



**Final Report
Gas Content and Reservoir Properties
W. Stein Unit #2
Athens Gas Field
Crawford County, PA**

Submitted To:
Schlumberger
Data and Consulting Services
1310 Commerce Drive
Park Ridge 1
Pittsburgh, PA 15275-1011

Attention: Mr. Ronald McDonald

Submitted By:
TICORA Geosciences, Inc.
19000 West Highway 72, Suite 100
Arvada, Colorado 80007
Office: (720) 898-8200
Fax: (720) 898-8222

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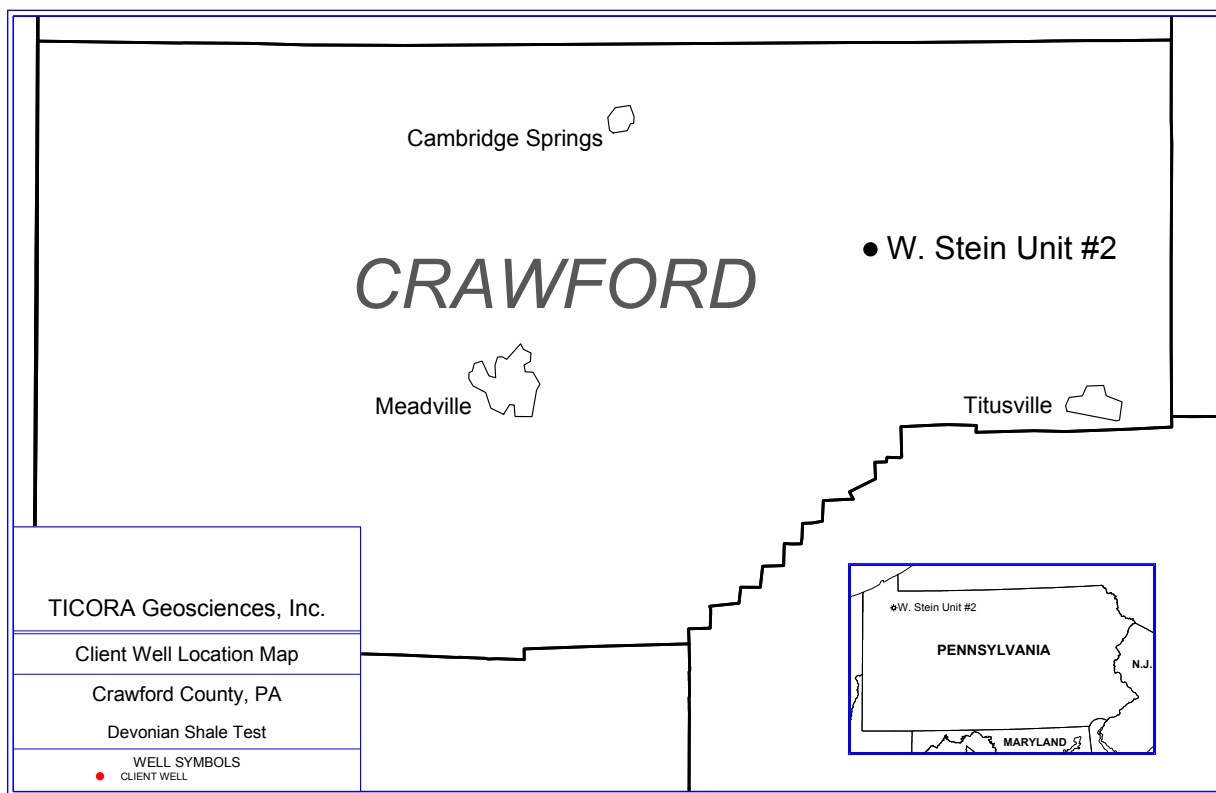
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1 INTRODUCTION

Ticora Geosciences, Inc. (TICORA) entered into an agreement for cooperative research services with Holditch Reservoir Technologies Consulting Services (Holditch) (now Schlumberger Data and Consulting Services), during May 2001 to conduct shale gas testing and analysis on a well drilled by Great Lake Energy Partnership, LLC (Great Lakes). The well was part of a reservoir characterization project Holditch conducted for the New York State Energy Development Authority (NYSERDA). The W. Stein Unit #2 well (Stein #2) is located in the Athens Gas Field, Athens Township in Crawford County, Pennsylvania.

Figure 1: W. Stein Unit #2 Well Location.



2 WELL OPERATIONS

The Stein #2 was drilled in August of 2001. Seven inch casing was set at 577 feet and a 6 ¼-inch diameter hole was drilled with air to a total depth of 1,609 feet (log depth). Allegheny Wireline Services, Inc. ran open-hole logs on Stein #2 on August 23, 2001. Four natural shows were identified on the open-hole temperature log. The well was left open hole and was flow tested (unstimulated) for three weeks during the month of October 2001. Holditch used PROMAT, a production data analysis software program to evaluate the production data (Appendix XI).

Schlumberger conducted rotary sidewall coring operations on December 5, 2001. The Stein #2 wellbore was not filled with fluid during the coring operations. Ten sidewall cores were drilled from four intervals (natural shows) within the Upper Devonian Rhinestreet shale. Rotary side-wall coring began at the deepest interval and ended at the shallowest interval. Core samples were collected from the following depths: 1) 1,149, 1,147, and 1,145 feet in the first interval, 2) 1,097, 1095, and 1,093 feet in the second interval, 3) 812 and 810 feet in the third interval, and 4) 762 and 760 feet in the final interval. The coring operation took approximately 1½-hours from cutting the first core to retrieval of the core from the sidewall rotary core barrel at the surface. Figure 2 highlights the core interval points on the Gamma Ray and Density logs from Stein #2.

Holditch personnel were on site during coring operation and placed the core samples in sidewall canisters provided by TICORA. Silicone beads were used to fill up the headspace in the all canisters except for the canister containing sample 203-10. No fluid was added to the canisters. The samples were packaged and shipped to TICORA.

A reservoir temperature of 71°F (initial reservoir temperature) and a reservoir pressure of 240 psia were supplied by Ronald McDonald (Holditch) on January 2, 2002. Ronald McDonald requested using a reservoir temperature of 80°F (revised reservoir temperature) on January 18, 2002. Measured gas content tests had already been conducted at 71°F.

The samples arrived at TICORA in early January 2002 and were placed in a water bath at 71°F (initial reservoir temperature). TICORA technicians took a single desorption reading from all the canisters on January 7-8, 2002. The samples were then removed from the canisters and processed for laboratory testing and analysis.

The shale gas testing consisted of determining weights, volumes, and densities of all the samples once they were pulled from the canisters. Photographs were taken prior to additional processing. The individual core samples (except 203-1) were combined to form a composite sample representing the Rhinestreet shale interval at Stein #2. Crushed gas testing was performed on the composite sample to measure any crushed gas. TICORA also conducted moisture holding capacity (in-situ moisture) on the composite sample. Splits from the composite were prepared and sent to various

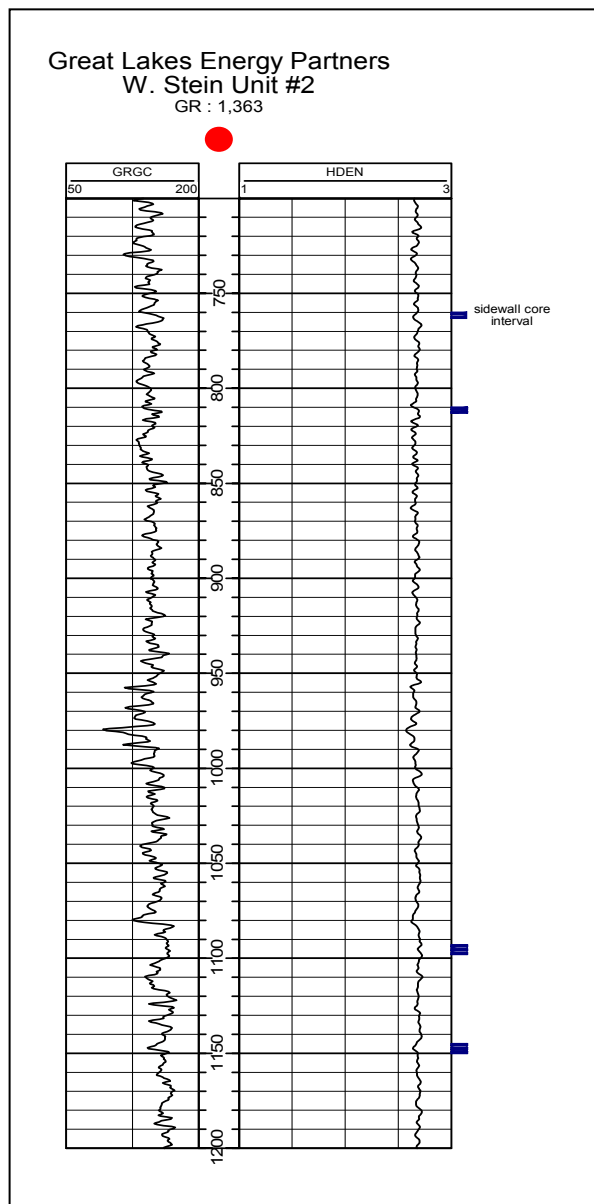


Figure 2: Gamma Ray and Density Log for the W. Stein #2 Well.

laboratories for comprehensive chemistry, x-ray diffraction, petrography, permeability, porosity, fluid saturation, total organic carbon, and methane sorption isotherm analyses. Table 1 outlines the analysis program for the side-wall and composite samples.

Table 1: Summary of Analysis Program Conducted on Sidewall Core and Composite Samples from the Stein #2 Well, Crawford County, Pennsylvania.

TICORA No.	Canister No.	Drill Depth feet	Analysis
203-1	4-10	760	Measured Gas, Photography, Plug Permeability, Porosity, Fluid Saturation
203-2	4-11	762	Measured Gas, Photography, Density
203-3	4-8	810	Measured Gas, Photography, Density
203-4	4-1	812	Measured Gas, Photography, Density
203-5	4-32	1093	Measured Gas, Photography, Density
203-6	4-19	1095	Measured Gas, Photography, Density
203-7	4-7	1097	Measured Gas, Photography, Density
203-8	4-4	1145	Measured Gas, Photography, Density
203-9	4-13	1147	Measured Gas, Photography, Density
203-10	4-12	1149	Measured Gas, Photography, Density
203-COMP-1	Na	762 – 1149	Crushed Gas, Crushed Gas Composition, Moisture Holding Capacity, Petrography, Comprehensive Chemistry, Petrography, Total Organic Carbon, X-Ray Diffraction, Methane Adsorption Isotherm

3 LABORATORY ACTIVITIES AND RESULTS

3.1 Measured Gas Content

Upon receipt of the test canisters at TICORA's laboratory, the sample canisters were placed in a water bath set at 71° F (initial reservoir temperature). Once the samples reached reservoir temperature, technicians made a **single** desorption volume reading using water displacement in a volumetric burette. The gas volume was adjusted to standard temperature and pressure (STP) using Equation (1). Table 2 summarizes the measured gas content results. The raw desorbed volumes ranged from 0 cm³ to 12.8 cm³. The average air-dry and dry ash free measured gas contents for the Rhinestreet shale desorption experiments are 2.43±3.10 scf/ton and 57.75±73.75 scf/ton, respectively. Gas content (scf/ton) is calculated by dividing the volume at STP (scm³) by the sample mass (g) multiplied by a unit conversion factor. No lost gas content extrapolations were possible due to the limited data available.

$$\text{Volume}_{\text{STP}} (\text{scm}^3) = \frac{V_1 P_1 (T_2 + 273.16)}{(T_1 + 273.16)P_2} \quad (1)$$

where:

V_1 = Initial measured volume (cm³),

P_1 = Barometric pressure during measurement of V_1 (psi),

P_2 = 14.696 psi

T_1 = Ambient temperature during measurement of V_1 (°F),

T_2 = 60°F.

3.2 Crushed Gas Measurements

Crushed gas measurements were performed on a composite of the sidewall core samples 203-2 through 203-10 (sample 203-1 was selected for special core analysis testing for which the whole core was required). Because of the small size of the composite sample, crushed gas analysis was conducted on one aliquot (analysis of triplicate aliquots is TICORA standard operating procedure).

The crushed gas volumes were determined by placing a 100-gram split of the composite sample (203-comp-1) into a sealed vessel that is capable of crushing the sample to a -200 US mesh particle size. The sample was crushed by a centrifugal acceleration of a billet-ring system within the sealed vessel. The sample was equalized to 71°F (initial reservoir temperature) and sample gas was then vented through a burette for volumetric measurement. No measurable volume of crushed gas was obtained during the crushed gas analysis.

Table 2: Desorption and Measured Sorbed Phase Gas Content Summary for Sidewall Core Samples From the Stein #2 Well.

Sample No.	Canister No.	Drill Depth <i>Feet</i>	Air-Dry Sample Weight <i>grams</i>	DAF Sample Weight <i>grams</i>	Measured Desorption Volume <i>cm³</i>	Measured Gas	
						Air-Dry Gas Content <i>scf/ton</i>	DAF Gas Content <i>scf/ton</i>
Devonian Shale, Sidewall Core, 71°F, Canister Headspace Filled With Silicone Beads and Air							
203-1	4-10	760	50.2	2.1	5.0	3.19	76.01
203-2	4-11	762	56.9	2.4	4.0	2.25	53.66
203-3	4-8	810	50.6	2.1	0.0	0.00	0.00
203-4	4-1	812	52.3	2.2	0.0	0.00	0.00
203-5	4-32	1093	56.3	2.4	0.0	0.00	0.00
203-6	4-19	1095	48.0	2.0	0.0	0.00	0.00
203-7	4-7	1097	55.8	2.3	5.6	3.22	76.61
203-8	4-4	1145	46.6	2.0	0.5	0.34	8.18
203-9	4-13	1147	40.8	1.7	8.1	6.36	151.38
203-10	4-12	1149	46.1	1.9	12.8	8.89	211.62
Desorption Data Summary							
Devonian Shale, Sidewall Core, 71°F, Canister Headspace Filled With Silicone Beads and Air							
Average			50.4	2.1	3.6	2.43	57.75
Standard Deviation			5.2	0.2	4.4	3.10	73.75

3.3 Sidewall Core Photography

Digital photography of all side-wall core samples was made before sample processing. Core photography is presented in Appendix I. Table 3 summarizes general core descriptions noted by TICORA personnel.

Table 3: Sidewall Core Descriptions from the Stein #2 Well.

TICORA No.	Canister No.	Drill Depth feet	Core Description
203-1	4-10	760	Shale, gray in color, laminated
203-2	4-11	762	Shale, gray in color, laminated
203-3	4-8	810	Shale, gray in color, laminated, small fracture on one end
203-4	4-1	812	Shale, gray in color, laminated
203-5	4-32	1093	Shale, gray in color, laminated, two fractures
203-6	4-19	1095	Shale, gray in color, laminated, one fracture
203-7	4-7	1097	Shale, gray in color, laminated, one fracture, red stain on one end of core
203-8	4-4	1145	Shale, gray in color, laminated
203-9	4-13	1147	Shale, gray in color, laminated, rubble on one end
203-10	4-12	1149	Shale, gray in color, laminations, rubble on one end

3.4 Moisture Holding Capacity

The moisture holding capacity of coal is the amount of moisture the coal can hold at 100 percent relative humidity without any moisture present on the surface of the coal particles. The moisture holding capacity approximates the in-situ moisture content of the coal seam. The moisture holding capacity analysis procedure used by TICORA differs from that of standard method ASTM D 1412, which is the analysis procedure followed by most commercial laboratories for determining the moisture holding capacity of coal.¹ In this ASTM analysis procedure, the moisture holding capacity value is defined as the percentage weight loss upon drying in an atmosphere of air –16 mesh (<1.19 mm), water saturated coal particles following equilibration at 96-97 percent relative humidity and 86°F (30 °C) for 48 hours. This ASTM analysis procedure has some inherent shortcomings with respect to accurately determining the in-situ moisture holding capacity of coalbed reservoirs.

The moisture holding capacity of coal varies inversely as a function of temperature. In order to obtain accurate in-situ moisture holding capacity values, the moisture equilibration procedure must be performed at reservoir temperature conditions. TICORA determines moisture holding capacity values by equilibrating super-saturated 5-gram samples at 96-97 percent relative humidity and reservoir temperature conditions in an inert atmosphere for a period of approximately 30 days.

The moisture holding capacity is then determined by measuring the weight loss after oven drying the samples.

A 5-grams split of the composite sample (203-comp-1) was equilibrated for 29-days at 80°F (revised reservoir temperature). A moisture holding capacity of 2.882% was determined from the analysis. Appendix II summarizes the moisture holding capacity results.

3.5 Gas Chromatography Analysis

TICORA technicians attempted to collect one gas sample for gas chromatography (GC) analysis. The results of the CG analysis indicate that the gas sample had a composition similar to ambient air. Due to the extremely low desorbed gas volume, which was well below the estimated canister headspace, the sample collected probably represents headspace air contained in the canister. Gas chromatography analysis results are presented in Appendix III.

3.6 Total Organic Carbon

TICORA sent a split of the composite sample (203-comp-1) to Core Laboratories Petroleum Services (Core Lab) for Total Organic Carbon (TOC) analysis. The TOC reported result was 0.36%. This value suggests the sample is extremely lean in organic material. A value of 0.36% is less than 0.50%, which is the classic definition of a source rock. TOC results are presented in Appendix IV.

3.7 Bulk Density

TICORA calculated bulk density from the measured mass and volume of the individual core samples. These results are summarized in Table 4. TICORA also ran a single density analysis using helium pycnometry on a split from the composite sample (203-comp-1), which is also reported in Table 4 and Appendix V. In addition to these density measurements, Core Lab ran grain density analysis on sample 203-1 (Appendix IX). The grain density analysis gave a result of 2.73 g/cm³ for sample 203-1 (c.f. value in Table 4).

Table 4: Bulk Density Analysis for Side-Wall Core and Composite Samples from the Stein Unit #2 Well.

TICORA No.	Canister No.	Drill Depth Feet	Density g/cm³
203-1	4-10	760	2.64
203-2	4-11	762	2.84
203-3	4-8	810	2.66
203-4	4-1	812	2.68
203-5	4-32	1093	2.82
203-6	4-19	1095	2.67
203-7	4-7	1097	2.79
203-8	4-4	1145	2.60
203-9	4-13	1147	2.72
203-10	4-12	1149	2.56
203-COMP-1	na	762 – 1149	2.73
Average (203-2 – 203-10)		762 – 1149	2.71
Average (all samples)		760-1149	2.70

3.8 Comprehensive Chemistry

TICORA sent one split of the composite sample (203-comp-1) to Commercial Testing and Engineering Co. (CT&E) for comprehensive chemistry testing. The comprehensive chemistry testing consists of proximate analysis (moisture, ash, and sulfur), ultimate analysis (hydrogen, oxygen, sulfur, nitrogen, and carbon), and gross calorific value. Appendix VI presents CT&E's reported results. A summary of these results is shown in Table 5.

3.9 Vitrinite Reflectance

TICORA sent one split of the composite sample (203-comp-1) to the Center for Applied Energy Research (CAER) for petrographic analysis by vitrinite reflectance. The results to the vitrinite reflectance analysis are reported in Appendix VII. The R_{MAX} value reported by CAER was 0.58. The sample was dominated by clay minerals and was lean with respect to organic matter. Therefore, TICORA believes there is a high level of uncertainty with the accuracy of the vitrinite reflectance value.

3.10 X-Ray Diffraction

TICORA sent split of the composite sample (203-comp-1) to the CAER for analysis by x-ray diffraction. Based on CAER's report sample 203-comp-1 has 70-75% quartz, 10-15% kaolinite,

and 10-15% illite. Small amounts of iron (Fe) were present on the XRF scan. The Fe could be a component within the illite or perhaps amorphous on mineral grains. The XRD plot is presented in Appendix VIII.

Table 5: Comprehensive Chemistry Analysis Results for 203-COMP-1 from the Stein #2 Well.

	As-Received	Dry	Dry Ash-Free	Moist
Moisture Holding Capacity				2.882
Moisture Holding Capacity Factor				0.971
	weight %	weight %	weight %	weight %
Proximate:				
Moisture	0.79			
Ash	95.01	95.77		93.01
Volatile Matter	0.01	0.01	0.24	0.01
Fixed Carbon	4.19	4.22	99.76	4.10
Total	100.00	100.00	100.00	100.00
Ultimate:²				
Moisture	0.79			
Hydrogen	<0.01	<0.01	0.24	0.01
Carbon	0.43	0.43	10.24	0.42
Nitrogen	0.06	0.06	1.43	0.06
Sulfur	0.62	0.62	14.76	0.61
Oxygen	3.08	3.11	73.33	3.02
Ash	95.01	95.77		93.01
Total	100.00	100.00	100.00	100.00
Parr Parameters				
SO ₃ in Ash (Eschka Method)		0.63		
SO ₃ in Ash, % of Coal	0.60	0.60		0.59
SO ₃ -Free Ash	95.01	95.16		92.42
Parr Mineral Matter, Adjusted for SO ₃ in Ash	102.95	103.12		100.15
Fixed Carbon Adjusted for SO ₃ in Ash	4.79	4.83		4.69

1. Composite sample formed by combining nine sidewall core samples (203-2 through 203-10) from the interval 762 ft to 1149 ft.
2. Ultimate Analysis: Hydrogen and oxygen values reported above do not include the hydrogen and oxygen in the free moisture found in the sample.

3.11 Permeability, Porosity, and Fluid Saturation

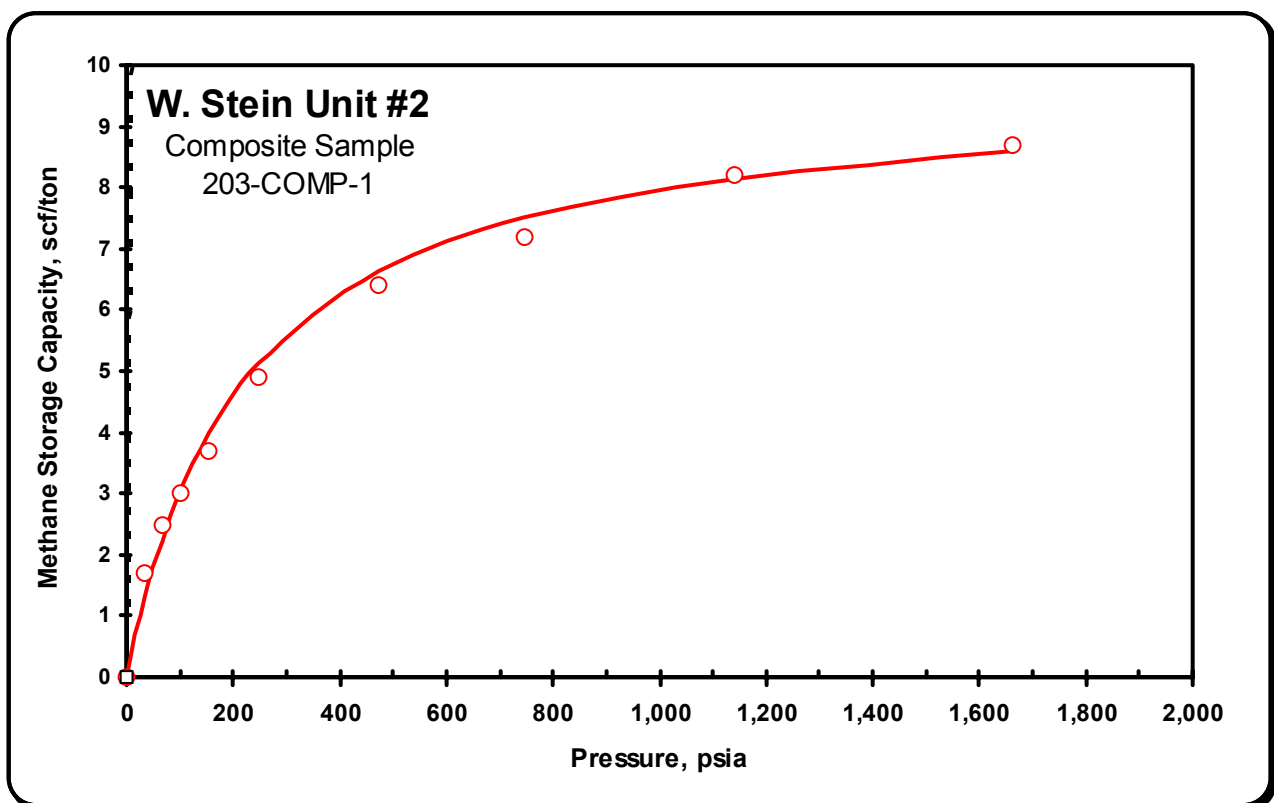
TICORA sent one split of the composite sample (203-comp-1) and the whole side-wall core sample 203-1 to Core Lab for permeability, porosity, and fluid saturation analysis. Core Lab was unable to run the tests as directed on 201-comp-1 due to equipment limitations and uncertainty in the results based on their analysis. Permeability, porosity, and saturation analysis were conducted on 203-1 using their rotary sidewall core protocol. Results are reported in Appendix IX. Measurements were done with a net overburden stress of 800 psia. Porosity was reported as 3.9% and permeability as 0.009 md. Fluid saturations by Dean Stark extraction were reported as 0.0% oil and 46.8% water, resulting in a gas filled porosity of 2.07%.

3.12 Gas Storage Capacity (Methane Adsorption Isotherm)

TICORA sent one split of the composite sample (203-comp-1) to TerraTek, Inc. (TerraTek) for sorbed phase gas storage capacity determination. A reservoir pressure of 240 psia and reservoir temperature of 80°F (revised reservoir temperature) were used for the isotherm analysis. The results of this analysis are presented in Appendix X.

A methane storage capacity of 5.1 scf/ton (as received basis) was determined from the methane adsorption isotherm at reservoir pressure (240 psia). Figure 3 shows pressure versus methane storage capacity (as received basis).

Figure 3: Methane Storage Capacity of the Composite Sample from the W. Stein Unit #2 Well on an As Received Basis.



4 GAS-IN-PLACE EVALUATIONS

For gas shale reservoir systems, the total volume of gas stored is the sum of the volume of gas sorbed into the organic matter, the volume stored as free gas in the porosity, and the volume of dissolved gas in water. Equation (2) summarizes this relationship.

$$G_t = G_s + G_f + G_d \quad (2)$$

where:

G_t	total gas content, scf/ton
G_s	sorbed gas content, scf/ton
G_f	free gas content, scf/ton
G_d	dissolved gas in water gas content, scf/ton

Gas content can be converted to gas-in-place (GIP) volume using Equation (3).

$$GIP = 1359.7 Ah\bar{p}\bar{G}_t \quad (3)$$

where:

GIP	gas-in-place, scf
A	drainage area, acres
h	reservoir thickness, feet
\bar{p}	average bulk density, g/cm ³

The 1,359.7 value in Equation (3) is the conversion factor to convert the units to standard cubic feet (scf). Since no significant water was produced during the production testing, dissolved gas in water is not expected to be a contributor to GIP for Stein #2. The gas content measurements conducted on Stein #2 along with the adsorption isotherm provide information for sorbed phase GIP. Table 6 summarizes the gas-in-place calculations using both the average measured gas content value (desorption-based) from the sidewall core samples and the adsorption-based gas storage capacity (isotherm) from the composite sample in the GIP equation. Both values are used to provide a minimum and maximum for sorbed GIP. The well spacing and reservoir thickness values were taken from the Holditch PROMAT analysis on Stein #2.

The free gas content is defined by Equation (4).

$$G_f = \frac{32.0268\phi(1 - S_w)}{\bar{p}B_g} \quad (4)$$

where:

ϕ	macroporosity, fraction of bulk volume
S_w	water saturation in the macroporosity, fraction of macroporosity volume
B_g	gas formation volume factor, reservoir volume/surface volume

The free gas content for Stein #2 was calculated by substituting the following values into Equation (4); average bulk density of 2.70 g/cm³, porosity of 3.9%, water saturation of 46.8%, and a gas formation volume factor of 0.0607 (z-factor of 0.970 at 71 °F and 240 psia). For these average reservoir properties, the free gas content (G_f) is calculated to be 4.05 scf/ton. The GIP for free gas was calculated using Equation (3) and the same values for well spacing, thickness and average density as provided in Table 6. The free gas GIP for Stein #2 using these data is 53.52 Mmcf.

Table 6: Sorbed Phase and Free Gas-In-Place Estimates for the Stein #2 Well.

Gas Content Data Source	Well Spacing (acres)	Thickness (feet)	Avg. Density (g/cc)	As-Received Gas Content (scf/ton)	GIP (mmcf)
Desorption	40	90	2.70	2.43	32.12
Sorption	40	90	2.70	5.10	67.40
Free Gas	40	90	2.70	4.05	53.32
Total Gas	40	90	2.70	6.48 to 9.15	85.44 to 120.72

The total GIP for Stein #2 is the summation of the sorbed GIP (or desorbed GIP) and the free gas GIP. The range for total GIP is 85.44 to 120.72 Mmcf (based on desorbed and sorped GIP, respectively). This range is based on the assumptions used in the above calculations. The results from the Holditch PROMAT analysis calculated an original GIP of 82.44 Mmcf based on history matching the production test data. This value is close to the lower range calculated above.

To assist in gaining further insight into the natural gas resource base for the Rhinestreet shale in Crawford County, Pennsylvania, a literature review was conducted. As part of the U.S. Department of Energy Eastern Gas Shale Project (EGSP) resource evaluations were performed for the Devonian shale in the Appalachian basin.² Estimates were made using three different techniques: 1) experimentally determined total gas, 2) geochemically determined total gas, and 3) estimated indigenous gas content. The experimentally determined total gas is the lower bound of the estimates that were performed and was selected for comparison. For the early and late Rhinestreet time in the vicinity of Stein #2, the experimentally determined total gas ranged from 20 to 30 Mcf/acre-foot. Using a well spacing of 40 acres and net reservoir thickness of 90 feet, the GIP using this approach for Stein #2 is 72 to 108 Mmcf. This range is similar to both above the calculations.

5 SUMMARY AND CONCLUSIONS

The gas content estimates from the Rhinestreet shale sampled in the Great Lakes Stein #2 well in Crawford County, Pennsylvania are low compared to other productive gas shale plays. Well and coring operations have likely contributed to an underestimation of the sorbed phase gas content of the reservoir. By producing the well prior to collecting the sidewall core samples, gas was likely desorbed from the near wellbore area sampled by the rotary sidewall coring operations. The long delay in between drilling and coring also may have introduced additional sources of error including oxidation and additional lost gas. In addition, no early time desorption measurements were done on site. Thus, no lost gas estimations were possible.

While the low gas content values may be attributed to well conditions and measurement error, the methane isotherm indicates that the methane storage capacity of the reservoir by adsorption is also very low compared to other productive gas shale plays. The low gas content and storage capacity are also supported by the low Total Organic Carbon determined from the composite sample (203-comp-1). The majority of the gas stored by adsorption in shale reservoirs is on the organic material within the rock.

The chemical analysis shows the composite sample (203-comp-1) to be high in ash (95.01%). The bulk density data (ranging from 2.56 g/cm³ to 2.84 g/cm³) support this finding. The high ash value is further supported by the x-ray diffraction analysis, which shows that the composite sample was made up of 70–75% quartz, 10–15% kaolinite, and 10–15% illite.

Vitrinite reflectance analysis was difficult due to the small percentage of organic carbon matter in the sample. In addition, the small particle size of the organics made it difficult for the analyst to differentiate between the specific carbon macerals. The analysis indicated subbituminous/high volatile C bituminous particles along with some higher reflecting vitrinites, possibly semifusinite. Because of the low TOC value, Rock Eval analysis would not be able to be performed on this sample to further determine maturation of the organic material.

6 RECOMMENDATIONS

Due to the uncertainty in the measured gas content data and the limited core analysis performed, TICORA recommends that additional reservoir characterization work be performed to better define GIP estimates. This additional work would include higher sampling density of the reservoir to determine porosity and fluid saturations. Reservoir characterization could be enhanced through the acquisition of full conventional core samples. Full diameter core (3–3 ½ inch) would provide a more representative sample of the reservoir for testing and analysis. More accurate gas content estimates could be made if a mobile laboratory was on site to collect the data during coring operations and measure gas content immediately upon sealing the canisters and placing them in a water bath at reservoir temperature. In addition, whole core would enable fracture characterization work to be performed, as well as other routine core analysis on samples not selected for gas content determination.

If sidewall coring is to be used in the future operations, additional care should be taken to acquire the core immediately upon completion of drilling and open hole logging operations. The well should not be flow tested prior to conducting sidewall coring operations. The core should be placed in canisters and if gas measurements cannot be made on site, the samples should be shipped immediately to the laboratory for testing and analysis. A minimum of 5 samples should be selected for sidewall coring from each interval of interest by the operator. Additional laboratory testing on samples with TOC values greater than 0.5% should include Rock Eval. Thermal alteration Index (TAI) should also be included in the analysis program for kerogen maturation indication.

7 REFERENCES

¹ 2001 Annual Book of ASTM Standards, Volume 05.05 Gaseous Fuels; Coal and Coke, American Society for Testing and Materials, Philadelphia, PA (2001).

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