North Dakota Geological Survey

Preliminary Examination of Source Beds within the Stonewall Formation (Ordovician-Silurian), Western North Dakota

By

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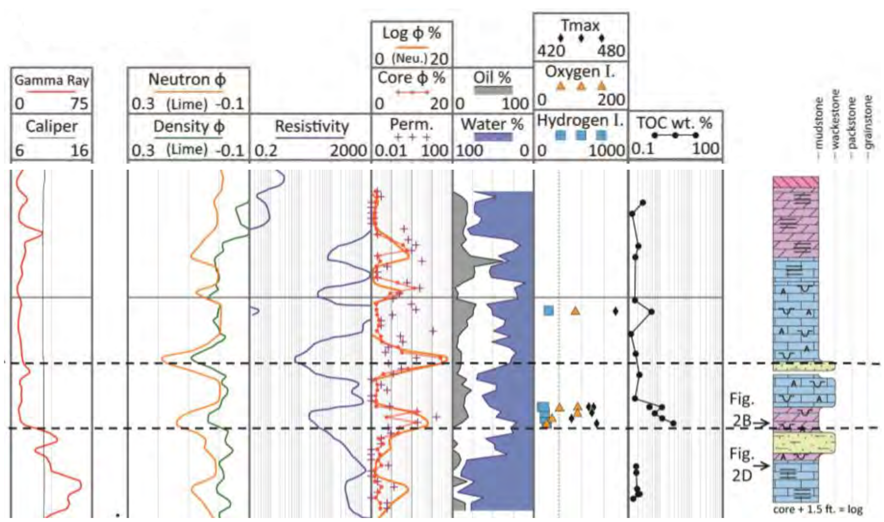

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Introduction

The Stonewall Formation is an Ordovician-Silurian carbonate interval that began commercially producing oil and gas within North Dakota in 1979. To date, 7.5 million barrels of oil and 17 billion cubic feet of gas have been cumulatively produced from 66 vertical Stonewall wells (Fig. 1) (Nesheim, 2014). While previous studies examined the Stonewall's stratigraphy, there have not been any published investigations related to the petroleum geology of the Stonewall Formation since the beginning of commercial hydrocarbon production in 1979 (Fuller, 1961; Carlson and Eastwood, 1962).

Geology

The Stonewall Formation extends beneath most of North Dakota and ranges from 0 to >120 ft. thick (Fig. 1). The Stonewall Formation consists of three carbonate-evaporite cycles deposited during the Late Ordovician through the Early Silurian within a shallow marine basin that was periodically restricted (Carlson and Eastwood, 1962; Haidl, 1991; Jin et al., 1999). The Stonewall Formation is both conformably underlain by the Ordovician Gunton Formation and overlain by the Silurian Interlake Formation. Each Stonewall cycle consists primarily of laminated to burrowed, lime/dolomite mudstone to fossil-peloidal wackestone (Fig. 2) overlain by interbedded anhydrite and dolomite mudstone (Plate 1). The anhydrite intervals extend continuously throughout the central, deeper portions of the Williston Basin and are not present towards the shallower, peripheral portions of the basin (Fuller, 1961). Each Stonewall cycle can be separated by thin, widespread, sandy argillaceous mudstone marker beds that display elevated gamma ray log responses (Fuller, 1961; Carlson and Eastwood, 1962; Kendall, 1976). Utilizing the argillaceous marker beds in combination with other geologic horizons, such as the anhydrite intervals, the Stonewall Formation can be informally divided into three members: upper, middle, and lower (Plate 1).

Methodology

Four partial to complete Stonewall Formation cores from western North Dakota were visually examined, sampled and analyzed to examine the quantity and quality of prospective source rock within the formation (Fig. 1, Table 1). 108 total samples were collected from the four cores. Each sample consisted of at least 1 to 2 grams. Three of the cores (#7612, #8073, and #9102) were systematically sampled approximately every two to four ft. in order to examine the organic content of all observed lithology types with the exception of anhydrite. A fourth core (#999) was sampled to preferentially collect the darkest colored, most prospective appearing source rock intervals. Each sample was analyzed using the LECO® TOC method at Weatherford Labs and most samples with >0.4 wt. % total organic carbon (TOC) were analyzed using RockEval 6 pyrolysis (Table 1). Geochemical results along with stratigraphic correlations and core data are presented on Plate 1 and discussed below.

The LECO® TOC method was used to measure the TOC of each rock sample. The LECO® TOC method is able to differentiate between organic carbon and inorganic carbon. RockEval pyrolysis is a separate analysis that measures several important geochemical parameters of potential source rock samples, including S1, S2, and S3. S1 is the milligram amount of free hydrocarbons (oil and/or gas) within each gram of rock sample. S1 values are assumed to be minimum estimates for in-place “free” hydrocarbons, because upon and following extraction, some of the oil and/or gas present within an extracted sample will escape through seepage and evaporation. S2 is the milligram amount of hydrogen bound organic carbon (kerogen) per gram of rock. S2 reflects the amount of organic carbon within a sample that is capable of converting into (generating) hydrocarbons. S3 is the amount of oxygen bound organic carbon present within each gram of rock sample. Tmax is the temperature (°F) at which the greatest volume of hydrocarbon vapor (S2) is produced during the RockEval Pyrolysis analysis. Tmax is used to define the level of thermal maturation in relation to oil and gas generation for a given sample. Reliable Tmax values can be produced with samples containing as little S2 as 0.2 mg/g, but for this study a more conservative minimum of 1.0 mg/g S2 was used to consider a Tmax value reliable. Production index (PI) is the ratio of S1 to S2 and is another tool used to evaluate the level of thermal maturation. Since PI is calculated using S1, PI values should be viewed with some caution. Hydrogen Index (HI) provides a relative ratio of the organic carbon that is hydrogen-bearing within a given sample. Oxygen index (OI) provides a relative ratio of the organic carbon that is oxygen-bearing within a given sample. The term organic-richness within this study refers to the quantity of both TOC and S2, with more emphasis placed on S2 because it reflects the hydrocarbon generative potential of a given sample. Publications that discuss interpretation and evaluation of TOC and RockEval pyrolysis data include: Peters, 1986; Peters and Cassa, 1994; Dembicki, 2009; and Nordeng, 2012.

Results

Well #7612

The upper part of the Stonewall Formation within the Berg #15-24 (#7612) core contains very thin, highly organic-rich laminations within the upper section (Fig. 2A). Three of the Berg #15-24 core samples yielded extremely high TOC values of 13.4-21.6% and corresponding S2 values of 95-136 milligrams/gram (mg/g), which classify as excellent quality source rock (source rock classification after Dembicki, 2009) and plot along a Type I/II kerogen curve (Figs. 3 and 4). However, all three of these samples were collected from thin (≤2 inch), black laminations that are irregularly dispersed across the basal portions of the upper Stonewall cycle and combine for a composite thickness of only several inches (Fig. 2A). A fourth sample, that yielded 4.5% TOC and 32 mg/g S2, appears to reflect a combination of another thin, highly organic-rich black lamination interbedded with a less organic-rich, lighter-colored mudstone. Tmax values from these four samples ranged from 437° to 448°.

Nine samples from the Berg #15-24 (#7612) Stonewall core yielded TOC values between 0.5 and 1.2% with corresponding S2 values of 2.3-8.1 mg/g. Most of these samples classify as fair (0.5 to <1.0% TOC and 2.5 to <5 mg/g) to good (1 to <2% TOC & 5 to <10 mg/g) quality source rock and plot near a Type II kerogen curve (Figs. 3 and 4). Tmax values from these nine samples ranged from 435° to 439°. These moderately organic-rich samples were collected from laminated to bedded, dark tan to dark brown mudstones which constitute several feet of net thickness within the Berg #15-24 core (e.g., Figs. 2a and 2c, Plate 1).

The remaining 31 Stonewall samples from the Berg #15-24 (#7612) yielded TOC values of <0.5% and were not analyzed using RockEval 6 pyrolysis (Table 1). These samples consisted mostly of light greenish grey, silty to sandy argillaceous mudstone or medium to dark brown, bioturbated, lime to dolomite mudstone to wackestone.

Well #8073

Eight Stonewall core samples were collected from the USA State #1-16 (#8073) and analyzed for TOC content. The TOC values ranged from 0.03-1.71% and average 0.52%. Three of the samples yielded >0.5% TOC and were subsequently analyzed using RockEval 6 pyrolysis. The S2 values produced from those three samples ranged from 2.34-5.24 mg/g, which classify approximately as fair to good quality source rock (Fig. 3). HI and OI values plot these three samples intermediately between Type II and Type III kerogen curves as displayed on Figure 4. The corresponding three Tmax values range from 439° to 444°. The sample with the highest TOC (1.71%) and S2 (5.24 mg/g) content was from a <1 inch thick black lamination, similar to those observed within the upper portions of the Berg #15-24 (#7612) Stonewall core. Another two of the USA State #1-16 core samples, including the sample with the second highest TOC (0.99%) and S2 (4.51 mg/g) content, consisted of very dark colored flakes that were removed and concentrated from a much lighter colored matrix.

Well #999

Eleven samples were collected from the darker colored, more prospectively organic-rich appearing portions of the J. M. Donahue #1 (#999) Stonewall core section (core depths: 13,629-13,713 ft.). All 11 samples were analyzed for TOC content and produced values of 0.06-1.65% TOC with an average of 0.66%. The eight samples with the highest TOC values (≥0.44%) were also analyzed using RockEval 6 pyrolysis and yielded S2 values of 0.49-2.03 mg/g (1.01 mg/g average) (Figs. 3 and 4). Four of those samples contained sufficient S2 (≥1.0 mg/g) to produce fairly reliable Tmax values. Three of the reliable Tmax values were very similar, ranging from 458° to 462°, while a fourth sample was significantly lower at 450°.

Well #9102

Thirty-four core samples were collected from the Gajewski #1-2-1A (#9102) in semi-regular, two to three ft. intervals across the core with the exception of the anhydrite-argillaceous marker bed interval, which likely has negligible hydrocarbon generation potential based on visual inspection and previously analyzed samples from the Berg #15-24 (#7612) core. The TOC values ranged from 0.03% to 2.57% and averaged 0.30%. Six samples were analyzed for RockEval 6 pyrolysis (≥0.45% TOC) and yielded S2 values of 0.39 to 3.46 mg/g for an average of 1.33 mg/g. Three samples contained adequate S2 content (≥1.0 mg/g) to yield fairly reliable Tmax values, two of which were similar at 458° and 460°, while the third was substantially lower at 444°. All but one of the samples from Gajewski #1-2-1A (#9102) core that yielded >0.4% TOC were collected from an approximately 4 ft. thick dark tan and black, burrowed mudstone located at the base of the upper Stonewall cycle (Fig. 2b, Plate 1). A dark to very-dark grey laminated mudstone near the top of the middle Stonewall cycle visually appeared to be a possible source bed, but TOC values from the interval were only 0.04-0.22% (Fig. 2d, Plate 1). Darker versus lighter colored laminations were sampled and analyzed separately from this interval to see if the darker colored laminations were more organic-rich, but coloration did not appear to correlate well with TOC content.

Discussion and Interpretations

Degree of Thermal Maturation

The Berg #15-24 and USA State #1-16 wells are located approximately 100 miles apart, but their Stonewall cores are from similar depths of approximately 10,750 ft. below the surface, 9,500 ft. below sea level (#7612 and #8073, Fig. 1, Table 1). Most of the Tmax values from both cores are 435-440°, a Tmax value range that indicates both cores had reached the early mature stage of oil generation at depth (Peters and Cassa, 1994). Oil saturations within the carbonate portions of each core are usually 10-50% (Plate 1). Corresponding low porosity (<5%) and permeability (<1 millidarcy) values of the core samples with oil saturations, as well as those without, indicates minimal fluid migration potential of the host rock which would mean the oil present was generated relatively in-place. Within the Berg #15-24 core, there appears to be a consistent correlation between intervals with higher TOC content and higher oil saturations, further indicating in situ oil generation (Plate 1). The HI values of the more organic-rich samples were 400 to 700, high enough to suggest most of the original kerogen is still present and has not been converted into hydrocarbons, otherwise the HI values would likely be much lower. The Berg #15-24 and USA State #1-16 Stonewall cores are interpreted to have reached thermal conditions necessary for the onset of oil generation, but have experienced only low levels of kerogen conversion to hydrocarbons and still retain the majority of their original organic-richness.

The Gajewski #1-2-1A and J. M. Donahue #1 cores are interpreted to have reached the late mature stage of oil generation and therefore have experienced a substantial reduction in their original organic-richness. The Gajewski #1-2-1A and J. M. Donahue #1 cores were collected from similar depths (13,100 and 13,650 ft.) and are located 23 miles apart, both in close proximity to most of the oil and gas productive Stonewall wells (#999 and #9102, Fig. 1, Table 1). Most of the PI values range from 0.33 to 0.43 for the Gajewski #1-2-1A samples and 0.27 to 0.52 for the J. M. Donahue #1 samples, value ranges that suggest these samples reached the peak to late mature stages of oil generation (Peters and Cassa, 1994). Since PI is calculated using S1, PI values are viewed by this study as minimal estimates for level of thermal maturation. The more reliable Tmax values (samples containing ≥1.0 mg/g S2) from these two cores range from 458° to 462°, a Tmax value range that indicates the Stonewall Fm. within the Gajewski-Donahue area has reached the late mature stage of oil generation (Peters and Cassa, 1994). By the late mature stage, most of the organic-carbon capable of being converted into hydrocarbons (kerogen) has been converted which substantially reduces a source bed's original organic-richness. The HI values of the more mature Gajewski and Donahue samples are only 87 to 157, while the less mature Berg and USA State samples are much higher at 306 to 766. These results indicate that the Stonewall Formation has reached the late mature stage of oil generation within the vicinity of the Gajewski and Donahue cores. However, was there originally sufficient quality and quantity of source rock to generate enough hydrocarbon volume to self-source the Stonewall reservoirs?

Original Organic-Richness

RockEval pyrolysis predicts the quantity of organic compounds that a sample could generate upon further maturation and reflects the present day quality (organic-richness) of a prospective source rock (Peters, 1986). Pyrolysis does not directly indicate the original generative potential of a thermally matured source rock, but may provide some insight into its original organic-richness. Source beds essentially contain two types of organic-carbon prior to thermal maturation: 1) generative organic carbon, also known as kerogen, which is capable of being converted into hydrocarbons, and 2) non-generative organic carbon, which is not capable of converting into hydrocarbons. As a source bed undergoes continued thermal maturation, generative organic carbon converts into hydrocarbons and the generative potential (organic-richness) of the source bed decreases. Source beds may expel most of their generated hydrocarbons, but will usually retain some measurable hydrocarbon volume, which is measured as S1 during pyrolysis. A source bed that has only experienced partial conversion of kerogen to hydrocarbons will still retain some generative organic carbon (measured as S2 and S3 during pyrolysis). The amount of non-generative organic-carbon (which is not directly measured during pyrolysis) within a source bed will remain approximately constant during thermal maturation. The original organic-richness of a thermally mature source rock (#999 and #9102) can be calculated by comparing the mature source rocks present day organic-richness geochemical parameters with those of an equivalent immature source rock (#7612 and #8073).

Methods for calculating original TOC have previously been proposed by Peters et al. (2005) and Jarvie et al. (2007). These two methods involve calculating a conversion ratio (similar to this studies conversion factor, discussed below) using the present day production index (PI) of a given sample/source bed to estimate the percentage of kerogen that has been converted to hydrocarbons. PI is calculated using S1, free hydrocarbons, which as stated earlier is suspect because oil and gas are prone to escape a sample following extraction from the subsurface. Each of these previous calculation methods also involve using the present day HI value/s of a mature source bed in combination with the source bed's estimated original (immature) average HI. Both of these previous calculation methods assume a uniform HI for a given source bed and do not directly address original S2, which are the primary reasons this study developed a new method for calculating original TOC and S2.

In this study, the original organic-richness (TOC and S2) for the Stonewall samples that have experienced higher levels of thermal maturity were calculated using new methodology that focuses on changes in the amount of S2. Within the Stonewall data set produced by this study, S3 values were all very low (≤0.80 mg/g) and display only minor variation between samples with varying levels of thermal maturity. Therefore, any change to S3 during thermal maturation is considered negligible in relation to calculating original TOC. The only generative organic carbon component that appears to change during thermal maturation within the Stonewall Formation is S2, which ranges from 2.3 to 136.5 mg/g in the less mature samples (#8073 and #7612, Table 1) and only 0.4 to 3.5 mg/g within the more mature samples (#999 and #9102, Table 1). The following section outlines how original organic-richness was calculated for core samples collected in closest proximity to Stonewall productive wells (#999 and #9102, Fig. 1 and Fig. 3). Original organic-richness is examined in order to evaluate whether the Stonewall Formation originally contained source rock of adequate quality and quantity to have generated (self-sourced) the hydrocarbon volumes observed and produced from the Stonewall Formation in North Dakota.

Original S2

Approximate original S2, S3, and TOC values of the highly mature Gajewski #1-2-1A (#9012) and Donahue #1 (#999) samples were calculated using present day S2, S3, and TOC values. The original S2 calculation, equation 1, is based on the estimated percentage of kerogen (S2) that has been converted into hydrocarbons, referred to herein as the conversion factor (CF). The CF for the Gajewski #1-2-1A and Donahue #1 samples is estimated to be 0.85, where 85% of the original kerogen has been converted into hydrocarbons and the present day S2 is 15% of the original. A CF of 0.85 was used for two reasons. First, the calculated original TOC and S2 values for the Gajewski #1-2-1A and Donahue #1 samples using a CF of 0.85 plot along an organic-richness trend very similar to the present day, less mature Berg #15-24 and USA State #1-16 samples (Fig. 3). Second, as discussed above, the Gajewski #1-2-1A and Donahue #1 cores are interpreted to have reached the late mature phase of oil generation, where most of the original kerogen (S2) has been converted into hydrocarbons (S1). Equation 1 was used to calculate the original S2:

Equation 1

$$S2_O = S2_P / (1\text{-}CF)$$

Where:

$S2_O$ = Original S2
$S2_P$ = Present day S2
CF = Conversion Factor

Original S3

Examining the S3 data from the four Stonewall cores, the average S3 from the more mature Gajewski #1-2-1A (#9102) and Donahue #1 (#999) samples is 0.45 mg/g, approximately 80% of the average S3 from the less mature Berg #15-24 (#7612) and USA State #1-16 (#8073) samples (0.57 mg/g). The original S3 values for the Gajewski #1-2-1A and Donahue #1 core samples are estimated using Equation 2, which assumes the present day S3 is 80% of the original S3. S3 values are calculated back to their approximate original values in order to estimate each sample's original OI.

Equation 2

$$S3_O = S3_P / 0.80$$

Where:

$S3_O$ = Original S3
$S3_P$ = Present day S3

Original TOC

Original TOC is estimated by using a two-step approach. First, the combined present day weight percent of organic carbon measured within the S1 and S2 values is subtracted from the present day TOC (S1 and S2 are converted to weight percent and a mass correction is made to remove the weight percent of hydrogen from both values). Second, the weight percent of the organic carbon within the calculated original S2 is added in. This calculation essentially adds in the original amount of generative organic carbon while removing the remaining, present day generative organic carbon and the carbon present within the generated hydrocarbon volume.

Equation 3

$$TOC_O = TOC_P - ((S1_P + S2_P)/10^{*}) \times 0.83^{**} + ((S2_O)/10^{*}) \times 0.83^{**}$$

TOC_O = Original TOC (wt. %)
TOC_P = Present day TOC (wt. %)
$S1_P$ = Present day S1 (mg HC/g sample)
$S2_O$ = Original S2 (mg HC/g sample)
$S2_P$ = Present day S2 (mg HC/g sample)

** S1 and S2 values are measured in parts per thousand (mg/g) and can be converted to weight percent (which is parts per hundred) by dividing by ten.*
*** Carbon constitutes approximately 83% of the total mass of hydrocarbons (hydrogen makes up the remaining 17%), borrowed from Jarvie et al. (2007).*

There are a few notable differences between the original TOC calculation developed by this study and the previous original TOC calculations from Peters et al. (2005) and Jarvie et al. (2007). The original TOC calculation method developed by this study avoids using S1 values except to remove S1 carbon from the present day TOC. Also, the calculations of this study allow for variable original HI values within a source bed instead of assuming a single, uniform HI value. This study's method does, however, require an immature (or at least low maturity) data set for the formation of interest in order to estimate the percentage of converted kerogen in thermally mature data sets.

The original TOC calculation used for this study was developed for the Stonewall Formation of North Dakota using several assumptions. The types/s of organic material within the Stonewall Formation is assumed to be relatively homogenous across the study area where all of the organic-rich samples from the Stonewall Formation initially plotted along the same organic-richness trend (S2 vs. TOC). The Berg #15-24 and USA State #1-16 core samples are assumed to represent immature samples, even though they have likely undergone low levels of thermal maturation that has slightly reduced their original organic-richness. Also, this method does not account for any adsorption of generated hydrocarbons into remaining kerogen and/or non-generative organic-carbon within the source rock. Therefore, the calculated original geochemical values of the Gajewski #1-2-1A and Donahue #1 core samples should be viewed as "ballpark" estimates when evaluating the Stonewall Formation's original organic-richness.

Stonewall Source Beds and Reservoirs

Based on the above calculations, the Gajewski #1-2-1A and Donahue #1 cores originally contained fair to excellent quality source rock prior to thermal maturation. The calculated original TOC and S2 for the Gajewski #1-2-1A and Donahue #1 samples range from 0.6-4.0% TOC with 3-23 mg/g S2, value ranges that classify as fair to excellent quality source rock (Fig. 3). These calculated values are similar, but slightly greater than those of the present day, less mature Berg #15-24 and USA State #1-16 sample values, which are located further away from the central portions of the Williston Basin and away from most of the productive Stonewall wells. The calculated original HI and OI values for the Gajewski #1-2-1A and Donahue #1 samples plot near a Type II (oil-prone) kerogen curve, similar to the more organic-rich samples from the Berg #15-24 and USA State #1-16 cores (Figure 4). The calculated original organic-richness and HI-OI values of these higher maturity samples indicates that the Stonewall source beds in the vicinity to Stonewall productive wells contained organic material of sufficient quality to generate oil and gas.

The carbonate portions of all three Stonewall members appear to be separate source rock intervals that each contain variable amounts of organic-rich mudstone. Within each core that was sampled and examined for this study, the carbonate portion of each Stonewall member contains one or more intervals of moderately organic-rich mudstone that range from several inches to 4 ft. in thickness. In cores spanning most of the upper Stonewall member (Berg #15-24 and Gajewski #1-2-1A), the basal half of the upper Stonewall appears to have originally contained 4-6 ft. (net thickness) of organic-rich mudstone (0.5% to ≥2% TOC, 3 to ≥10 mg/g S2) (Plate II). The middle Stonewall member contains approximately 2 ft. of organic-rich mudstone within the Berg #15-24 core and 6 ft. within the J. M. Donahue #1 core, which both extend across the entire middle member. Within the Berg #15-24 and USA State #1-16 cores, the lower Stonewall member contains <2 ft. of organic-rich mudstone while containing approximately 4-5 ft. within the J. M. Donahue core. The lateral continuity of these organic-rich mudstone intervals is not well understood by this study, but they do not appear to extend continuously between the four sampled cores. Containing upwards of several feet of organic-rich mudstone within each of the three Stonewall members, the Stonewall Formation appears to contain a sufficient quantity of source rock to have generated a significant volume of hydrocarbons.

Most of the perforated intervals within productive Stonewall wells are located within the basal, carbonate portion of the upper Stonewall Formation and less commonly within the basal, carbonate portion of the middle Stonewall Formation (Plate II). The conventional (vertical) well pay zones either overlap or are in very close stratigraphic proximity to the moderately organic-rich mudstones of the middle and upper Stonewall Formation, which, as discussed above, have reached the late stages of oil generation in the deeper portions of the basin. The stratigraphic proximity of thermally mature, organic-rich mudstone with the conventional reservoir rock indicates the Stonewall Formation is self-sourced, with at least a portion of the hydrocarbon volume internally generated within the formation. Also, regionally extensive, impermeable evaporite (anhydrite) beds are present near the top of both the Stonewall and underlying Gunton Formations (Plate I, Figure 5). The regional, continuous anhydrite intervals near the top and base of the Stonewall Formation likely provide seals that inhibit vertical hydrocarbon migration both into and out of the formation, which reduces the possibility of an external source for Stonewall hydrocarbons. However, some lateral and/or minor vertical hydrocarbon migration may still have taken place within the Stonewall Formation.

Conclusions

Four Stonewall Formation cores from western North Dakota were visually examined, sampled and analyzed to evaluate the quantity and quality of source rock within the formation. Two of the cores are interpreted to have undergone only marginal (early mature) levels of thermal maturation while the other two core have experienced high levels of thermal maturation and reached the late stages of oil generation based on Tmax and PI values. The original organic-richness (TOC and S2) for samples from the two cores that experienced high levels of thermal maturation was estimated by comparison with samples from the two marginally mature cores and calculations developed for study.

The Stonewall Formation contains upwards of several feet net thickness of organic-rich carbonate mudstone within each of its three members. Based on the present day values of the less mature samples and the calculated original geochemical values of the higher maturity samples, the organic-rich mudstone within the Stonewall Formation originally classified as as fair to excellent quality source rock (0.6 to 4% TOC, 3-23 mg/g S2) consisting of Type I/II oil-prone kerogen. Perforations within Stonewall productive wells are in stratigraphic proximity to the organic-rich mudstones within the two higher maturity Stonewall cores. Therefore, based on the results of this study, the Stonewall Formation is interpreted to contain thermally mature source rock that was originally of sufficient quantity and quality to internally generate (self-source) oil and gas.

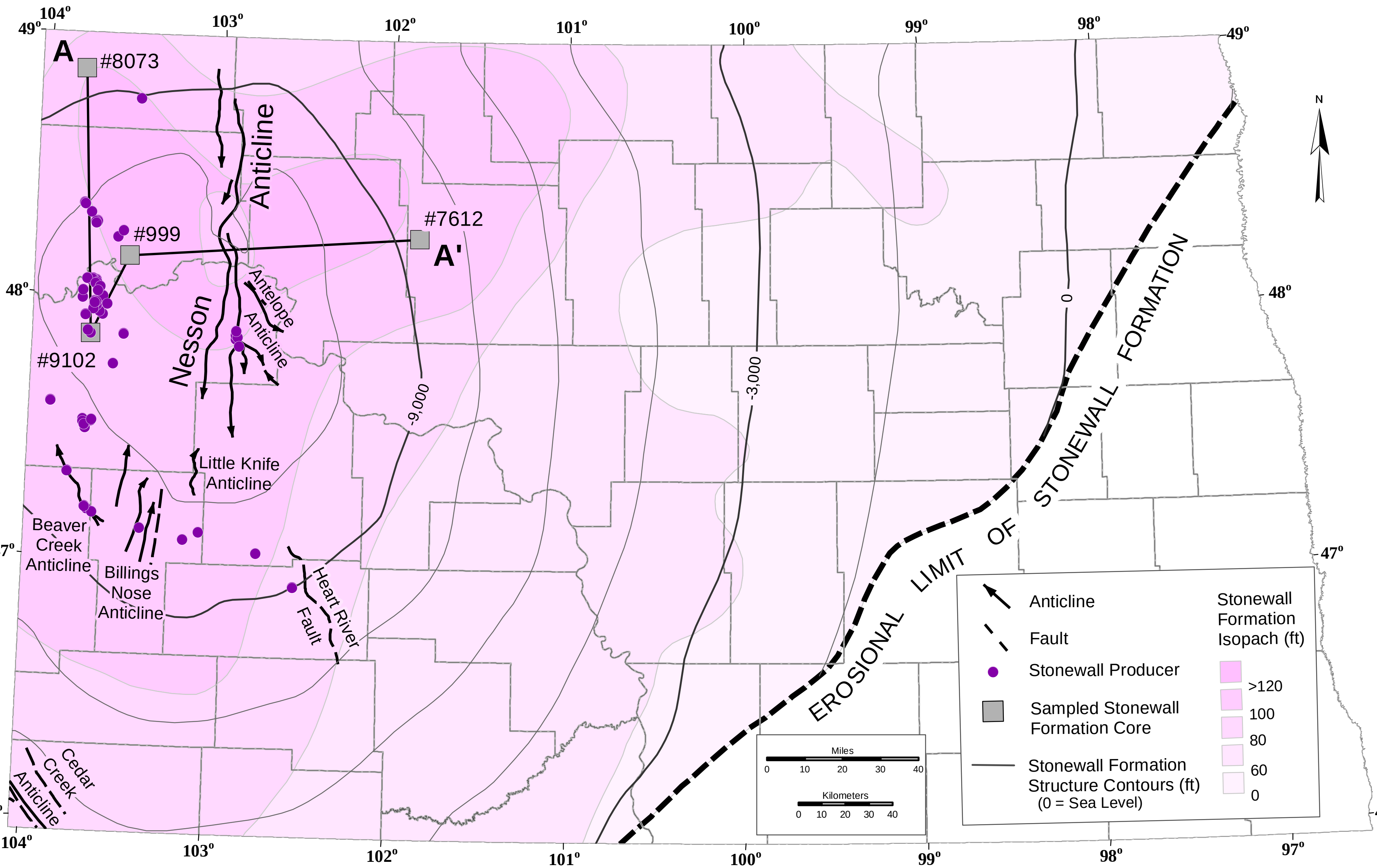

Figure 1. Map depicting the extent of the Stonewall Formation in North Dakota (colored area) and wells that have produced oil and gas from the Stonewall Formation (Carlson and Eastwood, 1962). A-A' indicates the location and orientation of the Plate 1 cross-section.

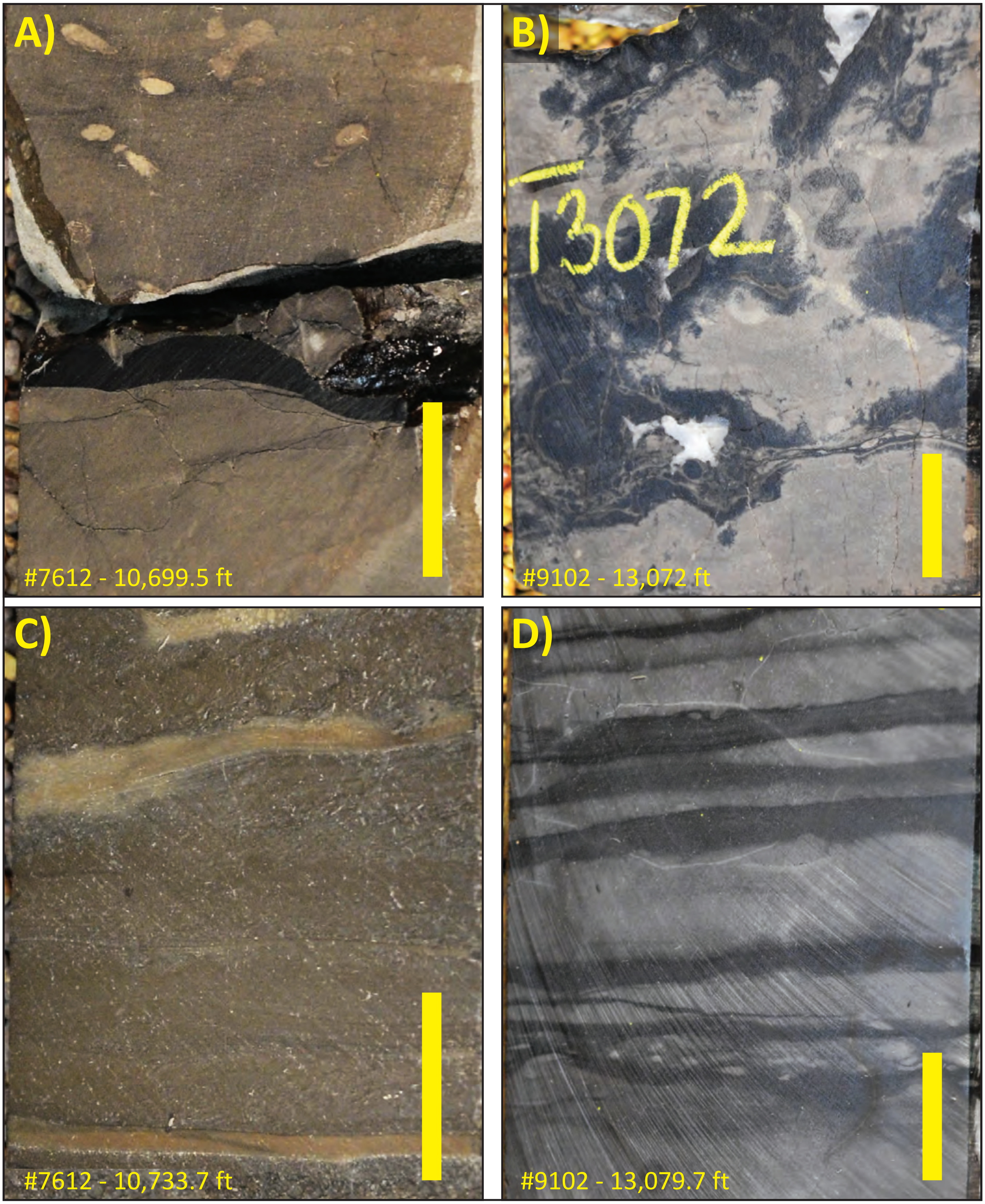

Figure 2. Core photograph examples from sampled Stonewall Formation cores. A) Dark brown dolomite mudstone (0.56-1.12% TOC) containing a black, highly organic-rich mudstone lamination (13.4% TOC, 102.7 mg/g S2), B) tan and very dark grey/black, burrow mottled, dolomi e mudstone (TOC: 0.65-2.56%), C) dark brown, laminated, lime mudstone (0.55-0.60% TOC), and D) grey to very dark grey, laminated, lime mudstone (0.06-0.22% TOC). The NDIC well number and approximate core depth of each sample is listed in bo om left hand corner of each photograph. Each thick yellow line represents 1 inch.

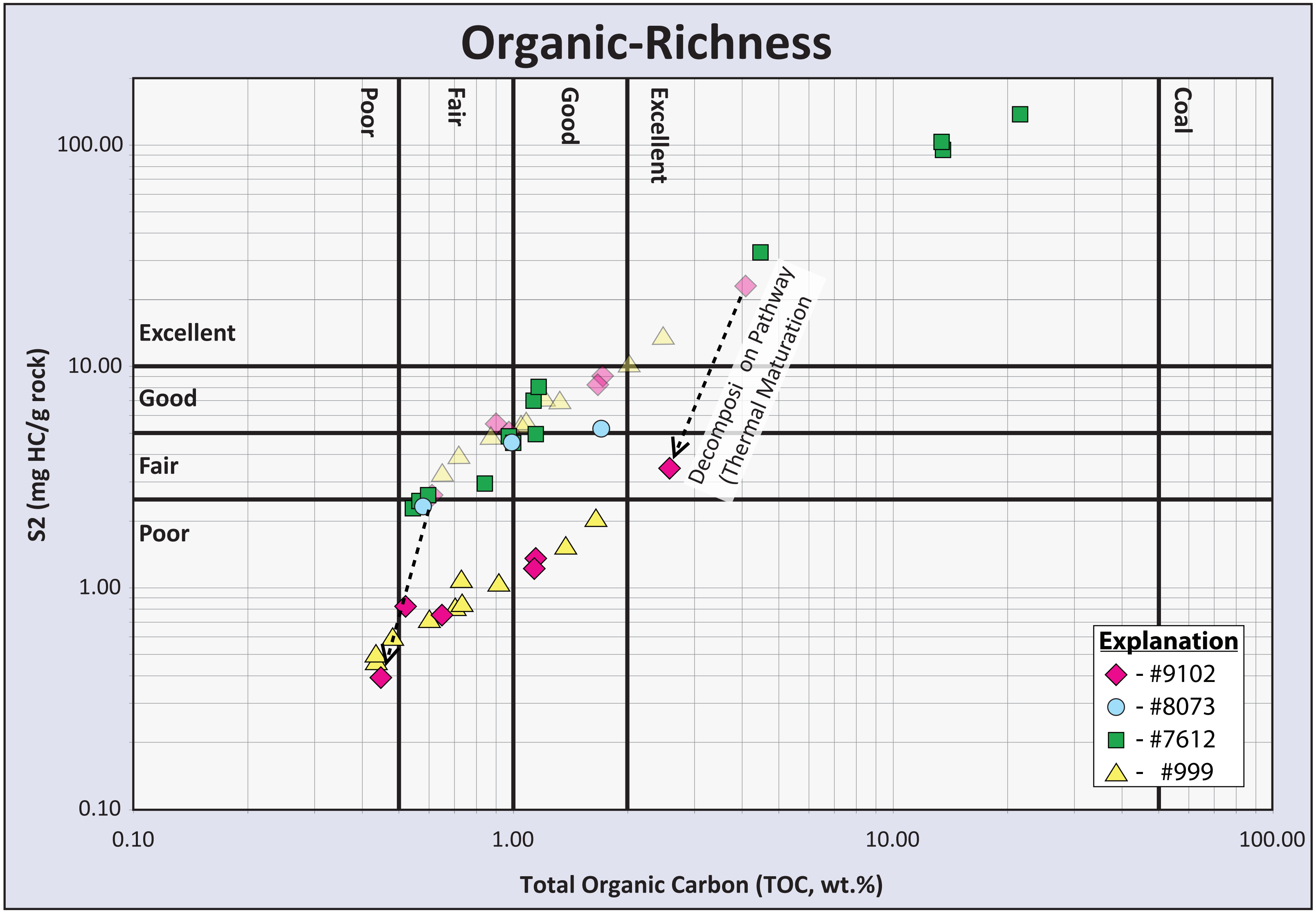

Figure 3. Organic-richness plot (Dembicki, 2009) of Stonewall Formation core samples. The semi-transparent symbols represent the estim ted original organic-richness of samples from the J. M. Donahue #1 (#999) and Gajewski #1-2-1A (#9102) cores assuming 85% conversion of S2 (kerogen) into hydrocarbons.

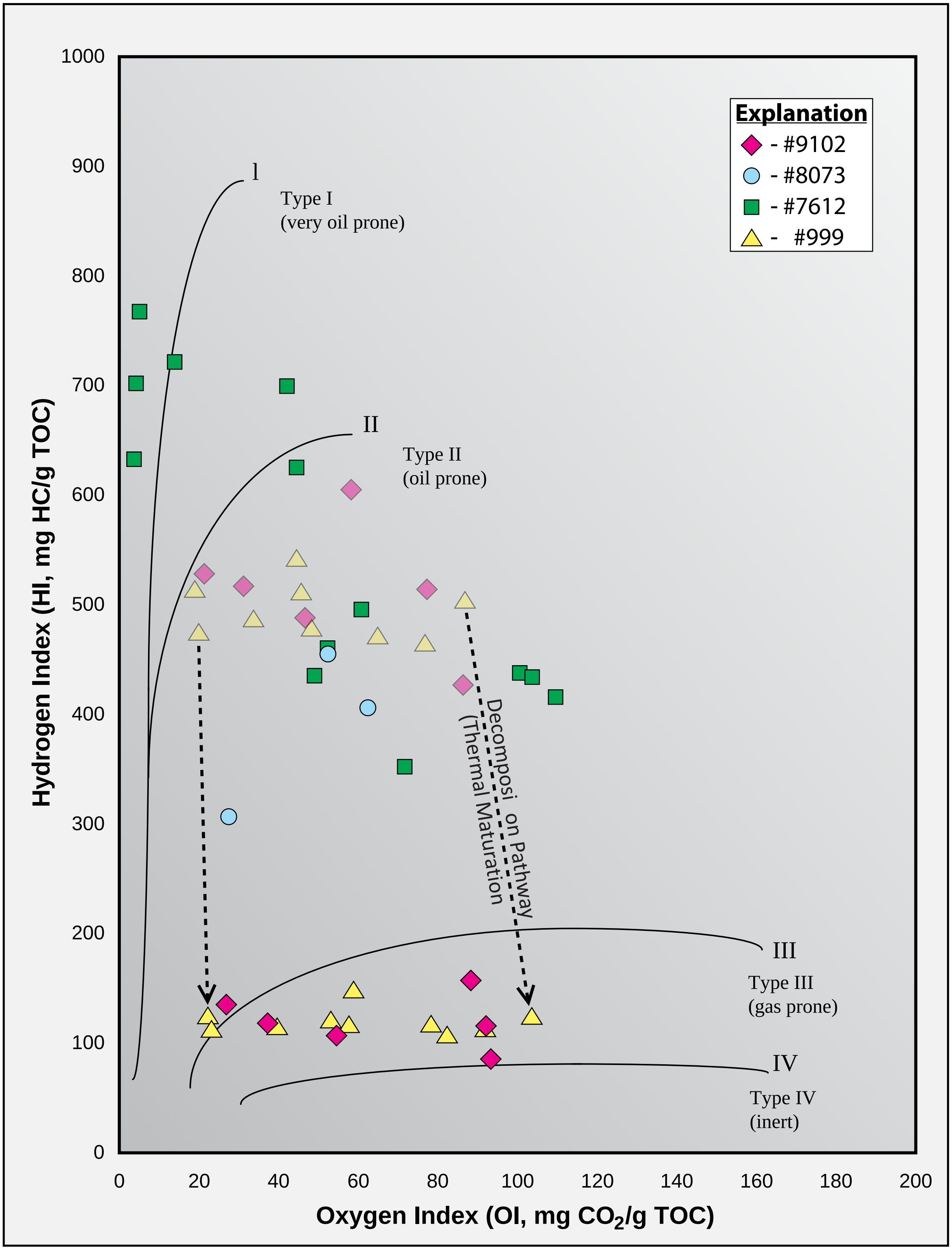

Figure 4. Modified Van Krevelen diagram depicting eochemical data from Stonewall Formation core samples as related to kerogen type/s. The semi-transparent symbols represent the estim ted original HI and OI values of Stonewall core samples from the J. M. Donahue #1 (#999) and Gajewski #1-2-1A (#9102) cores.

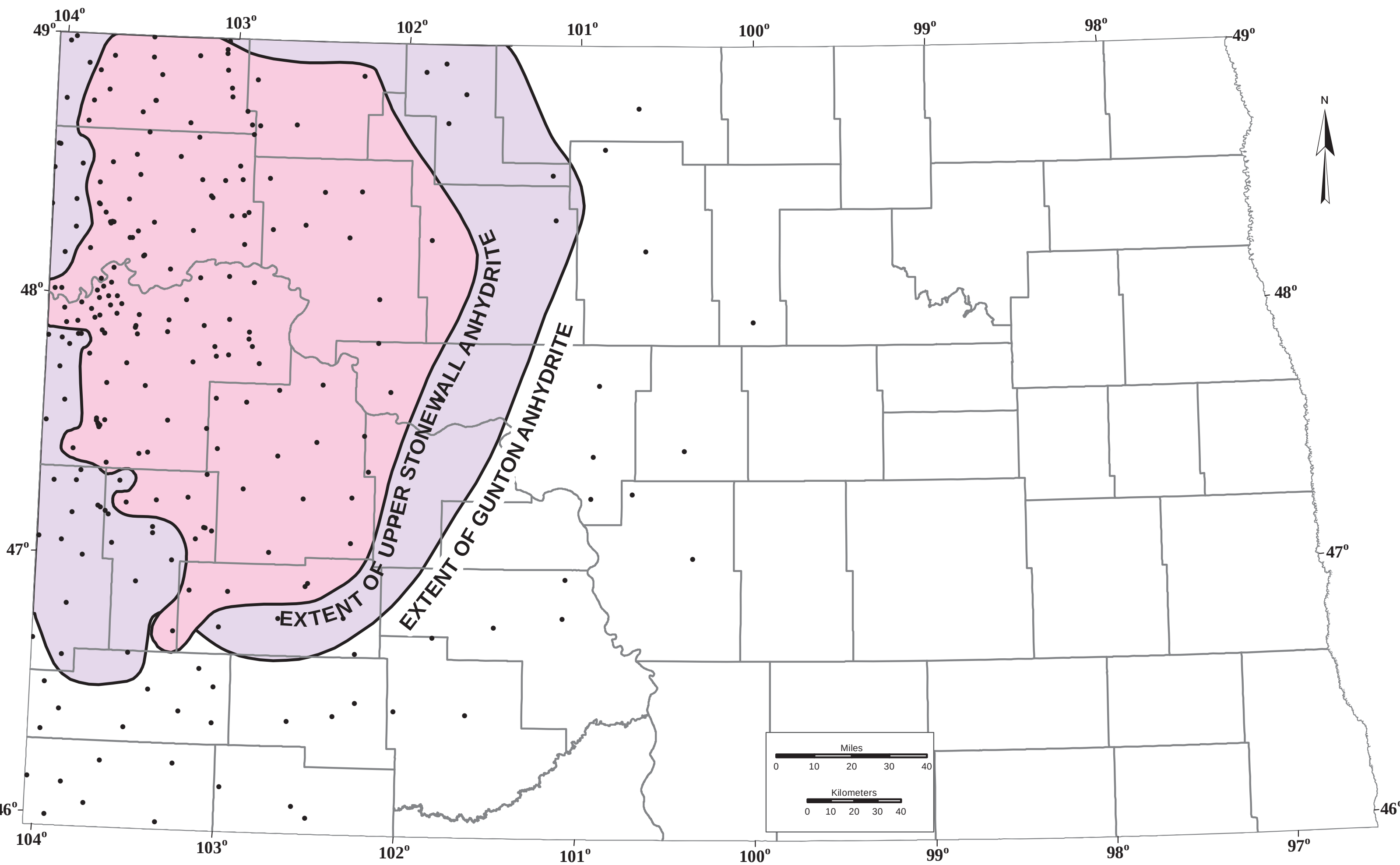

Figure 5 Map depicting the extent of the upper Stonewall and Gunton anhydrite intervals (Plate I). Black dots represent control wells. Wireline log examples of both anhydrite intervals are displayed on the Plate I cross-section.

Table 1. Geochemical data set from Stonewall Formation core samples

Well Name	NDIC	Location	Depth (ft.)	Formation	TOC (wt. %)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax (°C)	HI	OI	PI
USA State #1-16	8073	Sec.16-T162N-R101W	10770	Stonewall	1.712	1.16	5.24	0.47	439	306	27	0.18
USA State #1-16	8073	Sec.16-T162N-R101W	10771	Stonewall	0.094							
USA State #1-16	8073	Sec.16-T162N-R101W	10773	Stonewall	0.322							
USA State #1-16	8073	Sec.16-T162N-R101W	10776	Stonewall	0.227							
USA State #1-16	8073	Sec.16-T162N-R101W	10777	Stonewall	0.576	0.27	2.34	0.36	444	406	63	0.10
USA State #1-16	8073	Sec.16-T162N-R101W	10779	Stonewall	0.033							
USA State #1-16	8073	Sec.16-T162N-R101W	10781	Stonewall	0.23							
USA State #1-16	8073	Sec.16-T162N-R101W	10785	Stonewall	0.992	0.9	4.51	0.52	442	455	52	0.17
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13030.71	Stonewall	0.276							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13033	Stonewall	0.128							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13035	Stonewall	0.084							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13037	Stonewall	0.059							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13038.92	Stonewall	0.201							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13041	Stonewall	0.165							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13042.25	Stonewall	0.089							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13042.92	Stonewall	0.057							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13044.88	Stonewall	0.08							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13047	Stonewall	0.064							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13049	Stonewall	0.157							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13051	Stonewall	0.522	0.08	0.82	0.46	472	157	88	0.09
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13053	Stonewall	0.095							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13055.13	Stonewall	0.119							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13057	Stonewall	0.07							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13058.92	Stonewall	0.171							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13061.13	Stonewall	0.025							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13062.92	Stonewall	0.22							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13063.25	Stonewall	0.083							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13067.33	Stonewall	0.158							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13068.88	Stonewall	0.45	0.3	0.39	0.42	455	87	93	0.43
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13068.92	Stonewall	1.138	0.61	1.22	0.62	458	107	54	0.33

Well Name	NDIC	Location	Depth (ft.)	Formation	TOC (wt. %)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax (°C)	HI	OI	PI
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13070	Stonewall	0.652	0.41	0.75	0.6	457	115	92	0.35
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13071	Stonewall	1.147	0.65	1.34	0.43	444	117	37	0.33
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13071.92	Stonewall	2.568	1.83	3.46	0.69	460	135	27	0.35
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13077.92	Stonewall	0.057							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13080	Stonewall	0.175							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13081	Stonewall	0.176							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13081.88	Stonewall	0.04							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13083	Stonewall	0.062							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13084	Stonewall	0.184							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13084.88	Stonewall	0.221							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13085	Stonewall	0.196							
Gajewski #1-2-1A	9102	Sec.2-T150N-R102W	13085.83	Stonewall	0.141							
J. M. Donahue #1	999	Sec.23-T154N-R100W	13629	Stonewall	0.435	0.18	0.49	0.4	444	113	92	0.27
J. M. Donahue #1	999	Sec.23-T154N-R100W	13639	Stonewall	0.729	0.29	1.07	0.43	450	147	59	0.21
J. M. Donahue #1	999	Sec.23-T154N-R100W	13644	Stonewall	0.064							
J. M. Donahue #1	999	Sec.23-T154N-R100W	13658	Stonewall	1.381	1.05	1.53	0.32	462	111	23	0.41
J. M. Donahue #1	999	Sec.23-T154N-R100W	13677	Stonewall	0.729	0.44	0.84	0.42	447	115	58	0.34
J. M. Donahue #1	999	Sec.23-T154N-R100W	13679	Stonewall	0.703	0.3	0.81	0.55	450	115	78	0.27
J. M. Donahue #1	999	Sec.23-T154N-R100W	13682	Stonewall	0.162							
J. M. Donahue #1	999	Sec.23-T154N-R100W	13691	Stonewall	0.12							
J. M. Donahue #1	999	Sec.23-T154N-R100W	13701	Stonewall	0.483	0.48	0.59	0.5	432	122	104	0.45
J. M. Donahue #1	999	Sec.23-T154N-R100W	13701.5	Stonewall	0.913	0.85	1.04	0.36	460	114	39	0.45
J. M. Donahue #1	999	Sec.23-T154N-R100W	13702.5	Stonewall	1.65	1.73	2.03	0.37	458	123	22	0.46
J. M. Donahue #1	999	Sec.23-T154N-R100W	13713	Stonewall	0.603	0.79	0.72	0.32	456	119	53	0.52
J. M. Donahue #1	999	Sec.23-T154N-R100W	13720	Stoney Mtn.	0.161							
J. M. Donahue #1	999	Sec.23-T154N-R100W	13723	Stoney Mtn.	0.054							
J. M. Donahue #1	999	Sec.23-T154N-R100W	13725.5	Stoney Mtn.	0.309							
J. M. Donahue #1	999	Sec.23-T154N-R100W	13787	Stoney Mtn.	0.017							
J. M. Donahue #1	999	Sec.23-T154N-R100W	13795	Stoney Mtn.	0.074							
J. M. Donahue #1	999	Sec.23-T154N-R100W	13844	Stoney Mtn.	0.437	0.32	0.46	0.36	451	105	82	0.41
J. M. Donahue #1	999	Sec.23-T154N-R100W	13848	Stoney Mtn.	0.257							

Well Name	NDIC	Location	Depth (ft.)	Formation	TOC (wt. %)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax (°C)	HI	OI	PI
J. M. Donahue #1	999	Sec.23-T154N-R100W	13852	Stoney Mtn.	0.062							
J. M. Donahue #1	999	Sec.23-T154N-R100W	13856	Stoney Mtn.	0.093							
J. M. Donahue #1	999	Sec.23-T154N-R100W	13860	Stoney Mtn.	0.071							
Berg #15-24	7612	Sec.15-T155N-R87W	10681.1	Stonewall	0.123							
Berg #15-24	7612	Sec.15-T155N-R87W	10686.1	Stonewall	0.152							
Berg #15-24	7612	Sec.15-T155N-R87W	10691	Stonewall	0.171							
Berg #15-24	7612	Sec.15-T155N-R87W	10695	Stonewall	0.255							
Berg #15-24	7612	Sec.15-T155N-R87W	10699.1	Stonewall	0.422							
Berg #15-24	7612	Sec.15-T155N-R87W	10699.8	Stonewall	13.4	2.02	102.7	0.68	442	766	5	0.02
Berg #15-24	7612	Sec.15-T155N-R87W	10700	Stonewall	13.5	1.4	94.56	0.58	448	700	4	0.01
Berg #15-24	7612	Sec.15-T155N-R87W	10701	Stonewall	1.12	0.93	7	0.5	438	625	45	0.12
Berg #15-24	7612	Sec.15-T155N-R87W	10702.2	Stonewall	0.97	0.78	4.81	0.59	439	496	61	0.14
Berg #15-24	7612	Sec.15-T155N-R87W	10703	Stonewall	0.993	0.77	4.56	0.52	439	459	52	0.14
Berg #15-24	7612	Sec.15-T155N-R87W	10704	Stonewall	0.56	0.35	2.43	0.58	436	434	104	0.13
Berg #15-24	7612	Sec.15-T155N-R87W	10706.2	Stonewall	0.237							
Berg #15-24	7612	Sec.15-T155N-R87W	10707.9	Stonewall	0.412							
Berg #15-24	7612	Sec.15-T155N-R87W	10709.4	Stonewall	1.135	0.38	4.93	0.56	444	434	49	0.07
Berg #15-24	7612	Sec.15-T155N-R87W	10709.5	Stonewall	21.6	3.07	136.48	0.8	444	632	4	0.02
Berg #15-24	7612	Sec.15-T155N-R87W	10709.9	Stonewall	0.361							
Berg #15-24	7612	Sec.15-T155N-R87W	10712.2	Stonewall	4.495	1.58	32.38	0.62	437	720	14	0.05
Berg #15-24	7612	Sec.15-T155N-R87W	10718	Stonewall	0.093							
Berg #15-24	7612	Sec.15-T155N-R87W	10729	Stonewall	0.185							
Berg #15-24	7612	Sec.15-T155N-R87W	10730	Stonewall	0.115							
Berg #15-24	7612	Sec.15-T155N-R87W	10731	Stonewall	0.177							
Berg #15-24	7612	Sec.15-T155N-R87W	10732	Stonewall	0.151							
Berg #15-24	7612	Sec.15-T155N-R87W	10733	Stonewall	0.595	0.53	2.6	0.6	435	437	101	0.17
Berg #15-24	7612	Sec.15-T155N-R87W	10734.1	Stonewall	0.548	0.4	2.28	0.6	435	416	109	0.15
Berg #15-24	7612	Sec.15-T155N-R87W	10734.9	Stonewall	0.389							
Berg #15-24	7612	Sec.15-T155N-R87W	10736.1	Stonewall	0.119							
Berg #15-24	7612	Sec.15-T155N-R87W	10736.8	Stonewall	0.188							
Berg #15-24	7612	Sec.15-T155N-R87W	10739.3	Stonewall	0.208							

Well Name	NDIC	Location	Depth (ft.)	Formation	TOC (wt. %)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax (°C)	HI	OI	PI
Berg #15-24	7612	Sec.15-T155N-R87W	10740	Stonewall	0.083							
Berg #15-24	7612	Sec.15-T155N-R87W	10741	Stonewall	0.055							
Berg #15-24	7612	Sec.15-T155N-R87W	10745	Stonewall	0.104							
Berg #15-24	7612	Sec.15-T155N-R87W	10747.1	Stonewall	0.12							
Berg #15-24	7612	Sec.15-T155N-R87W	10748.9	Stonewall	0.221							
Berg #15-24	7612	Sec.15-T155N-R87W	10750	Stonewall	0.481							
Berg #15-24	7612	Sec.15-T155N-R87W	10757.8	Stonewall	0.029							
Berg #15-24	7612	Sec.15-T155N-R87W	10766	Stonewall	0.179							
Berg #15-24	7612	Sec.15-T155N-R87W	10769.8	Stonewall	0.322							
Berg #15-24	7612	Sec.15-T155N-R87W	10772	Stonewall	0.344							
Berg #15-24	7612	Sec.15-T155N-R87W	10773.9	Stonewall	0.262							
Berg #15-24	7612	Sec.15-T155N-R87W	10775.3	Stonewall	1.16	0.13	8.1	0.49	439	698	42	0.02
Berg #15-24	7612	Sec.15-T155N-R87W	10775.9	Stonewall	0.171							
Berg #15-24	7612	Sec.15-T155N-R87W	10778	Stonewall	0.124							
Berg #15-24	7612	Sec.15-T155N-R87W	10779.9	Stonewall	0.837	0.19	2.95	0.6	438	352	72	0.06
Berg #15-24	7612	Sec.15-T155N-R87W	10783.9	Stonewall	0.061							

TOC= Total Organic Carbon by weight percent
S1 = milligrams of free hydrocarbon per gram of sample
S2 = milligrams of live hydrocarbons per gram of sample
S3 = milligrams of oxygen-bound carbon per gram of sample
Tmax = temperature at which the greatest volume of hydrocarbon vapor (S2) is produced during the RockEval Pyrolysis
HI = Hydrogen Index (HI = S2/TOC x100)
OI = Oxygen Index (OI = S3/TOC x100)
PI = Production Index (PI =S1/(S1+S2))

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