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WELL LOG DETERMINATION OF THE ORGANIC RICHNESS
OF THE MOWRY SHALE IN THE NORTH PARK AND
DENVER BASINS AND THE NIOBRARA CHALK
IN THE DENVER BASIN

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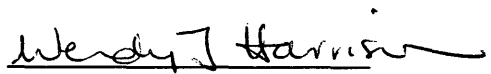
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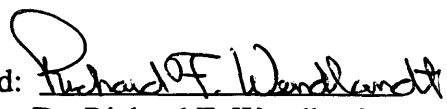
A thesis submitted to the Faculty and Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science in Geology.

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ABSTRACT

In recent years, the use of wireline logs for estimating the organic carbon content of potential hydrocarbon source rocks has become important because they can substitute for traditional geochemical analyses. The advantages of wireline log methods compared with laboratory analyses are that they are easier, faster, and cheaper to use. Another advantage is the ability to derive a continuous in situ estimation of the organic matter content. There are many well-log methods for identifying and quantifying organic richness of source rocks. Several methods employ only one log, such as the gamma-ray or the density log, others employ a pair of logs, such as porosity and resistivity logs. The Passey et al. (1990) method uses sonic transit time/resistivity pair to derive total organic carbon (TOC) values via level of organic metamorphism. In this study, the Passey et al. method is found to be reliable and accurate in quantifying organic richness of the Mowry Shale and Niobrara Chalk in the Denver and North Park basins.

When calibrated against the Niobrara Chalk, the difference between measured and calculated TOC values ranges from -1.41 to +3.52 wt.% TOC with a standard deviation of the difference of ± 1.4 wt.% TOC. For the Mowry Shale sample, the difference between core and calculated measurements range from -0.7 to +0.9 wt.% TOC with a standard deviation of the difference of ± 0.6 wt.%.

An exponential relationship between linearly scaled resistivity and sonic transit time indicates that the Passey et al. method works. Non-exponential relationships between the two logs lead to a condition without a baseline. Comparison of TOC values calculated from three different well-log methods against measured TOC values shows that the Passey

et al. method is the most accurate of the log-derived methods. One unique advantage of this method lies in the capability to derive TOC and LOM values interchangeably, providing either one of these is calibrated against analytical data.

Using available LOM data available, a TOC map of the Mowry Shale in the Denver basin was created from sixty-eight logs. Average calculated total organic carbon contents for individual wells penetrating the Mowry Shale range from 1.1 to 2.9 wt.% TOC, while corresponding TOC-ft values within the study area range from about 29 to 141 wt.%-ft. Anomalously low calculated TOC values of the Mowry Shale (1.1 to 1.5 wt.% TOC) combined with high LOM values (LOM 10 to 11.5), are presumably a result of the generation and migration of CO₂ and hydrocarbons out of the source rock.

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Chapter 1

INTRODUCTION

The Denver basin is a significant hydrocarbon-producing basin in Colorado, Wyoming and Nebraska. The best known producing zones are Cretaceous rocks, such as the Niobrara Formation, the D, and the J sandstones. There are 289 fields within the basin, and as of December 1993, more than 36 MMBbls of oil and 1.013 TSCF of gas have been produced from the Wattenberg Field alone of which more than 90% was derived from the D and the J sandstones (Oil and Gas Southern Rockies Production Report, 1993). Two of the source rocks believed to supply hydrocarbons for the D and the J sandstones are the Cretaceous Mowry Shale and Niobrara Chalk (de Rojas, 1980, Rice, 1984).

Early studies of the Mowry Shale and Niobrara Chalk in the northern Rocky Mountain region revealed that this organic-rich rock was probably one of the most significant source beds for hydrocarbon accumulations in the Denver basin as well as other basins around the region, including the Powder River, Big Horn, Wind River, Green-River-Washakie, Uinta-Piceance, and North Park basins (Nixon, 1973, Clayton and Swetland, 1980, Burtner and Warner, 1984, Fillmore, 1986). Unfortunately, none of those studies attempted to quantify total organic carbon (TOC) content of the Mowry Shale and Niobrara Chalk using well logs. The use of well log analyses to define geochemical parameters can contribute significantly to the petroleum assessment of a sedimentary basin because thermal maturity level and TOC values of potential source beds can be determined quickly and cheaply after proper calibration.

This study primarily deals with source rock evaluation using resistivity and sonic logs, supported by estimated level of organic metamorphism (LOM) values, to calibrate and measure TOC content of the Niobrara Chalk and Mowry Shale. The method for identifying and calculating TOC using these particular well-logs used was originally described by Passey et al. (1990). Their method has been modified for use in this study and a more statistical approach has been developed to strengthen the original method.

1.1 PURPOSE AND SCOPE

The purpose of this study is to identify and quantify the source rock potential of the Mowry Shale in the North Park and Denver basins and the Niobrara Chalk in the Denver basin. This study is also intended to map the Mowry Shale using log-derived TOC values in weight percent and TOC-foot units. Additionally, this study has provided insight into the limitations of the log-derived method and some improvements have been developed.

1.2 LOCATION

The Denver basin covers an area of more than 60,000 square miles (155,000 square kilometers) and is located east of the Front Range uplift. It extends from Colorado in the south to Wyoming and Nebraska in the north (Figure 1). Structurally, the Denver basin is bounded by the Front Range and the Hartville uplift on the western margin, whereas on the eastern margin, it is bounded by the Las Animas and the Chadron arch (Figure 1). The Niobrara Chalk and Mowry Shale wells within the study area are located between T.7N. and T.8S., and R.57W. and R.71W. (Figure 2). The Mowry Shale logs used for calibration in this study are taken from North Park basin, a basin west of the Denver basin (Figure 3).

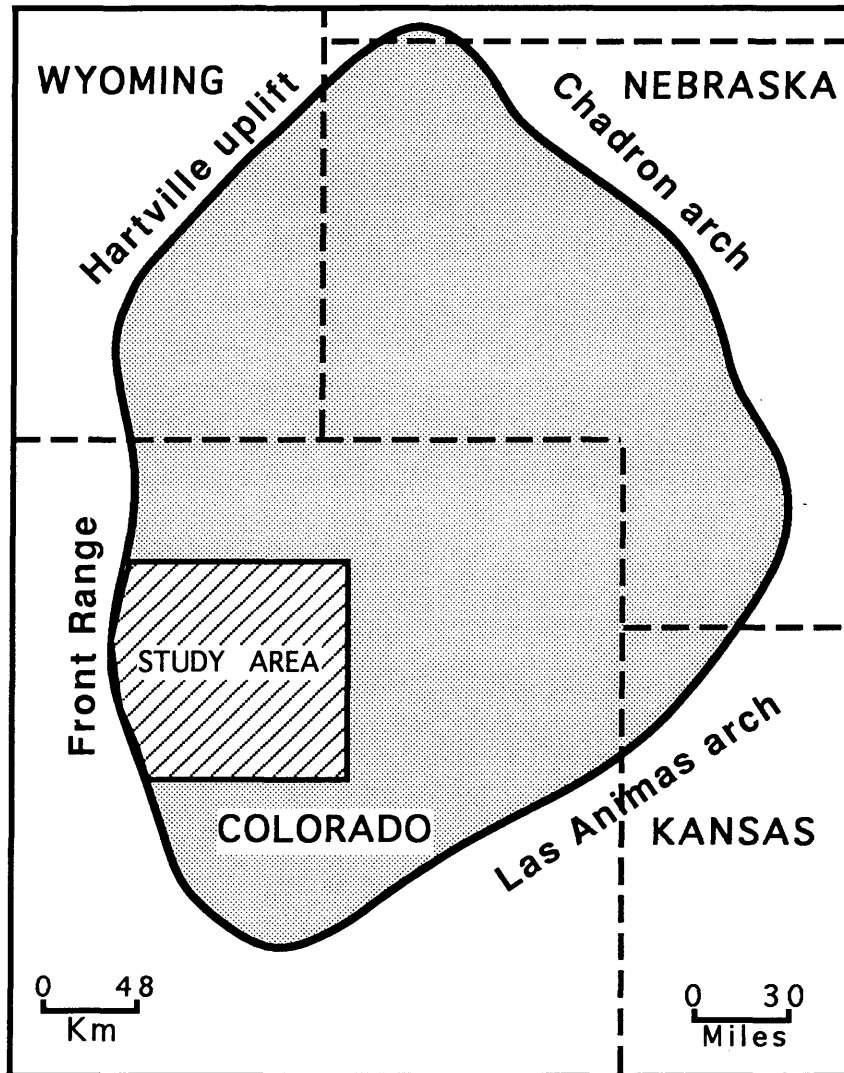


Figure 1. Index map showing study area within the Denver basin.

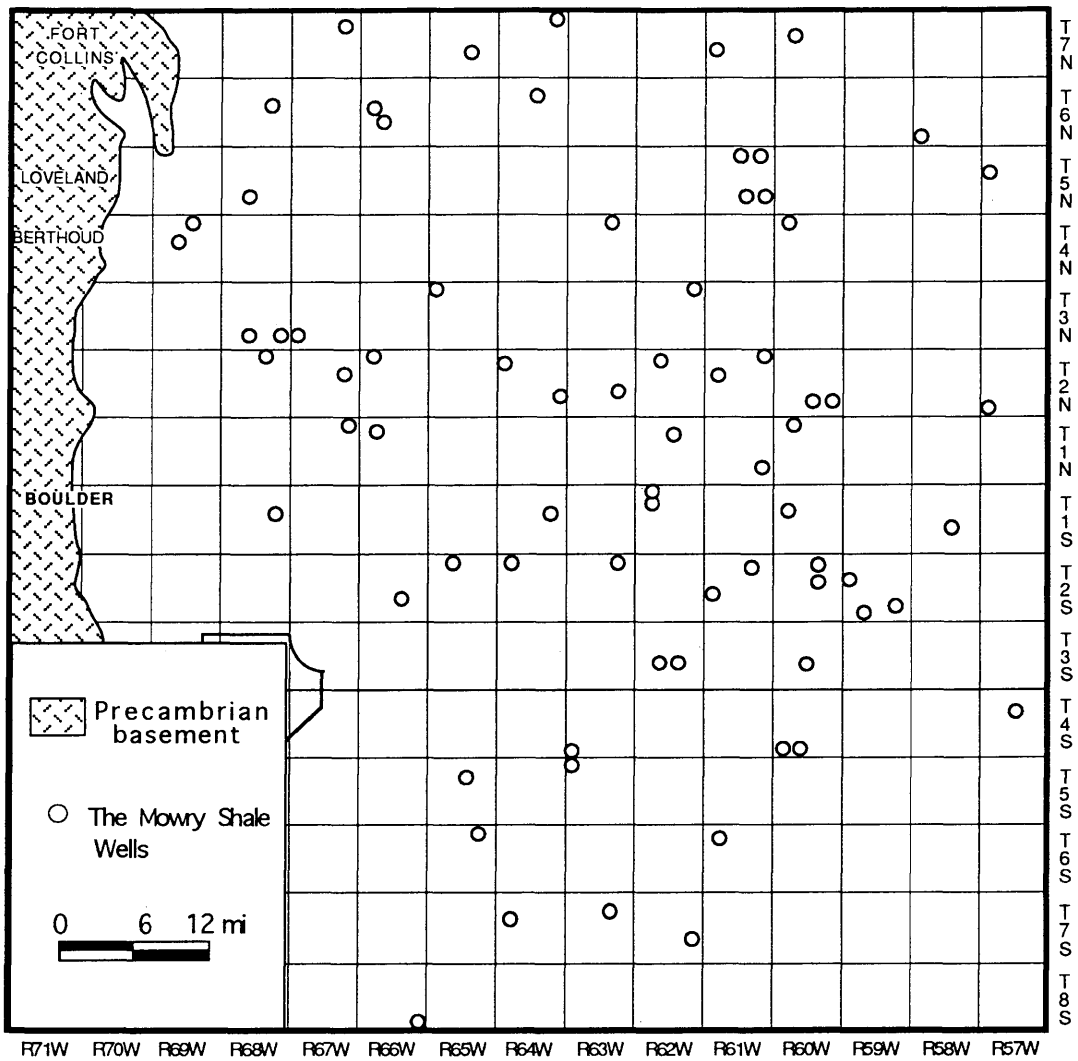


Figure 2. Location of the Mowry Shale wells within study area.

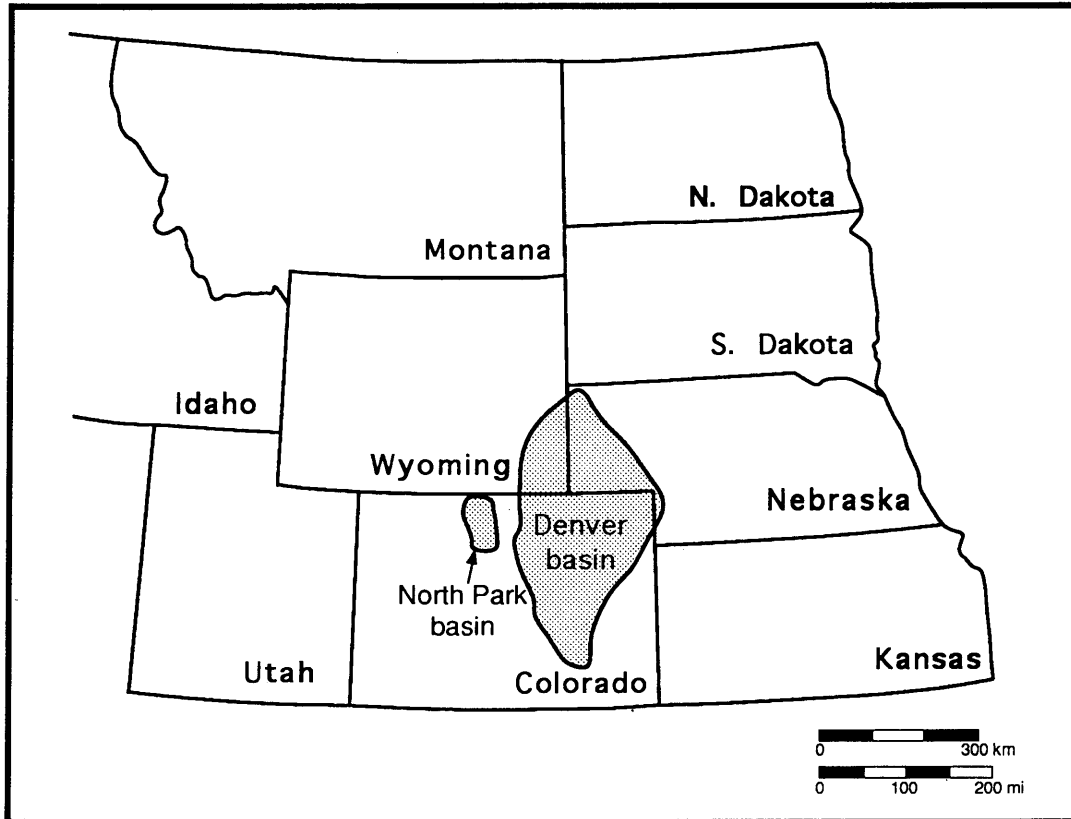


Figure 3. Location of North Park basin where calibration data are taken (modified from Burtner and Warner, 1984).

1.3 PREVIOUS WORK

The Mowry Shale was named by Darton (1904) from exposures on Mowry Creek, northwest of Buffalo, Wyoming. Cobban and Reeside (1952) placed the top of the Mowry Shale as the boundary between Upper and Lower Cretaceous rocks. Haun (1959) reported the Mowry as a stratigraphic unit distinct from the overlying marine Graneros Shale of Colorado. The relationship between the Mowry Shale and other Cretaceous rocks in the Denver basin is described in Figure 4.

Davis (1970), Larson (1977), and Byers and Larson (1979) studied paleoenvironments of the Mowry Shale in Wyoming and estimated that the Mowry was deposited at a minimum depth of 150 m on a continental paleoslope dipping 0°03' to the east. Cobban and Reeside (1954, 1960) studied the invertebrate fossil content of the Mowry Shale and concluded that the age of the Mowry Shale and equivalent rocks might be latest Albian to earliest Cenomanian. The foraminifer contents of the Mowry and Graneros Shales of Colorado, Wyoming, Utah, and Kansas were studied by Eicher (1965), and he suggested a Cenomanian age for both.

The Lower Cretaceous Mowry and Skull Creek Shales of the northern Rocky Mountain region are the sources of hydrocarbons in the Jurassic Nugget Sandstone in the western overthrust belt of Wyoming and Utah (Warner, 1982) and the Lower Cretaceous Muddy Sandstone of the Denver-Julesberg (Clayton and Swetland, 1982) and Powder River basins (Momper and Williams, 1979). Burtner and Warner (1984) analyzed the Mowry Shale TOC content distribution in the northern Rocky Mountain areas and found that low TOC values in the Mowry Shale coincide with Laramide structural basins and are associated with the generation and migration of CO₂ and hydrocarbons. Clayton and Swetland (1982) made an extensive evaluation of Cretaceous oil-source rock potential in

AGE	FORMATIONS	THICKNESS	
TERTIARY	DENVER-ARAPAHOE FORMATION	500' (152m)	
LATE CRETACEOUS	LARAMIE FORMATION	60' (18m)	
	FOX HILLS FORMATION		
	PIERRE SHALE	TERRY SANDSTONE	8000' (2439m)
		HYGIENE SANDSTONE	
		MITTEN MEMBER	
		SHARON SPRINGS MEMBER	
	NIOBRARA FORMATION	SMOKY HILL MEMBER	350' (107m)
		FORT HAYS LIMESTONE (TIMPAS Ls)	
	CARLILE SHALE	CODELL SANDSTONE MEMBER	420' (128m)
EARLY CRETACEOUS	GREENHORN LIMESTONE	370' (112m)	
	GRANEROS SHALE		"D" SANDSTONE OF DRILLERS
			HUNTSMAN OF DRILLERS
	MOWRY SHALE		
	DAKOTA SANDSTONE		"J" SANDSTONE OF DRILLERS
			SKULL CREEK EQUIVALENT
			PLAINVIEW EQUIVALENT
LYTLE EQUIVALENT			
JURASSIC	MORRISON FORMATION	475' (145m)	
	RALSTON CREEK FORMATION		
TRIASSIC	LYKINS FORMATION	400' (122m)	
PERMIAN	LYONS FORMATION	120' (37m)	
PENNSYLVANIAN	FOUNTAIN FORMATION	1000' (305m)	

Figure 4. Generalized geologic column, Denver basin. Dots indicate oil productive units (modified from Smagala et al., 1984).

the Denver basin. They proposed that most oil in the basin came from vertical and lateral migration from the Benton Group, including the Mowry Shale, located near the basin axis north of Denver along the deepest part of the basin.

In this thesis, the Upper Cretaceous Niobrara Chalk is only studied for calibration purpose. The chinks of the Niobrara Formation are important source rocks and also act as reservoirs in the Denver basin. The Niobrara Chalk is underlain and overlain by marine shales assigned to the Carlile and Pierre Shales, respectively (Figure 4). In the Denver basin, the Niobrara can be divided into two members. The lower member, the Fort Hays Limestone, consists of 10-25 m (33-82 ft) of relatively clean, well-indurated chalk. The upper member, the Smoky Hill Member, consists of 150-200 m (490 - 650 ft) of impure shaly chalk with locally massive chalk beds (Lockridge, 1977).

Chalk beds of the Niobrara Formation are organic-rich source rocks with organic carbon contents ranging from 0.43 to 5.8 weight percent and averaging 3.2 weight percent. Their maturation levels across the Denver basin vary from LOM less than 6 to LOM 9.5. These source rocks have generated oil and natural gas in the northwestern part of the Denver basin (Rice, 1984).

1.4 WELL-LOG ANALYSES OF SOURCE ROCKS

Beers (1945) was the first to relate anomalously high gamma-ray readings to organic-rich source rocks. Swanson (1966), through geochemical analyses of shales, attributed the anomalous gamma-ray values to uranium, associated with the organic matter. Schmoker (1981) noted that the total gamma-ray method is inconsistent in measuring the organic-richness of some Devonian source rock intervals in the Appalachian region.

The gamma-ray spectral log has been proposed as a tool that can be used effectively to identify and quantify organic-rich source rocks (Supernaw et al., 1978; Fertl and Rieke, 1980; Herron, 1987). Herron (1987) introduced natural gamma-ray and gamma-ray-spectrometry tools (NGT and GST) that can determine the elemental composition of the rocks. These measurements can be used to predict the mineralogical composition of sedimentary rocks and sediment organic content by recombination of the measured elemental abundances guided by a mineralogical model. The advantage of these tools is they measure elemental composition more accurately, when compared with geochemical methods. The deficiencies lie in their cost and their sensitivity to the mineralogical model selected. These methods cannot be applied in old wells where necessary logs are not available.

The use of the density log to evaluate the yield potential of oil shales was performed by Tixier and Curtis (1967). Schmoker (1979) determined the organic content of Devonian shales using the density log. Schmoker and Hester (1983) also used the density log to determine total organic carbon in the Bakken Shale. However, because the density log is a pad-type tool, it is sensitive to borehole rugosity and this characteristic leads to diminished accuracy. The density log reading, furthermore, is significantly affected by the presence of heavy minerals, such as pyrite, which are often associated with organic-rich sediment.

Dellenbach et al. (1983) and Autric and Dusmenil (1984, 1985) employed resistivity/sonic combinations to determine organic richness quantitatively. The weakness of this method is it requires calibration with sample data from specific wells in order to determine organic richness quantitatively. Meyer and Nederlof (1984) use this

combination of logs to discriminate between source rocks and non-source rocks without trying to measure the organic richness from this combination of logs.

On sonic transit time logs, the higher TOC contents are linearly related to higher Δt values, although the effect of the presence of kerogen on travel time can be dependent on the shape and distribution mode of kerogen within a given formation, e.g., dispersed versus laminated (Mendelson and Toksoz, 1985; Fertl, Chilingar, and Yen, 1986). Meyer and Nederlof (1984) noticed that the kerogenous organic matter derived from aquatic organisms and bacteria is usually in a laminated mode, whereas the humic organic matter derived from plants is usually dispersed through the source rocks.

According to Abrahao (1988), some studies have revealed that the determination of organic carbon content from well logs is not reliable, while others indicated that the responses of well logs are always consistent, and in accordance with theoretical models. To improve the well-log approach for quantifying organic richness of source rocks, better criteria defining how well logs can be effectively applied in the geochemical characterization of source rocks are needed.

Chapter 2

GEOLOGICAL SETTING

The Denver basin was formed during the Laramide orogeny and is one of the largest structural basins in the Rocky Mountain region. The basin is asymmetric with the basin axis parallel and adjacent to the Front Range of Colorado and the Laramie Range of Wyoming (Figure 5). The deepest parts of the basin are south of Denver and north of Cheyenne, where the Precambrian basement is overlain by a 13,000 ft thick sedimentary sequence. The eastern flank of the basin dips gently to the west and the western flank dips steeply to the east at approximately 10° or greater (Sonnenberg, 1981).

The Mowry Shale in the western Denver basin lies stratigraphically above deltaic and marginal marine deposits of the J sandstone of the Dakota Group (Weimer and Land, 1972). The Mowry Shale is the lowermost member of the Benton Group which consists of the Mowry Shale, Graneros Shale, Greenhorn Limestone, and Carlile Shale (Burtner and Warner, 1984). Within the Denver basin, the Mowry interval is recognized on electric logs by characteristic low resistivity values (Figure 6).

The Mowry Shale was deposited during latest Albian to earliest Cenomanian time (early to late Cretaceous) in a southern embayment of the Western Interior Cretaceous Sea that extended southward from the Arctic to southern Colorado (Figure 7). The Mowry Shale wedges out in the subsurface south of Denver (Haun, 1963), and it has not been described south of T.7S. at the surface. The rocks along the western flank of the basin were uplifted and exposed during the Laramide Orogeny (Late Cretaceous to early Tertiary). West of the outcrop, the metamorphic Paleozoic rocks and Precambrian

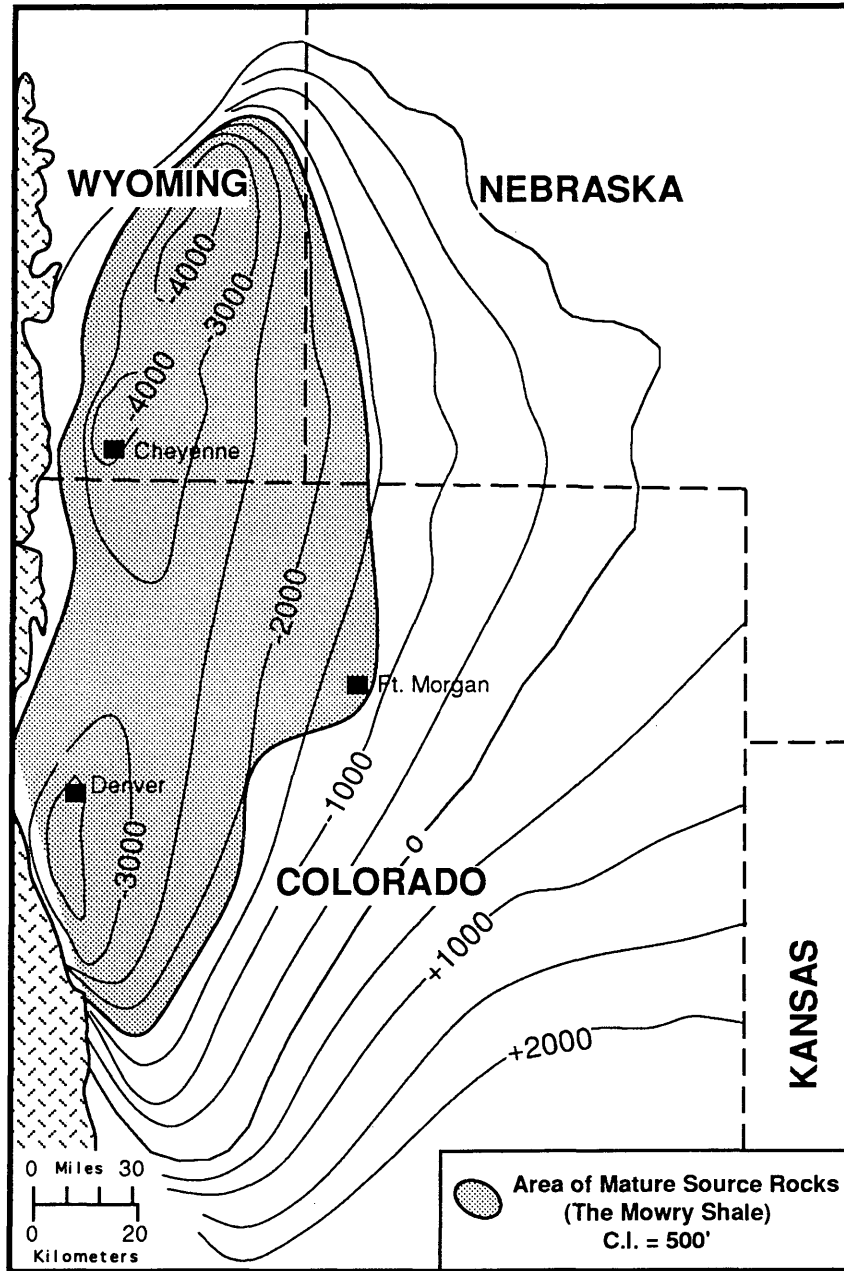


Figure 5. Structure contour map of the Denver basin on top of "J" sandstone (modified from Tainter, 1984).

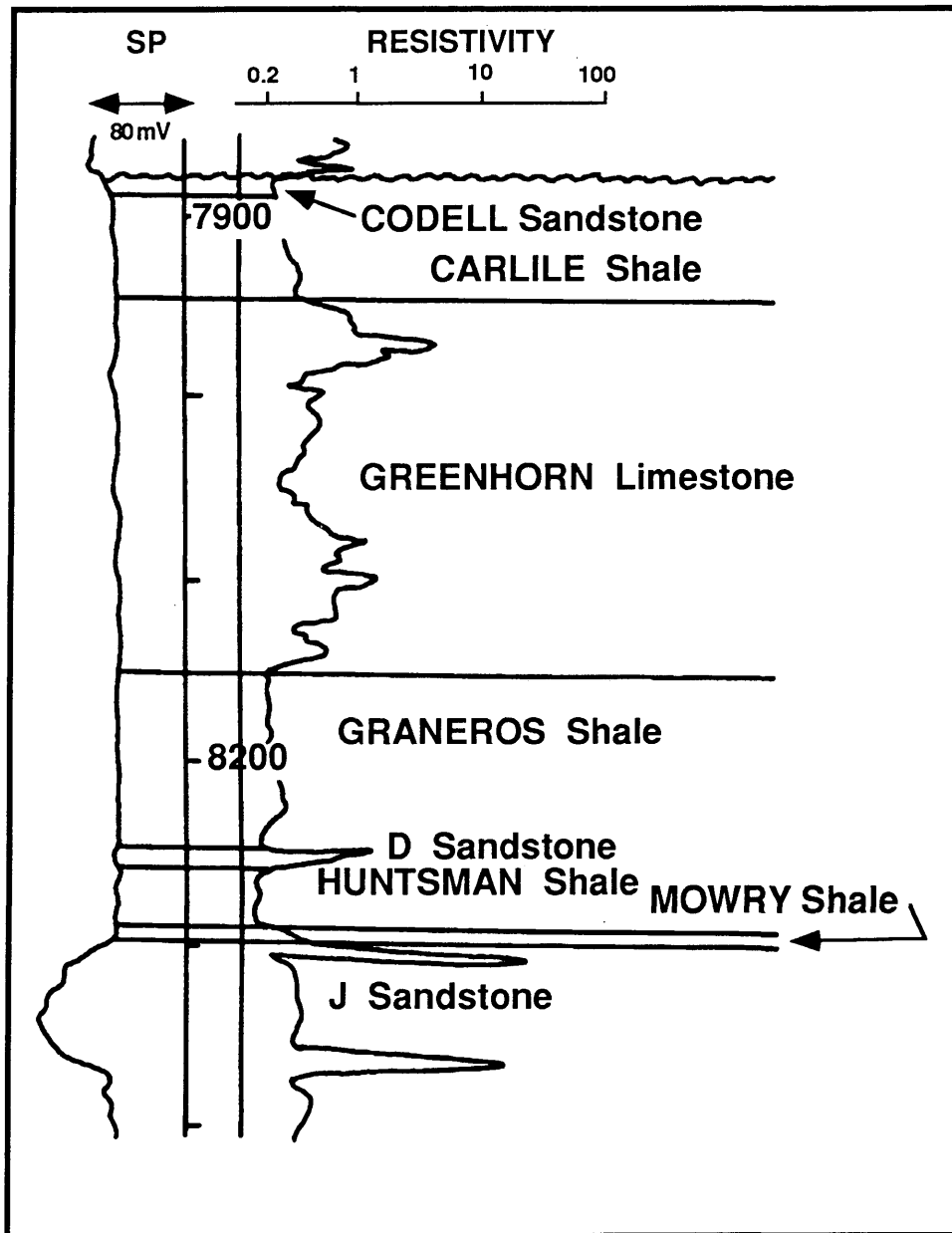


Figure 6. Typical electric log of Benton Group (modified from Sonnenberg, 1981).

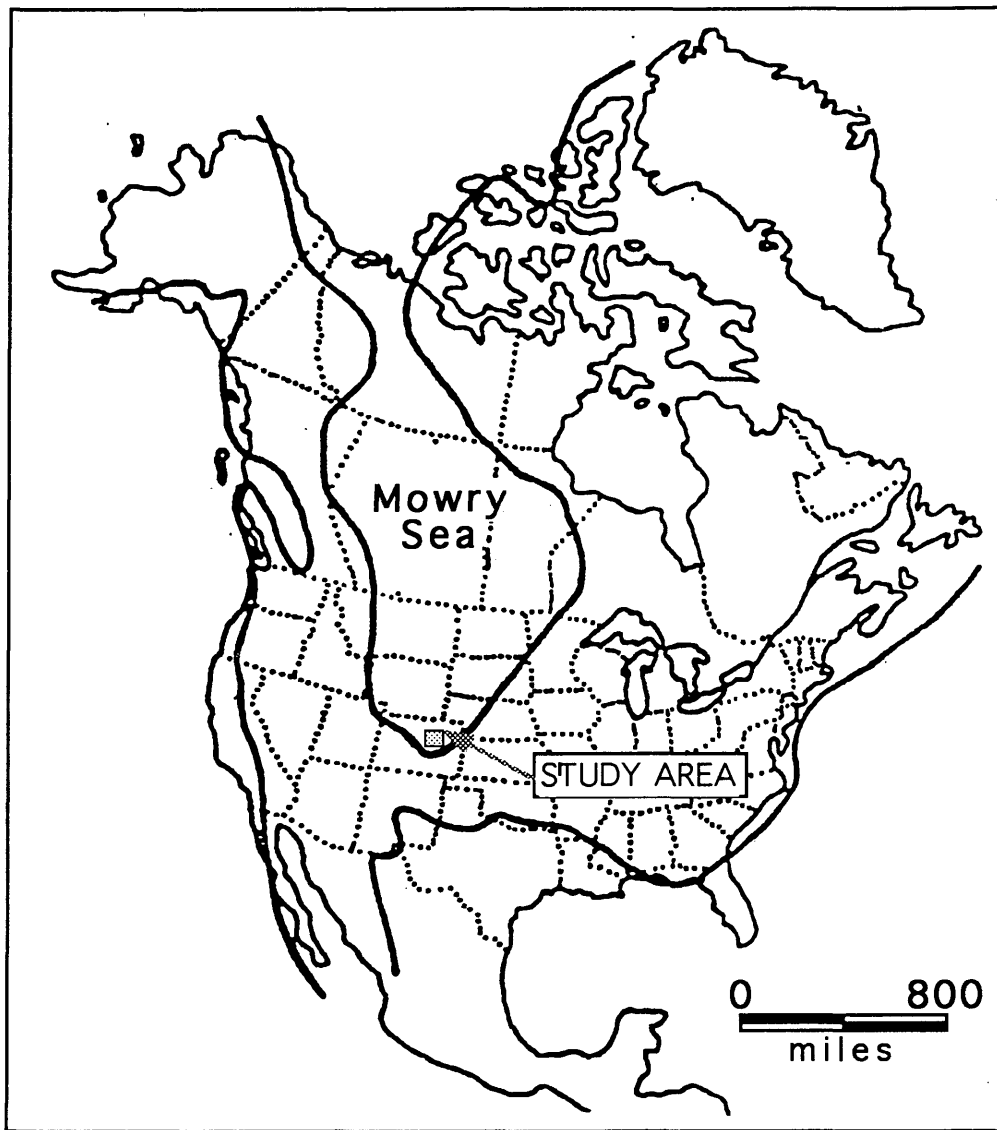


Figure 7. Extension of the Mowry Sea during latest Albian to earlier Cenomanian time (modified from Williams and Stelck, 1975).

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metamorphic basement are exposed in the Front Range. When exposed, this shale is usually hard and resistant to erosion (Nixon, 1973).

2.1 The Mowry Shale

To quantify the Mowry Shale as a petroleum source rock in the Denver basin, it is necessary to understand the occurrence and distribution of facies within the Mowry. The Mowry Shale in the Denver basin is composed dominantly of mudstones and shales, which are hard, dark gray to black, and contain disarticulated fish scales. The Mowry Shale was deposited at the beginning of the second major Cretaceous transgression that flooded the western interior of North America. Byers and Larson (1979) concluded that the Mowry Sea was an oxygen-deficient basin based on the assemblage and characteristics of biogenic structures. The Mowry Shale, present on the western flank of the Denver basin, consists of two facies, namely: the mudstone facies and the interbedded sandstone and mudstone facies.

2.1.1 Mudstone Facies

This facies comprises thin, graded, laminated mudstones intercalated with thin shales. Thin beds of ash falls, now altered to smectite, are interbedded within the unit. Smectite dominates more than 90% of the clay mineralogy of the shales and mudstone, while kaolinite is the remaining clay mineral (de Rojas, 1980).

Although disarticulated fish scales and spines are the only body fossils commonly found, Eicher (1965) was able to find various planktonic species. Biogenic structures are rare, but de Rojas (1980) recognized some burrowed beds at Eldorado Springs as

Planolites. de Rojas (1980) concluded that this facies was deposited in the offshore zones and appears to have the highest concentration of preserved organic matter.

2.1.2 Interbedded Sandstone and Mudstone Facies

This Mowry facies is composed of mudstones interbedded with very fine-grained sandstones, sandy siltstones, and shales. Thin beds of ash falls now altered to kaolinite are interbedded within this facies. Burrowing is more abundant in this facies than in the mudstone facies.

Disarticulated fish scales and small fish vertebra have been found in some lenticular beds. X-ray diffraction on some samples showed the presence of kaolinite and mixed layers of smectite-illite (de Rojas, 1980). According to Reineck and Singh (1975), this facies was deposited in the transition zone of a paleoshoreline.

2.2 Geochemistry of the Mowry Shale

The Mowry Shale organic matter is composed of a mixture of variable amounts of Type II-Type III kerogen (Fillmore, 1986). Rock-Eval T_{\max} values vary from 415 to 444 °C (Burtner and Warner, 1984). According to Espitalie (1977), T_{\max} values of about 435 - 460°C correlate with the oil window.

In North Park basin, Fillmore, 1986, found that the average extractable hydrocarbon values for this shale are over 1,000 ppm, well above the minimum value of 500 ppm for commercial consideration for shales. In the western Denver basin, Clayton and Swetland (1980) determined that the (TOC) content of the Mowry Shale ranges from 0.8 to 3.6 wt.%, while its vitrinite reflectance values (R_o) are about 0.5 (LOM 8.3) to 1.5 (LOM 11.8).

Burtner and Warner (1984), based on geochemical measurement, mapped the distribution of TOC within the Mowry Shale (Figure 8). The lowest TOC values seem to coincide with the paleoshoreline where the oxidation and benthic scavengers might have been the most active. In contrast, TOC values tend to increase toward the center of the seaway (Figure 8), where anoxic bottom conditions were prevalent (Byers and Larson, 1979).

Areas of anomalously low TOC values within the Mowry coincide with the deeper parts of Laramide structural basins which developed after the deposition of the Mowry Shale. These anomalously low TOC values, associated with Rock-Eval T_{max} values of 435°C or greater, reflect in part a reduction of the TOC by thermal maturation. Rock-Eval pyrolysis data provide some evidence that the reduction of TOC is the result of the generation and migration of CO₂ and hydrocarbons formed during thermal alteration of organic matter. Therefore, hydrocarbons are most abundant in Lower Cretaceous reservoirs that lie within or on the adjacent updip flank of areas where anomalously low TOC values met with T_{max} values greater than 435°C (Burtner and Warner, 1984).

2.3 The Niobrara Formation

The Niobrara Formation, which is composed of chalks and calcareous shales, was deposited in a deep-water, far-offshore environment during latest Cretaceous major transgression (Smagala et al., 1984). The carbonate Niobrara Formation forms tongues that grade north and west of the hydrocarbon-producing area near the Kansas-Colorado border into calcareous shales (Shurr and Sieverding, 1980). The calcareous shale in succession grades to noncalcareous shales and finally to sandstone along the western

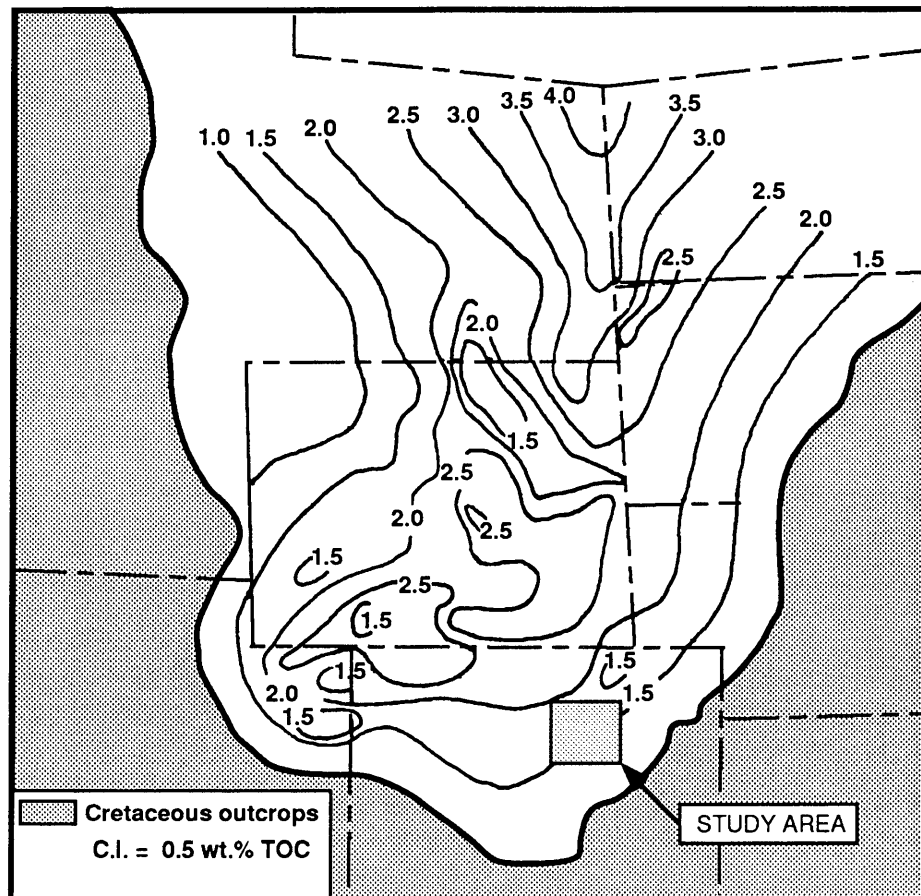


Figure 8. Regional distribution of total organic carbon (TOC) of the Mowry Shale in the Rocky Mountain area (modified from Burtner and Warner, 1984).

shoreline in central Utah (McGookey, 1972). The exact location of the eastern shoreline is unknown.

The chalks of the Niobrara Formation are fine-grained limestone, consisting mainly of calcareous nanofossils and other microfossils. They are also characterized by high porosity (30-45%) and low permeability (about 1 md). Core samples from hydrocarbon-producing areas average 30% acid-insoluble residue. Most of the insoluble residue, which consists of clay minerals and organic matter, is concentrated in laminations which alternate with the chalks (Rice, 1984). Well log characteristics of the Niobrara Formation can be seen in Figure 9.

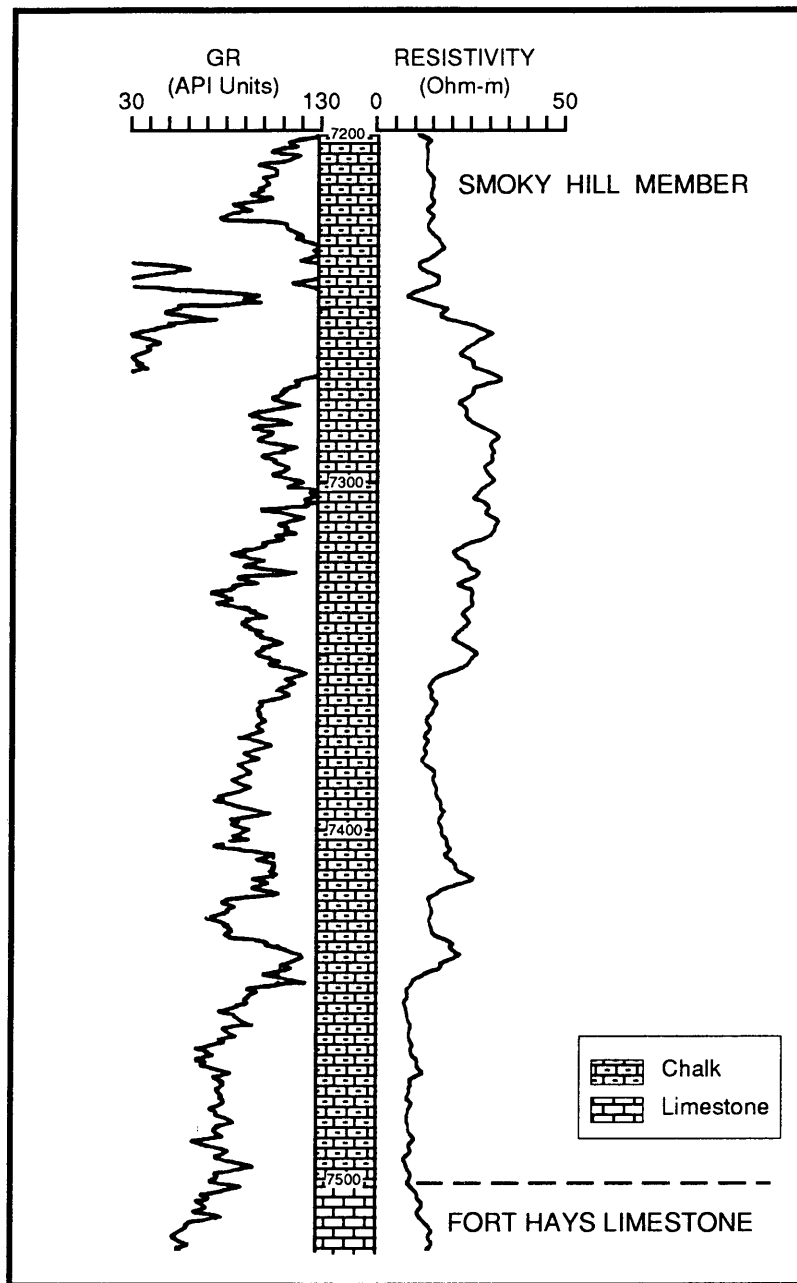


Figure 9. Typical electric log of the Niobrara Formation showing relatively high gamma-ray and resistivity values. Amoco-Champlin 344 A-1, SW SW Sec. 25 T10N R64W, Weld Co., Colorado (modified from Smagala et al., 1984).

Chapter 3

DATABASE AND METHODS

Sonic, resistivity, gamma-ray, and SP well-logs are the primary logs used in this study to identify and quantify total organic carbon of the subsurface Mowry Shale in the Denver basin. Gamma-ray and SP logs are used to discriminate non-reservoir from reservoir intervals, while sonic and resistivity curves are used as a pair to measure the TOC content of potential source rocks. In a relative sense, reservoir rock can be separated from non-reservoir rock by its low gamma-ray and SP log readings. To obtain reliable results, nineteen calculated TOC values from seven wells are calibrated against laboratory measured values of TOC. The use of well-logs to study source rocks becomes important because it is more practical to use, faster, and cheaper when compared to the geochemical analyses approach made using samples measured in the laboratory.

The focus of this research is the calibration of the subsurface tool responses with geochemical analyses of TOC. Some new developments of the original concepts have made the log prediction method more flexible and easier to apply. These are expected to make the original technique more applicable to a wider variety of source beds and sedimentary basins. In a previous study, Passey et al. (1990) calibrated their work using 148 samples from 7 wells for which geochemical measurements were made and found that the standard deviation of difference between the two methods is ± 1.4 wt.% TOC. In this study, the method was calibrated against available published TOC values for 2 different lithologies from the Denver and North Park basins. When calibrated against the Niobrara Formation of the Denver basin, the standard deviation of the difference is ± 1.4 wt.%

TOC, whereas the calibration against the Mowry Shale of North Park basin gives a standard deviation of the difference of ± 0.6 wt.% TOC.

3.1 Database

All logs used in this study were obtained from the Petroleum Information Library, Denver, Colorado. For the purpose of this study, 270 logs from eighty-six wells, including gamma-ray, SP, deep and shallow resistivity readings, conductivity, and sonic logs, were digitized. All well locations in section, range, and township are listed in Table 1.

Geochemical data needed for calculating TOC amount and calibrating these calculated TOC values were obtained from AAPG publications (Swetland and Clayton, 1980; Rice, 1984) and unpublished theses (Tainter, 1982; Fillmore, 1986). These data include measured TOC values, vitrinite reflectance, and spore coloration values (Tables 2 and 3).

3.2 Δ Log R Technique

The technique used in this work has been found to work adequately in both shale and carbonate source rocks, and it provides satisfactory estimates of TOC over a wide range of maturities, LOM 6 to LOM 12 (Passey et al., 1990). The method applies the separation, called Δ log R, between a transit time curve overlain on a resistivity curve to derive TOC content of source rocks.

The approach used in this study assumes that organic-rich rocks consist of the matrix and the fluid filling the pore space (Figure 10a). In immature source rocks (Figure 10b), solid organic matter and matrix together form the solid fraction and formation water fills the pore space. In this immature source rock, the sonic transit time reading is lower than

Table 1. Well log locations of the Mowry Shale within study area.

Well No	Location	Well Name	Company Name	Depth Interval (ft)
1	SW NE sec.4, T1N, R60W	No.1 Ralph E. Hanson Unit	Pan American Petroleum	6,460-6,508
2	SE SE sec.25, T1N, R61W	No 1-25 Evers	Cleary Petroleum	6,587-6,634
3	SE SE sec.10, T1N, R62W	No. 1 Reid Cooksey	Patrick Petroleum	6,986-7,034
4	NE SW SW sec.5, T1N, R66W	No.1 Gottlieb Gable Unit	Amoco	7,832-7,888
5	SW SE sec.1, T1N, R67W	Unit /A/ Richard L. Hein	Amoco	7,858-7,930
6	NW SE SE sec.31, T2N, R57W	No. 13-B Glenn-Biddle	Pure Oil	5,538-5,580
7	SW NW sec.26, T2N, R60W	No. 1 I C E Reed "B"	Pan American Petroleum	6,298-6348
8	SW NE sec.27, T2N, R60W	No.1 Meng	Western Slope Gas	6,304-6,354
9	NW SE sec.27, T2N, R60W	No.21 Roundup	Western Slope Gas	6,302.5-6355
10	SW NW sec.27, T2N, R60W	No.1 Midcap	Western Slope Gas	6,342-6,388
11	NW/4 NE/4 sec.1, T2N, R61W	No.1 Alkire Brothers	Wenner Petroleum	6,428-6,486
12	SE SE sec.17, T2N, R61W	No.1 Stanger	US Smelting Refining & Mining	6,632-6691
13	SW NW sec.3, T2N, R62W	No. 12-13 Premier Corp.	Beaver Mesa Expl.	6,797-6,841
14	C NW SE sec.23, T2N, R63W	No.1 Weickum	Franco-Western Oil	7,039-7078
15	NE SW SW sec.7, T2N, R64W	No. 1 UPRR Pan Am "E"	Amoco	7,566-7,606
16	C NE/4 SE/4 sec.24, T2N,R64W	No.1 Mc Cuntock	Juniper Oil & Gas, Texaco	7,319-7,374
17	NE SW sec.5, T2N, R66W	Unit "C" John A Kunzman	Amoco	7,710-7,766
18	NE SW sec.14, T2N, R67W	No.1Gas Unit No 1415 Corp.	Amoco	7,916-7976
19	SW NW sec.3, T2N, R68W	No.1 Clara A. Bacon	Amoco	7,714-7,740
20	SE NW sec.1, T3N, R62W	No.1 Parmlee	Energy Mineral Corp.	6,546.5-6602
21	SE SW sec.6, T3N, R65W	No.1 J.J Wardell	Amoco	7,792-7,844
22	SE SW SW sec.25, T3N, R68W	No.1 Edward Rademacher	Amoco	7,415-7,468
23	C NW SW sec.28, T3N, R68W	No.1 Elmer Hergenrader	Amoco	7,454-7,484
24	NW SE sec.5, T4N, R60W	No.1 Bosler Joanne	Sun Exploration	6,215.5-6271
25	E/2 SE/4 sec.3, T4N, R63W	1-B Ronald	Davis Oil	6,910-6,959
26	NW NW sec.3, T4N, R69W	Consolidated Oil & Gas	No.1 UPRR	3,851-3903
27	SE SW sec.16, T4N, R69W	No. 2 Berthoud State	Coquina Oil	3,572-3,615
28	NE SW sec.16, T4N, R69W	No.3 Berthoud State	Coquina Oil	3,622-3,664
29	SE NE sec.18, T5N, R57W	1 Weisbart-State	Davis Oil	5,830-5,880
30	NW SE sec.10, T5N, R61W	No.33-10 Packard	MGF Oil Corp.	6,718-6,766
31	C SW SW sec.11, T5N, R61W	13-11 Hendershot et al.	Enstar Petroleum	6,717-6,764
32	W/2 NW sec.23, T5N, R61W	11-23 Wildfong	MGF Oil Corp.	6,642-6,697
33	NW SW sec.22, T5N, R61W	1 Neil	British-American Oil	6,680-6,740
34	NE NE sec.28, T5N, R68W	1-B David R. Pulliam	Amoco	7,350-7,418
35	SE SE sec.31, T6N, R58W	No.1 Gronsten	Davis Oil	6,237-6,291
36	SW SW sec.10, T6N, R64W	No.1 Alex Heidenrieck	Tom Vessels	7,434-7,480
37	SE SE sec.17, T6N, R66W	No. 1-17 Fritzler	Hoppe, Kugler, W.B. Newberry & Gas	7,584-7,644
38	SE NW sec.20, T6N, R66W	No. 22-20 Linoblad	Hershey Oil Corp.	6,917-7000
39	NW SE sec.14, T6N, R68W	1 Syedman 33-14 (6-68)	Champlin Petroleum	6,610-6,652
40	SW NW sec.8, T7N, R60W	No. 8-3 Weitzel	Industrial Gas Services	6,908-6,970
41	W/2 SE SW sec.20, T7N, R61W	No. 20-1 Weld County	Benton Oil and Gas	6,940-7,000

Table 1. - continued

Well No	Location	Well Name	Company Name	Depth Interval (ft)
42	NE SW sec.1, T7N, R64W	No.23-1 CPC Travellers	Champlin Petroleum	7,429-7,480
43	SW NW sec.22, T7N, R65W	No.1 Wells Calve 12-22	Pan Canadian Petroleum	7,628-7,696
44	NW SE sec.11, T7N, R67W	No. 1-11 Amoco	Nortex Gas & Oil	7,560-7,590
45	SE SE sec.27, T1S, R58W	No.1-27 McLennan	Hershey Oil Corp.	5,796-5,830
46	SW SW sec.17, T1S, R60W	No. 17-1 UPRR	Sundance & Mc Culloch	6,446-6,482.5
47	SW SW sec.8, T1S, R62W	No.1 Beltz	Tom Vessels	7,224-7,270
48	NE SE sec.5, T1S, R62W	1 Champlin-524-Amoco-A	Amoco	7,085-7,125
49	NE NE sec.14, T1S, R64W	No.1 George Sauter	Amoco	7,653-7,702
50	SW SE sec.14, T1S, R68W	No. 1-14 North York Land As	Martin Exp. Management	8,414-8,470
51	S SW sec.18, T2S, R59W	1-18 Leasure	Mesa Petroleum	6,152-6,190
52	SW sec.26, T2S, R59W	No.1 Flader (25-625)	Tom Vessels	6,150-6,184
53	NE NE sec.32, T2S, R59W	No.1 Church	Tom Vessels	6,214-6,247
54	NE SE sec.10, T2S, R60W	No.1 Allis	Samedan & Le Clair	6,314-6,344
55	SW NE sec.15, T2S, R60W	No.1 CPC Alice, Irene & Harold F. Ebert	Champlin Petroleum	6,319-6,353
56	NE SW sec.11, T2S, R61W	A-1 Champlin 459 Amoco	Amoco	6,554-6,570
57	NE/4 NE/4 sec.19, T2S, R61W	No.1 Linnebur 41-19 (2-61)	Champlin Petroleum	6,534-6,570
58	NE NW sec.2, T2S, R63W	No.2 Vetter 21-2	Champlin Petroleum	7,354-7,7,380
59	SW SW sec.5, T2S, R64W	A-2 Kelton	Energy Minerals corp	7,890-7,934
60	SE NE sec.4, T2S, R65W	No.1 Krietser	Tom Vessels	8,106-8,142
61	SE NE sec.27, T2S, R66W	No.1 CPC Tower Investment	Champlin Petroleum	8,322-8,357
62	NE NE sec.22, T3S, R60W	No. 1-A Kroh	Tom Vessels	6,414-6,441
63	NW NW sec.21, T3S, R62W	No.2 Champlin 287 Amoco	Amoco	7,250-7,284
64	NW NW sec.22, T3S, R62W	No.1 J.C. Blauw	Amoco	7,200-7,224
65	C NE SE sec.9, T4S, R57W	No.4 UPRR-Cronk	Tiger Oil	5,336-5,371
66	C NW NE sec.9, T4S, R57W	No.3 UPRR-Cronk	Tiger Oil	5354.5-5390
66	SW SE sec.32, T4S, R60W	No.2 A.J. Ritter	Texaco	6,466-6,511
67	NE SE sec.33, T4S, R60W	No.18-6 UPRR	Pan American Petroleum	6,284-6,311
68	NE SW sec.31, T4S, R63W	No.2 Vince	Davis Oil	8,060-8,096
69	NE NE sec.31, T4S, R63W	No.1 Jo Ann	Davis Oil	7,955-8,010
70	NE NW sec.6, T5S, R63W	No.1 Rosenfield	Chandler & Associates	8,074-8,102
71	SE SE sec.10, T5S, R65W	No. 1-10 State	Tom Brown & Brownie, Wallace & Armstrong	8,530-8,562
72	SE SE sec.8, T6S, R61W	No.1 Ferman L. Mock	Amoco	6,926-6,950
73	NE NE sec.2, T6S, R65W	No. 1-2 Bates	Chandler and Associates	8,588-8,626
74	NE NE sec.25, T7S, R62W	No.1 UPRR	Pan American Petroleum	6,933-6,970
75	SE NW sec.11, T7S, R63W	No. 22-11 Johnson	Shell Oil	7,892-7,920
76	SE SE sec.17, T7S, R64W	No.1 Mary	Davis Oil	8,655-8,689
77	SW SW sec.36, T8S, R66W	No.1 Winkler State	Norsk Hydro Petroleum	9,251-9,270

Table 2. Geochemical data of the Niobrara Chalk used for calibration in this study (Rice, 1984)

Location	Well Name	Depth (ft)	Ro	Approx. LOM	TOC (wt.%)	
NW/4 SE/4 sec.14, T9N, R58W	Excelsior Oil 1 Alice G. Nay	5430	N/A		0.43	
		5433	N/A		2.66	
		5436.5	N/A		1.44	
		5439.5	N/A		2.02	
		5443	N/A		2	
		5446	N/A		1.74	
		5449.5	N/A		4.72	
		5453	N/A		2.56	
		5456	N/A		2.8	
		5459.5	0.69		9.5	4.53
		5462.5	N/A		1.08	
		5469	N/A	2.8		
5472.5	N/A	2.3				

Table 3. Geochemical data of the Mowry Shale used for calibration in this study (Fillmore, 1986)

Location	Well Name	Depth (ft)	Spore Color Index	Ro	Approx. LOM	TOC (wt.%)
NW NE sec.35, T6N, R81W	Trend Exploration-1 Fuipers	3•230	2	N/A	8.8 - 9.5	1.81
NE SE sec.9, T8N, R81W	Coseka Resources-South Coalmont No.1	7•505	3	N/A	9.6 - 10.7	1.65
NW SW sec.13, T7N, R82W	Cities Service Oil-1 Chedsey-A	2•867	2	N/A	8.8 - 9.5	2.05
SW NW sec.34, T9N, R80W	Cities Service-1 Federal B	8•445	4	N/A	10.8 - 11.8	1.42
NW SE sec.22, T7N, R79W	Ogle Corp., Cabot Corp., Bridger Pet.-1 Burr	3•168	3	N/A	9.6 - 10.7	1.48
SW SE sec.31, T10N, R80W	Mobil-1 Federal Alkali Lake Unit	5•011	3	N/A	9.6 - 10.7	1.7

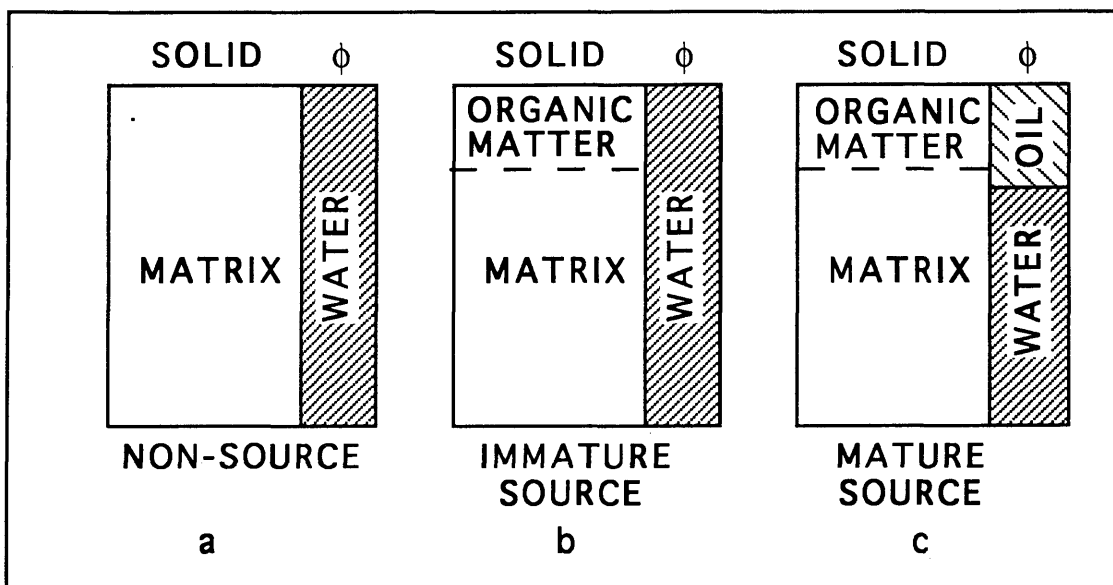


Figure 10. Schematic solid and liquid components in source and non-source rocks (modified from Passey et al., 1990).

it is in non-source rock because the sonic wave travels more slowly in a mixture of matrix and organic matter than it does in pure mineral matrix (Figure 10a). Resistivity readings in this rock are lower than in non-source rock because organic-rich shale containing organic matter is less resistive than pure matrix.

As the source rock matures (Figure 10c), a part of the solid organic matter is transformed into hydrocarbons (liquid or gaseous) which displace the formation water when moving into the pore space. In this mature source rock, the sonic transit time reading is higher than it is in immature source rock because the sonic wave travels more slowly in oil than it does in water. Resistivity in this mature source rock also increases since oil has a higher resistivity than formation water. These principles basically explain the relationship between the sonic transit time curve and resistivity readings in immature and mature source rocks. In addition, it must be remembered that TOC contents of source rocks (also separation between sonic and resistivity) decrease as hydrocarbons or gas are expelled from the source rock (Passey et al., 1990).

In this original application, the sonic transit-time curve and the resistivity curve are baselined in the scale of 100 $\mu\text{sec}/\text{ft}$ (328 $\mu\text{sec}/\text{m}$) per two logarithmic resistivity cycles. The baseline condition is a situation where the two curves directly cover each other over a significant depth range (± 30 m or more) in non-source, clay-rich rocks. By baselining the sonic curve with the resistivity curve, a shift in one curve will be compensated by a shift of comparable magnitude in the other curve. For example, an increase in porosity will result in an increase in Δt , but it also means an increase in the volume of conductive water, resulting in a decrease in resistivity (Figure 11). This compensation removes the porosity dependence (Passey et al., 1990).

The Passey et al. formula for calculating $\Delta \log R$ from the sonic/resistivity overlay is:

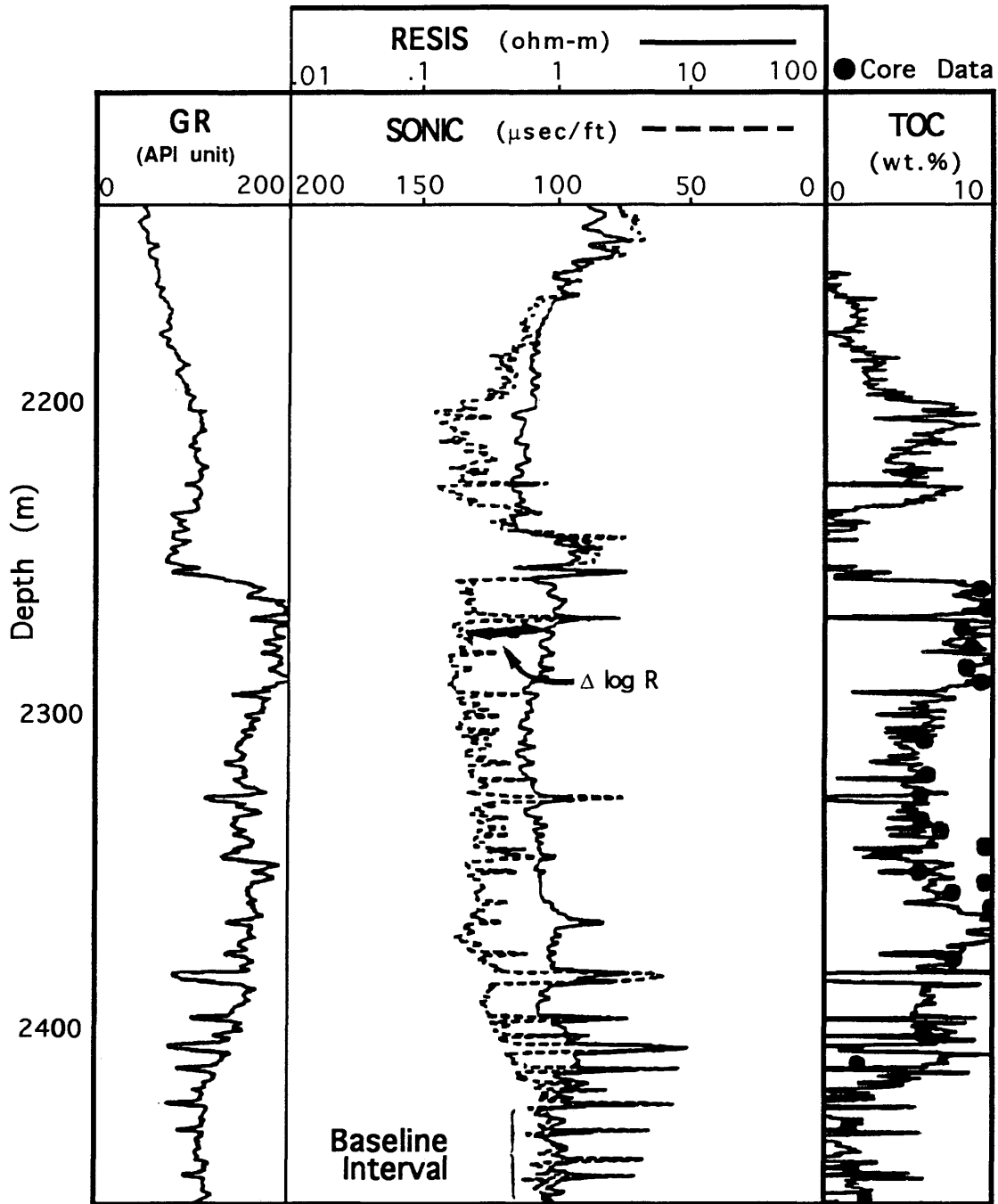


Figure 11. $\Delta \log R$ separation within sonic/resistivity overlay in the organic-rich interval. The relative scaling of the sonic and resistivity curves is $50 \mu\text{sec}/\text{ft}$. For this example, $R_{\text{baseline}} = 1 \text{ ohm-m}$ and $\Delta t_{\text{baseline}} = 100 \mu\text{sec}/\text{ft}$ (modified from Passey et al., 1990).

$$\Delta \log R = \log_{10} (R/R_{\text{baseline}}) + 0.02 \times (\Delta t - \Delta t_{\text{baseline}}) \quad (3.1)$$

where $\Delta \log R$ is the curve separation measured in logarithmic resistivity cycles, R is the resistivity measured in ohm-m, Δt is the measured transit time in $\mu\text{sec}/\text{ft}$, and 0.02 is the ratio of -50 msec/ft per one resistivity cycle. R_{baseline} and $\Delta t_{\text{baseline}}$ values correspond to the lowest TOC of the source rocks being studied. The empirical equation from Passey et al. (1990) to calculate TOC values via maturity from $\Delta \log R$ is:

$$\text{TOC} = (\Delta \log R) \times 10^{(2.297 - (0.1688 \times \text{LOM}))} \quad (3.2)$$

LOM of 7 corresponds to the onset of maturity for oil-prone kerogen, whereas LOM of 12 corresponds to the onset of overmaturity for oil-prone kerogen.

The LOM values used in this study were not directly acquired from published data, but they were converted from other thermal maturity indicators, namely vitrinite reflectance and spore coloration values. To simplify calculating TOC from $\Delta \log R$ via LOM, a map of vitrinite reflectance values in the study area, from Higley (1985), was converted into an LOM map (Figure 12; see step 7 below).

During this study, it was found that establishment of the baseline was not easily accomplished. In the Passey et al. (1990) examples, the baseline has the lowest gamma-ray reading, the lowest sonic transit time, and the highest resistivity values along the investigated interval. In this study, and possibly in most applications, many logs do not have such a long baseline interval (± 30 m) showing the characteristics mentioned above. For instance, Figure 13 represents a well with gamma-ray, resistivity, and sonic transit

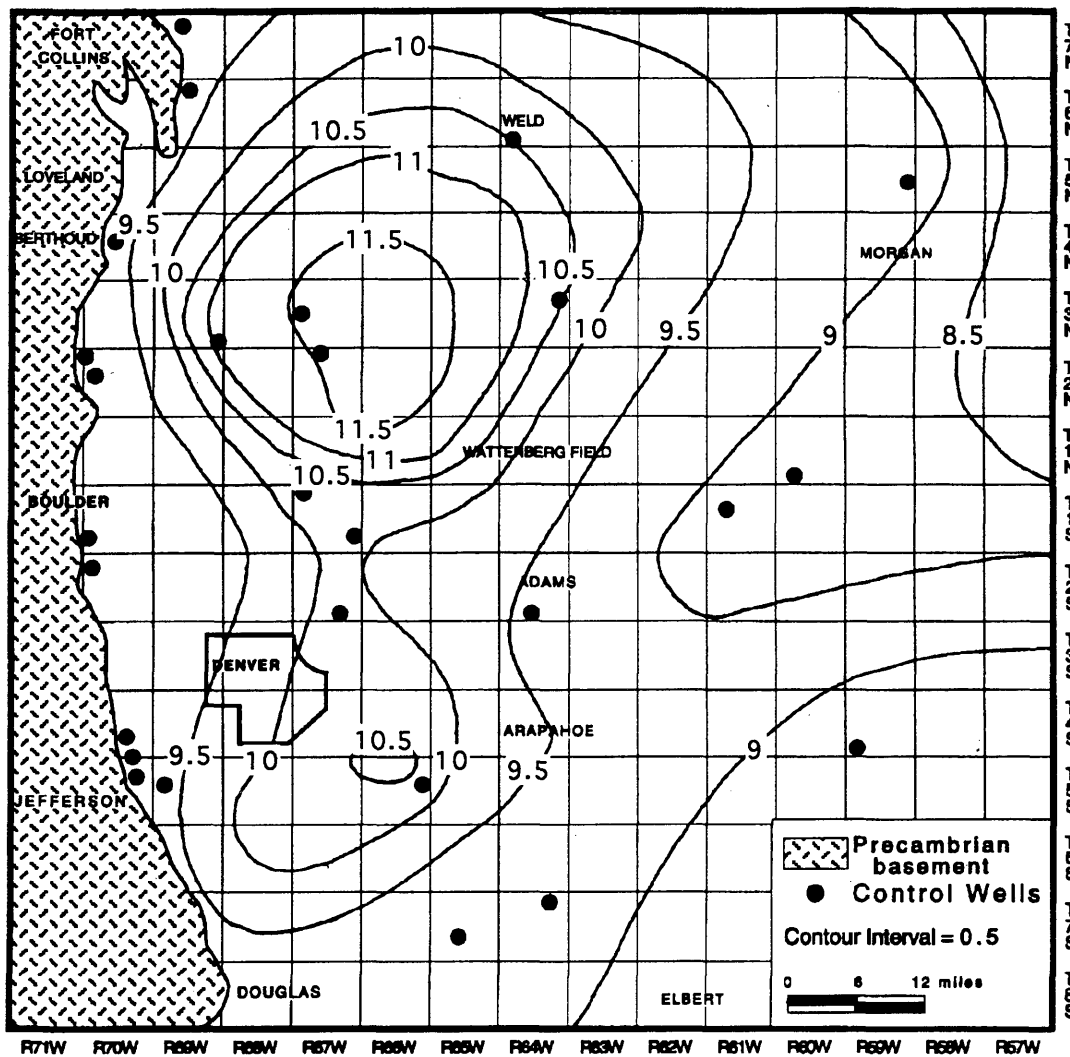


Figure 12. Level of organic metamorphism (LOM) map of the Mowry Shale in western Denver basin (modified from Higley, 1985).

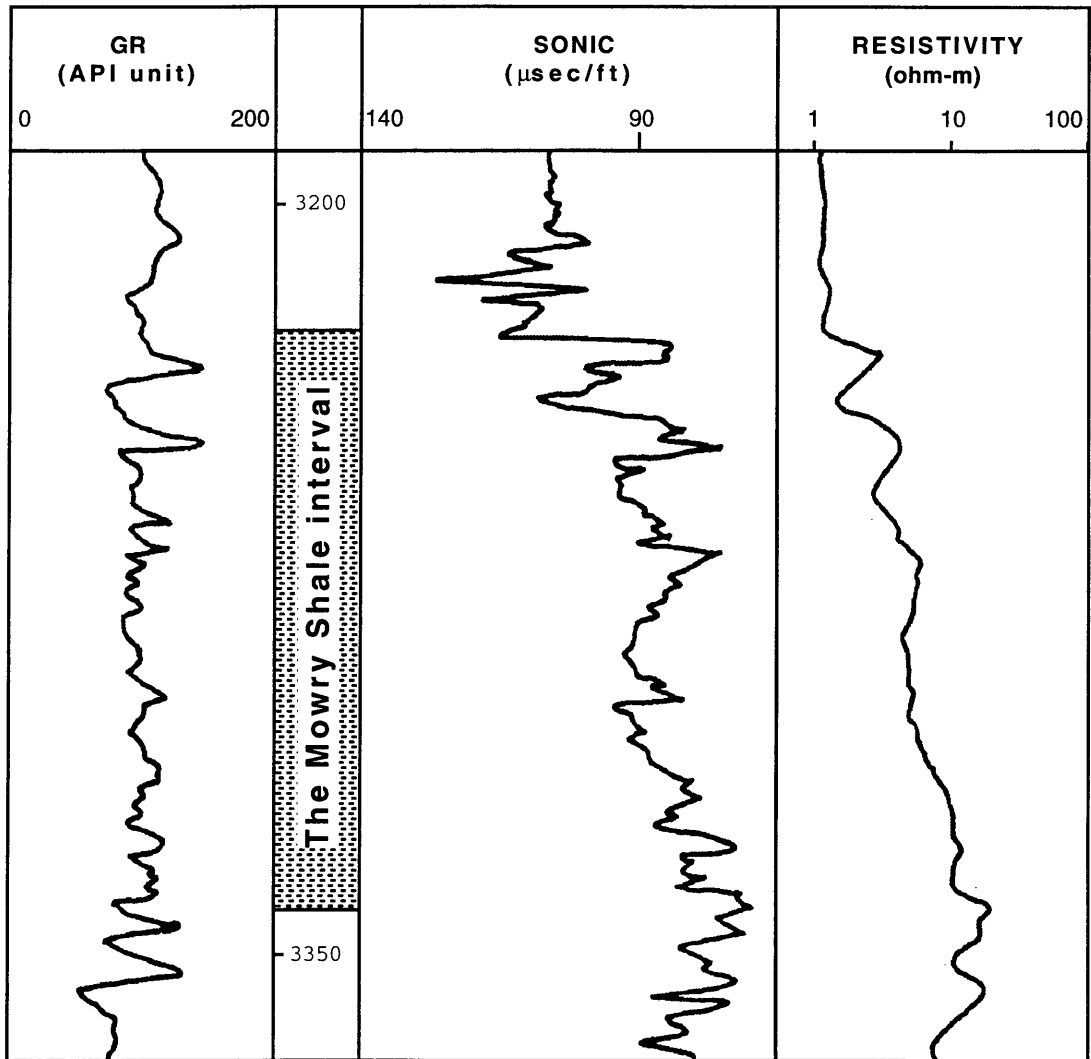


Figure 13. Source rock interval (The Mowry Shale) without an apparent baseline interval associated with low gamma-ray and sonic readings, and high resistivity reading over a significant depth range. Trend Exploration-1 Kuipers, NE SE 9-8N-81W, North Park, Colorado.

time, for which an apparent baseline could not be found, which makes the Passey et al. method difficult to apply. A new approach, however, is developed in this work to enable the use of poor baseline wells without changing the basic principle of combining low sonic transit time values and high resistivity readings.

3.3 TOC Determination Method

To quantify TOC content in organic-rich source rocks in this work, the following steps were undertaken:

1. Defining the top and bottom of the Mowry Shale for each studied well. For the purpose of this study, the Mowry Shale is defined as the shale interval between the D sandstone at the top and the Muddy (J) sandstone at its base.
2. Adjusting the depths of the top and bottom of the investigated interval with scout ticket information. To avoid defining an incorrect interval, the top and bottom of the Mowry Shale picked out on logs are adjusted with information from engineering data (scout ticket).
3. Digitizing selected intervals of gamma-ray, sonic, and resistivity curves for each 0.5 foot increment. Since the original tapes were not available, the logs needed to be digitized from paper copy. Gamma-ray and transit time curves are digitized within one decimal, while resistivity curves are digitized within 2 decimals. Depth matching between resistivity and sonic logs are done as accurately as possible based on the same recognizable log break of the two curves at comparable depths.
4. Crossplotting resistivity versus sonic transit time values. This step is necessary to determine whether the method used in this study will work for a particular well. The

method will work if Δt measurements decrease exponentially with respect to resistivity (Figure 14).

5. Determining R_{baseline} , $\Delta t_{\text{baseline}}$, and $\Delta \log R$. The lowest TOC values, associated with low transit time and high resistivity reading, will be accumulated near the right end of the resistivity-sonic crossplot. From the middle of the lowest point accumulation, a point representing "baseline" (R_{baseline} , $\Delta t_{\text{baseline}}$) was picked up to calculate $\Delta \log R$ (Figure 14). Scattered points at the end of the curve should not be picked up as a "baseline" since they may derive from tool error. $\Delta \log R$ is the separation between resistivity and sonic porosity curve representing variation in TOC values. The equation to obtain the baseline value is:

$$\Delta \log R = \log_{10}(R/R_{\text{baseline}}) + 0.02 \times (\Delta t - \Delta t_{\text{baseline}}) \quad (3.3)$$

where at the same level of maturity, the $\Delta \log R$ value is linearly related to the TOC value. For example, an increase in $\Delta \log R$ results in an increase in TOC, and vice versa. Figure 15 shows $\Delta \log R$ separation within Passey et al. (1990) sonic and resistivity overlay using the baseline value determined by this method. In this overlay, where the resistivity curve is on the left side of the sonic curve, calculated $\Delta \log R$ separation results in negative values, while positive $\Delta \log R$ separation occurs when the resistivity curve is on the right side of the sonic log (e.g. Figure 11). This negative $\Delta \log R$ separation can be corrected by using step number 6 below.

6. Correcting $\Delta \log R$ values. Step number 5 above may result in negative values of TOC. Since the lowest TOC value cannot be lower than 0, a correction must be made. For example, Figure 16 illustrates a condition where $\Delta \log R$ calculations

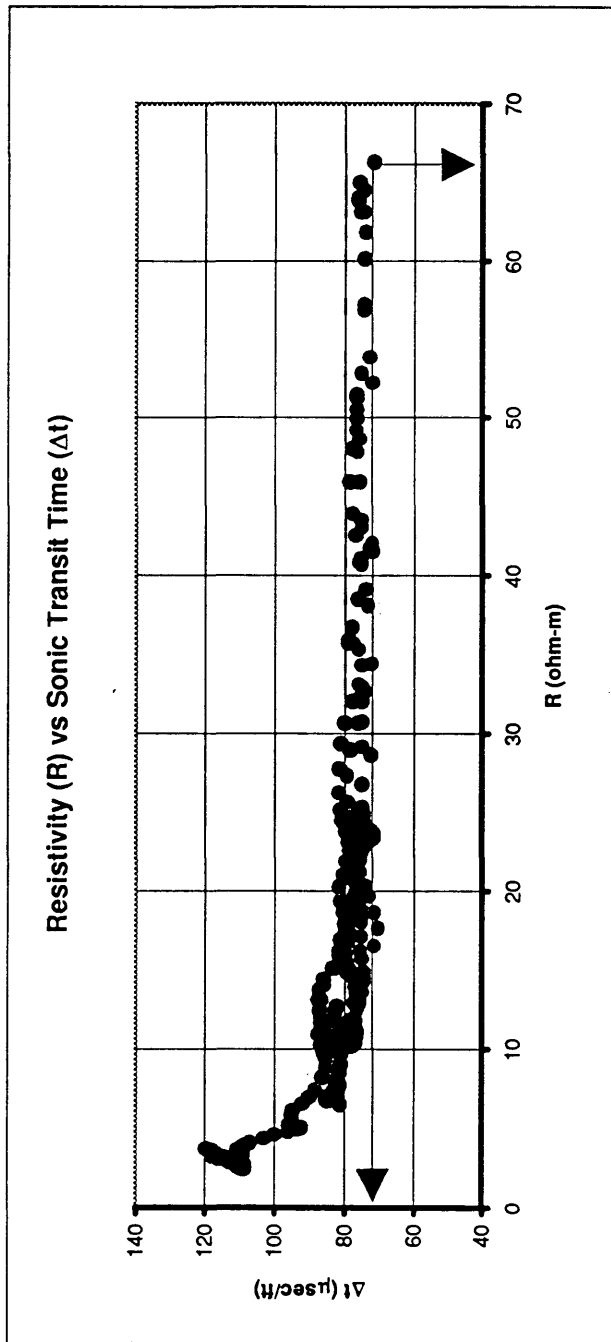


Figure 14. An ideal resistivity-sonic crossplot where sonic transit time (Δt) decreases exponentially with respect to resistivity (R). The arrows point to "baseline" (R_{baseline} , D_{baseline}). For this example, $R_{\text{baseline}} = 67$ ohm-m and $D_{\text{baseline}} = 71$ msec/ft. The Niobrara Formation, Excelsior Oil-1 Alice G. Nay, NW 1/4 SE 1/4 14-9N-58W, Weld Co, Colorado.

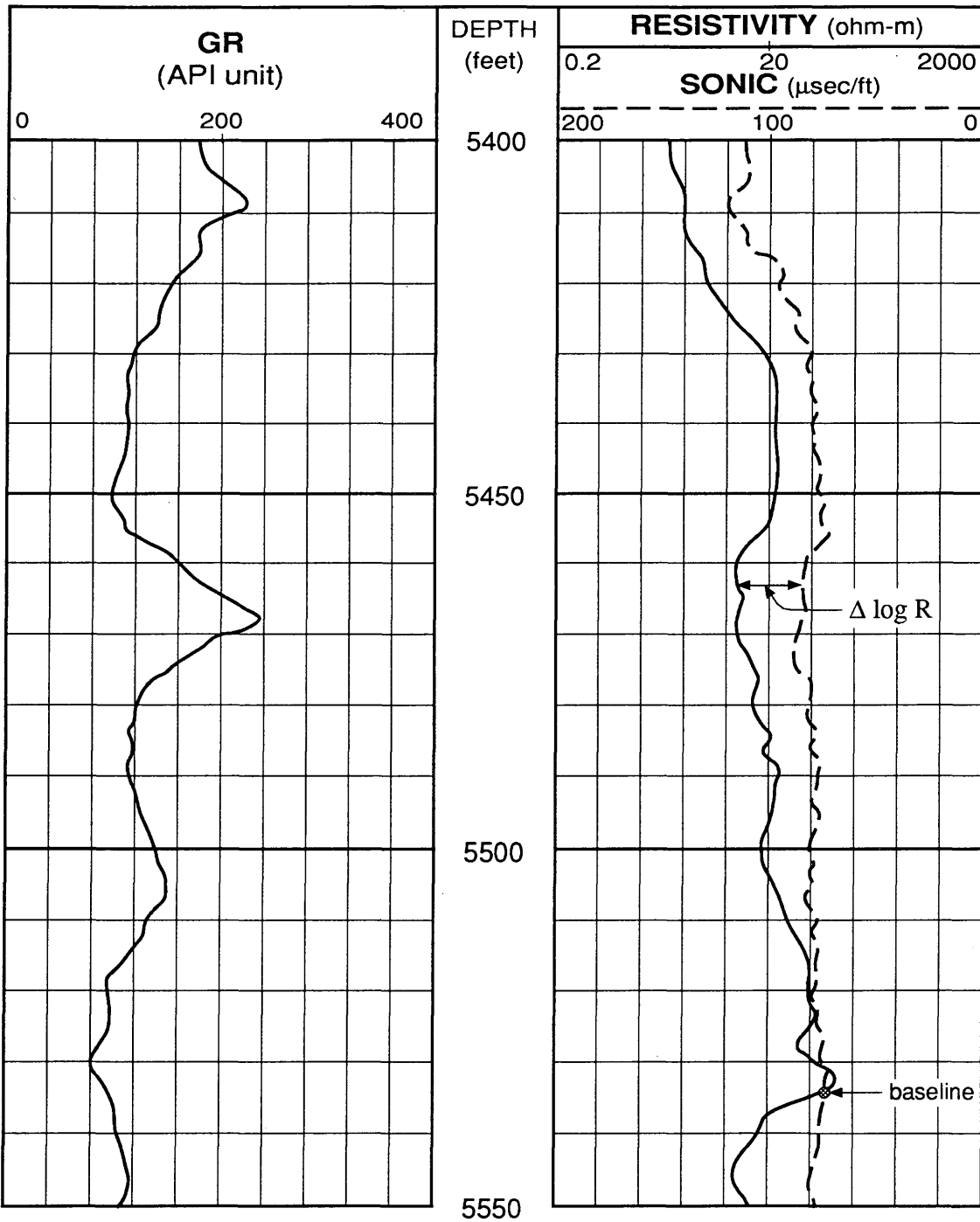


Figure 15. $\Delta \log R$ separation within sonic/resistivity overlay in the Niobrara Chalk interval. Baseline is determined by resistivity-sonic crossplot. For this example, $R_{\text{baseline}} = 67 \text{ ohm-m}$, $\Delta t_{\text{baseline}} = 71 \text{ } \mu\text{sec/ft}$. Excelsoir Oil-1 Alice G. Nay, NW 1/4 SE 1/4 14-9N-58W, Weld Co., Colorado.

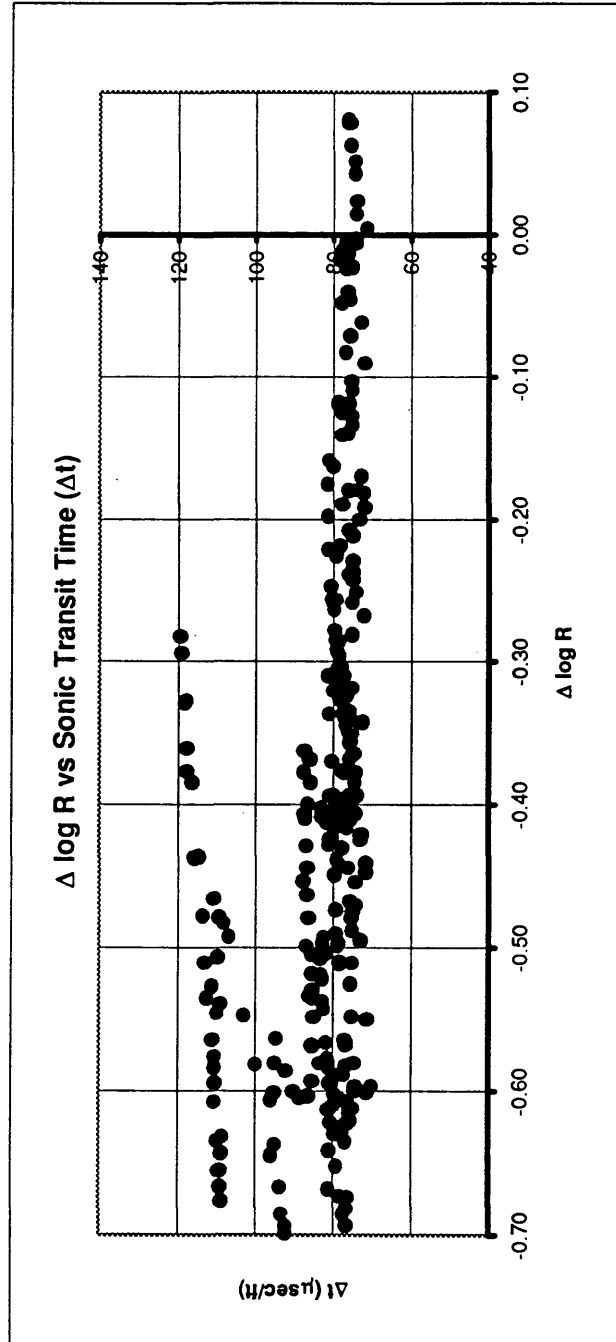


Figure 16. $\Delta \log R$ -sonic crossplot illustrating a condition where $\Delta \log R$ calculations result in negative values. Excelsior Oil-1 Alice G. Nay, NW 1/4 SE 1/4 14-9N-58W, Weld Co, Colorado

resulted in negative values. In this case, the most negative value in its cluster, which is -0.70, is shifted to 0 by adding +0.70. Then, all other $\Delta \log R$ values are shifted to the right by adding the same correction factor. There are two obvious trends observed in Figure 16, the upper straight trend and the bottom straight trend. These two trends have overlapping $\Delta \log R$ values at different Δt values. These two different trends are interpreted to reflect different kerogen type and composition in the source rock. These two data clusters are not clearly observed in Figure 14. The exponential line in Figure 14 is not truly composed of only a single line. The accumulation of data points between approximately $R = 10$ to $R = 30$ ohm-m actually consists of multiple overlapping short lines. These multiple single lines are interpreted as having come from different kerogen types and compositions. Notice that correcting all $\Delta \log R$ values does not change the original slope if $\Delta \log R$ is plotted against the gamma-ray or sonic readings (Figure 17).

7. Estimating LOM values. To facilitate calculating TOC amount from $\Delta \log R$ via LOM, a LOM map was created (Figure 12). LOM values used in this map were derived from converting available vitrinite reflectance and spore coloration data (Higley, 1985 and Fillmore, 1986) into LOM values. The conversion used in this work is listed in Table 4 and is based on conversion tables provided by Hood et al. (1982).
8. Calculating TOC values. Each corrected $\Delta \log R$ value is converted into an appropriate TOC value via the Passey et al. equation:

$$\text{TOC} = (\Delta \log R) \times 10^{(2.297 - (0.1688 \times \text{LOM}))} \quad (3.4)$$

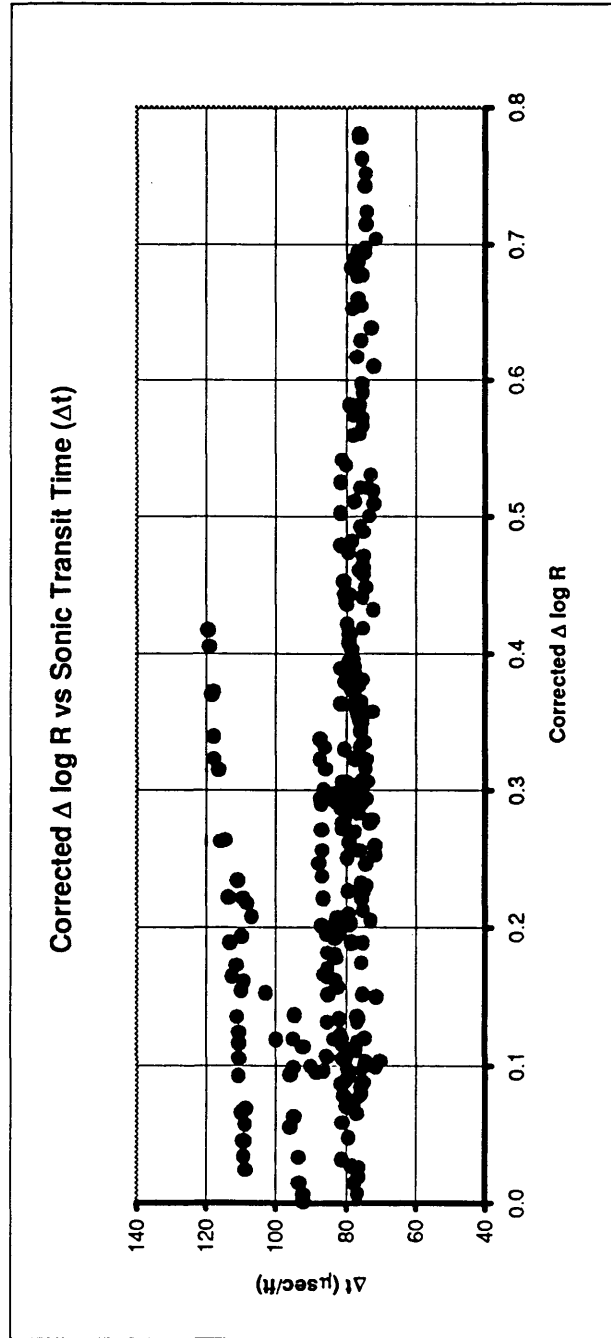


Figure 17. Corrected $\Delta \log R$ -sonic crossplot illustrating the same degree of slope after and before $\Delta \log R$ corrections. Excelsior Oil-1 Alice G. Nay, NW 1/4 SE 1/4 14-9N-58W, Weld Co, Colorado

Table 4. Conversion of vitrinite reflectance and spore coloration values into level of organic metamorphism, LOM (modified from ASTM standard, 1983; Hood et al., 1982)

Spore Color Index	Ro	Estimated LOM	Spore Color Index	Ro	Estimated LOM
	0.36	4.8	3	0.77	9.8
	0.37	5.0		0.78	9.9
	0.38	5.1		0.79	9.9
	0.39	5.3		0.80	9.9
	0.40	5.5		0.81	10.0
	0.41	5.7		0.82	10.0
	0.42	5.8		0.83	10.1
	0.43	6.0		0.84	10.1
	0.44	6.3		0.85	10.2
	0.45	6.6		0.86	10.2
	0.46	6.9		0.87	10.2
	0.47	7.2		0.88	10.3
	0.48	7.6		0.89	10.3
	0.49	7.9		0.90	10.4
	0.50	8.3		0.91	10.4
	0.51	8.7		0.92	10.4
	0.52	8.7		0.93	10.5
	0.53	8.8		0.94	10.5
	0.54	8.8		0.95	10.6
2	0.55	8.8	0.96	10.6	
	0.56	8.9	0.97	10.6	
	0.57	8.9	0.98	10.7	
	0.58	9.0	0.99	10.7	
	0.59	9.0	4	1.00	10.8
	0.60	9.1		1.01	10.8
	0.61	9.1		1.02	10.8
	0.62	9.2		1.03	10.9
	0.63	9.2		1.04	10.9
	0.64	9.3		1.05	11.0
	0.65	9.3		1.06	11.0
	0.66	9.4		1.07	11.0
	0.67	9.4		1.08	11.1
	0.68	9.5		1.09	11.1
	0.69	9.5	1.10	11.2	
	0.70	9.5	1.11	11.2	
	3	0.71	9.6	1.12	11.2
0.72		9.6	1.20	11.4	
0.73		9.7	1.30	11.5	
0.74		9.7	1.40	11.7	
0.75		9.7	1.50	11.8	
0.76		9.8	5	1.60	12.0

Since the lowest measured Mowry Shale TOC value is 0.8, a 0.8 wt.% correction factor was added to each calculated TOC value using equation 2 above assuming all wells having the lowest TOC value of 0.8 wt.% TOC. In summary, equation 3.4 is modified to:

$$\text{TOC} = (\Delta \log R) \times 10^{(2.297 - (0.1688 \times \text{LOM}))} + 0.8 \quad (3.5)$$

9. Calibrating calculated TOC values against measured TOC. To test the reliability of this method, calculated TOC values from several wells are calibrated against measured TOC values from the same depth in the same well. The calibration involves the Mowry Shale and Niobrara Chalk as potential source rocks.
10. Mapping TOC values. For each studied well, a TOC-ft value, derived from the sum of multiplication of TOC against each depth increment, was used to represent the TOC-ft value from that particular location. To map TOC, an average value for the entire well was used. Sixty-seven TOC calculations were used to obtain the average TOC values in each well.

Chapter 4

RESULTS AND COMPARISON

4.1 RESULTS OF STUDY

For seven wells studied, the comparison of well log-derived TOC values against core and cutting laboratory measurements shows good agreement. The difference between measured and calculated TOC values of the Niobrara Chalk varies from -1.4 to 3.5 wt. % TOC (Table 5). The standard deviation of difference between the measured and calculated values is ± 1.4 wt. % TOC.

For the Mowry Shale, lack of TOC measurements from core and cuttings limits the calibration procedure. Calibration was performed using only a single measurement from each of the six wells studied in North Park basin. Nevertheless, the results of this comparison show good agreement between measured and calculated TOC values. The differences between the two values range from -0.60 to 0.86 wt. % TOC with standard deviation of differences ranging from ± 0.3 to ± 0.6 wt.% TOC (Table 6).

Nine out of seventy-seven wells failed to pass resistivity vs sonic transit time curve (Δt) tests (Table 7). These eleven wells do not have a decreasing exponential relationship between their resistivity and sonic curves. An example of non exponential relationship between resistivity and sonic transit time curve can be seen in Figure 18. The average TOC values of the Mowry Shale for each particular well within the study area ranges from 1.1 to 3.1 wt.% TOC, while their TOC-ft values range from 31.3 to 141.3 wt.%-ft. The TOC distribution map of the Mowry Shale is presented in Figure 19, while the Mowry Shale TOC-ft map is presented in Figure 20.

Table 5. Total organic carbon calibration data of the Niobrara Chalk in the Denver basin. Alice G. Nay, NW 1/4 SE 1/4 14-9N-58W

DEPTH (ft)	GR (API)	RESIS (ohm-m)	SONI ($\mu\text{sec/ft}$)	$\Delta \text{Log R}$ R _{baseline} = 5 $\Delta\text{baseline} = 93$	Calculated TOC at LOM = 9.5 (wt.% TOC)	Measured TOC (wt.%)	Differences Meas. - Cal. TOC (wt.%)
5430.0	137.6	17.50	79.4	0.27	1.84	0.43	-1.41
5433.0	139.2	21.90	79.4	0.37	2.32	2.66	0.34
5436.5	146.5	24.70	78.4	0.40	2.49	1.44	-1.05
5439.5	139.2	23.00	77.5	0.35	2.24	2.02	-0.22
5443.0	128.9	23.90	76.0	0.34	2.18	2	-0.18
5446.0	123.2	24.20	74.9	0.32	2.09	1.74	-0.35
5449.5	124.5	24.40	75.7	0.34	2.19	4.72	2.53
5453.0	118.6	22.60	74.8	0.29	1.94	2.56	0.62
5456.0	108.7	17.70	70.1	0.09	0.95	2.8	1.85
5459.5	164.3	11.00	81.1	0.10	1.01	4.53	3.52
5462.5	185.7	11.90	83.2	0.18	1.39	1.08	-0.31
5469.0	320.0	10.20	85.1	0.15	1.25	0.57	-0.68
5472.5	232.2	12.10	86.8	0.26	1.78	2.3	0.52

Table 6. Total organic carbon calibration data of the Mowry Shale in North Park basin.

Well Location	Depth (ft)	RESIS (ohm-m)	SONI ($\mu\text{sec/ft}$)	Calculated TOC (wt.% TOC)	Measured TOC (wt.%)	Differences Meas. - Cal. TOC (wt.%)
SW SE 31-T10N-R80W	5010	1.60	105.1	2.6 if LOM 9.5 1.9 if LOM 10.8	1.7	0.9 - (-)0.2
NE SE 9-T8N-R81W	7505	3.67	98.5	2.0 if LOM 9.5 1.5 if LOM 10.8	1.7	0.3 - (-)0.2
NW NE 35-T6N-R81W	3230	2.54	98.5	1.8 if LOM 8.8 1.6 if LOM 9.5	1.8	0 - (-)0.1
NW SW 13-T7N-R79W	2867	2.89	105.2	1.7 if LOM 8.8 1.5 if LOM 9.5	2.1	(-)0.4 - (-)0.7
SW NW 13-T7N-R82W	8445	23.90	76	1.1 if LOM 10.8 1 if LOM 12	1.4	(-)0.3 - (-)0.4
NW SE 22-T7N-R79W	3168	8.54	111.5	2.2 if LOM 9.5 1.7 if LOM 10.8	1.5	0.7 - 0.2

Table 7. Calculated TOC contents of the Mowry Shale

Well Location	R vs Δt Test		Approx. LOM	Average calculated TOC (wt.%)	Σ TOC x thickness (wt.-%-ft)
	FAIL (F)	PASS (P)			
SW NE sec.4, T1N, R 60W			8.9	3.1	95
SE SE sec. 25, T1N, R61W		P	8.9	2.1	101
SE SE sec. 10, T1N, R62W		P	9.2	1.6	75
SW SW sec.5, T1N, R66W		P	11.0	1.5	86
SW SE sec. 1, T1N, R67W		P	11.5	1.2	89
SE SE sec.31, T2N, R57W		P	8.4	1.6	68
SW NW sec.26, T2N, R60W		P	8.9	1.6	81
SW NE sec.27, T2N, R60W		P	8.9	1.9	103
NW NE sec.1, T2N, R61W		P	9.2	2.1	123
SE SE sec.17, T2N, R61W		P	9.2	2.0	117
SW NW sec.3, T2N, R62W		P	9.5	1.7	75
C NW SE sec.23, T2N, R63W		P	9.7	1.6	63
SW SW sec.7, T2N, R64W		P	11.0	1.1	45
C NE SE sec.24, T2N, R64W		P	10.0	1.8	97
NE SW sec.5, T2N, R66W		P	11.5	1.2	89
NE SW sec.14, T2N, R67W		P	11.5	1.1	64
SW NW sec.3, T2N, R68W	F				
SE NW sec.1, T3N, R62W		P	9.6	1.6	87
SE SW sec. 6, T3N, R65W		P	11.5	1.1	60
SW SW sec.25, T3N, R68W	F				
NW SW sec.28, T3N, R68W		P	11.3	1.4	42
NW SE sec.5, T4N, R60W		P	9.3	2.2	123
E SE sec.3, T4N, R63W		P	10.3	1.4	54
NW NW sec.3, T4N, R69W		P	10.0	1.3	68
SE SW sec.16, T4N, R69W		P	10.0	1.5	64
NE SW sec.16, T4N, R69W		P	9.9	1.7	73
SE NE sec.18, T5N, R57W		P	8.5	2.2	112
NW SE sec.10, T5N, R61W		P	9.5	1.3	63
SW SW sec.11, T5N, R61W		P	9.5	1.7	80
W NW sec.23, T5N, R61W		P	9.5	1.9	106
NW SW sec.22, T5N, R61W		P	9.5	1.6	95
NE NE sec.28, T5N, R68W		P	10.5	1.6	107
SE SE sec.17, T6N, R58W		P	9.1	2.1	112
SW SW sec.10, T6N, R64W		P	10.0	1.3	57
SE SE sec.17, T6N, R66W		P	10.5	1.6	95
SE NW sec.20, T6N, R66W		P	10.6	1.6	132
NW SE sec.14, T6N, R68W		P	10.0	2.2	94
SW NW sec.8, T7N, R60W		P	9.3	1.4	86

Table 7. - continued

Well Location	R vs Δt Test		Approx. LOM	Average calculated TOC (wt.%)	Σ TOC x thickness (wt. %-ft)
	FAIL (F)	PASS (P)			
SE SW sec.20, T7N, R61W		P	9.4	1.7	102
NE SW sec.1, T7N, R64W		P	9.5	1.5	76
SW NW sec.22, T7N, R65W		P	10.0	2.1	141
NW SE sec.11, T7N, R67W		P	9.9	2.8	87
SE SE sec.27, T1S, R58W		P	8.8	1.7	57
SW SW sec.17, T1S, R60W		P	8.7	1.9	73
SW SW sec.8 T1S, R62W		P	9.2	1.5	70
NE SE sec.5, T1S, R62W		P	9.2	1.5	59
NE NE sec.14, T1S, R64W		P	9.6	1.3	62
SW SE sec.14, T1S, R68W		P	10.0	1.6	88
S SW sec.18, T2S, R59W		P	8.9	1.3	48
SW sec.26, T2S, R59W		P	8.8	1.9	64
NE NE sec.32, T2S, R59W		P	9.0	1.6	53
NE SE sec.10, T2S, R60W	F				
SW NE sec.15, T2S, R60W	F				
NE SW sec.11, T2S, R61W	F				
NE NE sec.19, T2S, R61W		P	8.9	2.3	79
NE NW sec.2, T2S, R63W		P	9.4	1.1	29
SW SW sec.5, T2S, R64W		P	9.6	1.3	56
SE NE sec.4, T2S, R65W		P	9.8	1.5	53
SE NE sec.27, T2S, R66W		P	9.9	1.3	46
NE NE sec.22, T3S, R60W		P	9.0	2.1	66
NW NW sec.21, T3S, R62W		P	9.0	1.2	40
NW NW sec.22, T3S, R62W	F				
NW NE sec.9, T4S, R57W		P	9.0	2.9	106
NE SE sec.9, T4S, R57W		P	9	2.7	130
SW SE sec.32, T4S, R60W		P	9.0	2.4	107
NE SE sec.33, T4S, R60W	F				
NE SW sec.31, T4S, R 63W		P	9.4	1.6	61
NE NE sec.31, T4S, R63W	F				
NE NW sec.6, T5S, R63W		P	9.4	1.6	47
SE SE sec.10, T5S, R65W		P	9.8	1.6	87
SE SE sec.8 T6S, R61W		P	9.0	1.6	87
NE NE sec.2, T6S, R65W		P	9.5	1.6	63
NE NE sec.25, T7S, R62W		P	9.0	2.3	84
SE NW sec.11, T7S, R63W		P	9.0	1.8	52
SE SE sec.17, T7S, R64W	F				
SW SW sec.36, T8S, R66W		P	9.1	1.6	31

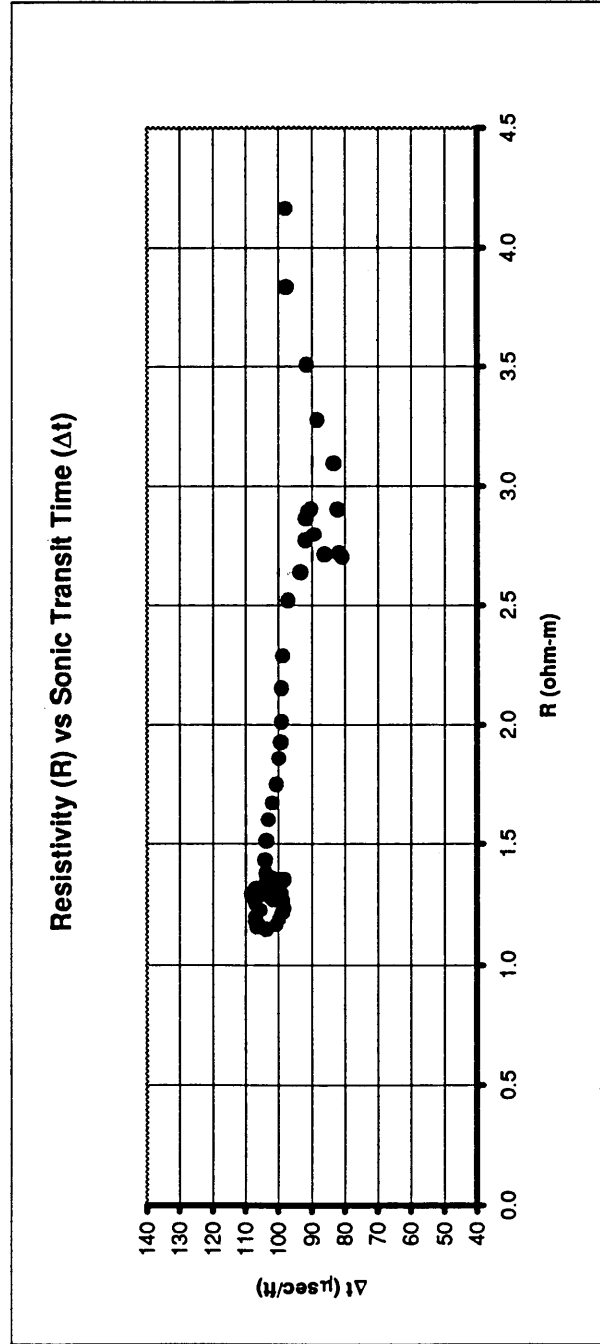


Figure 18. Non exponential relationship between resistivity and sonic transit time in the Mowry Shale. Allis-1, Samedan & Le Clair, NE SE sec.10, T2S, R60W. Adams Co, Colorado.

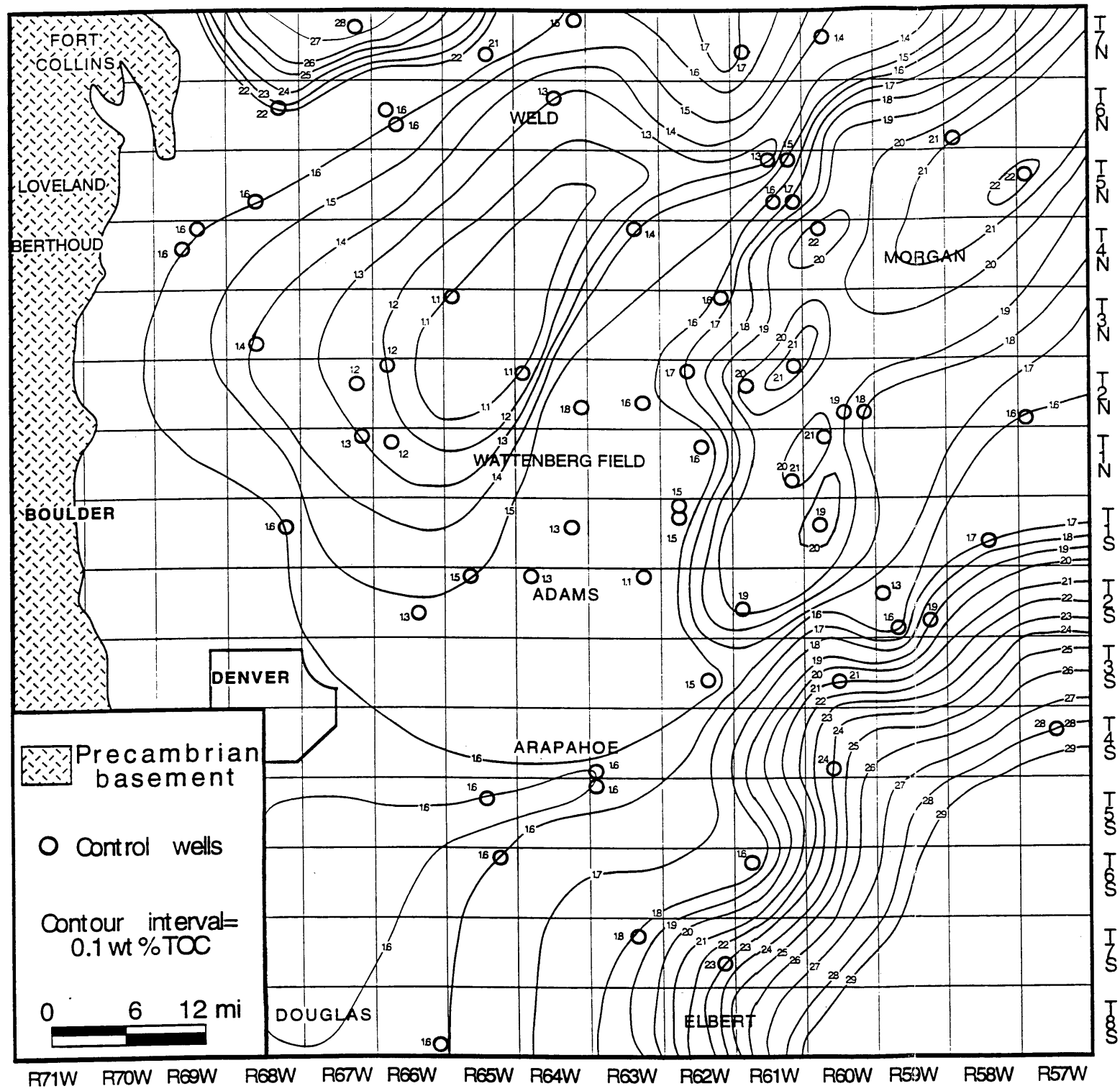


Figure 19. Distribution of calculated TOC of the Mowry Shale within study area.

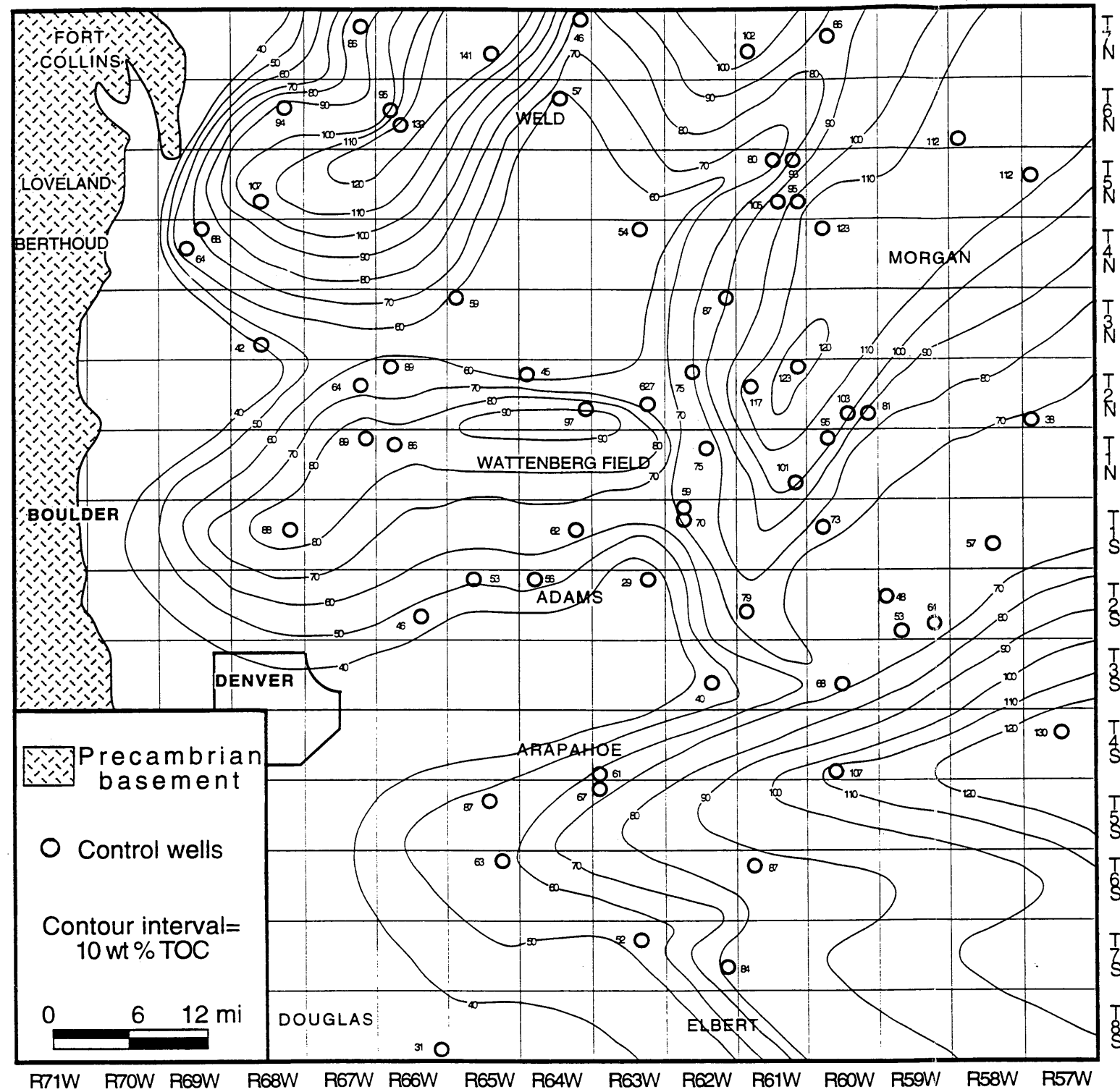


Figure 20. Total TOC-ft map of the Mowry Shale within study area.

4.2 COMPARISON WITH OTHER METHODS

To evaluate the advantage of this method with respect to other well-log methods in determining and quantifying log-derived TOC values, it is necessary to compare the results of the method used in this study with those of other well-log methods. The results of this comparison provide some options for choosing the most accurate and appropriate method to apply to a certain source bed in a particular basin. In this study, the Passey et al. method is compared with Meyer and Nederlof sonic transit time/resistivity crossplots and Schmoker and Hester density methods. The results of this study show that the Passey et al. method gives closer results to measured TOC values when compared with the Meyer-Nederlof and Schmoker-Hester methods.

Meyer and Nederlof (1984) discriminate source rocks and non-source rocks by a cut-off value of approximately 1.5 wt. % TOC. The discriminant (D) is defined as:

$$D = -6.906 + 3.186 \log \Delta t + 0.487 \log_{10} R75 \quad (4.1)$$

where Δt is in $\mu\text{sec}/\text{ft}$ and R75 is the resistivity corrected to a standard temperature of 75°F (24°C). If $D > 0$, the rock is a probable source rock; if $D < 0$, the rock is a probable non-source rock; if $D = 0$, the case remains undecided.

TOC determinations using the Meyer and Nederlof equation on the Niobrara Chalk and the Mowry Shale do not give good results. When applied to the Niobrara Chalk, all calculations fail to recognize the Niobrara Chalk as a potential source rock because all calculations end with $D < 0$, indicating that TOC values of the Niobrara samples are less than 1.5 wt. % TOC (Table 8). When applied to the Mowry Shale, the method also failed to recognize TOC contents of the Mowry Shale that exceed 1.5 wt.% TOC (Table 9).

Table 8. Niobrara Chalk total organic carbon determination data using Meyer and Nederlof equation in the Denver basin.

Well Name	Depth (ft)	Measured Resistivity (ohm-m)	Δt ($\mu\text{sec}/\text{ft}$)	Formation Temperature T ($^{\circ}\text{F}$)	Resistivity at 75 F R75 (ohm-m)	Discriminant D	Measured TOC (wt.%) (Rice, 1984)
	5430	17.5	79.4	148.5	33.19	-0.11	0.43
	5433	21.9	79.4	148.6	41.55	-0.07	2.66
	5436.5	24.7	78.4	148.6	46.88	-0.06	1.44
	5439.5	23	77.5	148.7	43.67	-0.09	2.02
	5443	23.9	76	148.8	45.4	-0.11	2
	5446	24.2	74.9	148.8	45.99	-0.12	1.74
Excelsior Oil 1 Alice G. Nay	5449.5	24.4	75.7	148.9	46.39	-0.11	4.72
	5453	22.6	74.8	149	42.99	-0.14	2.56
	5456	17.7	70.1	149	33.68	-0.28	2.8
	5459.5	11	81.1	149.1	20.94	-0.18	4.53
	5462.5	11.9	83.2	149.2	22.66	-0.13	1.08
	5469	10.2	85.1	149.3	19.44	-0.13	0.57
	5472.5	12.1	86.8	149.4	23.07	-0.07	2.3

Table 9. The Mowry Shale total organic carbon determination data using Meyer and Nederlof equation in North Park basin.

No	Well Name	Depth (ft)	Measured Resistivity RT (ohm-m)	Δt (μsec/ft)	Formation Temperature T (°F)	Resistivity at 75 F R75 (ohm-m)	Discriminant D	Measured TOC (wt.%) (Fillmore, 1986)
1	Trend Exploration-1 Fuipers	3230	2.54	109.6	105.0	3.5	-0.1	1.81
2	Coseka Resources-South Coalmont No.1	7505	3.67	98.5	189.6	8.8	-0.1	1.65
3	Cities Service Oil-1 Chedsey-A	2867	2.89	105.2	97.8	3.7	-0.2	2.05
4	Cities Service-1 Federal B	8445	4.55	78.3	208.2	11.9	-0.3	1.42
5	Ogle Corp., Cabot Corp., Bridger Pet.-1 Burr	3168	8.54	111.5	103.7	11.5	0.1	1.48
6	Mobil-1 Federal Alkali Lake Unit	5011	1.6	105.1	140.2	2.9	-0.2	1.7

According to Meyer and Nederlof (1984), these misclassifications occur at low interval velocities (i.e. less than 100 $\mu\text{sec}/\text{ft}$). The application of this method to the Niobrara Chalk and Mowry Shale shows that the lower the sonic transit time value the less reliable the method appears to be.

Schmoker and Hester (1983) quantify TOC contents of potential source rocks by using the density log. The equation to derive the TOC value for this method is:

$$\text{TOC} = (154.497/\rho) - 57.261 \quad (4.2)$$

where ρ (ρ_b) is bulk density of organic matter in g/cm^3 . The results of TOC calculations using this method reveal that this method cannot reliably quantify TOC contents of the Niobrara Chalk and the Mowry Shale as well as the Passey et al. method, especially for relatively low TOC contents (i.e. less than 5 wt. % TOC). Comparisons between measured and calculated TOC values using this method can be seen in Tables 10 and 11.

The cause of this inaccurate calculation is probably related to the density log being a pad-type tool, thus sensitive to borehole rugosity. Another problem with the Schmoker and Hester method is its dependence on porosity solely, while the Passey et al. method allows rocks with similar porosity values to have different TOC values.

Table 10. Total organic carbon determination data of the Niobrara Chalk using Schmoker and Hester equation.

Well Name	Depth (ft)	pb (g/cm ³)	Calculated TOC (wt.%)	Measured TOC (wt. %)	Differences Meas - Cal. TOC (wt. %)
Excelsior Oil 1 Alice G. Nay	5430	2.47	5.29	0.43	-4.86
	5433	2.46	5.54	2.66	-2.88
	5436.5	2.45	5.80	1.44	-4.36
	5439.5	2.45	5.80	2.02	-3.78
	5443	2.45	5.80	2.00	-3.80
	5446	2.45	5.80	1.74	-4.06
	5449.5	2.46	5.54	4.72	-0.82
	5453	2.5	4.54	2.56	-1.98
	5456	2.5	4.54	2.80	-1.74
	5459.5	2.53	3.81	4.53	0.72
	5462.5	2.5	4.54	1.08	-3.46
	5469	2.56	3.09	0.57	-2.52
	5472.5	2.52	4.05	2.30	-1.75

Table 11. Total organic carbon determination data of the Mowry Shale using Schmoker and Hester equation.

Well Name	Depth (ft)	pb (g/cm ³)	Calculated TOC (wt.%)	Measured TOC (wt. %)	Differences Meas-Cal. TOC (wt. %)
Cities Service Oil-1 Chedsey-A	2867	2.41	6.85	2.05	-4.8
Ogle Corp., Cabot Corp. Bridger Pet.-1 Burr	3168	2.47	5.29	1.48	-3.81
Mobil-1 Federal Alkali Lake Unit	5011	2.16	14.27	1.7	-12.57

CHAPTER 5

DISCUSSION AND SUMMARY

Areas of relatively low TOC values within the Mowry Shale appear to coincide with areas of relatively high LOM values (compare Figures 8 and 12). In this study, the original thickness and TOC values of the Mowry Shale cannot be restored to the original condition prior to the generation of hydrocarbons and CO₂, because kerogen type composition data within the Mowry Shale are not available. Regionally, average total organic carbon (TOC) contents of the Mowry Shale range from 1.1 to 2.9 wt.%, while the sum of TOC content multiplied by its thickness for each depth increment (TOC-ft) ranges from 31.3 to 141.3 wt.%-ft.

Based on a regional study of geochemical correlation of source rocks and oils, Clayton and Swetland (1980) suggested that the Cretaceous oils in the Denver basin were derived from organic matter contained in the Benton Group, including the Mowry Shale. They also mentioned that the effective source beds are limited to the deepest part of the basin-axis area. The deepest parts in this basin are located near Denver, Colorado and Cheyenne, Wyoming.

Within the study area, the deepest part of the Denver basin is associated with an area of high LOM values and low TOC values northwest of Wattenberg Field. Low average TOC and low TOC-ft values within this area suggest that part of the organic matter has expelled CO₂ and hydrocarbons (Clayton and Swetland, 1980, Burtner and Warner, 1984).

The use of the sonic/resistivity well-logs to identify and quantify geochemical properties of source rocks can provide an excellent alternative to laboratory geochemical analyses. The method works if the sonic readings decrease exponentially with respect to the resistivity readings. The accuracy of this method improves significantly when calibrated against measured vitrinite reflectance values and the lowest TOC value in an occurrence of interest. Log-derived source rock geochemical data may not always match laboratory measurements closely, because the logging tools read the average values of the rock properties for a certain depth interval (generally about 2 ft.), whereas the samples measured in laboratory are only about five grams in weight and only represent one point within the given depth interval. Another reason for this mismatch is the difference in sample treatment and measurement accuracy used in different laboratories.

It is difficult to determine the sensitivity of log-derived TOC values based on comparison between measured and calculated TOC content solely. Geochemical analyses in the laboratory can directly measure TOC contents of source rocks, while wireline logs measure two parameters, resistivity and sonic transit time. To acquire accurate TOC values of source rock, resistivity and sonic readings must be accurate. In addition, this well log method requires accurate LOM values which are difficult to determine.

To acquire accurate resistivity and sonic readings, some conditions must be met. First, sonic and resistivity logs should have comparable resolutions, preferably one foot or better. Second, it is important to have a tool configuration in which resistivity and sonic logs are run together to avoid mismatch and thus enhance the accuracy of measurement. To overcome this mismatch, depth matching between the resistivity and sonic logs is necessary.

Comparison between measured and calculated TOC values becomes less significant when the source rock has great variation in TOC values. Within this kind of source rock, a small number of samples selected for laboratory measurement may not represent the average values recorded by wireline logs. This condition implies a better accuracy is obtained when wireline logs are used to measure TOC in rocks having uniform distributions of organic matter.

The sensitivity of this well log method becomes important when evaluating source rocks with less than 1 weight percent TOC. In this case, the actual TOC baseline value of the source rock becomes critical because it greatly influences the value of measurements. To acquire more accurate results, more closely measured TOC and LOM values are needed to calibrate TOC baseline and LOM values.

For most studied wells, the calibrations of log-derived TOC values against core and cuttings measurements show good agreement. For the chalk of the Niobrara Formation, the differences between the results from the two different methods vary from -1.41 to +3.52 wt.% TOC with standard deviation of difference of ± 1.4 wt.% TOC. This calibration may not be accurate because core and log depth matching has not been undertaken in this study. Analyses of the Niobrara Chalk also reveal that the Passey et al. method will not work if sonic transit time does not have a decreasing exponential relationship with resistivity.

The exact cause of a non-exponential relationship between resistivity and sonic transit time curves for any given well is unknown. One possible explanation is a mismatch between resistivity and sonic log characteristics when measuring rock formations. The sonic log responds quickly to the changes in lithology variation, while the resistivity log response is slower. The quick response of the sonic log is characterized by its sharp

curve, while at the same depth interval, the resistivity curve looks blunter. These conditions may greatly affect the relationship between resistivity and sonic transit time, especially when the logged formation has many thin rock layers with different rock characteristics in each individual layer.

Another possible reason for this non-exponential relationship is a mismatch between resistivity and sonic logs when measuring rock formation of the same depth interval. This mismatch can occur because in a poor borehole, the logging tool may be jammed momentarily while the tool string is being continuously pulled out of the borehole. If this happens, the tool skips some formation intervals to compensate for stretching and shrinking of the tool string.

Due to the lack of laboratory measured data for the Mowry Shale, the calibration can only be performed for a single measurement from each of six studied wells. Nevertheless, the results of this comparison show good agreement between measured and calculated TOC values. The difference between the two values from six samples varies from -0.60 to +0.86 wt.% TOC with a standard deviation of difference of ± 0.6 wt.%. As in the case of the Niobrara Chalk, the Passey et al. method can also fail to work in the Mowry Shale if Δt measurements do not have a decreasing exponential relationship with resistivity.

Preliminary cross plot tests of resistivity against sonic transit time curve can provide a quick indication of whether the Passey et al. method will work in any given well. By rearranging the Passey et al. equation,

$$\Delta \text{Log } R = \log_{10}(R/R_{\text{baseline}}) + 0.02 \times (\Delta t - \Delta t_{\text{baseline}}) \quad (5.1)$$

into

$$R = R_{\text{baseline}} \times 10^{0.02\Delta t_{\text{baseline}}} \times 10^{\Delta \log R} \times 10^{-0.02\Delta t} \quad (5.2)$$

it is apparent that sonic transit time curve decreases exponentially with respect to resistivity. Based on this relationship, it is obvious that this method will only work if the resistivity vs sonic transit time cross plot shows an exponential relationship (e.g. Figure 14).

Since the cost of vitrinite reflectance (or LOM) analyses can be about six times the cost of TOC analyses, it is an advantage that the Passey et al. method allows us to derive either LOM or TOC values. To derive LOM values via measured TOC values, the original Passey et al. equation of

$$\text{TOC} = (\Delta \log R) \times 10^{(2.297 - 0.1688 \times \text{LOM})} \quad (5.3)$$

may be rearranged to

$$\text{LOM} = \frac{1}{0.1688} \times (2.297 + \log (\Delta \text{Log } R) - \log \text{TOC}) \quad (5.4).$$

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APPENDIX A
Total Organic Carbon Calculation Data of the Niobrara Chalk
Used for Calibration in this study
(well number: 1)

Well: Excelsior Oil-1 Alice G. Nay

NW 1/4 SE 1/4 14-9N-58W, Weld Co, Colorado

DEPTH (ft)	GR (API)	RESIS (ohm-m)	SONI (msec/ft)	Δ Log R R baseline = 67 Δ t baseline = 71	Δ Log R corrected by adding 0.70	TOC (wt.%) (LOM = 9.5) (baseline) + 0.5	Meas. TOC (wt.%)
5400	198.5	2.91	112.4	-0.53	0.17	1.32	
5400.5	198.5	2.91	110.9	-0.56	0.14	1.17	
5401	195.5	2.85	110.4	-0.58	0.12	1.08	
5401.5	189.3	2.79	110.3	-0.59	0.11	1.02	
5402	188.2	2.69	110.5	-0.61	0.09	0.96	
5402.5	186.8	2.62	109.7	-0.63	0.07	0.83	
5403	186.5	2.55	109.3	-0.65	0.05	0.73	
5403.5	195.2	2.52	109.0	-0.67	0.03	0.67	
5404	196.4	2.51	108.6	-0.68	0.02	0.62	
5404.5	206.0	2.60	108.8	-0.65	0.05	0.73	
5405	210.3	2.70	108.6	-0.64	0.06	0.79	
5405.5	213.8	2.80	108.4	-0.63	0.07	0.84	
5406	220.4	2.90	110.4	-0.58	0.12	1.12	
5406.5	235.7	3.00	113.0	-0.51	0.19	1.44	
5407	249.8	3.14	115.6	-0.44	0.26	1.80	
5407.5	269.5	3.29	117.6	-0.38	0.32	2.10	
5408	286.0	3.41	117.7	-0.36	0.34	2.18	
5408.5	306.5	3.59	118.1	-0.33	0.37	2.33	
5409	310.6	3.74	119.0	-0.29	0.41	2.51	
5409.5	302.6	3.78	119.3	-0.28	0.42	2.56	
5410	287.1	3.66	117.8	-0.33	0.37	2.34	
5410.5	267.8	3.43	116.4	-0.38	0.32	2.06	
5411	254.4	3.31	114.5	-0.44	0.26	1.80	
5411.5	228.9	3.17	113.4	-0.48	0.22	1.60	
5412	215.5	3.14	111.1	-0.53	0.17	1.36	
5412.5	206.2	3.20	109.8	-0.54	0.16	1.27	
5413	203.5	3.38	108.9	-0.54	0.16	1.30	
5413.5	204.3	3.54	109.6	-0.51	0.19	1.46	
5414	207.0	3.70	110.6	-0.47	0.23	1.66	
5414.5	213.0	3.82	109.3	-0.48	0.22	1.60	
5415	217.7	4.00	108.1	-0.48	0.22	1.58	
5415.5	226.4	4.16	106.8	-0.49	0.21	1.53	
5416	232.4	4.41	102.8	-0.55	0.15	1.26	
5416.5	231.9	4.69	99.7	-0.58	0.12	1.09	

5417	224.5	4.85	95.8	-0.64	0.06	0.78	
5417.5	218.7	4.99	93.2	-0.68	0.02	0.58	
5418	204.8	5.10	92.0	-0.70	0.00	0.51	
5418.5	195.5	5.16	92.0	-0.69	0.01	0.54	
5419	193.9	5.17	93.3	-0.67	0.03	0.67	
5419.5	187.6	5.19	94.7	-0.64	0.06	0.81	
5420	183.8	5.30	95.8	-0.61	0.09	0.97	
5420.5	185.1	5.60	94.9	-0.60	0.10	0.99	
5421	185.5	5.88	94.8	-0.58	0.12	1.09	
5421.5	185.4	6.23	94.5	-0.56	0.14	1.18	
5422	183.3	6.63	92.0	-0.59	0.11	1.07	
5422.5	179.5	7.03	90.0	-0.60	0.10	1.00	
5423	176.2	7.53	88.3	-0.60	0.10	0.97	
5423.5	174.2	8.29	86.3	-0.60	0.10	0.98	
5424	173.8	8.88	85.3	-0.59	0.11	1.03	
5424.5	175.9	9.42	85.2	-0.57	0.13	1.15	
5425	180.0	9.84	86.0	-0.53	0.17	1.32	
5425.5	182.5	10.30	86.8	-0.50	0.20	1.50	
5426	184.1	11.00	87.6	-0.45	0.25	1.72	
5426.5	177.8	12.50	87.0	-0.41	0.29	1.94	
5427	172.7	13.20	86.3	-0.40	0.30	1.99	
5427.5	169.7	14.10	85.7	-0.38	0.32	2.06	
5428	166.9	15.20	82.8	-0.41	0.29	1.94	
5428.5	162.0	16.00	80.9	-0.42	0.28	1.87	
5429	151.4	16.90	79.0	-0.44	0.26	1.80	
5429.5	138.9	17.30	78.4	-0.44	0.26	1.78	
5430	137.6	17.50	79.4	-0.42	0.28	1.91	0.43
5430.5	150.4	18.00	79.9	-0.39	0.31	2.02	
5431	151.2	18.70	80.3	-0.37	0.33	2.13	
5431.5	146.2	19.40	81.1	-0.34	0.36	2.30	
5432	139.1	20.30	81.5	-0.31	0.39	2.43	
5432.5	139.5	21.10	80.1	-0.32	0.38	2.38	
5433	139.2	21.90	79.4	-0.32	0.38	2.38	2.66
5433.5	134.1	22.60	78.3	-0.33	0.37	2.35	
5434	131.3	23.30	77.8	-0.32	0.38	2.36	
5434.5	142.2	23.90	78.7	-0.29	0.41	2.51	
5435	150.0	24.40	79.8	-0.26	0.44	2.66	
5435.5	156.0	24.50	80.5	-0.25	0.45	2.74	
5436	154.7	24.60	79.9	-0.26	0.44	2.68	
5436.5	146.5	24.70	78.4	-0.28	0.42	2.55	1.44
5437	139.5	24.60	77.3	-0.31	0.39	2.43	
5437.5	129.4	24.30	76.2	-0.34	0.36	2.30	
5438	121.3	24.00	75.6	-0.35	0.35	2.20	

5438.5	119.4	23.50	76.6	-0.34	0.36	2.26	
5439	126.9	23.20	77.1	-0.34	0.36	2.29	
5439.5	139.2	23.00	77.5	-0.34	0.36	2.30	2.02
5440	142.5	22.90	78.1	-0.32	0.38	2.36	
5440.5	141.7	23.10	78.8	-0.31	0.39	2.44	
5441	141.4	23.10	78.9	-0.30	0.40	2.45	
5441.5	139.8	23.40	77.9	-0.32	0.38	2.38	
5442	136.8	23.50	77.0	-0.34	0.36	2.30	
5442.5	130.3	23.80	76.2	-0.34	0.36	2.25	
5443	128.9	23.90	76.0	-0.35	0.35	2.24	2
5443.5	131.1	24.10	77.1	-0.32	0.38	2.37	
5444	133.0	24.40	77.8	-0.30	0.40	2.46	
5444.5	130.7	24.50	76.1	-0.33	0.37	2.30	
5445	128.6	24.70	75.4	-0.35	0.35	2.25	
5445.5	126.4	24.70	75.2	-0.35	0.35	2.23	
5446	123.2	24.20	74.9	-0.36	0.34	2.16	1.74
5446.5	124.7	23.70	74.6	-0.38	0.32	2.09	
5447	122.6	23.70	74.4	-0.38	0.32	2.06	
5447.5	116.1	24.30	74.2	-0.38	0.32	2.10	
5448	114.4	24.90	74.3	-0.36	0.34	2.16	
5448.5	120.5	25.20	75.2	-0.34	0.36	2.28	
5449	123.7	24.90	76.4	-0.32	0.38	2.36	
5449.5	124.5	24.40	75.7	-0.35	0.35	2.25	4.72
5450	119.4	24.00	73.7	-0.39	0.31	2.02	
5450.5	108.4	23.90	72.4	-0.42	0.28	1.88	
5451	99.0	23.70	71.6	-0.44	0.26	1.78	
5451.5	101.3	23.40	71.5	-0.45	0.25	1.75	
5452	109.3	23.10	72.9	-0.42	0.28	1.86	
5452.5	114.7	22.90	74.1	-0.41	0.29	1.96	
5453	118.6	22.60	74.8	-0.40	0.30	2.00	2.56
5453.5	117.9	22.00	75.5	-0.39	0.31	2.01	
5454	114.4	21.20	75.5	-0.41	0.29	1.93	
5454.5	109.3	20.40	74.2	-0.45	0.25	1.72	
5455	106.3	19.70	72.9	-0.49	0.21	1.52	
5455.5	103.8	18.70	71.3	-0.55	0.15	1.24	
5456	108.7	17.70	70.1	-0.60	0.10	1.01	2.8
5456.5	116.6	16.60	71.3	-0.60	0.10	0.99	
5457	123.9	14.60	74.3	-0.60	0.10	1.01	
5457.5	139.2	13.10	75.7	-0.61	0.09	0.92	
5458	149.0	12.00	78.1	-0.60	0.10	0.97	
5458.5	158.8	11.70	79.5	-0.59	0.11	1.05	
5459	161.3	11.20	80.2	-0.59	0.11	1.03	
5459.5	164.3	11.00	81.1	-0.58	0.12	1.08	4.53

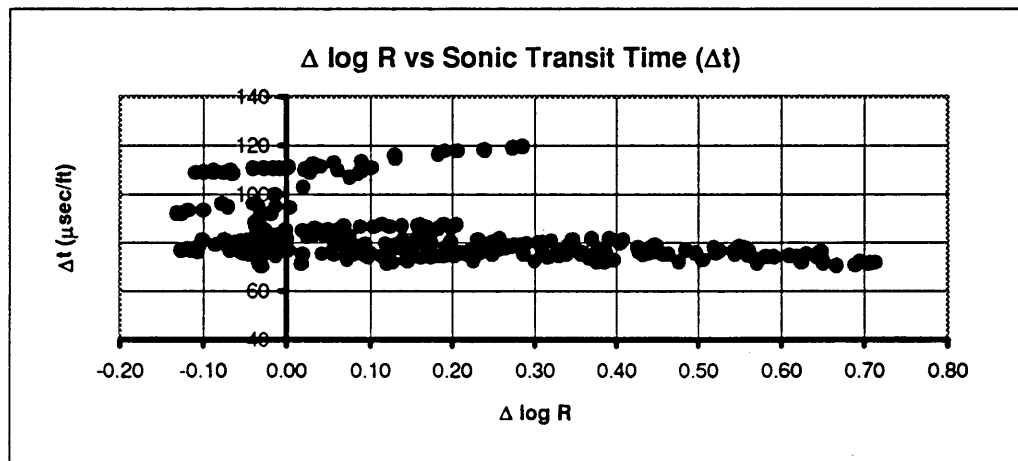
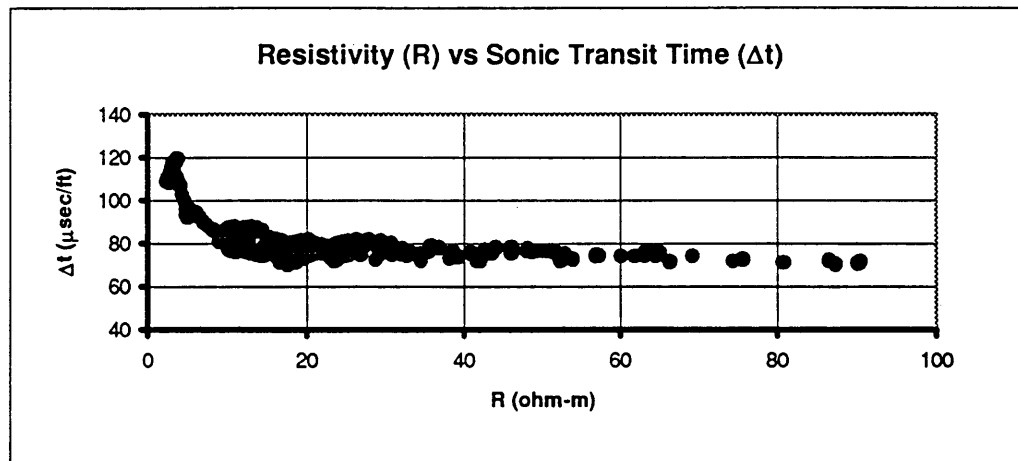
5460	169.1	10.90	81.5	-0.58	0.12	1.10	
5460.5	172.1	11.00	81.3	-0.58	0.12	1.10	
5461	172.2	11.10	81.8	-0.57	0.13	1.16	
5461.5	174.9	11.30	82.8	-0.54	0.16	1.31	
5462	179.2	11.60	83.2	-0.52	0.18	1.40	
5462.5	185.7	11.90	83.2	-0.51	0.19	1.45	1.08
5463	189.6	12.50	82.4	-0.50	0.20	1.48	
5463.5	193.6	12.80	81.8	-0.50	0.20	1.47	
5464	202.2	12.80	82.4	-0.49	0.21	1.53	
5464.5	215.4	12.50	82.7	-0.50	0.20	1.51	
5465	224.1	11.80	82.7	-0.52	0.18	1.38	
5465.5	230.6	11.40	82.4	-0.54	0.16	1.28	
5466	242.1	11.00	81.4	-0.58	0.12	1.11	
5466.5	252.9	10.80	80.9	-0.59	0.11	1.02	
5467	277.2	10.40	80.9	-0.61	0.09	0.94	
5467.5	303.4	10.20	81.3	-0.61	0.09	0.93	
5468	338.8	10.00	83.3	-0.58	0.12	1.09	
5468.5	341.3	10.00	84.9	-0.55	0.15	1.25	
5469	320.0	10.20	85.1	-0.53	0.17	1.32	0.57
5469.5	272.1	10.30	85.2	-0.53	0.17	1.34	
5470	240.5	10.60	85.2	-0.52	0.18	1.40	
5470.5	239.9	10.80	85.4	-0.50	0.20	1.47	
5471	240.2	11.00	86.3	-0.48	0.22	1.59	
5471.5	240.5	11.30	86.6	-0.46	0.24	1.67	
5472	238.3	11.80	86.6	-0.44	0.26	1.77	
5472.5	232.2	12.10	86.8	-0.43	0.27	1.84	2.3
5473	228.7	12.50	87.2	-0.41	0.29	1.95	
5473.5	225.9	13.20	87.5	-0.38	0.32	2.10	
5474	219.2	13.80	87.2	-0.36	0.34	2.17	
5474.5	203.7	14.50	85.9	-0.37	0.33	2.14	
5475	192.3	15.20	83.1	-0.40	0.30	1.97	
5475.5	184.6	16.00	81.5	-0.41	0.29	1.92	
5476	167.0	16.60	80.2	-0.42	0.28	1.87	
5476.5	160.2	16.10	79.5	-0.45	0.25	1.74	
5477	153.9	15.40	79.3	-0.47	0.23	1.62	
5477.5	147.4	14.90	79.2	-0.49	0.21	1.54	
5478	147.1	14.90	78.8	-0.50	0.20	1.50	
5478.5	149.0	14.80	78.3	-0.51	0.19	1.44	
5479	149.6	14.90	78.2	-0.51	0.19	1.44	
5479.5	148.2	15.10	78.6	-0.50	0.20	1.51	
5480	147.1	15.50	79.2	-0.47	0.23	1.62	
5480.5	148.7	15.80	81.0	-0.43	0.27	1.85	
5481	153.9	16.30	81.4	-0.41	0.29	1.95	

5481.5	157.5	17.00	81.1	-0.39	0.31	2.02
5482	147.2	17.70	79.4	-0.41	0.29	1.93
5482.5	132.7	18.40	77.6	-0.43	0.27	1.83
5483	127.2	19.10	76.1	-0.44	0.26	1.77
5483.5	128.9	20.10	76.4	-0.42	0.28	1.90
5484	131.6	21.40	77.0	-0.38	0.32	2.10
5484.5	136.5	23.70	78.2	-0.31	0.39	2.44
5485	142.2	25.70	79.0	-0.26	0.44	2.69
5485.5	148.3	27.40	79.2	-0.22	0.48	2.85
5486	148.7	29.00	78.3	-0.22	0.48	2.88
5486.5	139.2	30.70	76.1	-0.24	0.46	2.78
5487	131.6	32.10	74.9	-0.24	0.46	2.76
5487.5	128.9	32.70	74.1	-0.25	0.45	2.72
5488	130.0	32.80	74.7	-0.24	0.46	2.79
5488.5	134.1	33.00	75.0	-0.23	0.47	2.83
5489	137.1	32.50	75.0	-0.23	0.47	2.80
5489.5	134.9	30.80	75.0	-0.26	0.44	2.68
5490	133.3	29.20	75.0	-0.28	0.42	2.57
5490.5	135.9	26.80	75.0	-0.32	0.38	2.39
5491	140.3	25.40	75.0	-0.34	0.36	2.27
5491.5	144.1	25.00	75.7	-0.33	0.37	2.31
5492	145.3	24.60	76.9	-0.32	0.38	2.39
5492.5	149.9	24.20	78.3	-0.30	0.40	2.49
5493	154.3	24.10	78.5	-0.29	0.41	2.50
5493.5	153.7	24.20	77.5	-0.31	0.39	2.42
5494	144.4	24.20	76.5	-0.33	0.37	2.31
5494.5	140.3	23.80	75.7	-0.36	0.34	2.20
5495	141.5	23.10	75.8	-0.37	0.33	2.14
5495.5	143.1	22.70	75.8	-0.37	0.33	2.11
5496	144.2	22.10	75.5	-0.39	0.31	2.02
5496.5	145.8	21.20	76.0	-0.40	0.30	1.98
5497	148.3	20.50	76.7	-0.40	0.30	1.98
5497.5	150.2	19.70	77.3	-0.41	0.29	1.95
5498	153.1	18.90	78.2	-0.41	0.29	1.95
5498.5	157.7	18.00	79.1	-0.41	0.29	1.94
5499	158.9	17.40	79.7	-0.41	0.29	1.92
5499.5	157.7	17.20	79.8	-0.41	0.29	1.91
5500	158.3	17.80	79.7	-0.40	0.30	1.97
5500.5	154.3	18.60	79.1	-0.39	0.31	2.01
5501	151.2	19.30	78.1	-0.40	0.30	1.99
5501.5	148.7	20.80	77.6	-0.38	0.32	2.10
5502	149.3	23.20	78.0	-0.32	0.38	2.37
5502.5	161.3	23.90	79.2	-0.28	0.42	2.55

5503	168.1	23.80	79.6	-0.28	0.42	2.59
5503.5	175.2	23.70	79.0	-0.29	0.41	2.52
5504	175.8	23.60	78.3	-0.31	0.39	2.44
5504.5	171.6	23.50	78.5	-0.31	0.39	2.45
5505	169.8	23.70	79.1	-0.29	0.41	2.52
5505.5	177.6	24.40	80.2	-0.26	0.44	2.69
5506	187.5	25.20	81.2	-0.22	0.48	2.87
5506.5	194.8	26.30	81.5	-0.20	0.50	2.98
5507	192.9	27.80	81.4	-0.17	0.53	3.09
5507.5	189.9	29.40	81.0	-0.16	0.54	3.18
5508	184.2	30.70	79.9	-0.16	0.54	3.16
5508.5	174.1	32.10	77.6	-0.19	0.51	3.03
5509	162.4	33.20	75.9	-0.21	0.49	2.93
5509.5	153.9	34.40	75.0	-0.21	0.49	2.92
5510	150.1	35.40	75.9	-0.18	0.52	3.07
5510.5	157.2	35.80	77.6	-0.14	0.56	3.26
5511	163.3	35.80	78.7	-0.12	0.58	3.37
5511.5	166.0	36.00	78.6	-0.12	0.58	3.38
5512	165.1	36.80	77.8	-0.12	0.58	3.34
5512.5	158.9	38.60	76.0	-0.14	0.56	3.27
5513	150.4	41.10	75.3	-0.13	0.57	3.33
5513.5	146.4	43.60	75.2	-0.10	0.60	3.45
5514	147.2	46.00	75.6	-0.07	0.63	3.61
5514.5	147.7	47.90	76.3	-0.04	0.66	3.76
5515	148.2	49.30	76.5	-0.02	0.68	3.84
5515.5	148.2	50.60	76.5	-0.01	0.69	3.89
5516	147.4	51.30	76.5	-0.01	0.69	3.92
5516.5	139.8	51.50	76.5	0.00	0.70	3.93
5517	133.3	51.30	76.2	-0.01	0.69	3.89
5517.5	125.2	48.70	75.7	-0.04	0.66	3.73
5518	117.5	43.10	75.1	-0.11	0.59	3.42
5518.5	107.4	40.80	75.1	-0.13	0.57	3.30
5519	102.0	40.90	75.8	-0.12	0.58	3.37
5519.5	103.6	42.60	76.7	-0.08	0.62	3.55
5520	109.6	44.00	77.8	-0.05	0.65	3.72
5520.5	115.4	46.00	78.3	-0.02	0.68	3.87
5521	118.8	48.10	77.7	-0.01	0.69	3.90
5521.5	120.2	50.00	76.5	-0.02	0.68	3.87
5522	120.2	52.90	75.0	-0.02	0.68	3.85
5522.5	116.1	56.90	74.3	-0.01	0.69	3.93
5523	114.8	61.90	73.9	0.02	0.72	4.07
5523.5	116.4	64.60	74.4	0.05	0.75	4.21
5524	120.0	65.10	75.6	0.08	0.78	4.35

5524.5	126.3	64.10	76.0	0.08	0.78	4.36
5525	142.2	63.90	76.0	0.08	0.78	4.35
5525.5	147.2	63.20	75.4	0.06	0.76	4.27
5526	144.7	60.20	74.1	0.02	0.72	4.03
5526.5	136.0	53.90	72.7	-0.06	0.64	3.65
5527	123.3	42.10	72.0	-0.18	0.52	3.06
5527.5	114.8	41.80	72.8	-0.17	0.53	3.12
5528	118.0	38.20	73.2	-0.20	0.50	2.97
5528.5	122.4	39.20	73.7	-0.18	0.52	3.07
5529	121.4	57.30	74.3	0.00	0.70	3.94
5529.5	116.7	63.20	74.5	0.04	0.74	4.17
5534.5	113.1	66.40	71.4	0.00	0.70	3.98
5535	113.7	52.30	71.9	-0.09	0.61	3.51
5535.5	116.7	41.60	71.8	-0.19	0.51	3.01
5536	119.9	34.50	72.1	-0.27	0.43	2.64
5536.5	126.5	28.70	72.3	-0.34	0.36	2.27
5537	128.4	23.10	73.1	-0.42	0.28	1.88
5537.5	128.7	19.70	74.1	-0.47	0.23	1.64
5538	128.6	18.80	74.9	-0.47	0.23	1.62
5538.5	126.2	18.60	75.5	-0.47	0.23	1.65
5539	121.6	18.30	75.3	-0.48	0.22	1.59
5539.5	117.0	18.10	75.1	-0.49	0.21	1.55
5540	114.0	17.20	75.0	-0.51	0.19	1.44
5540.5	115.9	16.30	75.5	-0.52	0.18	1.37
5541	118.7	15.80	75.0	-0.55	0.15	1.25
5541.5	122.2	15.00	74.5	-0.58	0.12	1.09
5542	121.7	14.40	74.4	-0.60	0.10	1.00
5542.5	124.3	13.70	74.9	-0.61	0.09	0.94
5543	128.5	13.00	75.6	-0.62	0.08	0.90
5543.5	133.9	11.20	76.2	-0.67	0.03	0.63
5544	134.9	10.90	76.4	-0.68	0.02	0.60
5544.5	134.6	10.50	76.6	-0.69	0.01	0.54
5545	137.7	10.30	77.4	-0.68	0.02	0.58
5545.5	142.6	10.20	78.3	-0.67	0.03	0.64
5546	147.4	10.30	79.1	-0.65	0.05	0.74
5546.5	149.9	10.50	79.8	-0.63	0.07	0.85
5547	148.5	10.90	80.0	-0.61	0.09	0.95
5547.5	145.5	11.30	79.6	-0.60	0.10	0.99
5548	141.2	11.90	78.3	-0.60	0.10	0.97
5548.5	137.6	13.00	77.2	-0.59	0.11	1.05
5549	137.6	14.00	76.8	-0.56	0.14	1.17
5549.5	138.3	14.20	76.4	-0.57	0.13	1.17
5550	141.8	14.03	76.6	-0.57	0.13	1.16

5550.5	148.3	13.62	76.5	-0.58	0.12	1.08
5551	153.2	13.12	76.0	-0.61	0.09	0.96
5551.5	158.7	12.60	76.2	-0.62	0.08	0.89
5552	161.1	11.92	76.8	-0.63	0.07	0.83
5552.5	162.8	11.65	77.6	-0.63	0.07	0.86
5553	164.1	11.19	78.6	-0.63	0.07	0.87
5553.5	167.7	10.66	79.5	-0.63	0.07	0.85
5554	172.0	10.35	80.5	-0.62	0.08	0.89
5555	171.4	9.09	81.0	-0.67	0.03	0.66

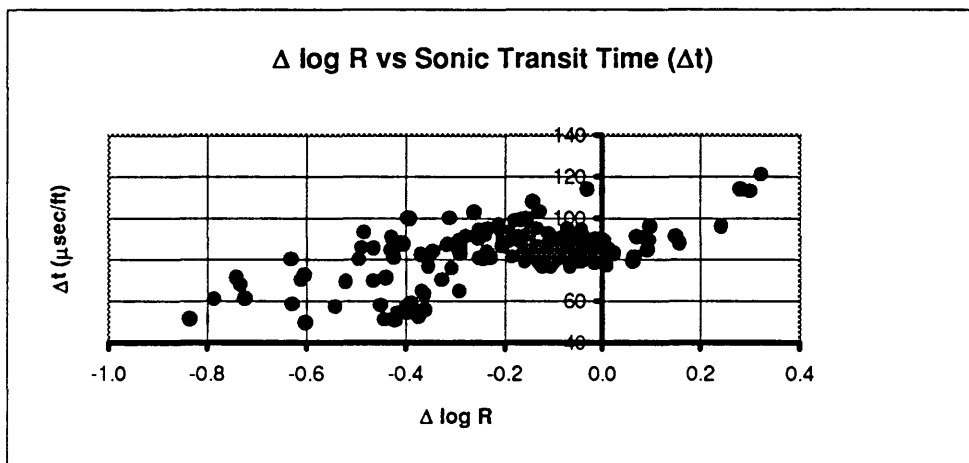
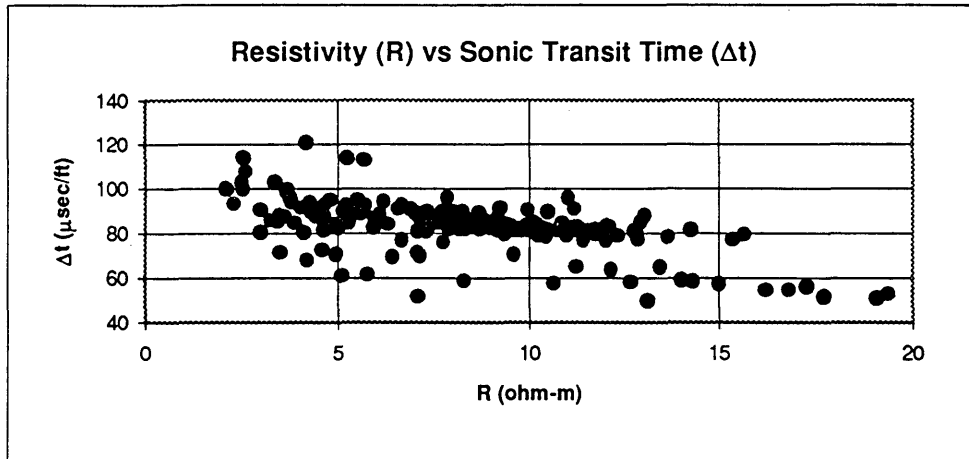


Resistivity (R) vs Sonic Transit Time (Δt) and $\Delta \log R$ vs Sonic Transit Time crossplots. Excelsior Oil-1 Alice G. Nay. NW 1/4 SE 1/4 14-9N-58W, Weld Co, Colorado.

APPENDIX B
Total Organic Carbon Calculation Data of the Mowry Shale
Used for Calibration in This Study
(well number: 6)

Well: Coseka Resources-South Coalmont No.1
NE SW 6-6N-80W, North Park basin, Colorado

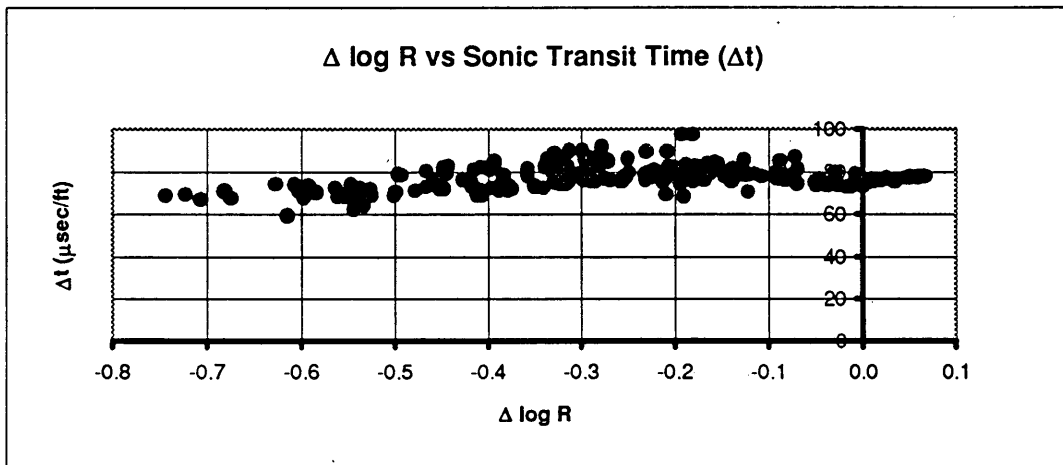
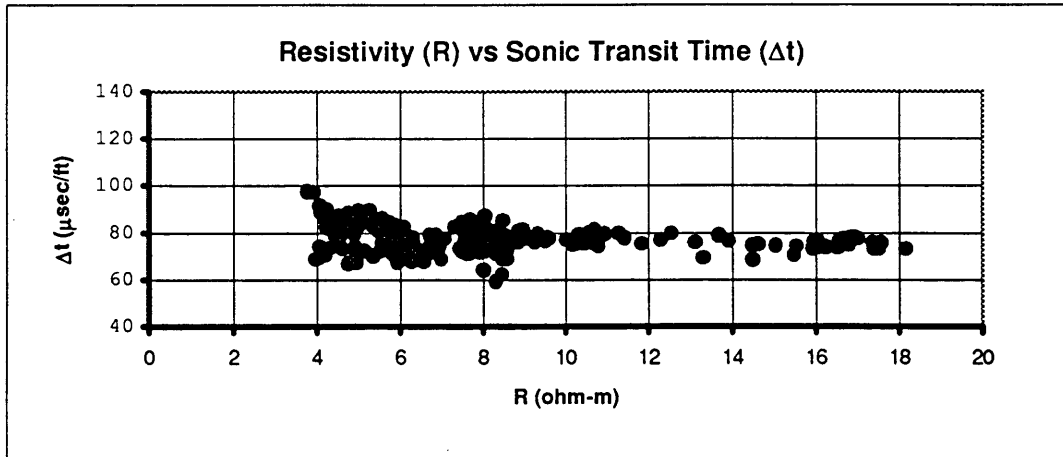
DEPTH (ft)	GR (API)	RESIS (ohm-m)	SONI (μ sec/ft)	Δ LOG R $R_{\text{baseline}} = 13$ $\Delta t_{\text{baseline}} = 80$	Δ LOG R corrected by adding 0.42	TOC if LOM = 9.54 SC = 3	TOC if LOM = 10.75 SC = 3	Meas. TOC (wt.%)
7502	148.0	3.71	99.4	-0.16	0.26	2.09	1.60	
7502.5	146.9	3.69	99.6	-0.15	0.27	2.09	1.61	
7503	142.6	3.69	99.0	-0.17	0.25	2.03	1.57	
7503.5	137.2	3.75	96.4	-0.21	0.21	1.82	1.44	
7504	134.1	3.81	94.1	-0.25	0.17	1.62	1.31	
7504.5	133.0	3.80	95.0	-0.23	0.19	1.70	1.36	
7505	151.5	3.67	98.5	-0.18	0.24	1.97	1.53	1.65
7505.5	188.8	3.38	102.9	-0.13	0.29	2.22	1.69	
7506	202.7	2.52	102.7	-0.26	0.16	1.58	1.29	
7506.5	201.3	2.14	99.7	-0.39	0.03	0.94	0.89	
7507	192.2	2.32	93.2	-0.48	0.00	0.80	0.80	
7507.5	156.3	3.64	87.3	-0.41	0.01	0.87	0.84	
7508	114.8	4.56	86.9	-0.32	0.10	1.30	1.11	
7508.5	93.8	7.04	88.9	-0.09	0.33	2.41	1.81	
7509	93.8	8.04	89.8	-0.01	0.41	2.78	2.04	
7509.5	94.9	7.33	89.8	-0.05	0.37	2.59	1.92	
7510	96.5	6.91	90.6	-0.06	0.36	2.54	1.89	
7510.5	96.6	6.68	92.4	-0.04	0.38	2.64	1.95	
7511	98.2	6.20	94.0	-0.04	0.38	2.64	1.95	
7511.5	103.8	5.53	95.0	-0.07	0.35	2.49	1.86	
7512	108.1	4.82	94.9	-0.13	0.29	2.20	1.67	
7512.5	109.6	4.28	93.8	-0.21	0.21	1.84	1.45	
7513	108.8	4.28	92.2	-0.24	0.18	1.68	1.35	
7513.5	108.9	4.59	89.9	-0.25	0.17	1.61	1.31	
7514	111.9	5.21	85.4	-0.29	0.13	1.44	1.20	
7514.5	114.2	6.31	83.9	-0.23	0.19	1.70	1.36	
7515	111.3	8.21	83.4	-0.13	0.29	2.20	1.67	
7515.5	106.2	9.92	83.1	-0.05	0.37	2.57	1.91	
7516	101.7	12.07	82.9	0.03	0.45	2.97	2.16	
7516.5	97.9	12.15	82.6	0.02	0.44	2.95	2.15	
7517	101.6	11.75	81.6	-0.01	0.41	2.79	2.04	
7517.5	105.7	11.20	90.9	0.15	0.57	3.58	2.54	
7518	128.2	9.24	91.1	0.07	0.49	3.20	2.30	
7518.5	157.8	5.71	112.9	0.30	0.72	4.31	2.99	
7519	182.4	4.20	120.7	0.32	0.74	4.41	3.06	
7519.5	188.8	2.57	113.8	-0.03	0.39	2.70	1.99	



Resistivity (R) vs Sonic Transit Time (Δt) and $\Delta \log R$ vs Sonic Transit Time crossplots. Coseka Resources-South Coalmont No.1. NE SW 6-6N-80W, North Park basin, Colorado.

Well: Cities Service-1 Federal B
 NW NE 34-9N-80W, North Park basin, Colorado

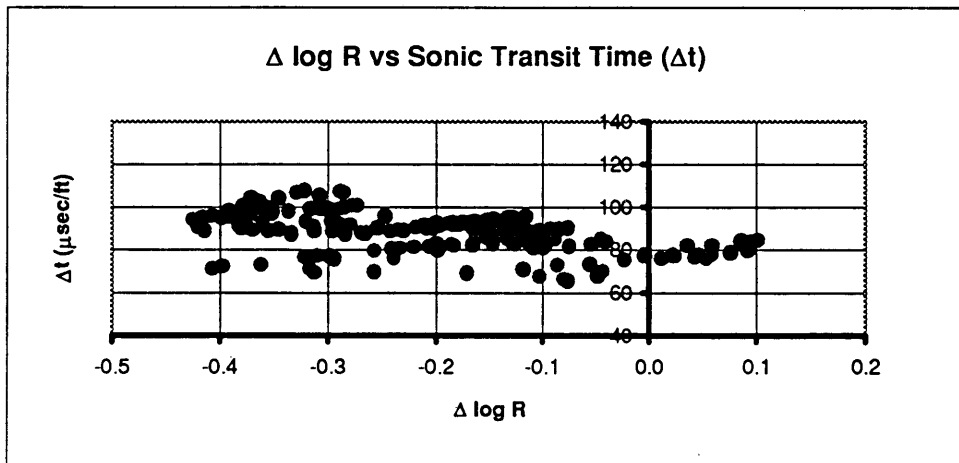
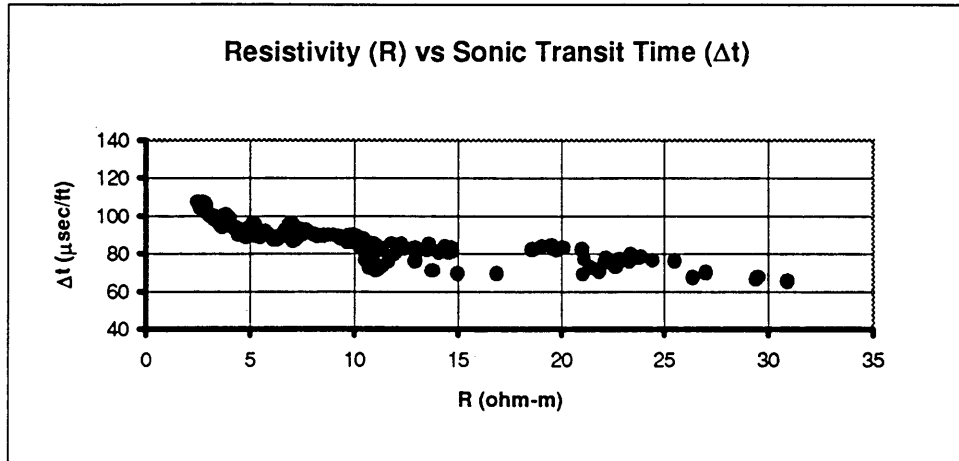
DEPTH (ft)	GR (API)	RESIS (ohm-m)	SONI (μ sec/ft)	Δ Log R $R_{\text{baseline}} = 16.5$ $\Delta T_{\text{baseline}} = 75$	Δ log R corrected by adding 0.6	TOC if LOM = 10.75 SC = 4	TOC if LOM = 12 SC = 4	Meas.TOC (wt.%)
8445	107.6	4.55	78.3	-0.49	0.11	1.12	1.00	1.42
8445.5	92.1	4.95	71.5	-0.59	0.01	0.82	0.81	
8446	84.7	5.14	72.1	-0.56	0.04	0.91	0.87	
8446.5	77.5	5.82	76.3	-0.43	0.17	1.32	1.12	
8447	79.3	6.09	80.1	-0.33	0.27	1.62	1.30	
8447.5	81.3	6.04	82.1	-0.29	0.31	1.73	1.37	
8448	85.3	5.87	83.5	-0.28	0.32	1.77	1.40	
8448.5	88.3	5.46	85.4	-0.27	0.33	1.79	1.41	
8449	90.1	5.13	85.6	-0.30	0.30	1.72	1.37	
8449.5	92.5	4.93	86.6	-0.29	0.31	1.73	1.37	
8450	98.5	4.77	88.0	-0.28	0.32	1.77	1.40	
8450.5	103.8	5.02	86.1	-0.29	0.31	1.73	1.37	
8451	107.2	5.36	82.9	-0.33	0.27	1.62	1.30	
8451.5	109.2	5.84	78.4	-0.38	0.22	1.46	1.21	
8452	108.2	6.26	72.8	-0.47	0.13	1.21	1.05	
8452.5	104.1	6.50	69.0	-0.52	0.08	1.03	0.94	
8453	100.7	6.62	71.0	-0.48	0.12	1.17	1.03	
8453.5	98.8	6.79	71.9	-0.45	0.15	1.27	1.09	
8454	109.4	7.10	77.4	-0.32	0.28	1.65	1.33	
8454.5	119.4	7.50	84.2	-0.16	0.44	2.14	1.63	
8455	125.9	7.84	83.5	-0.15	0.45	2.16	1.63	
8455.5	128.9	8.23	80.7	-0.19	0.41	2.05	1.57	
8456	130.2	8.60	72.1	-0.34	0.26	1.59	1.29	
8456.5	124.0	8.60	68.8	-0.41	0.19	1.39	1.16	
8457	114.1	8.05	71.8	-0.37	0.23	1.48	1.22	
8457.5	108.8	7.68	80.5	-0.22	0.38	1.95	1.51	
8458	107.9	7.32	82.3	-0.21	0.39	2.00	1.54	
8458.5	108.2	7.49	83.9	-0.16	0.44	2.12	1.61	
8459	108.2	8.30	80.7	-0.18	0.42	2.07	1.58	
8459.5	108.4	8.87	80.4	-0.16	0.44	2.13	1.62	
8460	106.1	9.51	76.4	-0.21	0.39	1.98	1.53	
8460.5	103.0	10.13	76.2	-0.19	0.41	2.05	1.57	
8461	97.8	10.62	76.2	-0.17	0.43	2.11	1.61	
8461.5	93.6	10.70	75.4	-0.18	0.42	2.08	1.58	
8462	90.5	10.79	74.5	-0.19	0.41	2.03	1.56	
8462.5	87.7	10.44	75.4	-0.19	0.41	2.04	1.56	
8463	85.5	9.60	77.6	-0.18	0.42	2.06	1.58	
8463.5	84.7	8.41	79.1	-0.21	0.39	1.98	1.53	
8464	90.0	7.57	79.5	-0.25	0.35	1.87	1.46	



Resistivity (R) vs Sonic Transit Time (Δt) and $\Delta \log R$ vs Sonic Transit Time crossplots. Cities Service-1 Federal B. NW NE 34-9N-80W, North Park basin, Colorado.

Well: Cities Service Oil-1 Chedsey-A
NW SW 13-7N-82W

DEPTH (ft)	GR (API)	RESIS (ohm-m)	SONI (μ sec/ft)	$\Delta \log R$ $R_{\text{baseline}} = 14.5$ $\Delta t_{\text{baseline}} = 82$	$\Delta \log R$ corrected by adding 0.37	TOC if LOM = 8.84 SC = 2	TOC if LOM = 9.54 SC = 2	Meas.TOC (wt.%)
2867	87.0	2.89	105.2	-0.24	0.13	1.65	1.45	2.05
2867.5	89.4	3.05	100.7	-0.30	0.07	1.23	1.12	
2868	92.1	3.29	99.9	-0.29	0.08	1.33	1.21	
2868.5	92.7	3.57	95.7	-0.34	0.03	1.02	0.97	
2869	92.1	3.69	94.0	-0.35	0.02	0.90	0.88	
2870	93.0	3.70	95.4	-0.32	0.05	1.09	1.02	
2870.5	98.1	3.58	96.7	-0.31	0.06	1.16	1.07	
2871	105.0	3.31	98.1	-0.32	0.05	1.12	1.04	
2871.5	113.6	3.08	100.3	-0.31	0.06	1.20	1.11	
2872	126.4	2.80	104.0	-0.27	0.10	1.41	1.27	
2872.5	132.8	2.77	107.1	-0.22	0.15	1.77	1.54	
2873	137.4	2.85	106.6	-0.21	0.16	1.79	1.55	
2873.5	131.3	2.89	102.4	-0.29	0.08	1.29	1.18	
2876	95.4	3.66	94.7	-0.34	0.03	0.96	0.92	
2876.5	97.5	3.86	96.7	-0.28	0.09	1.37	1.23	
2877	99.5	3.90	98.8	-0.24	0.13	1.66	1.45	
2877.5	101.6	3.86	100.6	-0.20	0.17	1.87	1.62	
2878	102.5	3.83	100.6	-0.21	0.16	1.84	1.59	
2878.5	101.2	3.79	98.9	-0.24	0.13	1.60	1.41	
2879	98.7	3.79	97.1	-0.28	0.09	1.38	1.24	
2879.5	96.1	3.80	95.1	-0.32	0.05	1.12	1.05	
2880	93.4	3.80	94.7	-0.33	0.04	1.07	1.01	
2880.5	90.9	3.80	96.2	-0.30	0.07	1.26	1.15	
2881	92.4	3.81	97.8	-0.27	0.10	1.47	1.31	
2881.5	94.4	3.85	99.1	-0.23	0.14	1.67	1.46	
2882	96.2	3.85	99.4	-0.23	0.14	1.70	1.49	
2882.5	98.1	3.85	99.3	-0.23	0.14	1.69	1.48	
2883	100.3	3.94	99.6	-0.21	0.16	1.80	1.56	
2883.5	104.0	4.06	98.6	-0.22	0.15	1.75	1.53	
2884	108.8	4.18	93.7	-0.31	0.06	1.21	1.11	
2884.5	112.7	4.38	93.5	-0.29	0.08	1.31	1.19	
2885	110.3	4.66	91.1	-0.31	0.06	1.17	1.08	
2885.5	94.2	4.90	90.1	-0.31	0.06	1.19	1.10	
2886	90.5	5.10	93.4	-0.23	0.14	1.72	1.50	
2886.5	93.2	5.22	95.4	-0.18	0.19	2.04	1.74	
2887	94.4	5.14	95.7	-0.18	0.19	2.03	1.74	
2887.5	94.4	4.91	93.0	-0.25	0.12	1.57	1.39	
2888	95.0	4.44	90.3	-0.35	0.02	0.94	0.90	
2890.5	152.6	2.60	104.3	-0.30	0.07	1.25	1.14	

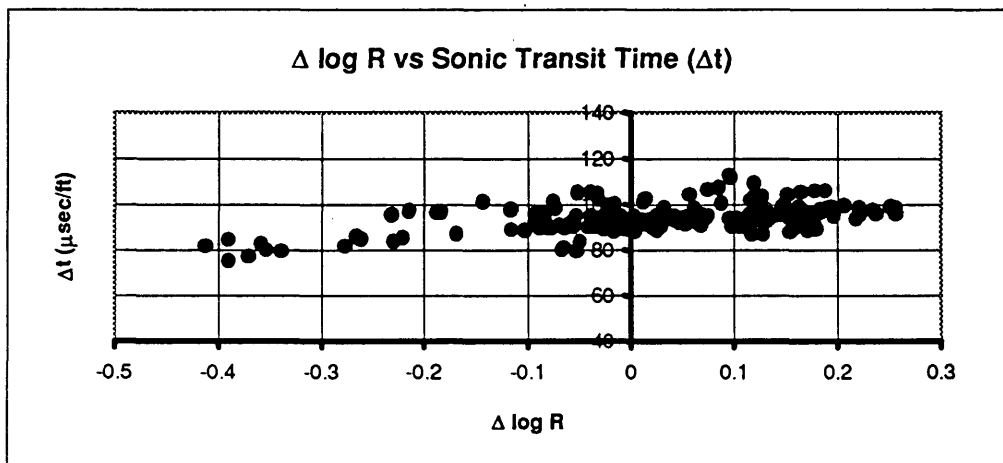
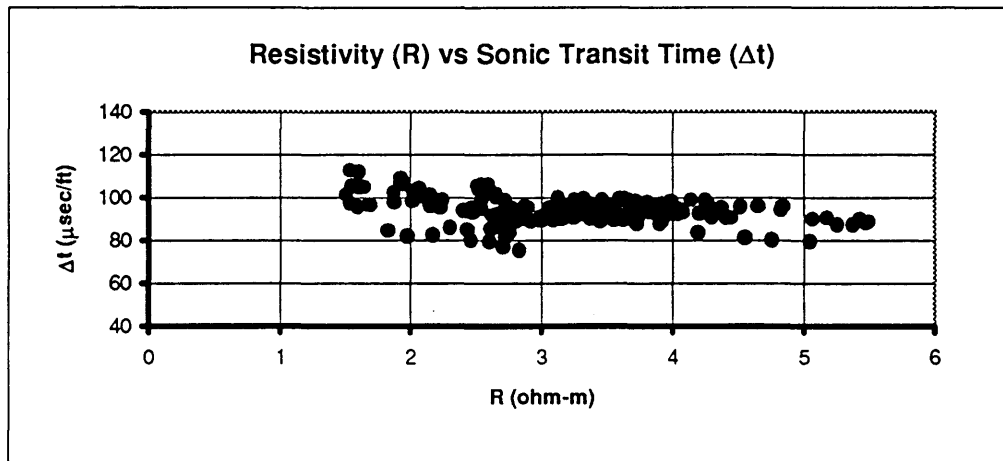


Resistivity (R) vs Sonic Transit Time (Δt) and $\Delta \log R$ vs Sonic Transit Time crossplots. Cities Service Oil-1 Chedsey-A. NW SW 13-7N-82W, North Park basin, Colorado.

Well: Mobil-1 Federal Alkali Lake Unit

SW SE 31-10N-80W, North Park basin, Colorado

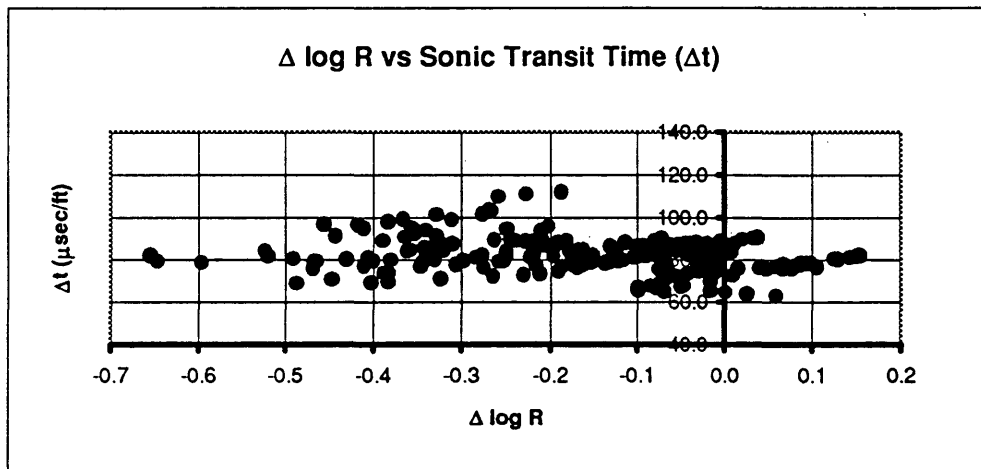
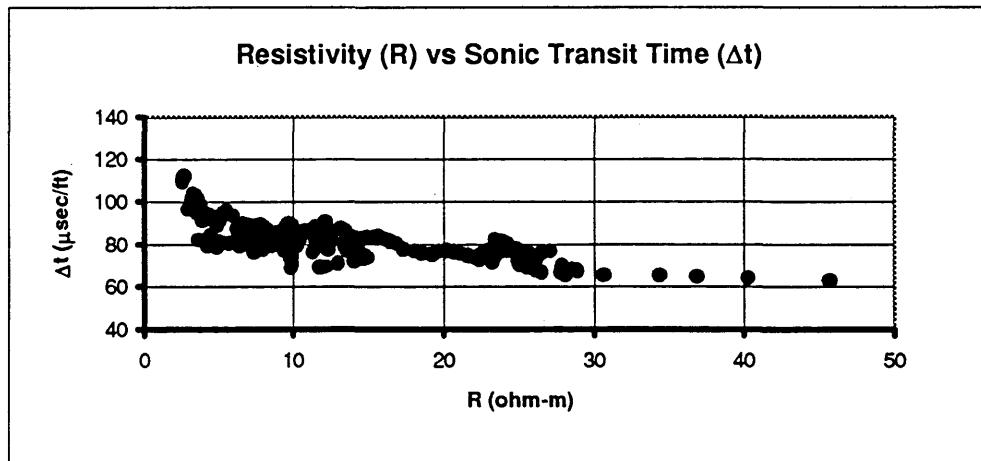
DEPTH (ft)	RESIS (ohm-m)	SONI (msec/ft)	D log R $R_{\text{baseline}} = 3$ $\Delta t_{\text{baseline}} = 90$	D LOG R corrected by adding 0.4	TOC if LOM = 9.54 SC = 3	TOC if LOM = 10.75 SC = 3	Meas. TOC (wt.%)
5010	1.60	105.1	-0.04	0.36	2.56	1.90	1.70
5010.5	1.55	105.2	-0.05	0.35	2.50	1.86	
5011	1.51	101.2	-0.08	0.32	2.38	1.79	
5011.5	1.51	101.1	-0.14	0.26	2.05	1.58	
5012	1.54	97.2	-0.21	0.19	1.70	1.36	
5012.5	1.60	95.5	-0.23	0.17	1.62	1.31	
5013	1.68	96.6	-0.19	0.21	1.84	1.45	
5013.5	1.88	97.7	-0.12	0.28	2.18	1.66	
5014	2.02	98.3	-0.07	0.33	2.39	1.79	
5014.5	2.16	96.0	-0.09	0.31	2.30	1.74	
5015	2.23	95.6	-0.08	0.32	2.34	1.76	
5015.5	2.25	98.5	-0.02	0.38	2.64	1.95	
5016	2.15	101.2	0.01	0.41	2.80	2.05	
5016.5	2.07	104.3	0.06	0.46	3.02	2.19	
5017	1.96	106.4	0.08	0.48	3.11	2.24	
5017.5	1.93	108.9	0.12	0.52	3.32	2.38	
5018	1.93	107.2	0.09	0.49	3.16	2.27	
5018.5	2.02	102.6	0.01	0.41	2.81	2.06	
5019	2.15	96.3	-0.08	0.32	2.34	1.76	
5019.5	2.30	85.8	-0.27	0.13	1.45	1.21	
5020	2.46	80.0	-0.35	0.05	1.03	0.94	
5020.5	2.60	79.5	-0.34	0.06	1.10	0.99	
5021	2.73	81.6	-0.28	0.12	1.40	1.17	
5021.5	2.76	83.7	-0.23	0.17	1.63	1.32	
5022	2.71	87.1	-0.17	0.23	1.92	1.50	
5022.5	2.65	101.9	0.12	0.52	3.31	2.37	
5023	2.59	105.9	0.19	0.59	3.66	2.58	
5023.5	2.54	105.8	0.18	0.58	3.61	2.56	
5024	2.55	102.8	0.12	0.52	3.32	2.38	
5024.5	2.62	85.3	-0.22	0.18	1.67	1.35	
5025	2.71	77.1	-0.37	0.03	0.94	0.89	
5025.5	2.83	75.1	-0.39	0.01	0.85	0.83	
5026	3.01	89.5	-0.08	0.32	2.37	1.78	
5026.5	3.26	90.6	-0.02	0.38	2.65	1.95	



Resistivity (R) vs Sonic Transit Time (Δt) and $\Delta \log R$ vs Sonic Transit Time crossplots. Mobil-1 Federal Alkali Lake Unit. SW SE 31-10N-80W, North Park basin, Colorado.

Well: Trend Exploration-1 Fuipers
NE SE 9-8N-81W, North Park basin, Colorado

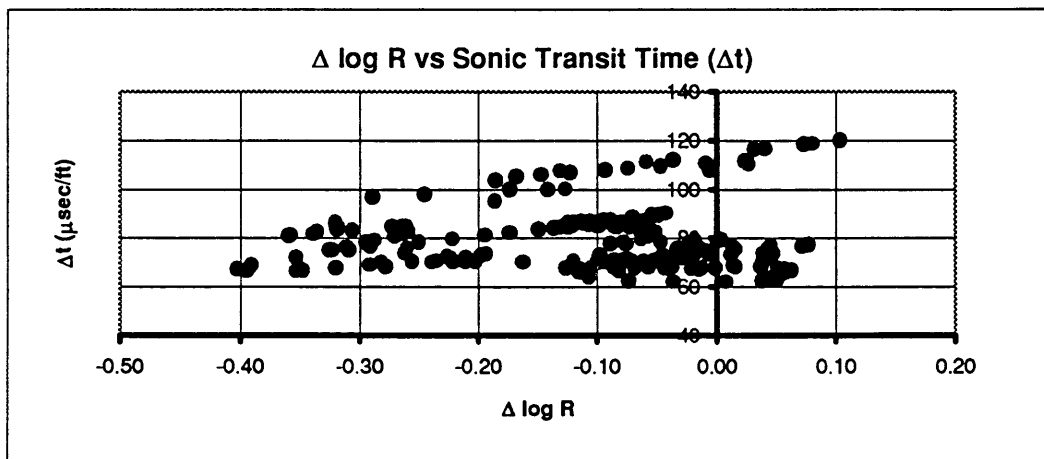
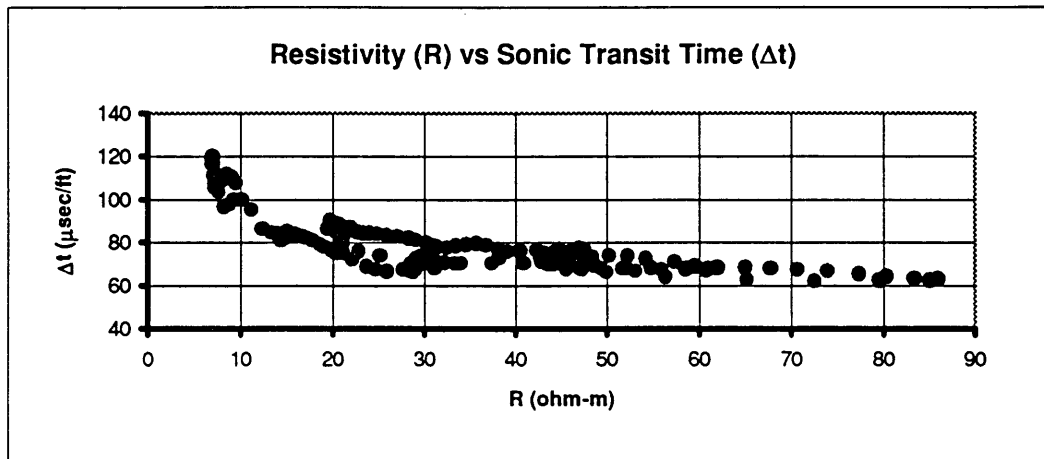
DEPTH (ft)	GR (API)	RESIS (ohm-m)	SONI (μ sec/ft)	Δ Log R $R_{\text{baseline}} = 26$ $\Delta t_{\text{baseline}} = 72$	Δ Log R corrected by adding 0.42	TOC if LOM = 8.84 SC = 3	TOC if LOM = 9.54 SC = 3	Meas. TOC (wt.%)
3230	88.9	2.54	109.6	-0.26	0.16	1.83	1.59	1.81
3230.5	94.7	2.58	110.8	-0.23	0.19	2.03	1.74	
3231	97.0	2.70	111.8	-0.19	0.23	2.28	1.93	
3231.5	97.3	2.93	96.6	-0.46	0.00	0.80	0.80	
3232	97.2	3.24	96.4	-0.42	0.00	0.82	0.82	
3232.5	97.0	3.63	82.0	-0.65	0.00	0.80	0.80	
3233	98.0	4.24	79.1	-0.65	0.00	0.80	0.80	
3233.5	99.1	4.88	78.5	-0.60	0.00	0.80	0.80	
3234	102.2	6.40	79.2	-0.46	0.00	0.80	0.80	
3234.5	106.4	6.64	80.1	-0.43	0.00	0.80	0.80	
3235	110.9	7.56	79.8	-0.38	0.04	1.06	1.00	
3235.5	118.4	7.36	79.4	-0.40	0.02	0.93	0.90	
3236	127.7	6.81	80.9	-0.40	0.02	0.90	0.87	
3236.5	136.0	6.46	84.2	-0.36	0.06	1.17	1.08	
3237	137.8	5.93	93.6	-0.21	0.21	2.14	1.82	
3237.5	127.4	5.53	95.5	-0.20	0.22	2.19	1.86	
3238	120.6	5.25	94.3	-0.25	0.17	1.89	1.63	
3238.5	110.4	5.05	91.2	-0.33	0.09	1.39	1.25	
3239	85.9	4.89	88.9	-0.39	0.03	1.00	0.95	
3239.5	75.7	4.76	90.7	-0.36	0.06	1.16	1.07	
3240	67.6	4.59	92.0	-0.35	0.07	1.23	1.13	
3240.5	65.6	4.35	93.8	-0.34	0.08	1.31	1.19	
3241	66.3	4.15	94.2	-0.35	0.07	1.22	1.12	
3241.5	69.5	3.95	95.1	-0.36	0.06	1.21	1.11	
3242	71.6	3.72	98.7	-0.31	0.11	1.50	1.33	
3242.5	73.6	3.55	101.4	-0.28	0.14	1.72	1.50	
3243	72.6	3.37	103.1	-0.27	0.15	1.78	1.55	
3243.5	72.4	3.27	103.6	-0.27	0.15	1.76	1.53	
3244	74.1	3.20	101.1	-0.33	0.09	1.39	1.25	
3244.5	75.8	3.23	99.0	-0.37	0.05	1.15	1.06	
3245	78.1	3.30	97.7	-0.38	0.04	1.04	0.98	
3245.5	80.0	3.53	94.9	-0.41	0.01	0.86	0.85	
3246	82.6	3.90	91.0	-0.44	0.00	0.80	0.80	
3246.5	85.7	4.44	84.2	-0.52	0.00	0.80	0.80	
3247	87.6	5.08	81.5	-0.52	0.00	0.80	0.80	
3247.5	91.4	5.68	80.5	-0.49	0.00	0.80	0.80	



Resistivity (R) vs Sonic Transit Time (Δt) and $\Delta \log R$ vs Sonic Transit Time crossplots. Trend Exploration-1 Fuiipers. NE SE 9-8N-81W, North Park basin, Colorado.

Well: Ogle Corp., Cabot Corp., Bridger Pet.-1 Burr
 NWSE 22-7N-79W, North Park basin, Colorado

DEPTH (ft)	GR (API)	RESIS (ohm-m)	SONI (μ sec/ft)	Δ Log R $R_{\text{baseline}} = 60$ $\Delta T_{\text{baseline}} = 68$	Δ log R corrected by adding 0.26	TOC if LOM = 9.54 SC = 3	TOC if LOM = 10.75 SC = 3	Meas.TOC (wt.%)
3158	157.7	9.97	99.9	-0.14	0.12	1.38	1.16	
3158.5	158.8	9.31	99.8	-0.17	0.09	1.22	1.06	
3159	158.8	8.70	97.7	-0.25	0.01	0.87	0.84	
3159.5	158.1	8.21	96.7	-0.29	0.00	0.80	0.80	
3160	156.0	7.63	103.5	-0.19	0.07	1.16	1.03	
3160.5	154.1	7.30	111.9	-0.04	0.22	1.89	1.48	
3161	153.4	7.02	116.1	0.03	0.29	2.22	1.68	
3161.5	152.7	7.00	118.7	0.08	0.34	2.45	1.83	
3162	154.0	6.99	119.8	0.10	0.36	2.57	1.90	
3162.5	155.4	6.99	118.4	0.07	0.33	2.42	1.81	
3163	157.1	7.01	116.6	0.04	0.30	2.26	1.71	
3163.5	157.1	7.12	111.4	-0.06	0.20	1.78	1.41	
3164	155.2	7.22	107.5	-0.13	0.13	1.43	1.19	
3164.5	155.0	7.32	105.3	-0.17	0.09	1.25	1.08	
3165	155.1	7.46	105.9	-0.15	0.11	1.35	1.14	
3165.5	154.8	7.57	106.8	-0.12	0.14	1.47	1.22	
3166	152.0	7.71	107.9	-0.09	0.17	1.61	1.31	
3166.5	148.7	7.85	108.5	-0.07	0.19	1.70	1.37	
3167	146.6	8.05	109.3	-0.05	0.21	1.84	1.45	
3167.5	143.5	8.29	110.5	-0.01	0.25	2.02	1.56	
3168	137.8	8.54	111.5	0.02	0.28	2.18	1.66	1.48
3168.5	133.4	9.03	110.5	0.03	0.29	2.19	1.67	
3169	130.2	9.55	107.6	-0.01	0.25	2.04	1.57	
3169.5	126.5	10.24	100.1	-0.13	0.13	1.45	1.21	
3170	127.9	11.20	95.2	-0.19	0.07	1.16	1.03	
3170.5	128.2	12.43	86.2	-0.32	0.00	0.80	0.80	
3171	122.9	13.38	84.7	-0.32	0.00	0.80	0.80	
3171.5	115.9	14.04	83.6	-0.32	0.00	0.80	0.80	
3172	110.6	14.30	82.4	-0.34	0.00	0.80	0.80	
3172.5	108.5	14.40	81.1	-0.36	0.00	0.80	0.80	
3173	105.0	14.50	80.9	-0.36	0.00	0.80	0.80	
3173.5	103.8	14.72	81.6	-0.34	0.00	0.80	0.80	
3174	106.1	14.77	83.1	-0.31	0.00	0.80	0.80	
3174.5	111.6	14.93	84.6	-0.27	0.00	0.80	0.80	
3175	118.0	15.09	84.9	-0.26	0.00	0.79	0.80	
3175.5	125.6	15.31	84.5	-0.26	0.00	0.78	0.79	
3176	131.8	15.71	84.0	-0.26	0.00	0.79	0.79	



Resistivity (R) vs Sonic Transit Time (Δt) and $\Delta \log R$ vs Sonic Transit Time crossplots. Ogle Corp., Bridger Pet-1 Burr. NW SE 22-7N-79W, North Park basin, Colorado.