STRATIGRAPHIC INTERPRETATION, GEOCHEMISTRY, AND PETROPHYSICS
OF THE NIOBRARA FORMATION, NORTH PARK BASIN,
JACKSON AND GRAND COUNTIES,
NORTH-CENTRAL COLORADO

by

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ABSTRACT

This study investigates the stratigraphic, geochemical, and petrophysical properties of the Niobrara Formation in the North Park Basin. Recent exploration and production of the Niobrara in North Park has renewed interest in the petroleum system of the basin. This study aims to add to the knowledge of the Niobrara Formation in the North Park Basin, aiding in future hydrocarbon exploration. As part of this study, the Roaring Fork outcrop of the Niobrara was identified, measured, and described. The section was also logged by a gamma-ray scintillometer, and samples were collected for petrographic thin sections and pyrolysis analysis. Well logs from the basin were used to identify the Niobrara in the subsurface. The formation was divided into 8 units: the Fort Hays, basal chalk, lower marl, lower chalk, middle marl, middle chalk, upper marl, and upper chalk. These units were correlated across the basin and structure and isopach maps were constructed. Cuttings from eight wells from across the basin were collected and underwent pyrolysis and total organic carbon analysis. The results of the pyrolysis show that the Niobrara contains Types II and III kerogen. The Tmax values indicate that the Niobrara is immature to peak mature with respect to oil in different parts of the basin; a maturity map was constructed from these values. All of the Niobrara samples range from 1-5% total organic carbon; most samples fall within the 2-3% total organic carbon interval. These total organic carbon values indicate a good to very good petroleum potential for the Niobrara. Using the gamma-ray, resistivity, sonic, density, and neutron porosity logs, computations for log derived total organic carbon content, porosity, and water saturation were calculated. Log derived total organic carbon approximations from the resistivity and sonic logs act as a good proxy in areas where no measured total organic carbon measurements are available, provided care is taken in identifying anomalous values, mainly in tight or very porous intervals. Porosity values from density and neutron logs range from 4-36%. The water saturation values in calculated wells range from 40-100%. These data are valuable to the ongoing evolution of the understanding of the Niobrara petroleum system in the North Park Basin.

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LIST OF ACRONYMS

DEN – Bulk Density Log

DHPI – Density Porosity Log

FID – Flame Ionization Detector

GR – Gamma-ray Log

HI – Hydrogen Index

Kc – Carlile Formation

Kf – Frontier Formation

Kn – Niobrara Formation

Kp – Pierre Formation

LOM – Level of Maturation

NPHI – Neutron Porosity Log

OI – Oxygen Index

PGC – Pyrolysis-Gas Chromatography

PI – Production or Productivity Index

RES – Resistivity Log

Ro – Vitrinite Reflectance

TAI – Thermal Alteration index

TOC – Total Organic Carbon

Tmax – Pyrolysis oven temperature at maximum S2

SONIC – Sonic Log

SP – Spontaneous Potential Log

SRA – Source Rock Analyzer™

Sw – Water Saturation

WIS – Western Interior Seaway

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Tweto (1957, 1980a, b) Numerous studies of this area have been published on its petroleum resources and potential. Richard Oppel (1953) Richard Zoerb (1954) Robert Osborne (1957) Win Aldy (1994)

CHAPTER 1

INTRODUCTION

The geology of the North Park structural basin has long been studied, beginning with mapping conducted by King (1878), F. V. Hayden (1873), and S. F. Emmons and Arnold Hague (1877) The area has been the location of petroleum exploration since 1912 when the South McCallum anticline was drilled unsuccessfully. In 1925 the first discovery well was drilled on the North McCallum anticline and the Dakota Sandstone was the producing interval. Success on the South McCallum anticline, however, was delayed due to carbon dioxide and water production. In the 1950s, the Coalmont, Battleship, and Canadian River fields were discovered and developed mainly from the Dakota and Lakota intervals. In 1971, the Lone Pine Oil Field was discovered, producing substantial amounts of oil from the Lakota Formation, over 2.5MMBO, from a small 160 acre area. Potential remains for the discovery of new fields in this basin. Complex structural traps may be numerous in the area, due to numerous periods of structural deformation and limited seismic and well data. Basin-centered hydrocarbon plays may exist. Also, stratigraphic traps in the Jurassic Entrada Sandstone may exist where it onlaps in the vicinity of the Rabbit Ears Range. In addition, traps created by thrusts, such as the Independence Mountain Thrust, remain largely untested. (Hembre and TerBest, 1997; Oburn, 1966)

The Niobrara Formation of the North Park Basin has recently received renewed attention for its petroleum potential. In 2007, EOG Resources drilled the #1-32H Buffalo Ditch discovery well in the Eclipse Field in the SE ¼ of the SE ¼ of Sec. 32, T7N, R80W which targeted the Niobrara. The concept utilizes horizontal well technology and multistage fracture stimulation (Rocky Mountain Oil Journal, 2009b). Through February 2009, two wells have produced 36,669 barrels of oil, 40.4 mmcf gas, and 21,061 barrels of water (Colorado Oil and Gas Conservation Commission, 2009a). EOG has shot a 36 square-mile 3D seismic survey and has plans to proceed with a nine-well test program. EOG estimates that on its acreage the reservoir of the Niobrara is 90-450 feet thick with an average porosity of 3.5-6%, has an initial reservoir pressure of 3700 psi, and a bottom hole temperature of 210°F (Oil & Gas Journal, 2008).

As outlined above, the petroleum system present in the North and Middle Park Basin has been productive in the past and has the potential for the discovery of new resources, both conventional and unconventional. A summary of this petroleum system has been compiled into a key events chart and is shown in Figure 1.1.

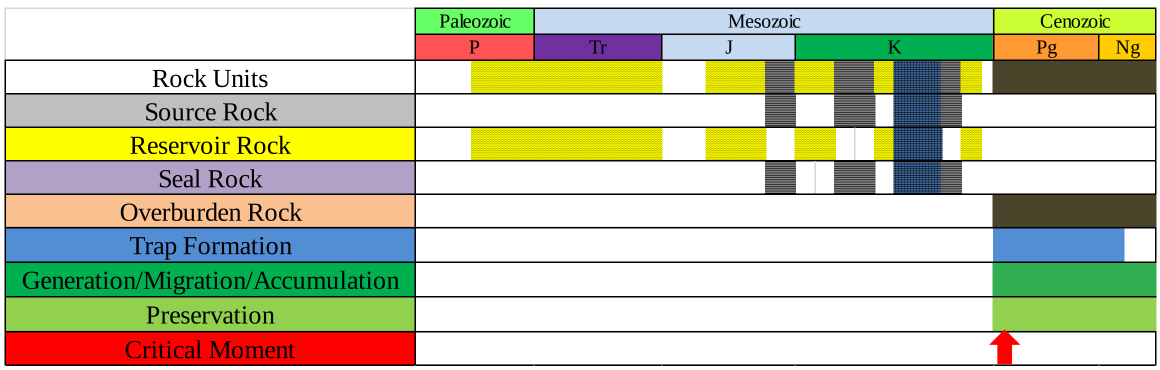


Figure 1.1 Key Events Chart of North Park Basin. This chart was compiled by the author from numerous studies and reports on the petroleum history of the basin. (Hembre and TerBest, 1997; Newton, 1957; Oburn, 1966), (Biggs, 1957; Carpen, 1957a, b; Grote, 1957; Saterdal, 1957), (Park, 1977; Wellborn, 1977).

1.1 OBJECTIVES AND PURPOSE OF RESEARCH

The purpose of this study was to examine the stratigraphy of the Niobrara Formation and determine how this formation relates to the petroleum system located in the North Park Basin. Specifically, the source and reservoir rock potential of the Niobrara Formation has been analyzed. Data used in this study included measured sections, outcrop gamma-ray logs, petrographic thin sections from outcrop samples, geochemical analysis, and subsurface logs (Gamma-ray, Resistivity, Density, etc).

1.2 Study Area Location

The study area incorporates both the North and Middle Park areas located in Grand and Jackson Counties, North-Central Colorado (Figure 1.2). Both of these basin areas are topographic basins, separated by intrusive rocks; together they represent one structural basin. For the purpose of this proposal, the basin will be referred to as the North Park Basin. The North Park Basin is located from Townships 1 South-12 North and Ranges 76-82 West. Outcrops of the Niobrara Formation are intermittently present on the margins of this basin. These exposures are limited due to both erosion and glacial cover.

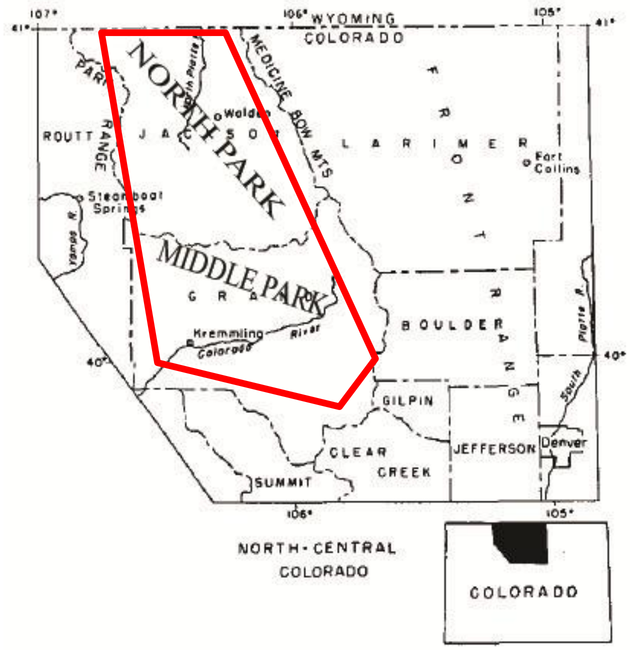


Figure 1.2 The location of the North and Middle Park Basins, Jackson and Grand Counties, North Central Colorado is outlined in red. (from Kinney and Hail, 1959)

1.3 Geologic Overview

The North Park Basin is a single structural basin, broken into two distinct topographic areas. Together they constitute an area that is about 100 miles long and 30 miles wide. North Park is bounded by the Park Range on the west, the Independence Mountain Thrust on the north, the Medicine Bow Mountains of the Front Range on the east, the Never Summer Thrust on the southeast, and the Rabbit Ears Range on the south. Middle Park is bounded by the Park Range to the west, the Rabbit Ears Range to the north, the Front Range to the east, and the Williams River Mountains, and the Vasquez

Mountains to the south. These relationships are best seen in Figure 1.8, in Section 1.3.4 on the structure of North Park.

1.3.1 Stratigraphy

As the basin coincides with the axial trend of the ancestral Rocky Mountains, the sedimentary rocks in the basin range from Permian to Quaternary as older units have either been eroded or were never deposited. These sediments reach maximum thicknesses of 17,000 feet (Hail, 1965). The rocks that lie on the Precambrian basement get younger from the Permian in the north to Cretaceous to the south (Tweto, 1957). The Permian through Jurassic rocks are predominately non-marine and collectively reach thicknesses of 1,400 feet (Stites, 1986). The Cretaceous interval of marine sandstones, limestones, and shales reach thicknesses of 6,000 feet. The Cretaceous Dakota Sandstone, Mowry Shale, Benton Shale, Frontier Sandstone, Niobrara Formation, and the Pierre Shale were deposited in the epicontinental seas of the Western Interior Seaway. Non-marine Tertiary units are up to 10,000 feet thick and represent basin fill deposits that are the result of adjacent uplifts of Laramide and post-Laramide tectonism (Stites, 1986). In addition to these sediments, Pleistocene glacial till and Holocene colluvial and alluvial material has been deposited.

The Arctic sea transgressed the Rocky Mountain Region beginning in the Early Cretaceous, setting the stage for the formation of the Western Interior Seaway. Units such as the Dakota Group and Frontier were deposited in transitional terrestrial to marine environments at the margins of the sea. Sediment was supplied from both the eastern and western margins, and the supply from the west deposited the thickest successions. More shale rich units were deposited when the Arctic sea had joined the Gulf of Mexico over the transcontinental arch (Haun and Kent, 1965), creating one of the largest foreland basins in the world (Weimer, 1984). These units get progressively younger to the south as a result of the progressive encroachment of the Arctic Sea toward to the Gulf of Mexico. Numerous progradational and retrogradional sequences occurred during the Cretaceous resulting in the various units seen in the area.

The Niobrara Formation was deposited during the Coniacian (Weimer, 1984). It consists of intervals of calcareous chalk and organic-rich shale units. Within the Niobrara, four limestone intervals and three shale intervals are recognized, both in outcrop and on geophysical logs. In the North Park Basin and the Denver Basin the lowermost limestone is known as the Fort Hays Limestone and the rest of the units are grouped together as the Smoky Hill Member (Figure 1.3). The Fort Hays Limestone lies on an erosional surface above the units of the Carlile Shale through Greenhorn Formation; the upper boundary varies from an erosional to transitional contact with the overlying pelagic Pierre Shale (Weimer, 1984). Thickness variations and unconformities previously identified in the Niobrara Formation are interpreted to be the result of northwest movement of the American Plate, portions of the sea floor developing compression and uplift, and submarine scour during contemporaneous sea-level drop (Weimer, 1984).

1.3.2 Past Stratigraphic Correlation

The members of the Niobrara were deposited in the Denver Basin and correlations exist into other Rocky Mountain basins. The most recent published studies of the Niobrara are by Longman, Landon, and Luneau in 1998 and 2001. These papers characterize the nature and distribution of the Niobrara lithologies and their potential as a hydrocarbon source rocks throughout the Rocky Mountain region, including North Park Basin. These workers break the Niobrara Formation into eight members, based primarily on their chalk content. The units are described using the chalk to marl to shale definitions as seen in Figure 1.4 The following descriptions of the Niobrara interval summarizes the work of Longman et al. (1998) and Landon et al. (2001).

The lowermost member of the Niobrara Formation is the Fort Hays Limestone (N900 in Figure 1.5). It is generally a tan to light gray, bioturbated chalk with shaly, microstylolitic interbeds. The chalk beds generally range from 0.5-5 feet thick, with an average thickness of 2 feet, while the shaly partings are typically 0.5-2 inches thick. The entire Fort Hays ranges in thickness from less than 10 feet (in SE Wyoming) to upwards

System	Series	Northwestern North Park, Colorado	
Tertiary	Paleocene	Coalmont Formation (lower part)	
Cretaceous	Upper		
		Pierre Shale	Sandy Member
			Shaly Member
		Niobrara Formation	Smoky Hill Shale Member
			Fort Hays Limestone Member
		Benton Group	Carlile Shale
			Greenhorn
			Graneros Shale
			Mowry Shale
		Dakota Sandstone	Upper Part
			Lower Part
Jurassic	Upper	Morrison Formation	
		Sundance Formation	Upper Member
			Lower Member
	Middle		
	Lower		
Triassic	Upper	Chugwater Formation	
	Middle		
	Lower		
Permian			

Figure 1.3 Generalized stratigraphy of the North and Middle Park Basin
(from Stites, 1986 after Hail, 1965; Weimer et al., 1986)

of 120 feet (in New Mexico). In the North Park Basin, the thickness of the unit ranges from about 10-40 feet thick, although it is notably less rich in carbonate. The Fort Hays has a finely crystalline carbonate matrix of disaggregated coccolith fragments with suspended skeletal fragments comprising mostly of planktonic foraminifer tests, oyster shell fragments, inocerimid shell fragments, and disaggregated calcite prisms. Chondrites, Planolites, Thalassinoides, Teichichnus, Zoophycos are important trace fossils present in the unit. The Fort Hays can be distinguished on wireline logs by a low blocky gamma-ray, a high resistivity, a convergence of the neutron and density porosity, and a high sonic response.

The remaining portion of the Niobrara is known as the Smoky Hill member. It consists of alternating chalk and marl-rich units. These units are the basal chalk, lower shale, lower chalk, middle shale, middle chalk, upper shale, and upper chalk.

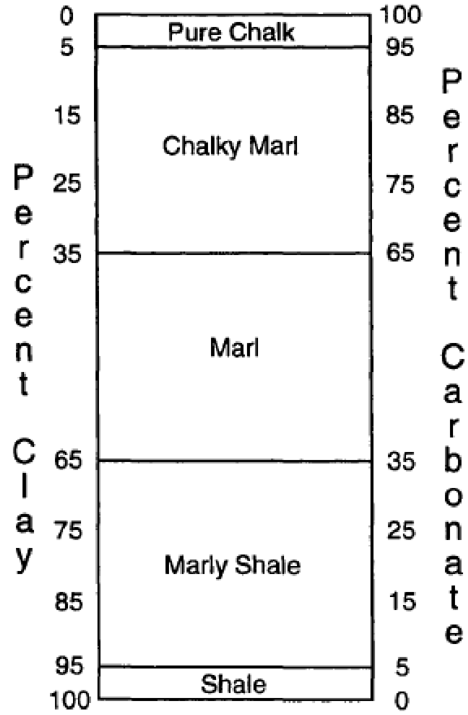


Figure 1.4 Carbonate to Shale Spectrum. This spectrum, a simplification of Pettijohn (1975) is used by Longman et al. (1998) in their study on the Niobrara.

The lower most part of the Smoky Hill member is the basal chalk (N850 in Figure 1.5). It is a light colored, bioturbated chalk and chalky marl interbedded with marl and marly shale. The basal chalk varies in thickness in the region from zero (in southeastern Wyoming) to over 180 feet (in the Raton Basin), and is 20-60 feet thick in North Park. The thickness of the unit is influenced by paleostructures in the area. Plantonic foraminifer tests and inocermid shell fragments are common while chalk pellets are present in the marl interbeds. The contact with the overlying unit is gradational, as can be noted by an upward increasing gamma-ray response.

The next unit is the lower shale (N800 in Figure 1.5). It is a brownish-gray laminated marl with a slightly silty, clay matrix. Some chalky marl interbeds exist in the unit. It is characterized by flattened chalk pellets and, to a lesser degree, planktonic foraminifer. It ranges in thickness from zero to eighty feet across the Rocky Mountain region. A high gamma-ray response is noted in this unit.

The lower chalk (N700 in Figure 1.5) overlies the lower shale. It is a brownish-gray, wispy laminated, slightly burrowed chalky marl. It is mostly comprised of chalk pellets, usually 65-85%, but may also contain planktonic foraminifers and oyster and inocerimid fragments. The lower chalk is zero to seventy-five feet thick in the region, with a thickness of 10-65 feet thick in North Park. Thickness variations of this unit have been observed, characterized by northeast-southwest trending discontinuous lenses and pods of chalk-rich fecal pellets coined “pilenpoopen” bars by Longman et al. (1998). The lower chalk is seen on gamma-ray logs by a three fingers response, indicating the presence of three main chalk beds.

Above the lower chalk, is the middle shale (N500 in Figure 1.5). It is a dark olive-gray and wispy to parallel laminated to massive marl with medium to light gray bioturbated chalky marl beds. Planktonic foraminifer tests, oyster shells, inocermid fragments, and flattened chalk pellets can be observed in a clay matrix in the middle shale.

The middle chalk overlies the middle shale. The middle chalk is composed of three units: two units predominately composed of chalky marl (N460 & N400 in Figure 1.5) separated by a dark-colored massive or parallel laminated marl with marly shale interbeds (N430 in Figure 1.5). Flattened chalk pellets, planktonic foraminifer, Inoceramus, and oyster fragments can be seen in the more

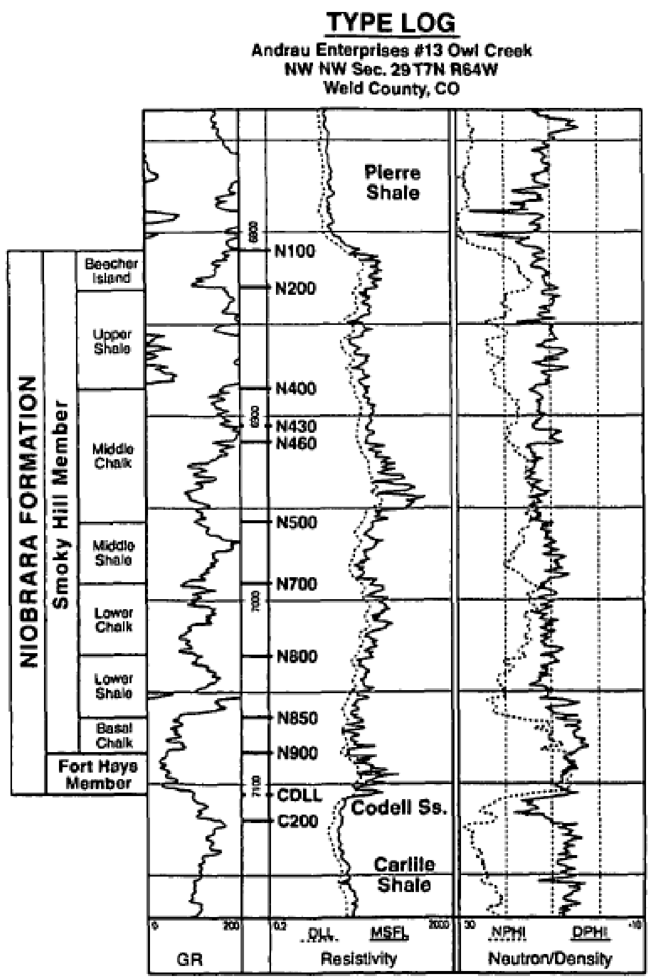


Figure 1.5 Type log for the Niobrara Formation in the Denver Basin. (Longman et al., 1998)

chalk rich units while the marl units are composed of primarily flattened chalk pellets. The lowest has a more micritic matrix compared to the clay matrixes of the marl and upper chalk units. The upper chalk unit of the middle chalk is more varied than its lower counterpart. The lower chalk exhibits convergence on the neutron and density porosity logs, while the gamma-ray response is upward increasing through the middle chalk.

The upper shale (N200 in Figure 1.5) is stratigraphicly above the middle chalk. It is composed of dark massive marly shales to chalky marls. The unit is 30-500 feet thick through the region, with thicknesses from 30-100 feet within North Park. Flattened chalk pellets, oyster and Inoceramus shell fragments, pyrite framboids can be seen in the clay matrix of these shales and marls. The upper shale is typified by a high gamma-ray response.

The uppermost unit of the Niobrara is the upper chalk (N100 in Figure 1.5), also known as the Beecher Island Zone. It is a light tan, speckled, microporous chalky marl, that is massive with faint wispy laminae. Chalk pellets, planktonic foraminifer, Innoceramus fragments, oyster fragments are common in its micritic to clay matrix. The upper chalk is zero to fifty feet thick throughout the region, including North Park.

1.3.3 Niobrara Formation Depositional Environment

Carbonate deposition began after the complete flooding of the Hartville Uplift around 88.8 Ma, connecting the north and south arms of the Western Interior Seaway (Longman et al., 1998).This set up a counter-clockwise flow pattern from the ancestral Gulf of Mexico to the Arctic Sea (Slingerland et al., 1996). The warm southern currents allowed for the coccoliths and planktonic forams abundant in intervals of the Niobrara to be present. Throughout the overall deposition of the Niobrara, this overall marine transgression persisted, albeit with lower order fluctuations. Figure 1.6 shows a schematic of these transgressive-regressive cycles. The lower order cycles control the amount of current flow in the WIS. During the transgressive cycles, higher relative sea level allowed for more of the carbonate-rich waters from the south to invade the area of the WIS which is now Colorado. Four trangressive cycles occurred during the Niobrara cyclothem, resulting in the deposition of the Fort Hays, basal chalk, lower chalk, middle chalk, and

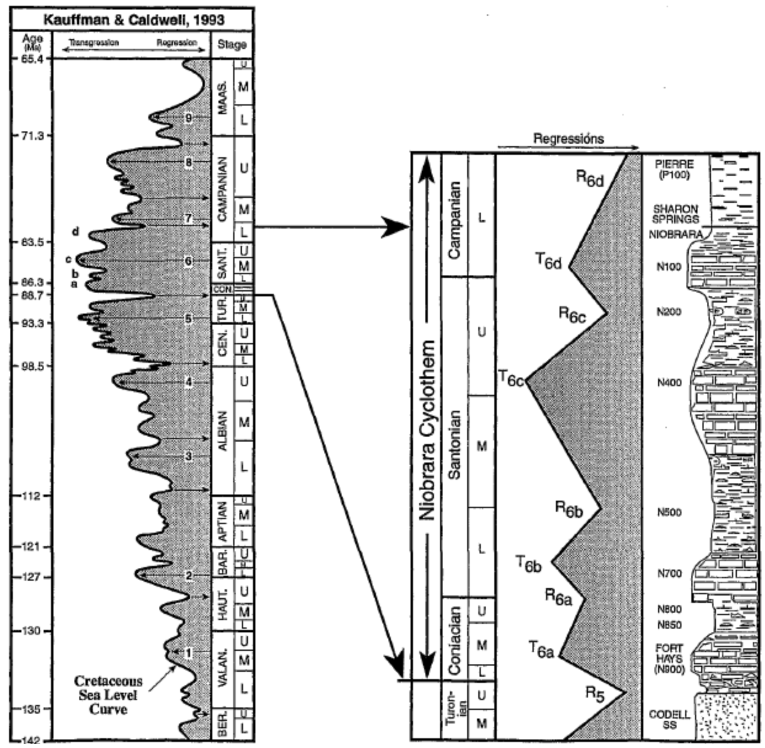


Figure 1.6 Cretaceous transgressive-regressive cycles. Four trangressive cycles and three regressive cycles occurred during the Niobrara cyclothem. The transgressive periods favored chalk-rich deposition, while regressive cycles favored more marl-rich deposition as a result of fluctuating current flow. From Longman et al, (1998) after Kauffman and Caldwell (1993), Obradovich (1993), and Barlow and Kauffman (1985)

upper chalk intervals. Alternatively, during the regressive cycles, the currents from the south were reduced, and the southward flowing Arctic currents inhibited carbonate production and deposition. Three regressive cycles took place during the Niobrara cyclothem, resulting in the deposition of the lower shale, middle shale, and upper shale intervals. In addition to the fluctuating current flows, a gradual deepening of the WIS resulted in time periods when bottom waters throughout parts of the WIS were anoxic, favoring the preservation of organic matter. Paleogeographic reconstructions of different time periods during the Niobrara cyclothem can be viewed in Figure 1.7.

1.3.4 Structure

This study primarily deals with the stratigraphy of the basin and less concerned with its structure. However, a basic understanding of the structural evolution and elements of the basin is essential. The North Park Basin is considered one of the most structurally complex Rocky Mountain intermontane basins (Wellborn, 1977). Three periods of deformation are known to have occurred in the basin during the late Cretaceous-Eocene, late Eocene, and Miocene-Pliocene (Hembre and TerBest, 1997).

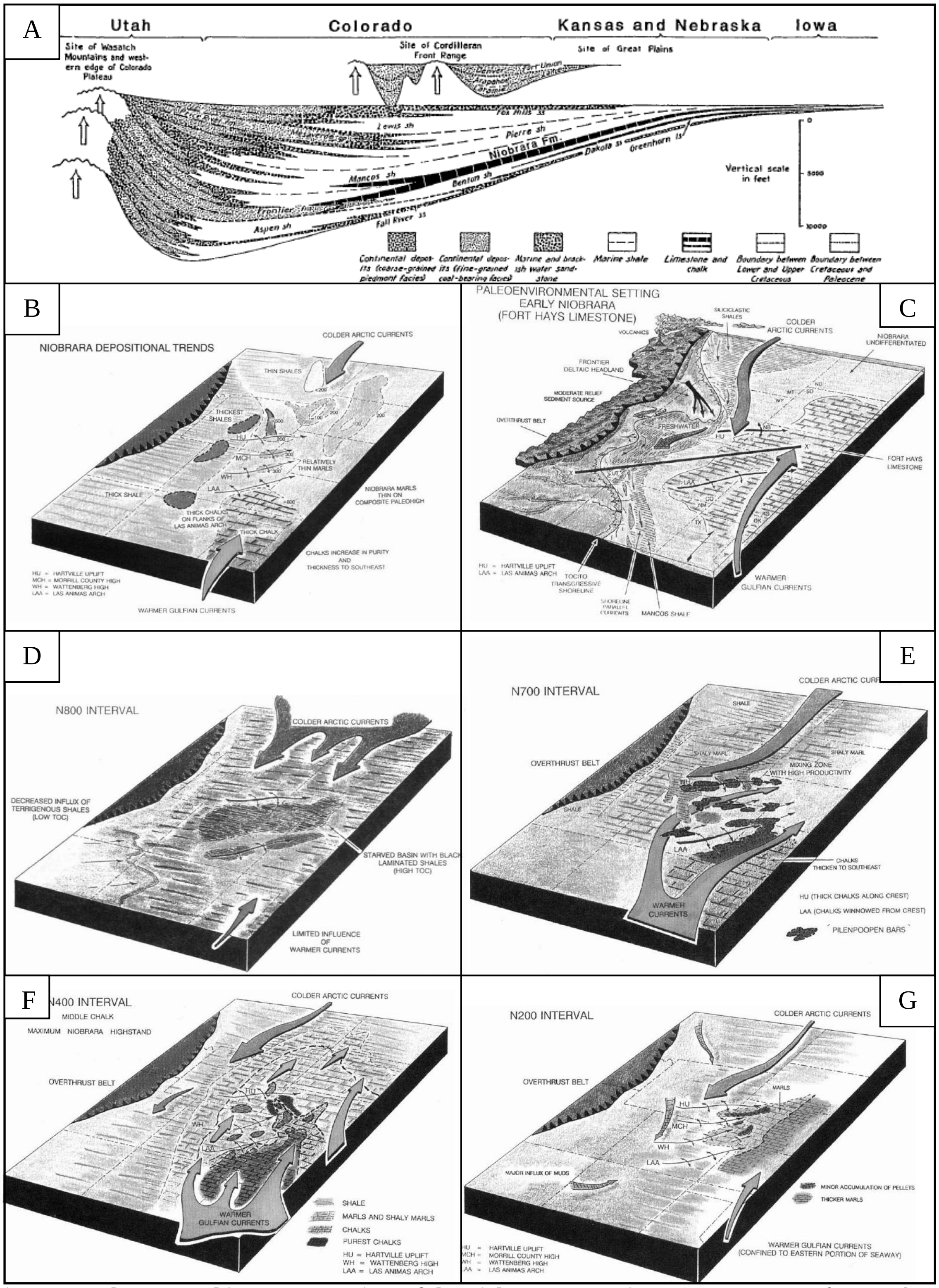


Figure1.7 Paleogeographic Representations of the Niobrara Formation. A) Cross Section from Utah to Iowa. B) Overall Niobrara depositional trend. C) Paleoenvironmental setting during the deposition of the Fort Hays. D) Paleoenvironmental setting during the deposition of the lower marl. E) Paleoenvironmental setting during the deposition of the lower chalk. F) Paleoenvironmental setting during the deposition of the middle Chalk. G) Paleoenvironmental setting during the deposition of the upper marl. From Longman et al. (1998)

Northeast-southwest compressional forces of Laramide tectonism of late Cretaceous through Eocene time are responsible for most of the major deformational features (Lange and Wellborn, 1985). North Park Basin was formed during the Larimide as the surrounding mountain ranges, Front, Medicine Bow and Park Ranges, were uplifted. These ranges were all part of the Ancestral Rocky Mountain Highland. During late Eocene time, folds and north and northwest trending reverse faults resulting in tightly folded and even overturned and thrusts with thousands of feet of displacement (Wellborn, 1977). During Miocene-Pliocene time, widespread volcanism and intrusion occurred, and is exemplified by the Rabbit Ears Range (Hembre and TerBest, 1997). The main structures present in the basin are summarized in Figure 1.8.

Mountain ranges bound the North Park Basin. The Medicine Bow, Park, Never Summer, Williams River, Vasquez, and Front Ranges consists of Precambrian igneous and metamorphic rocks. These ranges form the boundaries of the basin. The Rabbit Ears Range separates North Park from Middle Park. This range is formed from intrusive and extrusive igneous activity.

Folding associated with uplift of the surrounding mountain ranges is present in the basin. The major folds of the basin will be briefly discussed. Three named synclines are present in the area: the North Park, Walden, and Sulfur Springs synclines. The North Park syncline is an asymmetrical fold. Of the anticlines located in the basin, three are known for their petroleum traps: the McCallum, Battleship, and Coalmont anticlines. The McCallum anticline is broken into north and south components by a small saddle. Other anticlines present in the basin are the Elk Mountain, Sentinel Mountain, Spring Creek, Sand Creek, Sheep Creek, and Granby anticlines.

Faults in the basin are a result of the uplifts that occurred in this region. The main faults that are located in this basin will be briefly summarized here. Oblique, dip-slip normal faults are present in the basin, including the Boettcher, Sheep Mountain, Delaney Butte, South McCallum, and Coalmont Faults. The Sentinel Mountain and Elk Mountain Faults are two of the reverse faults noted in the basin. Thrust faults present include the Never Summer-Stillwater-Vasquez Overthrust Zone, Mt. Bross-Buffalo Creek Thrust plate, Williams Range Thrust plate, Independence Mountain thrust, and the Central

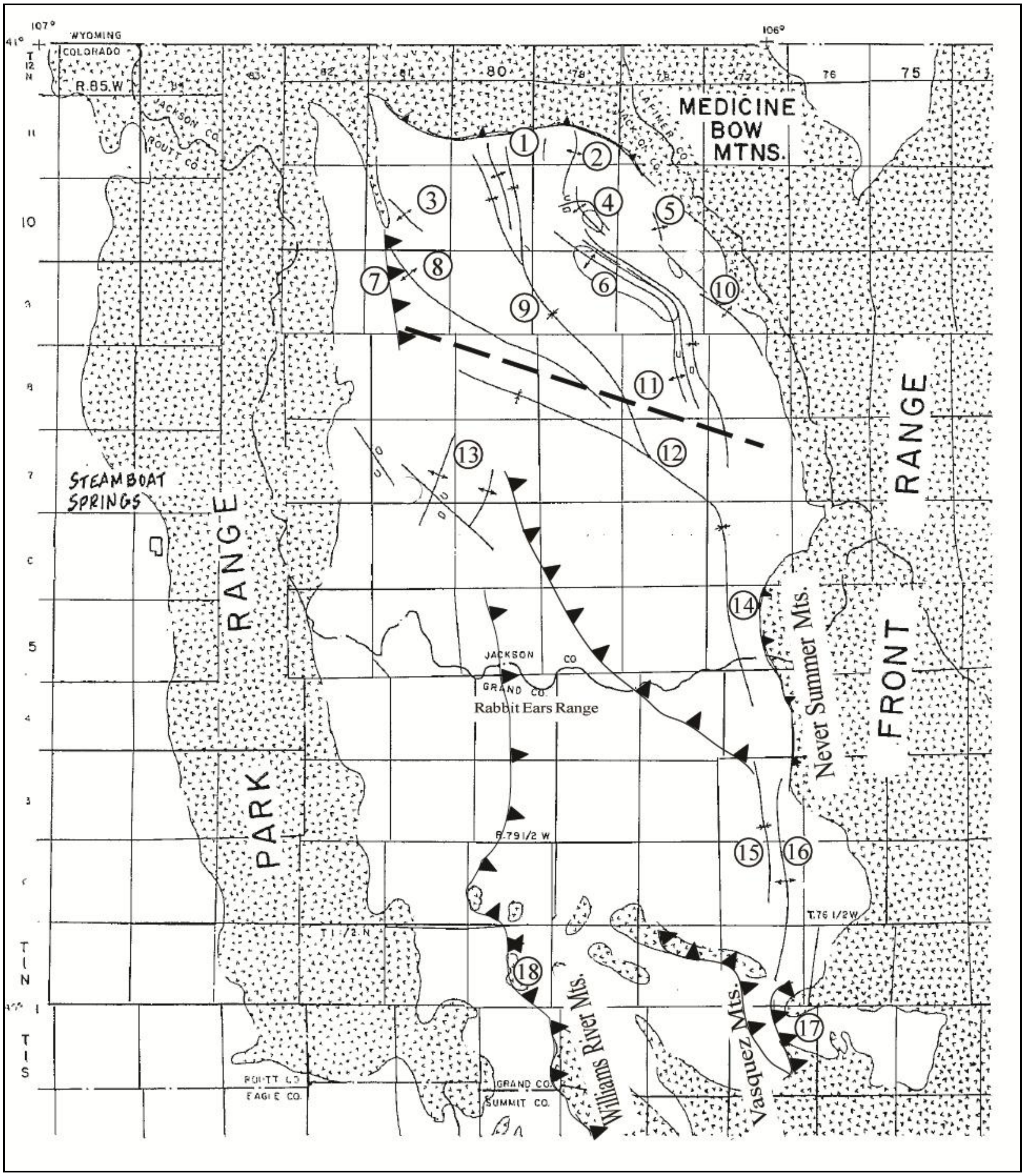


Figure 1.8 Map of the main structural elements of the North and Middle Park Basin (modified after Haverfield, 1970; Lange and Wellborn, 1985)

1. Independence Mt. Thrust
2. Sentinel Mt. Anticline
3. Sand Creek Anticline
4. Battleship Anticline
5. Spring Creek Anticline
6. McCallum Anticline
7. Central Thrust Belt
8. Sheep Creek Anticline
9. Walden Syncline
10. Elk Mt. Anticline
11. Spring Creek Fault Zone
12. North Park Syncline
13. Coalmont Anticline
14. Never Summer Thrust
15. Hot Sulfur Springs Syncline
16. Granby Anticline
17. Vasquez Thrust
18. Williams Range Thrust

Thrust Belt. The Spring Creek Fault Zone divides the northern third of the basin, where faulted anticlines prevail, from the southern third, where thrusting is predominate.

1.4 Methods

The first phase of this study involves the identification and interpretation of the Niobrara Formation and surrounding units in outcrop. An outcrop of the Niobrara was located in North Park and was measured; the lithology was described in detail. Samples were collected from each outcrop. These samples were used to create petrographic thin sections that were analyzed under a petrographic microscope to identify the constituents and to classify each sample. The samples were also used for pyrolysis and total organic carbon geochemistry analyses. The outcrop was also logged by a gamma-ray RS-125 Spectrometer. This allows for the outcrop to be correlated to subsurface gamma-ray logs.

The next phase of this study investigated the Niobrara Formation in the subsurface. This work integrated data collected from the outcrop investigation, especially the outcrop gamma-ray readings, with subsurface well logs. The data for this project consist of digital and raster logs acquired from IHS and MJ Services under agreements with the Colorado School of Mines. The well logs were imported into the IHS GeoPlus Petra software through which the correlation of the subsurface well logs took place. Important horizons of the Niobrara and other important formations were identified. These correlations are based on both previous correlations as well as the outcrop study. Contour and isopach maps of each of these horizons were constructed. Important rock properties were also evaluated across the basin as part of the subsurface study using petrophysical techniques. These properties include porosity, water saturation, total organic-carbon content, and maturity. The methods used in evaluating these properties include basic well log analysis (Asquith et al., 2004) and a technique developed by Passey et al. (1990) for calculating organic richness from porosity and resistivity logs. In addition to the well logs, geochemical data from subsurface cuttings was also used. These data have been obtained on the USGS Core Website and includes a study of eight wells in Jackson and Grand Counties by EOG in 2006. These wells have available data for bulk x-ray diffraction, total organic carbon, pyrolysis, and vitrinite reflectance for select intervals.

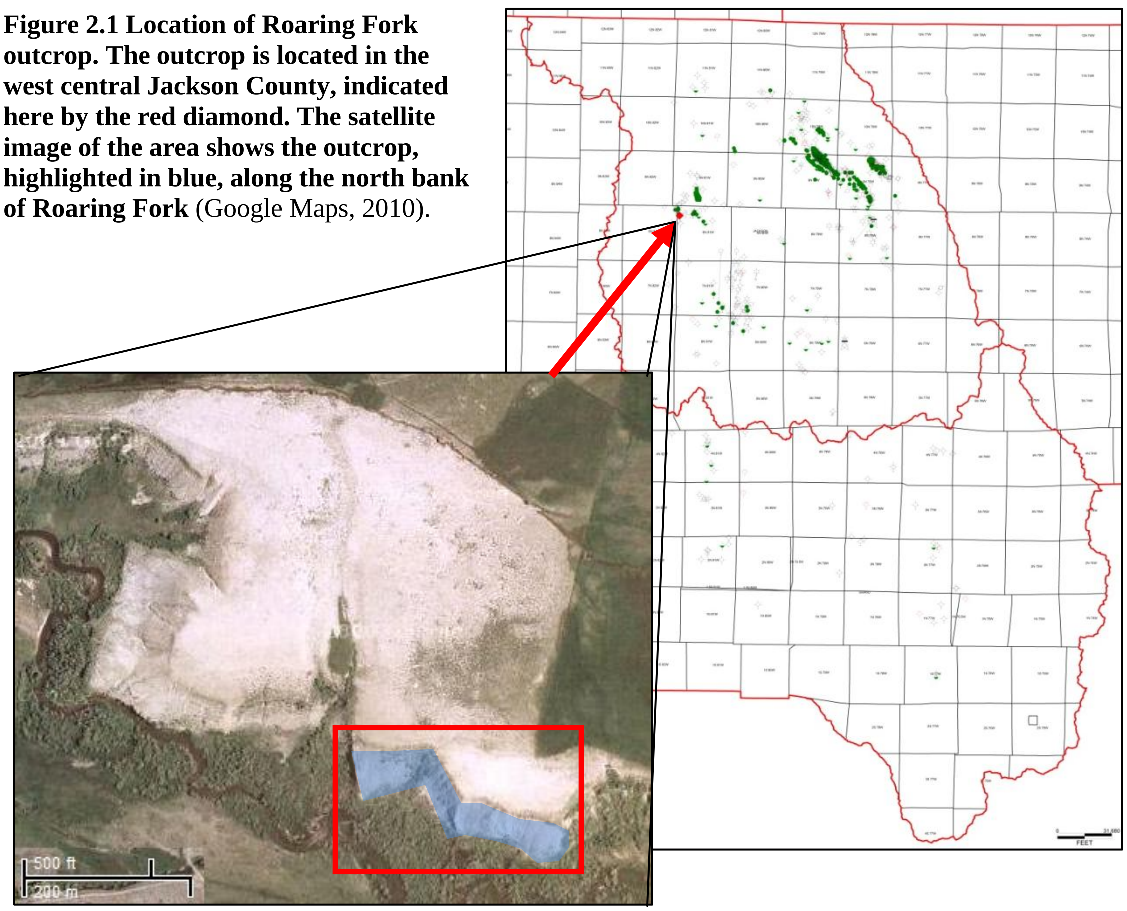
The methods for evaluating these data (and geochemical data from outcrop samples) are based on analysis techniques and guidelines outlined by Peters (1986), Langford and Blanc-Valleron (1990), and Peters and Cassa (1994). All of the above data are used to interpret the Niobrara Formation. The role that the Niobrara plays in the petroleum system of the basin was evaluated, specifically the potential source and reservoir rocks. As a result of this study of the Niobrara, future exploration areas are suggested.

CHAPTER 2

ROARING FORK OUTCROP STUDY

The outcrop used in this study is located on the western margin of the North Park Basin and is exposed along the north side of Roaring Fork Creek in the se $\frac{1}{4}$, se $\frac{1}{4}$, Sec. 1, T8N, R82W; sw $\frac{1}{4}$, sw $\frac{1}{4}$, Sec. 6, T8N, R1W; and nw $\frac{1}{4}$, nw $\frac{1}{4}$, Sec. 7, T8N, R81W as shown in Figure 2.1. This outcrop was found by consulting past outcrop work in the basin (Stites, 1986) and geologic maps (RMAG, USGS). Other outcrops were investigated; however, exposure of the Niobrara is very limited in the basin as it is prone to erosion, and this exposure was deemed the best exposed.

Figure 2.1 Location of Roaring Fork outcrop. The outcrop is located in the west central Jackson County, indicated here by the red diamond. The satellite image of the area shows the outcrop, highlighted in blue, along the north bank of Roaring Fork (Google Maps, 2010).



This outcrop totals about 300 feet in thickness. The outcrop represents portions of the Frontier, Carlile, and Niobrara Formations. Fifteen samples were collected from the outcrop, at 20 foot intervals. Ten petrographic thin sections were prepared from these samples and were analyzed under a petrographic microscope to identify the constituents and the classification of each sample. The samples were also used for whole rock pyrolysis and total organic carbon geochemistry analyses. The outcrop was logged by a gamma-ray RS-125 Spectrometer, allowing for the outcrop to be correlated to subsurface gamma-ray logs.

2.1 Measured Section, Lithologic Description, and Petrographic Thin Sections

The measured section, lithologic description, and petrographic thin sections are compiled together in Plate 2.1. Figure 2.2 shows an example of the outcrop. The intervals seen in the outcrop are the Frontier Sandstone, the Carlile Shale, and the Niobrara Formation. Sub-units of the Niobrara present in the outcrop are the basal chalk, lower marl, lower chalk, middle marl, middle chalk, and the upper marl. The following sections present the observations seen in the outcrop by interval.

2.1.1 Frontier Sandstone

The section exposed begins in the Frontier Sandstone. The Frontier is a fine-grained sandstone and is fossiliferous, containing shell fragments. The Frontier exposed in this outcrop is about 20 feet thick. The unit is composed of angular quartz grains with porous intervals between the grains.

2.1.2 Carlile Shale

The Carlile Shale lies above the Frontier Sandstone. This unit is composed mainly of shales, but chalk-rich intervals are interbedded within the unit. One such interbed is seen about 15 feet above the Frontier measuring about a foot in thickness. This chalk bed had a very strong effervescence when a diluted HCl was applied. The unit is a grainstone composed of skeletal grains, including shells and foraminifera. Chalk units within the Carlile are limited. Above this chalk unit, the outcrop is covered for an estimated stratigraphic thickness of 250 feet until the next exposed unit of the Carlile. This unit is a gray calcareous shale intramicrite wackestone with thin laminae about 16 feet (exposed) thick and contains carbonate skeletal grains, including foraminifera.

2.1.3 Basal Chalk

The Niobrara Formation lies above the Carlile Shale. The first unit of the Niobrara is the basal chalk. It is more resistant in the outcrop than the underlying shale unit. It is gray and calcareous, moderately effervescing to acid. The basal chalk is about 15 feet thick in this outcrop and has thin layers present.

2.1.4 Lower Marl

Above basal chalk is the lower marl. This unit is less resistant than the underlying chalk. It contains many bentonite layers, ranging from ¾ - 2 inches thick each. Overall, the lower marl is about 10 feet thick.

2.1.5 Lower Chalk

The lower chalk lies above the lower marl. It is about 25 feet in thickness. The lower chalk is a pelintramictite wackestone composed of many skeletal grains, including globigerinid planktic foraminifers with calcite-spar filled chambers.

2.1.6 Middle Marl

Above this unit lies a more recessive gray, calcareous marl, the middle marl. This marl unit is about 70 feet think, though only about 30 feet thick are exposed in this outcrop. The marl is calcareous as the interval reacts strongly to acid. The units is laminated and is a pelmictite wackestone.

2.1.7 Middle Chalk

The middle chalk lies above the middle marl. In this outcrop, the middle chalk is about 100 feet in thickness. The middle chalk is mainly an intramicrite wackestone as the unit has skeletal grains within the matrix of the rock, including globigerinid planktic foraminifers with spar filled chambers. Intervals that are more pellet and marl-rich are interbedded within the chalk. The unit reacts moderately to acid. Bentonite layers, about ½ to 1 inch thick each, are present in this interval. Portions of this interval are sandy and contain dark fossil fragments.

2.1.8 Upper Marl

The upper marl is the last unit exposed in the Roaring Fork outcrop. About 50 feet of the marl is present. It is calcareous, with portions that react weakly, and others with moderate to strong effervescence. It contains some silty to very fine grains, and is classified as a pelmicrite wackestone. The pellets in this unit are flattened, most likely as a result of compaction. The exposure of this outcrop ends as intervals above this unit are covered.

Figure 2.2 Photo of the lower chalk in the Roaring Fork Outcrop of the Niobrara.

2.2 TOC and Pyrolysis Data

The 15 samples that were collected from the Roaring Fork outcrop were analyzed at the Colorado School of Mines using a Source Rock Analyzer™. Figures 2.3 and 2.4 summarize these data. A table of these data is compiled in Appendix A. Total organic carbon values ranged from 0.28 wt% (Frontier) to 3.14 wt.% (lower shale). All of the samples, excluding the Frontier, have TOC values above 1 wt. %; the majority of the Niobrara samples are above 2 wt. %, and have good to very good hydrocarbon potential. However, the S1 values range from 0.01 - 0.30 and indicate poor hydrocarbon source potential zone. The S2 values range from 0.08 (Frontier) to 10.57 (basal chalk). Most of the samples are in the fair to good hydrocarbon source potential interval; three of the samples, including two in the Frontier, are in the poor petroleum potential range. When plotted on a modified van Krevelen diagram, the samples plot between the Type II and Type III lines. The HI values of the samples rank as Type III, mixed Type II and III and Type II kerogen. The S2/S3 values are variable and range from Type I to Type III kerogen. When TOC is plotted against S2, the samples plot as Type III, mixed Type II and III, and Type II kerogen. Based on the interpreted marine depositional environment of this interval, it is expected that a mixture of Type II and Type III would be present. These data from the pyrolysis support this expectation.

In order to evaluate the maturity of the interval sampled, the Tmax values must be used as no vitrinite reflectance or thermal alteration index data were analyzed for this well. The Tmax values for the outcrop samples range from 383-458°C, with an average of 423°C. These values indicate that the samples are immature for oil generation. The production index (PI) values for the Niobrara samples range from 0.02 to 0.07. This indicates that all of the samples are immature. These both support the conclusion that the interval tested has not reached maturity. This maturity represents the maximum thermal maturation the samples have undergone, and are not necessarily representative of the present heat flow conditions.

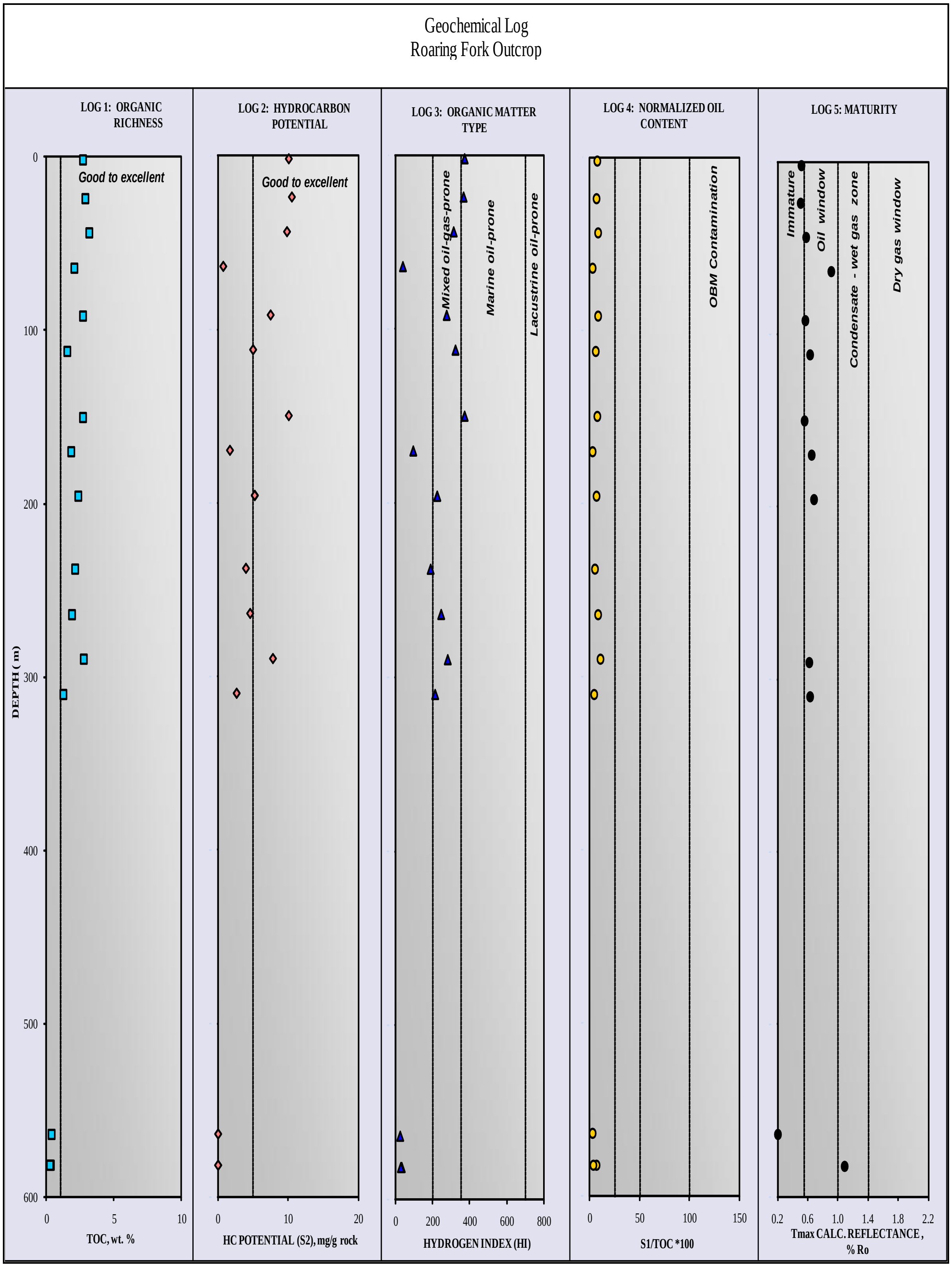


Figure 2.3 Geochemical Log of the Roaring Fork Outcrop. TOC (wt. %), S2 (mg HC/g rock), HI, S1/TOC*100, and Tmax calculated vitrinite reflectance are presented.

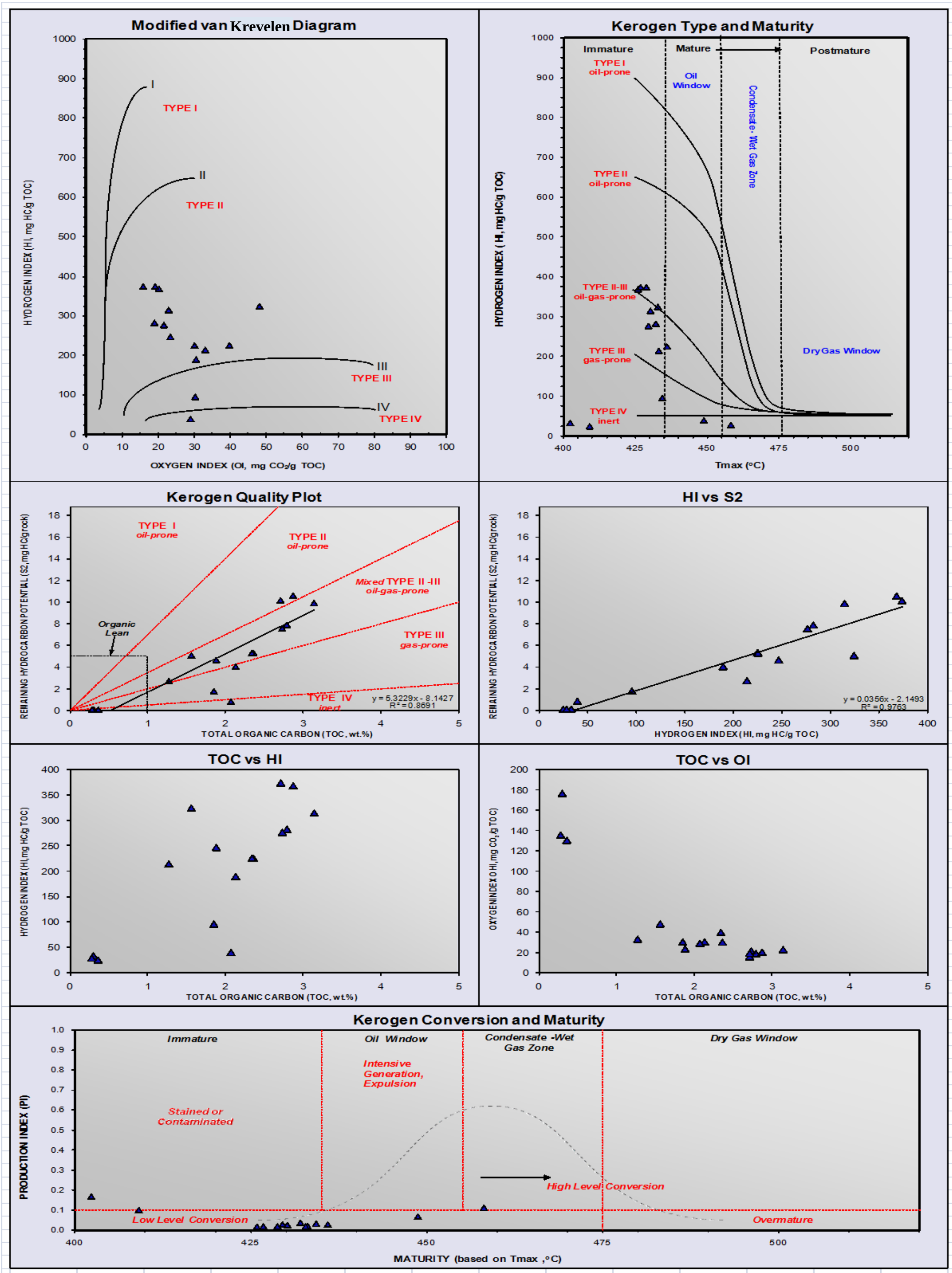


Figure 2.4 Geochemical Graphs of the Roaring Fork Outcrop samples. From Top to Bottom: Modified van Krevelen diagram HI vs. OI, Kerogen Type and Maturity Tmax vs. HI, Kerogen Quality TOC vs. S2, HI vs. S2, TOC vs. HI, TOC vs., OI, and Kerogen Conversion Maturity Tmax vs. PI.

2.3 Outcrop Gamma-ray Log

The Roaring Fork outcrop was measured with a portable GR spectral scintillometer. This provides readings of the total radioactivity as well as a breakdown of the amount derived from potassium, thorium, and uranium of each interval tested. Readings were taken every 2 feet, with each measurement taking 120 seconds. These gamma-ray readings are useful in that they can be used as an aid in determining lithology and correlating, in this case, from an outcrop to the subsurface. When analyzing spectral GR in mudrocks, potassium is associated with clay minerals and feldspar, uranium is associated with organic matter and phosphates, and thorium is associated with heavy minerals and volcanic ash (Bohacs, 1998).

The total and spectral gamma-ray logs for the Roaring Fork outcrop can be seen in Figure 2.5. The potassium and thorium curves appear to be tracking each other. This allows for the variations in the uranium curve to have a greater effect on the total GR curve. As the uranium curve is associated with organic matter, and one would expect, in the context of the Niobrara Formation, that more organic matter would be present in the more marl-rich intervals when compared to more chalk-rich intervals. This allows for use of the GR curves in identifying these alternating chalk-rich and marl-rich intervals in the Niobrara.

In order to correlate the units seen in the outcrop to those in the subsurface, the outcrop gamma-ray readings were compared to gamma-ray readings from a well. The well used in this correlation is Federal 32-1, located about 9600 feet from the location of the outcrop. The comparison of the logs can be seen in Figure 2.6. The lower GR readings in the Frontier sandstone correlate to the lower readings from the lowest portion measured in the outcrop. At the base of the main portion of the measured section, lower gamma-ray readings can be correlated to the basal chalk. Above this unit, the GR readings increase in the lower marl. Next, the readings begin to lower, and the unit is interpreted to be the lower chalk. Above this, the outcrop was too weathered to measure the GR in all but two spots; it is inferred from these somewhat higher readings that this interval is the middle marl. Above the middle marl, the lower GR readings indicate the presence of the middle chalk. The more marl-rich interval within the middle chalk can be

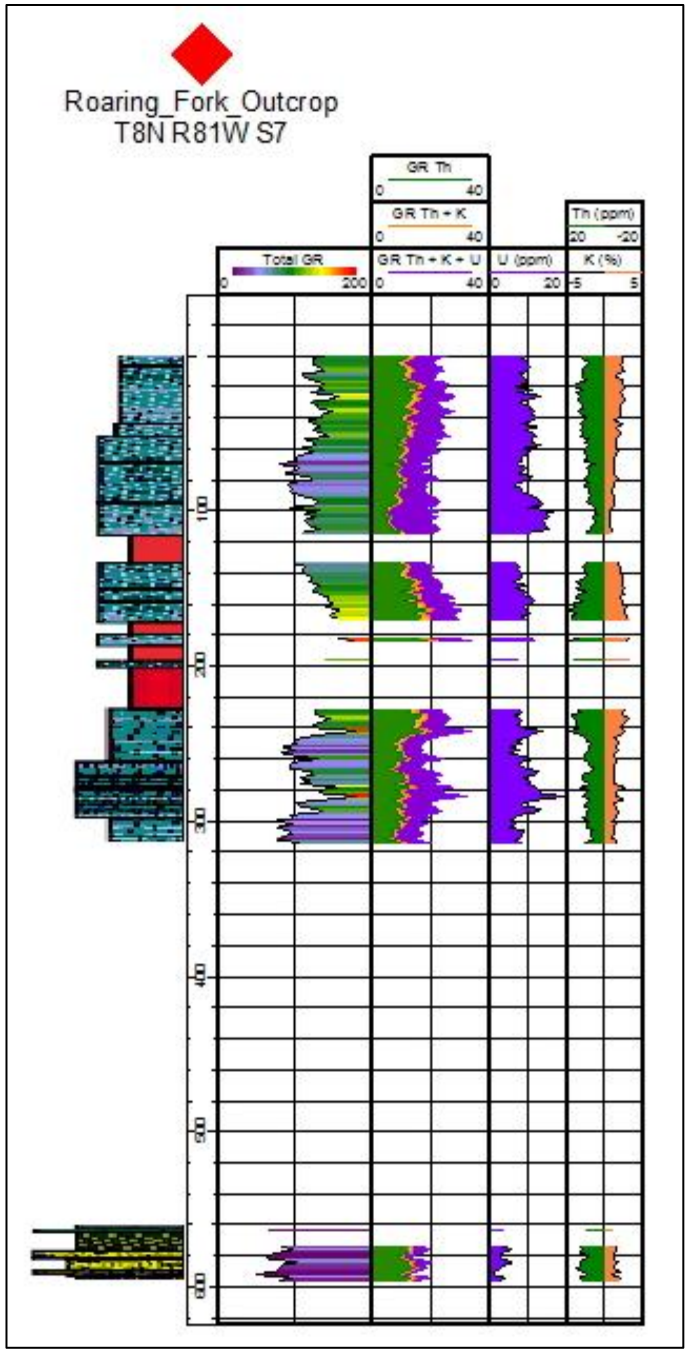


Figure 2.5 Gamma-ray Logs from the Roaring Fork Outcrop. A graphical representation of the measured section is seen in the left most track and the total gamma-ray log in the next track. The spectral gamma-ray logs are shown together in the 3rd track, and separate in tracks 4 and 5. Uranium (ppm) is shown in purple, Thorium (ppm) in green, and Potassium (%) in orange.

seen as the GR readings increase, and then track back down as the interval returns to being chalk rich. Above the middle chalk, the GR readings begin to increase; this interval is interpreted as the upper marl. The measured section and gamma-ray readings end in the upper marl.

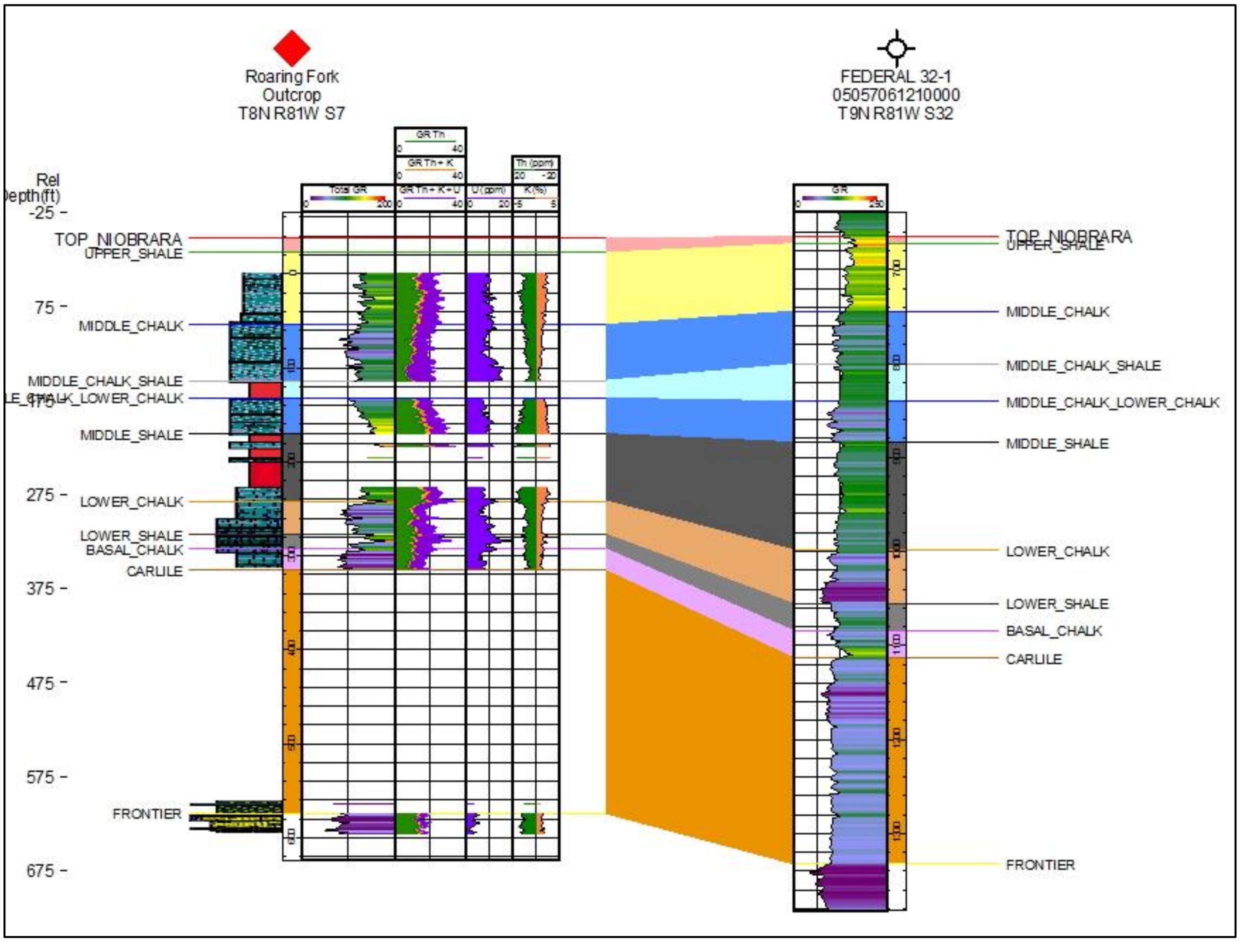


Figure 2.6 Comparison of the GR from the Roaring Fork Outcrop to Federal 32-1. The outcrop and well are about 9600 feet away from one another. An extended cross-section can be seen on Plate 3.1 in D-D'.

2.4 Summary and Discussion

The Roaring Fork Outcrop of the Niobrara was analyzed as part of this study. In addition to a measured section, petrographic thin sections were created and pyrolysis analysis was performed from samples collected in the field. An outcrop gamma-ray log was also created. The measured section and thin sections (Plate 2.1) provide detail on the lithology of the Niobrara, including that portions of the Frontier, Carlile, basal chalk, lower marl, lower chalk, middle marl, middle chalk, and upper marl are present in the outcrop. The pyrolysis data show that the samples most likely contain Types II and III Kerogen and were deposited in a marine environment. TOC measurements on the samples reveal that most samples have at least 1 wt.%, and most contain more than 2 wt.% TOC, rating as a good potential source rock. Hydrogen indices of the samples range from 200-400. The samples are thermally immature, but would generate oil and gas upon generation. The outcrop gamma-ray log provided a means to tie the outcrop to the subsurface. This also provides a level of lithologic control to the subsurface stratigraphic interpretation.

CHAPTER 3

STRATIGRAPHY

Although studies on the stratigraphy of the Niobrara Formation have been published, none have provided a detailed description of Niobrara sediments in North Park Basin. This chapter explains the methodology in the identification of the stratigraphic intervals, presents structural maps, and details the stratigraphic characteristics of each unit described.

3.1 Stratigraphic Correlation Methods

Stratigraphic correlations in this thesis were performed using IHS Petra^{TM} software. Wells with log data within the Niobrara units were used. Figure 3.1 shows the location of the wells used and regional cross-sections presented in this study. The log data included, but were not limited to, gamma-ray, resistivity, density, spontaneous potential, and sonic logs. The majority of these logs were in raster image form. The digital logs that were used were digitized by the author. Regrettably, there are no core data from the Niobrara interval in North Park available to the public, and thus, none has been used in this study to compare with the log data. The type log presented in this chapter is located at the intersection of the B-B' and D-D' cross-sections.

3.2 Correlated Intervals

Ten intervals were correlated based on the log character of the Niobrara interval. These intervals are, in ascending order, the Frontier Sandstone, Carlile Shale, Fort Hays Limestone, basal chalk, lower marl, lower chalk, middle marl, middle chalk (the middle chalk is further subdivided into two chalk units, divided by a marl unit), upper marl, and upper chalk. These tops are based primarily on the work done by Longman et al. (1998) ; however, the term marl is used instead of shale in order to reflect the calcareous nature of

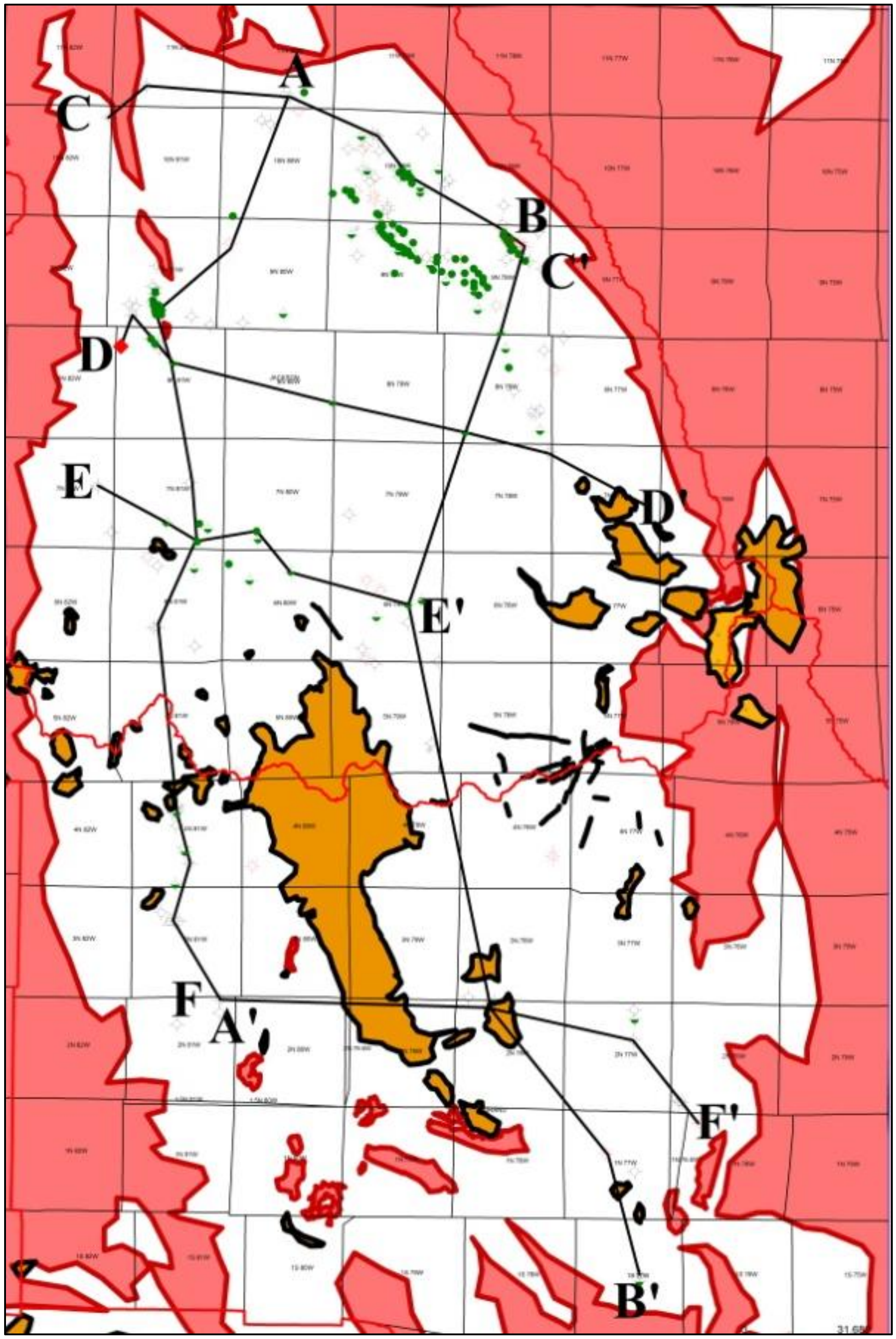


Figure 3.1 Location of Wells and Cross Sections. Location of the 240 wells used in identifying intervals in this study. The location of the six regional cross-sections presented in this study is shown in black. Two north-south sections, A-A' and B-B', and four east-west sections, C-C', D-D', E-E', and F-F'. These cross-sections can be seen in Plate 3.1. Precambrian surface outcrops are shown in pink. Tertiary intrusive surface outcrops are shown in orange. Both the Precambrian and Tertiary intrusive units act as constraints on the presence of the Cretaceous interval in the region.

the interval. The work of Longman et al. (1998) is summarized in the stratigraphy section of Chapter 1 of this thesis.

The characteristics of these units on well logs can be seen in Figure 3.2, a type-log from USA 32-2-1 located in the eastern region of the North Park Basin, just north of the Spring Creek Fault Zone. The well is part of both cross-sections B-B' and D-D'. Starting from the base of the type log, the Frontier Sandstone is identified by its low gamma-ray (GR) and high resistivity (RES) log response. The overlying Carlile Shale is identified by lower RES and higher GR responses than the Frontier. The Fort Hays, located at the base of the Niobrara, is indicated a low blocky gamma-ray, a dramatically higher resistivity than in the Carlile, a convergence of the neutron (NPHI) and density (DPHI) porosity logs, and a high sonic response. The basal chalk of the Smoky Hill Member is similar to the Fort Hays, but is recognized by a higher, less clean GR response, a lower, less consistent RES response, and a lack of convergence of the NPHI and DPHI logs. The lower marl is distinguished by a higher GR and lower RES response when compared to the units above and below it. The lower chalk is indicated by a decrease in GR values. The overlying middle marl is noted by higher GR and lower RES curve values. The middle chalk is broken into three units; a lower chalk, a marl, and an upper chalk. The lower chalk is indicated by a low GR and a high RES response, and a convergence of the NPHI and DPHI logs. The marl unit of the middle chalk is characterized by a higher GR and a decrease in the RES response. The upper chalk is similar to the lower chalk, but is more varied and has a higher GR response (but lower than the separating marl) and lower RES values. The upper marl is recognized by an increase in GR and a decrease in RES. The top of the Niobrara (also the top of the upper chalk) was picked where the resistivity curve values dramatically drop off. The upper chalk interval also contains lower GR values than the marl it overlies.

Many cross sections were constructed throughout the interpretation work completed in this study. In this report, only cross-sections representing the regional nature of the units are shown. These regional cross sections include two north-south sections, A-A' and B-B', and four east-west sections, C-C', D-D', E-E', and F-F' and may be viewed together on Plate 3.1.

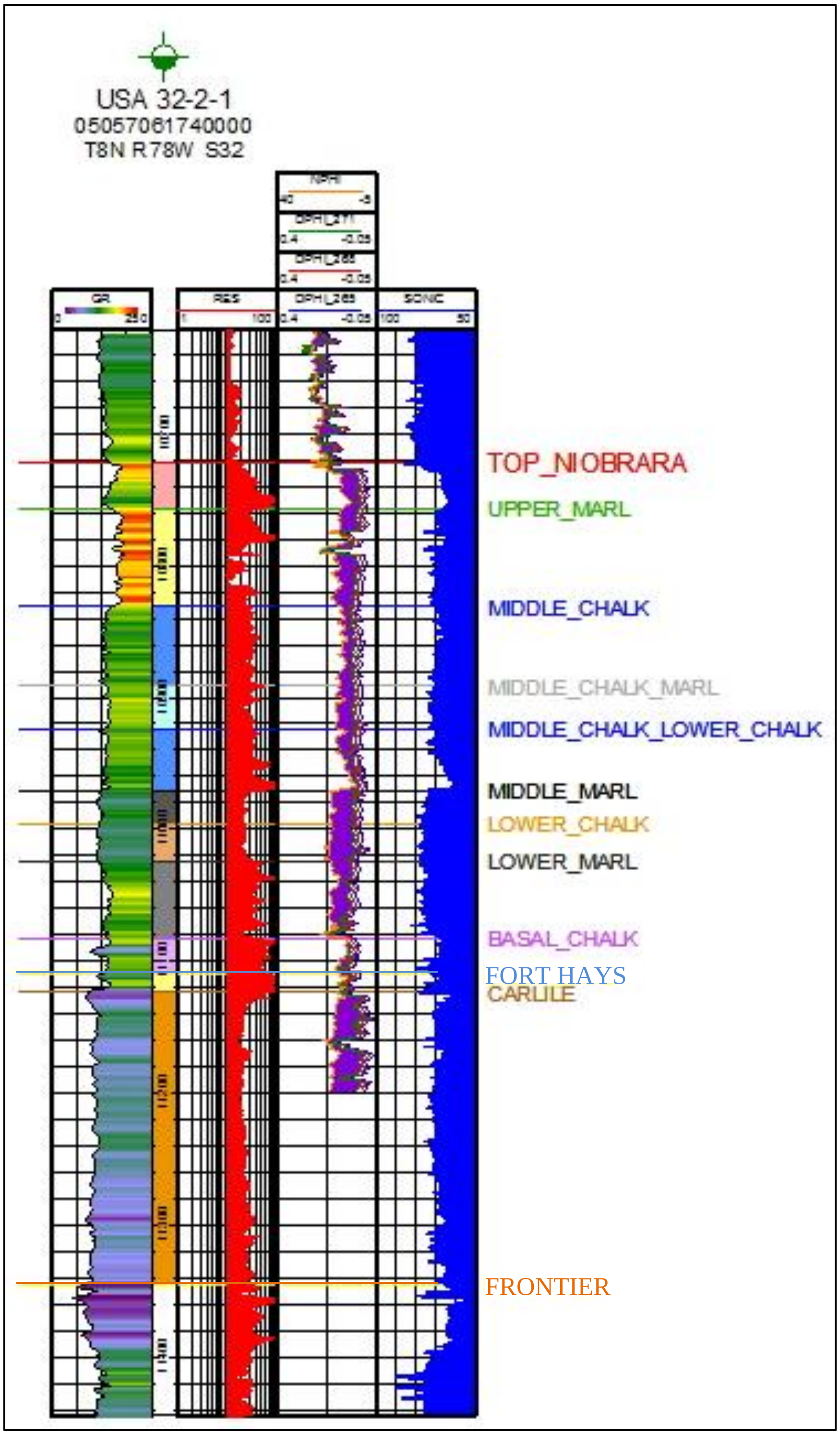


Figure 3.2 Type Log. Type log for the Niobrara Formation in the North Park Basin. Gamma-ray response in combination with Resistivity, Density Porosity, Neutron Porosity, and Sonic Logs from well USA 32-2-1.

3.3 Frontier Sandstone

The Frontier Sandstone is composed of thin-bedded, ripple-laminated sandstone and shaly interbeds with calcareous cement. The Frontier was deposited in both marine and non-marine environments. The Frontier Sandstone is identified by its low gamma-ray and high resistivity log response. It is a very distinctive marker bed throughout the study area. Only the top of the Frontier was picked on well log interpretation for this study, and, as a result, an isopach of the unit cannot be constructed. However, a structure map, Figure 3.3, of the top of the Frontier Sandstone is important as the units studied in this thesis overlay the Frontier.

This structure map indicates the subsea depth of the top of the Frontier. The formation generally dips into the center of the basin. North of the Spring Creek Fault Zone, which separates the northern third of the basin from the rest, there is no major faulting, and the Frontier dips away from the margins of the basin. South of the Spring Creek Fault Zone the presence of at least one major fault can be seen. This fault is indicated by the shallow wedge of the Frontier in the center of the basin. Further south, in Grand County, the number and coverage of wells is limited, and thus, evidence supporting the previous interpretation of the numerous thrust faults is inadequate to confirm or contradict their presence. Though the elevation data from the Frontier Formation are not present to support these interpretations, the presence of these faults is not unreasonable as previous outcrop mapping and gravity data support them.

3.4 Carlile Shale

The Carlile Shale conformably overlies the Frontier Sandstone. It is composed of siltstone, shale, sandstone, and limestone deposited under marine conditions. The Carlile Shale is identified on well logs by low resistivity and high gamma-ray responses. The thickness of the Carlile Shale in the wells studied ranges

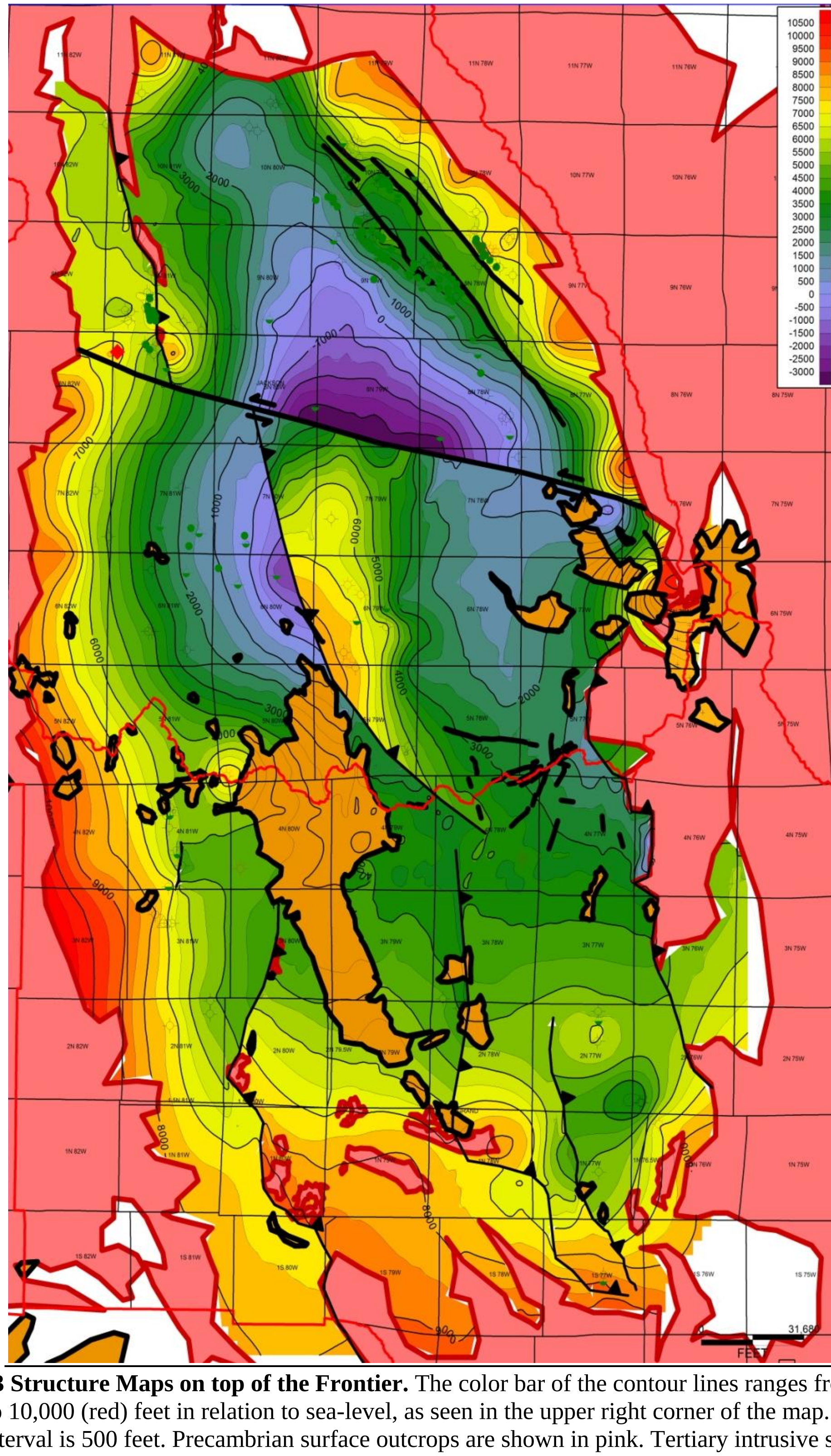


Figure 3.3 Structure Maps on top of the Frontier. The color bar of the contour lines ranges from -3000 (purple) to 10,000 (red) feet in relation to sea-level, as seen in the upper right corner of the map. The contour interval is 500 feet. Precambrian surface outcrops are shown in pink. Tertiary intrusive surface outcrops are shown in orange. Both the Precambrian and Tertiary intrusive units act as constraints on the presence of the Cretaceous interval in the region.

between 45 and 720 feet, and averages about 250 feet thick. The thickness of the Carlile Shale is generally uniform. However, a few areas do show thickness variations. A portion of the Carlile interval was eroded in two wells in the center of the basin, resulting in a thinner area. In Grand County in the south of the basin, the Carlile thickens from east to west; however, the number and coverage of wells is sparse in this area and many faults are believed to be present causing the trends seen to be of limited confidence.

A structure map of the Carlile Shale was constructed in Figure 3.5. This structure map is very similar to the structure map of the Frontier. The regions that are the deepest, mainly in the center of the basin, are the same. The thrust fault in the center of the basin, south of the Spring Creek Fault Zone, is also present at the Carlile interval.

3.5 Niobrara Formation

The Niobrara Formation overlies the Carlile Shale in the study area. It is composed of alternating marl-rich and chalk-rich intervals. The Niobrara Formation ranges from 250 to 1100 feet in thickness in North Park and averages 475 feet thick. The Niobrara has historically been broken into two members, the Fort Hays and the Smoky Hill Members. In this study, the Smoky Hill has been further subdivided into 7 intervals based on their log character, mainly the GR and RES log responses. The following sections will discuss each of these intervals in detail. An isopach map of the total Niobrara is shown in Figure 3.6. The total Niobrara interval seems relatively uniform in thickness, but a thickening to the north is present.

3.5.1 Fort Hays Limestone

The Fort Hays Limestone lies at the base of the Niobrara Formation and overlies the Carlile Shale. This contact, as noted in Kansas, Wyoming, and eastern Colorado by Weimer (1984) is sharp and is a regional unconformity. The Fort Hays is a tan to light gray, bioturbated chalk with shaly, microstylolitic interbeds. The Fort Hays interval is

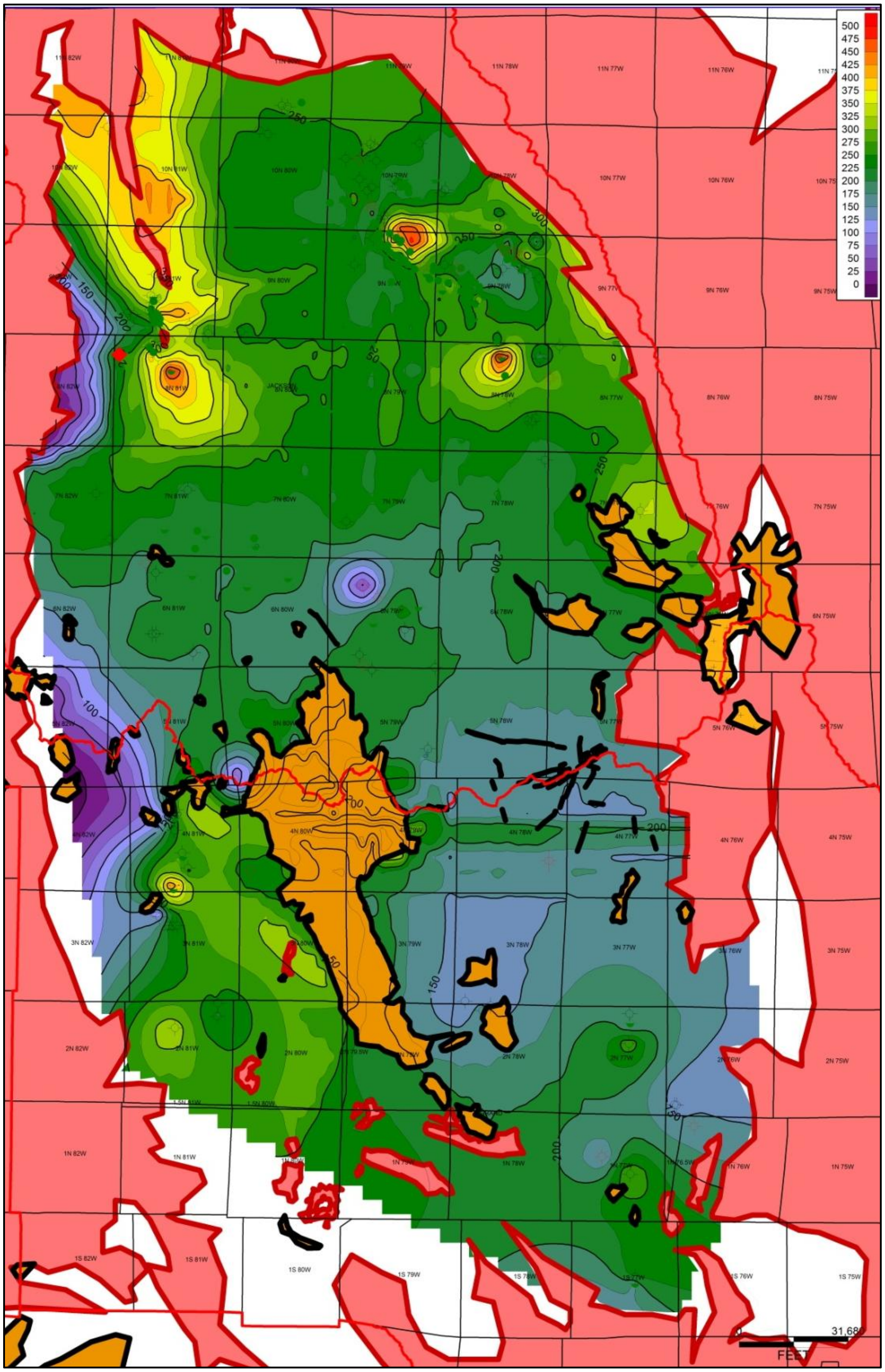


Figure 3.4 Isopach Map of the Carlile. The color bar of the contour lines ranges from 0 (purple) to 500 (red) feet, as seen in the upper right corner of the map. The contour interval is 25 feet.

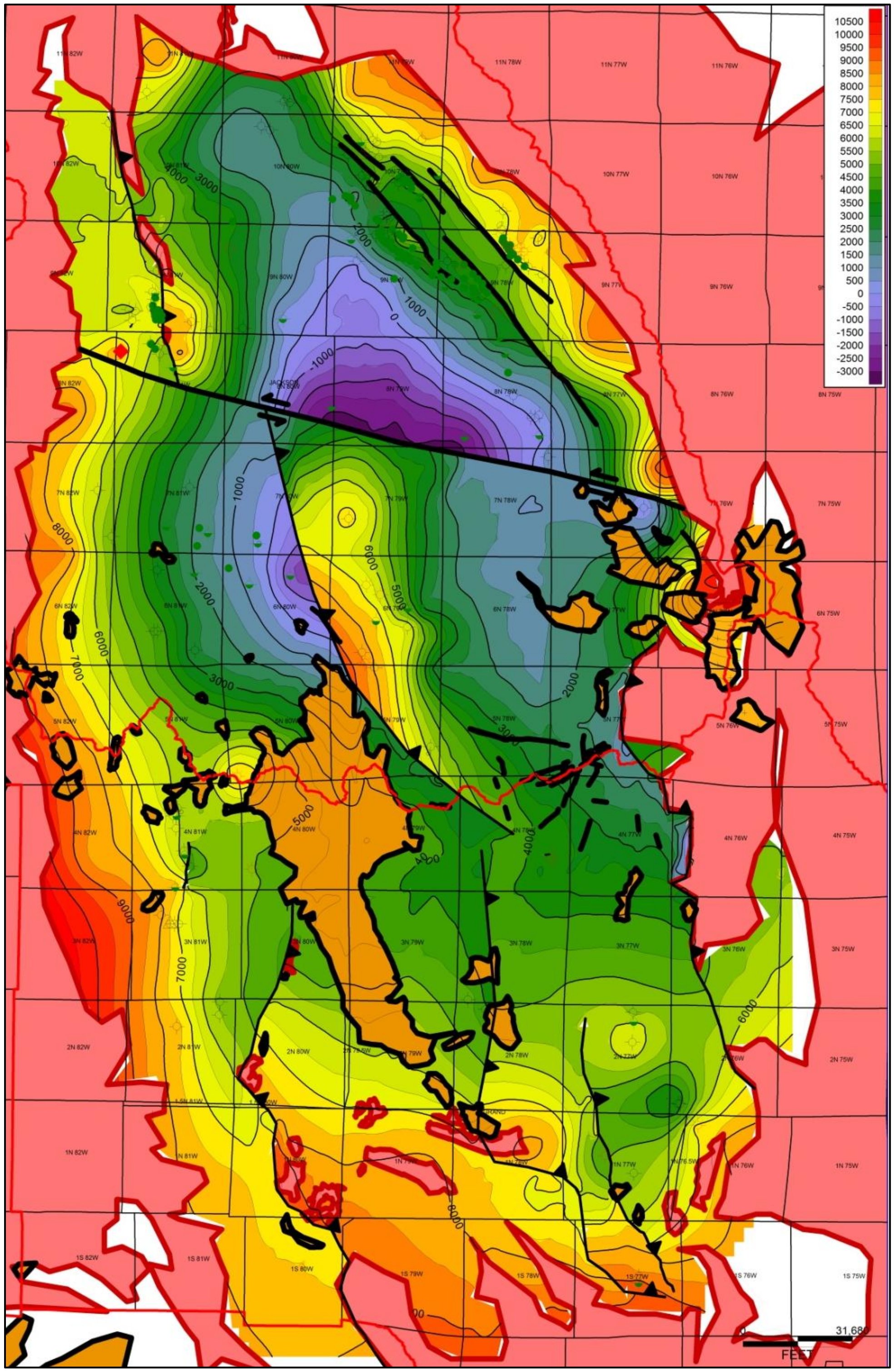


Figure 3.5 Structure Map on top of the Carlile. The color bar of the contour lines ranges from -3000 (purple) to 10,000 (red) feet relative to sea-level, as seen in the upper right corner of the map. The contour interval is 500 feet.

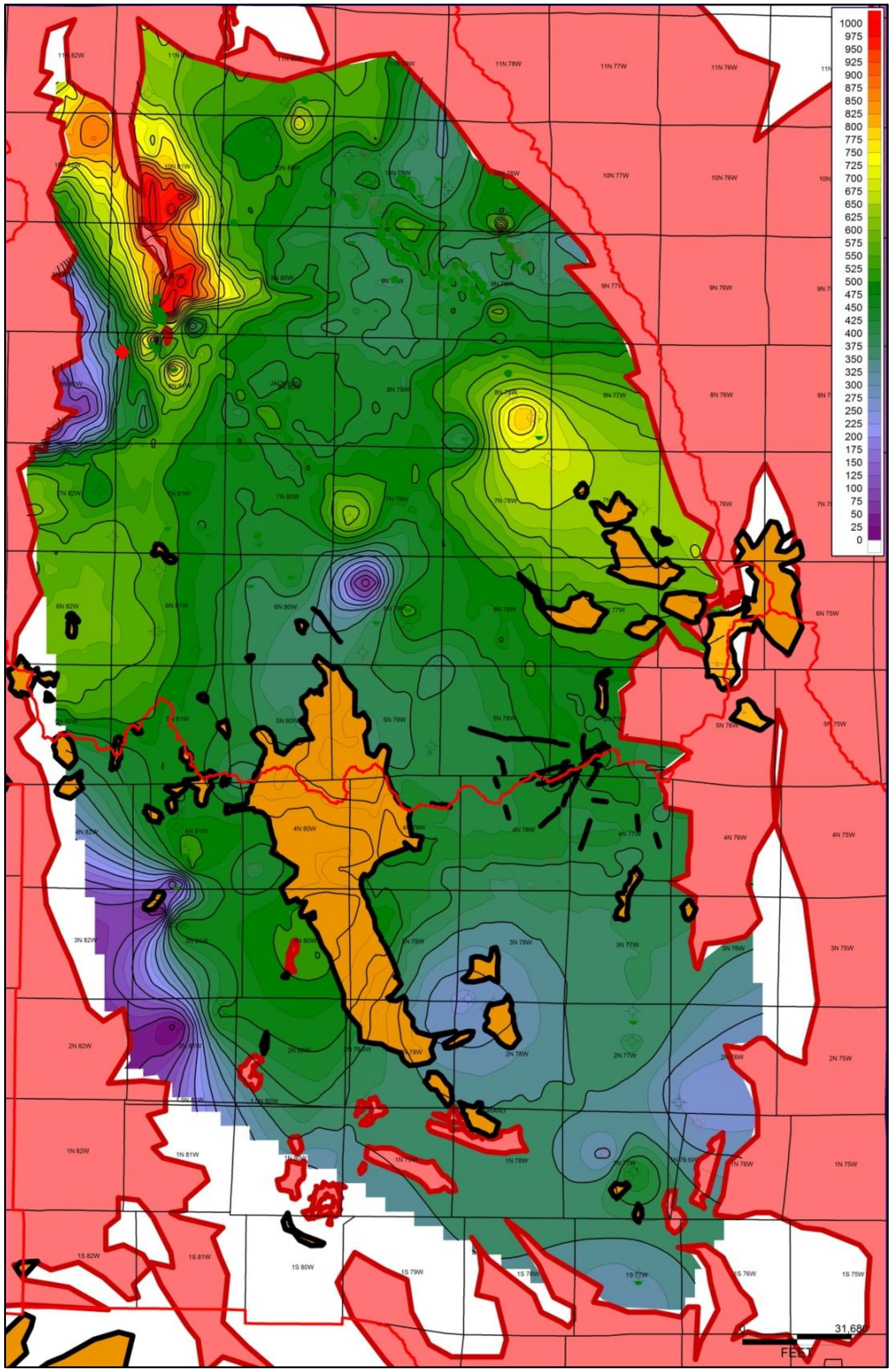


Figure 3.6 Isopach Map of the Niobrara Formation. The color bar of the contour lines ranges from 0 (purple) to 1000 (red) feet, as seen in the upper right corner of the map. The contour interval is 25 feet. The purple zone in the center of each of the maps is a result of the Niobrara not being present in two wells; the interval was eroded away in these wells.

distinguished on wireline logs by a low blocky gamma-ray, a high resistivity, a convergence of the neutron and density porosity, and a high sonic response. In the North Park Basin, the Fort Hays ranges in thickness from 0 to 50 feet and averages about 15 feet thick. The isopach map of the Fort Hays, Figure 3.7 indicates the thickness variation of the unit throughout the North Park Basin. The Fort Hays does not vary that much across the basin, but a thickening of the unit to the west does exist. The zero contour in the center of the basin is a result of erosion of the unit as seen to two wells.

3.5.2 Basal Chalk

The basal chalk lies above the Fort Hays Limestone. It is a light colored, bioturbated chalk and chalky marl interbedded with marl and marly shale. The basal chalk has a similar log response to the Fort Hays, but can be distinguished from it by a higher, less clean GR response, a lower, less consistent RES response, and a lack of convergence of the NPHI and DPHI logs. The basal chalk ranges in thickness from 0 to 65 feet and averages 25 feet throughout the study area. Figure 3.8 shows the thickness trends of the basal chalk in the North Park Basin. The unit appears to thicken to the north and west. As data are limited in Grand County, the thickness increase in the southern end of the study area is artificially enhanced by the gridding process in Petra.

3.5.3 Lower Marl

The lower marl lies above the basal chalk. The contact between the two units is gradational. It is a brownish-gray laminated marl with a slightly silty, clay matrix. The lower marl is recognized on wireline logs by a higher GR and lower RES response when compared to the units above and below it. The lower marl ranges in thickness from 5 to 165 feet in the study area and averages 35 feet thick. The isopach map of the lower

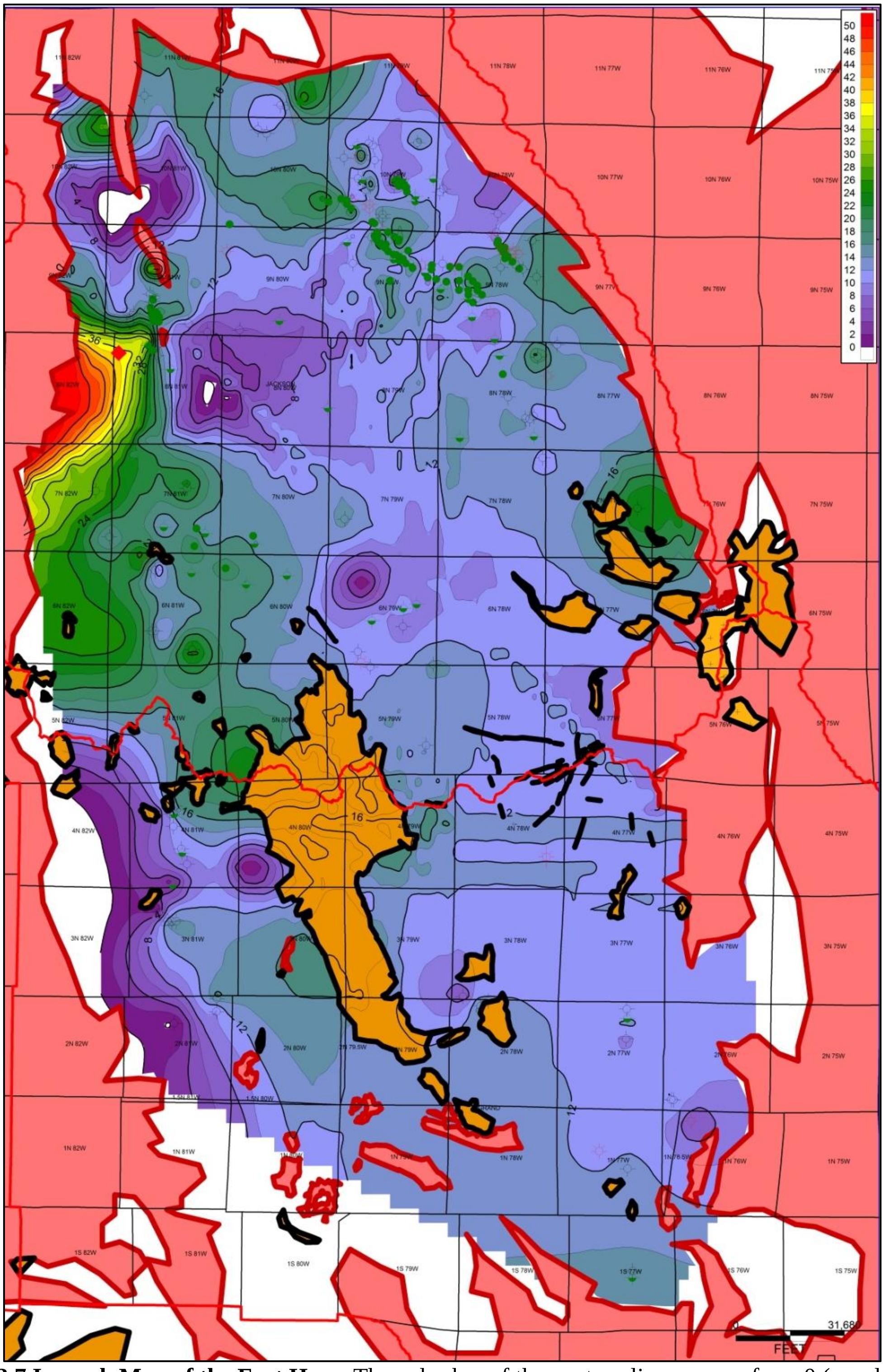


Figure 3.7 Isopach Map of the Fort Hays. The color bar of the contour lines ranges from 0 (purple) to 100 (red) feet, as seen in the upper right corner of the map. The contour interval is 2.5 feet.

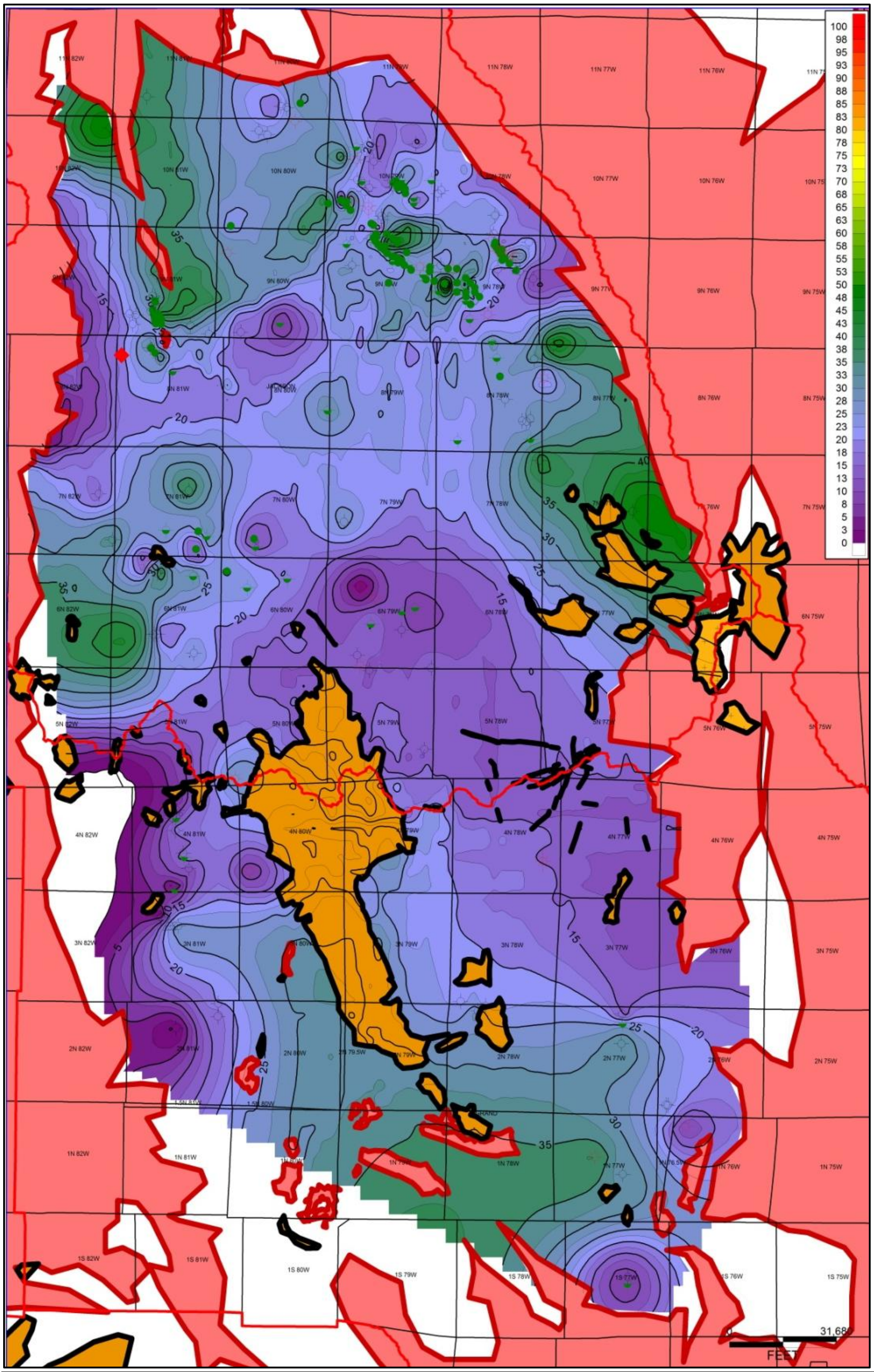


Figure 3.8 Isopach Map of the basal chalk. The color bar of the contour lines ranges from 0 (purple) to 100 (red), as seen in the upper right corner of the map. The contour interval is 2.5 feet.

marl, Figure 3.9, indicates the regional variations in thickness throughout the basin. The lower marl thickens to the north of the basin. The zero contour in the center of the basin is a result of erosion of the lower marl in two wells.

3.5.4 Lower Chalk

The lower chalk overlies the lower marl. It is a brownish-gray, wispy laminated, slightly burrowed chalky marl comprised of chalk pellets. A “three-fingers” GR response is characteristic of this unit, caused by the presence of three main chalk beds. A RES response higher than the units above and below is also noted. The thickness of the lower chalk ranges from 7 to 110 feet and averages 35 feet. Figure 3.10 shows the isopach thicknesses of the lower chalk across the basin. The lower chalk is thicker in the northern part of the basin. Longman et al. (1998) described this interval as containing ‘pilenpoopen’ bars; such bars may exist in North Park, however, a higher well density is needed to positively identify them.

3.5.5 Middle Marl

The middle marl overlies the lower chalk. It is a dark olive-gray and wispy to parallel laminated to massive marl with medium to light gray bioturbated chalky marl beds. The middle marl is recognized on well logs by a higher GR and lower RES than the units it over- and under- lies. The thickness of the middle marl ranges from 10 to 290 feet, with an average of 60 feet in the study area. An isopach of the middle marl, Figure 3.11, indicates that the unit thickens slightly towards the west. The thickness increase in the east is artificially created by the Petra gridding process due to faulting in one well on the margin of the basin.

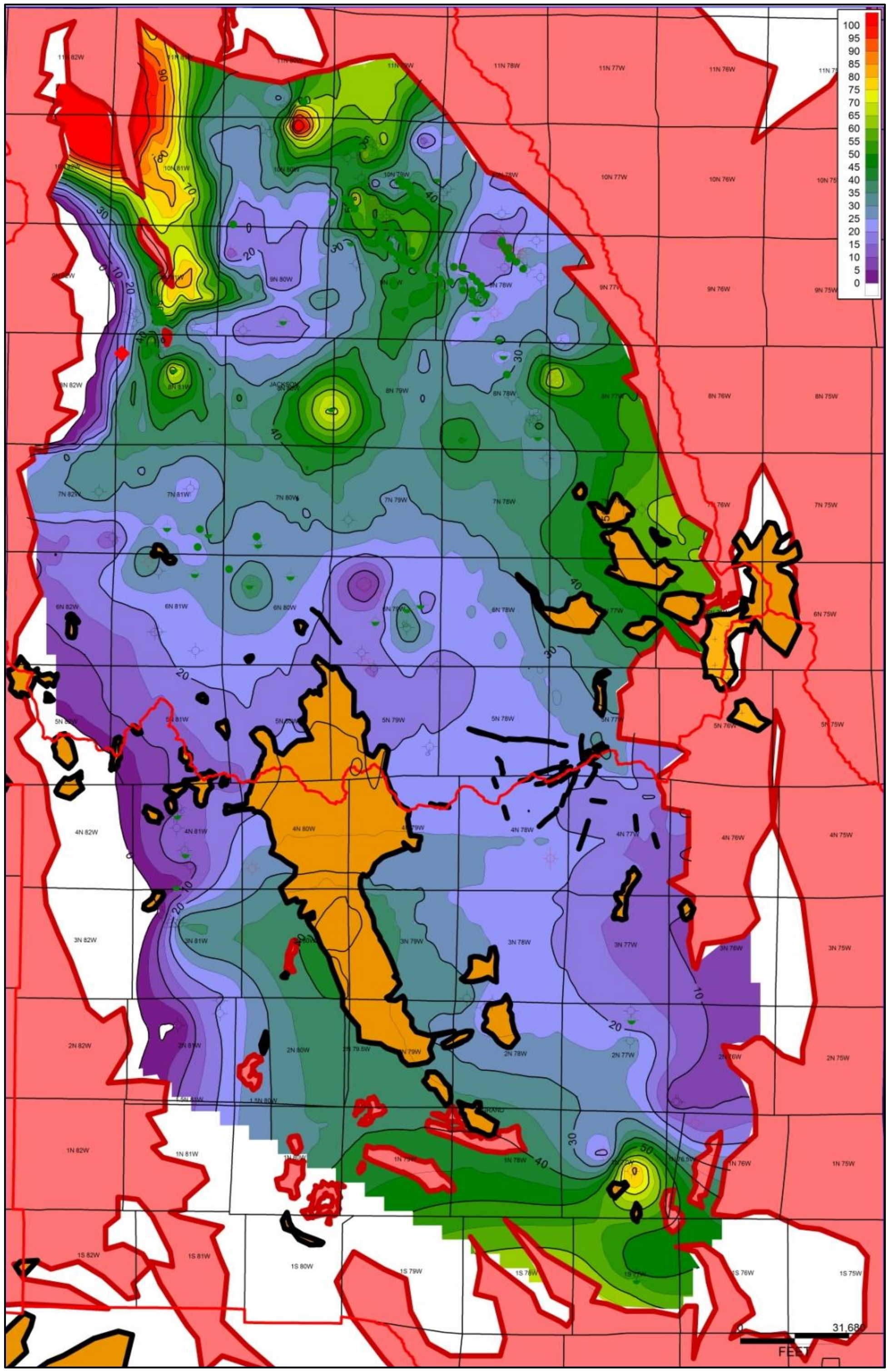


Figure 3.9 Isopach Map of the lower marl. The color bar of the contour lines ranges from 0 (purple) to 100 (red) feet, as seen in the upper right corner of the map. The contour interval is 5 feet.

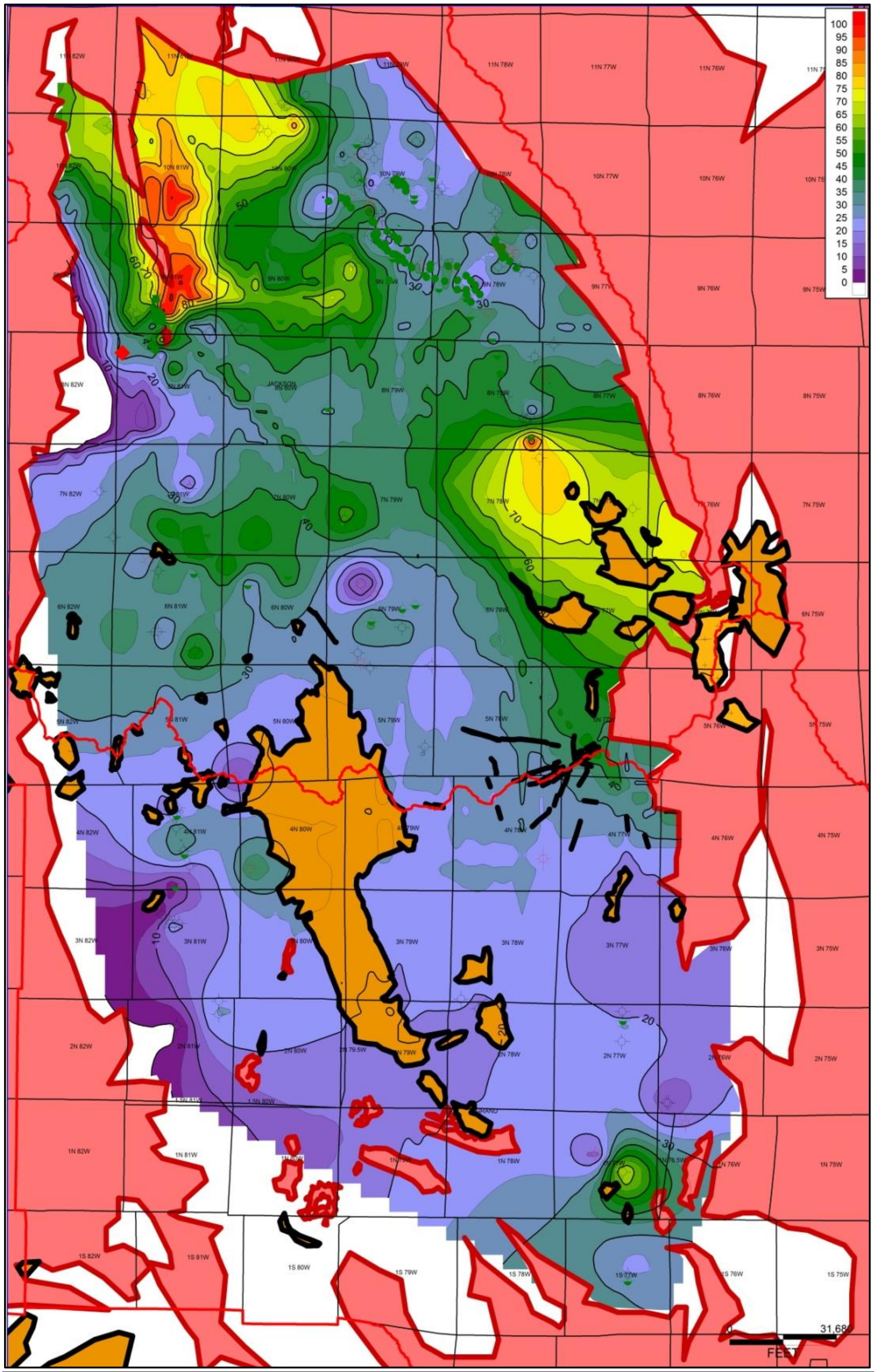


Figure 3.10 Isopach Map of the lower chalk. The color bar of the contour lines ranges from 0 (purple) to 100 (red), as seen in the upper right corner of the map. The contour interval is 5 feet.

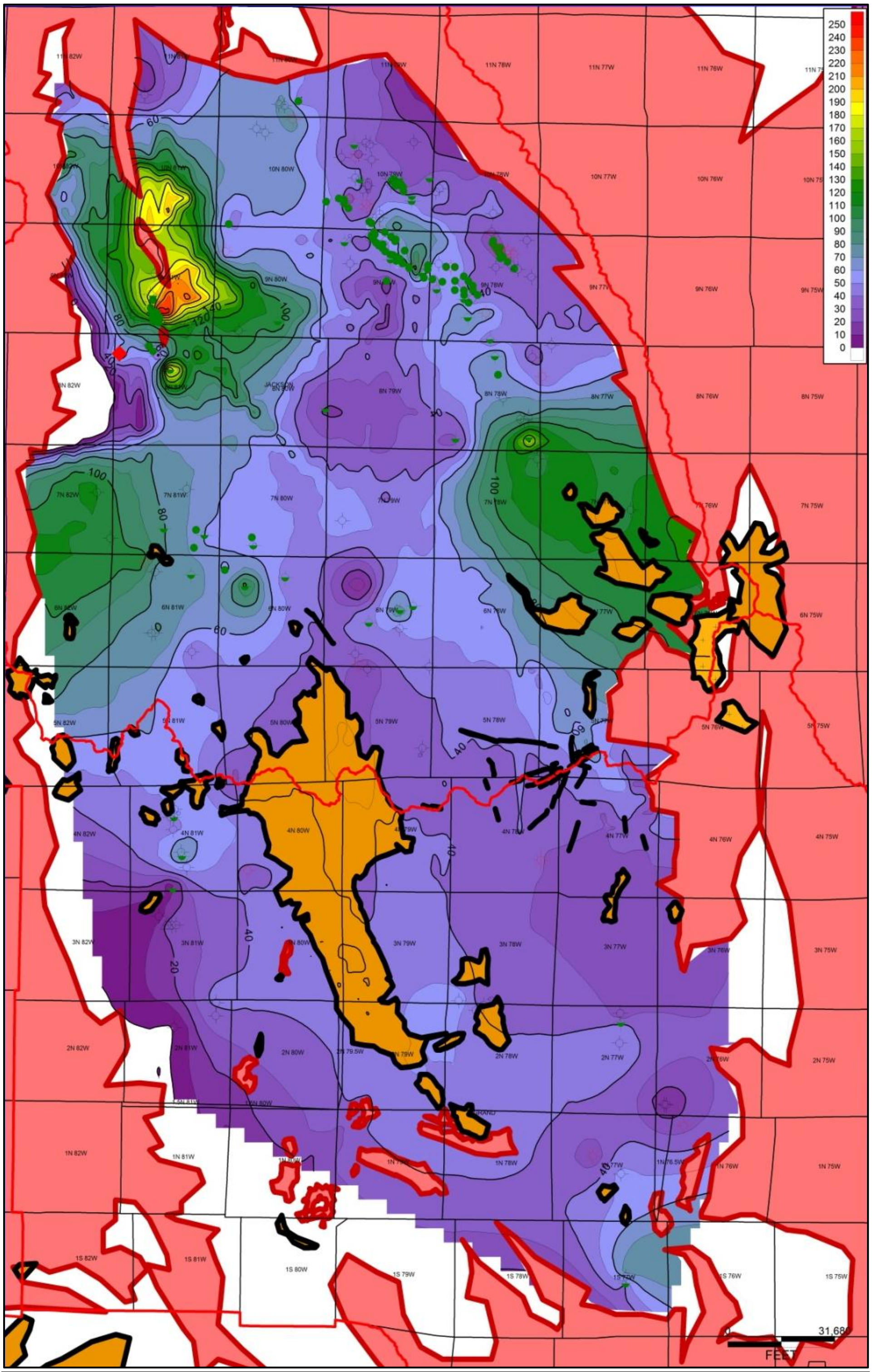


Figure 3.11 Isopach Map of the middle marl.. The color bar of the contour lines ranges from 0 (purple) to 250 (red), as seen in the upper right corner of the map. The contour interval is 10 feet.

3.5.6 Middle Chalk

The middle chalk overlies the middle marl. The middle chalk is mainly composed of chalk, but can be further divided into two chalk-rich units, divided by a dark-colored, massive or parallel laminated marl with marly shale interbeds. The lower chalk of the middle chalk can be recognized by a low GR and a high RES response, as well as a convergence of the NPHI and DPHI logs. The marl unit of the middle chalk is characterized by a high GR and a decrease in the RES response. The upper chalk of the middle chalk is similar to the lower chalk of the middle chalk, but is more varied and subsequently has a higher GR response (but lower than the separating marl) and lower RES values. The entire middle chalk ranges in thickness from 30 to 520 feet and averages 180 feet. Figure 3.12 shows the thickness variations of the entire middle chalk interval. The middle chalk appears to thicken to the west, but is relatively consistent in thickness throughout much of the study area with higher well density.

The thickness of the lower chalk of the middle chalk ranges from 10 to 185 feet, with an average of 60 feet. Isopach maps of the lower chalk of the middle chalk, Figure 3.13, show its regional thickness variations. The lower chalk of the middle chalk is generally uniform in thickness, however a few areas of variation exist, mainly as thicker areas in the north part of the basin.

The marl unit of the middle chalk varies from 10 to 150 feet thick and with an average thickness of 45 feet. Isopach maps of the marl unit of the middle chalk, Figure 3.14, show its regional thickness variations. The marl thickens to the western margin of the basin. The area in the northwest portion of the basin is artificially shown as thickened by the Petra gridding process.

The upper chalk of the middle chalk ranges from 20 to 290 feet in thickness and has an average thickness of 75 feet. Isopach maps of the upper chalk of the middle chalk, Figure 3.15, show the thickness variations of the unit throughout the North Park Basin. The unit does not exhibit a trend of thickening, but areas of increased thickness do exist. These areas include the eastern and western areas north of the Spring Creek Fault Zone, as well as the eastern fault block to the south of the zone, in the areas where the unit has not been eroded.

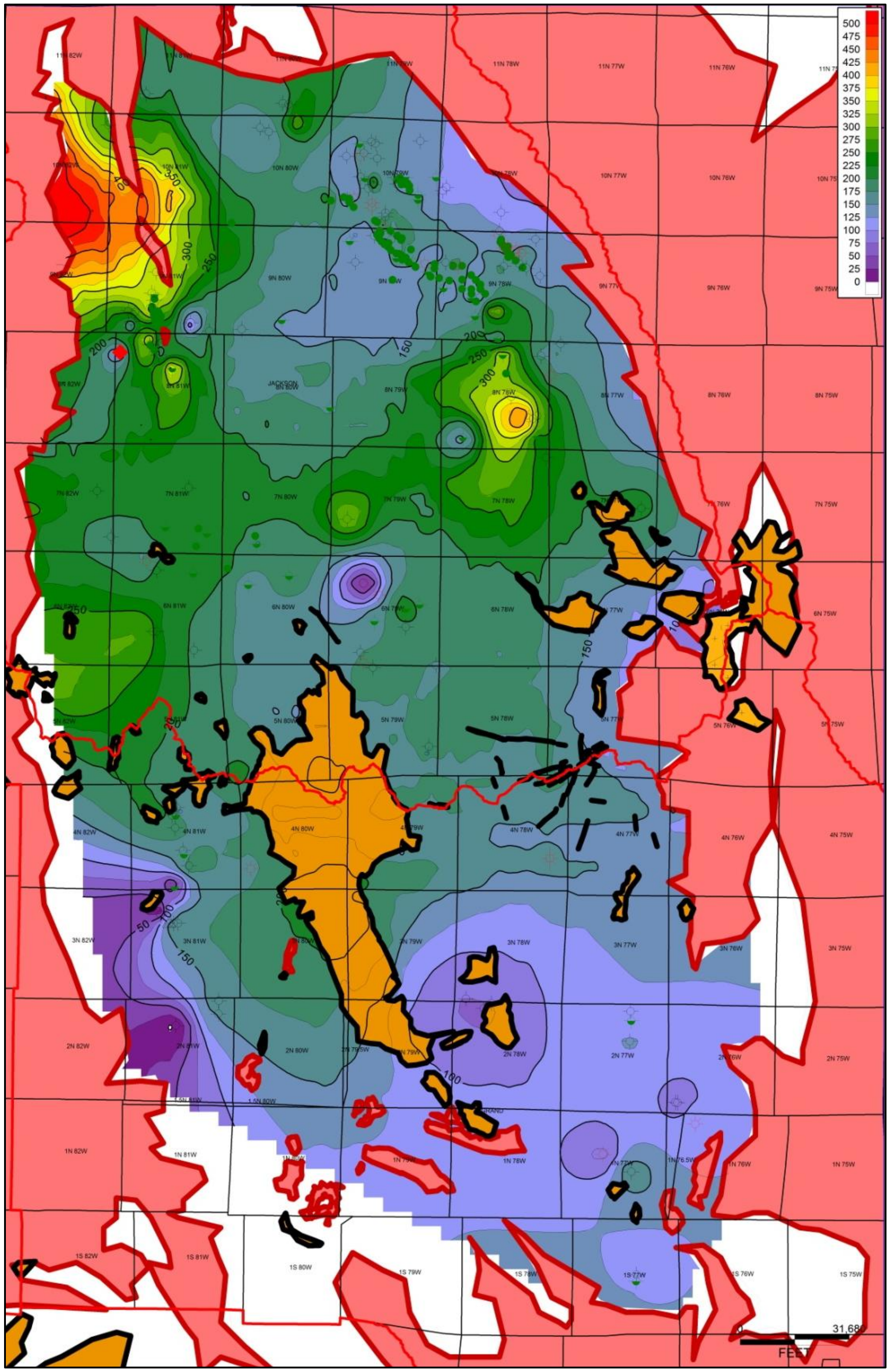


Figure 3.12 Isopach Map of the middle chalk. The color bar of the contour lines ranges from 0 (purple) to 500 (red) feet, as seen in the upper right corner of the map. The contour interval is 25 feet.

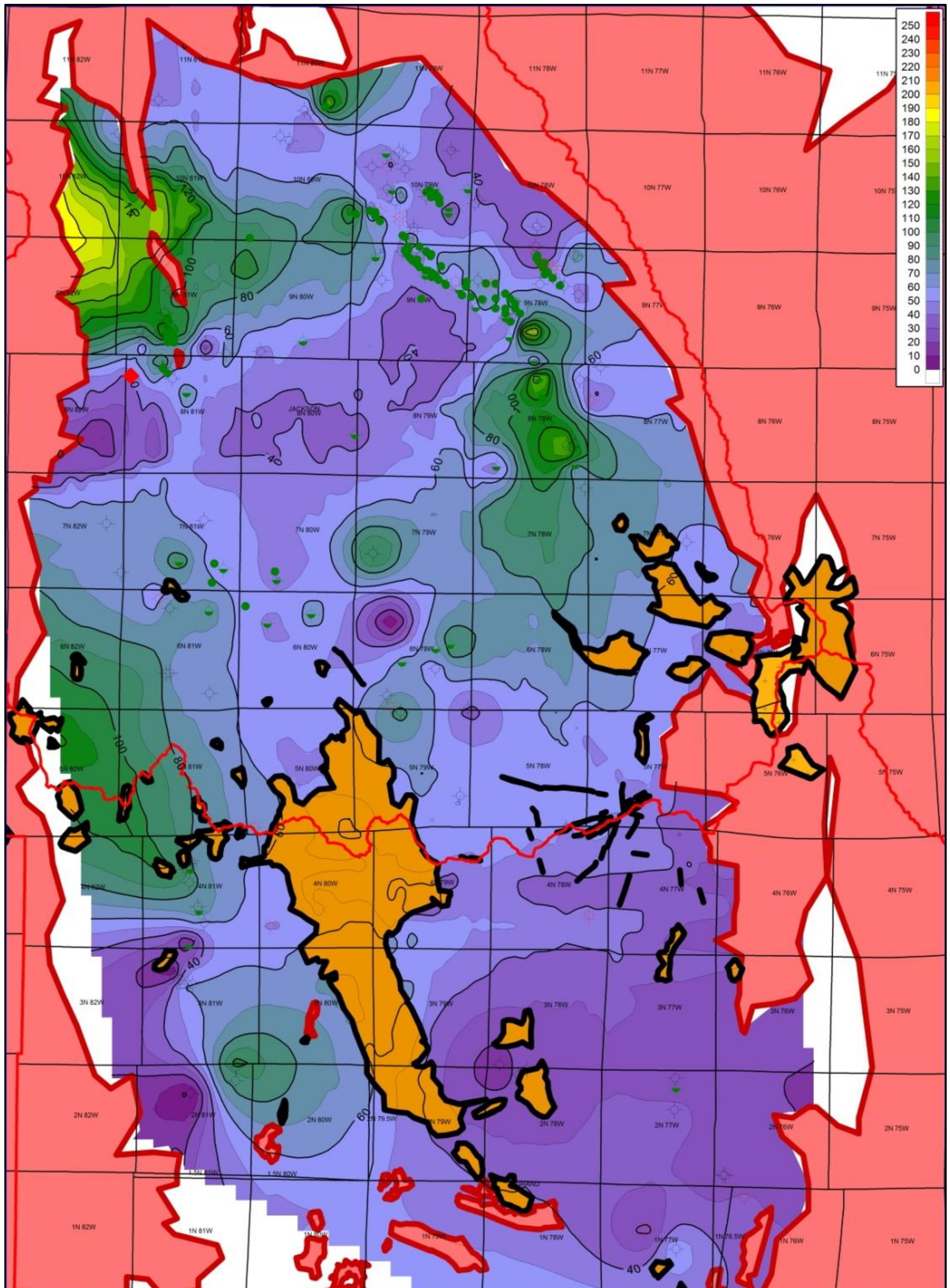


Figure 3.13 Isopach Map of the lower chalk of the middle chalk. The color bar of the contour lines ranges from 0 (purple) to 250 (red) feet, as seen in the upper right corner of the map. The contour interval is 10 feet.

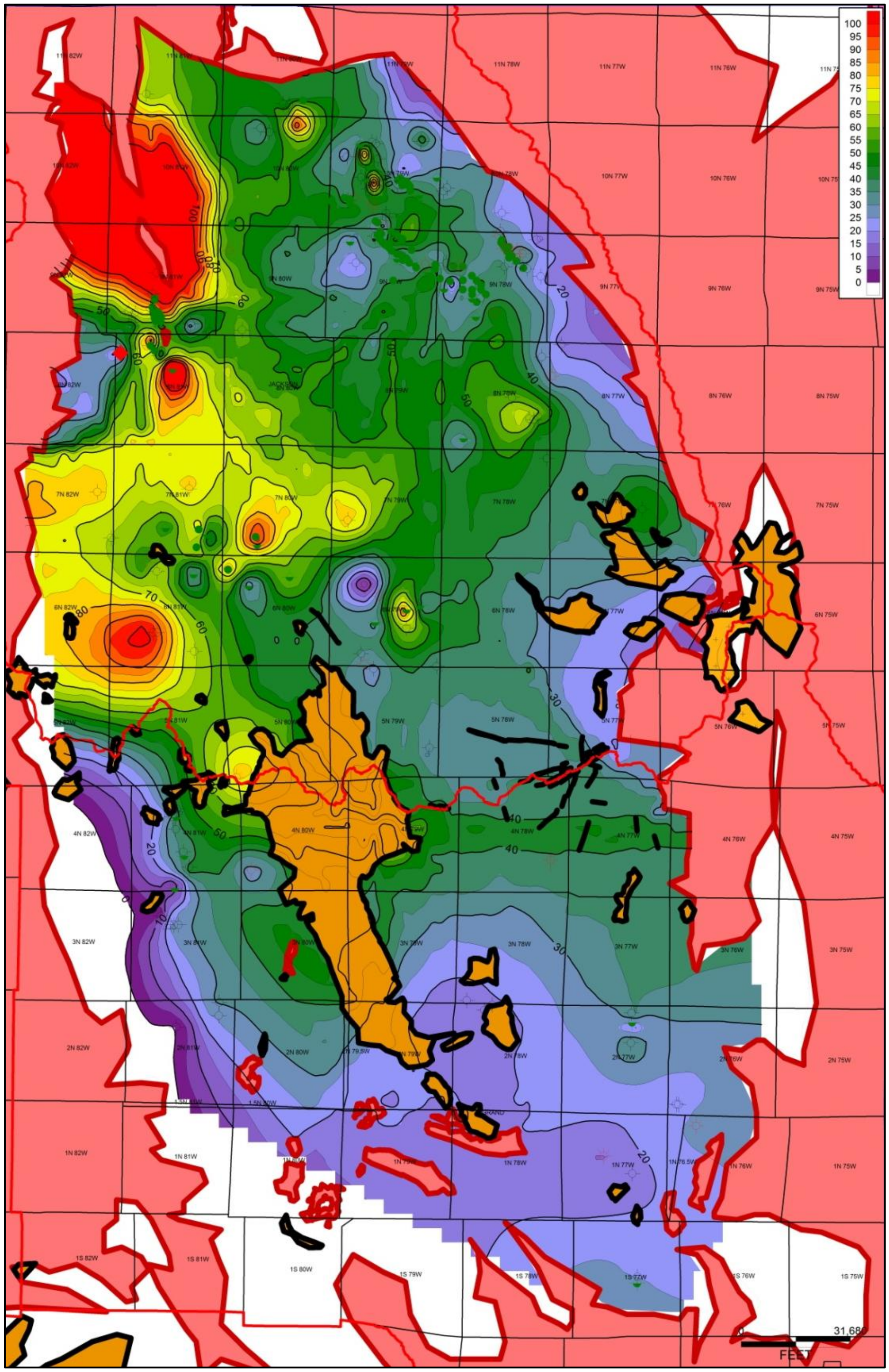


Figure 3.14 Isopach Map of the Marl of the middle chalk. The color bar of the contour lines ranges from 0 (purple) to 100 (red) feet, as seen in the upper right corner of the map. The contour interval is 5 feet.

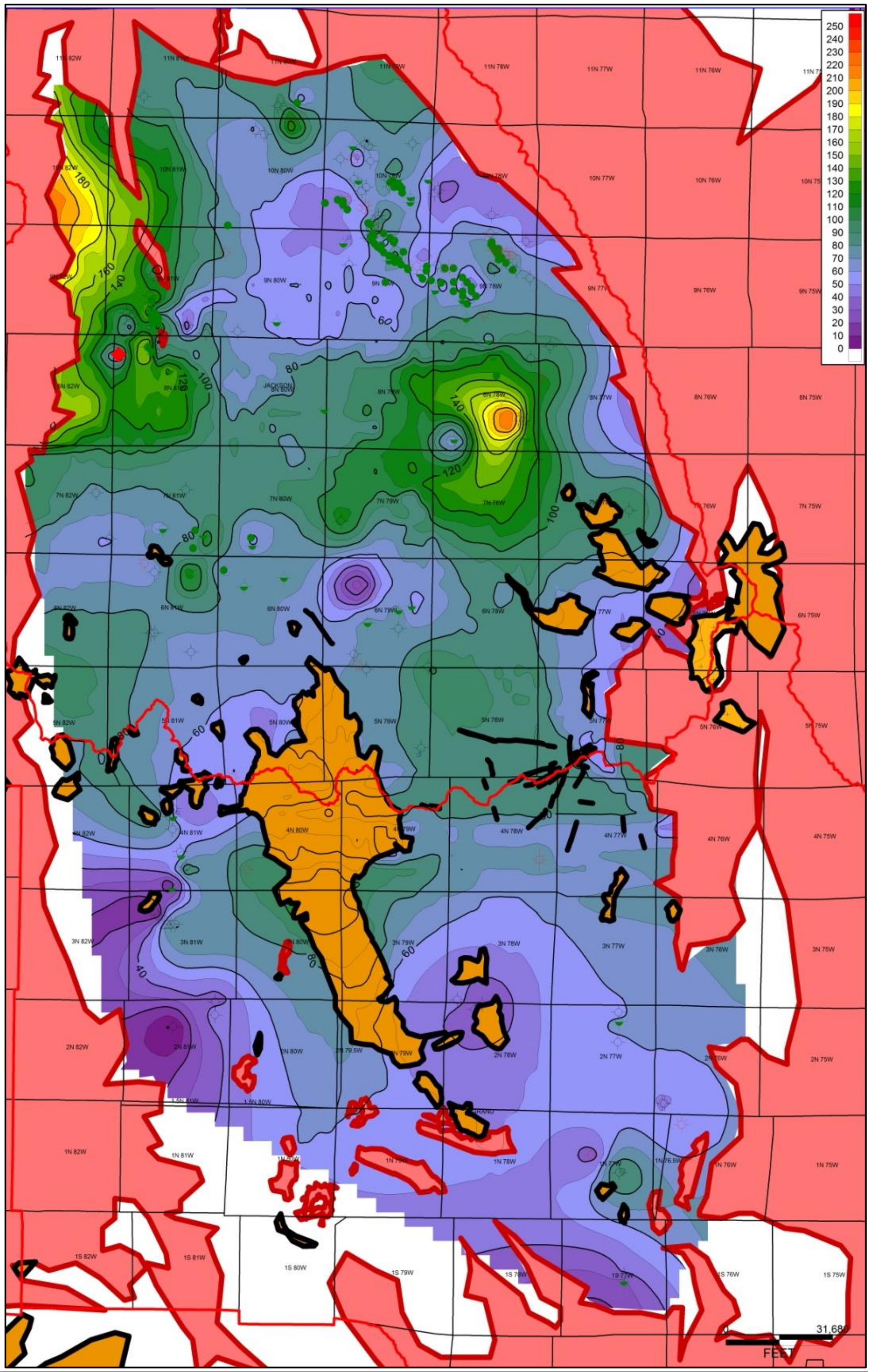


Figure 3.15 Isopach Map of the upper chalk of the middle chalk. The color bar of the contour lines ranges from 0 (purple) to 250 (red) feet, as seen in the upper right corner of the map. The contour interval is 10 feet.

3.5.7 Upper Marl

The upper marl overlies the middle chalk units. It is composed of dark massive marly shales to chalky marls, with a clay matrix. The upper marl is characterized by a high GR response and a lower RES response relative to the under- and overlying chalks. The upper marl ranges in thickness from 15 to 320 and averages 75 feet thick. The regional thickness trends of the upper marl are seen in Figure 3.16. No clear regional trends exist in the upper marl; this is most likely caused by the top of this interval having an erosional unconformity with the Pierre Shale in some areas. Thicker areas of the upper marl include the northwest and central regions of the basin.

3.5.8 Upper Chalk

The upper chalk is the uppermost unit of the Niobrara Formation. It overlies the upper marl. It is a light tan, speckled, microporous chalky marl, that is massive with faint wispy laminae contained in a micrtic to clay matrix. The upper chalk is noted by a low GR and a high RES response. The thickness of the upper chalk ranges from 2 to 220 feet, with an average of 55 feet thick. Figure 3.17 shows the thickness variations of the upper chalk in the North Park Basin. No clear regional trends exist in the upper chalk; and, as in the upper marl, this is most likely caused by the top of this interval having an erosional unconformity with the Pierre Shale in some areas. Thicker areas of the upper chalk include the northwest and central regions of the basin.

3.6 Pierre Shale

The Pierre Shale overlies the Niobrara Formation. It is equivalent to the Mancos shale to the west. Throughout the Rocky Mountain Region it is known to be a silty, carbonaceous, non-calcareous to calcareous shale. The top of the Pierre is not correlated

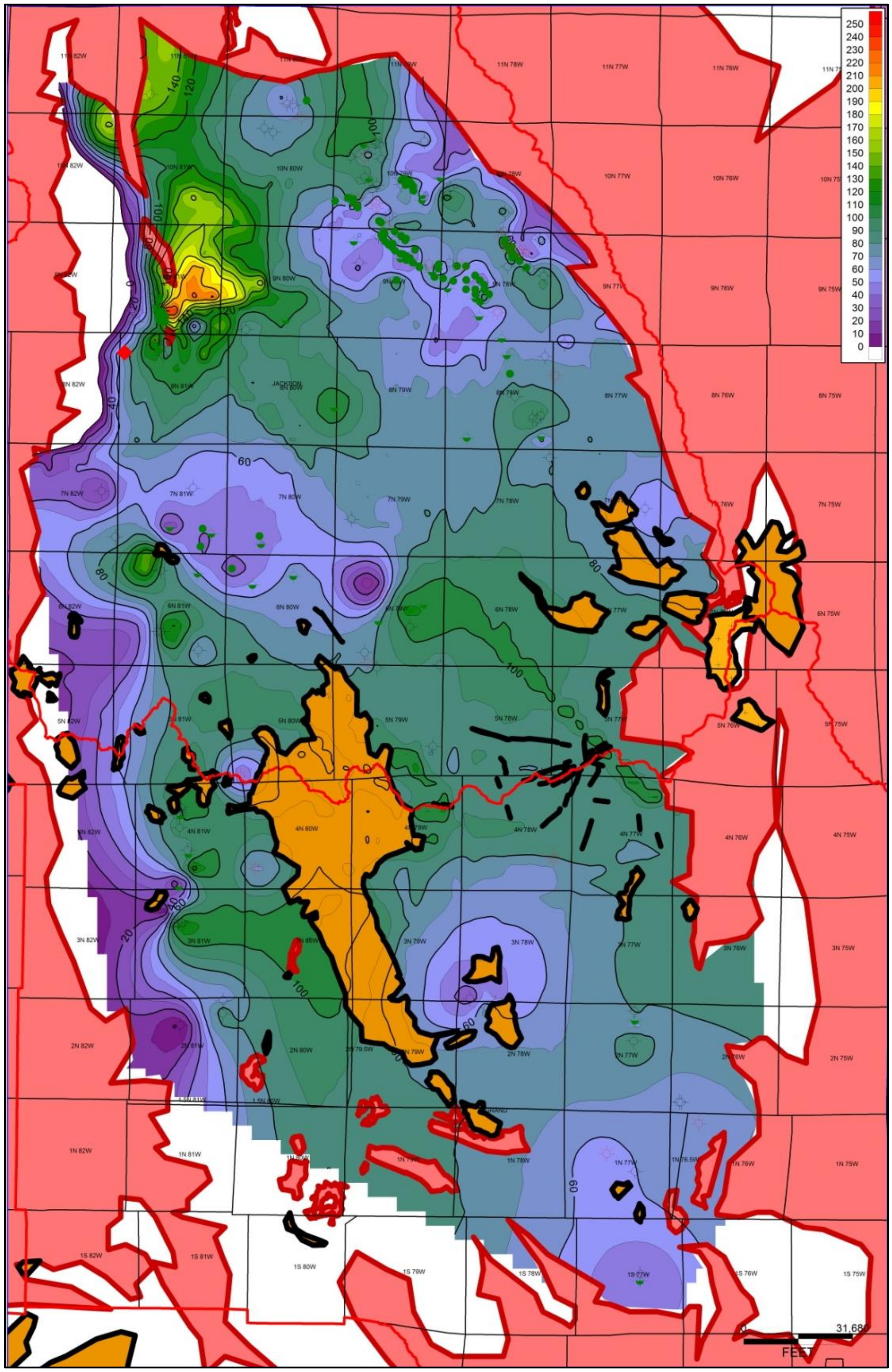


Figure 3.16 Isopach Map of the upper marl. The color bar of the contour lines ranges from 0 (purple) to 250 (red) feet, as seen in the upper right corner of the map. The contour interval is 10 feet.

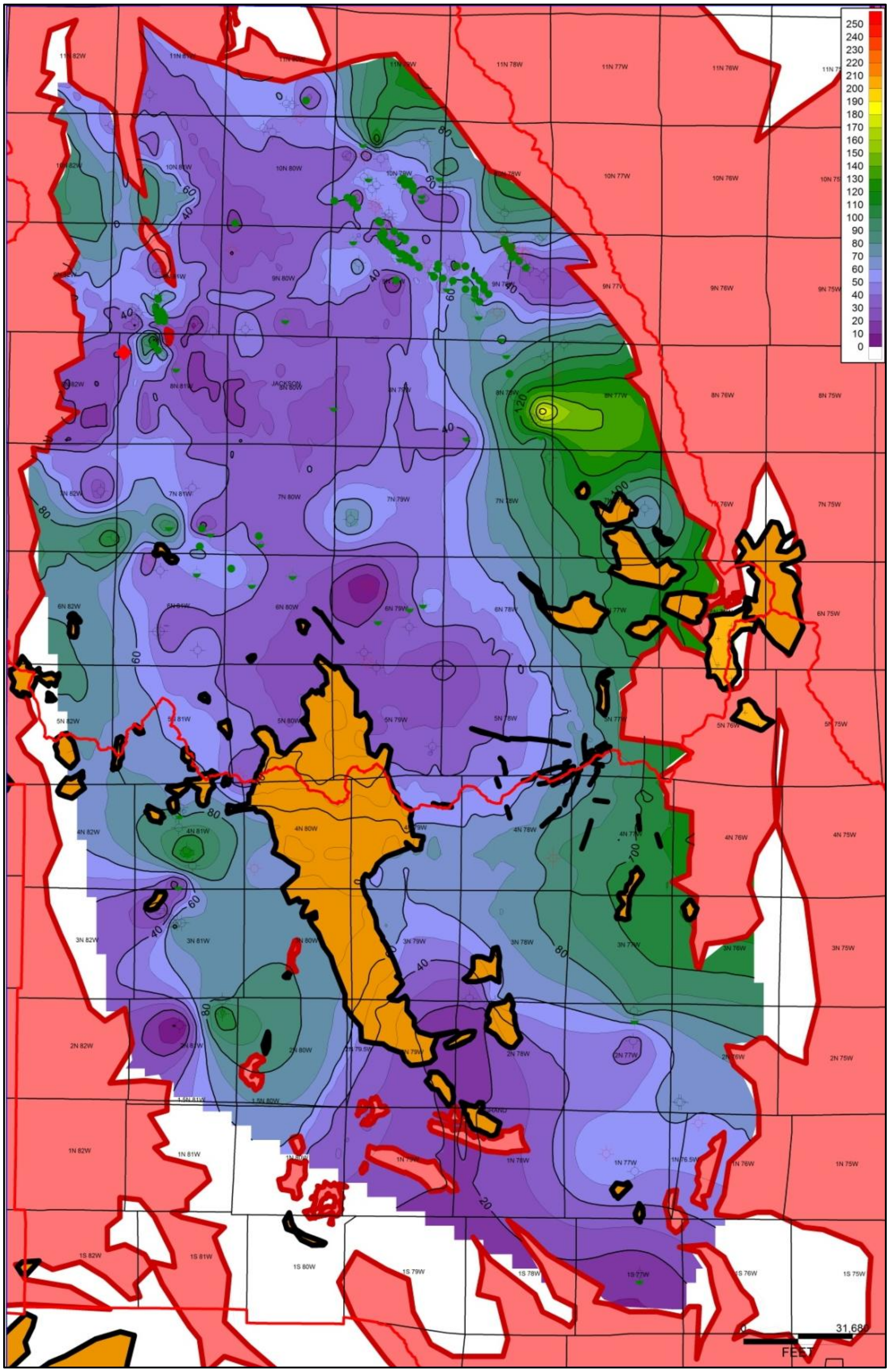


Figure 3.17 Isopach Map of the upper chalk. The color bar of the contour lines ranges from 0 (purple) to 250 (red) feet, as seen in the upper right corner of the map. The contour interval is 10 feet.

in North Park as a part of this study, but its base (the top of the Niobrara) can be noted by a dramatic decrease in the RES log.

A structure map of this surface has been created, Figure 3.18. This structure map is very similar to the structure map of the Frontier, the main difference being that the bottom of the Pierre is shallower. The regions that are the deepest, mainly in the center of the basin, are the same. The thrust fault in the center of the basin, south of the Spring Creek Fault Zone, is also present at the Pierre interval.

3.7 Discussion of Depositional Environment

The Niobrara Formation was deposited in the marine setting of the Cretaceous Western Interior Seaway. As presented in this study, the Niobrara can be further subdivided into alternating intervals of chalk and marl-rich intervals. This cyclicity exhibited in the Niobrara is undoubtedly controlled by a multitude of factors including tectonic and climatic control. These controls influence the rates of sediment supply and accommodation space which restrict deposition. Understanding which of these controls enhance and inhibit the favoring of chalks versus marls, and vice-versa, is important in understanding Niobrara deposition.

Changes in sea-level may be caused by tectonic and climatic factors. Tectonic forces control the amount of subsidence and uplift, and thus controlling the amount of accommodation space relative to sea-level. Changes in climate can cause sea-level to rise during periods of warming and recede during times of prolonged cooling. In the Longman et al. (1998) model of Niobrara deposition, increased sea-level favors deposition of chalk-rich intervals due to increased warm currents, and marl-rich intervals during low relative sea-level. In addition, raised relative sea-level may also limit the distance siliciclastic material is able to be transported into the basin, and favor chalk-rich intervals; conversely, during times of lower relative sea-level, marl-rich deposition may be favored as siliciclastic material may reach deeper into the basin. Since tectonic forces remained relatively quiet during the deposition of the Niobrara, global climatic changes

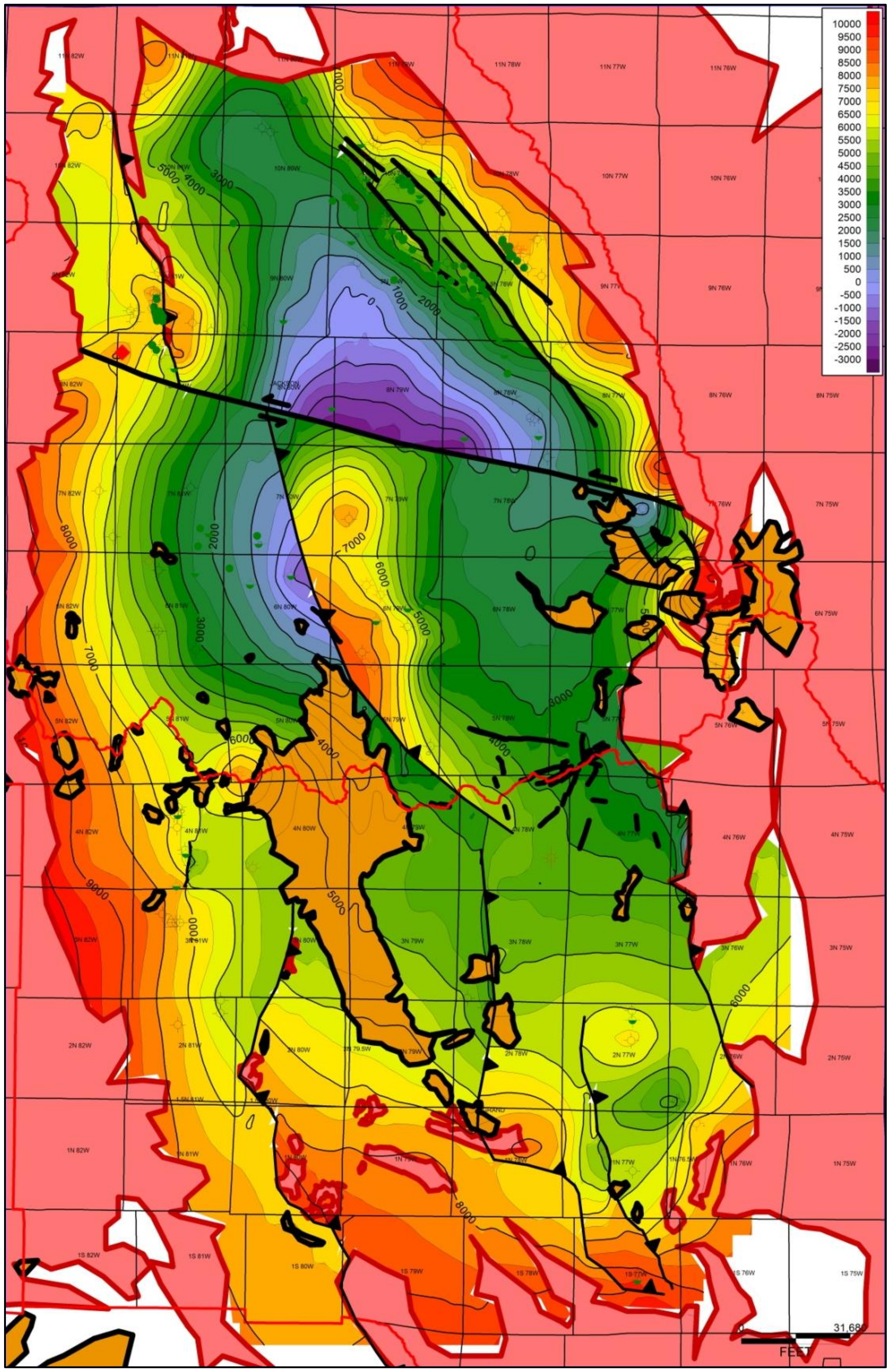


Figure 3.18 Structure Map on the bottom of the Pierre (Top of Niobrara). The color bar of the contour lines ranges from -3000 (purple) to 10,000 (red) feet, as seen in the upper right corner of the map. The contour interval is 500 feet.

most likely are the cause for fluctuations in sea-level, assuming such fluctuations occurred.

Changes in local climate can influence the rate of the influx of sediment from the overthrust belt. During periods of wetter climate, a greater amount of sediment is transported from the highland to the basin; during periods of drought, the basin may become sediment starved. In relationship to the Niobrara, wetter climates may have contributed to the presence of marls due to an increased amount of siliciclastic material, and chalks during periods of limited sediment supply. Tectonic forces may also increase or decrease the influx of sediment by raising or lowering the area in which the sediment is derived. As the tectonic forces during this time remained subdued, local climatic changes most likely played a larger role on Niobrara deposition.

The interpretation presented by Longman et al. (1998), seen in Figure 3.19, is a valid interpretation when considering the available data. However, other interpretations may be made using the same data. These interpretations include those presented above, but are by no means the only plausible explanations of Niobrara deposition. With time, more data will be collected from the North Park Basin, and other basins in the Rocky Mountain region and, hopefully, a more complete understanding of the deposition of the Niobrara will be developed.

3.8 Summary

This chapter identified and described the stratigraphic intervals studied in this thesis. These intervals include, from oldest to youngest, the Frontier Sandstone, the Carlile Shale, the Niobrara Formation, and the Pierre Shale. The primary focus of this thesis is the Niobrara Formation and thus, it has been further subdivided into smaller units: the Fort Hays, basal chalk, lower marl, lower chalk, middle marl, middle chalk, upper marl, and upper chalk. The thicknesses of each of these units, along with spatial trends of the units, is summarized in Table 3.1, and shown in detail for each unit in the figures throughout this chapter. The log character of these units within the North Park Basin is shown on Figure 3.2; regional cross-sections can be seen in Plate 3.1. The environment at the time of the deposition of the Niobrara interval, as discussed in Chapter 1, was noted by Longman et al. (1998) to be marine, as the units were deposited in the Western Interior Seaway. Minor trangressive and regressive cycles influenced the current flows from the carbonate-rich proto-Gulf of Mexico, resulting in alternating periods of chalk and marl-rich deposition.

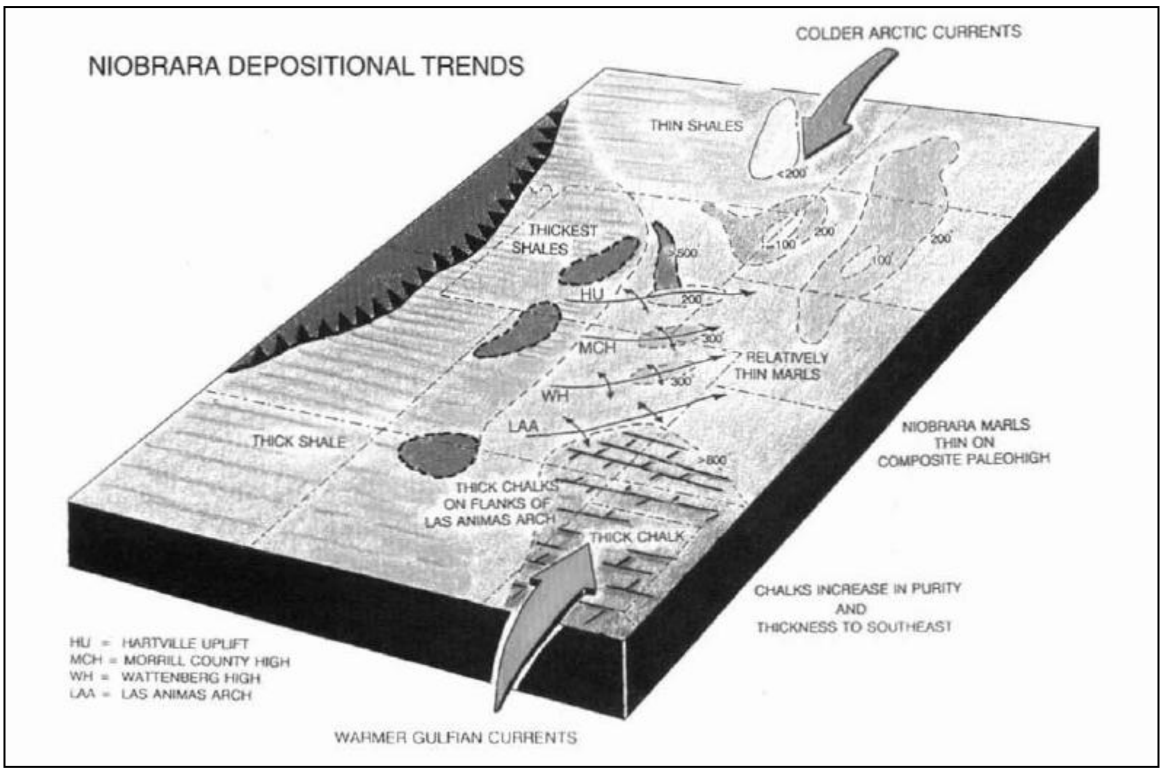


Figure 3.19 Niobrara Depositional Trends. Schematic model for deposition of the Niobrara. A combination of sea level and current flow changes control the variations in the chalk deposits seen on the area. From Longman et al. (1998)

Table 3.1 Summary of the thickness of the studied intervals.

	Thickness					
	Number of wells	**Minimum (ft)**	**Mean (ft)**	**Maximum (ft)**	**Standard Deviation**	**Trend**
Total Niobrara	216	243	478	1176	157	Thickens to the north
Upper chalk	195	2	54	221	33	Variable due to possible areas of erosional contact with Pierre
Upper marl	199	16	75	320	38	Variable due to possible areas of erosional contact with Pierre
Middle chalk	210	30	179	517	69	Thickens to west
Upper chalk	206	20	75	291	33	Generally uniform
Marl	207	9	45	149	25	Thickens to west
Lower chalk	207	14	61	185	29	Generally uniform
Middle marl	207	10	63	291	45	Thickens to west
Lower chalk	207	7	37	111	19	Thickens to the north
Lower marl	211	7	36	166	23	Thickens to the north
Basal chalk	201	7	25	64	11	Thickens to north and west
Fort Hays	201	4	14	48	6	Apparent thickening to the west
Carlile	222	46	245	721	80	Thickens to west

CHAPTER 4

GEOCHEMICAL ANALYSIS

This chapter presents the results and interpretation of geochemical analyses performed as a part of this thesis. However, before conducting and interpreting geochemical analysis, an understanding of what is being analyzed, the methods in which it is analyzed, and guidelines in interpreting the results must be obtained. Therefore, an introduction to the classification, creation, accumulation, preservation and alteration of organic matter, the methods in which geochemical data are collected, and guidelines in interpreting the results of geochemical analysis are presented in the first sections of this chapter. This is followed by the results and interpretation of geochemical analyses performed on cuttings from the Niobrara interval of eight wells in the North Park Basin.

4.1 Organic Matter and its Classification

Organic matter is produced by simple animal and plant plankton and algae and terrestrial vascular plants. These sources produce different maceral types. The three principal maceral groups in sedimentary rocks are liptinite, vitrinite, and inertinite. Liptinite is derived from megaspores, microspores, and seeds. Vitrinite is derived from plant cell-wall cavities and the organic contents of cell cavities. Inertinite is derived from wood tissue in which the cell structure is preserved. Identification of these maceral types can be done by using microscopic morphology. Some insight can also be gained from elemental chemistry. These organic matter maceral types undergo decomposition and alteration and are present in source rock in two main forms based on their solubility: kerogen and bitumen. Kerogen is the insoluble fraction of organic matter macerals and their degradation products. Bitumen is the soluble fraction of organic matter, mostly generated by the thermal dissociation of kerogen, but small quantities may derive from lipid components in once-living organisms. As kerogen is the main precursor of oil and gas, further classification of kerogen types is useful in characterizing source rocks.

Kerogen is classified by both its physical appearance and chemical composition. Its physical appearance under a microscope is generally divided into five main categories: algal, amorphous, herbaceous, woody, and coaly. Algal kerogen is recognizable algal material of marine or lacustrine origin. Amorphous kerogen is mainly sapropelic organic matter from plankton and other low forms of life either of marine or lacustrine origin. Herbaceous kerogen consists of pollen, spores, cuticles, leaf epidermis, and cellular structures of plants and is continental in origin. Woody kerogen is recognizable woody structure and is also continental in origin. Coaly kerogen is recycled organic material that has undergone natural carbonization.

The compositional grouping of kerogen is divided into four types: I, II, III, and IV. This classification is based on the van Krevelen diagram (originally created to classify coals) of atomic H/C vs. O/C ratios. The van Krevelen diagram can be modified to use hydrogen and oxygen indices, which are commonly available from pyrolysis and TOC analyses. An example of these diagrams can be seen in Figure 4.1. Type I kerogen has a high H/C ratio. It contains many aliphatic chains of hydrocarbons and few aromatic nuclei. It is derived mainly from lacustrine algae and bacteria. Type I kerogen is oil-prone. Type II kerogen has an intermediate H/C ratio. It contains more aromatic and napthene rings of hydrocarbons than type I. It is derived mainly from marine phytoplankton. Upon maturity, type II kerogen produces both oil and gas. A subdivision of type II kerogen, type II-S exists. Type II-S kerogen is similar to type II, but is high in sulfur and cracks at lower temperatures. Type III kerogen has a low H/C ratio. It is composed of mainly condensed aromatic hydrocarbons and O-functional groups. It is derived mostly from terrestrial plants. Type III kerogen is generally gas-prone, but can produce oil under special conditions. Type IV kerogen is highly oxidized or reworked organic material of any origin. Kerogen type IV does not produce any notable hydrocarbons.

4.2 Environment of deposition

Knowing the environment of deposition of a sediment is important in analyzing its potential as a hydrocarbon source. The depositional environment is vital in the creation of organic matter, determining the type(s) of organic matter present, and the preservation of organic matter. The organic matter that is responsible for the generation of hydrocarbons in source rocks is either lacustrine, marine, or terrigenous in origin. Organic matter deposited in a lacustrine environment from algae and bacteria is known as Type I kerogen. Organic matter deposited in an oxidizing marine environment from marine algal, pollen, spores, leaf waxes, and fossil resins is known as Type II kerogen. Organic matter deposited in a reducing marine environment derived from terrestrial-derived woody and cellulosic materials is known as Type III kerogen. A distinction between the depositional environment of where the organic matter was created and the depositional environment where the organic matter ultimately is deposited must be made, as, once organic matter is created, it may (or may not) be transported to a different environment. This allows for mixtures of kerogen types to be present in a given sediment. The creation and accumulation of organic matter is important, but if a sediment is to become a source rock, the organic matter must be preserved. Many factors play a role in the preservation of organic matter including the oxygen content of the water column and sediment, the primary production of new organic matter, water circulation, and sedimentation rate. Of these, the oxygen content seems to have the greatest effect on organic matter preservation. Under oxic conditions aerobic bacteria dominate and organic matter is degraded. In anoxic water conditions, however, the preservation of organic matter is favored as the bacteria that degrade organic matter cannot survive. Four main environments exist in which anoxic water conditions are favored: large anoxic lakes, anoxic silled basins, anoxic layers due to upwelling, and anoxic open ocean layers (Demaison and Moore, 1980).

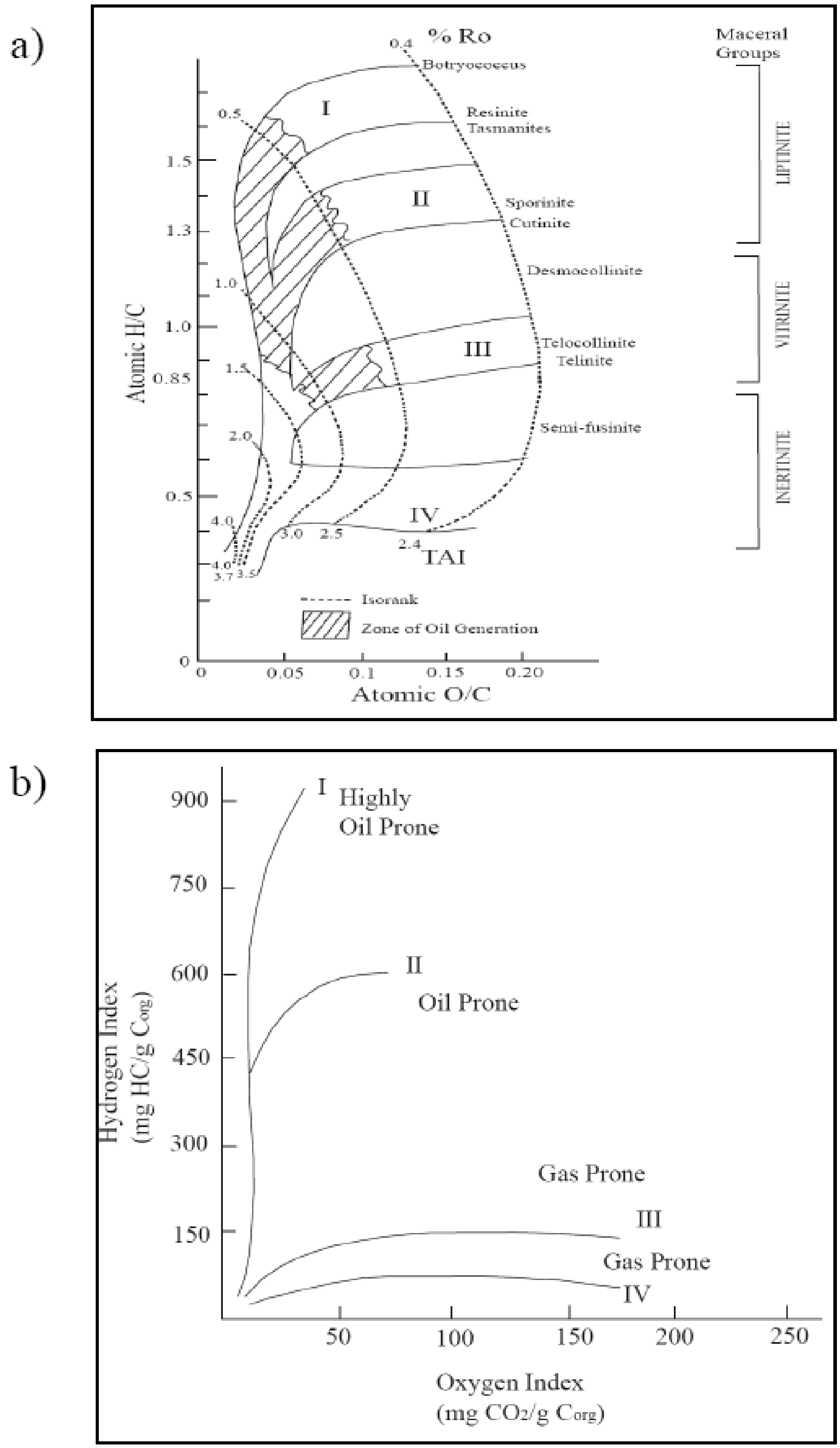


Figure 4.1 van Krevelen and Modified van Krevelen Diagrams. A) A van Krevelen diagram showing maturity pathways, maceral groups, and kerogen types. B) A modified van Krevelen diagram plotting HI vs. OI showing maturity pathways. (modified after Kuzniak (2010) after Peters (1986))

4.3 Alteration of Organic Matter

Organic matter undergoes alterations in the subsurface. These alterations occur in stages as temperature and pressure changes occur: diagenesis, catagenesis, and metagenesis. Diagenesis usually occurs at depths up to 4500 feet and temperatures less than 60-80°C while the sediment is being consolidated and lithified. These limits are dependent on the rate of burial, the temperature regime, and the type of organic matter. During diagenesis, anaerobic microbial bacteria, fungi, and protists are involved in converting biopolymer compounds of organic matter into simpler biomonomers, organic acids, and a residual material, humin. As diagenesis progresses, condensed biomonomers and humin combine create large complex geo-macromolecules known as kerogen. During diagenesis, it is possible for vast amounts of bacterial methane gas to be produced. The amount and quality of the organic matter preserved during diagenesis determines the eventual petroleum potential of the rock. Next, catagenesis occurs. As the kerogen is buried deeper and exposed to greater temperatures, a portion of the kerogen is transformed into bitumen. Products of thermal cracking, decarboxylation, and hydrogen disproportionation include oil, gas, carbon dioxide, and water. Initially, liquid oil and associated gas are formed and later lighter hydrocarbons are more prevalent. Most oil and gas are created during catagenesis. The next stage in the alteration of organic matter is metagenesis. During this stage, dry methane gas is formed from residual kerogen, bitumen, and continued thermal cracking of oils produced during catagenesis that have not migrated. By the end of metagenesis, the remnants of the original organic material are residual thermally stable carbon, resembling graphite, and unmigrated methane gas. (Meissner, 1991)

4.4 Geochemical Methods

This study uses pyrolysis, Total Organic Carbon, Vitrinite Reflectance, and Thermal Alteration Index in order to evaluate the geochemical properties of potential source intervals of the Niobrara Formation. pyrolysis and TOC analysis in this study are performed using a Source Rock Analyzer™. In order to use the data from these techniques, the methods involved in obtaining them must be understood.

Pyrolysis is used to measure the petroleum generative potential as well as the thermal maturity of samples of rocks. A sample of pulverized rock, usually about 100 mg, is first heated to a temperature of 300°C for a short period of time (3-4 minutes). This distills the free organic compounds, bitumen, in the sample. Next, the sample is gradually heated to a maximum temperature, usually at a rate of 25°C/minute to 550°C. The sample is then allowed to cool. The entire process is conducted under a helium atmosphere. A thermocouple and a flame ionization detector (FID) measure the temperature and amount of organic compounds, respectively, during pyrolysis. The FID measures three key peaks during the process. The first peak, S1, occurs during the initial phase of heating and represents the amount of hydrocarbons that can be thermally distilled from the sample. The second peak, S2, occurs while the sample is gradually heated and represents the hydrocarbons generated by pyrolytic degradation of the kerogen in the sample. Both S1 and S2 are usually measured in milligrams of hydrocarbons per gram of rock. The temperature at which the maximum S2 peak occurs is recorded and known as Tmax, and is an indicator of thermal maturity. A third peak, S3, represents the amount of carbon dioxide generated from the sample during pyrolysis up to a temperature of about 400°C and is measured by an IR detector or thermal conductivity detection in milligrams of CO_2 per gram of sample. After pyrolysis, the residual organic matter can be oxidized at a temperature equal to or less than the maximum temperature during pyrolysis. A fourth peak, S4, is measured as the carbon dioxide and carbon monoxide released during oxidation. By summing this with the carbon in the pyrolyzate, a value for total organic carbon, TOC, can be obtained. By using the S1, S2, S3, S4, Tmax, and TOC values, parameters that are useful in evaluating the sample as a source rock can be created. The Hydrogen Index, HI, is the quantity of pyrolyzable organic compounds from S2 relative to the TOC (S2/TOC x 100). HI is an indicator of the generative potential of oil for the sample; high HI indices indicate a greater potential to generate oil. The Oxygen Index, OI, is the quantity of CO_2 relative to the TOC (S3/TOC x 100) and is therefore related to the amount of oxygen in the kerogen.

The Production Index, PI, measures the potential productivity of the sample [S1/(S1+S2)].

Variations in the types of organic matter, coal and other extremely organic-rich samples, organic-lean samples, altered samples, contamination by well additives, bitumen and migrating oil, interference of mineral matrix are all variables that may influence the results of pyrolysis and TOC analysis, and should be taken into account by the interpreted during analysis. Despite these difficulties, pyrolysis provides a quick means of checking a large number of whole rock samples and an inexpensive way of procuring valuable source rock information, without the requirement of kerogen isolation like more traditional elemental analysis. Guidelines exist in interpreting what the S1, S2, S3, S4, Tmax, TOC, HI, OI, and PI values mean in terms of the potential source rock characteristics of the samples for which pyrolysis is performed.

TOC, S1, and S2 ranges have been assigned by Peters (1986), and Peters and Cassa (1994) for samples with poor, fair, good, very good, and excellent petroleum potential, as seen in Table 4.1. It is important to note that TOC alone is not sufficient to indicate the amount of hydrocarbons a sediment can produce. First, not all organic matter generates the same type of hydrocarbons; under the right conditions, some produce oil, others produce gas, and some produce nothing at all. Secondly, organic matter must contain sufficient hydrogen to generate hydrocarbons. Although the most direct measurement of hydrogen is through elemental analysis, hydrogen content is estimated

Table 4.1 Geochemical Parameters Describing the Petroleum Potential of an Immature Source Rock. (Modified after Peters and Cassa 1994).

Petroleum Potential	**TOC** (wt. %)	**S1** (mg HC/g)	**S2** (mg HC/g)	**Hydrocarbons** (ppm)
Poor	0-0.5	0-0.5	0-2.5	0-300
Fair	0.5-1	0.5-1	2.5-5	300-600
Good	1-2	1-2	5-10	600-1200
Very Good	2-4	2-4	10-20	1200-2400
Excellent	>4	>4	>20	>2400

indirectly by the S2 value in pyrolysis. By plotting TOC vs. S2 one can get an estimate of the amount of hydrogen associated with the organic matter. Third, as a sediment matures, organic matter and hydrogen are converted into hydrocarbons, and the organic matter and hydrogen present in the rock decrease from the original levels. Knowing the type of kerogen present, the amount of hydrogen present, and the maturation history of the sediment sampled is important in interpreting its organic and hydrogen content. (Dembicki, 2009)

As stated in section 4.1 of this thesis, HI and OI can be plotted against one another to create a modified van Krevelen diagram that can approximate the type of kerogen in a sediment. These plots can be very useful, however, understanding their limits is important before making interpretations. The kerogen type lines on the van Krevelen diagrams are based on a pure sample of the respective kerogen types. Unfortunately, most source rocks contain a mixture of kerogen types. Dembicki (2009) warns that when plotted on a modified van Krevelen these mixtures do not always accurately represent the types of hydrocarbon generated from a rock; an example of this would be a mixture of Type I and Type III kerogen plotting on a van Krevelen diagram on the Type II curve, when in fact, no Type II kerogen is present. Dembicki (2009) suggests the use of pyrolysis-gas chromatography (PGC) to aid in determining the kerogen type(s) present as the kerogen chromatographs of each type are distinct and can be identified even in mixtures of different kerogen types. In addition, the mineral matrix of a rock can influence the kerogen typing. In sediments with 2% or less TOC, a significant reduction of HI can result from hydrocarbon retention on mineral grains (Esptalie et al., 1980); (Katz, 1983). Also, an increase in OI may result from thermal decomposition of small amounts of carbonate minerals during pyrolysis (Katz, 1983). Keeping the potential of kerogen mixtures in mind, having information about the depositional setting, and conducting PGC all aid in a better interpretation of data. Other parameters can be used to determine the type of hydrocarbons that could be generated, as well as the kerogen type of the samples. Table 4.2 shows the HI, S2/S3, and Atomic H/C values associated with each kerogen type, and the hydrocarbons that would be expected to be expelled upon generation. Again, one should keep in mind the potential of kerogen mixtures when considering the application of these guidelines.

Vitrinite reflectance (R_o), thermal alteration index (TAI), and Tmax from pyrolysis are all used to measure the maturity of a sediment. Vitrinite reflectance is a measure of the amount of vitrinite contained in a sample. This is obtained through a petrographic analysis of a sample, and measured in % R_o. Vitrinite reflectance increases during thermal maturation, and thus is a good indicator of the thermal maturity of a sample. Table 4.3 shows the vitrinite reflectance values and the stage of generation for both oil and gas –prone kerogen types. Vitrinite reflectance data do not indicate if a source rock is currently generating, but if generation could have occurred and to what extent during the maximum heating in its thermal history (Dembicki, 2009). In-depth basin modeling is necessary to evaluate the timing of generation within a basin.

Thermal Alteration index is a numerical scale based on the color of spores and pollen in a sample. The color of the spores and pollen change as they are subjected to thermal maturation. An analyst looks at the sample under a microscope, and matches the color seen to developed color scales. As the greatest changes occur in the oil window, this technique is useful in interpreting the maturity of a source rock, but is dependent on the presence of palynomorphs and the subjectivity of the analyst. The Tmax indicated from pyrolysis is also associated with thermal maturity. Table 4.5 shows the stages of thermal maturity for oil, and the corresponding values for vitrinite reflectance, Tmax, TAI, and PI.

Table 4.2 Geochemical parameters from pyrolysis describing kerogen type and expelled products. (Modified after Peters and Cassa 1994)

Kerogen Type	HI (mg HC/g TOC)	S2/S3	Atomic H/C	Expelled products
I	>600	>15	>1.5	Oil
II	300-600	10-15	1.2-1.5	Oil
II/III	200-300	5-10	1.0-1.2	Mixed oil and gas
III	20-200	1-5	0.7-1.0	Gas
IV	<50	<1	<0.7	None

Table 4.3 Vitrinite Reflectance and Hydrocarbon Generation. (From Dembicki (2009) after Dow (1997) and Senftle, and Landis (1991))

Oil-Prone Generation		Gas-Prone Generation	
Generation Stage	**R_o(%)**	**Generation Stage**	**R_o(%)**
Immature	<0.6	Immature	<0.8
Early oil	0.6-0.8	Early gas	0.8-1.2
Peak oil	0.8-1.0	Peak gas	1.2-2.0
Late oil	1.0-1.35	Late gas	>2.0
Wet gas	1.35-2.0		
Dry gas	>2.0		

Table 4.4 Adjusting the onset of significant hydrocarbon generation for kerogen type. (from Dembicki (2009) after Tissot (1984), Petersen and Hickey (1987), Sweeney et al. (1987), and Tissot et al. (1987)

Kerogen Type	R_o(%)
Type I	0.7
Type II	0.6
Type IIS	0.45-0.5
Type III	0.8

Table 4.5 Geochemical parameters describing kerogen's level of thermal maturation (Modified after Peters and Casa 1994).

Stage of Thermal Maturity for Oil	Maturation			Generation
	R_o (%)	**Tmax** (°C)	**TAI**	**PI** [S1/(S1+S2)]
Immature	0.2-0.6	<435	1.5-2.6	<0.10
Early Mature	0.6-0.65	435-445	2.6-2.7	0.10-0.15
Peak Mature	0.65-0.9	445-450	2.7-2.9	0.25-0.40
Late Mature	0.9-1.35	459-470	2.9-3.3	>0.40
Postmature	>1.35	>470	>3.3	-

4.5 Data

As a part of this thesis cuttings from eight wells were collected from the USGS Core Depository Center in Denver. The wells were selected to sample the Niobrara Formation throughout the North Park Basin. Only wells with resistivity and sonic logs were considered in order to aid in the calibration of the Passey et al. (1990) TOC Method (see Chapter 6). The location of these wells, as well as the well for which geochemical data are available from the USGS website, can be seen on Figure 4.2. Samples were collected from each well from about the interpreted top of the Niobrara Formation to the Frontier Formation. The sampling rate was determined for each well based on the sampling rate of the cuttings themselves and limited by the sample amount of the available cuttings at each depth as, per USGS policy, at least 50 ml of sample must be remain at the depository. After collection, the samples were pulverized and analyzed by a Source Rock Analyzer at the Colorado School of Mines. For every sample pyrolysis followed by an oxidation stage was performed and the TOC, Tmax, S1, S2, and S3 peaks were measured. From these results, one can calculate the HI, OI, PI, calculated %Ro, S2/S3, and S1/TOC x 100 for each sample. These parameters were used to create graphs and logs that are helpful in determining and/or interpreting certain characteristics of the units. Geochemical logs can be produced to show the change in these values with depth. In the case of the Niobrara, these logs may aid in distinguishing the more chalk-rich units from the more marl rich units. A modified van Krevelen diagram, OI vs. HI, wa used to distinguish the kerogen type(s) of samples. A graph of Tmax vs. HI was used to determine the kerogen type and maturity of the samples. After Langford and Blanc-Valleron (1990), a plot of TOC vs. S2 was also used to evaluate the petroleum potential and kerogen type of the samples. Tmax and PI were plotted against each other to approximate kerogen conversion and the maturity of the samples. Other graphs were constructed to view other relationships, including HI vs. S2, TOC vs. OI, and TOC vs. HI. The remaining sections of this chapter present these data on a well by well basis. All of the parameters are evaluated according to the guidelines presented in the preceding sections. A table of all of these pyrolysis data can be viewed in Appendix B.

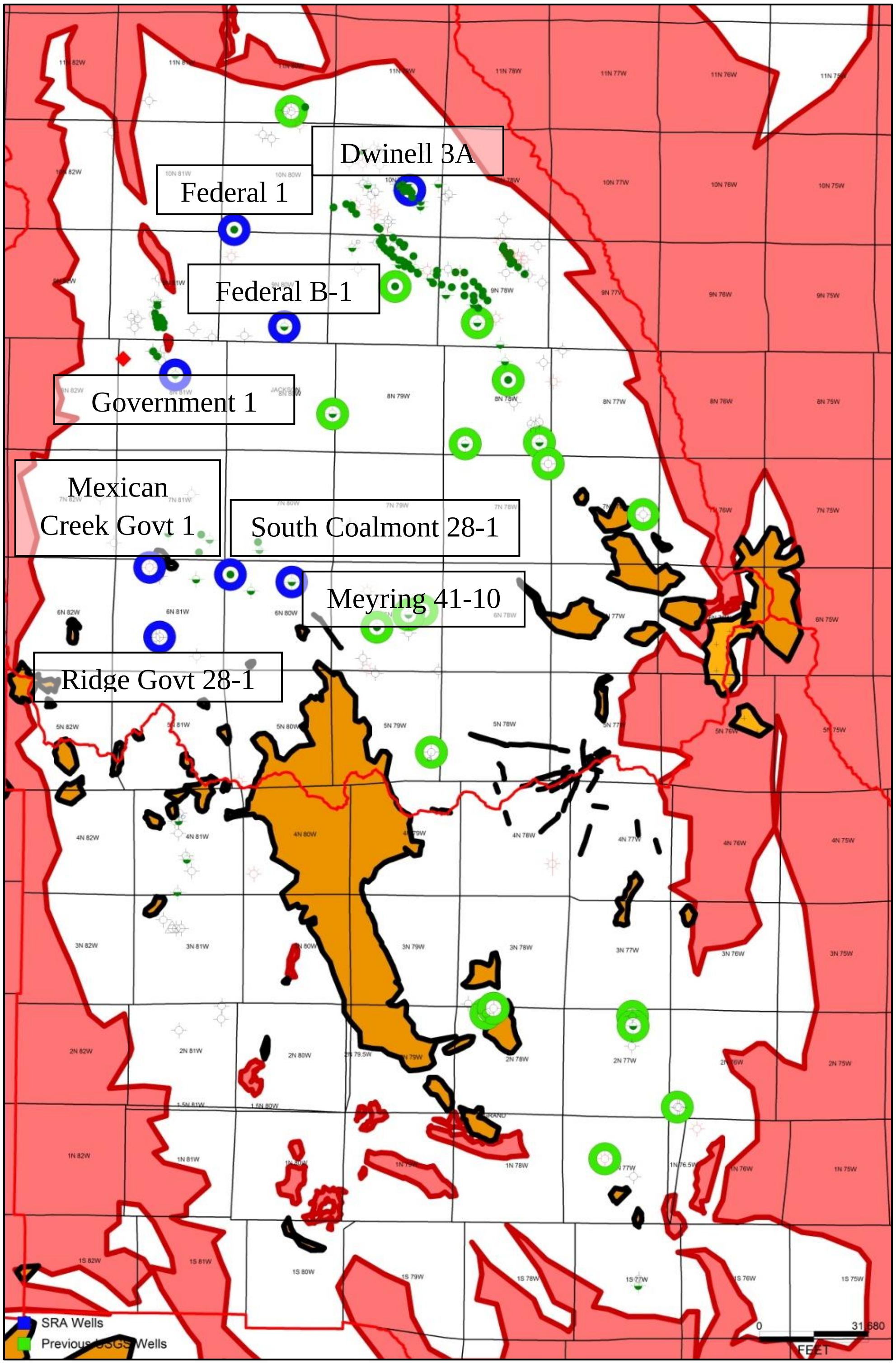


Figure 4.2 Map showing the cuttings from the eight wells for which cuttings were analyzed for this study highlighted in blue and the 19 wells in which previous geochemical analyses are available through USGS highlighted in green.

4.5.1 Dwinell 3A

Dwinell 3A, API 05057062260000, was completed in 1982 by Monsato Company in Battleship field. The well is located in the SE ¼ of the NW ¼ of sec. 23, T 10 N, R 79 W. It has produced over 50,000 barrels of oil from the Frontier Sandstone and continues to add to that number. Cuttings from Dwinell 3A were sampled on about 30 feet intervals, with a total of 12 samples, from 3220 to 3740 feet. The samples were collected from the Pierre Shale (1), the Niobrara Formation (8), and the Carlile Shale (3). The samples from the Niobrara Formation represent the upper marl, middle chalk, middle marl, lower chalk, and lower marl.

Of the samples tested, the total organic carbon values ranged from 0.92 (Carlile Shale) to 3.78 wt.% (lower marl). All of the samples but one have TOC values above 1 wt. %; all of the Niobrara samples are above 2 wt. %, rating in the very good petroleum potential window. However, the S1 values range from 0.03 (lower marl) - 0.3 (Pierre) and, being under 0.5, are in the poor petroleum potential zone. The S2 values range from 0.31 (Carlile) -17.01 (lower marl), with most of the samples being in the poor to fair petroleum potential interval; two S2 samples are in the very good petroleum potential. When plotted on a modified van Krevelen diagram, the samples plot between the Type II and Type IV lines, mainly between the Type III and Type IV lines. The HI values of the samples rank, according to Table 4.2, as mainly Type III kerogen, with two of the samples ranking as Type II. The S2/S3 values are in the Type III kerogen window, aside from two samples in the Type II zone, and one as Type I. When TOC is plotted against S2, the majority of the samples plot as Type III kerogen, with two samples plotting as Type II. Identification of kerogen types and other interpretations from these geochemical plots assumes an immature sample. As the samples from this well have reached maturity, the initial levels of hydrogen and carbon have been altered, and as a result, the location of the samples on the geochemical plots is different than that of an immature sample. When these samples were immature, they would have higher HI, TOC, and S2 values and lower Tmax and S1 values. The original immature samples would plot closer to the Type II kerogen type lines. Based on the assumed depositional environment of this interval, it is expected that Type II kerogen would be present, perhaps mixed with some Type III kerogen. These data from the pyrolysis support this expectation.

In order to evaluate the maturity of the interval sampled, the Tmax values must be used as no vitrinite reflectance or thermal alteration index data were analyzed for this well. The Tmax values for this well range from 423-466°C. By referencing Table 4.5, these values indicate that most of the samples are in an early to peak maturity window for oil generation. The PI values for these samples are from 0.01 to 0.14. This indicates that all but one of the samples is immature or has a low level of conversion. Though these contradict each other, the interval tested has reached early to peak maturity as the Tmax maturity indicators provide a more reliable trend. This level of maturity maintained even after uplift after initial burial. Therefore measured maturity may not relate directly to current depth of burial. This is true for this and all other wells in this study.

4.5.2 Federal 1

Federal 1 was completed in 1982 by Mobil Oil. This well is located in the SE ¼ of the SW ¼ of the SE ¼ of Section 31, T 10 N, R 80 W. Only about 4,000 barrels of oil were produced from the Dakota Sandstone. Cuttings from Federal 1 were sampled on about 30 feet intervals, with a total of 20 samples, from 3800 to 4460 feet. The samples were collected from the Pierre Shale (1), the Niobrara Formation (16), and the Carlile Shale (3). The samples from the Niobrara Formation represent the upper marl, middle chalk, middle marl, lower chalk, and basal chalk.

Of the samples tested, the total organic carbon values ranged from 1.55 (Carlile Shale) to 3.33 wt.% (upper marl). All of the samples have TOC values above 1 wt. %; all of the Niobrara samples are above 2 wt. %, rating in the very good petroleum potential window. However, the S1 values range from 0.03 (Carlile) – 0.84 (Pierre) and, all but two samples are under 0.5 in the poor petroleum potential zone. The S2 values range from 2.65 (Carlile) to 15.58 (middle chalk), with most of the samples being in the good to very good petroleum potential interval. Four S2 samples are in the fair petroleum potential. When plotted on a modified van Krevelen diagram, the samples plot between the Type II and Type III lines. The HI values of the samples rank, according to Table 4.2, as mainly Type II kerogen and Type III Kerogen. Most of the S2/S3 values are in the Type I and Type II windows, with a few in the Type III range. When TOC is plotted

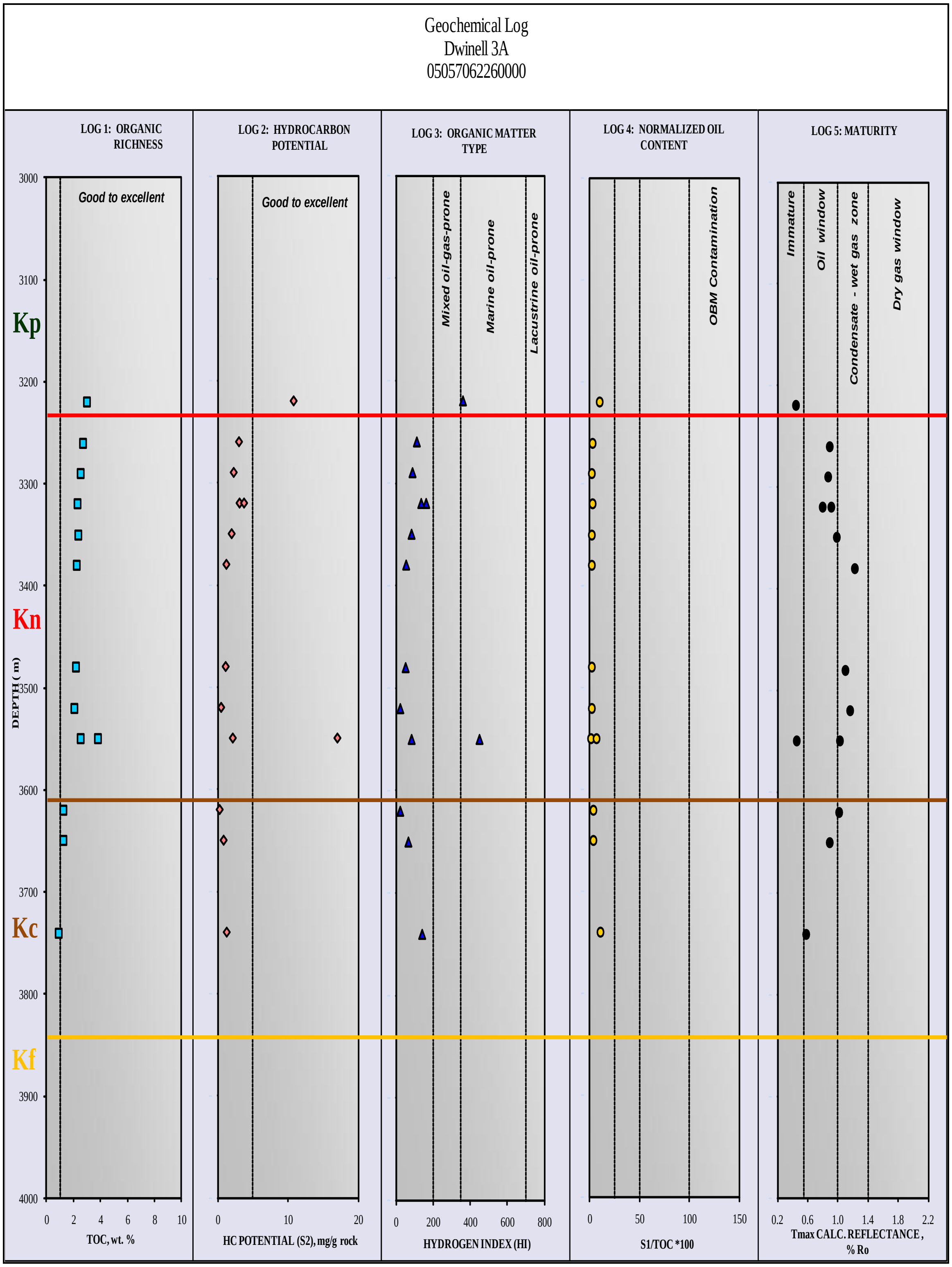


Figure 4.3 Geochemical Log for the samples tested for Dwinell 3A. TOC (wt. %), S2 (mg HC/g rock), HI, S1/TOC*100, and Tmax calculated vitrinite reflectance are presented. Cuttings from Dwinell 3A were sampled on about 30 feet intervals, with a total of 12 samples, from 3220 to 3740 feet. Formations are indicated by labels; Kc (Carilie), Kf (Frontier), Kn (Niobrara) and Kp (Pierre).

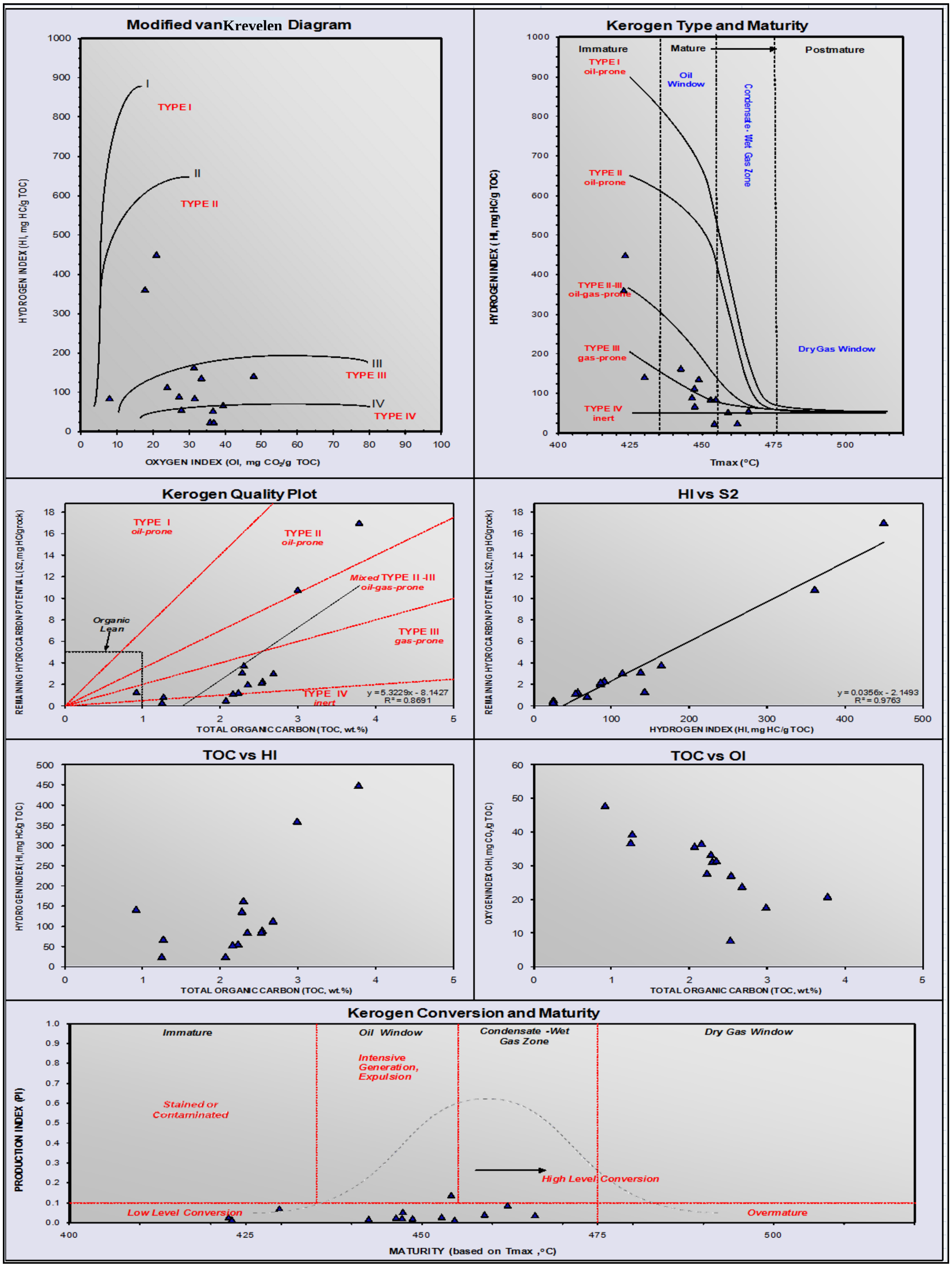


Figure 4.4 Geochemical Graphs for Dwinell 3A. From Top to Bottom: Modified van Krevelen diagram HI vs. OI, Kerogen Type and Maturity Tmax vs. HI, Kerogen Quality TOC vs. S2, HI vs. S2, TOC vs. HI, TOC vs, OI, and Kerogen Conversion Maturity Tmax vs. PI.

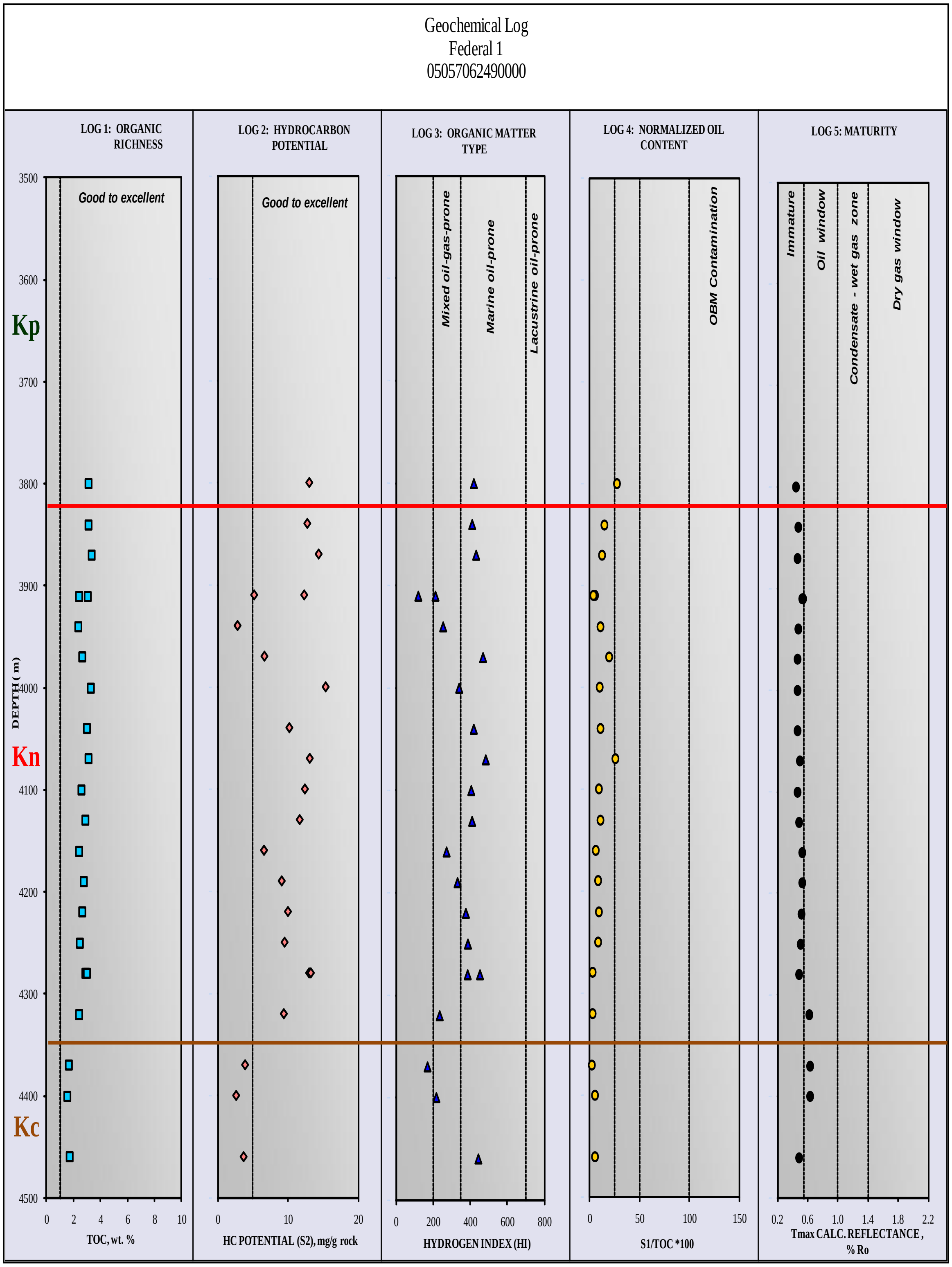


Figure 4.5 Geochemical Log for the samples tested for Federal 1. TOC (wt. %), S2 (mg HC/g rock), HI, S1/TOC*100, and Tmax calculated vitrinite reflectance are presented. Cuttings from Federal 1 were sampled on about 30 feet intervals, with a total of 20 samples, from 3800 to 4460 feet. Formations are indicated by labels; Kc (Carilie), Kf (Frontier), Kn (Niobrara) and Kp (Pierre).

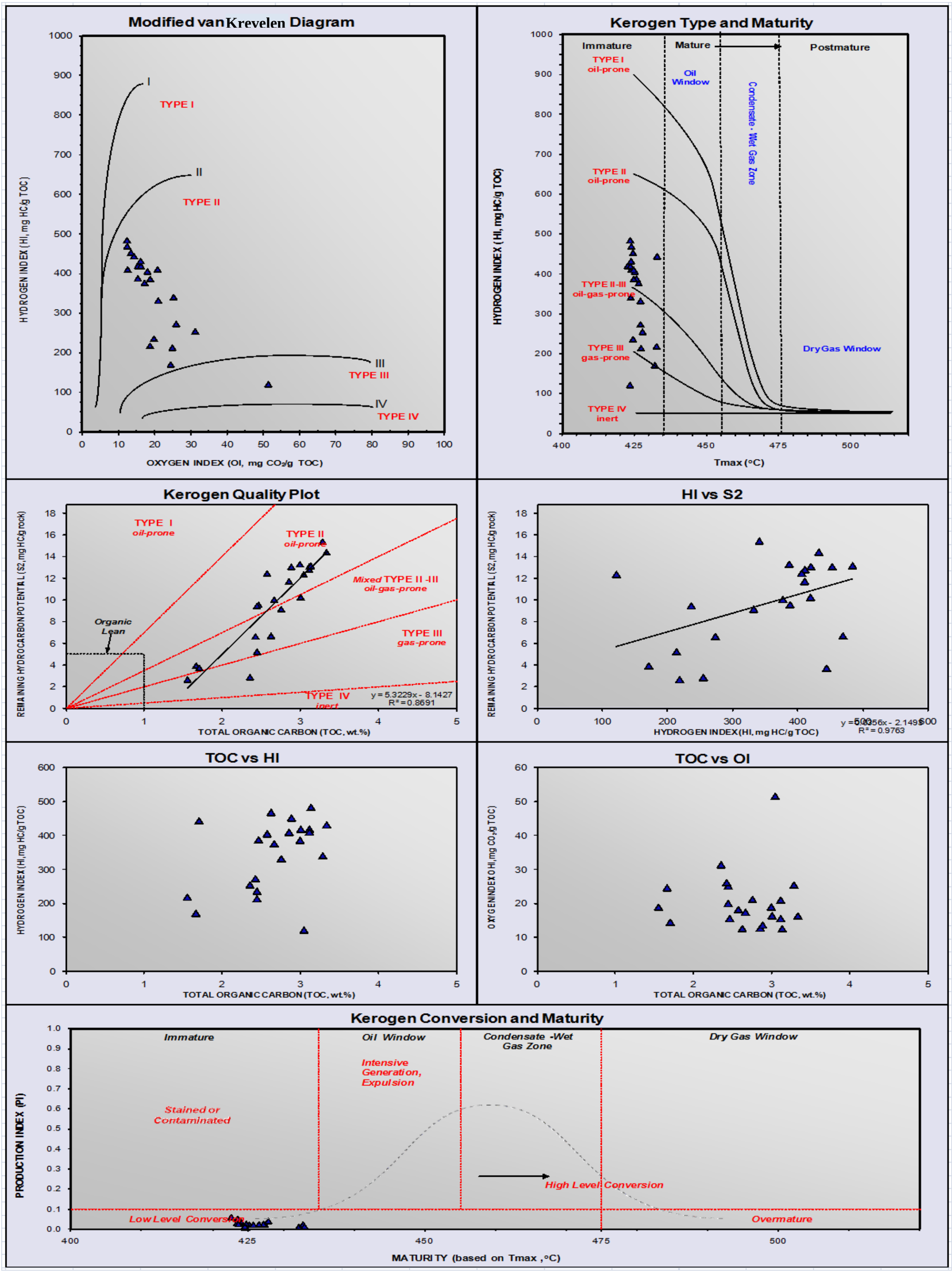


Figure 4.6 Geochemical Graphs for Federal 1. From Top to Bottom: Modified van Krevelen diagram HI vs. OI, Kerogen Type and Maturity Tmax vs. HI, Kerogen Quality TOC vs. S2, HI vs. S2, TOC vs. HI, TOC vs., OI, and Kerogen Conversion Maturity Tmax vs. PI.

against S2, the majority of the samples plot as Type II and mixed Type II and III kerogen; two remaining samples plot as Type III. Based on the assumed depositional environment of this interval, it is expected that Type II kerogen would be present, perhaps mixed with some Type III kerogen. These data from the pyrolysis support this expectation.

In order to evaluate the maturity of the interval sampled, the Tmax values must be used as no vitrinite reflectance or thermal alteration index data were analyzed for this well. The Tmax values for this well range from 422-433°C, with an average of 426°C. By referencing Table 4.5, these values indicate that the samples are immature for oil. The PI values for these samples are from 0.01 (lower chalk) to 0.06 (Pierre). This also indicates that all the samples are immature. These both support that the interval tested has not reached maturity.

4.5.3 Federal B-1

Federal B-1 was completed in 1973 by Cities Service. The well is located in the SW ¼ of the NW ¼ of the NE ¼ of Section 34, T 9 N, R 80 W. Cuttings from Federal B-1 were sampled on 30-110 feet intervals, with a total of 9 samples, from 7500 to 8080 feet. The samples were collected from the Niobrara Formation (6) and the Carlile Shale (3). The samples from the Niobrara Formation represent the upper marl, middle chalk, middle marl, and lower chalk.

Of the samples tested, the total organic carbon values ranged from 1.18 (middle marl) to 2.87 wt.% (Carlile Shale). All of the samples have TOC values above 1 wt. %, rating in the good to very good petroleum potential window. However, the S1 values range from 0.05 (middle chalk) to 1.5 (Carlile) and, being under 0.5, are in the poor petroleum potential zone. The S2 values range from 1.12 (Carlile) to 5.31 (upper marl), with most of the samples being in the poor to fair petroleum potential interval. When plotted on a modified van Krevelen diagram, the samples plot between the Type II and Type IV lines, mainly between the Type II and Type III lines. The HI values of the samples rank, according to Table 4.2, as mainly Type III kerogen and mixed Type II and III. The S2/S3 values are variable and rank from Type I through Type III. When TOC is plotted against S2, the majority of the samples plot as Type III kerogen, with two samples plotting as mixed Type II and III. As noted in previous wells, since these samples have reached a level of maturity, the original immature samples would plot closer to the Type II kerogen type lines. Based on the assumed depositional environment of this interval, it is expected that Type II kerogen would be present, perhaps mixed with some Type III kerogen. These data from the pyrolysis support this expectation

In order to evaluate the maturity of the interval sampled, the Tmax values must be used as no vitrinite reflectance or thermal alteration index data were analyzed for this well. The Tmax values for this well range from 418-455°C, with an average of 442°C. By referencing Table 4.5, these values indicate that most of the samples are in an early maturity window for oil. The PI values for these samples are from 0.01 to 0.07. This indicates that all of the samples are immature. As the Tmax maturity indicators provide a more reliable trend, the samples from this well have reached early maturity.

4.5.4 Government 1

Government 1 was completed in 1973 by Trend Exploration. The well is located in the SW ¼ of the SW ¼ of Section 10, T 8 N, R 81 W. Cuttings from Government 1 were sampled on 30-240 feet intervals, with a total of 6 samples, from 2330 to 2840 feet. The samples were collected from the Niobrara Formation (6). The samples represent the upper chalk, middle chalk, and middle marl.

. Of the samples tested, the total organic carbon values ranged from 1.79 (middle chalk) to 3.48 wt.% (middle chalk). All of the samples but one have TOC values above 2 wt. %, rating in the very good petroleum potential window. However, the S1 values range from 0.05 (middle chalk) - 0.2 (middle chalk) and, being under 0.5, are in the poor petroleum potential zone. The S2 values range from 0.66 (middle chalk) -17.12 (middle chalk), with most of the samples being in the poor to good petroleum potential interval, and one ranking as very good. When plotted on a modified van Krevelen diagram, the samples plot between the Type II and Type IV lines, mainly between the Type III and Type IV lines. The HI values of the samples rank, according to Table 4.2, as mainly Type III kerogen, with two of the samples ranking as outside this window, one as a mixed Type

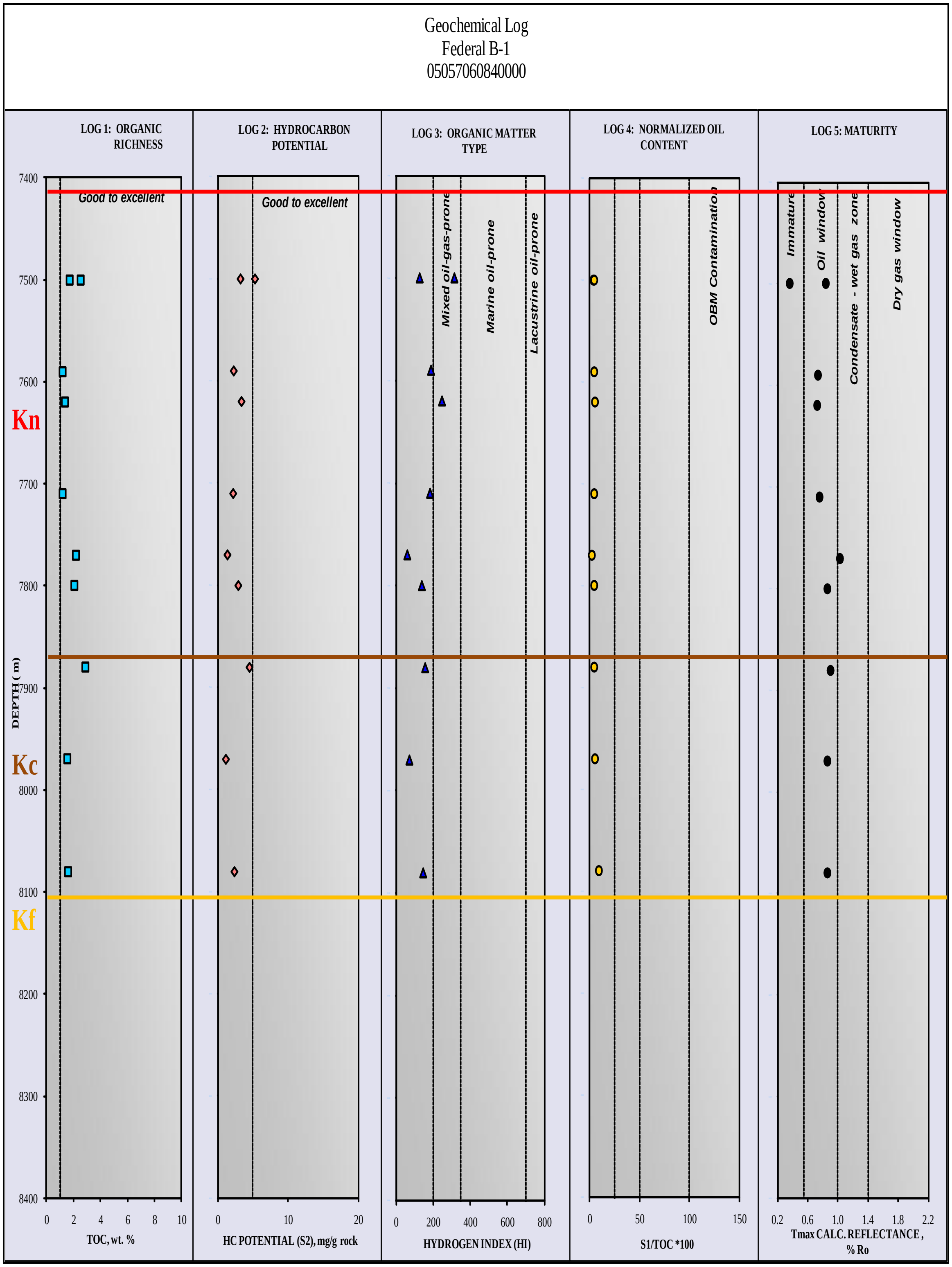


Figure 4.7 Geochemical Log for the samples tested for Federal B-1. TOC (wt. %), S2 (mg HC/g rock), HI, S1/TOC*100, and Tmax calculated vitrinite reflectance are presented. Cuttings from Federal B-1 were sampled on 30-110 feet intervals, with a total of 9 samples, from 7500 to 8080 feet. Formations are indicated by labels; Kc (Carilie), Kf (Frontier), Kn (Niobrara) and Kp (Pierre).

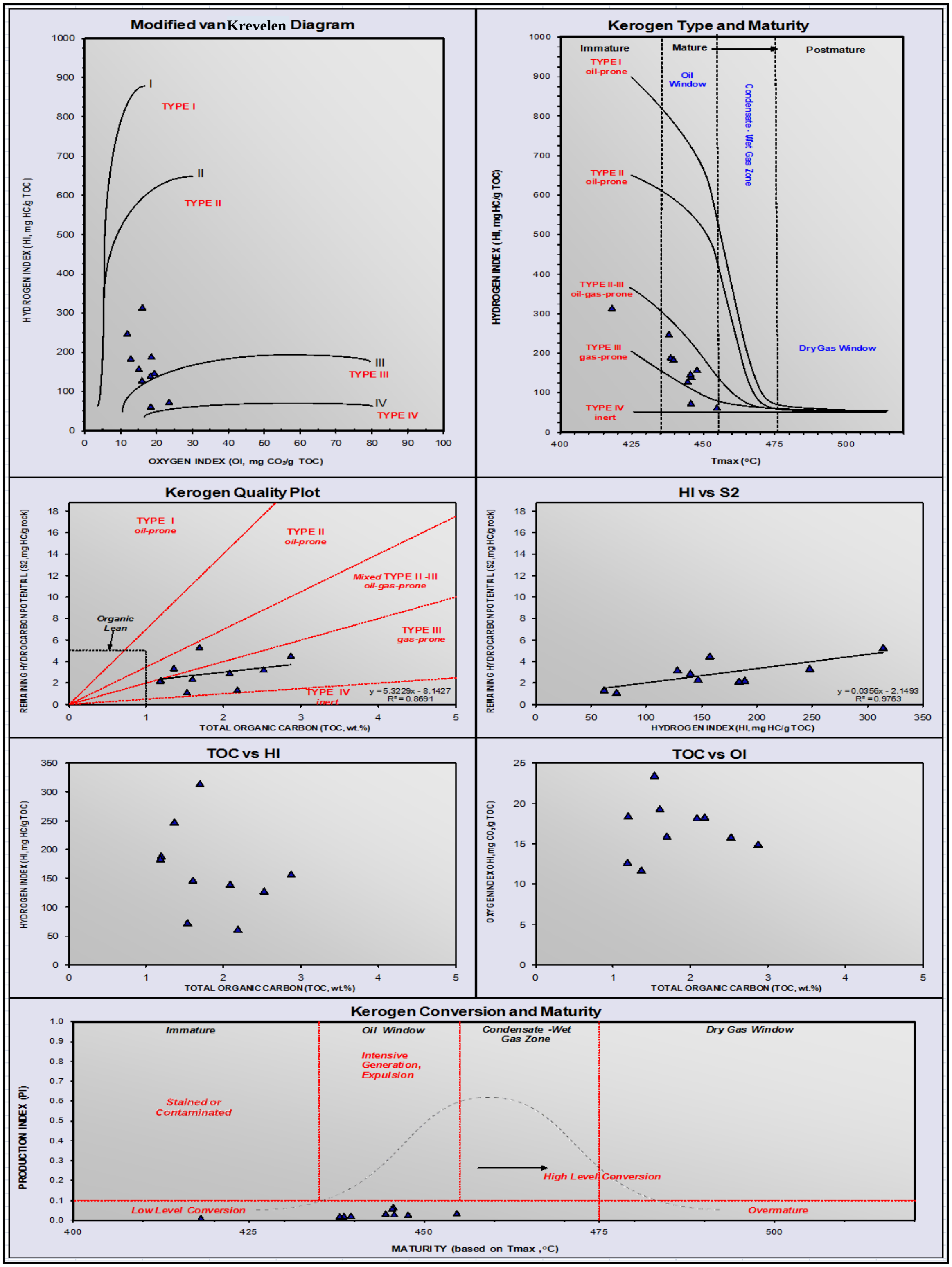


Figure 4.8 Geochemical Graphs for Federal B-1. From Top to Bottom: Modified van Krevelen diagram HI vs. OI, Kerogen Type and Maturity Tmax vs. HI, Kerogen Quality TOC vs. S2, HI vs. S2, TOC vs. HI, TOC vs., OI, and Kerogen Conversion Maturity Tmax vs. PI.

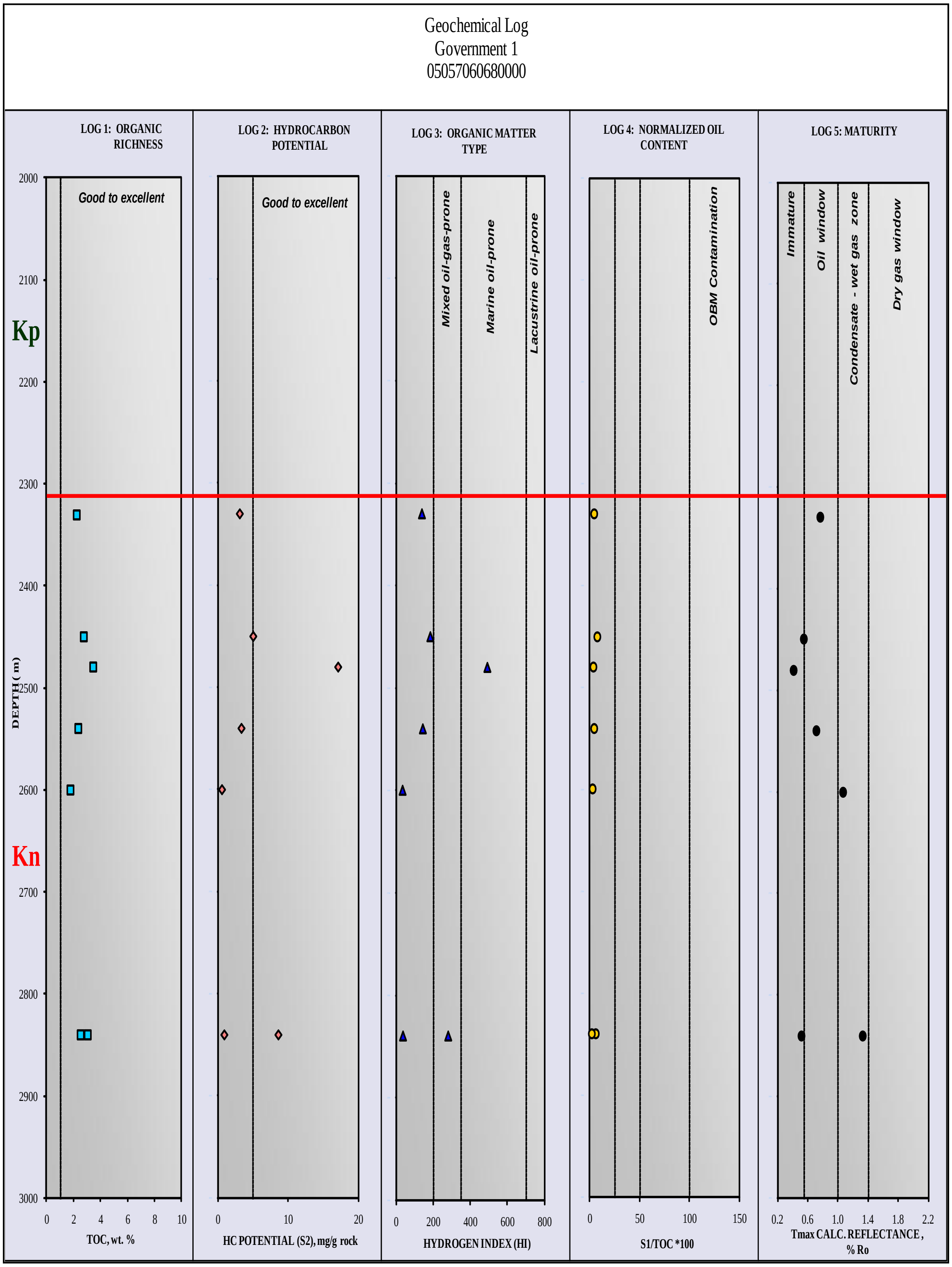


Figure 4.9 Geochemical Log for the samples tested for Government 1. TOC (wt. %), S2 (mg HC/g rock), HI, S1/TOC*100, and Tmax calculated vitrinite reflectance are presented. Cuttings from Government 1 were sampled on 30-240 feet intervals, with a total of 6 samples, from 2330 to 2840 feet. Formations are indicated by labels; Kc (Carilie), Kf (Frontier), Kn (Niobrara) and Kp (Pierre).

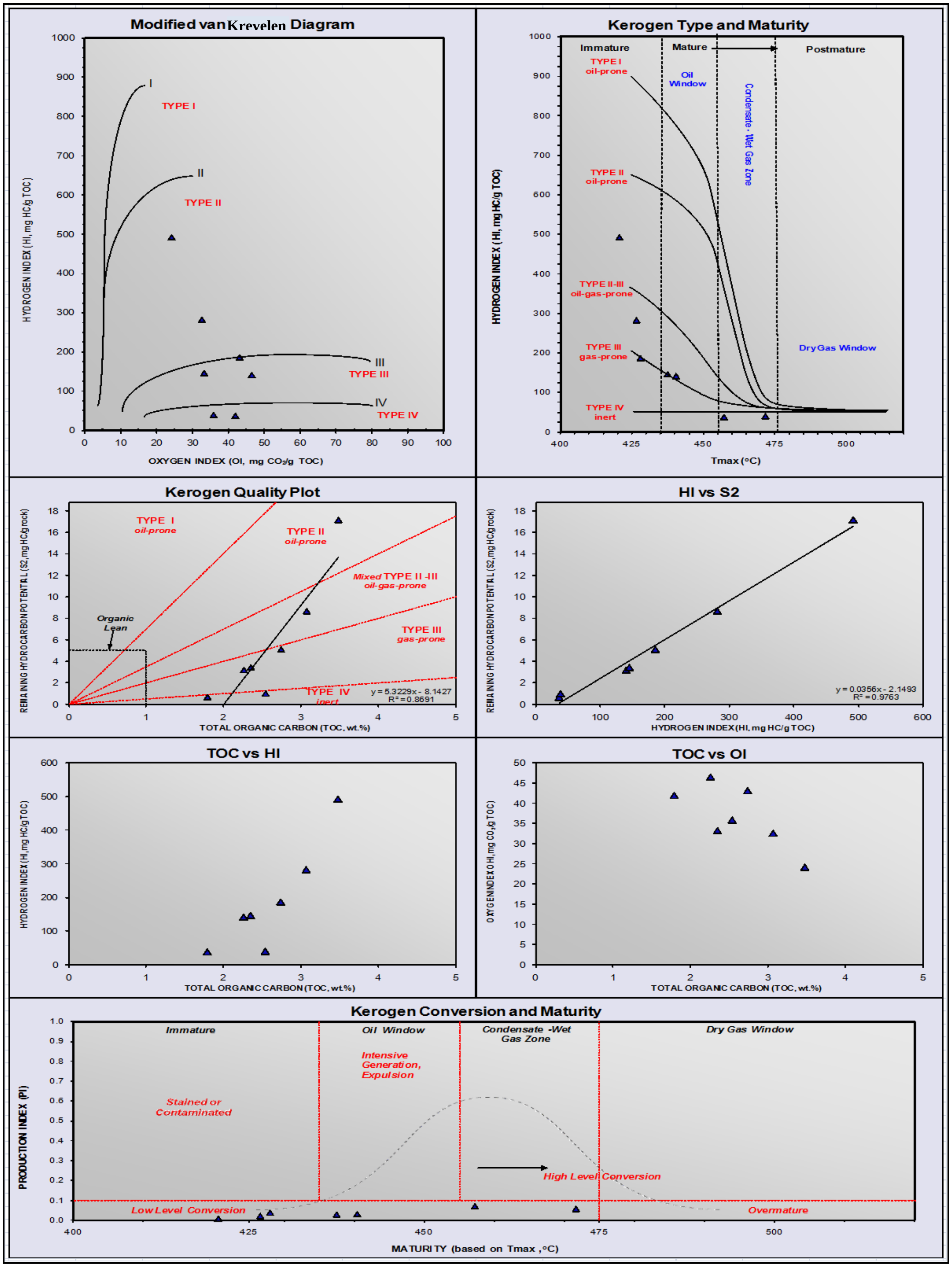


Figure 4.10 Geochemical Graphs for Government 1. From Top to Bottom: Modified van Krevelen diagram HI vs. OI, Kerogen Type and Maturity Tmax vs. HI, Kerogen Quality TOC vs. S2, HI vs. S2, TOC vs. HI, TOC vs., OI, and Kerogen Conversion Maturity Tmax vs. PI.

II and III and the other as Type II. The S2/S3 values are in the Type III and mixed Type II and II kerogen windows, aside from one sample in the Type I zone. When TOC is plotted against S2, one plots as Type II, one as mixed Type II and III, two a Type III, and two as Type IV. As noted in previous wells, since some of these samples have reached a level of maturity, the original immature samples would plot closer to the Type II kerogen type lines. Based on the assumed depositional environment of this interval, it is expected that Type II kerogen would be present, perhaps mixed with some Type III kerogen. These data from the pyrolysis support this expectation. In order to evaluate the maturity of the interval sampled, the Tmax values must be used as no vitrinite reflectance or thermal alteration index data were analyzed for this well. The Tmax values for this well range from 421-440°C. By referencing Table 4.5, these values indicate that the samples are immature to early mature for oil. The PI values for these samples are from 0.01 (middle chalk) to 0.07 (middle chalk). This indicates that the samples are immature. Though these contradict each other, the interval tested has reached early maturity as the Tmax maturity indicators provide a more reliable trend.

4.5.5 Mexican Creek Government 1

Mexican Creek Government 1, API 05057060230000, was completed in 1972 by Burton-Hawks. It is located in the SW ¼ of the SE ¼ of the NE ¼ of Section 5, T 6 N, R 81 W. Cuttings from Mexican Creek Government 1 were sampled on about 30 feet intervals, with a total of 20 samples, from 4320 to 4920 feet. The samples were collected from the Niobrara Formation (16) and the Carlile Shale (4). The samples from the Niobrara Formation represent the upper marl, middle chalk, middle marl, lower chalk, basal chalk, and Fort Hays.

Of the samples tested, the total organic carbon values ranged from 1.48 (Carlile) to 3.84 wt.% (Fort Hays). All of the samples have TOC values above 1 wt. %; all of the Niobrara samples are above 2 wt. %, rating in the very good petroleum potential window. However, the S1 values range from 0.02 (lower chalk) - 0.21 (upper shale) and, being under 0.5, are in the poor petroleum potential zone. The S2 values range from 2.44

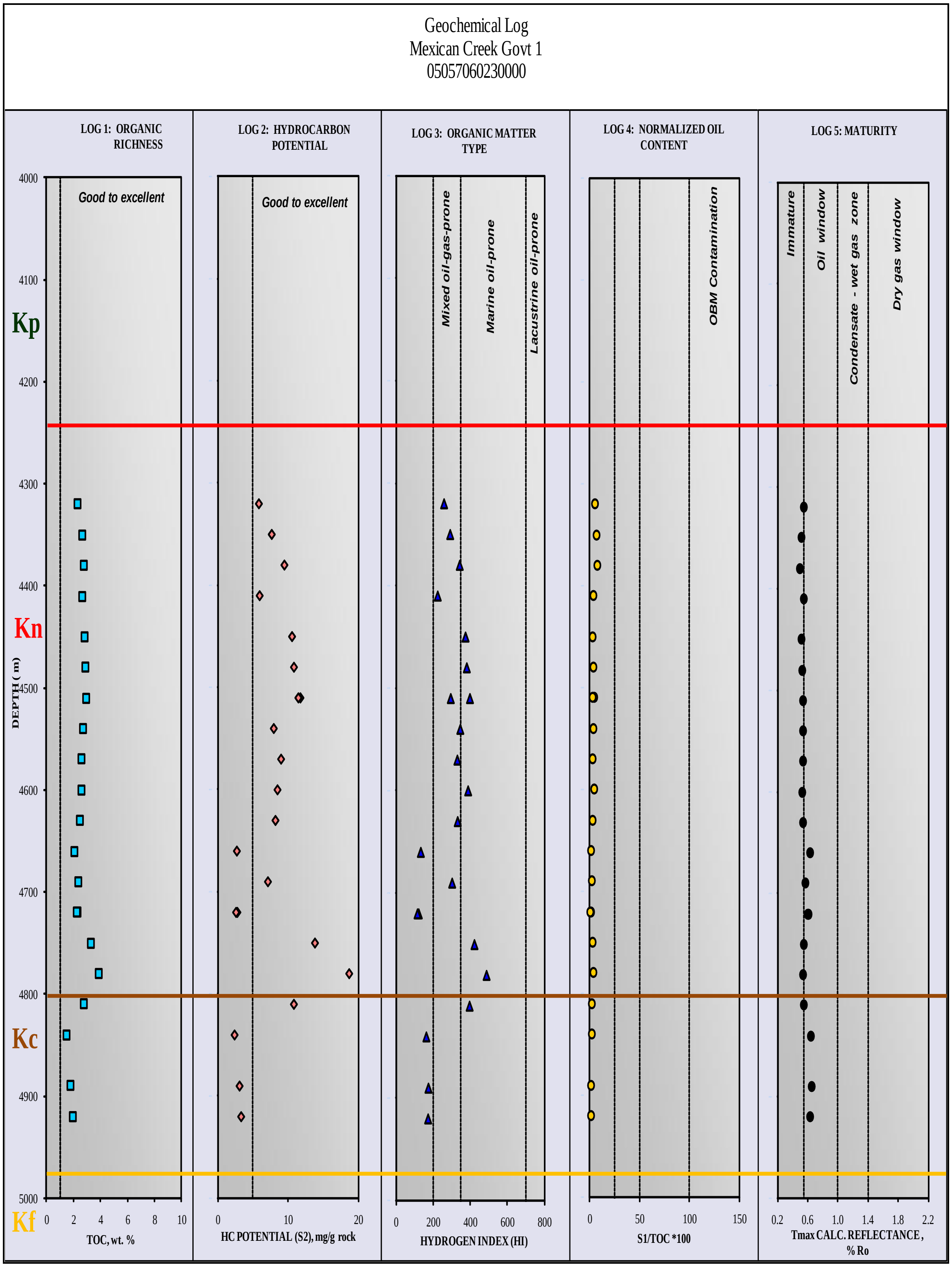


Figure 4.11 Geochemical Log for the samples tested for Mexican Creek Government 1. TOC (wt. %), S2 (mg HC/g rock), HI, S1/TOC*100, and Tmax calculated vitrinite reflectance are presented. Cuttings from Mexican Creek Government 1 were sampled on about 30 feet intervals, with a total of 20 samples, from 4320 to 4920 feet. Formations are indicated by labels; Kc (Carilie), Kf (Frontier), Kn (Niobrara) and Kp (Pierre).

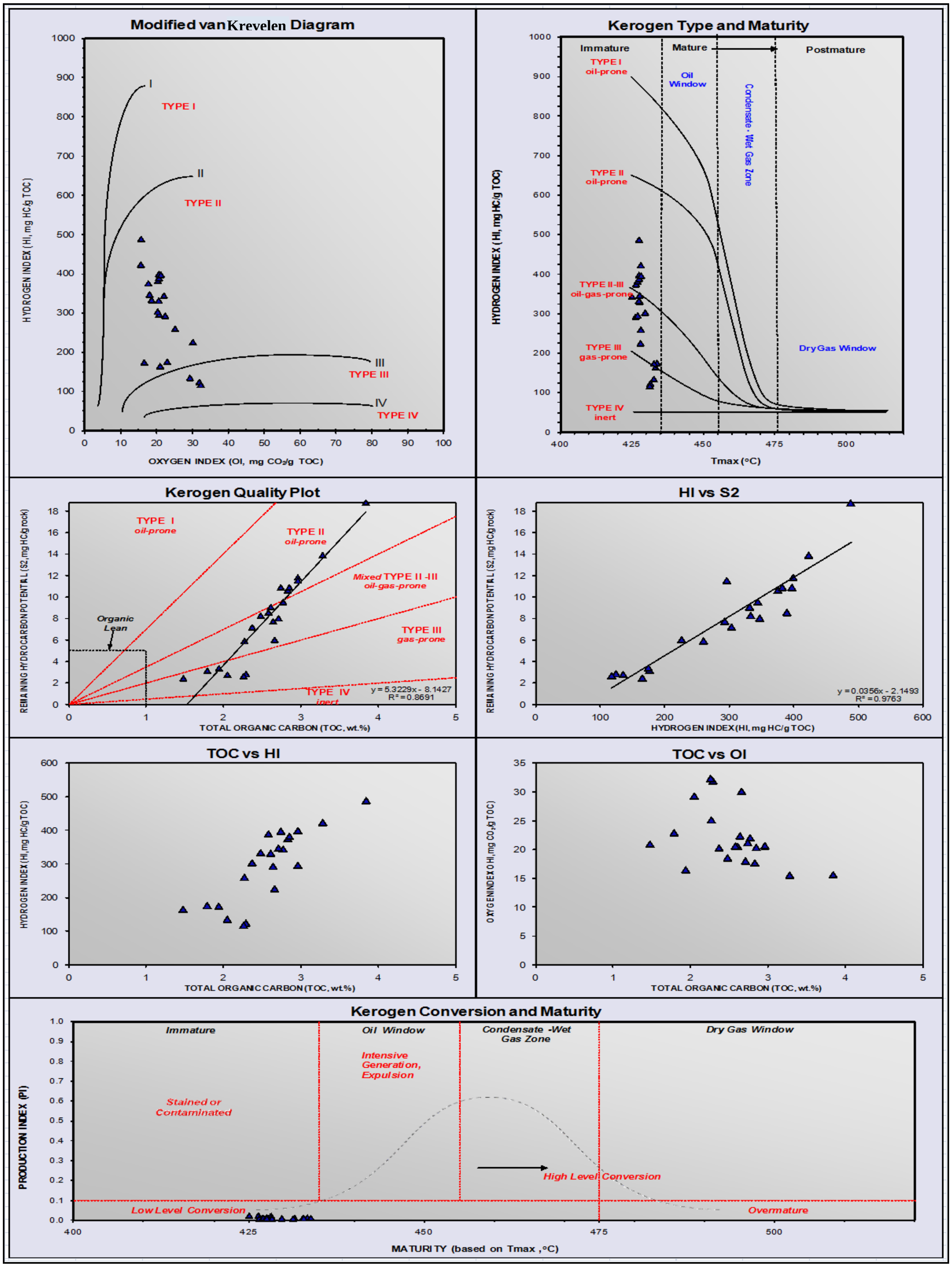


Figure 4.12 Geochemical Graphs for Mexican Creek Government 1. From Top to Bottom: Modified van Krevelen diagram HI vs. OI, Kerogen Type and Maturity Tmax vs. HI, Kerogen Quality TOC vs. S2, HI vs. S2, TOC vs. HI, TOC vs., OI, and Kerogen Conversion Maturity Tmax vs. PI.

(Carlile) -18.75 (Fort Hays), with most of the samples being in the good to very good petroleum potential interval; six of the S2 samples are in the fair petroleum potential range. When plotted on a modified van Krevelen diagram, the samples plot between the Type II and Type III lines. The HI values of the samples rank, according to Table 4.2, as Type III, mixed Type II and III and Type II kerogen. The S2/S3 values are variable and range from Type I to Type III kerogen. When TOC is plotted against S2, the samples plot as Type III, mixed Type II and III, and Type II kerogen. Based on the assumed depositional environment of this interval, it is expected that Type II kerogen would be present, perhaps mixed with some Type III kerogen. These data from the pyrolysis support this expectation.

In order to evaluate the maturity of the interval sampled, the Tmax values must be used as no vitrinite reflectance or thermal alteration index data were analyzed for this well. The Tmax values for this well range from 425-434°C. By referencing Table 4.5, these values indicate that the samples are immature for oil. The PI values for these samples are from 0.01 to 0.02. This indicates that all of the samples are immature. These both support that the interval tested has not reached maturity.

4.5.6 Meyring 41-10

Meyring 41-10 was completed in 1975 by True Oil. It is located in the SW ¼ of the NE ¼ of the NE ¼ of Section 10, T 6 N, R 80 W. Cuttings from Meyring 41-10 were sampled on about 30 foot intervals, with a total of 9 samples, from 9300 to 9940 feet. The samples were collected from the Niobrara Formation (6), the Carlile Shale (2), and Frontier Sandstone (1). The samples from the Niobrara Formation represent the upper chalk, upper marl, middle chalk, and lower chalk.

Of the samples tested, the total organic carbon values ranged from 1.64 (Carlile) to 2.56 wt.% (middle chalk). All of the samples have TOC values above 1 wt. %; all of the Niobrara samples are above 2 wt. %, rating in the very good petroleum potential window. However, the S1 values range from 0.05 (Frontier) - 0.3 (lower chalk) and, being under 0.5, are in the poor petroleum potential zone. The S2 values range from 0.6 (Carlile) -1.8 (middle chalk), all samples ranking in the poor petroleum potential interval.

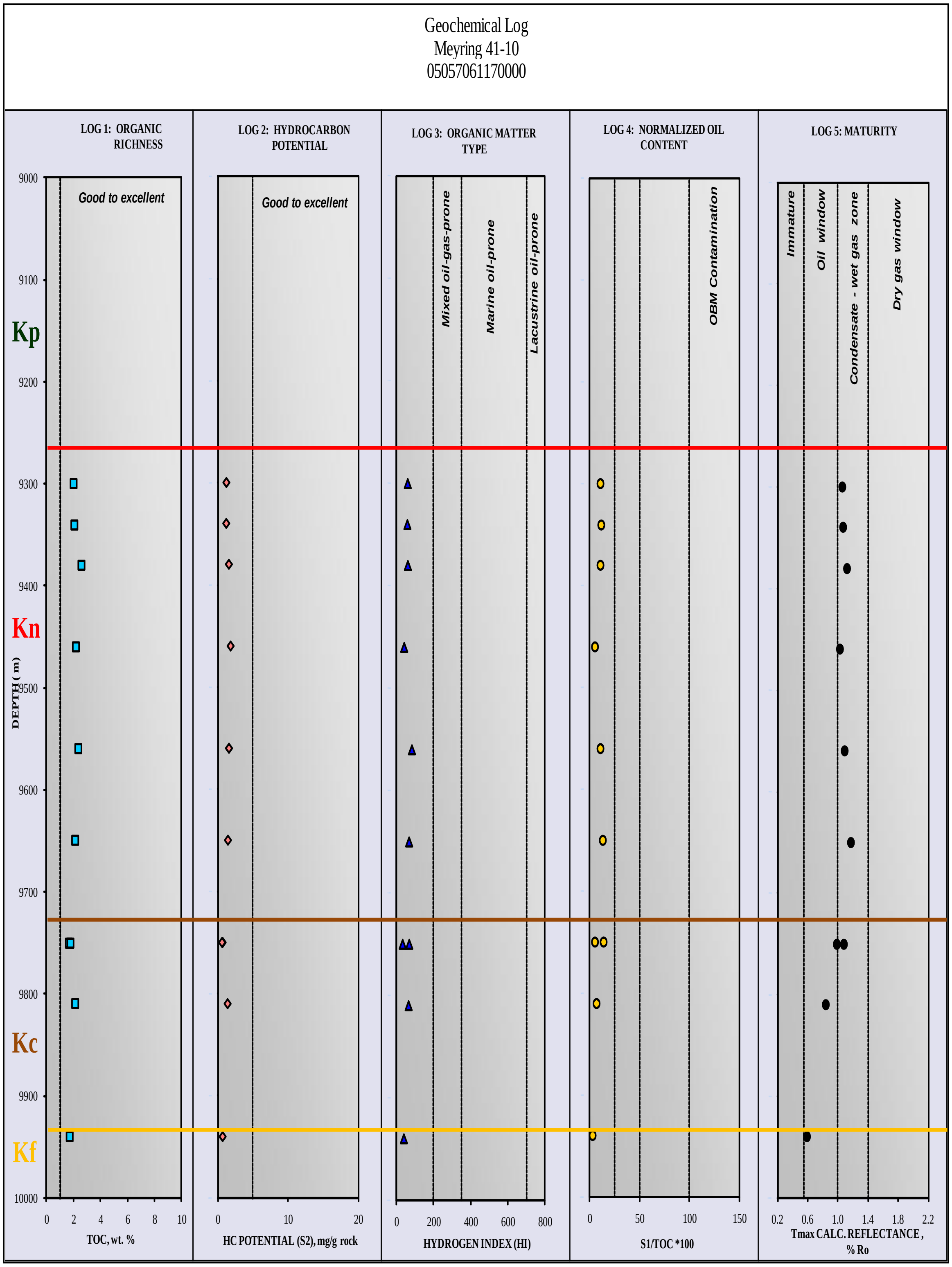


Figure 4.13 Geochemical Log for the samples tested for Meyring 41-10. TOC (wt. %), S2 (mg HC/g rock), HI, S1/TOC*100, and Tmax calculated vitrinite reflectance are presented. Cuttings from Meyring 41-10 were sampled on about 30 foot intervals, with a total of 9 samples, from 9300 to 9940 feet. Formations are indicated by labels; Kc (Carilie), Kf (Frontier), Kn (Niobrara) and Kp (Pierre).

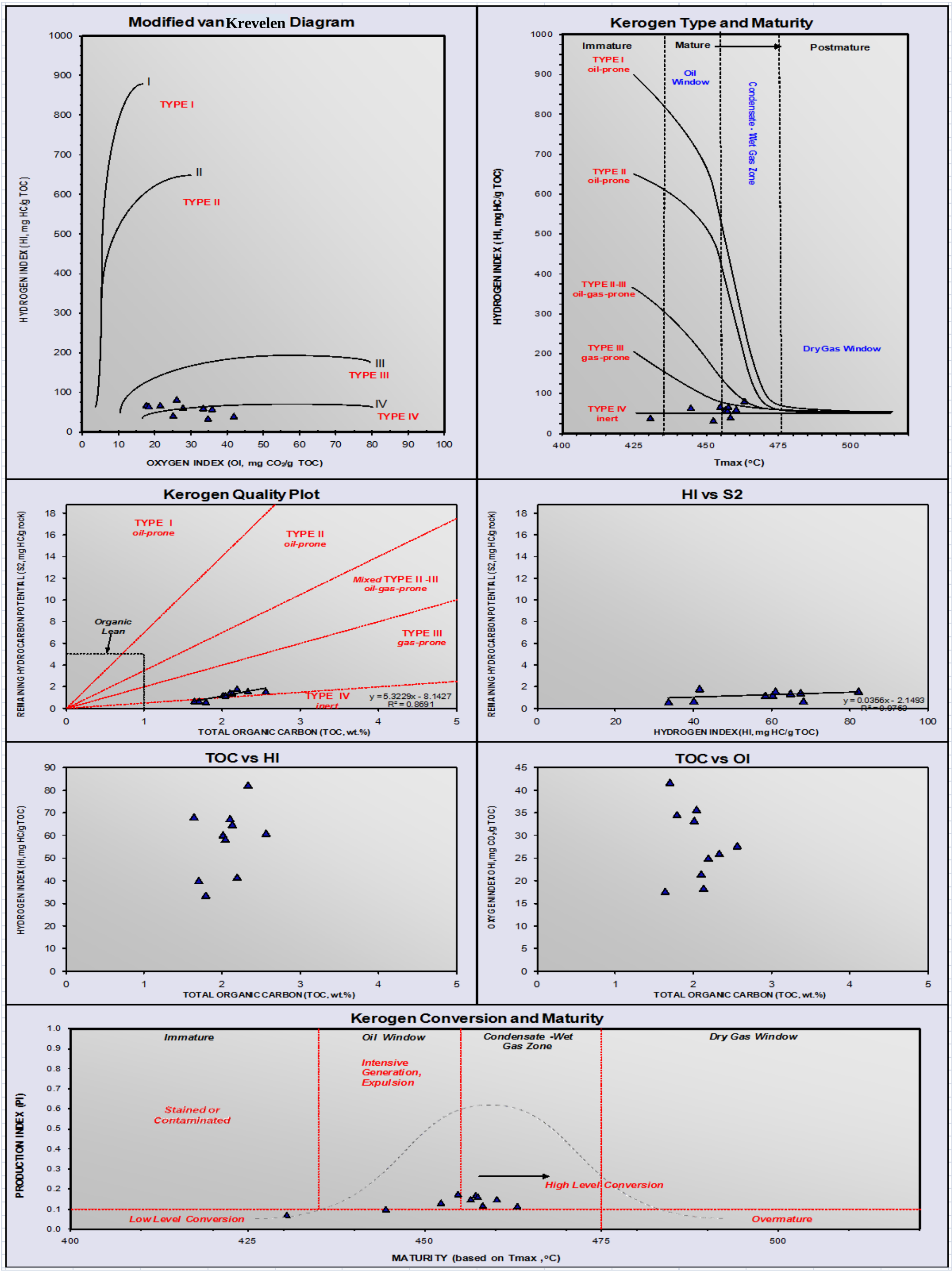


Figure 4.14 Geochemical Graphs for Meyring 41-10. From Top to Bottom: Modified van Krevelen diagram HI vs. OI, Kerogen Type and Maturity Tmax vs. HI, Kerogen Quality TOC vs. S2, HI vs. S2, TOC vs. HI, TOC vs., OI, and Kerogen Conversion Maturity Tmax vs. PI.

When plotted on a modified van Krevelen diagram, the samples plot between the Type III and Type IV lines. The HI values of the samples rank, according to Table 4.2, as Type III kerogen. The S2/S3 values are also in the Type III kerogen window. When TOC is plotted against S2, the majority of the samples plot as Type III kerogen, with two samples plotting as Type IV. As noted in previous wells, since these samples have reached a level of maturity, the original immature samples would plot closer to the Type II kerogen type lines. Based on the assumed depositional environment of this interval, it is expected that Type II kerogen would be present, perhaps mixed with some Type III kerogen. These data from the pyrolysis support this expectation.

In order to evaluate the maturity of the interval sampled, the Tmax values must be used as no vitrinite reflectance or thermal alteration index data were analyzed for this well. The Tmax values for this well range from 445-463°C, with an average of 456°C. By referencing Table 4.5, these values indicate that most of the samples are in a peak to late maturity window for oil. The PI values for these samples are from 0.07 (Frontier) to 0.17 (upper marl). This indicates that all but one of the samples are in the early mature window; the remaining sample is in the immature zone. These data support that the interval tested has reached maturity, most likely peak maturity to oil.

4.5.7 Ridge Government 28-1

Ridge Government 28-1 was completed in 1972 by Basin Petro. It is located in the SW ¼ of the NW ¼ of the NE ¼ of Section 28, T 6 N, R 81 W. Cuttings from Ridge Government 28-1 were sampled on about 30 feet intervals, with a total of 14 samples, from 4270 to 5000 feet. The samples were collected from the Niobrara Formation (11) and the Carlile Shale (3). The samples from the Niobrara Formation represent the upper chalk, upper marl, middle chalk, middle marl, and Fort Hays.

Of the samples tested, the total organic carbon values ranged from 1.85 (Carlile Shale) to 3.16 wt.% (middle chalk marl). All of the samples, but one, have TOC values above 2 wt. %; rating in the very good petroleum potential window. However, the S1 values range from 0.04 (middle chalk) - 0.3 (middle chalk marl) and, being under 0.5, are

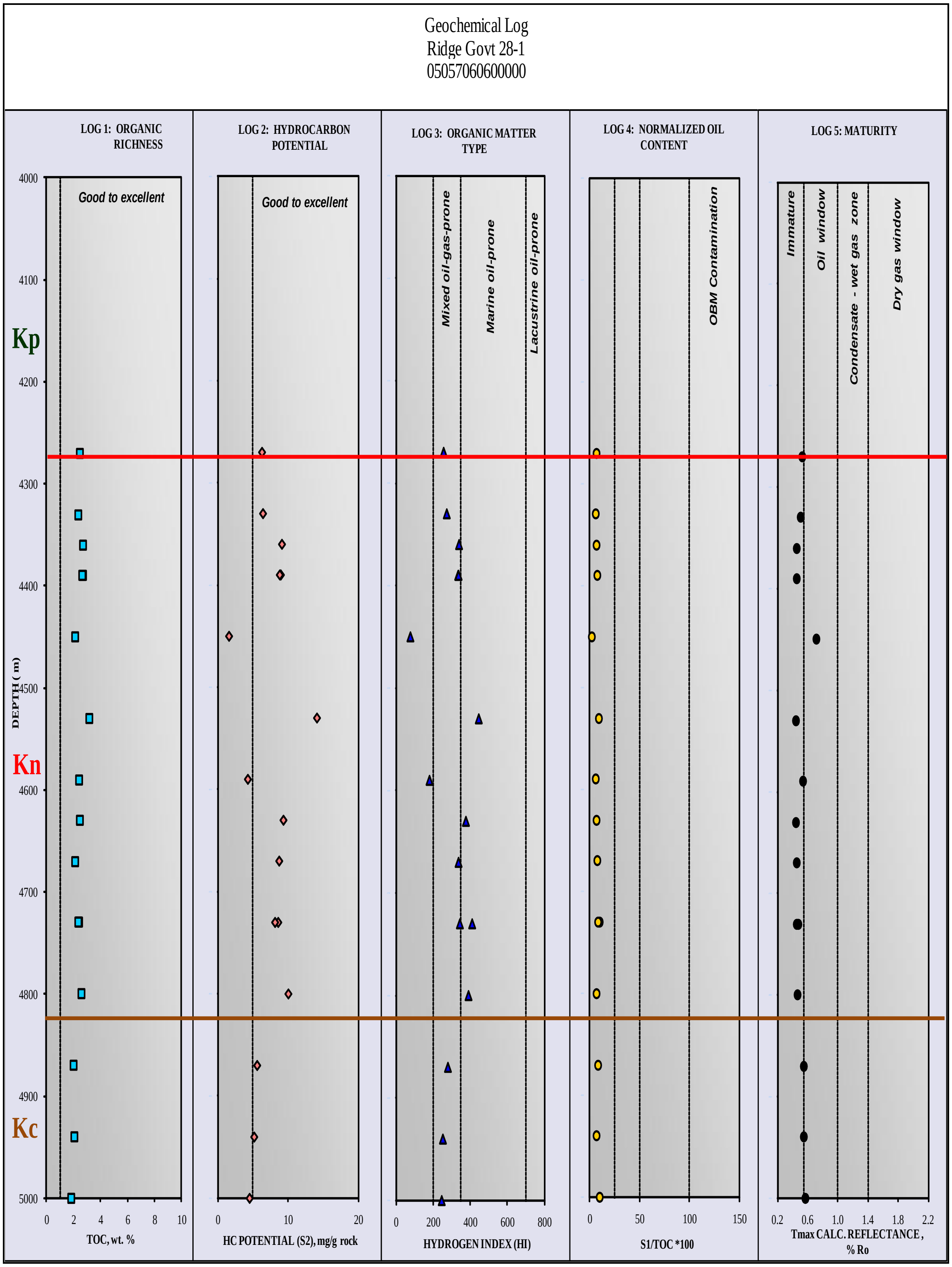


Figure 4.15 Geochemical Log for the samples tested for Ridge Government 28-1. TOC (wt. %), S2 (mg HC/g rock), HI, S1/TOC*100, and Tmax calculated vitrinite reflectance are presented. Cuttings from Ridge Government 28-1 were sampled on about 30 feet intervals, with a total of 14 samples, from 4270 to 5000 feet. Formations are indicated by labels; Kc (Carilie), Kf (Frontier), Kn (Niobrara) and Kp (Pierre).

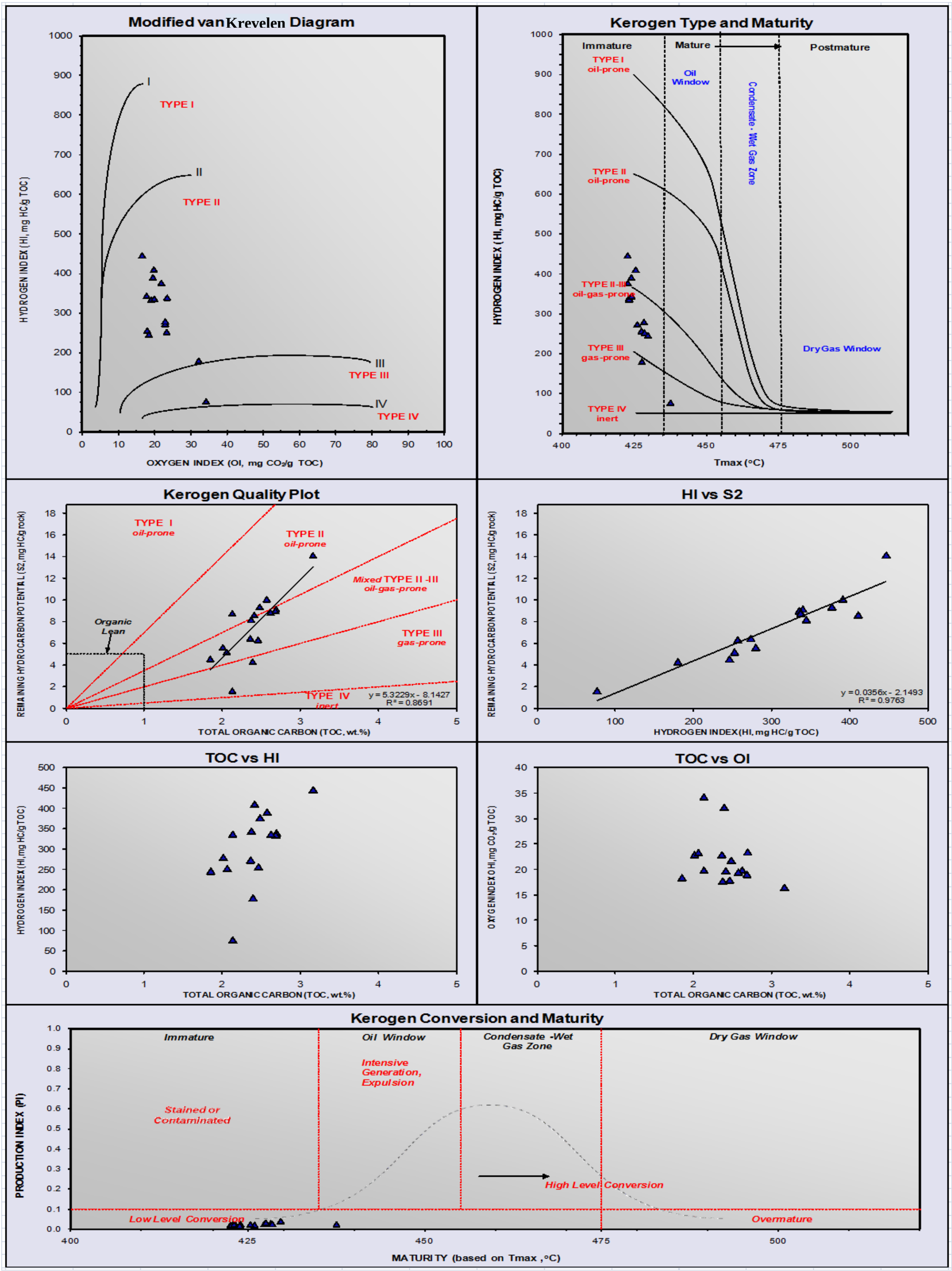


Figure 4.16 Geochemical Graphs for Ridge Government 28-1. From Top to Bottom: Modified van Krevelen diagram HI vs. OI, Kerogen Type and Maturity Tmax vs. HI, Kerogen Quality TOC vs. S2, HI vs. S2, TOC vs. HI, TOC vs., OI, and Kerogen Conversion Maturity Tmax vs. PI.

in the poor petroleum potential zone. The S2 values range from 1.63 (middle chalk) - 14.11 (middle chalk Marl), with most of the samples being in the good petroleum potential interval; Two S2 samples are in the very good petroleum potential. When plotted on a modified van Krevelen diagram, the samples plot between the Type II and Type III lines. The HI values of the samples rank, according to Table 4.2, as mainly mixed Type II and III kerogen. The S2/S3 values are in the Type I and Type II kerogen windows, aside from two samples, one in the Type III zone, and one in the mixed Type II and III interval. When TOC is plotted against S2, the majority of the samples plot as Type II and mixed Type II and III kerogen. One sample (Between 4,400 and 4,500 ft) has very low values and plots as Type IV. As the sample size for this analysis is already small (only 100mg), this outlier may be due to sampling an organic-lean interval. Based on the assumed depositional environment of this interval, it is expected that Type II kerogen would be present, perhaps mixed with some Type III kerogen. These data from the pyrolysis support this expectation.

In order to evaluate the maturity of the interval sampled, the Tmax values must be used as no vitrinite reflectance or thermal alteration index data were analyzed for this well. The Tmax values for this well range from 423-438°C. By referencing Table 4.5, these values indicate that most of the samples are immature for oil. The PI values for these samples are from 0.02 to 0.04. This indicates that all of the samples are immature. These data support that the interval tested has not reached maturity.

4.5.8 South Coalmont 1

South Coalmont 1 was completed in 1982 by Coseka Resources. It is located in the SW ¼ of the NW ¼ of the SW ¼ of Section 6, T 6 N, R 80 W. The well produced about 850 barrels of oil from the Niobrara and about 500 barrels from the Shannon Sandstone. Cuttings from South Coalmont 1 were sampled on about 20 feet intervals, with a total of 28 samples, from 6450 to 6990 feet. The samples were collected from the Pierre Shale (2), the Niobrara Formation (25), and the Carlile Shale (1). The samples from the Niobrara Formation represent the upper chalk, upper marl, middle chalk, middle marl, lower chalk, lower marl, basal chalk, and Fort Hays.

Figure 4.17 Geochemical Log for the samples tested for South Coalmont 1. TOC (wt. %), S2 (mg HC/g rock), HI, S1/TOC*100, and Tmax calculated vitrinite reflectance are presented. Cuttings from South Coalmont 1 were sampled on about 20 feet intervals, with a total of 28 samples, from 6450 to 6990 feet. Formations are indicated by labels; Kc (Carilie), Kf (Frontier), Kn (Niobrara) and Kp (Pierre).

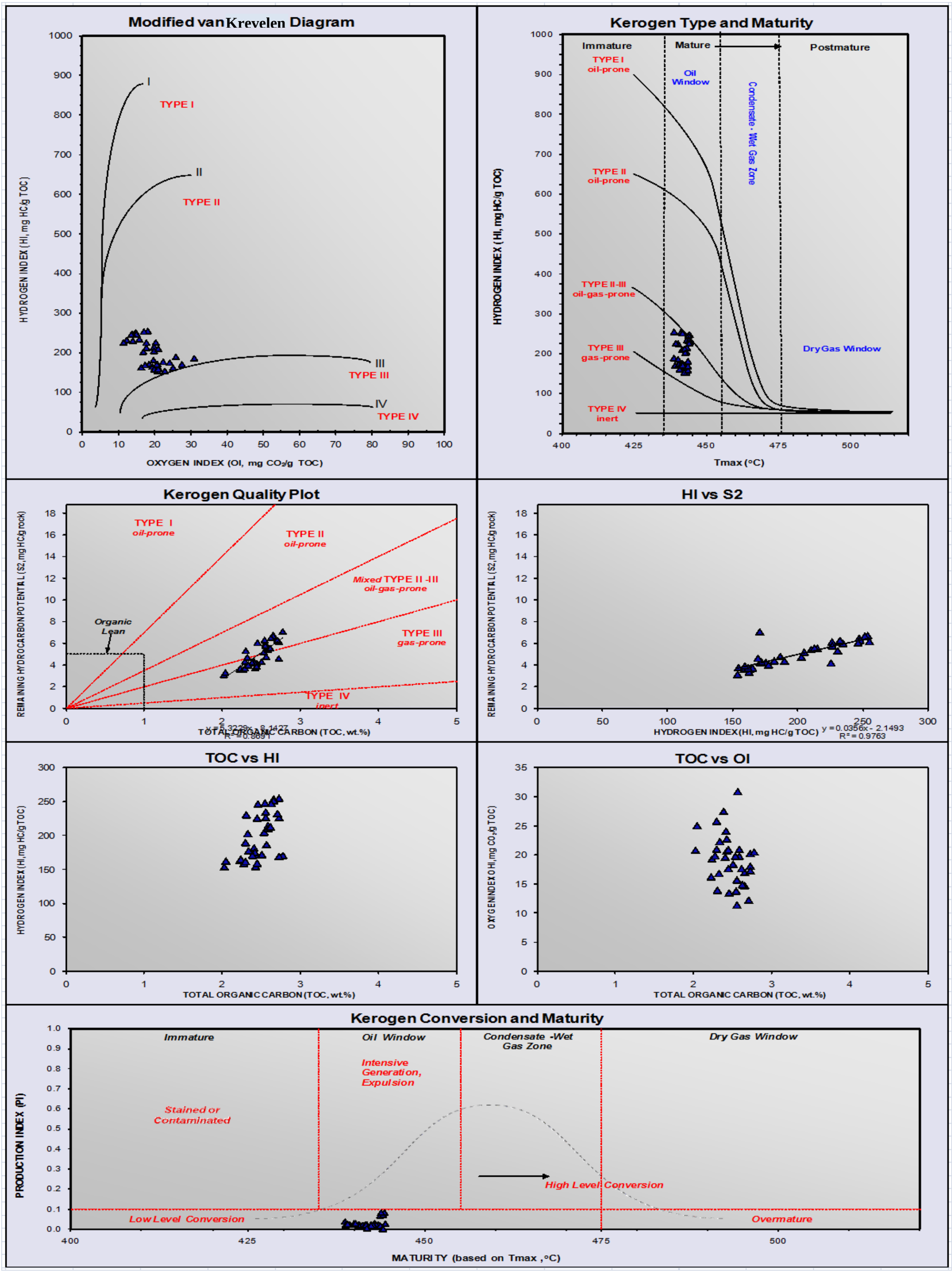


Figure 4.18 Geochemical Graphs for South Coalmont 1. From Top to Bottom: Modified van Krevelen diagram HI vs. OI, Kerogen Type and Maturity Tmax vs. HI, Kerogen Quality TOC vs. S2, HI vs. S2, TOC vs. HI, TOC vs., OI, and Kerogen Conversion Maturity Tmax vs. PI.

Of the samples tested, the total organic carbon values ranged from 2.02 (Pierre) to 2.77 wt.% (middle chalk). All of the samples have TOC values above 2 wt. %, rating in the very good petroleum potential window. However, the S1 values range from 0.01 (Fort Hays) - 0.17 (Pierre) and, being under 0.5, are in the poor petroleum potential zone. The S2 values range from 3.1 (Pierre) -7.06 (middle chalk), with most of the samples being in the fair to good petroleum potential interval. When plotted on a modified van Krevelen diagram, the samples plot between the Type II and Type III lines, but closer to the Type III line. The HI values of the samples rank, according to Table 4.2, as mainly mixed Type II and III kerogen. The S2/S3 values are varied and plot in the Type I, Type II, and Type III kerogen windows. When TOC is plotted against S2, the majority of the samples plot as mixed Type II and III and Type III kerogen. As noted in previous wells, since these samples have reached a level of maturity, the original immature samples would plot closer to the Type II kerogen type lines. Based on the assumed depositional environment of this interval, it is expected that Type II kerogen would be present, perhaps mixed with some Type III kerogen. These data from the pyrolysis support this expectation.

In order to evaluate the maturity of the interval sampled, the Tmax values must be used as no vitrinite reflectance or thermal alteration index data were analyzed for this well. The Tmax values for this well range from 439 to 444°C, averaging 441°C. By referencing Table 4.5, these values indicate that most of the samples are in the early maturity window for oil. The PI values for these samples are from 0 to 0.04. This indicates that all of the samples are immature. Though these contradict each other, the interval tested has reached early maturity as the Tmax maturity indicators provide a more reliable trend.

4.6 Summary and Discussion

This chapter presented and interpreted the results of the pyrolysis and TOC analysis performed on cuttings from eight wells from around the North Park Basin. Much of details of these results are unique to each well, but there are some characteristics that all of them share. The TOC content of the Niobrara is consistently from 1-4 wt.% TOC, mostly being in the 2-3 wt.% interval. This ranks the Niobrara as having a good to very good petroleum potential. The kerogen type indicators of the samples show that Kerogen Type II is dominantly present in all of the samples, with some Type III kerogen. This is supported by the interpreted depositional environment of the Western Interior Seaway. The maturity indicators from the analysis show that the Niobrara is immature to peak mature to oil in different areas across the basin.

The cuttings of three of the wells, Federal 1, Mexican Creek Government 1, and Ridge Government 28-1, are immature based on their Tmax values, and consequently remain at or near their original hydrogen and carbon levels. The samples from these wells plot in similar trends and plot the closest to the Type II kerogen lines on the geochemical plots. It can be inferred that these samples contain mainly Type II kerogen, with some Type III probably present. The samples for the remaining wells have reached differing levels of maturation. As hydrocarbons have been generated from these samples, some of the original hydrogen and carbon have been depleted, and plot with lower hydrogen and carbon values when compared to the immature samples. The original composition of these samples is closer to that of the immature samples.

The Niobrara samples contain mainly Type II kerogen. Type II kerogen first produces oil upon maturation. With increased maturity, condensate and gas are produced from Type II kerogen. Based on the Tmax values seen in the mature samples, the Niobrara has reached maturation levels that correspond to the generation of oil and condensate, and consequently mostly liquid hydrocarbons should have been generated from the Niobrara.

As the shoreline of the WIS trended north and south, facies changes would be expected to be present perpendicular to this direction, in an east to west direction. Samples closest to the margins would be expected to contain more type III kerogen; samples in furthest from the shoreline would be dominated by type II kerogen and contain little type III kerogen. As there are only three wells which contain immature samples it is difficult to observe such trends in these data.

CHAPTER 5

SOURCE ROCK EVALUATION

The aim of this chapter is to evaluate the source potential of each of the identified intervals of the Niobrara. In order to characterize the source rock potential of each of the intervals, data from pyrolysis and a log-derived TOC petrophysical technique are compared. The measured pyrolysis data from 17 wells available from the USGS were combined and analyzed on an interval to interval basis, including the TOC values. The pyrolysis data are also used to estimate the maturity across the basin. The method developed by Passey et al. (1990) is used to approximate TOC in 34 wells, 18 without pyrolysis data, by using the resistivity and sonic logs.

5.1 TOC Analysis

As part of this study, cuttings from 8 wells from the North Park Basin were collected and analyzed using a SRA-TOC analyzer. In addition, data from similar previous analysis are available from the USGS. These analyses were performed on cuttings from 19 wells. The location of these wells may be seen in Figure 4.1, in the preceding chapter of this thesis. Reports from these previous studies can be seen in Appendix C. The data from the previous studies were combined with the data collected as part of this thesis. This compilation was divided by interval based on the depth of the cuttings and the interpreted interval as a result of the stratigraphic evaluation detailed in chapter 3 of this study. Table 5.1 provides a summary of the TOC data by interval.

5.2 Log-derived TOC

A technique developed by Passey et al., (1990), has been found to estimate the TOC of both shale and carbonate source rocks over a range of maturities, LOM 6 to LOM 12. This method uses the separation between the sonic transit time log and the

Table 5.1 Table of measured TOC from samples from wells in North Park Basin.

		TOC				
		Number of samples	**Minimum**	**Mean**	**Maximum**	**Standard Deviation**
Total Niobrara		168	0.47	2.34	4.89	0.65
	Upper chalk	16	0.47	1.80	2.99	0.72
	Upper marl	29	1.25	2.55	4.67	0.58
	Middle chalk	60	1.19	2.39	3.73	0.57
	Upper chalk	26	1.19	2.50	3.73	0.60
	Marl	22	1.31	2.30	3.16	0.58
	Lower chalk	12	1.32	2.32	2.85	0.49
	Middle marl	22	1.18	2.29	3.07	0.42
	Lower chalk	17	1.09	2.40	4.89	0.80
	Lower marl	9	0.81	2.05	3.78	0.82
	Basal chalk	10	1.28	2.47	3.87	0.73
	Fort Hays	5	1.77	2.69	3.84	0.74
Carlile		55	0.51	1.48	2.87	0.62

resistivity log. This separation is called Δ log R. It is based on the relationship between the solid and fluid components of rocks, and the response they have on sonic and resistivity logs. In organic-lean, water-saturated rocks both curves respond to variations in formation porosity. However, in organic-rich rocks and hydrocarbon reservoirs, a separation of the two curves exists from the porosity log response to low density, low velocity kerogen and the increase in resistivity from the presence of hydrocarbon filled porosity. A relationship between the separation of the curves and the maturity of the rocks, using baseline values for the logs, has been developed to estimate the TOC. The following equations demonstrate this relationship (Passey et al., 1990):

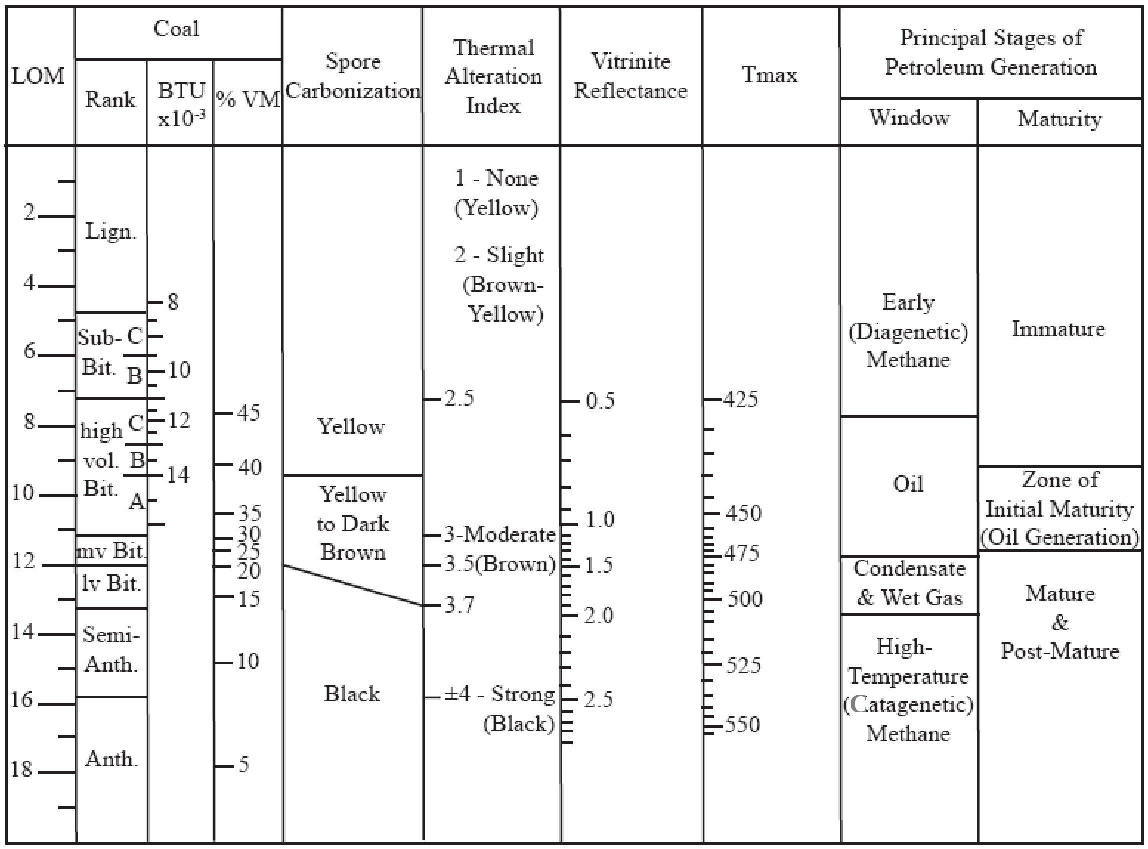
$$\Delta \log \mathrm{R} = \log_{10}\left(\frac{R}{R_{baseline}}\right) + 0.02 \times (\Delta t - \Delta t_{baseline})$$

$$TOC = (\Delta \log R) \times 10^{(2.297-(0.1668 \times LOM))} + 0.8$$

R is the resistivity measured in ohm-m; Δt is the measured transit time in µsec/ft. $R_{baseline}$ and $\Delta t_{baseline}$ are the values of the resistivity and sonic logs in a non-source, clay-rich rock in the well, as defined by the interpreter. The constant 0.02 is multiplied to the Δt value based on the ratio of -50μsec/ft per one resistivity cycle. LOM is the level of maturity, usually estimated from vitrinite reflectance, spore coloration, or Tmax data. A LOM of 7 corresponds to the onset of maturity and a LOM of 12 corresponds to the onset of overmaturity, both in oil-prone kerogen. Table 5.2 shows the relationship between other indicators of maturity, including thermal alteration index, vitrinite reflectance, and Tmax. (Appendix D). The constant 0.8 is added to the TOC to account for background TOC A chart was constructed from this relationship in order to convert Ro to LOM values Otherwise the non-source, baselined intervals would have a TOC of 0, which is not geologically reasonable for a clay-rich rock. Since the Δ log R separation may occur in both reservoir and source units, gamma-ray and spontaneous potential logs can be used to remove the reservoir units.

In practice, difficulty in determining the baseline and LOM values is not uncommon. Passey et al. (1990) suggest that for each well, the sonic baseline value should remain constant and the resistivity baseline value should vary with depth (e.g. due to a change in lithology) in order to "baseline" the curves. The baseline interval, in addition to being a non-source clay-rich rock, needs to be at a similar stratigraphic interval, as well as share similar lithology as the interval for which the analyst is attempting to approximate TOC values. In addition, direct maturity indicators are usually not available for most wells and must be approximated. In this study TOC is derived for 34 wells with resistivity and sonic logs (Figure 5.1). The baseline interval used is the Carlile Shale, as the lowest TOC values measured are from this unit. For each well for which TOC values were log derived, the mean resistivity and mean sonic values from the Carlile were used as the baseline values. In addition, a maturity map was created using the Niobrara Tmax mean values. The Tmax values were converted into LOM values (based on Table 5.2) and the LOM values were contoured throughout the basin. The maturity for wells without measured Tmax was extrapolated from this map. A TOC log for each of the 34 wells was constructed. Figure 5.2 shows the TOC log for the type well for this study. TOC logs for other wells may be seen in Appendix E. The calculated TOC log values in each well were averaged for each interval of the Niobrara. A table of these averages may be seen in Tables 5.3 and 5.4, in which the calculated TOC log values are

Table 5.2 Relationship between indicators of thermal maturity and the stages of petroleum generation. This diagram depicts a mix of thermal stress indicators (e.g. Vitrinite Reflectance) and hydrocarbon generation indicators (e.g. Tmax). Tmax and petroleum windows and maturity vary with kerogen type; this table is based on Type II kerogen. Modified after Hood et al. (1975).



averaged for each unit by well; Table 5.5 combines the information from each well. Overall, the Niobrara log derived TOC averaged 2.75 wt. %, and ranged from 0.61 to 5.57 wt. %.

This application of the Passey et al. (1990) method allows for the TOC of the Niobrara to be approximated in wells for which there is no measured TOC but resistivity and sonic logs exist. However, it is just that, an approximation. Care must be taken in interpreting the approximated values. In the particular case of the Niobrara, portions of the unit contain intervals of potential reservoir quality rocks (mainly in the purest chalks). These reservoir units are prone to erroneous TOC approximations, as the method is meant

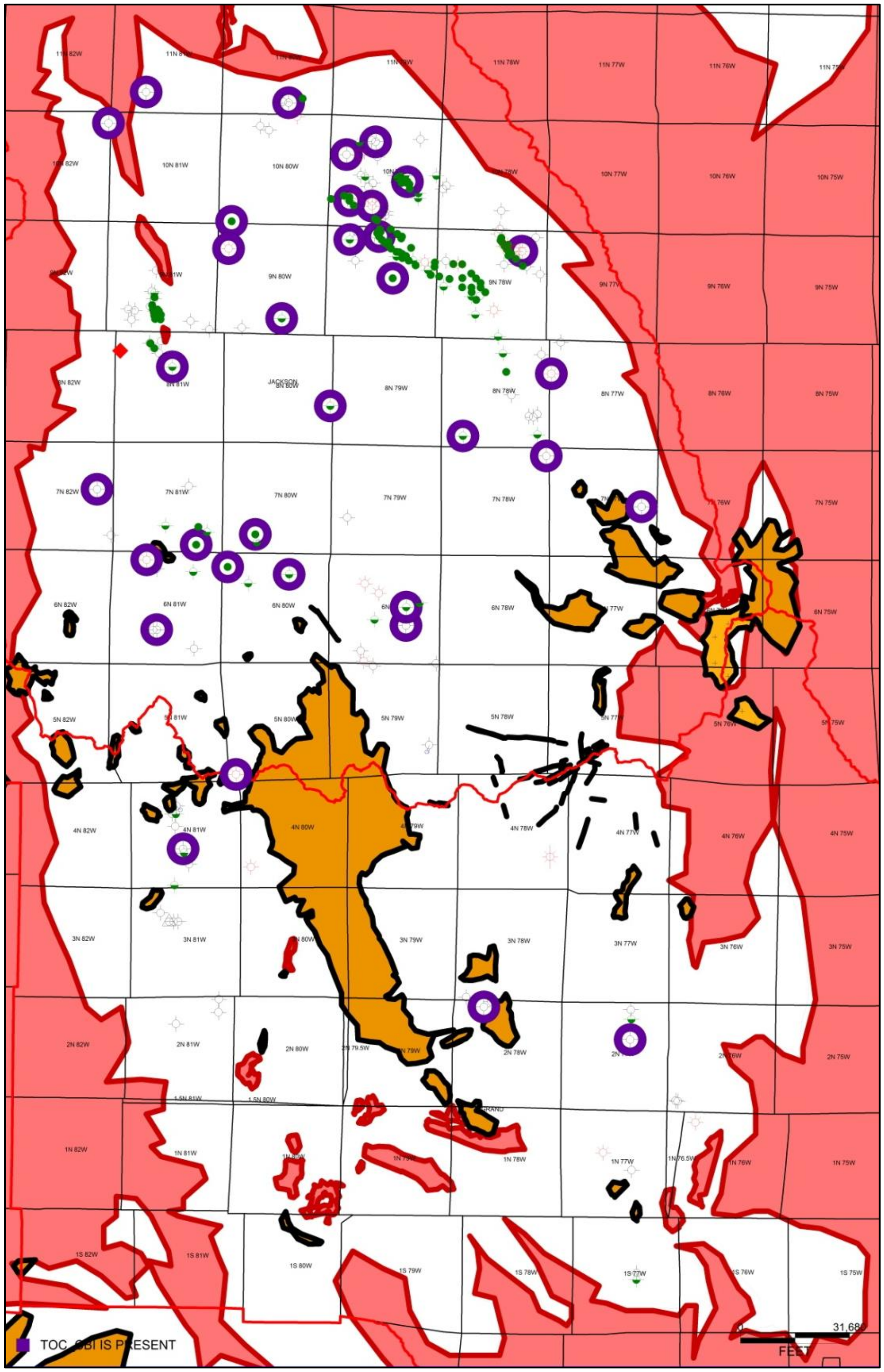


Figure 5.1 Location of the 34 wells for which TOC is derived from resistivity and sonic logs in the Niobrara Formation using the Passey et al. (1990) method.

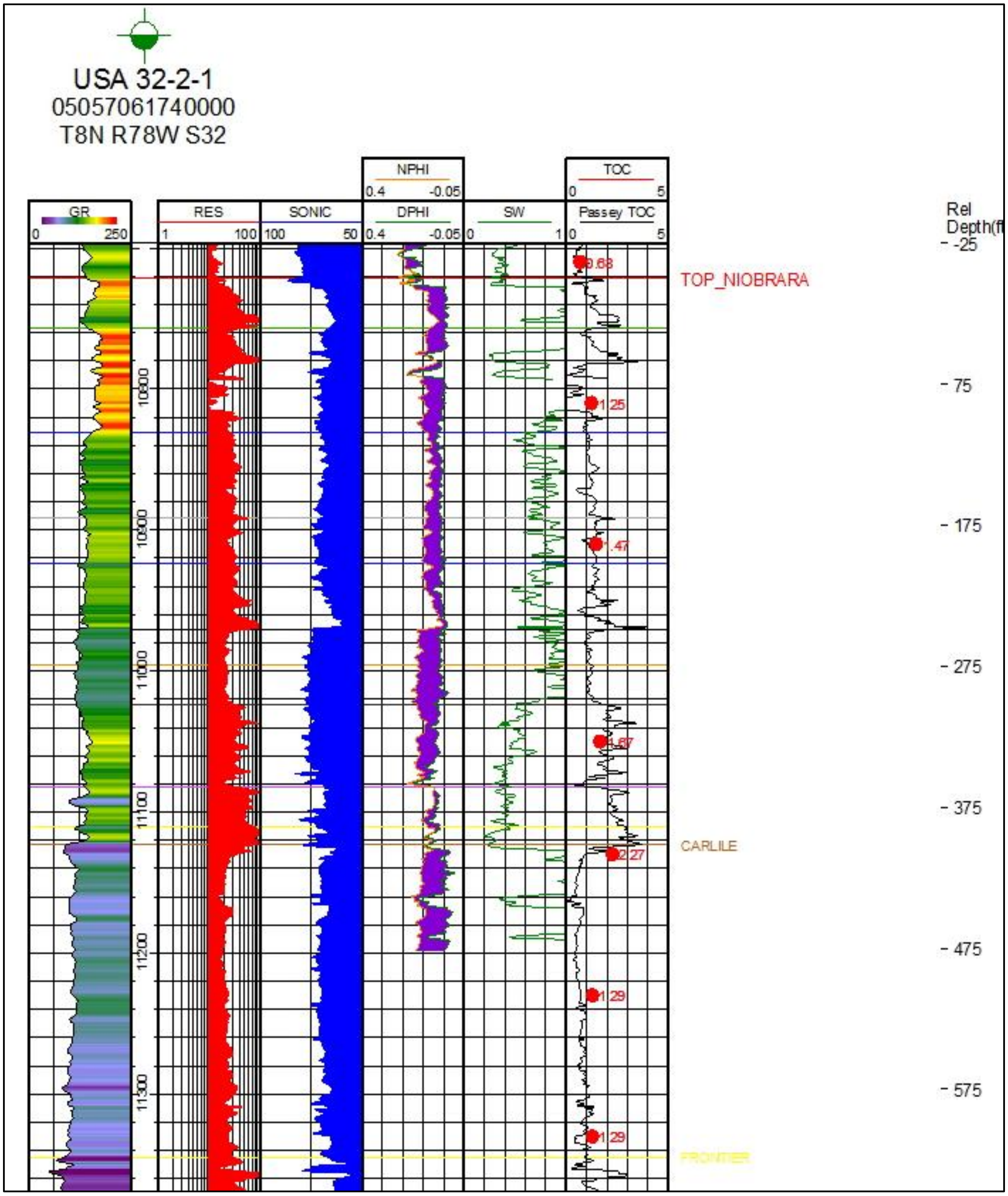


Figure 5.2 The Type Log for this study, here demonstrating the DPHI and NPHI logs in the fourth track, Sw in the fifth track, and log derived TOC in the sixth track with measured TOC values from cuttings analysis.

Table 5.3 Average of Log Derived TOC by Interval by well (1 of 2). These values were calculated from the TOC log derived from the Resistivity and Sonic Logs after Passey et al. (1990)

AVERAGE LOG DERIVED TOC (1 of 2)																	
WELL NAME	STATE-B 1	USA-William Hewit 1	GRANBY UNIT 1	32	Federal 1	South Coalmont 1	Conoco Fischer 15-1	2	Dwinell 3-A	STATE C-NCT 1	GOVT 1-35 1	VOLUSIA LOCATIONS	USA 32-2-1	Funk Trust 1-1	1-5	JONES 41-18	CRYSTAL SPRINGS 22
API NUMBER	0504905020000	0504906001000	0504906024000	0505705110000	0505706249000	0505706244000	0505706260000	0505706141000	0505706226000	0505705086000	0505706061000	0505706072000	0505706174000	0505706338000	0505706339000	0505706377000	0505706380000
TOTAL NIOBRARA	4.48	3.20	5.57	2.81	4.69	2.92	3.75	1.60	1.36	1.30	3.57	3.74	1.49	1.68	1.61	1.75	1.14
UPPER CHALK	4.64	3.00	5.34	2.73	8.40	2.06	2.05	1.33	1.16	2.07	2.29	5.53	1.49	1.64	1.41	1.63	0.98
UPPER MARL	4.49	3.40	5.36	3.14	4.10	2.73	3.37	1.47	1.32	1.53	3.66	4.53	0.93	0.01	1.01	1.80	1.19
MIDDLE CHALK	4.87	3.43	5.28	3.17	5.51	3.07	4.40	1.76	1.33	1.32	3.96	4.57	1.36	1.67	1.66	2.10	0.96
***UPPER MIDDLE CHALK**	5.80	2.83	4.91	2.91	5.20	2.97	4.10	1.83	1.30	1.29	3.91	4.20	1.21	1.19	1.33	2.06	1.16
***MIDDLE CHALK MARL**	4.74	3.64	5.47	3.23	4.34	3.08	4.40	1.94	1.49	1.23	4.15	4.52	1.38	1.62	1.47	2.12	1.00
***LOWER MIDDLE CHALK**	4.31	4.24	5.69	3.67	6.34	3.16	4.80	1.58	1.26	1.41	3.78	5.38	1.55	2.52	1.90	2.14	0.71
MIDDLE MARL	4.32	2.98	7.47	2.48	3.07	2.74	3.58	1.28	1.29	1.14	3.11	2.74	1.13	2.12	1.18	1.48	1.30
LOWER CHALK	5.82	2.64	5.97	2.30	2.07	3.71	3.55	1.65	1.56	1.19	3.90	1.43	1.24	2.25	2.44	1.43	1.43
LOWER MARL	1.97	2.61	5.73	2.54	3.07	2.99	3.33	1.80	1.69	1.04	3.93	2.18	1.99	2.48	2.21	1.55	1.48
BASAL CHALK	0.36	3.28	4.65	2.07	3.74	3.56	3.11	1.03	1.27	1.02	3.94	4.25	2.40	2.47	1.84	1.35	1.11
FORT HAYS	0.00	3.59	5.50	2.55	3.51	1.94	4.19	1.26	1.36	0.63	3.99	4.15	3.11	0.98	1.21	1.49	1.00
CARLILE	0.74	0.71	0.70	0.77	0.70	0.78	0.66	0.76	0.76	0.77	0.67	0.57	0.75	0.78	0.52	0.77	0.77

Table 5.4 Average of Log Derived TOC by Interval by well (2 of 2). These values were calculated from the TOC log derived from the Resistivity and Sonic Logs after Passey et al. (1990)

AVERAGE LOG DERIVED TOC (2 of 2)																	
WELL NAME	FEE 1	Ridge-Govt 28-1	CHEDSEY-A 1	13-7	29-12-7	Mexican Creek-Govt 1	LANMON-GOVT 1-A	GOVT 1	Federal 1-24	23-13	Lindland Unit 1-24	Holliday 14-1	Federal B-1	1-N-31	Meyring 41-10	Platte Cattle Co 1	VANETA 1-32D
API NUMBER	05057051500000	05057060600000	05057060630000	05057062830000	05057061280000	05057060230000	05057050890000	05057060680000	05057060710000	05057062910000	05057062300000	05057062570000	05057060840000	05057060980000	05057061170000	05057060860000	05057064670000
TOTAL NIOBRARA	3.05	3.39	3.68	2.69	2.58	3.33	4.23	1.31	3.39	3.42	0.61	3.90	2.91	2.07	1.84	1.43	3.09
UPPER CHALK	4.83	3.08	3.67	2.71	2.62	2.60	4.26	2.11	2.58	3.00	0.82	3.69	2.32	1.78	1.39	1.54	2.03
UPPER MARL	3.98	2.89	4.14	2.21	2.17	3.40	4.40	1.56	3.32	3.74	1.62	3.97	2.72	1.49	1.25	1.50	2.53
MIDDLE CHALK	2.50	3.77	3.84	2.67	3.29	3.75	4.84	1.35	4.12	3.74	1.04	3.98	3.48	2.08	1.96	1.62	3.39
***UPPER MIDDLE CHALK**	3.03	4.78	4.22	2.60	2.45	3.73	5.69	1.38	3.95	3.82	1.91	4.03	3.05	2.05	1.88	1.54	3.58
***MIDDLE CHALK MARL**	3.17	3.74	4.12	2.61	2.61	3.35	5.72	1.49	4.56	3.69	0.30	3.82	3.39	1.54	1.93	1.64	3.48
***LOWER MIDDLE CHALK**	0.70	2.69	3.04	2.99	4.31	4.16	3.81	1.13	3.85	3.70	0.19	4.16	4.05	2.69	2.07	1.91	3.01
MIDDLE MARL	2.94	2.83	3.31	3.00	2.76	2.43	3.02	1.26	2.77	2.65	0.21	3.30	2.69	1.41	1.76	1.25	2.97
LOWER CHALK	2.98	3.46	3.13	3.79	2.33	4.22	2.35	1.10	2.84	2.93	0.11	4.65	2.41	1.82	2.30	1.34	3.08
LOWER MARL	2.80	4.69	4.13	2.36	1.81	4.34	4.89	1.11	2.55	4.11	0.00	4.85	2.82	2.53	2.11	1.03	3.34
BASAL CHALK	1.95	5.67	3.64	2.34	1.64	5.16	3.81	0.83	3.13	0.94	0.26	4.27	2.90	3.14	2.37	1.09	2.91
FORT HAYS	1.31	1.32	3.67	2.95	1.63	2.19	2.40	0.81	3.40	0.68	0.00	1.30	3.26	2.81	1.48	1.24	3.37
CARLILE	0.54	0.75	0.83	0.72	0.77	0.78	0.66	0.79	0.69	0.74	0.36	0.73	0.74	0.74	0.77	0.79	0.67

Table 5.5 Summary of Log Derived TOC by Interval. These values represent the minimum, maximum, average, and standard deviation by interval for the 34 well in which log derived TOC was calculated from the Resistivity and Sonic Logs after Passey et al. (1990)

AVERAGE LOG DERIVED TOC SUMMARY				
	min	max	mean	stdev
TOTAL NIOBRARA	0.61	5.57	2.75	1.19
UPPER CHALK	0.82	8.40	2.73	1.59
UPPER MARL	0.01	5.36	2.68	1.31
MIDDLE CHALK	0.96	5.51	2.99	1.33
***UPPER MIDDLE CHALK**	1.16	5.80	3.00	1.40
***MIDDLE CHALK MARL**	0.30	5.72	2.97	1.39
***LOWER MIDDLE CHALK**	0.19	6.34	3.03	1.51
MIDDLE MARL	0.21	7.47	2.47	1.28
LOWER CHALK	0.11	5.97	2.63	1.31
LOWER MARL	0.00	5.73	2.71	1.29
BASAL CHALK	0.26	5.67	2.57	1.41
FORT HAYS	0.00	5.50	2.18	1.35
CARLILE	0.36	0.83	0.71	0.09

to measure the TOC of only source rocks. It is believed that such intervals are responsible for the anomalously high TOC values, such as the 8.40% TOC approximation in the upper chalk due to increases in the resistivity values related to increased porosity. In addition, this method only estimates the carbon content of an interval and not the amount of hydrogen present in the sample. In order to have generated hydrocarbons, both carbon and sufficient hydrogen must have been present in the original organic matter.

5.4 Maturity

The maturity of the Niobrara Formation throughout the North Park Basin was analyzed using the Tmax values from pyrolysis. Landon et al. (2001) determined that the Niobrara source rock begins to generate hydrocarbons at a thermal maturity equivalent to a Tmax value of 432°C. A contour map of the Tmax values from pyrolysis was constructed (Figure 5.3). This map shows that much of the basin has Tmax values in the Niobrara above the 432°C threshold, and that the interval is mature for oil generation. This map suggests that the movement of the faults is responsible for increasing the thermal maturity of the Niobrara. Areas in which the Niobrara is the most mature are located in the most deeply buried areas on the low side of the faults. The most obvious of these areas is located in the center of the basin, south of the Spring Creek Fault Zone and to the west of the main thrust fault. In addition, north of the Spring Creek Fault Zone the northern and eastern areas are more mature.

5.5 Source Rock Discussion

Based on the pyrolysis data from the outcrop and subsurface cuttings, kerogen Type II is dominantly present in the Niobrara, with some Type III kerogen. This kerogen type implies a reducing marine depositional environment. With increasing maturation, Type II kerogen will generate oil, condensate, and then gas. Total organic content was measured in both outcrop and subsurface cuttings and estimated in the subsurface using resistivity and sonic logs. The TOC measured in the samples from the Niobrara ranges from 0.5-5 wt% TOC, with the majority of these samples ranging from 2-3 wt. % TOC and average 2.3 wt. %. The log derived TOC calculations (after Passey, 1990) match the measured values but are, as expected, more variable. The log derived TOC measurements in the Niobrara range from 0 to 8.40 wt.% TOC and average 2.75 wt.%. In the absence of measured TOC, the log-derived TOC act as a good proxy. However, anomalous measurements may be in response to very tight or very porous intervals, and care should be used in using these measurements. This TOC rates the Niobrara as having very good source rock potential. As previously discussed, sufficient hydrogen must also have been available in order to produce hydrocarbons. Hydrogen indices measured in immature samples from outcrop and the subsurface indicate that HI values between 100 and 500 are originally present in the Niobrara. Maturity in the basin was measured with Tmax values from pyrolysis from samples from both the outcrop and subsurface cuttings. Areas in which the maturity of the Niobrara is highest are located in the center of the basin where the Niobrara is buried the deepest. The areas north of the Spring Creek Fault Zone in the northern and eastern areas are also more mature. Based on this maturity and the presence of type II kerogen, oil and condensate should have been generated in mature areas of the Niobrara.

Based on the data present, there are no predictable differences between the source rock quality of the chalk-rich intervals when compared to the marl-rich intervals. This may be in part because these intervals are more variable than their counterparts to the east in the Denver Basin, and in part because the intervals are defined from the log characteristics with little pure lithologic control (e.g. no core analysis). This may also be a result of the lack of a connection between chalk or marl richness and the amount of organic matter present. More likely however, is that this apparent lack of correlation is a result of contamination of cutting samples by the mixing of cuttings from the desired interval with cuttings from overlying intervals. In addition, cuttings are sampled on 20 to 30 foot intervals, which may overlap a boundary between marl- and chalk-rich units. More detailed analysis than was available for this study (e.g. core) is necessary to determine differences between chalk- and marl-rich intervals.

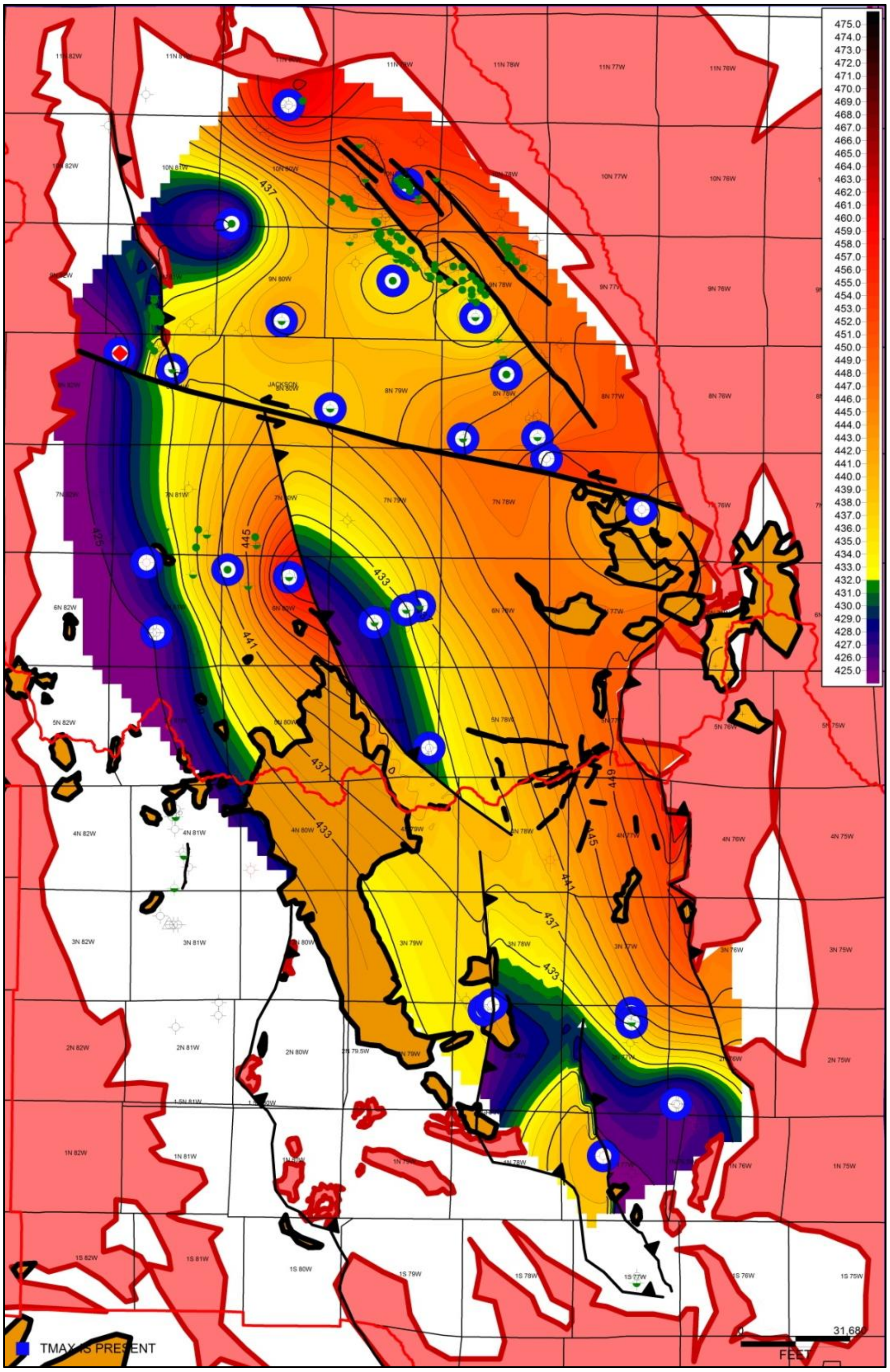


Figure 5.3 Maturity Map of the Niobrara Formation in the North Park Basin using Tmax. The wells with Tmax values used to construct this map are shown in blue. The color bar ranges from 425-475°C, using a 2° contour interval. Immature Tmax values range in color from purple to blue to green. The onset of maturity, 432°C, begins with yellow shading. At the beginning of peak maturity, 445°C, orange shading is used. Red shading begins at the onset of late maturity, 450°C. The shading is interpolated in between these critical points. This map suggests that the movement of the faults is responsible for increasing the thermal maturity of the Niobrara.

CHAPTER 6

RESERVOIR ROCK EVALUATION

This chapter evaluates the reservoir rock quality of the intervals of the Niobrara Formation. Reservoir properties are evaluated in 16 wells in the North Park Basin. These properties include porosity and water saturation and are measured using density and neutron logs.

6.1 Porosity

The porosity of the Niobrara was evaluated in order to determine the reservoir potential of each interval. Density porosity (DPHI) and neutron porosity (NPHI) logs were used to estimate porosity. Figure 6.1 shows the location of the wells used. Thirteen wells had DPHI logs and porosity logs were estimated using a limestone matrix of 2.71 g/cc. Twelve wells had NPHI logs that were originally calculated using a sandstone matrix. These logs were converted to limestone matrix NPHI logs by decreasing the sandstone values by 5 percentage points. These logs can be seen for the type well in Figure 5.2, and for the rest of the wells in Appendix F. Tables 6.1 and 6.2 show the average porosity values for each interval studied on a well by well basis for the DPHI and NPHI logs.

The density and neutron log readings were plotted on a density neutron crossplot for ten wells in which both are available. These plots are variable from well to well. This variability is due mainly to porosity changes with depth as noticed when the wells are sorted by depth. Of the ten wells in which porosity crossplots were constructed, porosity ranges from about 5-10% in the deepest well (about 11,000 feet deep) to about 30% in the shallowest well (about 800 feet deep).

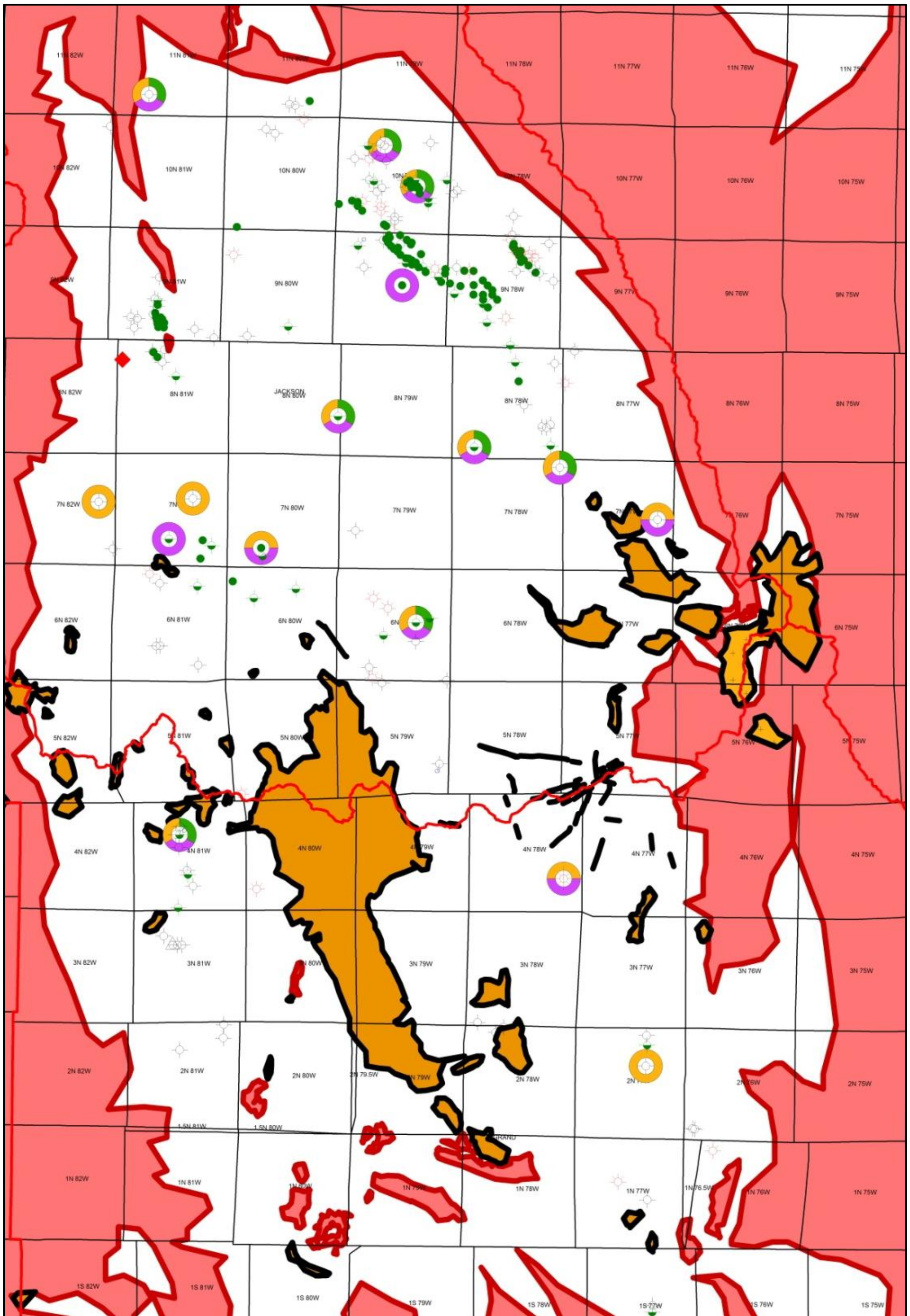


Figure 6.1 Location of wells with DPHI, NPHI, and SW logs. Density porosity logs (orange), using a limestone matrix, are located in 13 wells. Neutron porosity logs (purple) are found in 12 wells. Eight wells have logs for water saturation (green).

Table 6.1 Average DPHI by interval by well.

AVERAGE DPHI													
WELL NAME	CRYSTAL SPRINGS 22-9	FEE 1	GRANBY UNIT 1	CHEDSEY-A 1	GRANNY GOVT 9-1	Dwinell 3-A	Holliday 14-1	Lindland Unit 1-24	CHEDSEY 1	Funk Trust 1-1	VANETA 1-32D	Federal 1-24	USA 32-2-1
API NUMBER	05057063800000	05057051500000	05049060240000	05057060630000	05049060070000	05057062260000	05057062570000	05057062300000	05057060030000	05057063380000	05057064670000	05057060710000	05057061740000
DEPTH OF NIOBRARA	748	1010	1681	1785	1980	3232	3353	4752	5469	7067	7306	10623	10721
TOTAL NIOBRARA	22.3	24.1	4.3	14.0	12.7	16.0	10.7	7.6	10.5	7.5	9.3	3.7	5.9
UPPER CHALK	23.9	23.1	5.6	12.4	12.2	21.0	10.4	7.8	7.1	7.1	7.7	2.9	5.1
UPPER MARL	21.7	24.8	3.4	16.1	11.7	15.2	10.9	12.9	12.9	14.8	8.5	4.0	5.5
MIDDLE CHALK	24.6	26.5	3.8	14.5	13.5	16.6	10.7	5.5	9.5	6.4	9.2	3.8	5.1
***UPPER MIDDLE CHALK**	23.3	27.0	3.7	14.9	13.8	16.4	10.9	5.1	5.9	7.8	9.0	4.4	5.5
***MIDDLE CHALK MARL**	22.1	25.1	4.8	13.2	12.5	16.1	10.5	6.4	8.3	4.4	8.7	3.0	4.8
***LOWER MIDDLE CHALK**	27.3	27.6	2.9	15.5	13.7	17.3	10.7	5.4	16.5	5.2	10.7	3.5	4.7
MIDDLE MARL	18.3	32.0	4.0	12.1	13.0	13.0	10.1	7.4	15.8	6.4	11.2	3.3	5.2
LOWER CHALK	18.0	20.2	4.4	14.1	13.0	12.9	10.1	9.4	5.3	6.6	9.5	2.7	5.1
LOWER MARL	20.1	21.1	6.8	15.1	15.1	14.4	12.5	9.3	19.5	6.7	9.1	4.0	8.0
BASAL CHALK	19.1	20.7	5.0	15.8	13.7	12.5	12.5	7.2	5.4	6.5	9.4	4.0	7.3
FORT HAYS	20.0	24.6	7.8	15.8	8.1	12.3	7.3	6.3	8.1	3.4	10.5	3.3	8.4
CARLILE	14.1	15.2	3.3	8.3	8.2	9.6	7.3	10.2	15.2	4.0	6.2	0.9	4.4

Table 6.2 Average NPHI by interval by well.

AVERAGE NPHI												
WELL NAME	CRYSTAL SPRINGS 22-9	FEE 1	GRANNY GOVT 9-1	Dwinell 3-A	Holliday 14-1	Lindland Unit 1-24	FEDERAL 1-28 1	Funk Trust 1-1	Conoco Fischer 15-1	VANETA 1-32D	Federal 1-24	USA 32-2-1
API NUMBER	05057063800000	05057051500000	05049060070000	05057062260000	05057062570000	05057062300000	05057060660000	05057063380000	05057062600000	05057064670000	05057060710000	05057061740000
DEPTH OF NIOBRARA	748	1010	1980	3232	3353	4752	5198	7067	7232	7306	10623	10721
TOTAL NIOBRARA	31.6	31.1	25.8	28.1	22.7	16.2	13.5	15.1	17.1	15.9	10.2	7.2
UPPER CHALK	33.5	33.1	27.7	29.5	24.9	18.5	14.6	14.6	20.5	17.2	9.7	6.8
UPPER MARL	33.6	32.6	27.8	30.5	24.7	20.1	14.5	25.8	17.4	17.0	11.1	7.6
MIDDLE CHALK	31.3	30.9	24.8	27.6	21.9	16.8	12.8	14.1	14.9	15.7	8.8	5.5
***UPPER MIDDLE CHALK**	30.9	31.1	26.5	27.9	22.8	14.4	12.9	16.5	15.4	15.2	9.7	5.2
***MIDDLE CHALK MARL**	31.1	30.4	25.8	27.7	23.4	19.5	13.6	12.2	16.7	16.4	10.2	7.3
***LOWER MIDDLE CHALK**	31.7	31.0	23.3	27.0	18.6	18.4	12.2	11.2	12.2	14.9	5.1	4.6
MIDDLE MARL	29.9	29.6	25.4	28.0	23.3	16.0	15.4	11.6	20.3	19.0	11.7	10.1
LOWER CHALK	30.6	30.6	22.2	28.5	18.6	14.9	11.4	15.4	20.7	11.5	13.8	10.9
LOWER MARL	30.5	30.5	26.6	27.9	23.9	16.1	13.4	14.1	19.2	15.7	11.7	9.5
BASAL CHALK	28.7	29.4	24.7	24.3	21.9	10.4	13.3	10.5	16.5	12.4	8.7	5.0
FORT HAYS	28.6	28.3	18.1	22.1	19.0	10.9	12.7	9.1	15.1	16.1	7.1	5.3
CARLILE	26.5	26.0	21.9	24.3	20.9	21.4	12.1	13.2	17.5	16.2	11.9	9.0

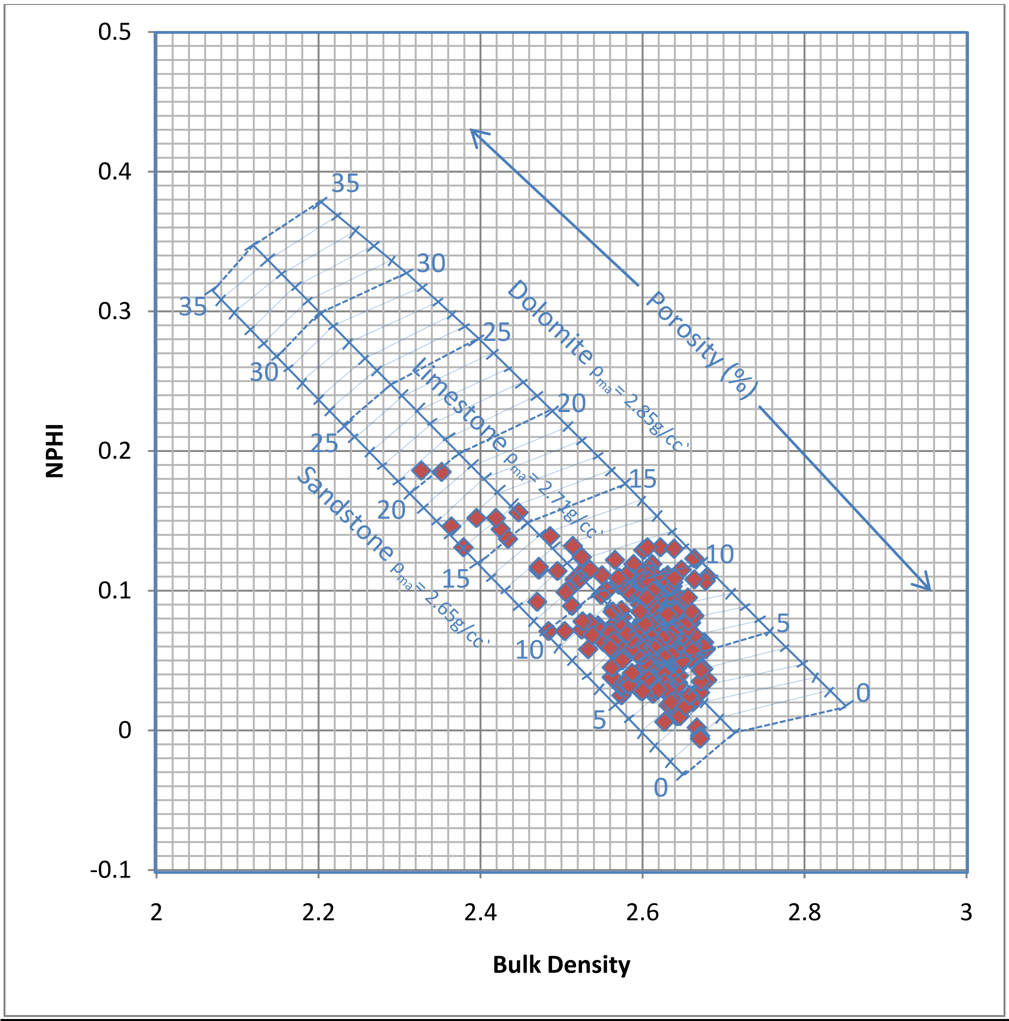


Figure 6.2 Density-Neutron Crossplot for USA 32-2-1. Bulk density is measured in g/cc. NPHI is measured in percentage, on a 0-1 scale. The depth of the top of the Niobrara is 10,721 (MD) and the depth of the top of the Carlile is 11,123 (MD). Crossplots for other wells can be seen in Appendix G.

6.2 Water Saturation

Water saturation logs were constructed for eight wells using the Archie equation for water saturation:

$$S_w = \left(\frac{a \times R_w}{R_t \times \phi^m}\right)^{\frac{1}{n}}$$

where a=tortousity factor, R_w=formation water resistivity, R_t=formation resistivity, ϕ=porosity, m=cementation exponent, n=saturation exponent. For this study the constant 1 is used for a; m and n both used the constant 2. The DPHI log was used for porosity and the resistivity log for R_t. A value of 0.05 was used for R_w. An example of one of the S_w logs is shown in Figure 5.2 and for other wells in Appendix F. Table 6.3 lists the average S_w for each well by interval.

6.3 Reservoir Rock Discussion

The original porosity and permeability of the Niobrara units have been altered by diagenesis. As noted by Longman et al. (1998) most of this diagenesis is related to burial. Mechanical compaction reduces the original porosity and permeability through grain reorientation and breakage. Subsequent chemical compaction can further reduces porosity and permeability through calcite dissolution, formation of microstylolites, pressure solution at grain-to-grain contacts, and the reprecipitation of calcite as overgrowths. In the basins in which the Niobrara has produced, production has been related to high microporosity in pure chalks and fracture porosity in tight marls, chalky marls, and chalks. The porosity values from the Niobrara interval in the North Park Basin range from 4 to 24% for DPHI and 12 to 36% for NPHI. Of the ten wells in which porosity crossplots were constructed, porosity ranges from about 5-10% in the deepest well (about 11,000 feet deep) to about 30% in the shallowest well (about 800 feet deep). Calculated water saturation values for the Niobrara ranged from 40 to 100% in the North Park Basin. The water saturation values calculated are not without uncertainty. The Archie equation was developed using sandstones, and thus, may not always be valid in a carbonate rich interval. The cementation (m) and saturation (n) exponents in this study were assumed to be equal to 2. The resistivity of water (R_w) value used in the calculation was assumed to be equal to 0.05 ohm-m. The R_w value will vary with depth and should not be expected to remain consistent. The porosity values, as indicated in the previous paragraph are estimated from wire-line well logs and, aside from different detector types and log vintages, the changes in porosity values should be valid. These assumptions may not be the best fit for every well, but, with the given data, are used to estimate a suitable approximation for water saturation.

Table 6.3 Average S_w by interval by well.

AVERAGE SW								
WELL NAME	CRYSTAL SPRINGS 22-9	FEE 1	GRANNY GOVT 9-1	Dwinell 3-A	Holliday 14-1	Funk Trust 1-1	Federal 1-24	USA 32-2-1
API NUMBER	05057063800000	05057051500000	05049060070000	05057062260000	05057062570000	05057063380000	05057060710000	05057061740000
DEPTH OF NIOBRARA	748	1010	1980	3232	3353	7067	10623	10721
TOTAL NIOBRARA	44.8	42.5	41.9	44.8	46.4	46.3	100.0	79.3
UPPER CHALK	45.7	45.1	49.5	39.7	51.0	47.9	100.0	100.0
UPPER MARL	46.7	40.8	50.9	48.1	45.8	48.3	100.0	100.0
MIDDLE CHALK	39.7	37.6	33.8	40.9	43.5	51.9	87.9	78.5
***UPPER MIDDLE CHALK**	38.2	36.5	33.3	41.6	42.6	54.4	79.4	74.7
***MIDDLE CHALK MARL**	42.7	36.9	40.0	39.9	47.8	66.8	100.0	86.4
***LOWER MIDDLE CHALK**	39.9	40.5	31.2	40.5	38.3	39.1	81.4	77.8
MIDDLE MARL	51.3	30.7	39.9	57.4	54.6	37.9	100.0	91.2
LOWER CHALK	55.0	53.0	32.8	53.4	39.2	39.8	100.0	100.0
LOWER MARL	47.3	47.4	27.5	44.2	36.1	34.1	100.0	47.8
BASAL CHALK	49.6	45.7	37.6	53.9	39.6	32.3	88.3	40.3
FORT HAYS	46.0	36.8	68.2	49.8	97.8	100.0	99.4	30.0
CARLILE	70.2	64.1	85.8	89.2	100.0	100.0	100.0	100.0

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

The Niobrara Formation in the North Park Basin was investigated in outcrop, correlated in the subsurface, analyzed for TOC and pyrolysis properties, and evaluated as a source and as a reservoir.

The stratigraphic intervals of the Niobrara and surrounding units were identified in the North Park Basin in this thesis. These intervals include, from oldest to youngest, the Frontier Sandstone, the Carlile Shale, the Niobrara Formation, and the Pierre Shale. As the Niobrara was deposited in the Western Interior Seaway, marine deposition dominated. Alternating periods of chalk and marl-rich deposition were most likely the consequence of climatic effects resulting in minor trangressive and regressive cycles that influenced the current flows from the carbonate-rich proto-Gulf of Mexico and the depth of the seaway. These alternations of chalk and marl are the basis of further subdivisions of the Niobrara into the Fort Hays, basal chalk, lower marl, lower chalk, middle marl, middle chalk, upper marl, and upper chalk. These units were identified in outcrop and in subsurface wireline logs. Outcrop analysis reveals that the Niobrara is a calcareous shale to chalk and contains many carbonate skeletal grains, including foraminifera and shell fragments. An outcrop gamma-ray log provided a means to tie the outcrop to the subsurface revealing that portions of the Frontier, Carlile, basal chalk, lower marl, lower chalk, middle marl, middle chalk, and upper marl are present in the outcrop and providing a means to validate the stratigraphic interpretation. The stratigraphic units were correlated across the North Park Basin based on their log character. The thicknesses of each of these units, along with spatial trends of the units, is summarized in Table 3.1, and shown in detail for each unit in the figures throughout the stratigraphy section of this thesis in chapter 3.

Samples from the outcrop and subsurface were analyzed for their geochemical properties using pyrolysis to evaluate its source rock quality and potential. The Kerogen Type from the pyrolysis from both the outcrop and subsurface indicate Type II Kerogen, with some Type III Kerogen. With maturation, these kerogen types will generate oil, condensate, and then gas. The TOC measurements from the outcrop and eight wells in the basin show that the TOC content of the Niobrara is consistently in the range of 1-4 wt.% TOC, mostly being in the 2-3 wt.% interval. This ranks the Niobrara as having a good to very good petroleum potential. Log-derived TOC estimates were generated by using a technique developed by Passey et al. (1990) involving resistivity and sonic logs. The log-derived TOC estimates range from 0 to 8.4 wt. % TOC and are more variable than the measured TOC samples. Where no measured TOC is available, the log derived TOC estimates act as a good proxy. However, care should be taken in interpreting these values, as certain variables can contribute to anomalous results, including very tight or porous intervals. In addition to the carbon present, hydrogen concentrations in the Niobrara organic matter were adequate for the generation of hydrocarbons. The maturity of the Niobrara in the North Park Basin was approximated by Tmax values from the outcrop and subsurface sample pyrolysis analysis. Areas in which the maturity of the Niobrara is highest are located in the center of the basin where the Niobrara is buried the deepest. The areas north of the Spring Creek Fault Zone in the northern and eastern areas are also more mature. The Niobrara has reached maturation levels that correspond with the generation of oil and condensate and thus, mostly liquid hydrocarbons are present in mature areas. .

Porosity and water saturation values were calculated from subsurface well logs using petrophysical techniques from density, neutron, and resistivity log curves. Porosity values range from 4-36%. This range in porosities is large, and is a result of changes in porosity related to mechanical and chemical diagenesis related to burial. In areas where the Niobrara is the most mature, porosities range from 5 to 10%. These porosities, low by conventional standards, are adequate for production from an unconventional resource. Water saturation calculations range from 40-100%. Though these values do carry some uncertainty, they are a first approximation of water saturation in the North Park Basin.

Locating areas of potential hydrocarbon accumulations related to the Niobrara in the North Park Basin is primarily based on locating areas in which the interval is thermally mature. Known areas of higher thermal maturity exist in the center of the basin, west of the main thrust fault. In addition, areas in the northern and northeastern areas of the basin may also be mature.

This study is by no means a complete analysis of the Niobrara in the North Park Basin, as the understanding of the Niobrara petroleum system is an ongoing process. The following are suggestions on what aspects would be most important to investigate. A better understanding of the structure of the Niobrara interval would be very beneficial in identifying areas in which the Niobrara may be thermally mature, especially in areas in the south where there is less data available. Additional well data and seismic surveys would provide more structural data. Core data in the Niobrara could lead to identifying important intervals that otherwise might go unnoticed. As fracturing may be important in production, identifying fracture patterns and locating potential areas of enhanced fracturing could allow for better production. Finally, an in-depth basin model of the basin could provide useful information on the timing and potential generation of hydrocarbons, and the influence of the Tertiary volcanic units in the basin.

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APPENDIX

The following appendices can be found on the CD-ROM accompanying this thesis:

APPENDIX A – OUTCROP GEOCHEMICAL REPORT

APPENDIX B – WELL CUTTINGS GEOCHEMICAL REPORTS

APPENDIX C – PREVIOUS GEOCHEMICAL DATA AVAIABLE FROM USGS

APPENDIX D – Ro TO LOM TABLE

APPENDIX E – MEASURED TOC TO LOG DERIVED TOC CROSS-SECTION

APPENDIX F – DPHI, NPHI, and SW CROSS-SECTION

APPENDIX G – DENSITY-NEUTRON POROSITY CROSSPLOTS

APPENDIX H – WELL DATA