**REGIONAL STRATIGRAPHY, ELEMENTAL CHEMOSTRATIGRAPHY, AND
ORGANIC RICHNESS OF THE NIOBRARA MEMBER OF THE MANCOS SHALE,
PICEANCE BASIN, COLORADO**

by

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Find that both the content and the form meet acceptable presentation standards
Of scholarly work in the above mentioned discipline.

ABSTRACT

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Regional Stratigraphy, Elemental Chemostratigraphy, and Organic Richness of the Niobrara Member of the Mancos Shale, Piceance Basin, Colorado

Thesis directed by Professor Matthew J. Pranter

The elemental chemostratigraphy of the Upper Cretaceous Niobrara Member of the Mancos Shale shows that six chemostratigraphic zones can be identified in the Piceance Basin, Colorado, based on geochemical data collected from cuttings at 10-, 20-, and 30-ft (3.05, 6.10, and 9.14 m) intervals. Chemostratigraphic correlations of nine wells spaced 20 mi (~32 km) apart closely match lithostratigraphic correlations made using gamma-ray and deep-resistivity logs. Lithologic interpretations made from wireline logs indicate that the Niobrara Member and equivalent strata consist primarily of interbedded calcareous shale and shaley limestone facies that increase in thickness to the northwest of the basin. The geochemical data suggest that during deposition of the Niobrara Member, anoxia and calcium enrichment increased to the east of the basin, whereas terrestrial input and clay enrichment increased to the northwest. Element cross-plots suggest that a large portion of the silicon is detrital and that the Niobrara Member becomes an increasingly more clastic than carbonate system to the west.

The $\Delta \text{Log R}$ -derived total organic carbon (TOC) calculated using a sonic-resistivity overlay analysis technique shows that the Niobrara Member comprises organic-rich and organic-poor deposits. Average TOC values range between 1 (in organic-poor deposits) and 2.37 wt.%

(in organic-rich deposits) with higher TOC values recorded in the southern and eastern portions of the basin. Relative-rock brittleness estimates from element and TOC data show the stratigraphic variability of alternating ductile (TOC rich, Ca and Si/Al poor) and brittle intervals (TOC poor, Ca and Si/Al rich) for the Niobrara Member.

DEDICATION

I would like to dedicate this thesis to my parents, Najwa and Ghassan, and to my sisters, Sana and Nour.

À Mr. S. Zarifé.

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INTRODUCTION

The Upper Cretaceous Niobrara Formation and its stratigraphic equivalents produce both oil and gas in the Rocky Mountain region. Hydrocarbon production from chalks, marls, and marine shales of the Niobrara Formation and correlative parts of the Mancos Shale occurs in the Powder River, Denver, North Park, Sand Wash, San Juan, and Piceance basins. In 2009, the success of the horizontally drilled EOG Jake #2-01H discovery well marked the beginning of an on-going exploitation of these low-permeability oil reservoirs in the Denver Basin in northeastern Colorado (Durham, 2012). In 2013, WPX Energy's Williams # GM 801-4 HN1 discovery well (API#: 05-045-21487; 04 07S 96W) produced at an initial rate of 16 million ft³ (4.53 x 10⁻⁷ km³) of gas per day choked back (Durham, 2013), suggesting that the Niobrara Member gas play has the potential to be substantially prolific and economically viable in the Piceance Basin in northwestern Colorado. Unconventional shale gas resource plays are self-sourced systems, having generally low matrix permeability and continuous-type accumulations of biogenic and/or thermogenic gas.

The interval encompassed by the Niobrara Formation and equivalent rocks in Colorado is studied by several authors (e.g., Clayton and Swetland, 1980; Rice, 1984a, b; Barlow, 1985; Pollastro and Martinez, 1985; Precht and Pollastro, 1985; Molenaar and Wilson, 1990; Nuccio, 1990). However, published accounts detailing the hydrocarbon source-rock potential of the Niobrara Member and equivalent parts of the Mancos Shale are sparse, especially in northwestern Colorado (e.g., Vincelette and Foster, 1992; Longman et al., 1998; Landon et al., 2001; Fisher, 2007; Kuzniak, 2009; Rogers, 2012). Longman et al. (1998) showed that the organic-rich marine shales provide the main hydrocarbon source rocks of the Niobrara Member, and Vincelette and Foster (1992) tied major hydrocarbon production from the Niobrara Member

in northwestern Colorado to the presence of post-Laramide fractures in the calcareous shales and marls. A comprehensive understanding of the stratigraphic and geographic relationships, as well as the origin and distribution of lithologies of source and reservoir rocks within the Niobrara, is essential in providing a framework for predicting the occurrence and distribution of hydrocarbon accumulations.

Seismic and petrophysical data are commonly used to develop lithostratigraphic and seismic stratigraphic frameworks. These data allow interwell correlations to be made; however, they sometimes lack the necessary resolution for detailed stratigraphic analysis (Pearce et al., 2005). The fine-grained, organic-rich, and seemingly homogenous nature of shale sequences has stimulated the search for new techniques that allow an improved understanding of reservoir stratigraphy. Consequently, chemical data and chemical stratigraphy (or chemostratigraphy) have become useful as an aid for stratigraphic correlation. Chemostratigraphic zonation relies upon the characterization of a sedimentary interval in terms of its major- and trace-element concentrations, whereas chemostratigraphic correlations refer to the extension of this characterization from one wellbore section to another (Ratcliffe et al., 2007; Pearce et al., 2008). To date, several authors have tested and reported the applicability of this technique in frontier and mature basins across the world (e.g., Ehrenberg and Siring, 1992; Racey et al., 1995; Pearce et al., 1999, 2005; Ratcliffe et al., 2004, 2007; Wright et al., 2010a, b). For example, Pearce et al. (2008) showed how a blind test of chemostratigraphic correlations compared well with lithofacies correlations made from outcrop measured sections of the Green River Formation, whereas Wright et al. (2010b) used chemostratigraphy as a means to infer bulk mineralogy and to model organic content using the Haynesville and Eagle Ford Formations shale gas plays as case studies.

In this study, an approach to chemostratigraphy is used for stratigraphic correlation of the Niobrara Member interval in the Piceance Basin. A subsurface lithostratigraphic framework was established using gamma-ray (GR) and deep-induction resistivity (ILD) logs from 251 wells. After identifying key surfaces and correlating mappable intervals within the Niobrara Member, subdivisions were compared to previous work on the Lower Mancos Shale on the Douglas Creek Arch (Fisher, 2007; Kuzniak, 2009), and in the Piceance Basin (Rogers, 2012), as well as to the study by Vincelette and Foster (1992) in northwestern Colorado. Elemental data were acquired from a total of 960 drill-cutting samples (total footage of 15,430 ft [4,703.1 m]) from 9 wells across the basin using the Thermo Scientific Niton[®] XL3t 950 X-ray fluorescence (XRF) portable hand-held analyzer (Figure 1; Table 1). Average well spacing is approximately 20 mi (32.2 km) and vertical sample spacing is 10, 20, or 30 ft (3.05, 6.10, or 9.14 m) (Appendix A, Table A-1). The geochemical data allowed the subdivision of the Niobrara Member into chemostratigraphic zones based on changes in elemental composition. Interwell correlations were made, and by generating element maps for each unit, stratigraphic and lateral changes of key elements were investigated.

In addition to the Niobrara Member chemostratigraphy, this study uses a petrophysical approach to evaluate the stratigraphic variation and lateral distribution of organic-rich intervals within the Niobrara Member. Total organic carbon (TOC) describes the organic matter concentration (in weight percent of organic carbon) in sedimentary rocks and is used to assess the quality of hydrocarbon source rocks. The Δ Log R technique (Passey et al., 1990), a porosity/resistivity overlay analysis, was applied in this study in order to identify organic-rich intervals and calculate TOC in 68 wells. The technique yields profiles of TOC at the combined resolution of the logging tools of approximately 3 ft (1 m) (Passey et al., 1990). Profiles

Figure 1. Map of Piceance Basin showing Mancos Shale outcrops, major Mancos Shale oil and gas fields, and wells used for this study. XRF analyzed cuttings from wells labeled A through I listed in adjoining Table 1. Modified from Hoak and Klawitter (1997) and Pranter et al. (2009). Mancos Shale oil and gas fields from Kirschbaum (2003).

Map Label (Figure 1)	Well API #	Well Name/No	County	Section/Township /Range	Latitude/Longitude	Operator
A	05045067230000	O'CONNELL #F11X-34P	Garfield	34 07S 092W	39.408002/-107.660352	MOBIL OIL
B	05077081060000	KATHLYN YOUNG #1-15	Mesa	15 10S 095W	39.186315/-107.984875	BLACK HILLS PLATEAU PRODUCTION
C	05045065100000	ARCO-DEEP #1-27	Garfield	27 06S 097W	39.492574/-108.20776	WPX ENERGY ROCKY MOUNTAIN
D	05045060420000	ROAN CREEK #4-C-2	Garfield	02 06S 101W	39.561684/-108.624673	CHORNEY OIL
E	05045051060000	BAXTER PASS UNIT #4-25	Garfield	25 05S 103W	39.590582/-108.912762	PAN AMERICAN PETROLEUM
F	05103083570000	BARCUS CREEK FEDERAL #22-12	Rio Blanco	12 01N 099W	40.071148/-108.455023	NATURAL GAS CORP OF CALIFORNIA
G	05103652610000	DOUGLAS A #16	Rio Blanco	19 01S 101W	39.945618/-108.770711	PHILLIPS PETROLEUM
H	05103085970000	WHT FACE BT FED #12	Rio Blanco	31 03S 103W	39.74594/-109.00404	FOUNDATION ENERGY MANAGEMENT
I	05103076190000	DEEP WHITE RIVER DOME #1	Rio Blanco	13 02N 097W	40.143029/-108.233087	ENCANA OIL & GAS (USA)

Table 1. Well name, API number, operator, and geographic location for the nine wells labelled A through I on Figure 1 (wells of XRF analyzed cuttings).

produced by this method were used to evaluate the stratigraphic changes of source-rock richness, and data of this resolution have not been previously reported for the Niobrara Member of the Mancos Shale interval in this area.

This thesis addresses: 1) how chemostratigraphy was used as an independent technique for stratigraphic correlation, 2) how chemostratigraphic zonations relate to lithostratigraphic units, and 3) how organic richness varies spatially throughout the study area. Together, the chemostratigraphic and petrophysical techniques allow a better understanding of the source- and reservoir-rock potential of the Niobrara Member. The results of this study establish a database from which correlations can be made for the Niobrara Member in the Piceance Basin. Additionally, some implications of the changes in elemental composition and organic richness are investigated; changes in the depositional environment (e.g., oxygenation level and terrestrial input) of the Niobrara Member are interpreted, and a qualitative approach to interpret relative changes in rock brittleness is discussed, which would aid in assessing variations in potential reservoir quality. Moreover, this study aims to provide direction and insight for further chemostratigraphic study and petrophysical interpretations of this interval.

TECTONIC AND STRATIGRAPHIC SETTING

Geologic History

During the Late Cretaceous, an epeiric seaway, the Western Interior Seaway, covered the central part of North America from the Gulf of Mexico to northern Canada (Kauffman, 1977; Kauffman and Caldwell, 1993). The seaway inundated an asymmetric foreland basin, the Western Interior Basin, which resulted in the deposition of widespread marine sediments (Figure 2) (Longman et al., 1998). The process of mountain building from the tectonically active Sevier

Figure 2. Cross section of Cretaceous strata deposited in eastern Utah and western Colorado. Niobrara Member of Mancos Shale study interval is shown with red bar. From Cole (2008), modified from Dyman et al. (1994).

Orogenic belt to the west supplied coarse siliciclastic sediments into the western portion of the seaway. Eastward-flowing currents transported finer grained siliciclastic silts and muds onto the low relief eastern part of the seaway (Longman et al., 1998; Finn and Johnson, 2005). Across the western part of the foreland basin, a “complex pattern of intertonguing marine and nonmarine” sediments was deposited (Finn and Johnson, 2005, p. 3). Westward-thinning tongues of marine shale and siltstone characterize the marine deposits, whereas eastward-thinning clastic wedges of sandstone, siltstone, shale, and coal are representative of the nonmarine deposits (Figure 2) (Dyman et al., 1994; Finn and Johnson, 2005; Cole 2008). On the eastern shelf of the seaway, where the influx of siliciclastic sediments was restricted and conditions were favorable for carbonate deposition, a variety of carbonate sediments ([many] rich in coccolith debris and planktonic foraminifers) accumulated (Roberts and Kirschbaum, 1995; Longman et al., 1998; Finn and Johnson, 2005). The Niobrara Formation (as named in the eastern part of the seaway), which is part of a sequence of “thick Upper Cretaceous marine shales that blanket the entire Western Interior of North America” (Johnson, 2003, p.6) was deposited during a time of major marine transgression.

During the Laramide Orogeny, a period of mountain building in western North America that started in the Late Cretaceous (approximately 70 Ma) and ended in the Eocene (approximately 55 to 40 Ma), a series of north-trending uplifts and intermontane structural basins formed. In the United States, these basins occur primarily in the central Rocky Mountains from Colorado and Utah to Montana. The area presently occupied by the Piceance Basin was partitioned during Laramide tectonism from the larger pre-existing Western Interior foreland basin (Johnson and Flores, 2003; DeCelles, 2004).

The Piceance Basin is a highly asymmetrical northwest-trending structural depression located entirely in northwestern Colorado and is part of the Colorado Plateau physiographic province. The basin is bounded by the Rangely Anticline and Axial Arch to the north, the Grand Hogback Monocline to the east, the Gunnison Uplift, Elk Mountains, and Sawatch Uplift to the south and southeast, the Uncompahgre uplift to the southwest, and the Douglas Creek Arch to the west (Figure 1) (Johnson, 1989).

This study focuses on the Niobrara Member of the Mancos Shale and equivalent rocks in the Piceance Basin. The study area covers part or all of these counties: Moffat, Routt, Rio Blanco, Garfield, Mesa, Delta, and Pitkin, over an area of approximately 6,000 mi² (15,540 km²).

Review of Niobrara Stratigraphy and Lithology

The Niobrara Formation was first described by Meek and Hayden (1861) for exposures near the mouth of the Niobrara River in Nebraska. Longman et al. (1998) thoroughly reviewed the various published descriptions of the Niobrara stratigraphy in the Western Interior Seaway of the Rocky Mountain Region. In the eastern part of the seaway, the Niobrara Formation is formally divided into two members: the lower Fort Hays Limestone Member and the overlying Smoky Hill Member (e.g. in Kansas and in the Denver Basin, in eastern Colorado) (Landon et al., 2001). These stratigraphic intervals were correlated northward and westward from the Denver Basin. In the western part of the seaway (that includes the Piceance Basin), stratigraphic correlations become difficult “due to the disappearance of distinctive log markers and the relatively uniform log character in the thick shaly section of the Mancos” (Longman et al., 1998, p. 138).

In the westernmost part of the Piceance Basin, primarily at Rangely, production from fractured Cretaceous shales has been referred to as Mancos production (Vincelette and Foster, 1992). However, log correlations indicate that most of this production is from the “lower third of the Mancos, which is the Niobrara Formation equivalent and has a lithology typical of the Niobrara Formation in areas farther east” (Vincelette and Foster, 1992, p. 233). In the southern Piceance Basin, the Niobrara Member is underlain by the Montezuma Valley and Juana Lopez Members of the Mancos Shale (Figure 3). This nomenclature conforms with usage by Ball et al. (2009), Merewether et al. (2006), and Gustason (E. R., 2013, personal communication). Over the extent of the basin, a consistent and distinctive well-log marker below the Niobrara Member corresponds to the Juana Lopez Member of the Mancos Shale. The Niobrara Member is overlain by the Prairie Canyon Member (Cole, 1997). To the west of the Piceance Basin, the Niobrara Member is likely equivalent to the Blue Gate Shale (Johnson, 2003; Rogers, 2012). The Niobrara Member is considered to be Coniacian to Campanian in age (Scott and Cobban, 1964), and Ball et al. (2009) show that the base of the formation corresponds to the inoceramid biozone of *Creminoceras erectus*.

The Niobrara Formation and stratigraphically equivalent strata contain a spectrum of lithologies ranging from limestone and chalks to marls and less calcareous shales (Longman et al., 1998). In the eastern part of the seaway, typical Niobrara Formation lithologies are chalks and limestone (Finn and Johnson, 2005). A gradual westward decrease in chalk and other carbonate components characterizes the lithology variation of the Niobrara Formation as it grades into the Niobrara Member of the Mancos Shale (Longman et al., 1998). This is considered to be the result of a closer proximity to the Sevier thrust belt to the west, which constitutes the primary detrital source (Longman et al., 1998). In the western part of the seaway which includes

Figure 3. Generalized stratigraphic column and lithologic section showing nomenclature used in this study. The interval of study is shown with a red bar. Nomenclature adopted from Merewether et al. (2006) tied to Ball et al. (2009) and Gustason (pers. comm., 2013).

the study area, typical Niobrara Member calcareous (limestone and chalk) facies grades laterally into calcareous shale (marl) and weakly to noncalcareous shale of the Mancos Shale. However, “the limits of the calcareous facies of the Niobrara [Formation] are not well mapped” (Finn and Johnson, 2005, p. 6).

METHODOLOGY

Chemostratigraphic Analysis

Whole-rock quantitative data were acquired for 40 elements: 8 major elements (Al, Si, Ti, Fe, Mn, Ca, Mg, and K) and 32 minor and trace elements (Ag, As, Au, Ba, Bi, Cd, Cl, Co, Cr, Cs, Cu, Hg, Mo, Nb, Ni, P, Pb, Pd, Rb, S, Sb, Sc, Se, Sn, Sr, Te, Th, U, V, W, Zn, and Zr). Counting times were 30 seconds each on the low- and main-energy filters and 45 seconds on the light-filter setting (105 seconds total counting time) for the “mining” analysis mode (used to detect metals), and 45, 35, and 30 seconds respectively on the low-, main-, and high-filter settings (110 seconds total counting time) for the “soils” analysis mode (used to detect elements typically associated with soils). Elements Ti to U were analyzed using the low-, main-, and high-filter settings, and the light-filter setting was used to analyze Mg to S. Measurements in the “mining” mode were recorded in weight percent (wt. %), and those in the “soils” mode in parts per million (ppm). Precision and repeatability of the major-, minor-, and trace-element data are detailed in Appendix A.

Total Organic Carbon and Δ Log R Technique

Several well-log techniques have been developed for identifying and calculating total organic carbon (TOC) of subsurface strata (Appendix B, Table B-1). The Δ log R method of

Passey et al. (1990) uses the well-log curve separation resulting from the overlay of properly scaled porosity and resistivity logs to determine TOC. When plotted on the same log track, the porosity and resistivity curves parallel each other and can be overlain in a non-source rock. For hydrocarbon-bearing (reservoir) or organic-rich non-reservoir intervals, a separation between the two curves, termed “ $\Delta \log R$ ”, occurs. A gamma-ray log can be used to differentiate between lithologies and to eliminate reservoir sections from the analysis. In an immature source rock, the $\Delta \log R$ separation is primarily caused by the porosity curve responding to the low-density organic matter. However, in a mature source rock, the separation results from the additional response of the resistivity log to the presence of hydrocarbons (Passey et al., 1990) (Figure 4). Three curves (sonic, bulk density, and neutron porosity) produce a response that can mimic an increase in porosity, but the use of a sonic/resistivity combination is recommended because it is shown to be more accurate than the density/resistivity and neutron/resistivity combinations (Passey et al., 1990).

The TOC content in mature source rocks is calculated using the $\Delta \log R$ separation (measured in logarithmic resistivity cycles) and by applying a maturity factor expressed as LOM (level of organic metamorphism). Two empirical equations are used to quantify TOC:

$$\Delta \log R = \log_{10} (R/R_{\text{baseline}}) + 0.02 * (\Delta t - \Delta t_{\text{baseline}}) \quad (1)$$

$$\text{TOC} = (\Delta \log R) * 10^{(2.297 - 0.1688 * \text{LOM})} \quad (2)$$

R is the measured deep resistivity value in ohm.m and Δt is the measured transit time in $\mu\text{s}/\text{ft}$.

R_{baseline} and $\Delta t_{\text{baseline}}$ are the respective resistivity and transit-time values when the curves are overlain (baselined) in a non-source rock.

Figure 4. Schematic guide for interpreting various log motifs observed on Δ Log R overlays. Modified from Passey et al. (1990).

Differential transit-time, or sonic (DT), and deep-induction resistivity logs (ILD or LLD) were used (as recommended by Passey et al., 1990) to solve for TOC in 68 wells (Figure 1; Appendix B, Table B-2).

The first step in applying the $\Delta \log R$ technique is to adjust the sonic (DT) and resistivity (ILD or LLD) logs such as their relative scaling is -100 $\mu\text{s}/\text{ft}$ (-328 $\mu\text{s}/\text{m}$) per two logarithmic resistivity cycles. The two curves are then overlain and baselined over a fine-grained, “non-source” interval. A baseline condition is identified when the two log profiles directly track each other over a considerable depth range (e.g. 400 ft [121.9 m]) (Passey et al., 1990). Once the baseline is established, organic-rich zones are identified by 1) the separation and 2) non parallelism of the two curves (Figure 4). A TOC profile is then constructed, first by quantifying the $\Delta \log R$ separation (equation 1), and then by calculating TOC (equation 2) when the maturity factor (LOM) is determined.

LOM is a thermal maturity indicator that “describes how far the thermal metamorphism of sedimented organic matter has progressed during subsurface burial” (Hood et al., 1975, p. 986). It is a linear scale used for numerically correlating different indicators of organic metamorphism, such as coal rank, carbonization of structured organic matter, and vitrinite reflectance (%Ro).

Thermal maturity data used in this study are from average %Ro values (N = 81 samples from 18 wells, at sample frequency ranging between < 100 ft [< 30.5 m] and 970 ft [295.7 m]; USGS Core Research Center) for the Niobrara Member interval converted to LOM using a rearranged LeCompte and Hursan’s (2010) formula (Appendix B; Cardneaux, 2012). To determine LOM values at each well used for TOC calculations, known LOM values from 18 wells were

used to map the LOM distribution across the study area and assign values for wells at which no published maturity data were available.

In addition, because baselining the transit-time and resistivity curves considers the baselined interval as “zero TOC”, “background” TOC must be added back to the TOC calculated from equation (2) (Passey et al., 1990). The average TOC in shales worldwide generally exceeds 0.8 wt.% (Tissot and Welte, 1984) and 1 wt.% TOC is used in this study to account for this “background” TOC. Because the $\Delta \text{Log R}$ technique can yield high anomalous $\Delta \text{Log R}$ separation values (not related to an increase in both resistivity and sonic values), a resistivity/sonic log cross-plot was used to qualitatively eliminate potentially anomalous TOC from the analysis. By using a lower TOC cutoff value of 1 wt.%, only TOC associated with both high resistivity and high sonic values is kept in the analysis (detailed in Appendix B, Figure B-2) (M. Connolly, 2013, personal communication). Figure 5 provides an example of the application of the $\Delta \text{Log R}$ technique for the South Baxter Pass Unit #2-20 well in Garfield County, Colorado.

SUBSURFACE STRATIGRAPHY

The subsurface stratigraphy of the Niobrara Member of the Mancos Shale in northwestern Colorado has previously been described by Vincelette and Foster (1992), Longman et al. (1998), Fisher (2007), Kuzniak (2009), and Rogers (2012), although subdivisions of the Niobrara Member in the Piceance Basin remain as informal nomenclature. In this study eight lithostratigraphic units are defined and correlated across much of the basin based on changes in gamma-ray and deep-resistivity logs (Figure 6; Appendix C). These units are termed from the

Figure 5. $\Delta \log R$ technique (Passey et al., 1990) applied to “South Baxter Pass Unit #2-20” (API#: 05-045-05112) well in western Garfield county. The first log track shows the overlay of the sonic and the resistivity logs. The logs are properly scaled and baselined over a “non-source” interval. A portion of the interval over which the baseline was established is shown with a blue bar in the first track. The orange filling highlights the ($\Delta \log R$) separation between the two curves. The second log track shows the “ $\Delta \log R$ ” curve. The third and fourth log tracks show the initial TOC and the TOC+1 curves respectively, as they both compare to TOC data points (from USGS Core Library data files). The TOC Flag log track highlights in red intervals over which the $\Delta \log R$ separation is likely due to the increase in both the DT and the ILD values (detailed in Appendix B). The Final TOC curve is the curve yielded after potentially-anomalous TOC is removed from the analysis.

Figure 6. Type Log for the Niobrara Member in the Piceance Basin. Eight lithostratigraphic units are identified. Location of well is shown on Figure 1 (labelled C).

base to the top (oldest to youngest) of the Niobrara Member as Niobrara 1 to 8. The Niobrara Member ranges in thickness between less than 750 ft (228.6 m) in the southeast to more than 1700 ft (518.16 m) in the northwest of the Piceance Basin. In general, all Niobrara Member lithostratigraphic units thicken to the northwest (Figure 7; Appendix C).

The base of the Niobrara Member as defined in this study is a laterally consistent surface across the Piceance Basin that marks a shift on the gamma-ray curve with lower values recorded in the underlying units. Where the gamma-ray character change was less readily identifiable, the base of Niobrara Member was picked at an increase in deep resistivity values (from lower values below to higher values above). Within the Niobrara Member, the key surfaces (“markers”) that were used for stratigraphic correlation correspond to sharp shifts on the gamma-ray curve from lower values below to higher values above. The character of the gamma-ray log was more extensively used for correlating key surfaces, whereas the deep-resistivity log proved less helpful over large areal extents. All stratigraphic markers are generally well-retained across the study area, although log characters of the tops of lithostratigraphic units Niobrara 1, Niobrara 3, and Niobrara 7 appear to be more readily identifiable across the entire study area. The “Niobrara Hot Shale” marker (top of Niobrara 7) is regionally very consistent and was used to identify the Niobrara Member within the Lower Mancos Shale, and the high gamma-ray values recorded at this surface can be attributed to the presence of a regionally organic-rich interval. The top of the Niobrara Member is picked in this study at the first decrease of a highly-resistive marker which is interpreted to correspond to the top of the calcareous lithology (Haskett, 1959; Vincelette and Foster, 1992; Finn and Johnson, 2005; Rogers, 2012).

Figure 7. Cross sections AA' (7a.) and BB' (7b.) flattened on top of the “Niobrara Hot Shale” marker. Space between wells is equal and not representative of actual distances. Numbers at log tops correspond to well API numbers. Eight lithostratigraphic units (Niobrara 1 to Niobrara 8) are identified from the logs. In general, all units thicken to the northwest.

Based on interpretations made from well-log characteristics, all units appear to be similar in terms of lithologic composition (non-calcareous, calcareous, and very calcareous shale), varying primarily in shale/carbonate content and organic richness (Appendix C).

ELEMENTAL CHEMOSTRATIGRAPHY

Chemostratigraphic Zonation

Chemostratigraphic zonation is defined as the subdivision of sedimentary intervals based on changes in inorganic geochemical composition (Pearce et al., 2008). In this study, abundance profiles (or geochemical logs) of elemental data are plotted versus depth. Elemental data are expressed as absolute concentrations (ppm or wt.%) or as a ratio of one element against another. Analytical data from the ratio plots highlight compositional changes associated with mineralogy (Pearce et al., 2008), and normalizing the data against Al values compensates for changes in geochemistry that can be attributed to grain-size variations (Pearce et al., 2008). The subdivision of a sedimentary interval into chemostratigraphic zones was established on the basis of the changing morphology (log motifs) of the geochemical logs.

X-ray fluorescence (XRF) data were acquired for 40 elements from well cuttings. However, many element concentrations fell below the quantification limits of the instrument (Ag, Au, Bi, Cd, Cl, Co, Hg, Mg, Nb, Ni, Pb, Pd, Sb, Se, Sn, U, and W), and only certain detected elements (with measurement error < 20%) were used to develop geochemical fingerprints for each zone. These elements, referred to as chemostratigraphic index elements, are selected on the basis of their systematic variation as they relate to stratigraphy. From well data, distinctive trends can be recognized because changes in elemental composition with depth are directly related to stratigraphy (Ratcliffe et al., 2007).

The Kathlyn Young #1-15 well (API#: 05-077-08106; 15 10S 95W; having cuttings sampling interval of 10 ft [3.05 m] over complete Niobrara Member) is used as the chemostratigraphic reference well for the Niobrara Member in the Piceance Basin. Key geochemical profiles of ten index elements and element ratios were used to independently define six chemostratigraphic zones within the Niobrara Member interval (Figure 8; Appendix D). The chemostratigraphic zones are designated stratigraphically upward as CN1 to CN6. Representative elements and element ratios used for geochemical zonation are: Ca, Si, Si/Al, Al, Fe, K/Al, Mo, Cr+V, Ti, and Zr.

Overall, four calcium-enriched zones are identified (CN1, CN2, CN4, and CN6) (Figure 8). In general, Ca and Si geochemical logs show opposite trends, and this observation is most apparent in the O'Connell well (Figure 1; Appendix D). Si, Al, Fe, Ti, and Zr logs generally track each other, although some exceptions exist locally. Similarly, curves of Si/Al and K/Al closely track each other.

Chemostratigraphic Zone CN1 is the first calcium-enriched zone and begins with high values of Ca (up to 12wt.% in the O'Connell well) that gradually decrease upward. The base of this zone (base of Niobrara Member) is marked by higher Si/Al and K/Al values. Overall, curves of Si/Al and K/Al show an increasing-upward trend, whereas values Si, Fe, Mo, Cr+V, Ti, and Zr slightly increase upward. Al values remain relatively constant in most wells. The top of this zone is characterized by an abrupt decrease in Si and Ti values and an increase in Si/Al and K/Al values.

Chemostratigraphic Zone CN2 is the second calcium-enriched zone. Overall, values of Si/Al and K/Al slightly increase upward, and this change is most pronounced in Baxter Pass

Figure 8. Geochemical profiles for chemostratigraphic reference well Kathlyn Young #1-15 (15 10S 95W) as correlated to gamma-ray and deep-resistivity logs from nearby well Swetland #1-5 (05 11S 95W). Six chemostratigraphic zones (CN1 to CN6) are identified from the geochemical logs. Location of both wells is shown on Figure 1.

South Unit well. Values of Fe slightly decrease upward, whereas curves of Ti and Zr show an increase in the lower half of this zone followed by lower values. Within zones CN1 and CN2, values of Mo and Cr+V are among the lowest across the Niobrara Member. The top of this zone is defined by lower Si/Al, K/Al, and Fe values, and higher Al values.

Chemostratigraphic Zone CN3 is characterized by lower Ca values. Si, Ti, Fe, and Zr log curves show similar slightly upward-decreasing trends in five wells (Wht Face BT Fed, Deep White River Dome, Kathlyn Young, Baxter Pass South Unit, and Douglas A), and a constant trend in Barcus Creek Federal, Arco Deep, and O'Connell. Si/Al and K/Al curves show a slight decrease in most wells, with exceptions occurring within two wells (Wht Face BT Fed and Douglas A). Within this interval, Mo and Cr+V curves display laterally persistent peaks of higher values. In most wells, the top of this zone is defined by an increase in Ca, Si, and Al values and a decrease in ratios Si/Al and K/Al.

Chemostratigraphic Zone CN4 is the third calcium-enriched zone, with its base defined by a shift to higher Ca, Si/Al, Mo, and Cr+V values. Overall, Ca values gradually increase upward, although local constant trends are noted (e.g., Kathlyn Young and Wht Face BT Fed). Curves of Si/Al, K/Al, Mo, and Cr+V show an upward-increasing trend, with exceptions occurring in the O'Connell, Deep White River Dome, and Barcus Creek Federal wells that show and upward decrease in Cr+V values. Al and Zr values appear to decrease over this interval, whereas Fe and Ti curves show a uniform character. The top of this zone is characterized by an abrupt decrease in Si/Al and K/Al and an increase in Fe and Al values.

Chemostratigraphic Zone CN5 is one of the most geochemically distinctive zones within the study interval, displaying pronounced changes in log character. Overall, this interval has

lower Ca values than the underlying zone. Si, Al, Mo, Cr+V, and Ti values increase upward within most wells, whereas ratios Si/Al and K/Al decrease upward. Zr and Fe values show a slightly-increasing upward trend. The top of this zone is characterized by a shift to higher Si/Al and K/Al values.

Chemostratigraphic Zone CN6 is the fourth calcium-enriched zone. CN6 is along with CN5, an easily-identifiable geochemical zone across the 9 wells, with its top (corresponding to the top of the Niobrara Member) defined by a marked decrease in Ca values. In general, Si/Al and K/Al decrease upward, whereas Al and Fe values slightly increase upward in most wells. Zr and Ti values slightly decrease upward although some constant trends are noted locally. CN6 displays the highest Mo values recorded from the study interval, with Mo curves showing a slight decrease at the upper half of this zone.

Chemostratigraphic Correlations

The correlation of the six chemostratigraphic zones between wells was accomplished through the visual identification of significant trends. Although several compositional changes are consistent between the nine wells, many trends are not recognized within all wells, particularly when using lower-resolution datasets (e.g., 30 ft. [9.14 m] sampling interval). To the north, interwell correlations are more difficult and chemostratigraphic zones more poorly defined, with the geochemical differences between wells becoming more marked. Important geochemical differences that were recognized between wells are significant changes in Ca content: although four Ca-enriched zones are identified to the south and to the east of the study area, these defined cycles of Ca-enrichment are not laterally continuous features, suggesting that they are localized trends. Curves of Si/Al and K/Al appear to have the most laterally consistent trends and were the most useful in identifying correlative features over large distances.

In siliciclastic sequences, the primary control on whole-rock geochemistry is lithology (Ratcliffe et al., 2007), and lateral changes of geochemical features can be attributed to (1) changes in detrital mineralogy and provenance composition, (2) changes in depositional environment and facies, and (3) diagenesis (Pearce et al., 2005).

Comparison of chemostratigraphic and lithostratigraphic correlations show that four “marker” horizons identified on the geochemical logs correspond to “marker” beds picked using gamma-ray and resistivity logs. The tops of chemostratigraphic zones CN1, CN2, CN3, and CN5 closely match the tops of lithostratigraphic units Niobrara 1, Niobrara 3, Niobrara 4, and Niobrara 6 respectively. Discrepancies involve the tops of chemostratigraphic zones CN2 and CN3 that were picked below the tops of Niobrara 3 and 4 within two wells (Baxter Pass South Unit and Douglas A wells; Appendix D), and top of CN5 that was picked above Niobrara 6 within White Face BT Fed well. These discrepancies may be accounted for by the low-resolution sampling intervals.

Lateral Variation of Elements

Average values of element concentrations and element ratios vary laterally for the six chemostratigraphic zones of the Niobrara Member. Limited data points toward the east-central portion of the basin make the constructed element contour maps less reliable over this area where no well control exists (Figures 9 to 12). Average Ca maps (Figure 9) indicate that Ca enrichment increased eastward, with the lowest values observed to the north and west. Chemostratigraphic zones CN1 and CN4 display the most dramatic lateral changes of average Ca concentrations whereas CN6 exhibits the highest degree of homogeneity of Ca enrichment. Similarly, average Mo maps (Figure 10) show a consistent gradual enrichment eastward, with chemostratigraphic zones CN4, CN5, and CN6 recording the highest Mo values. Cr+V maps also show an eastward

Figure 9. Average Ca (wt.%) maps for the six chemostratigraphic zones of the Niobrara Member of the Mancos Shale. Stratigraphically upward, these zones are CN1 to CN6. Overall, Ca values increase to the east of the Piceance Basin.

Figure 10. Average Mo (ppm) maps for the six chemostratigraphic zones of the Niobrara Member of the Mancos Shale. Stratigraphically upward, these zones are CN1 to CN6. Overall, Mo values increase to the east of the Piceance Basin, suggesting that during deposition of the Niobrara Member, anoxia increased to the east.

Figure 11. Average Al (wt.%) maps for the six chemostratigraphic zones of the Niobrara Member of the Mancos Shale. Stratigraphically upward, these zones are CN1 to CN6. Overall, Al values increase to the northwest of the Piceance Basin, reflecting a closer proximity to the primary detrital source.

Figure 12. Average Si/Al maps for the six chemostratigraphic zones of the Niobrara Member of the Mancos Shale. Stratigraphically upward, these zones are CN1 to CN6. Overall, Si/Al values increase to the east of the Piceance Basin, demonstrating that the relative amount of quartz vs. clay increases to the east.

trend (Appendix E). Average Al (Figure 11), Si, and Ti+K (Appendix E) maps display similar trends, with values of Si and Ti+K significantly increasing to the northwest in all six chemostratigraphic zones. CN1 through CN4 exhibit the highest degree of Si enrichment, whereas CN1 through CN5 show the highest Ti+K values. Si/Al ratio maps (Figure 12) display an eastward-increasing trend, with the lowest values to the northwest, and moderate to high values westward. K/Al maps (Appendix E) show a consistent trend within all six chemostratigraphic zones: average K/Al ratio values increase to the northwest, with the most pronounced lateral variation exhibited within chemostratigraphic zone CN2.

Controls on Element Distribution and Abundance

Element ratios and element cross-plots highlight possible controls on element distribution and abundance, as well as element-mineral affinities (Pearce et al., 2005). In siliciclastic sediments, the Si/Al ratio can be used as a proxy for the amount of quartz vs. Al-silicates (clays) (Ratcliffe et al., 2007). Laterally, the Si/Al ratio map (Figure 12) demonstrates that the relative amount of quartz vs. clay increases to the east within all chemostratigraphic zones. Peaks of Si/Al on geochemical profiles suggest more silica input into the system from sources other than clays. Figure 8 indicates that the Niobrara Member comprises at least four intervals of increased Si/Al (upper half of chemostratigraphic zone CN1, zone CN2, base of zone CN4, and zone CN6). To evaluate whether the excess silica in the Niobrara Member is of detrital or biogenic origin, cross-plots of Si with Al were used (Tribovillard et al., 2006). As shown in Figure 13, Si exhibits a linear relationship with Al suggesting that a large portion of the Si is detrital and resides within the clay fraction. This correlation increases consistently westward and northward, with the highest R^2 recorded in the Barcus Creek Federal well ($R^2 = 0.87$). The lowest R^2 values

Figure 13. Variation of Al content (wt.%) as a function of Si content (wt.%) for all Niobrara Member samples within 9 wells. Al and Si show a moderate to strong linear relationship, suggesting that a large portion of the Si is detrital and resides with the clay fraction.

are observed in the eastern part of the basin (O'Connell well, $R^2 = 0.56$), suggesting that in that area Si is more likely to be found in other compounds such as detrital or biogenic quartz.

Si exhibits a moderate to weak inverse correlation with Ca that is highest in the southeastern part of the basin ($R^2 = 0.53$) (Figure 14). R^2 values significantly and gradually decrease westward and northward, with the lowest value recorded in the White Face BT Fed well ($R^2 = 0.05$). This relationship suggests that in the Piceance Basin, the Niobrara Member is not a strictly bimodal carbonate and siliclastic system, but rather contains a mixture of clastic and carbonate deposits. Unlike descriptions of the Niobrara Member equivalent in the eastern and central parts of the Western Interior Seaway (e.g., in the Denver Basin) where informal subdivisions are based on varying proportions of carbonate and clastic minerals (Dean and Arthur, 1998), gradually decreasing R^2 values indicate that the Niobrara Member becomes increasingly mixed to the west and to the north of the study area.

Levels of K/Al may indicate the relative abundance of the clay minerals illite/mica and kaolinite, as K is generally abundant in illite/mica and Al is abundant in kaolinite (Pearce et al., 2005). Increasing values of K/Al thus reflect increasing illite/mica levels versus kaolinite. Stratigraphically, higher K/Al values are recorded within Ca-enriched chemostratigraphic zones (CN1, CN2, CN4, and CN6) suggesting higher relative illite/mica versus kaolinite levels compared to other intervals (Figure 8; Appendix D). K/Al maps (Appendix E) show that higher relative illite/mica versus kaolinite levels are recorded to the northwest of the study area within all six chemostratigraphic zones.

Interpretation of Changes in Paleoredox Conditions

High organic-carbon concentrations are typically associated with sediments deposited in anoxic bottom-water conditions (Wright et al., 2010b). The use of elemental geochemistry in

Figure 14. Variation of Si content (wt.%) as a function of Ca content (wt.%) for all Niobrara Member samples within 9 wells. Ca and Si show a moderate to weak inverse relationship. R^2 values decrease to the west and to the north of the study area, suggesting that the Niobrara Member becomes an increasingly mixed more clastic than carbonate system.

sediments as a proxy for paleoredox conditions is a well-documented application (e.g., Tribovillard et al., 2006; Turgeon and Brumsack, 2006; Tribovillard et al., 2008; Jenkyns, 2010). Trace-metal concentrations and element ratios involving Mo, Cr, V, Ni, and Zn are geochemical proxies used as paleo-oxygenation indicators. This study uses variations in Mo, Cr, and V concentrations to identify zones deposited during low-oxygenation levels.

In sedimentary rocks, the presence of Mo is generally associated with authigenic enrichment under anoxic conditions. In oxic-water columns, Mo is highly stable in suspension and forms molybdate oxyanion (MoO_4^{2-}), but adsorbs into humic substances, Mn-oxyhydroxides, or Fe-sulfides in anoxic environments (Berrang and Grill, 1974; Magyar et al., 1993; Morse and Luther III, 1999; Algeo and Lyons, 2006). Under reducing conditions, Cr substitutes for Al within clays, and V bonds with organic matter (Jones and Manning, 1994; Rimmer, 2004; Mackenzie, 2005). Therefore, an increase in the sum Cr+V marks a reduction in the availability of oxygen in the system (Mackenzie, 2005).

Stratigraphic (depth) profiles of Mo and Cr+V suggest that more anoxic conditions existed during deposition of the upper zones (CN4, CN5, and CN6), whereas higher oxygenation levels were present during deposition of the stratigraphically lower zones (CN1 through CN3) (Figure 8; Appendix D). Average Mo and Cr+V maps show that during deposition of the Niobrara Member, anoxia increased to the east (Figure 10; Appendix E). Authigenic enrichment of V is further supported by cross-plots of Al vs. V that do not show linear trends (Appendix F).

Interpretation of Changes in Terrestrial Input

In addition to bottom-water redox conditions, terrestrial input controls the amount of organic matter preserved in shales (Tribovillard et al., 2006; Turgeon and Brumsack, 2006,

Tribovillard et al., 2008, Negri et al., 2009, Jenkyns, 2010), and changes in terrestrial input can be interpreted from major and trace-element data.

Al is a detrital element commonly used as a proxy for clay because it is scarce in seawater and is generally not affected by biologic or diagenetic processes (Orians and Bruland, 1986, Brumasck, 2006). Similarly, Ti and Zr have very low seawater concentrations and are not involved in biologic cycling (Li, 1982), with Ti being usually associated with Ti oxides, and Zr with zircon. Therefore, peaks of Al, Ti, and Zr on geochemical logs indicate detrital input into the system (Piper and Calvert, 2009).

Stratigraphically, two to three pulses of increased terrestrial input within the Niobrara Member are identified (Figure 8): CN1 transitioning to CN2, CN3 (locally), and CN4 transitioning to CN5. Laterally, the highest level of detrital elements is recorded to the northwest of the study area, reflecting a closer proximity to the detrital source (Figure 11; Appendix D).

Geochemical plots of Ca, Al, Ti, and Zr show that the chemostratigraphic zonation of the Niobrara Member corresponds with shifts in depositional systems (Figure 8). Chemostratigraphic zones CN1 and CN2 contain higher Ca content than the overlying zone CN3, and within these zones, where Ca values appear to decrease, terrestrial input can be seen to increase. The base of chemostratigraphic zone CN3 marks a shift from a carbonate depositional system to a siliciclastic depositional system. Terrestrial input increases through chemostratigraphic zone CN3, before shifting to lower values at the base of the Ca-enriched chemostratigraphic zone CN4 (carbonate depositional system). Within chemostratigraphic zone CN5, terrestrial input is seen to increase again, reflecting a second shift to a siliciclastic depositional system, and coinciding with a lower Ca content. The base of chemostratigraphic zone CN6 marks a shift to a carbonate depositional system with Al, Ti, and Zr shifting to lower values and slightly decreasing upward.

Moreover, comparison of Al, Ti, and Zr with Mo logs suggests that when terrestrial input was highest, bottom-water conditions were at their least reducing.

STRATIGRAPHIC AND GEOGRAPHIC DISTRIBUTION OF ORGANIC MATTER

Thermal Maturity

This study uses average vitrinite reflectance (%Ro) data converted to LOM for TOC calculations. %Ro data were selected instead of Tmax because they are typically more representative of thermal maturity, particularly in highly mature samples (D. Thul, 2013, personal communication).

LOM changes within the Niobrara Member in the study area are depicted in Figure 15. Contours of LOM indicate that maturation of the Niobrara Member exceeds values of 7.5 LOM (corresponding to 0.5 %Ro) over much of the Piceance Basin. Thermal maturity increases to the northeast attaining the highest values (LOM = 11, corresponding to 1.2 %Ro) within the center of the Piceance Basin, suggesting that the Niobrara Member (Lower Mancos Shale) has passed through the oil window and is presently within the gas generation window (Kirschbaum, 2003).

Organic Richness

Two cross sections (CC' and DD') using TOC profiles produced from applying the Δ Log R technique are presented in Figure 16. Two important features of the Δ Log R-derived TOC profiles for the Niobrara Member interval are (1) the vertical variation in TOC and (2) the apparent similarity in vertical TOC distribution among the investigated wells. Three main intervals of higher TOC values are identified: chemostratigraphic zone CN6, chemostratigraphic zone CN5, and the lower third of chemostratigraphic zone CN2. Estimated TOC values are

Figure 15. Contour map of level of organic metamorphism (LOM) for the Niobrara Member of the Mancos Shale. LOM values for control wells obtained using vitrinite reflectance data (from USGS Core Library data files) converted to LOM using the formula of LeCompte and Hursan (2010). Thermal maturity of the Niobrara Member increases toward the center of the Piceance Basin.

16a.

Figure 16. Δ Log R-derived TOC curves cross sections CC' (16a.) and DD' (16b.) flattened on the top of the Niobrara Member (top chemostratigraphic zone CN6). Space between wells is equal and not representative of actual distances. Numbers at log tops correspond to well API numbers. TOC values are only calibrated for the Niobrara Member interval. The highest TOC values are recorded in chemostratigraphic zones CN5, CN6 and base of CN2. Zones CN4 and CN5 show higher TOC values to the northeast.

relatively low through most of chemostratigraphic zones CN1, CN3, and CN4. The highest average TOC value is recorded in Mesa County within chemostratigraphic zone CN6 (2.37 wt.%), whereas the lowest (1 wt.%) is recorded in both Moffat and Mesa counties (chemostratigraphic zones CN2 and CN3 respectively) (Table 2). For the entire study area, the highest average TOC value is recorded within chemostratigraphic zone CN6 (1.46 wt.%), and the lowest within chemostratigraphic zone CN1 (1.08 wt.%). Cross section DD' (Figure 16) shows that chemostratigraphic zones CN4 and CN5 exhibit locally high TOC values to the north and to the northeast of the study area.

Average Δ Log R-derived TOC maps for the six chemostratigraphic zones of the Niobrara Member (Figure 17) show that TOC values generally increase from 1 to 3 wt.% to the south and to the east within chemostratigraphic zones CN2, CN5, and CN6. Zones CN4 and CN5 also display a local increase to the northeast, whereas zones CN1 and CN3 show relatively lower values across the basin.

Areas recording anoxic bottom-water conditions appear to correspond to areas of higher TOC values. Chemostratigraphic zones CN4 and CN5 display relatively higher TOC values to the northeast of the basin (Figure 16). This area also exhibits higher Mo levels (Figure 10). Mo maps also suggest relatively less anoxic conditions within chemostratigraphic zones CN1 through CN3, which appear to correspond to lower overall TOC values in these zones compared to CN5 and CN6.

Calibration and Accuracy of TOC Calculations

The mean absolute error (MAE; measured in wt.%) is provided to show how close the Δ Log R-derived TOC values are to measured TOC values from cutting samples. Wells of higher

Chemostratigraphic Zone	N	Min TOC (wt.%)	Mean TOC (wt.%)	Max TOC (wt.%)	Std TOC (wt.%)
Garfield County	16				
CN6		1.00	1.92	4.90	1.04
CN5		1.00	1.42	3.86	0.73
CN4		1.00	1.16	3.41	0.45
CN3		1.00	1.05	2.66	0.22
CN2		1.00	1.56	4.94	1.03
CN1		1.00	1.22	4.18	0.53
Mesa County	1				
CN6		1.00	2.37	4.77	1.14
CN5		1.00	1.38	3.14	0.63
CN4		1.00	1.10	3.11	0.40
CN3		1.00	1.00	1.00	0.00
CN2		1.00	1.19	2.82	0.50
CN1		1.00	1.10	5.12	0.56
Moffat County	1				
CN6		1.00	1.32	8.05	0.70
CN5		1.00	2.33	5.07	0.53
CN4		1.00	1.27	2.31	0.39
CN3		1.00	1.09	1.90	0.20
CN2		1.00	1.00	1.34	0.05
CN1		1.00	1.03	3.72	0.20
Rio Blanco County	50				
CN6		1.00	1.27	3.29	0.38
CN5		1.00	1.40	2.94	0.34
CN4		1.00	1.37	3.44	0.38
CN3		1.00	1.11	2.85	0.27
CN2		1.00	1.40	2.94	0.34
CN1		1.00	1.04	3.64	0.26
All counties	68				
CN6		1.00	1.46	3.76	0.55
CN5		1.00	1.43	3.19	0.44
CN4		1.00	1.31	3.41	0.40
CN3		1.00	1.1	2.76	0.26
CN2		1.00	1.27	4.10	0.59
CN1		1.00	1.08	3.79	0.33

N = Number of Wells; Min = Minimum; Max = Maximum; Std = Standard Deviation

Table 2. Statistical summary of Δ Log R-derived TOC for each chemostratigraphic zone (CN1 to CN6) of the Niobrara Member of the Mancos Shale. The minimum calculated TOC value is constant (=1 wt.% TOC) because baselining the transit-time and resistivity curves considers the baselined interval as “zero TOC” and therefore background TOC (of 1 wt.%) was added back to the calculated value.

Figure 17. Average $\Delta \text{Log R}$ -derived TOC maps for the six chemostratigraphic zones of the Niobrara Member of the Mancos Shale. Stratigraphically upward, these zones are CN1 to CN6. Yellow discs on maps are well control locations. Chemostratigraphic zones CN2, CN5, and CN6 show increasing TOC values to the southern and eastern portions of the basin, whereas zones CN4 and CN5 show a local increase to the northeast.

maturity (LOM = 8.92 and LOM = 9.36) exhibit lower MAE (and thus higher accuracy) compared to wells of lower maturity (LOM < 8) (Table 3).

As detailed in Passey et al. (1990), anomalous sonic or resistivity log responses not associated with source intervals may result in inaccurate TOC calculations. Although a qualitative method was used to remove potentially anomalous TOC values (associated with anomalous sonic or resistivity values) from the analysis (Appendix B), this method may underestimate TOC over some organic-rich intervals, because only background TOC (1 wt.%) is accounted for.

The estimation of the maturity parameter (LOM) is another factor potentially contributing to the discrepancy between measured and log-derived TOC values. Although LOM values were obtained from the conversion of vitrinite reflectance data in 18 wells, a margin of error may be present when estimating LOM within other wells. However, if the value of LOM is not properly estimated, “absolute TOC values will be somewhat in error, but the vertical variability in TOC will be correctly represented” (Passey et al., 1990, p. 1779).

In addition, because little is known about the cuttings data (e.g., hole quality, possible high-grading), uncertainty may arise regarding the quality of the comparison between cuttings- and Δ Log R-derived data.

Qualitative Interpretation of Relative Rock Brittleness

Production from shale-gas reservoirs typically require fracture stimulation and wells are typically drilled horizontally in the most brittle rock. Brittle rocks are generally silica and/or carbonate enriched, whereas ductile rocks are considered to be clay-mineral and organic (TOC) rich (Slatt and Abousleiman, 2011).

Well Name/No	API#	LOM	N	MAE (wt.%)
Taiga Mtn #6-22	05103089200000	7.38	18	0.53
Baxter Pass South Unit - G#4-25	05045051060000	7.66	6	0.51
Federal #9-25-1-2	05103084610000	7.99	2	0.65
Lynch Creek-Gov #1	05081060900000	8.00	4	0.62
South Baxter Pass Unit #2-20	05045051120000	8.92	32	0.40
Arco Deep #1-27	05045065100000	9.36	9	0.25

$$\text{with MAE} = \frac{1}{N} \sum_{i=1}^N |FinalTOC - TOC_m|$$

N = number of samples analyzed; FinalTOC = Δ Log R-derived TOC; TOC_m = measured TOC values from cuttings data

Table 3. Accuracy of Δ Log R-derived TOC in terms of mean absolute error (MAE) between cuttings TOC data (from USGS Core Library files) and Δ Log R-derived TOC values in 6 wells.

As previously discussed, chemostratigraphic zones CN1, CN2, CN4, and CN6 are Ca-enriched and are associated with a relatively high quartz/clay ratio (with CN1, CN2, and CN4 being TOC poor). These zones can be interpreted to be relatively brittle. Chemostratigraphic zone CN5 (organic-rich) and CN3 have lower Ca and Si/Al values and higher Al values. These zones can be interpreted to be more ductile. These interpretations suggest that within the Niobrara Member, rocks occur as alternating brittle and ductile intervals. Brittle intervals are suggested to be better targets for horizontal wells, as they are considered better stimulated by artificial fracturing and appear to be occurring in stratigraphic proximity to organic-rich zones.

CONCLUSIONS

Elemental chemostratigraphy based on changes in major and trace elements and element ratios is used to subdivide the Niobrara Member of the Mancos Shale into six chemostratigraphic zones (CN1 to CN6). Chemostratigraphic correlations from nine wells show that four markers identified on the geochemical logs correspond to markers used for lithostratigraphic correlations, which highlights the potential of chemostratigraphy as an independent tool for stratigraphic correlations.

The geochemical data were also used to infer stratigraphic and lateral changes in the depositional environment of the Niobrara Member. Trace elements Mo, Cr, and V indicate that during deposition of the Niobrara Member, more anoxic conditions were present to the east of the study area and that lower oxygenation levels existed during deposition of the stratigraphically upper intervals. Elements Ti, Si, K, and Al show the occurrence of two to three pulses of increased terrestrial input from a source area to the northwest. The geochemical logs suggest that when terrestrial input was increasing, bottom-water conditions were at their least reducing.

Cross-plots of Si vs. Al show a positive relationship indicating that the quartz in the Niobrara Member is dominantly detrital in origin, whereas cross-plots of Si and Ca show that the Niobrara Member gradually moves away from its bimodal (clastic/carbonate) character identified in the eastern and central portions of the Western Interior Seaway.

Total Organic Carbon (TOC) calculated for 68 wells using a sonic-resistivity overlay analysis technique ($\Delta \text{Log R}$) and calibrated to measurements from available TOC data show that TOC varies laterally and stratigraphically throughout the study area. TOC values tend to be highest to the south and west of the study area and TOC profiles identify three organically-rich intervals within the Niobrara Member. The $\Delta \text{Log R}$ technique of Passey et al. (1990) shows reasonable results when compared to measured TOC data. Level of organic metamorphism (LOM) maps (from %Ro data conversions) show that the Niobrara Member is more thermally mature within the east-central parts of the basin, where LOM values are as high as 11 (corresponding to 1.2 %Ro).

Interpretations of relative changes in rock brittleness made using geochemical data coupled with TOC profiles show that the Niobrara Member is composed of alternating brittle and ductile rocks. Organic (TOC)- and clay-mineral rich intervals are considered mechanically ductile, while more Si/Al (quartz/clay) and Ca-enriched rocks are considered mechanically brittle.

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Appendix A

XRF Data Collection

Well API #	Well Name/No	County	Section/Township /Range	Latitude/Longitude	Operator	Top Niobrara MD (ft.)	Base Niobrara MD (ft.)	Depth XRF analyzed	Sampling interval
05045067230000	O'CONNELL #F11X-34P	Garfield	34 07S 092W	39.408002/-107.660352	MOBIL OIL	10361	11334	10390-11140 11140-11560	30 ft. 10 ft.
05077081060000	KATHLYN YOUNG #1-15	Mesa	15 10S 095W	39.186315/-107.984875	BLACK HILLS PLATEAU PRODUCTION	7752	8628	7800-9110	10 ft.
05045065100000	ARCO-DEEP #1-27	Garfield	27 06S 097W	39.492574/-108.20776	WPX ENERGY ROCKY MOUNTAIN	11816	12923	11740-12000 12000-13380	20 ft. 30 ft.
								5840-6480 6480-6510 6540-6950 6950-7730 6950-7730	30 ft. missing missing 10 ft. 10 ft.
05045060420000	ROAN CREEK #4-C-2	Garfield	02 06S 101W	39.561684/-108.624673	CHORNEY OIL	5793	7124		
05045051060000	BAXTER PASS UNIT #4-25	Garfield	25 05S 103W	39.590582/-108.912762	PAN AMERICAN PETROLEUM	4680	5745	4700-6400	10 ft.
05103083570000	BARCUS CREEK FEDERAL #22-12	Rio Blanco	12 01N 099W	40.071148/-108.455023	NATURAL GAS CORP OF CALIFORNIA	13360	14875	13330-15350	10 ft.
05103652610000	DOUGLAS A #16	Rio Blanco	19 01S 101W	39.945618/-108.770711	PHILLIPS PETROLEUM	3256	4879	3310-5180 5180-5200 5200-5380	30 ft. 20 ft. 10 ft.
05103085970000	WHT FACE BT FED #12	Rio Blanco	31 03S 103W	39.74594/-109.00404	FOUNDATION ENERGY MANAGEMENT	4709	6169	4730-6500 6500-6600	30 ft. 10 ft.
05103076190000	DEEP WHITE RIVER DOME #1	Rio Blanco	13 02N 097W	40.143029/-108.233087	ENCANA OIL & GAS (USA)	11203	12801	11280-12910	10 ft.

Table A-1. Investigated depths and sampling interval for XRF analyzed cuttings used in this study.

Figure A-1. Thermo Scientific Niton® XL3t Series 950 XRF device and sample cups used in this study.

Measurement modes

Elements detected in both “mining” and “soils” modes: As, Ca, Cr, Cu, Fe, K, Rb, S, Sr, Ti, and Zn.

Elements only detected in “mining” mode (wt.%): Al, P, Si, and Zr.

Elements only detected in “soils” mode (ppm): Ba, Mn, Mo, Sc, Te, Th, and V.

Elements (generally) below quantification limit: Ag, Au, Bi, Cd, Cl, Co, Hg, Mg, Nb, Ni, Pb, Pd, Sb, Se, Sn, U, and W.

Elements with measurement error >20%: Ag, As, Cd, Cu, Mg, Pb, Pd, Sc, Se, Sn, and Th.

Precision and repeatability of data

Comparison of the Thermo Scientific® XL3 Series analyzer with laboratory analyses (obtained by ICP-MS) on 160 sedimentary rock samples resulted in correlations (R^2) > 0.90 and repeatability < 5 % relative standard deviation for major, minor, and trace elements from Mg to U. Counting times of 30 seconds on low, main, and high energy filters, and 60 seconds on the light filter. “Studies of solid cores and cuttings provide results within 5 to 20 % of this data quality”.

[Thermo Scientific, 2010, Upstream Exploration and Production with the Thermo Scientific Niton XL3t 900 GOLDD Series XRF Analyzer,
http://www.niton.com/docs/literature/Upstream_Exploration_Production_with_the_Thermo_Scientific_Niton_XL3t_900_GOLDD.pdf?sfvrsn=2, (accessed May 25, 2013)]

Appendix B
TOC and Δ Log R

Method	Description	Reference
Spectral GR - Uranium Enrichment	Linear relationship of Uranium (ppm) to Organic Carbon content for Appalachian Devonian black shales	Fertl and Rieke 1980, Fertl and Chilinger 1988, Guidry and Walsh 1993, GRI 950496
GR Intensity	Derivation of TOC volume from total GR intensity	Fertl and Chilinger 1988
Bulk Density	Empirical relationship of Bulk Density to TOC weight %	Schmoker 1979, Schmoker and Hester 1983
Gamma Ray Intensity - Formation Density	Derivation of TOC volume from the relationship of GR intensity and formation density in a Devonian black shale of the Appalachian basin	Schmoker 1981
Delta Log R	Scaled porosity log - resistivity overlay method	Passey et al. 1990
Neural Networks	Usage of conventional well logs to predict TOC	Rezaee et al. 2007
Pulsed Neutron - Spectral GR	Pulsed-neutron mineralogy and Spectral Gamma Ray methodology used to discriminate excess carbon	Pemper et al. 2009

Table B-1. Summary of geophysical methods to determine Total Organic Carbon from well logs. Adapted from Sondergeld et al. (2010).

Table B-2. List of wells, associated well-logs, baseline depths, and differential transit time (Δt) and Resistivity (R) values at baseline condition used for TOC calculations using the Delta Log R technique.

County	API#	Well Name/No	Section/Township/ Range	Baseline Depth	$\Delta t_{\text{baseline}}$	R _{baseline}	Logs used for TOC calculation
Garfield	0504505106	BAXTER PASS SOUTH UNIT- G #4-25	25 5S 103W	3500	78.241	9.882	DT, ILD
Garfield	0504505108	GOVERNMENT BUTTRAM #1	30 5S 102W	2500	82.117	7.587	DT, ILD
Garfield	0504505112	SOUTH BAXTER PASS UNIT #2-20	20 5S 102W	2900	97.101	4.583	DT, ILD
Garfield	0504506009	NORTH RIFLE UNIT #1	31 4S 93W	11000	69.237	7.519	DT, SN
Garfield	0504506212	GENTRY 6-5-103 #1	6 5S 103W	3500	74.587	16.837	DT, ILD
Garfield	0504506286	BEAR GULCH #26-2	26 5S 101W	6000.5	77.884	10.201	DT, ILD
Garfield	0504506294	Twin Buttes #7101	23 5S 102W	4000	80.228	8.191	DT, ILD
Garfield	0504506510	ARCO DEEP #1-27	27 6S 97W	10000	65.578	11.875	DT, ILD
Garfield	0504506572	Cedar Bench Federal #6307	28 6S 100W	5000	84.723	6.598	DT, ILD
Garfield	0504506688	Cedar Bench Federal #6305	17 6S 100W	5000.092	75.999	9.011	DT, ILD
Garfield	0504506723	O'CONNELL #F11X-34P	34 7S 92W	9500	72.142	9.885	DT, ILD
Garfield	0504506728	NARCO FEDERAL	1 6S 100W	6000	77.292	8.156	DT, ILD
Garfield	0504506752	FEDERAL	17 6S 100W	5000	78.061	7.226	DT, ILD
Garfield	0504506759	CEDAR BENCH UNIT #6308	15 6S 100W	6500	85.385	6.333	DT, ILD
Garfield	0504506776	DESERT STORM UNIT #1	34 7S 98W	6500	76.233	10.289	DT, IDPH
Garfield	0504506913	Standard Shale #6401	9 7S 99W	6000.303	74.228	9.458	DT, AF90
Garfield	0504506914	STANDARD SHALE #6402	11 7S 99W	6500.098	82.314	5.463	DT, AF90
Mesa	0507708901	ORCHARD UNIT #17-13DT (M170U)	17 8S 96W	7500	76.568	7.694	DT, ILD
Moffat	0508106090	LYNCH CREEK-GOV #1	16 3N 90W	2500.5	81.713	10.284	DT, ILD
Rio Blanco	0510305835	BRADSHAW (GOV) #1	8 2N 93W	5000	81.708	7.95	DT, ILD
Rio Blanco	0510305920	DAVID R SEELY G #1	23 3N 90W	1500	87.329	10.011	DT, ILD
Rio Blanco	0510306377	ERVING WOLF GOV #1-A	27 1N 102W	4000	100.049	7.088	DT, ILD
Rio Blanco	0510306432	WILSON CREEK UNIT #50	19 3N 94W	4500	88.831	6.603	DT, SN
Rio Blanco	0510307261	DOUGLAS PASS UNIT ##1 (33-10)	10 1S 101W	4000.043	83.236	7.161	DT, ILD
Rio Blanco	0510307265	WILSON CREEK UNIT #53	23 3N 94W	4000	96.958	6.331	DT, SN
Rio Blanco	0510307432	EAST RANGELY #1-14	14 1N 100W	7000	81.044	6.508	DT, ILD
Rio Blanco	0510307619	DEEP WHITE RIVER DOME #1	13 2N 97W	10500.055	67.113	6.15	DT, ILD
Rio Blanco	0510307859	TAIGA-GREAT BASINS #1-17	17 4S 103W	3000	73.157	12.691	DT, ILD
Rio Blanco	0510308197	COLOROW-GULCH FEDERAL #15-29	29 3N 97W	6500	84.981	6.126	DT, ILD

County	API#	Well Name/No	Section/Township/ Range	Baseline Depth	Δtbaseline	Rbaseline	Logs used for TOC calculation
Rio Blanco	0510308212	SOLDIER CANYON #30-3	30 4S 100W	6000.141	74.14	10.537	DT, ILD
Rio Blanco	0510308452	THUNDER FED #13-9-4-102	9 4S 102W	3000	81.996	9.149	DT, ILD
Rio Blanco	0510308461	FEDERAL #9-25-1-2	25 1S 102W	2900	86.457	7.993	DT, ILD
Rio Blanco	0510308603	ROCK CANYON FED #2-34-4-101	34 4S 101W	4000	75.318	11.559	DT, ILD
Rio Blanco	0510308678	WHITE FACE BT FED #1-23-3-104	23 3S 104W	4500	73.63	14.283	DT, ILD
Rio Blanco	0510308824	FEDERAL #7-12-4-104	12 4S 104W	3500	74.349	16.092	DT, RD
Rio Blanco	0510308825	COLUMBINE SP #8-11-4-104 WD	11 4S 104W	3500	74.08	14.892	DT, LLD
Rio Blanco	0510308891	FEDERAL #6-23-4-104	23 4S 104W	4500	78.342	14.186	DT, LLD
Rio Blanco	0510308920	FEDERAL #6-22	22 1N 103W	4000	80.345	8.56	DT, LLD
Rio Blanco	0510308951	PMF #9007	14 3S 104W	5000	76.309	13.293	DT, LLD
Rio Blanco	0510308967	FEDERAL #12-19-1N-102	19 1N 102W	4000	83.371	8.516	DT, LLD
Rio Blanco	0510308982	TAIGA MTN #6-14-1-103	14 1N 103W	5000	80.604	10.954	DT, LLD
Rio Blanco	0510308998	MOORE #2-12MH	12 1N 93W	2000	86.699	11.742	DT, LLD
Rio Blanco	0510309022	COSEKA #3-20-IN-103	20 1N 103W	5500	82.553	7.797	DT, LLD
Rio Blanco	0510309073	FEE #10-1-1S-104	1 1S 104W	6000	84.461	6.319	DT, LLD
Rio Blanco	0510309092	SOLDIER CANYON #25-4	25 4S 101W	4500	79.679	10.444	DT, LLD
Rio Blanco	0510309093	SOLDIER CANYON #26-4	26 4S 101W	3000	83.307	10.023	DT, LLD
Rio Blanco	0510309098	SOLDIER CANYON #35-1	35 4S 101W	3000	81.566	8.203	DT, ILD
Rio Blanco	0510309164	PMF #9003	2 3S 104W	5000	72	12.677	DT, ILD
Rio Blanco	0510309167	HH #9119	1 2S 104W	3000	77.9	11.967	DT, ILD
Rio Blanco	0510309170	P M FEDERAL #1-26-2-104	26 2S 104W	5000	73.204	14.07	DT, ILD
Rio Blanco	0510309192	HH #9102	36 1S 104W	3500.019	78.356	10.715	DT, ILD
Rio Blanco	0510309259	RABBIT MOUNTAIN #6-1	6 2S 103W	4000	77.026	9.8	DT, ILD
Rio Blanco	0510309262	FOURMILE FEDERAL #1-28	28 1S 101W	3000.146	82.079	10.448	DT, LLD
Rio Blanco	0510309267	H H FEDERAL #2-31-1-103	31 1S 103W	5000	85.172	5.599	DT, RILD
Rio Blanco	0510309270	PMF #9008	1 3S 104W	4000	75.7	13.143	DT, ILD
Rio Blanco	0510309279	HH #9114	31 1S 103W	5000.091	84.096	6.779	DT, ILD
Rio Blanco	0510309294	HH #9113	14 2S 104W	4000	77.1	12.218	DT, ILD
Rio Blanco	0510309331	RM #9109	7 2S 103W	5000	78.9	9.27	DT, ILD
Rio Blanco	0510309385	HH #9105	1 2S 104W	4000	76.256	8.72	DT, ILD
Rio Blanco	0510309462	PARK MOUNTAIN #9015	12 3S 104W	4500	84.417	8.613	DT, ILD
Rio Blanco	0510309623	HH #9107	11 2S 104W	3500	78.2	11.739	DT, AF90
Rio Blanco	0510309624	HH #9111	14 2S 104W	4000	73.088	10.308	DT, ILD
Rio Blanco	0510309625	PMF #9009	1 3S 104W	5000	80.2	10.819	DT, AF90

County	API#	Well Name/No	Section/Township/ Range	Baseline Depth	Δ tbaseline	Rbaseline	Logs used for TOC calculation
Rio Blanco	0510309694	PMF #9004	36 2S 104W	6000	73.3	11.233	DT, ILD
Rio Blanco	0510309775	PMF #9011	5 3S 103W	6000.14	80.016	8.141	DT, AHT90
Rio Blanco	0510309844	PMF #9016	18 3S 103W	4500	81.241	9.601	DT, AT90
Rio Blanco	0510309927	LOWER HORSE DRAW UNIT #2246	29 2S 103W	4500	83.149	7.599	DTCO, AHT90
Rio Blanco	0510309942	LOWER HORSE DRAW #2186	26 2S 103W	3150	79.48	10.404	DTCO, AHT90
Rio Blanco	0510310250	SE RANGELY #1000	33 1N 101W	3500	87.942	6.236	DTCO, AT90
Rio Blanco	0510365261	DOUGLAS A #16	19 1S 101W	3000	82.036	7.789	DT, ILD

Well Log Acronyms:

AF90, AHT90, AT90: Deep Resistivity Logs
 DT: Differential Transit Time Log
 IDPH: Deep Induction Phasor Resistivity Log
 ILD: Deep Induction Resistivity Log
 LLD: Laterlog Deep Resistivity
 RD: Deep Resistivity Log
 SN: Short Normal Resistivity Log

Table B-3. Compiled list of LOM values for wells used for TOC calculation using the Delta Log R technique. Columns 4 and 5 are respectively %Ro data (from USGS CRC data files) averaged over the Niobrara interval and the corresponding conversion to LOM using LeCompte and Hursan's formula (2010). The average %Ro values are assumed constant over the complete Niobrara Member interval. Column 6 contains assigned LOM values for wells for which no data on maturity level were available.

Well API#	Well Name/No	CRC Library Number	Average %Ro	Average LOM	Sampled LOM value
05029060550000	SELL ET AL #1	DZ 18458		10.45	
05045051060000	BAXTER PASS SOUTH UNIT-G #4-25	DZ 13065		7.66	
05045051080000	GOVERNMENT BUTTRAM #1				8.85
05045051120000	SOUTH BAXTER PASS UNIT #2-20	DC 01320		8.92	
05045060090000	NORTH RIFLE UNIT #1				10.6
05045062120000	GENTRY 6-5-103 #1				8.32
05045062860000	BEAR GULCH #26-2				9.34
05045062940000	Twin Buttes #7101				9.1
05045063470000	TATE FEDERAL #6212	DZ 18762		8.39	
05045065100000	ARCO DEEP #1-27				9.36
05045065720000	Cedar Bench Federal #6307				8.51
05045066880000	Cedar Bench Federal #6305				8.69
05045067230000	O'CONNELL #F11X-34P				10.02
05045067280000	CEDAR BENCH UNIT #6308				8.89
05045067520000	FEDERAL #22-17				8.76
05045067590000	CEDAR BENCH UNIT #6308				8.84
05045067760000	DESERT STORM UNIT #1				8.59
05045069130000	Standard Shale #6401				8.32
05045069140000	STANDARD SHALE #6402				8.43
05077051230000	DIVIDE CREEK UNIT #1	DZ 03996		9.61	
05077080420000	MORAN #27-2	DZ15803		9.44	
05077081060000	KATHLYN YOUNG #1-15	DZ 16640		10.16	
05077089010000	ORCHARD UNIT #17-13DT (M17OU)				9.32
05081060900000	LYNCH CREEK-GOV #1	DZ 13987		8	
05103058350000	BRADSHAW (GOV) #1				9.87
05103059200000	DAVID R SEELY G #1				7.78
05103063770000	ERVING WOLF GOV #1-A				6.6
05103064320000	WILSON CREEK UNIT #50				10.04
05103072610000	DOUGLAS PASS UNIT ##1 (33-10)				8.18

Well API#	Well Name/No	CRC Library Number	Average %Ro	Average LOM	Sampled LOM value
05103072650000	WILSON CREEK UNIT #53				9.92
05103074320000	EAST RANGELY #1-14				9.08
05103076190000	DEEP WHITE RIVER DOME #1				10.2
05103076390000	MORAN #27-2 (PL27SW)	DZ 15984		8.78	
05103078590000	TAIGA-GREAT BASINS #1-17				7.87
05103080960000	FEDERAL 1-30 #1	DZ 16747		9.38	
05103081290000	FEDERAL MILK CREEK #21-28	DZ 16910		8.76	
05103081830000	CORRAL CREEK #4512	DZ 17290		10.45	
05103081970000	COLOROW-GULCH FEDERAL #15-29				9.67
05103082120000	SOLDIER CANYON #30-3				9.68
05103084520000	THUNDER FED #13-9-4-102				8.63
05103084610000	FEDERAL #9-25-1-2	DZ 17517		7.38	
05103085680000	ROCK CANYON FED #9-34-4-101	DZ 17850		10.63	
05103085970000	WHT FACE BT FED #12-31-3S-103	DZ 18106		7.42	
05103086030000	ROCK CANYON FED #2-34-4-101				9.47
05103086780000	WHITE FACE BT FED #1-23-3-104				6.65
05103088070000	THEOS & SON #1	DZ 18531		9.29	
05103088240000	FEDERAL #7-12-4-104				7.32
05103088250000	COLUMBINE SP #8-11-4-104 WD				7.22
05103088610000	MOORE #1-12 MH	DZ 18726		10.41	
05103088910000	FEDERAL #6-23-4-104				7.46
05103089200000	FEDERAL #6-22				5.44
05103089510000	PMF #9007				6.22
05103089670000	FEDERAL #12-19-1N-102				5.7
05103089820000	TAIGA MTN #6-14-1-103				5.25
05103089980000	MOORE #2-12MH				10.25
05103090220000	COSEKA #3-20-IN-103				4.69
05103090730000	FEE #10-1-1S-104				4.49
05103090920000	SOLDIER CANYON #25-4				9.63

Well API#	Well Name/No	CRC Library Number	Average %Ro	Average LOM	Sampled LOM value
05103090930000	SOLDIER CANYON #26-4				9.55
05103090980000	SOLDIER CANYON #35-1				9.52
05103091640000	PMF #9003				5.83
05103091670000	HH #9119				4.94
05103091700000	P M FEDERAL #1-26-2-104				5.48
05103091920000	HH #9102				4.92
05103092590000	RABBIT MOUNTAIN #6-1				5.18
05103092600000	CONOCO FEDERAL 36 #3	DZ 20573		6.62	
05103092620000	FOURMILE FEDERAL #1-28				8.08
05103092670000	H H FEDERAL #2-31-1-103				5.11
05103092700000	PMF #9008				6.04
05103092790000	HH #9114				5.11
05103092940000	HH #9113				5.04
05103093310000	RM #9109				5.17
05103093850000	HH #9105				4.98
05103094620000	PARK MOUNTAIN #9015				6.13
05103096230000	HH #9107				4.85
05103096240000	HH #9111				4.97
05103096250000	PMF #9009				6.04
05103096940000	PMF #9004				5.92
05103097750000	PMF #9011				6.18
05103098440000	PMF #9016				6.67
05103099270000	LOWER HORSE DRAW UNIT #2246				6.29
05103099420000	LOWER HORSE DRAW #2186				6.39
05103102500000	SE RANGELY #1000				7.51
05103652610000	DOUGLAS A #16				7.55

Table B-4. API numbers of wells with TOC data from the Niobrara Member available on the USGS Core Research Center website.

[<http://geology.cr.usgs.gov/crc/>]

API#	Well Name/No	Section/Township/Range	CRC Library #	TOC Data Depth Interval (ft.)
5029060550000	SELL ET AL 1	SESE 14 13S 91W	DZ18458	3085-4335
5045051060000	BAXTER PASS SOUTH UNIT- G 4-25	SWSW 25 5S 103W	DZ13065	2450-6765
5045051120000	SOUTH BAXTER PASS UNIT 2-20	NWSW 20 5S 102W	DC01320	4450-6710
5045060380000	FEDERAL-MAGNUSON 11-16	NESW 16 7S 103W	DZ15541	1408.5-4115
5045063470000	TATE FEDERAL 6212	NENE 30 6S 99W	DZ18762	1405-8785
5045065100000	ARCO DEEP 1-27	NESW 27 6S 97W	DZ20838	9280-13630
5077051230000	DIVIDE CREEK UNIT 1 (1U)	SWNW 36 8S 91W	DZ03996	10245-11245
5077080420000	MORAN 27-2	NWSW 27 10S 96W	DZ15803	3230-7560
5077081060000	KATHLYN YOUNG 1-15	NWSW 15 10S 95W	DZ16640	4250-9150
5077083450000	MCDANIEL 1-11	NWSE 11 9S 94W	DZ16222	10850-12450
5081060900000	LYNCH CREEK-GOV 1	SWSW 16 3N 90W	DZ13987	4045-4865
5097050050000	UNIT (MILLER) 1	NWNW 9 10S 89W	DZ01617	1950-3750
5103070900000	FEDERAL 1 (14-15)	SWSW 15 1N 103W	DZ04462	3420-7800
5103076390000	SOLDIER CANYON 26-1	SENE 26 4S 101W	DZ15984	965-5970
5103080960000	FEDERAL 1-30 1	NENE 30 3N 97W	DZ20838	9280-13630
5103081290000	FEDERAL MILK CREEK 21-28	NENW 28 3N 92W	DZ16910	1180-6620
5103081830000	CORRAL CREEK 4512	NENE 36 1S 100W	DZ17290	8680-11570
5103084610000	FEDERAL 9-25-1-2	NESE 25 1S 102W	DZ17517	3985-5455
5103085680000	ROCK CANYON FED 9	SENE 34 4S 101W	DZ17850	4315-6250
5103088070000	THEOS & SON 1	SESE 8 1N 92W	DZ18531	900-3350
5103088610000	MOORE 1-12 MH	NWNW 12 1N 93W	DZ18531	1290-4200
5103088820000	ARCO FED 4-	SWSW 33 4S 103W	DD19204	1100-2450
5103089200000	FEDERAL 6-22	NESW 22 1N 103W	DZ18975	4377-7565
5103092600000	CONOCO FEDERAL 36 3	NENE 36 2S 103W	DZ20573	1720-4680
5103104090000	BANTA RIDGE FED 12A-18-1-103	SWNW 18 1S 103W	DZ18106	1595-6535
5103664230000	U S A-PICEANCE CREEK 52-19G	NWNE 19 2S 96W	DZ13902	15500-17318

Assigning LOM values

LOM sampled values were assigned (for wells with no available maturity data) using the “Sample Grid to Wells” in the map module in IHS Petra. First, a grid is created using LOM values from %Ro conversions (with a grid size estimated from the well data, and “no trend-residual surface” assigned). Next, LOM values are sampled from the created grid using a minimum-curvature style. This surface style is used to create contour lines that are smooth and evenly spaced. This method was selected because it assumes gently changing petrophysical properties within simple structural settings. A drawback to this method of contouring is its tendency to smooth over some of the variations in data points.

Figure B-1. A- LeCompte and Hursan's (2010) formula to convert LOM to %Ro.
 B- Re-arranged LeCompte and Hursan's formula to solve for LOM using %Ro.
 From Cardneaux (2012).

Figure B-2. As detailed in Passey et al. (1990), the $\Delta \log R$ technique can yield high anomalous TOC values. In order to properly apply this method, only “real” TOC within a source rock interval should be accounted for. Organic content within the studied section is expected to cause a separation resulting from an increase in both the porosity and resistivity values. To qualitatively eliminate what is suggested to be “anomalous” TOC from the TOC curve, a DT/ILD cross-plot for each well was constructed. By choosing a lower TOC cutoff of 1, and determining the area of high TOC values, four quadrants in each cross-plot are identified. Quadrant 1 (high ILD values, low DT values), 3 (high DT values, low ILD values), and 4 (low DT and ILD values) contain data points that are suggested not to cause the proper $\Delta \log R$ separation, and are therefore removed from the analysis by setting lower values of ILD ($=10$ ohm.m) and DT ($=80$ μ s/ft). TOC flags are used to identify intervals based on these selected cutoffs, and only those intervals that have ILD and DT values higher than the cutoff values are considered to yield “real” TOC values. The remaining intervals are considered to only have a “background” TOC of 1 wt.% (Connolly, pers. comm., 2013).

Appendix C

Lithostratigraphic Units

Appendix C contains detailed descriptions (based on well-log signatures) for each lithostratigraphic unit of the Niobrara Member (Niobrara 1 to Niobrara 8), as well as isopach maps for each unit.

Detailed Descriptions of the eight lithostratigraphic units (Niobrara 1 to Niobrara 8)

Niobrara 1 is characterized by high gamma-ray values at the base that generally increase upward. Lower gamma-ray values that slightly increase upward are recorded in the upper half of this interval although some exceptions are noted locally (in the southeast, north, and northeast portions of the basin). Resistivity values over much of the basin show an upward increase reaching a local resistivity maximum in some areas. Lithologically, this interval is interpreted to have an overall higher shale content than the underlying intervals (higher gamma-ray values recorded). The top of this interval is defined as a sharp increase on the gamma-ray signature.

Niobrara 2 exhibits a laterally consistent upward-decreasing gamma-ray-log signature trend across the basin. In general, higher resistivity values are recorded at the base of this interval. The dominant lithology is interpreted to be calcareous to very calcareous shale (by comparison to regional work; Vincelette and Foster, 1992; Rogers, 2012). The top of this interval is marked by a subtle decrease in gamma-ray values (Rogers, 2012).

Niobrara 3 also shows an upward-decreasing gamma-ray and resistivity trends. Within this interval, the gamma-ray curve appears to closely track the resistivity curve, with higher gamma-ray values corresponding to higher resistivity values. The overall log-signature trend is not well retained across portions of the basin. The dominant lithology is calcareous sandstone (low gamma-ray values) with interlaminar shale (higher gamma-ray values) (by comparison to regional work; Vincelette and Foster, 1992; Rogers, 2012) overlying carbonaceous to non-calcareous shale. The top of this interval is identified by relatively low values on the gamma-ray curve that are more subtle to the south and southeast portions of the basin.

Niobrara 4 is characterized by slightly-increasing gamma-ray values and overall higher resistivity values at the base of this interval. The log character in this interval is not well retained in the north and northeast portions of the basin. The top of this unit marks the transition from overall lower (Niobrara 1 to Niobrara 6) to higher gamma-ray values (Niobrara 7 to Niobrara 10) suggesting a shift to higher organic-shale content.

Niobrara 5 is characterized by high overall gamma-ray values that slightly increase upward. Within portions of the basin, high gamma-ray values are recorded at the base of this interval. Resistivity values do not show laterally-consistent trends, although overall, higher values are recorded within the lower half of this interval. Lithologically, this interval is considered limestone-rich facies overlain by calcareous shale (Rogers, 2012). The top of this interval is defined as the uppermost low gamma-ray value.

Niobrara 6 starts with a low gamma-ray value marker that is laterally consistent throughout the study area. Gamma-ray values are generally uniform, although lower values in the upper third of this interval are recorded locally. The dominant lithology is considered to be calcareous to very calcareous shale (by comparison to regional work; Vincelette and Forster, 1992; Rogers, 2012). The top of this interval is defined at the shift to higher gamma-ray values.

Niobrara 7 is characterized by low gamma-ray values that increase upwards. Where this interval is thickest to the northwest, gamma-ray curves first show a decrease followed by an increase in values. This interval is interpreted to be dominantly calcareous to non-calcareous shale (by comparison to regional work; Vincelette and Foster; Rogers, 2012). The top of this interval is a very distinctive high gamma-ray horizon (“Niobrara Hot Shale”) marker, which is considered to be a regionally correlative marker (Rogers, 2012).

Niobrara 8 is characterized by upward-decreasing gamma-ray values with typically high resistivity values at the base. The dominant lithology is interpreted to be organic-rich shale. The top of this interval (top of Niobrara Member) is picked at a highly-resistive marker which is interpreted to correspond to the top of the calcareous lithology (also noted on PE curve) (Haskett, 1959; Vincelette and Foster, 1992; Finn and Johnson, 2005; Rogers, 2012).

Isopach map of lithostratigraphic unit Niobrara 1.

Isopach map of lithostratigraphic unit Niobrara 2.

Isopach map of lithostratigraphic unit Niobrara 3.

Isopach map of lithostratigraphic unit Niobrara 4.

Isopach map of lithostratigraphic unit Niobrara 6.

Isopach map of lithostratigraphic unit Niobrara 7.

Isopach map of lithostratigraphic unit Niobrara 8.

Appendix D

Geochemical Profiles

Appendix D contains geochemical profiles of chemostratigraphical index elements (Ca, Si, Si/Al, Al, Fe, K/Al, Mo, Cr+V, Ti, and Zr) for 8 wells.

Appendix E

Element and Element Ratio Maps

Appendix E contains average element maps (Cr+V, Si, Ti+K) and element ratio (K/Al) maps for the six chemostratigraphic zones of the Niobrara Member.

Average Cr+V (ppm) maps for the six chemostratigraphic zones of the Niobrara Member. Overall, Cr+V values increase to the east of the Piceance Basin.

Average Si (wt.%) maps for the six chemostratigraphic zones of the Niobrara Member. Overall, Si values increase to the northwest of the Piceance Basin.

Average Ti+K (ppm) maps for the six chemostratigraphic zones of the Niobrara Member. Overall, Ti+K values increase to the northwest of the Piceance Basin.

Average K/Al maps for the six chemostratigraphic zones of the Niobrara Member. Overall, K/Al values increase to the northwest of the Piceance Basin.

Appendix F

Element Cross-Plots

Appendix F contains element cross plots (Fe vs. Al, Si vs. Zr, Ti vs. Al, and V vs. Al) constructed for all nine wells.

- ◆ Arco Deep 1-27
 ◆ Kathlyn Young #1-15
 ◆ O'Connell #F11X-34P
- ◆ White Face Bt Fed 12-31-35 #103
 ◆ Baxter Pass South Unit-G #4-25
 ◆ Roan Creek #4-C-2
- ◆ Deep White River Dome #1
 ◆ Barcus Creek Federal #22-12
 ◆ Douglas A #16

- Arco Deep 1-27
 Kathlyn Young #1-15
 O'Connell #F11X-34P
- White Face Bt Fed 12-31-3S #103
 Baxter Pass South Unit-G #4-25
 Roan Creek #4-C-2
- Deep White River Dome #1
 Barcus Creek Federal #22-12
 Douglas A #16

- ◆ Arco Deep 1-27
 ◆ Kathlyn Young #1-15
 ◆ O'Connell #F11X-34P
- ◆ White Face Bt Fed 12-31-3S #103
 ◆ Baxter Pass South Unit-G #4-25
 ◆ Roan Creek #4-C-2
- ◆ Deep White River Dome #1
 ◆ Barcus Creek Federal #22-12
 ◆ Douglas A #16

- ◇ Arco Deep 1-27
- ◇ Kathlyn Young #1-15
- ◇ O'Connell #F11X-34P
- ◇ White Face Bt Fed 12-31-3S #103
- ◇ Baxter Pass South Unit-G #4-25
- ◇ Roan Creek #4-C-2
- ◇ Deep White River Dome #1
- ◇ Barcus Creek Federal #22-12
- ◇ Douglas A #16

Appendix G

TOC Statistics

Table G-1. Statistical data (Mean, Minimum, Maximum, and Standard Deviation) of TOC values for the six chemostratigraphic zones of the Niobrara Member (CN1 to CN6) of 68 wells for which $\Delta \text{Log R} - \text{TOC}$ was calculated. All values are in wt.% TOC. The minimum value is set to the baseline value of 1 wt.%. Geographic location for all wells in Appendix B, Table B-2.

API#	CN1				CN2				CN3				CN4				CN5				CN6			
	Mean	Min	Max	Std	Mean	Min	Max	Std	Mean	Min	Max	Std	Mean	Min	Max	Std	Mean	Min	Max	Std	Mean	Min	Max	Std
05045051060000	1.03	1	4.38	0.25	1.55	1	4.1	0.95	1	1	1	0	1.05	1	2.06	0.19	1.25	1	4.73	0.73	1.04	1	1.77	0.15
05045051080000	1.01	1	2.82	0.11	1.21	1	3.39	0.49	1	1	1.59	0.04	1.12	1	2.58	0.31	1.26	1	2.71	0.45	1.55	1	2.81	0.58
05045051120000	1.1	1	2.78	0.35	1.24	1	2.92	0.42	1.03	1	1.68	0.11	1.56	1	2.88	0.45	1.6	1	2.42	0.54	1.49	1	2.49	0.53
05045062120000	1	1	1.65	0.04	1	1	2.63	0.18	1	1	1	0	1	1	1	0.23	0.8	1	1.42	0.31	0.83	1	1	0.29
05045062860000	1.08	1	3.37	0.42	1.31	1	4.62	0.79	1.08	1	2.45	0.26	1.01	1	1.65	0.08	1.24	1	2.22	0.38	1.26	1	2.37	0.39
05045062940000	1	1	1	0	1	1	1	1	0	1	1	0	1	1	1	0	1	1	1	1	0	1	1	0
05045065100000	1.04	1	5.15	0.38	1.71	1	5.6	1.46	1	1	1	0	1.11	1	5.15	0.6	1.5	1	6.17	1.25	1.97	1	6.03	1.44
05045065720000	1.04	1	6.28	0.4	1.52	1	5.79	1.19	1.17	1	5.48	0.75	1.21	1	3.7	0.53	1.73	1	6.31	1.23	2.34	1	7.31	1.86
05045066880000	3.54	1	13.22	3.79	1.23	1	5.57	0.76	1.01	1	2.99	0.14	1.06	1	4.25	0.42	1.1	1	3.55	0.43	1.79	1	6.64	1.36
05045067230000	1.02	1	2.88	0.19	3.27	1	7.56	2.57	1.14	1	4.11	0.57	1.06	1	3.81	0.35	1.96	1	4.19	1.08	1.66	1	4.65	0.88
05045067280000	1.15	1	3.66	0.48	1.28	1	3.48	0.62	1	1	1	0	1.4	1	3.58	0.71	2.02	1	3.88	1.02	2.33	1	6.64	1.15
05045067520000	1.02	1	2.93	0.16	1.88	1	5.29	1.44	1.1	1	4	0.44	1.23	1	4.61	0.68	1.14	1	4.26	0.55	1.55	1	4.58	0.98
05045067590000	1.03	1	3.36	0.25	1.13	1	3.17	0.44	1.04	1	3.14	0.21	1.11	1	4.91	0.55	1.15	1	3.26	0.47	2.03	1	5.49	1.33
05045067760000	1.04	1	3.53	0.27	2.11	1	9.72	1.74	1	1	1	0	1.21	1	3.94	0.68	1.54	1	3.67	0.85	2.98	1	8.54	1.6
05045069130000	1.14	1	4.83	0.62	1.82	1	8.12	1.8	1.13	1	7.14	0.68	1.18	1	4.8	0.74	1.59	1	6.22	0.99	2.28	1	5.75	1.59
05045069140000	1.21	1	5.06	0.74	1.77	1	6.01	1.57	1.04	1	3.92	0.32	1.18	1	4.66	0.73	1.8	1	5.72	1.35	4.57	1	11.26	2.46
05077089010000	1.1	1	5.12	0.56	1.19	1	2.82	0.5	1	1	1	0	1.1	1	3.11	0.4	1.38	1	3.14	0.63	2.37	1	4.77	1.14
05081060900000	1.03	1	3.72	0.2	1	1	1.34	0.05	1.09	1	1.9	0.2	1.27	1	2.31	0.39	2.33	1	5.07	0.53	1.32	1	8.05	0.7
05103058350000	1.27	1	2.93	0.55	1.37	1	3.58	0.55	1.3	1	2.41	0.42	2.02	1	3.33	0.63	1.93	1	2.62	0.27	1.15	1	2.08	0.27
05103059200000	1	1	2.05	0.17	0.98	1	1	0.12	1.01	1	1.87	0.23	1.24	1	2.14	0.38	2.04	1	2.8	0.26	1.35	1	2.61	0.46
05103063770000	1	1	1.53	0.23	1.04	1	3.14	0.36	1.03	1	2.38	0.25	1.67	1	2.53	0.38	1.35	1	2.57	0.5	1.09	1	2.41	0.28
05103064320000	1.01	1	2.08	0.35	1.57	1	5.56	0.65	1.85	1	2.85	0.53	2.67	1	3.78	0.28	2.22	1	2.65	0.16	1.44	1	3.76	0.54
05103072610000	1.01	1	2.9	0.13	1.13	1	2.79	0.37	1.06	1	2.33	0.24	1.51	1	3.29	0.61	1.48	1	2.57	0.54	1.29	1	3.21	0.56
05103072650000	1	1	1.32	0	0.89	1	2.18	0.45	1.39	1	2.23	0.47	1.98	1	3.16	0.36	1.59	1	2.12	0.2	1.02	1	2.46	0.31
05103074320000	1	1	2.33	0.05	1.37	1	6.69	0.91	1.06	1	3.93	0.35	1.02	1	2.6	0.15	1.18	1	4.7	0.56	1.21	1	3.57	0.54
05103076190000	1	1	2.99	0	1	1	1	1	0	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0
05103078590000	1.03	1	4.18	0.26	1.23	1	6.22	0.78	1.04	1	3.13	0.27	1.03	1	3.09	0.2	1.24	1	4.41	0.59	1.49	1	8.08	0.92
05103081970000	1.01	1	2.18	0.08	1.17	1	2.92	0.42	1.02	1	2.03	0.13	1.5	1	2.87	0.64	1.6	1	2.45	0.5	1.22	1	3.36	0.48
05103082120000	1.07	1	4.11	0.39	1.39	1	3.97	0.82	1	1	1	0	1.09	1	2.72	0.33	1.19	1	2.37	0.4	1.34	1	3.47	0.51
05103084520000	1.02	1	3.17	0.14	1.1	1	4.32	0.38	1	1	1.4	0.02	1.02	1	1.74	0.09	1.11	1	1.62	0.18	1.22	1	2.09	0.26
05103084610000	1	1	1.64	0.02	1.03	1	1.82	0.11	1.04	1	1.92	0.15	1.45	1	8.62	0.73	1.06	1	1.9	0.17	1.08	1	2.19	0.24
05103086030000	1.02	1	3.25	0.16	1.32	1	3.55	0.6	1.01	1	1.88	0.07	1	1	1	0	1	1	1	0	1	1	1	0

API#	CN1			CN2			CN3			CN4			CN5			CN6			Min	Max	Std			
	Mean	Min	Max	Std	Mean	Min	Max	Std	Mean	Min	Max	Std	Mean	Min	Max	Std	Mean	Min				Max	Std	
05103086780000	1.09	1	5.04	0.44	1.01	1	2.18	0.09	1	1	1	0	1	1	0	1.02	1	3.55	0.21	1.01	1	3.49	0.18	
05103088240000	1	1	4.17	0.53	1	1	1.86	0.39	1	1	3.01	0.6	1.06	1	2.5	0.38	1.07	1	2.5	0.32	1.29	1	3.08	0.33
05103088250000	1.04	1	3.64	0.32	1.02	1	2.77	0.17	1.03	1	3.06	0.22	1.01	1	1.97	0.07	1.08	1	2.84	0.29	1.14	1	3.5	0.4
05103088910000	1	1	1	0.13	1	1	2.76	0.26	1	1	2.64	0.16	1	1	1.59	0.06	1.08	1	1.94	0.19	1.06	1	1.97	0.15
05103089200000	1.04	1	2.53	0.21	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0
05103089510000	1.01	1	3.81	0.15	1	1	1.83	0.06	1	1	1	0	1	1	1.6	0.02	1.01	1	1.99	0.09	1.07	1	2.89	0.27
05103089670000	1.06	1	2.77	0.28	1.24	1	5.86	0.88	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0
05103089820000	1	1	1.58	0.03	1	1	1	0	1	1	1	0	1	1	1	0	1.07	1	3.61	0.37	1.19	1	5.6	0.59
05103089980000	0.96	1	1.26	0.12	1.39	1	2.06	0.28	1.04	1	1.61	0.22	1	1	2.01	0.21	0.94	1	1.28	0.08	1	1	1.22	0.07
05103090220000	1.46	1	8.63	1.5	1.95	1	8.13	1.77	1.23	1	6.8	0.79	1.21	1	4.69	0.76	1.23	1	5.17	0.84	1.84	1	7.02	1.41
05103090730000	1.02	1	3.3	0.19	1.04	1	3.84	0.32	1.07	1	6.05	0.5	1	1	1	0	1.1	1	3.61	0.48	1.54	1	18.23	1.62
05103090920000	1.06	1	3.6	0.31	1.34	1	4.34	0.75	1	1	1.09	0.01	1.03	1	2.45	0.16	1.21	1	3.13	0.54	1.4	1	5.38	0.88
05103090930000	1.12	1	3.46	0.45	2.18	1	4.72	1.05	1.34	1	2.37	0.38	1.82	1	5.1	0.94	2.02	1	3.11	0.76	1.6	1	3.18	0.69
05103090980000	1.14	1	10.58	1.05	1.53	1	8.34	1.07	1.01	1	1.73	0.07	1.04	1	2.15	0.19	1.55	1	3.53	0.87	1.25	1	2.94	0.49
05103091640000	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1.86	0.06
05103091670000	1	1	1	0	1	1	1.27	0.02	1	1	1.12	0.01	1	1	1.64	0.07	1	1	1	0	1	1	1.39	0.05
05103091700000	1.01	1	2.14	0.06	1	1	2.77	0.06	1.02	1	2.45	0.13	1.01	1	1.87	0.06	1.05	1	2.21	0.19	1	1	1.27	0.02
05103091920000	1	1	1	0	1	1	1.33	0.02	1.01	1	1.51	0.06	1	1	1.8	0.04	1	1	1.3	0.03	1	1	1.49	0.04
05103092620000	1.01	1	2.38	0.1	2.44	1	29.53	4.96	1.58	1	23.5	2.2	4.46	1	28.62	4.17	3.84	1	20.71	3.37	1.73	1	2.99	0.36
05103092670000	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1	0
05103092700000	1.05	1	5.04	0.29	1.01	1	3.63	0.16	1.04	1	2.47	0.19	1	1	1.44	0.02	1.01	1	1.59	0.07	1.01	1	1.89	0.1
05103092790000	1	1	1	0	1.02	1	2.71	0.19	1.02	1	2.26	0.15	1.05	1	2.46	0.23	1	1	2.03	0.07	1.06	1	2.69	0.28
05103092940000	1.03	1	5.46	0.28	1.04	1	2.99	0.21	1.05	1	2.41	0.2	1.07	1	3.63	0.34	1.16	1	4.32	0.48	1.02	1	2.15	0.12
05103093310000	1.05	1	38.44	1.42	1.02	1	3.53	0.19	1	1	1	0	1.03	1	2.61	0.19	1.02	1	2.12	0.12	1.07	1	2.62	0.26
05103093850000	1	1	1	0	1	1	2.96	0.09	1	1	2.6	0.08	1.01	1	2.89	0.15	1	1	1	0	1.04	1	2.83	0.25
05103094620000	1.01	1	4.46	0.15	1.08	1	4.27	0.32	1.02	1	2.65	0.15	1.01	1	2.84	0.11	1.03	1	1.98	0.13	1.03	1	2.19	0.13
05103096230000	1	1	1	0	1	1	2.03	0.04	1.01	1	1.84	0.08	1.02	1	2.17	0.13	1.01	1	1.52	0.05	1.02	1	1.59	0.09
05103096240000	1	1	1	0	1	1	2.88	0.09	1.21	1	4.68	0.72	1.02	1	2.69	0.15	1	1	1	0	1.01	1	2.62	0.1
05103096250000	1	1	1.43	0.02	1.03	1	2.97	0.23	1.12	1	3.49	0.45	1.23	1	3.28	0.41	1.29	1	2.73	0.41	1.31	1	3.28	0.48
05103096940000	1	1	1	0	1.01	1	2.89	0.12	1.02	1	2.83	0.18	1	1	1	0	1.04	1	2.83	0.22	1.01	1	2.46	0.13
05103097750000	1	1	4.6	0.65	1.62	1	7.79	0.91	2.39	1	4.98	0.97	2.89	1	7.02	0.89	2.94	1	4.36	0.42	2.97	1	5.75	0.66
05103098440000	1.54	1	7.64	1.36	1.78	1	7.15	1.31	1.59	1	8.75	1.6	5.23	1	13.17	2.12	6.78	1	10.36	0.95	4.2	1	8.44	1.3
05103099270000	1.02	1	4.1	0.21	1.04	1	4.7	0.3	1.02	1	3.4	0.18	1.26	1	4.34	0.73	1.2	1	4.44	0.58	1.35	1	4.84	0.85
05103099420000	1	1	1	0	1.01	1	3.28	0.13	1	1	1.56	0.03	1.09	1	4	0.34	1.03	1	2.14	0.15	1.08	1	3.15	0.34
05103102500000	1.02	1	3.45	0.18	1.07	1	3.24	0.32	1.04	1	2.36	0.2	1.49	1	2.85	0.58	1.22	1	2.55	0.45	1.21	1	3.76	0.56
05103652610000	1	1	1	0	1	1	2.29	0.07	1	1	1	0	1.09	1	8.61	0.64	1	1	1.88	0.05	1.03	1	2.53	0.17