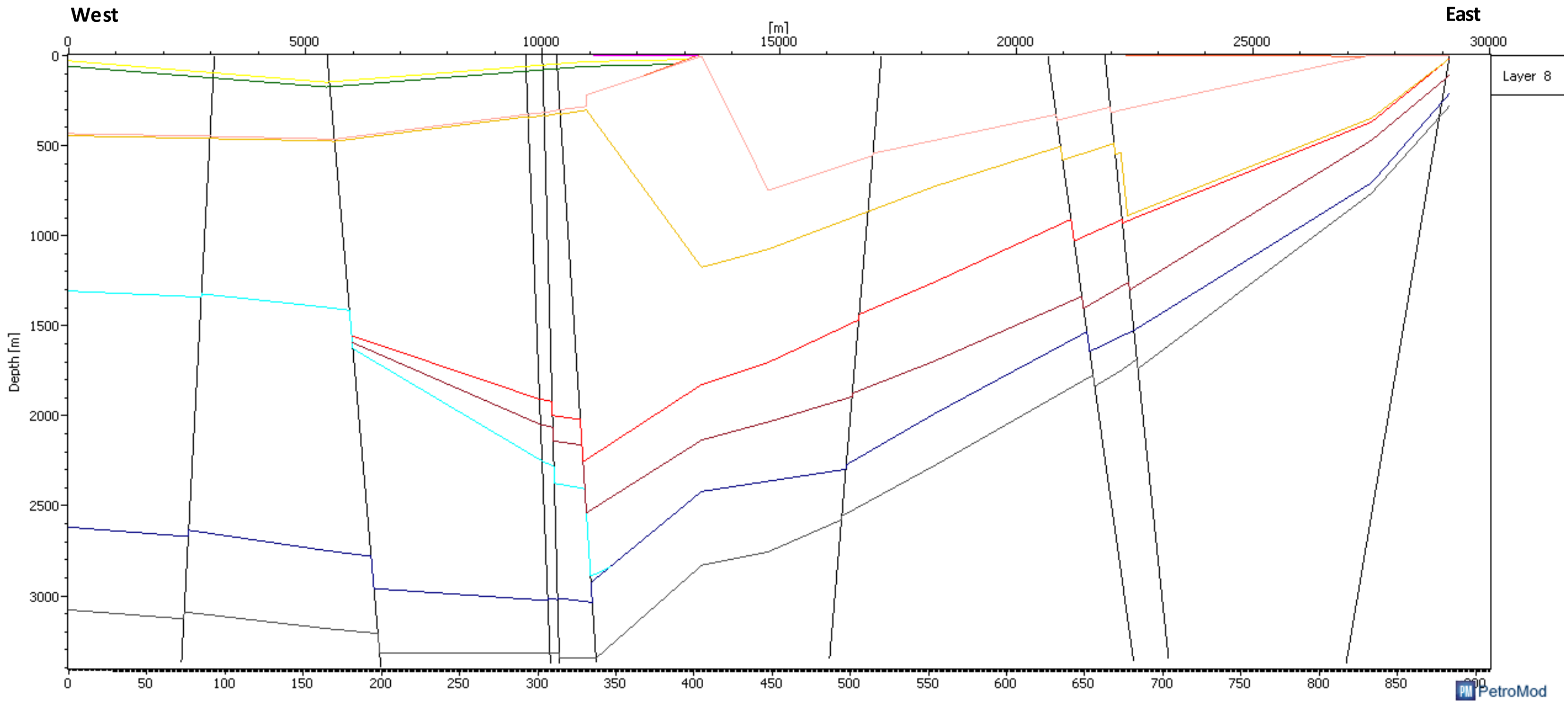

Figure 64. ***Pre-gridded formation tops and faults digitized from cross section and well data.***

In the digitizing process several minor facies changes were joined as one to accommodate a single unit in the gridded 2D model (Figure 65). This included the combination of the Tesuque-Cuarteles Member with the Tesuque Distal Cuarteles Member and the Bishop's Lodge Member of the Espinaso formation was not separated out as an individual unit. These minor changes occurred at very shallow depths and as they represent young overburden rocks, joining these facies should not create any changes in the petroleum system.

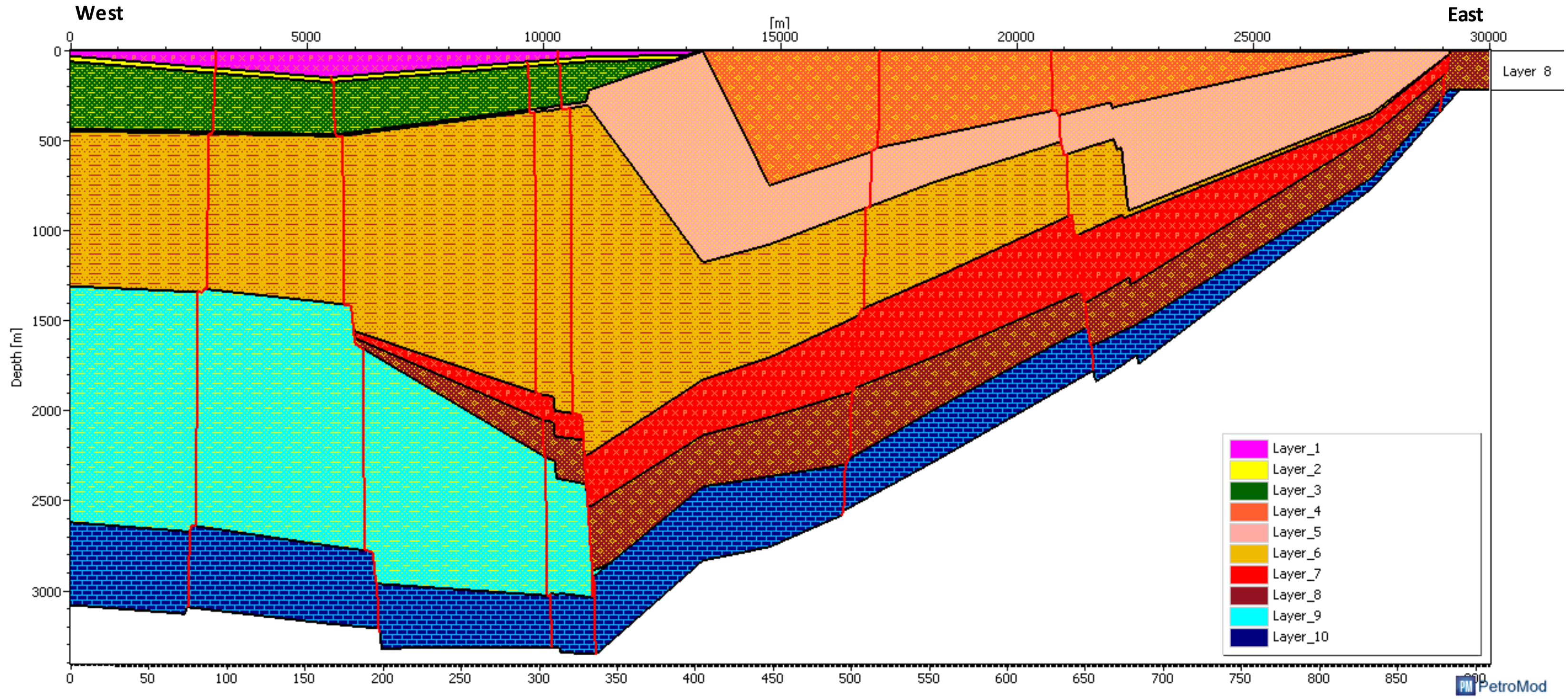

Figure 65. *Gridded layers from the digitized horizon and faults for the southern Española Basin.*

After gridding of the layers the 2D model (Figure 66) starts to closely resemble the geologic cross section with the major offsetting faults in place. The same petroleum system elements and properties were assigned to the proper horizons as well as layer properties including age of deposition and thicknesses. The same kinetic stretching model properties were also used in the creation of the 2D model to recreate stretching from 27 Ma to present and have relatively high basin heat flow.

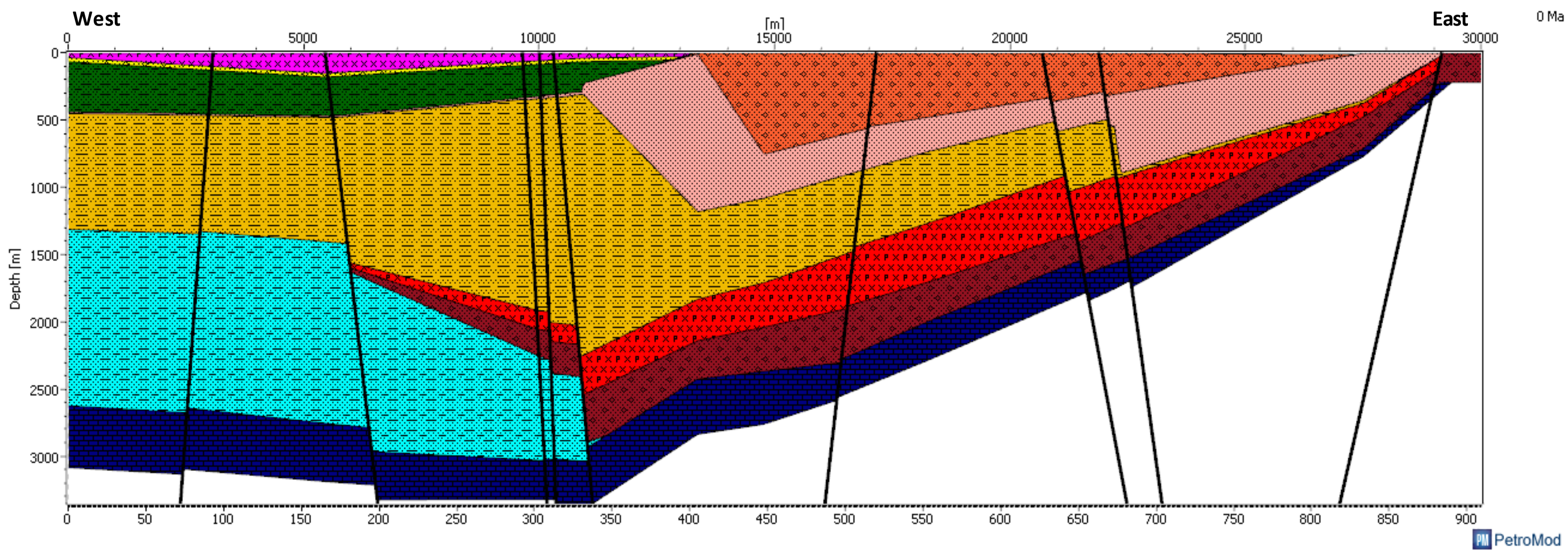

Figure 66. ***The 2D basin model of the southern Española Basin, showing not only the basin geometry but also that the Petromod 2D software produced no hydrocarbon accumulation in this area of the basin.***

Figure 66 represents the final evaluation of the southern Española Basin. This is the completed 2D basin model, displaying faults as well as layers. It should be noted that this stage model was set to display any hydrocarbon accumulations that might be located in this section of the basin. In other words, the results of the 2D modeling and petroleum systems analysis indicate that there are no hydrocarbon accumulations in the southern Española Basin.

CHAPTER 7: CONCLUSIONS

The Española Basin of the Rio Grande represents an underexplored rift basin in which very few wells have been drilled since the 1980's. The Petromod models run for different well sites and pseudo-well sites were used to gain a better understanding of basin processes and analyze the basin for potential petroleum systems. The chosen sites were modeled using standard petroleum systems analysis as well as the Yates La Mesa #2 well being modeled for two separate petroleum systems.

The results and the data show that the Pennsylvanian Madera Formation is the source rock in the southern Española Basin and that it is capable of producing hydrocarbons under the right conditions. The main conditions that need to be present for this to happen is that there needs to be sufficient burial depth so that the source rock can reach higher temperatures and thermal maturity. The Española Basin displays high heat flow values but the heat flow is relatively young. The high levels of heat flow began when the Rio Grande rift started to form, only in the last 27 Ma. This study found that this heat flow and elevated temperatures due to rifting were not enough on their own to generate hydrocarbons with the source shallow in the subsurface. The C&W #1 well for example shows this fact. The source rock was simply too shallow and did not reach the necessary thermal maturity to generate and expel hydrocarbons. The Yates #2 well represented an exploration well that penetrated the entire rift basin down to the basement similar to the C&W well with the exception that it was drilled to a depth of 7,710 feet (2,350 meters). This depth proved to be the difference needed to reach the point of minor hydrocarbon generation. The Yates #2 well was modeled for the Pennsylvanian source rock and a Tertiary reservoir/seal pair as well as a Pennsylvanian source rock and Pennsylvanian carbonate reservoirs. The model results show that the same amount of generation occurred in both models of the Yates #2 well but that expulsion was not needed in the model testing the Pennsylvanian carbonates as the source and reservoir. Therefore the Pennsylvanian carbonates of the Madera Formation are a viable target for exploration in the southern Española Basin according to the model. The final model was a simulation of an exploration well drilled in an area of the Española Basin where a thick Mesozoic stratigraphic section was present above the Pennsylvanian source rock. This model actually proved to provide the most compelling model results. The overburden of the Mesozoic section and the subsequent deeper depth of the source horizon led to thermal maturation of the source rock. This thermal maturation led to generation and expulsion of hydrocarbons in the Petromod model.

The results of the 2D basin model were interesting in the fact that all of the previous 1D well models showed generation of hydrocarbons but exhibited no hydrocarbon accumulations. After examining that the petroleum system elements and basin models were congruent in the 1D and 2D models, the conclusion of this final is that insignificant amounts of hydrocarbons were possibly produced in the basin but that migration and accumulation never occurred. Future modeling of the Española Basin would be best served by determining the true amount of erosion of the Mesozoic sediments that took place in this area. The model as well as the petroleum system analysis would be greatly swayed if a more significant Mesozoic section was present in this area of the Española Basin. This is especially true for the Mesozoic reservoirs as well as the Pennsylvanian carbonate reservoirs.

The modeling of the southern Española Basin at several points and penetrating different lithologies helped to produce a better understanding of the effects rifting and the subsequent heat flow have on basin stratigraphy. The Española Basin is a relatively shallow rift basin and it shows high heat flow values. Perhaps this study aided in understanding the source and duration of the heat flow and temperature in the Española Basin as an effect of continental rifting that is still ongoing at present day as well as volcanic activity in a shallow sedimentary basin.

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