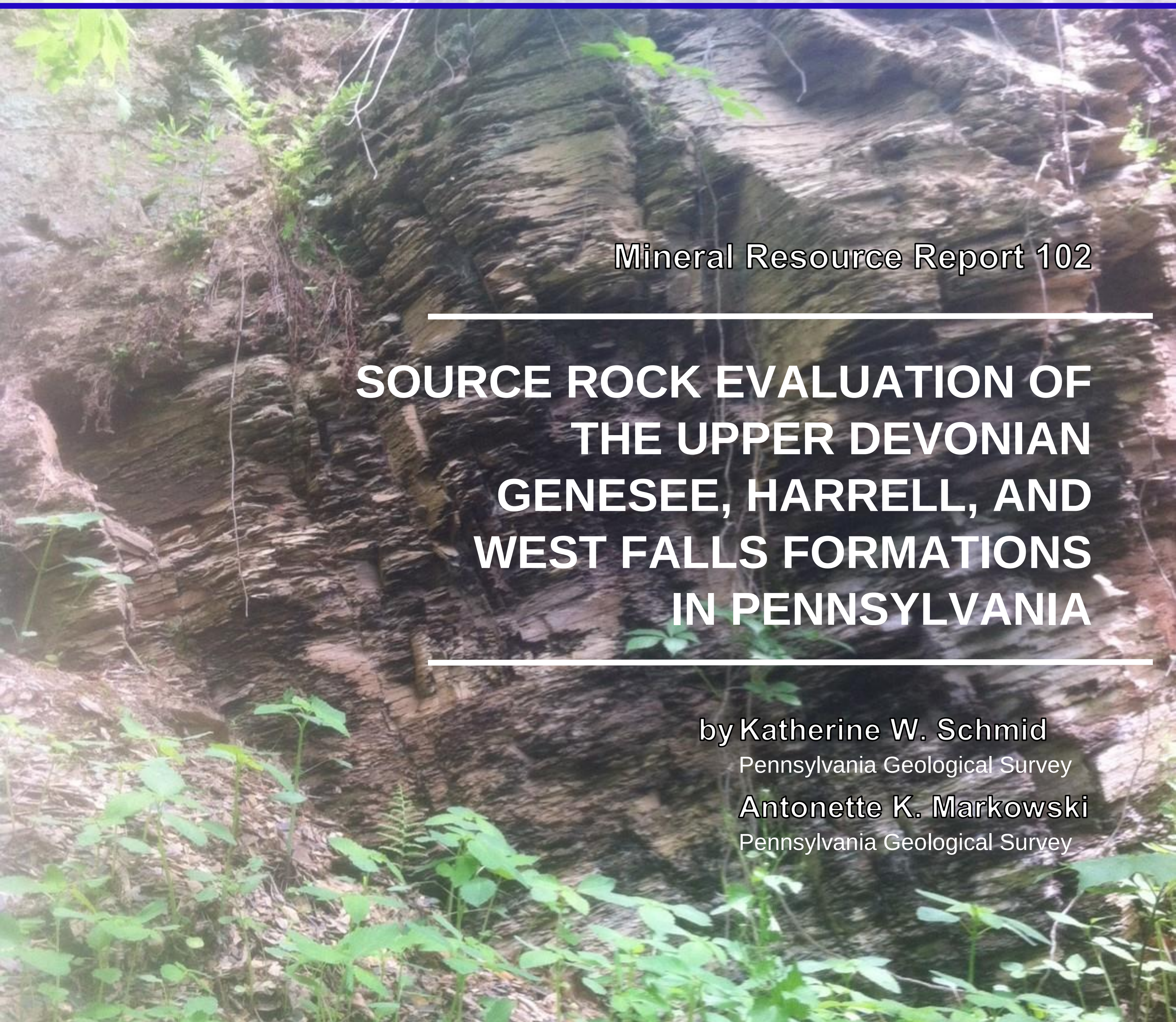

pennsylvania
DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

Mineral Resource Report 102

SOURCE ROCK EVALUATION OF THE UPPER DEVONIAN GENESEE, HARRELL, AND WEST FALLS FORMATIONS IN PENNSYLVANIA

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PENNSYLVANIA GEOLOGICAL SURVEY
FOURTH SERIES
HARRISBURG

2017

COMMONWEALTH OF PENNSYLVANIA

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Cover Photo: Outcrop of the Upper Devonian Burket Shale Member of the Harrell Formation in Clinton County, Pennsylvania. Photo by Rose-Anna Behr.

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Suggested citation: Schmid, K. W., and Markowski, A. K., 2017, Source rock evaluation of the Upper Devonian Genesee, Harrell, and West Falls Formations in Pennsylvania: Pennsylvania Geological Survey, 4th ser., Mineral Resource Report 102, 45 p. plus appendix and 4 plates.

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SOURCE ROCK EVALUATION OF THE UPPER DEVONIAN GENESEE, HARRELL, AND WEST FALLS FORMATIONS IN PENNSYLVANIA

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ABSTRACT

Commercial production of natural gas from the Middle Devonian Marcellus shale in Pennsylvania has sparked interest in shallower organic-rich shales. According to the Pennsylvania Geological Survey Exploration and Development Wells Information Network (PaGS EDWIN), oil and gas companies have drilled and completed more than 80 wells in Upper Devonian organic-rich shales in this commonwealth. Primarily, these shales include the Geneseo Member of the Genesee Formation, Burket Member of the Harrell Formation (partial lateral equivalent to the Genesee), and Rhinestreet Member of the West Falls Formation.

Most of the data used in this study were supplied by external entities that analyzed samples of drill cuttings from the PaGS inventory for parameters including total organic carbon content (TOC), calculated vitrinite reflectance (R_o), and mineralogy. The authors validated 121 data points by checking sample depths against available geophysical and drillers' logs to ensure accurate formation identification. In most cases, organic members of these formations had been selected for sampling. Where available, the authors also used mineral information to confirm the formations.

The authors created scatter plots for TOC versus gamma-ray, TOC versus quartz, and R_o versus depth to further evaluate these organic-rich shale members. TOC and gamma-ray values did not exhibit any relationship, implying rapid sedimentation rates. Positive relationships between TOC and quartz indicate the presence of biogenic silica. The plot of R_o versus depth suggests the expected relationship of increasing thermal maturity with increasing depth in the West Falls Formation and nonlinear trends in the Genesee and Harrell Formations invite further assessment.

Tectonic forces and basement structures played key roles in the development and distribution of TOC and thermal maturity in these Upper Devonian formations. The Acadian and Alleghanian orogenies and subsequent mobility of hydrothermal fluids along lineaments demonstrated the strongest influence on thermal maturities for these formations. The Rome trough, a deep basement structure in the Appalachian basin, exhibited strong effects on TOC distribution in the Genesee and Harrell Formations which may be the result of anoxic subbasins within the trough. Periodic algal blooms of *Tasmanites* enhanced organic matter preservation in shales above the subbasins. The trough influenced thermal maturity to a lesser extent than it did TOC in these formations. Depositional conditions changed when the Appalachian basin's depocenter shifted to the west, diminishing the Rome trough's impact on TOC and thermal maturity in the West Falls Formation.

Maps of TOC and R_o reveal areas of hydrocarbon potential for these Upper Devonian shales. Genesee and Harrell organic-rich shales show potential for expanded production over much of the study area. The Rhinestreet Shale also displays further oil and gas production potential in northwestern Pennsylvania.

INTRODUCTION

Study Objectives

Just over a decade ago, the Middle Devonian Marcellus shale—an organic-rich source rock—became a major target for the oil and gas industry in Pennsylvania. The Upper Ordovician Utica Shale became attractive to companies more recently, but these are not the only organic-rich shales that drillers have targeted in this state. Oil and gas companies have drilled and completed more than 80 wells in the organic-rich members of the Upper Devonian Genesee, Harrell, and West Falls Formations (Exploration and Development Wells Information Network [EDWIN], 2016). These organic-rich shales are known as the Geneseo Shale Member in the Genesee Formation, which is partially correlative to the Burket Shale Member where the Harrell Formation is present, and the Rhinestreet Shale Member in the West Falls Formation (Figure 1).

Total organic carbon (TOC) and calculated vitrinite reflectance (R_o) are two measurable parameters that are often used to determine a rock's potential for hydrocarbon production. The purpose of this report is to present and interpret TOC and R_o data from these Upper Devonian shales. The authors illustrated these data in graphs, maps, and raw spreadsheet format.

A shale source rock must contain more than 1 percent TOC to generate hydrocarbons (Laughrey, 2009). There are different points of view on the factors governing the amount of organic carbon preserved in a rock. Smith (2014) and Katz (2015) regard initial carbon productivity, preservation of organic carbon, and sedimentation rate as the most important factors while Hunt (1996) and Laughrey (2009) consider transport and preservation of organic material as more important than original productivity.

Researchers often use the thermal maturity of a rock to determine the quality of the reservoir—that is, what types of hydrocarbons could have been produced by the rock already (Tissot and Welte, 1978; Laughrey, 2009). It is also significant in the development of a porosity and permeability system in the source rock (Carr and others, 2014). Thermal maturity was first reported in coal as units of percent R_o in oil immersion under microscopic examination. R_o is the measured percentage of reflected light from a vitrinite-rich sample. Vitrinite is a type of maceral (microscopic organic component of coal or oil shale) derived from woody plants commonly found in coal, but it is not common in marine shales (Laughrey, 2009; Pawlewicz and Finn, 2012; Finn and Pawlewicz, 2013). Alternate methods for obtaining thermal maturity values equivalent to the R_o values include the Conodont Alteration Index (CAI), Thermal Alteration Index, or maturities calculated from values obtained from Rock-Eval experiments (Laughrey, 2009). Rock-Eval pyrolysis experiments progressively heat samples to 1,022° Fahrenheit (F) (550° Celsius [C]) in an inert atmosphere and the amount of hydrocarbons released at each stage is measured (Tissot and Welte, 1978). The R_o values used in this study are R_o equivalence values calculated from Rock-Eval experiments. The methods used to calculate these R_o values are proprietary to the companies that analyzed the samples.

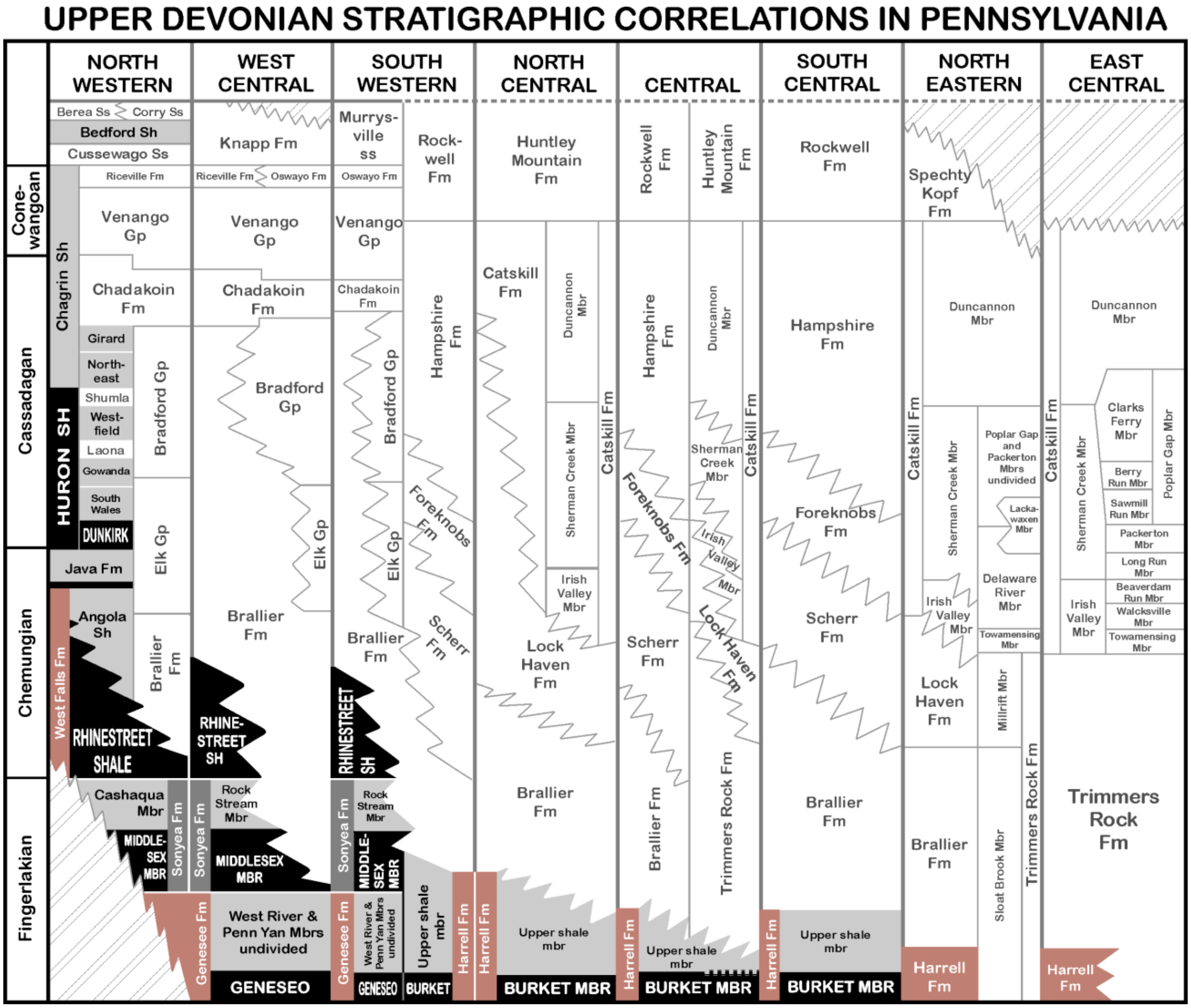


Figure 1: Subsurface rock correlation diagram of Pennsylvania's Upper Devonian oil and gas producing regions, including the stratigraphic positions of the Genesee, Harrell, and West Falls Formations as featured in this study (modified from Harper, 1999, p. 112). Stage names listed on the left are North American names. Formations discussed in this report are highlighted in brown. Organic-rich shales are shown in black. The Tully Limestone, which underlies the organic Geneseo and Burket Members, marks the top of the Middle Devonian sequence.

The data in this report focus on shales from the Upper Devonian Genesee, Harrell, and West Falls Formations and their respective organic members: the Geneseo, Burket and Rhinestreet Shales. The authors did not differentiate the partially correlative Geneseo and Burket Shales in the results and discussion sections of this report. The information presented indicates that these organic-rich shales have potential for hydrocarbon production. Organic carbon concentration and vitrinite reflectance analyses (Repetski and others, 2008) indicate that the Genesee and Marcellus Formations of the Marcellus magnafacies contain enough organic carbon to be valuable source beds as evidenced by today's production (Schmid and Schmid, 2014). The term "magnafacies" *sensu* (in the sense of) Caster (1934), refers to a major belt of homogeneous deposits which span across several time-stratigraphic units despite variations in provenance, transport system, and depositional setting (Harper and Laughrey, 1987; Figure 2).

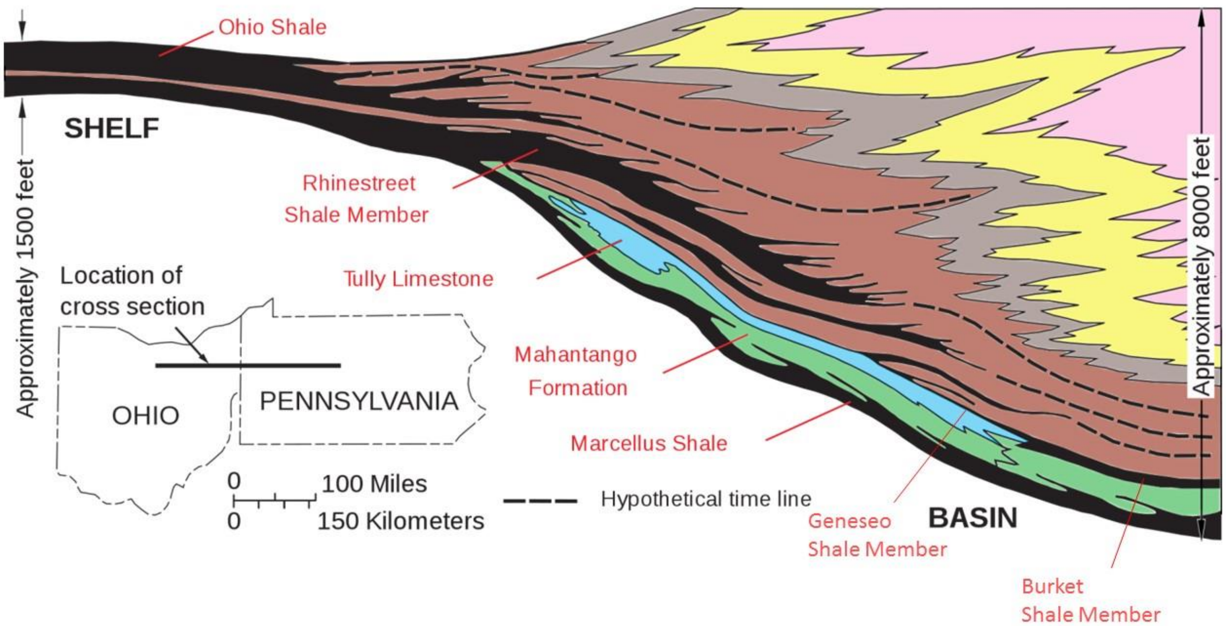


Figure 2: Schematic of Upper and Middle Devonian magnafacies, indicated by different colors, across the western Appalachian basin including the Geneseo, Burket, and Rhinestreet Members as pertinent to this report (modified from Harper, 1999, and Milici and Swezey, 2006). These organic-rich shale members are represented by the black shaded areas. Approximate thicknesses range from 1,500 feet (ft) (457.2 meters [m]) in northcentral Ohio to 8,000 ft (2,438.4 m) in northcentral Pennsylvania. This figure is not to scale.

Data Sources

The Bureau of Topographic and Geologic Survey, better known as the Pennsylvania Geological Survey (PaGS), maintains several facilities that store rock core and cuttings from oil and gas wells drilled in the commonwealth. A majority of these samples have been donated to the PaGS by various companies or individuals and are stored for use in geologic studies. Anyone may analyze samples for individual studies, but data obtained from the analyses must be shared with the bureau. All of the samples used in this particular study had been donated to the PaGS. Most of the data reported herein have been supplied by outside entities who analyzed cuttings from the bureau inventory. Company names are not associated with the data in order to not put them at a potential competitive disadvantage. This encourages the use and reporting of material in the authors' repository. Data are reported "as received," with the exception of associating a lithologic unit to a depth interval. Other data were obtained from the PaGS's publically available database (Laughrey and others, n.d.).

Regional Geologic Setting of the Appalachian Basin

All but the southeastern corner of Pennsylvania lies within the Appalachian basin—a composite, retroarc foreland basin (Ettensohn, 2008) that has formed a northeast-southwest trending sediment-filled trough extending from southern New York to central Alabama (Ryder, 1995). The Appalachian basin contains about 50,000 ft (15,240 m) of Neoproterozoic and Paleozoic (Cambrian through Permian Periods) rocks (Roen, 1993). The entire basin encompasses about 185,500 square miles (sq mi) (480,443 square kilometers [sq km]) throughout the eastern United States (Ryder, 1995). The study area is located within a portion of the Appalachian basin that covers western and north-central Pennsylvania (Figure 3). It extends from Greene County in the southwest corner of the state, northward through Erie County, and eastward to the western half of Bradford and Sullivan Counties.

The Rome trough is a complex graben system which lies near the central portion of the Appalachian basin in the region studied (Figure 3). Early to Middle Cambrian rifting, which formed the Iapetus Ocean (a proto-Atlantic sea that existed through the Carboniferous and Permian Periods before the European and African plates collided with the North American plate), created the Rome trough (Gao and others, 2000). This may have facilitated the creation of accommodation space and the opportunity for increased preservation of organic material in Upper Devonian shales of this study.

Three Paleozoic mountain building events, or orogenies, shed wedges of clastic sediments into the east flank of the basin, east of the study area—the Taconic, Acadian, and Alleghanian orogenies. The Taconic orogeny occurred in the Ordovician about 470 to 440 millions of years before present (Ma) when volcanic islands collided with the North American plate margin, leaving roots from the eroded mountain range in the Eastern Piedmont (Plank and Schenck, 1998). The Acadian and Alleghanian orogenies were most noteworthy in their depositional contribution to Pennsylvania's share of the basin. The authors used approximate age ranges for these orogenies because a wide variety of ages have been reported in the literature. The Acadian orogeny produced significant amounts of sediments approximately 390 to 350 Ma which contributed to extensive sedimentary deposits—including the Catskill delta complex—throughout much of Devonian to Middle Mississippian time for the entire Appalachian region (Lyons and Faul, 1968; Rodgers, 1970; Palmer, 1983; Faill, 1985, 1999; Ettensohn, 1985, 2004, 2008; Stoffer, 2003). A reduction in sediment input enabled an extensive marine incursion in the western Appalachian basin which indicates the end of Acadian activity and the Catskill delta complex (Ettensohn, 1985; Faill, 1999; Stoffer, 2003). The Alleghanian orogeny occurred between the Middle Carboniferous and Early Permian about 320 to 275 Ma (Rodgers, 1970; Van der Voo, 1979; Palmer, 1983; Ettensohn, 1994, 2004; Faill, 1999; Stoffer, 2003). The present architecture of the Appalachian foreland basin is mainly due to the Alleghanian orogeny (Ettensohn, 2008). This orogeny was followed by the initial fragmenting of supercontinent Pangaea in the Triassic around 220 Ma (MacLachlan, 1999).

The Allegheny Front is an abrupt structural boundary that was created during the Alleghanian orogeny (Figure 3). Open folds generally characterize the gently deformed region west of the front. Fractures, faults, and lineaments that are recognized west of the front today formed before, during, and after the main phase of Alleghanian folding (Faill, 1985, 1999; Gold, 1999; Lash and Engelder, 2011). Specifically, the lineaments or cross-strike discontinuities (CSDs) of this study are related to basement structures that could have been reactivated during the Acadian and Alleghanian orogenies (Canich and Gold, 1985).

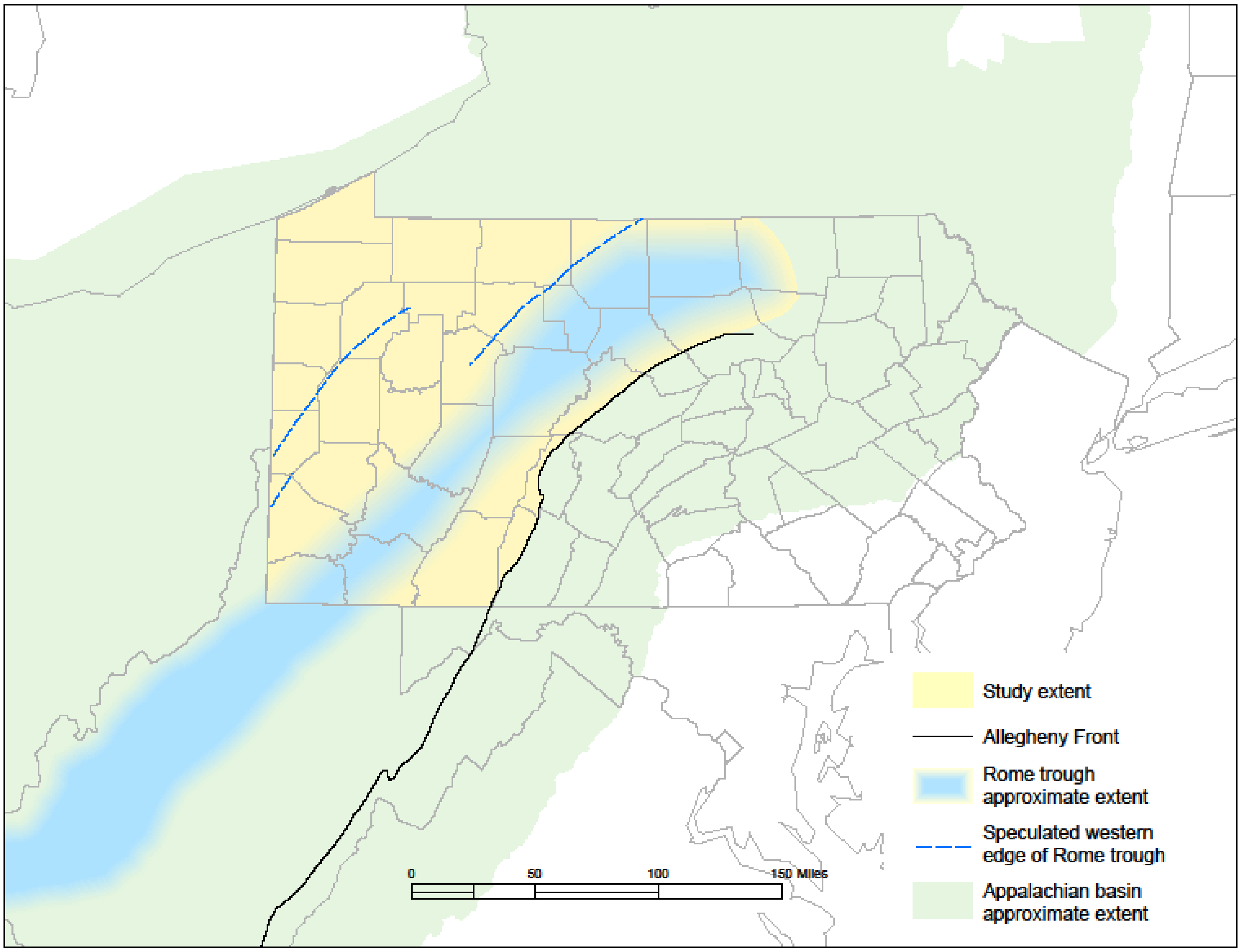


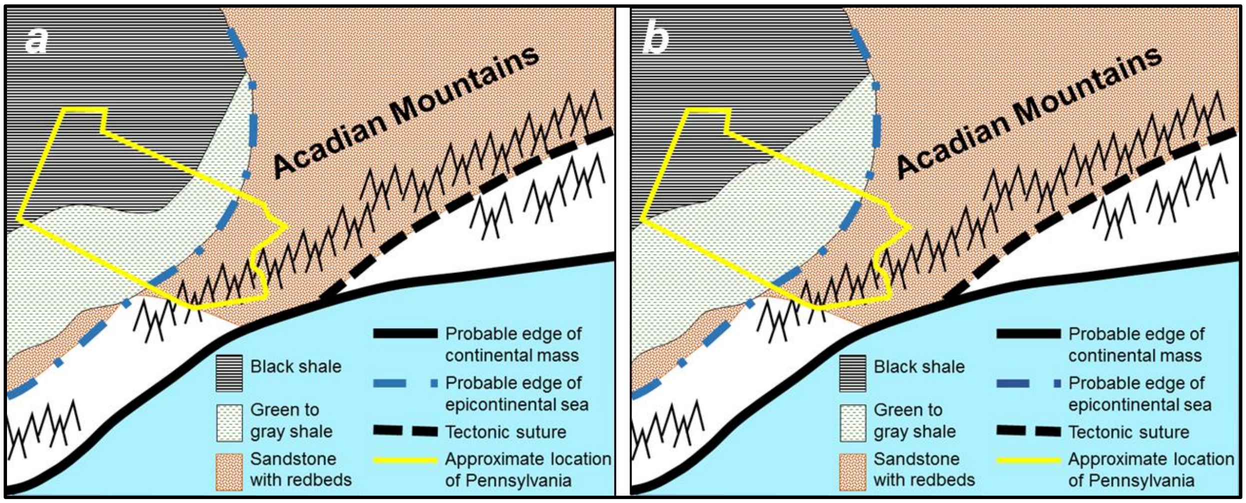
Figure 3: Areal extent of the Appalachian basin in Pennsylvania and portions of surrounding states (modified from Ryder, 1995). Also shown are the Allegheny Front (slightly modified from Faill, 2011, and West Virginia Geological and Economic Survey, n.d.), the approximate extent of the Rome trough (modified from Harris and others, 2004, Alexander and others, 2005, and Repetski and others, 2008), and the speculated western edge of the Rome trough as shown by dashed blue lines (Harper, 1989, 2004). The extent of this study is shown in yellow.

Late Devonian Depositional History

During the Devonian, most of Pennsylvania was part of an extensive inland sea receiving intermittent influxes of older continental sediment from an eastern source area (Harper, 1999). Sea level varied throughout the Devonian in response to global eustasy and tectonic pulses of the Acadian orogeny.

Regional subsidence in the Late Devonian halted proliferation of shallower, unnamed Middle Devonian depositional systems, shifting the strandline to the east, as evidenced by black shale (Burket Shale Member) deposition across the basin (Faill, 1999; Figure 4a). Over time, westward deepening of the basin may have shifted black shale deposition to the west (Ettensohn and Barron, 1981; Figure 4b).

Late Devonian marine and nonmarine rocks in Pennsylvania result from east-to-west clastic deposition across the Appalachian basin by a prograding deltaic complex known as the Catskill delta (Dennison, 1985). In the Catskill deltaic system, there were "multiple contiguous deltas operating in the same sedimentary basin at approximately the same time." (Sevon and Woodrow, 1981, p. 11). More than 69,000 cubic miles (cu mi) (287,604.6 cubic kilometers [cu km]) of sediment were introduced into the Catskill deltaic system (Dott and Batten, 1976; Harper, 1999). Sediment thicknesses of up to 44,950 ft (13,700 m) accumulated in parts of central Pennsylvania (Patchen and others, 1985a, 1985b; de Witt and Milici, 1989).



Figures 4a and 4b: Late Devonian paleogeography and lithofacies of Pennsylvania and surrounding areas (modified from Ettensohn and Barron, 1981, p. 18, and Harper, 1999, p. 124). The light blue in the southeastern corner of these figures represents the waterway between the Ouachita Sea and the Rheic Ocean (the Paleozoic ocean that separated the Gondwanan and Laurussian continents). The dark blue dashed line north of this marks the probable southeastern edge of the epicontinental sea in which the black shales formed. Figure 4a represents deposition early in the Late Devonian when the Geneseo and Burket Shales were deposited. The authors estimated the extent of these shales for this figure using data from oil and gas wells. Figure 4b represents deposition slightly later in this time period when the Rhinestreet shales were being deposited. The authors approximated the Rhinestreet extents used in this map from Pennsylvania Department of Conservation and Natural Resources (2009). The westward spread of green to gray shales is a response to the westward deepening of the basin as black shale deposition shifted further to the west (Ettensohn and Barron, 1981).

The Catskill deltaic system is a classic facies example of a tectonic delta complex dominated by orogenic sediments derived from erosion of an active tectonic complex into a neighboring marine basin (Friedman and Johnson, 1966). Characterized by interfingering strata including flysch and molasse sequences, it is the thickest integrated sediment wedge in the Appalachian basin and represents one of the most complex rock sequences in North America (Harper, 1999). Middle and Late Devonian depositional systems introduced silt into small areas of black mud on the eastern edge of the inland seaway, suggesting that new streams drained newly uplifted areas (Dennison, 1985). Deltas east of Pennsylvania probably generated enough turbiditic flysch to push the black mud deposits into western Pennsylvania during the Fingerlakian

Stage of the Late Devonian (Faill, 1999; Harper, 1999; Figure 1). By the end of the Late Devonian to as late as the Middle Mississippian (Ettensohn, 1985), the Acadian orogeny waned and the Catskill delta complex sedimentation diminished along the entire Appalachian region (Ettensohn, 1985; Stoffer, 2003). This marks the end of one orogenic phase or the beginning of the fourth tectophase—one of four major episodes of Ettensohn's (1985; Figure 5) intense deformational model. Tectophase refers to all the events that take place during one phase of an orogeny (Ettensohn, 2004).

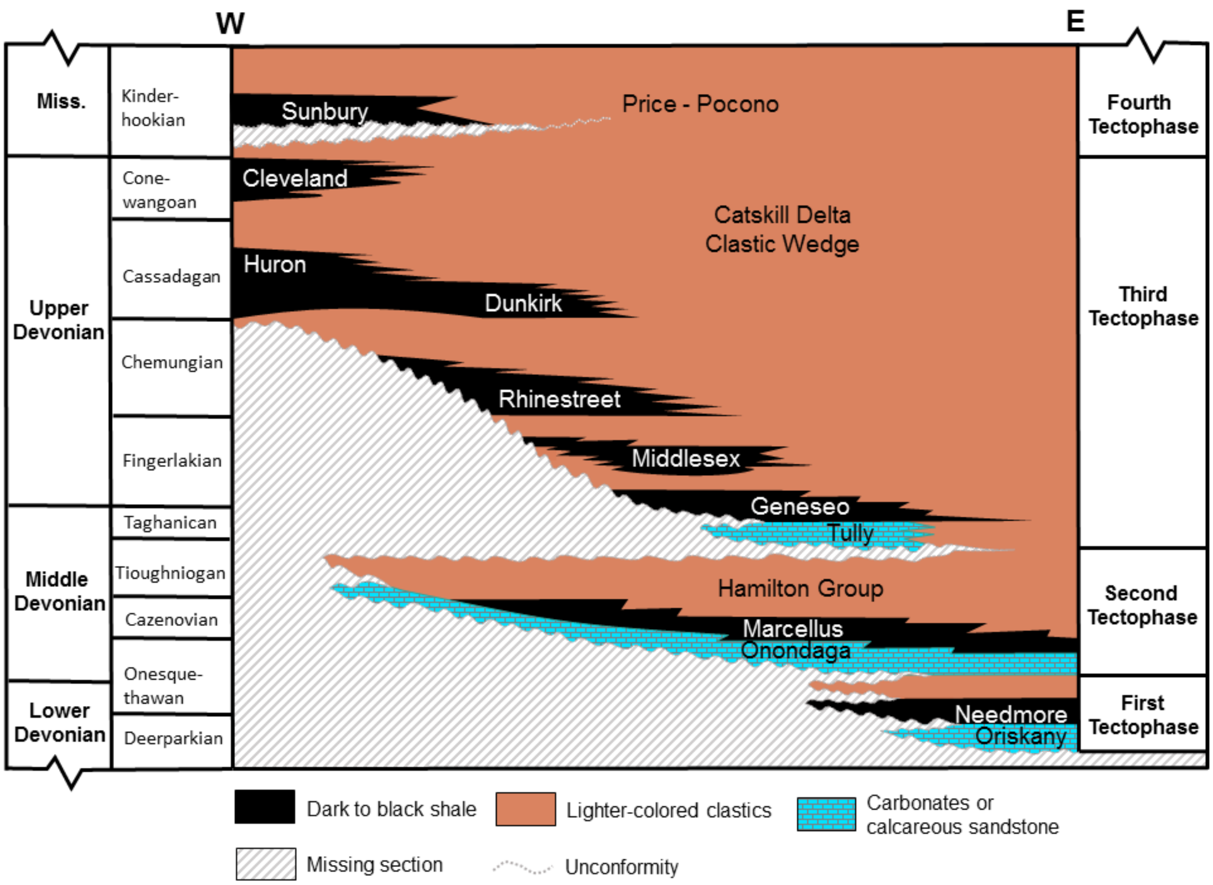


Figure 5: Schematic from north-central Ohio to east-central New York showing the composition of the Catskill delta complex and the four tectophases described by Ettensohn (modified from Harper, 1999, Ettensohn, 2004, and Carter, 2007). The fourth tectophase, the Mississippian sequence, is not completely depicted here. North American stage names are shown in the second column. Note the westward shift of the Catskill delta sequences over time. Figure is not to scale.

Late Devonian regressive strata intercalate from offshore to land and consist mainly of upward and eastward coarsening of intergraded dark shale, siltstone, sandstone (Harper and Laughrey, 1987; Harper, 1999), and conglomerate (Harper, 1999). These strata represent magnafacies and remain relatively consistent throughout the section regardless of differences in specific provenance, transport systems, and depositional settings.

The black shale magnafacies of the Genesee, Harrell, Sonyea, West Falls, and Ohio Formations (Huron Shale) dominate the lower third to half of these formations (Figure 1). Dark, organic and sometimes pyritic shales that are rarely fossiliferous and somewhat calcareous make up this magnafacies which is commonly interbedded with lighter colored, less organic-rich shales and siltstones. This magnafacies is generally less than 250 ft (76.2 m) thick in any given formation (Piotrowski and Harper, 1979). The black shales may have formed in anoxic bottom muds in shallow or deep water in the main part of the basin (Harper, 1999).

New research by Wilson and Schieber (2014) and Patchen and Carter (2015) challenge the standard paradigm for deposition of black shales in quiescent, anoxic basin muds. Their research on the lower Genesee Group of central New York and the Point Pleasant Formation of Ohio and Kentucky, respectively, shows the organic-rich sediments could have accumulated in a high-energy environment with multiple modes of transport, especially offshore hyperpycnal flows—strong turbidity currents at a river mouth/ocean interface due to different water densities. These flows rapidly deposited large volumes of fine-grained sediment that over time became the organic-rich mudstones throughout the Appalachian basin. Through the process of hyperpycnal flows or deposition in anoxic subbasins, these black shale magnafacies were deposited throughout much of the Appalachian basin.

Vertical and lateral facies changes in the marine black shales of the Geneseo/Burket (Genesee and Harrell Formations), Middlesex (Sonyea Formation), Rhinestreet (West Falls Formation), and Huron (Ohio Formation) represent a slow, persistent and westward progradation of the Catskill deltaic system through the Late Devonian (Harper and Laughrey, 1987). Coincident third- and fourth-order pulses of sea level rise at irregular intervals resulted in stacking as well as vertical and lateral facies changes of these formations (Harper and Laughrey, 1987). The shale facies grade upwards and eastwards into the coarser clastics of the Harrell and Brallier Formations, and Elk Group (Figure 1). The stage was set for future economic hydrocarbon production with deposition of organic-rich shales of the Upper Devonian Genesee, Harrell, and West Falls Formations.

Formation Descriptions

Genesee and Harrell Formations

The Upper Devonian Genesee and Harrell Formations of the Fingerlakian Stage (Figure 1), were deposited at approximately 376 to 374 Ma (Berg and others, 1983; Briggs and Shultz, 1999). The dark gray to brownish-black shales at the base of these formations generally represent the next prominent onlap deposit after the Tully Limestone (Lash, 2007). The slow-transgressive Middle Devonian Tully Limestone (Ettensohn, 1985) underlying the Geneseo-Burket acts as a key marker bed in well logs, except where it thins or is absent to the northwest and southwest in Pennsylvania.

The Genesee Formation is comprised of (in ascending stratigraphic order) the Geneseo, Penn Yan, and West River Members. The formation generally thickens toward the southeast similar to the Early Devonian Oriskany Sandstone (Carter and others, 2010). Either erosion or nondeposition may have caused northwest thinning into Erie County (Piotrowski and Harper, 1979). Thicknesses of the Genesee Formation range from less than 10 ft (3 m) in Mercer County to more than 300 ft (91.4 m) in Tioga County. Depths to the base of the Genesee Formation range from 1,028 ft (313.3 m) in northern Erie County to more than 6,930 ft (2,112.3 m) in Westmoreland County (EDWIN, 2016). In southwestern Pennsylvania, the shales of the Genesee Formation are predominantly black and dark gray with many calcareous nodules, and minor amounts of limestone and siltstone (de Witt and others, 1993). The average thickness is about 200 ft (61 m) (Harper and Laughrey, 1987).

The black Geneseo Shale Member of the Genesee Formation extends from western Pennsylvania to the north-central area of the state. Lesley (1892, p. 1,323) observed, “In New York and in other states it is a black laminated mud formation, with wall-like outcrops; but where its surfaces are exposed it weathers into loose leaves; often iron-stained on account of the abundance of iron pyrites; but usually deep black.” Carbonate concretions were also recognized as discriminating features then as they are today, with pyrite found in the cavities of the concretions. Lesley (1892, p. 1,334) was obviously a visionary when he foretold “and in future times when the petroleum production has been exhausted and our cities must again be lighted by artificial coal shale gas by Young’s process this ‘black shale’ formation will yield an infinite supply.”

The Genesee Formation grades southeastward into the dark gray, thinly laminated shale of the Harrell Formation, which is characterized by platy to sheety weathering (Hasson and Dennison, 1978). The Harrell Formation averages about 240 ft (73.2 m) thick in the central part of the outcrop in fold belts southeast of the Allegheny Front, becoming thinner to the east and grading into the upper Mahantango Formation and basal Brallier (Hasson and Dennison, 1978). Thicknesses of the Harrell Formation range from 80 ft (24.4 m) in Somerset County to over 800 ft (243.8 m) in Potter County (EDWIN, 2016). Depths to the base of the formation range from 713 ft (217.3 m) in Bedford County near the Allegheny Front to 8,205 ft (2,501 m) in Somerset County with depths in the north-central portion of the state mainly ranging between 5,000 and 6,000 ft (1,524 and 1,828.8 m) (EDWIN, 2016).

The organic-rich black shale of the Burket Member, the eastern facies equivalent of the Geneseo Shale, occurs at the base of the Harrell Formation in central Pennsylvania. The dark Burket Shale Member is distinguished by a chippy weathering pattern (Harper, 1999) and contains discoidal limestone nodules up to 2 ft (0.61 m) in diameter intercalated within the shale (de Witt and others, 1993). The Burket Shale thins to the northwest and appears to split into two black shales in northcentral Pennsylvania—the upper Renwick shale and a lower Geneseo shale (Piotrowski and Harper, 1979). Interpreted as a highstand systems tract from late-stage eustasy, these two black shale tongues interfinger with gray shales and siltstones in Potter County, Pennsylvania (Arnold, 2010). Here, black shale blanketed two marine flooding surfaces that bounded a progradational gray shale.

Two depocenters controlled the deposition of the Geneseo and Burket Shales (Arnold, 2010). Thicknesses of the Geneseo-Burket reservoir package vary across the state from less than 5 ft (1.5 m) near the Ohio border to more than 150 ft (45.7 m) in Potter County (EDWIN, 2016). Other colors and lithologies observed for the Geneseo and Burket Shales include grayish-black, brownish-black, and black, with dark gray siltstone layers, and nodular brownish-black limestone (de Witt and others, 1993).

Harper and Laughrey (1987) regarded the Geneseo Shale’s potential as a standalone gas producer to be limited due to its thin nature. Combined with recent interest in the Burket and other organic-rich Devonian shales, however, the Geneseo may prove to be of high commercial value with the prevalence of horizontal drilling in this basin. Combined, the Geneseo and Burket Shale Members exceed a thickness of 150 ft (45.7 m) in north-central Pennsylvania (Arnold, 2010) and represent the second greatest lateral expanse of the Marcellus magnafacies in the state next to the Marcellus shale (Harper and Laughrey, 1987).

West Falls Formation

The Late Devonian West Falls Formation, which contains the Rhinestreet and Angola Members (in ascending stratigraphic order) of the Chemungian Stage (Figure 1), was deposited at approximately 374 to 372 Ma (Berg and others, 1983; Briggs and Shultz, 1999). Thicknesses of the West Falls Formation range from about 200 ft (61 m) in Erie County to more than 1,300 ft (396.2 m) in Westmoreland County. Depths to the base of the formation range from about 850 ft (259 m) in Erie County to more than 6,300 ft (1,920 m) in Westmoreland County (EDWIN, 2016).

The Rhinestreet Shale Member featured in this study exhibits variable characteristics across the state. It is a massive black, organic-rich shale overlying the Sonyea Formation in northwestern Pennsylvania. The Rhinestreet facies grades into coarser clastics to the east and thins to the southeast (Tetra Tech, Inc., 1979). In southwestern Pennsylvania, the Rhinestreet Shale is the upper tongue of the Marcellus magnafacies and contains less than 400 ft (121.9 m) of dark-gray to black shales interbedded with lighter colored shales and thin siltstones (Harper and Laughrey, 1987; Figure 2). The Rhinestreet Shale is thickest at 600 ft (183 m) in southeastern Crawford County. It thins to 60 ft (18.3 m) in Erie County to the northwest (EDWIN, 2016) and to 0 ft (0 m) approaching the Allegheny Front to the east (Pennsylvania Department of Conservation and Natural Resources, 2009). Depths to the base of the shale range from 832 ft (253.6 m) in Erie County to over 5,000 ft (1,524 m) in Clarion County (EDWIN, 2016). As is common for unconventional Devonian black shales, the Rhinestreet Shale is an important source rock for conventional reservoirs (Harper and Laughrey, 1987; Roth, 2011).

METHODS

Data Analysis

The authors collected all of the existing data on the Upper Devonian shales in PaGS records. Sample depths were checked against geophysical logs (where available) and drillers' logs to verify that they were from the Genesee or West Falls Formations. In most cases, various researchers who worked with the samples had selected drill cuttings from the organic members of these formations (the Geneseo and Rhinestreet Shales) for sampling. The authors found mineral information for some of these samples, which was also consulted to confirm formation identification. For example, they presumed a sample composed mostly of calcite to be the Tully Formation and did not use it in this study even if the sample depths agreed with the depths of the Geneseo Member interpreted from the geophysical log.

Drill cuttings are samples of rock ground up by the drill bit, captured during the drilling process, and placed into labeled bags for later use. The depths reported on sample bags are normally estimated based on the drilling rate or rate of penetration at a given well site. Sample bag depths may be inaccurate due to poor sampling techniques, contamination from cavings in the wellbore, and/or from incorrect estimates of the cuttings' return rates. Because most of the cuttings used in this study were collected over a particular depth interval (e.g. 6,000 to 6,010 ft [1,828.8 to 1,831.8 m]), laboratory results represent an average over that range and may provide a more representative result for the formation being tested than a depth-specific sample from a core (Katz, 2015).

Table 1 shows the TOC and R_o values used in this study, and Table 2 shows mineralogic data. In some cases, investigators collected multiple samples from the formation of interest within a single well, so the authors show average values on the maps and tables in this report. Appendix A provides the full set of values, including Rock-Eval measurements not used in this study, from every well in spreadsheet form. This appendix also includes data from formations not analyzed during this study. The authors plotted TOC and R_o values from each formation against mineral concentrations and gamma-ray readings from geophysical logs using Microsoft® Excel 2010 and used these plots to look for trends that might assist their mapping efforts and their understanding of the genesis of potential source beds in these two formations.

Mapping

After the validation work described above, TOC and R_o values were plotted on a blank base map at a scale of 1 inch (in) (2.54 centimeters [cm]) = 20 mi (32.2 km) and contoured by hand. After creation of the initial contour maps, the contours were compared to existing structures and trends paralleling known structures were observed. These trends were used to bias contours in areas with sparse data. Because data from multiple samples were available from some wells, maps were created showing the highest and lowest measured values from those wells. These maps were also hand-contoured and compared to the contours of the average values. Trends illustrated by the high and low sample values were examined and used to create the final maps so long as they did not conflict with the average values. The final hand-contoured maps were then scanned and digitized in ArcMap™ 10.1.

Table 1: TOC and R_o data presented in this report. Units reported as follows: interval depths (ft), average TOC (weight percent), and average R_o (percent reflectance).

Well Permit Number	Top Sampled Interval (ft)	Bottom Sampled Interval (ft)	Formation Name	Latitude (NAD83)	Longitude (NAD83)	County	Quadrangle (1:24,000)	Average TOC (wt %)	Number of Samples Analyzed	Average R_o (%)
003-20980	7060	7060	Genesee	40.197239	-79.900003	Allegheny	Monongahela	5.37	1	2.27
005-21201	5260	5560	West Falls	40.884843	-79.346824	Armstrong	Distant	0.58	5	
005-21201	5930	5990	Genesee	40.884843	-79.346824	Armstrong	Distant	0.58	1	
007-20025	4082	4125	West Falls	40.751611	-80.455267	Beaver	New Galilee	1.95	3	1.68
007-20060	4660	4760	West Falls	40.602100	-80.433737	Beaver	Hookstown	2.53	3	1.32
007-90003	4730	4765	West Falls	40.607933	-80.227882	Beaver	Ambridge	2.45	3	1.71
007-90021	4796	4825	West Falls	40.789763	-80.184493	Beaver	Zelienople	2.10	3	1.59
015-20010	2630	4090	West Falls	41.861277	-76.763421	Bradford	Troy	0.20	48	
015-20010	4400	4430	Genesee	41.861277	-76.763421	Bradford	Troy	1.26	2	
023-00015	5114	5124	Genesee	41.333566	-78.173109	Cameron	Driftwood	4.20	1	2.04
023-00033	4638	4680	Genesee	41.475855	-78.051950	Cameron	First Fork	3.43	2	1.99
023-20005	5772	5794	Genesee	41.365126	-77.995374	Cameron	Keating	4.17	2	2.04
023-20020	6100	6120	Genesee	41.516973	-78.152388	Cameron	Emporium	4.65	1	2.01
023-20034	5180	5190	Genesee	41.482717	-78.396246	Cameron	Rathbun	5.88	1	1.88
023-20035	6000	6010	Genesee	41.552053	-78.151382	Cameron	Emporium	3.91	1	2.07
023-20042	5600	5610	Genesee	41.585349	-78.237295	Cameron	Emporium	4.98	1	2.07
023-20047	5130	5140	Genesee	41.554797	-78.325547	Cameron	Rich Valley	4.84	1	1.94
023-90014	5376	5411	Genesee	41.342348	-78.175477	Cameron	Driftwood	3.88	2	1.97
031-20168	4960	5090	West Falls	41.191578	-79.369998	Clarion	Strattanville	2.80	3	1.73
031-20185	4990	5020	West Falls	41.210764	-79.357802	Clarion	Strattanville	1.11	2	
031-20615	4690	4720	West Falls	41.237057	-79.615993	Clarion	Knox	2.56	3	1.43
031-20672	4400	4460	West Falls	41.328514	-79.530004	Clarion	Kossuth	2.39	3	1.53
035-20157	5115	5150	Genesee	41.390051	-77.949354	Clinton	Hammersley Fork	4.00	2	2.10

Well Permit Number	Top Sampled Interval (ft)	Bottom Sampled Interval (ft)	Formation Name	Latitude (NAD83)	Longitude (NAD83)	County	Quadrangle (1:24,000)	Average TOC (wt %)	Number of Samples Analyzed	Average R_o (%)
035-20276	6110	7001	West Falls	41.371300	-77.566305	Clinton	Glen Union	0.25	14	2.21
035-20276	7121	7180	Genesee	41.371300	-77.566305	Clinton	Glen Union	2.13	1	
035-21311	7316	7390	Genesee	41.250606	-77.477597	Clinton	Jersey Mills	2.61	4	1.97
035-90009	7029	7053	Genesee	41.339876	-77.526459	Clinton	Glen Union	2.83	2	1.85
035-90013	5501	5576	Genesee	41.377402	-77.979976	Clinton	Hammersley Fork	3.11	3	1.96
035-90027	6850	6864	Genesee	41.211996	-77.817903	Clinton	Snow Shoe NE	2.93	1	1.85
035-90041	6855	6875	Genesee	41.392247	-77.784687	Clinton	Tamarack	3.48	2	2.05
035-90051	7151	7226	Genesee	41.258738	-77.435448	Clinton	Jersey Mills	2.30	4	1.96
039-20023	2255	2283	West Falls	41.825108	-80.219476	Crawford	Edinboro South	3.71	2	0.70
039-20131	2950	2960	West Falls	41.836725	-79.889719	Crawford	Millers Station	4.03	1	0.91
039-20429	2580	2620	West Falls	41.833706	-80.018486	Crawford	Cambridge Springs	2.79	3	0.86
039-20462	3370	3400	Genesee	41.725034	-79.797467	Crawford	Centerville	2.39	1	0.96
039-20467	3050	3110	West Falls	41.833706	-79.738927	Crawford	Spartansburg	2.79	2	0.94
039-20468	3330	3360	West Falls	41.656246	-79.866211	Crawford	Centerville	0.49	1	
039-20483	2970	3000	West Falls	41.535090	-80.253788	Crawford	Conneaut Lake	3.49	3	0.79
047-20005	5790	5800	Genesee	41.245206	-78.648536	Elk	Sabula	2.60	1	1.85
047-20028	5050	5200	West Falls	41.378800	-78.362571	Elk	West Creek	1.01	3	
047-20028	6120	6130	Genesee	41.378800	-78.362571	Elk	West Creek	3.04	1	
047-20033	4630	4690	West Falls	41.244383	-78.470009	Elk	Huntley	0.43	2	
047-20033	5800	5810	Genesee	41.244383	-78.470009	Elk	Huntley	4.32	1	1.70
047-20036	6530	6535	Genesee	41.254762	-78.492250	Elk	Weedville	3.90	1	2.02
047-20042	5220	5270	West Falls	41.254762	-78.454585	Elk	Weedville	0.46	3	
047-20042	6320	6330	Genesee	41.254762	-78.454585	Elk	Weedville	0.92	1	
047-20287	5480	5500	Genesee	41.415988	-78.692270	Elk	Ridgway	1.14	2	

Well Permit Number	Top Sampled Interval (ft)	Bottom Sampled Interval (ft)	Formation Name	Latitude (NAD83)	Longitude (NAD83)	County	Quadrangle (1:24,000)	Average TOC (wt %)	Number of Samples Analyzed	Average R_o (%)
047-20306	4790	4800	West Falls	41.503663	-78.459140	Elk	Wildwood Fire Tower	0.66	1	
047-20306	5780	5790	Genesee	41.503663	-78.459140	Elk	Wildwood Fire Tower	3.09	1	1.91
047-20334	5780	5790	Genesee	41.363619	-78.747038	Elk	Brandy Camp	1.85	1	
047-20383	6110	6120	Genesee	41.307681	-78.515006	Elk	Kersey	1.83	1	
047-90000	5090	5132	Genesee	41.454636	-78.905551	Elk	Hallton	2.11	3	1.73
047-90007	5457	5464	Genesee	41.315709	-78.841614	Elk	Carman	4.44	1	1.82
049-20078	2372	2400	West Falls	42.037034	-79.800254	Erie	Wattsburg	4.09	2	0.95
049-20568	1320	1360	West Falls	42.174036	-79.834102	Erie	North East	3.66	3	0.81
049-20846	756	930	West Falls	42.153417	-80.126718	Erie	Erie North	0.34	2	
049-90071	2548	2604	West Falls	41.933641	-79.739334	Erie	Corry	3.96	3	0.99
053-20898	3980	4000	West Falls	41.573324	-79.234751	Forest	Mayburg	3.08	2	1.24
053-21250	4050	4140	West Falls	41.563170	-79.267647	Forest	Kellettville	1.75	4	
081-20001	5630	5640	Genesee	41.525204	-77.374466	Lycoming	Morris	1.92	1	
081-20002	6550	6560	Genesee	41.421699	-77.255143	Lycoming	English Center	2.56	1	1.96
081-20004	6800	6810	Genesee	41.471051	-77.565988	Lycoming	Slate Run	2.08	1	1.97
081-20019	5490	5500	Genesee	41.293267	-76.647226	Lycoming	Picture Rocks	1.58	1	
081-90003	5376	5390	Genesee	41.540160	-77.287660	Lycoming	Morris	2.61	1	1.99
083-22503	3677	3682	Genesee	41.898931	-78.650367	McKean	Bradford	3.60	1	1.39
083-27520	3240	3250	Genesee	41.986969	-78.916758	McKean	Cornplanter Run	2.54	1	1.10
083-29158	2900	2980	West Falls	41.969817	-78.858807	McKean	Stickney	2.01	3	1.13
083-29530	4330	4480	West Falls	41.682268	-78.646139	McKean	Mount Jewett	0.53	3	
083-30394	3250	3470	West Falls	41.879898	-78.794877	McKean	Stickney	0.94	4	
083-31252	4040	4100	West Falls	41.669919	-78.926280	McKean	Ludlow	1.49	3	1.31
083-31252	4680	4690	Genesee	41.669919	-78.926280	McKean	Ludlow	3.35	1	1.36
083-31392	5370	5380	Genesee	41.669644	-78.539996	McKean	Hazel Hurst	3.07	1	1.78

Well Permit Number	Top Sampled Interval (ft)	Bottom Sampled Interval (ft)	Formation Name	Latitude (NAD83)	Longitude (NAD83)	County	Quadrangle (1:24,000)	Average TOC (wt %)	Number of Samples Analyzed	Average R_o (%)
083-33110	3900	4000	West Falls	41.794163	-78.417384	McKean	Smethport	1.57	3	
083-33110	4180	4190	Genesee	41.794163	-78.417384	McKean	Smethport	5.18	1	1.81
083-37291	4600	4600	Genesee	41.868829	-78.612420	McKean	Cyclone	2.90	1	0.88
083-90028	3940	3960	Genesee	41.966100	-78.279254	McKean	Bullis Mills	2.73	2	1.51
085-20036	3450	3630	West Falls	41.351272	-80.176199	Mercer	Jackson Center	1.89	3	
105-00420	5450	5465	Genesee	41.526371	-77.946678	Potter	Conrad	3.93	1	2.09
105-00441	5512	5523	Genesee	41.552189	-77.905120	Potter	Conrad	4.36	1	1.85
105-00444	5526	5534	Genesee	41.514777	-77.985716	Potter	Conrad	3.29	1	2.07
105-20118	6080	6110	Genesee	41.570998	-77.637907	Potter	Oleona	2.45	2	
105-20124	5500	5510	Genesee	41.533986	-77.696669	Potter	Oleona	2.05	1	1.95
105-20139	6360	6370	Genesee	41.602700	-77.691529	Potter	Oleona	3.17	1	1.85
105-20149	5470	5480	Genesee	41.584662	-78.041212	Potter	Wharton	4.20	1	2.01
105-20269	5215	5220	Genesee	41.670053	-77.729992	Potter	Galeton	2.44	1	1.88
105-20314	5850	5860	Genesee	41.578947	-78.132284	Potter	Emporium	3.64	1	1.88
105-20381	5576	5596	Genesee	41.495866	-77.755418	Potter	Tamarack	2.03	1	1.80
105-20413	5450	5460	Genesee	41.573595	-77.849106	Potter	Short Run	4.56	1	2.18
105-20414	5510	5520	Genesee	41.588505	-78.066783	Potter	Wharton	4.28	1	2.07
105-20438	5590	5620	Genesee	41.549993	-77.657762	Potter	Oleona	2.74	1	1.99
105-20456	6100	6110	Genesee	41.577987	-78.068594	Potter	Wharton	4.45	1	2.07
105-20468	6140	6150	Genesee	41.619652	-77.917090	Potter	Conrad	3.90	1	2.06
105-90001	4305	4324	Genesee	41.840424	-77.820360	Potter	Brookland	4.39	2	2.21
105-90061	4675	4715	Genesee	41.836706	-77.681499	Potter	West Pike	2.92	4	1.95
105-90065	4747	4766	Genesee	41.871842	-77.618853	Potter	Sabinsville	4.66	1	2.09
105-90155	4875	4902	Genesee	41.845598	-78.009861	Potter	Coudersport	3.70	2	1.94
111-20045	4710	7230	West Falls	39.977789	-79.333614	Somerset	Kingwood	0.27	42	2.55
111-20045	7590	7650	Genesee	39.977789	-79.333614	Somerset	Kingwood	1.04	1	2.86
117-00040	3000	3078	Genesee	41.925172	-77.268647	Tioga	Elkland	1.85	5	
117-20016	4940	4950	Genesee	41.697728	-77.420681	Tioga	Tiadaghton	2.63	1	1.75

Well Permit Number	Top Sampled Interval (ft)	Bottom Sampled Interval (ft)	Formation Name	Latitude (NAD83)	Longitude (NAD83)	County	Quadrangle (1:24,000)	Average TOC (wt %)	Number of Samples Analyzed	Average R_o (%)
117-20019	4410	4420	Genesee	41.886961	-77.598720	Tioga	Potter Brook	3.73	1	
117-20036	4310	4320	Genesee	41.689685	-77.310645	Tioga	Antrim	2.25	1	1.94
117-20037	5011	5133	Genesee	41.591522	-77.532047	Tioga	Lee Fire Tower	1.35	4	1.97
117-20043	4420	4430	Genesee	41.986142	-77.514392	Tioga	Potter Brook	3.82	1	1.86
117-20056	6140	6150	Genesee	41.629346	-77.298292	Tioga	Antrim	1.71	1	
117-20057	2380	4360	West Falls	41.689400	-77.546656	Tioga	Marshlands	0.33	31	1.67
117-20057	4690	4720	Genesee	41.689400	-77.546656	Tioga	Marshlands	2.31	1	1.86
117-20062	5250	5260	Genesee	41.549307	-77.596173	Tioga	Lee Fire Tower	2.23	1	1.82
117-90001	3637	3662	Genesee	41.870654	-77.507586	Tioga	Sabinsville	2.29	2	1.82
121-22166	4020	4050	West Falls	41.248091	-79.969368	Venango	Barkeyville	2.54	2	1.07
121-22642	3840	3970	West Falls	41.414207	-79.809104	Venango	Franklin	3.17	3	1.01
121-25224	4110	4130	West Falls	41.224763	-79.947519	Venango	Barkeyville	2.16	2	1.07
123-20150	3698	3763	West Falls	41.653913	-79.368939	Warren	Cobham	3.65	3	1.14
123-20281	3964	3978	Genesee	41.671663	-79.373390	Warren	Cobham	2.61	1	1.08
123-20609	3010	3160	West Falls	41.770610	-79.069264	Warren	Clarendon	3.80	3	1.00
123-20982	3101	3131	West Falls	41.959939	-78.965416	Warren	Cornplanter Run	1.53	3	
123-90000	3809	3871	West Falls	41.643622	-79.422996	Warren	Tidioute	2.73	2	1.17
123-90001	3160	3350	West Falls	41.933087	-79.028309	Warren	Scandia	2.60	3	1.17
123-90004	3264	3375	West Falls	41.880000	-79.465975	Warren	Lottsville	2.81	2	0.98
123-90004	3399	3408	Genesee	41.880000	-79.465975	Warren	Lottsville	2.45	1	0.98
123-90007	3301	3380	West Falls	41.774796	-79.581382	Warren	Spring Creek	3.50	2	1.03

Table 2: Mineralogic data used in this report. Units reported as follows: interval depths (ft), quartz and calcite concentrations (weight percent).

Well Permit Number	Top Sampled Interval (ft)	Bottom Sampled Interval (ft)	Formation Name	Latitude (NAD83)	Longitude (NAD83)	County	Quadrangle (1:24,000)	Quartz (wt %)	Calcite (wt %)
007-20025	4082	4125	West Falls	40.751611	-80.455267	Beaver	New Galilee	28.86	0.90
007-20060	4660	4760	West Falls	40.602100	-80.433737	Beaver	Hookstown	28.13	7.72
007-90003	4730	4765	West Falls	40.607933	-80.227882	Beaver	Ambridge	32.05	0.90
007-90021	4796	4825	West Falls	40.789763	-80.184493	Beaver	Zelienople	29.66	2.08
023-00008	6220	6230	Genesee	41.342073	-78.183128	Cameron	Driftwood	26.17	2.61
023-00015	5114	5124	Genesee	41.333566	-78.173109	Cameron	Driftwood	28.95	1.85
023-00033	4638	4680	Genesee	41.475855	-78.051950	Cameron	First Fork	25.38	21.77
023-20005	5772	5794	Genesee	41.365126	-77.995374	Cameron	Keating	29.23	9.26
023-20020	6100	6120	Genesee	41.516973	-78.152388	Cameron	Emporium	32.62	4.07
023-20034	5180	5190	Genesee	41.482717	-78.396246	Cameron	Rathbun	34.11	1.72
023-20035	6000	6010	Genesee	41.552053	-78.151382	Cameron	Emporium	21.85	8.60
023-20042	5600	5610	Genesee	41.585349	-78.237295	Cameron	Emporium	28.85	13.57
023-20047	5130	5140	Genesee	41.554797	-78.325547	Cameron	Rich Valley	34.76	8.57
023-90014	5376	5411	Genesee	41.342348	-78.175477	Cameron	Driftwood	25.58	13.47
031-20168	4960	5090	West Falls	41.191578	-79.369998	Clarion	Strattanville	31.11	0.32
031-20185	4990	5020	West Falls	41.210764	-79.357802	Clarion	Strattanville	27.07	0.58
031-20615	4690	4720	West Falls	41.237057	-79.615993	Clarion	Knox	32.38	0.20
031-20672	4400	4460	West Falls	41.328514	-79.530004	Clarion	Kossuth	32.07	1.06
035-20157	5115	5150	Genesee	41.390051	-77.949354	Clinton	Hammersley Fork	27.73	7.27
035-21311	7316	7390	Genesee	41.250606	-77.477597	Clinton	Jersey Mills	25.71	4.56
035-90009	7029	7053	Genesee	41.339876	-77.526459	Clinton	Glen Union	25.75	6.37
035-90013	5501	5576	Genesee	41.377402	-77.979976	Clinton	Hammersley Fork	24.30	14.27
035-90027	6850	6864	Genesee	41.211996	-77.817903	Clinton	Snow Shoe NE	29.63	4.80

Well Permit Number	Top Sampled Interval (ft)	Bottom Sampled Interval (ft)	Formation Name	Latitude (NAD83)	Longitude (NAD83)	County	Quadrangle (1:24,000)	Quartz (wt %)	Calcite (wt %)
035-90041	6855	6875	Genesee	41.392247	-77.784687	Clinton	Tamarack	27.39	10.12
035-90051	7151	7226	Genesee	41.258738	-77.435448	Clinton	Jersey Mills	26.13	3.40
039-20023	2255	2283	West Falls	41.825108	-80.219476	Crawford	Edinboro South	30.99	0.23
039-20131	2950	2960	West Falls	41.836725	-79.889719	Crawford	Millers Station	33.36	0.26
039-20429	2580	2620	West Falls	41.833706	-80.018486	Crawford	Cambridge Springs	27.90	0.81
039-20462	3370	3400	Genesee	41.725034	-79.797467	Crawford	Centerville	29.82	0.63
039-20467	3050	3110	West Falls	41.833706	-79.738927	Crawford	Spartansburg	32.61	1.98
039-20468	3330	3360	West Falls	41.656246	-79.866211	Crawford	Centerville	24.06	1.92
039-20483	2970	3000	West Falls	41.535090	-80.253788	Crawford	Conneaut Lake	34.26	2.32
047-20005	5790	5800	Genesee	41.245206	-78.648536	Elk	Sabula	18.59	21.91
047-20028	5050	5200	West Falls	41.378800	-78.362571	Elk	West Creek	26.33	0.00
047-20028	6120	6130	Genesee	41.378800	-78.362571	Elk	West Creek	35.31	1.10
047-20033	4630	4690	West Falls	41.244383	-78.470009	Elk	Huntley	30.15	0.00
047-20033	5800	5810	Genesee	41.244383	-78.470009	Elk	Huntley	28.46	3.95
047-20036	6530	6535	Genesee	41.254762	-78.492250	Elk	Weedville	30.78	2.87
047-20042	5220	5270	West Falls	41.254762	-78.454585	Elk	Weedville	27.42	0.01
047-20042	6320	6330	Genesee	41.254762	-78.454585	Elk	Weedville	26.96	8.86
047-20287	5480	5500	Genesee	41.415988	-78.692270	Elk	Ridgway	27.88	4.06
047-20306	4790	4800	West Falls	41.503663	-78.459140	Elk	Wildwood Fire Tower	30.27	0.00
047-20306	5780	5790	Genesee	41.503663	-78.459140	Elk	Wildwood Fire Tower	21.79	49.68

Well Permit Number	Top Sampled Interval (ft)	Bottom Sampled Interval (ft)	Formation Name	Latitude (NAD83)	Longitude (NAD83)	County	Quadrangle (1:24,000)	Quartz (wt %)	Calcite (wt %)
047-20334	5780	5790	Genesee	41.363619	-78.747038	Elk	Brandy Camp	27.73	3.20
047-20383	6110	6120	Genesee	41.307681	-78.515006	Elk	Kersey	25.93	8.08
047-90000	5090	5132	Genesee	41.454636	-78.905551	Elk	Hallton	27.25	7.03
047-90007	5457	5464	Genesee	41.315709	-78.841614	Elk	Carman	28.60	6.66
049-20078	2372	2400	West Falls	42.037034	-79.800254	Erie	Wattsburg	36.73	0.00
049-20568	1320	1360	West Falls	42.174036	-79.834102	Erie	North East	34.45	0.00
049-90071	2548	2604	West Falls	41.933641	-79.739334	Erie	Corry	40.34	0.19
053-20898	3980	4000	West Falls	41.573324	-79.234751	Forest	Mayburg	34.51	0.00
053-21250	4050	4140	West Falls	41.563170	-79.267647	Forest	Kellettville	29.42	0.02
081-20001	5630	5640	Genesee	41.525204	-77.374466	Lycoming	Morris	29.19	1.80
081-20002	6550	6560	Genesee	41.421699	-77.255143	Lycoming	English Center	25.55	0.76
081-20004	6800	6810	Genesee	41.471051	-77.565988	Lycoming	Slate Run	27.24	0.90
081-20019	5490	5500	Genesee	41.293267	-76.647226	Lycoming	Picture Rocks	22.57	0.23
081-90003	5376	5390	Genesee	41.540160	-77.287660	Lycoming	Morris	27.26	2.21
083-22503	3677	3682	Genesee	41.898931	-78.650367	McKean	Bradford	33.58	1.67
083-27520	3240	3250	Genesee	41.986969	-78.916758	McKean	Cornplanter Run	22.12	16.57
083-29158	2900	2980	West Falls	41.969817	-78.858807	McKean	Stickney	27.82	0.24
083-29530	4330	4480	West Falls	41.682268	-78.646139	McKean	Mount Jewett	27.90	0.20
083-30394	3250	3470	West Falls	41.879898	-78.794877	McKean	Stickney	29.03	0.00
083-31252	4040	4100	West Falls	41.669919	-78.926280	McKean	Ludlow	26.30	5.25
083-31252	4680	4690	Genesee	41.669919	-78.926280	McKean	Ludlow	31.13	5.55
083-31392	5370	5380	Genesee	41.669644	-78.539996	McKean	Hazel Hurst	22.27	17.61

Well Permit Number	Top Sampled Interval (ft)	Bottom Sampled Interval (ft)	Formation Name	Latitude (NAD83)	Longitude (NAD83)	County	Quadrangle (1:24,000)	Quartz (wt %)	Calcite (wt %)
083-33110	3900	4000	West Falls	41.794163	-78.417384	McKean	Smethport	32.71	0.67
083-33110	4180	4190	Genesee	41.794163	-78.417384	McKean	Smethport	36.75	5.59
083-90028	3940	3960	Genesee	41.966100	-78.279254	McKean	Bullis Mills	34.02	0.49
105-00420	5450	5465	Genesee	41.526371	-77.946678	Potter	Conrad	31.12	4.81
105-00441	5512	5523	Genesee	41.552189	-77.905120	Potter	Conrad	24.79	17.45
105-00444	5526	5534	Genesee	41.514777	-77.985716	Potter	Conrad	34.75	1.05
105-20118	6080	6110	Genesee	41.5709982	-77.637907	Potter	Oleona	29.27	2.31
105-20124	5500	5510	Genesee	41.533986	-77.696669	Potter	Oleona	24.53	1.51
105-20139	6360	6370	Genesee	41.602700	-77.691529	Potter	Oleona	29.40	1.93
105-20149	5470	5480	Genesee	41.584662	-78.041212	Potter	Wharton	32.99	4.65
105-20269	5215	5220	Genesee	41.670053	-77.729992	Potter	Galeton	30.28	1.57
105-20314	5850	5860	Genesee	41.578947	-78.132284	Potter	Emporium	24.62	22.59
105-20381	5576	5596	Genesee	41.495866	-77.755418	Potter	Tamarack	20.46	27.67
105-20413	5450	5460	Genesee	41.573595	-77.849106	Potter	Short Run	32.78	0.86
105-20414	5510	5520	Genesee	41.588505	-78.066783	Potter	Wharton	30.10	5.80
105-20438	5590	5620	Genesee	41.549993	-77.657762	Potter	Oleona	27.09	1.77
105-20456	6100	6110	Genesee	41.577987	-78.068594	Potter	Wharton	25.48	22.23
105-20468	6140	6150	Genesee	41.619652	-77.917090	Potter	Conrad	29.42	3.78
105-90001	4305	4324	Genesee	41.840424	-77.820360	Potter	Brookland	32.49	3.69
105-90061	4675	4715	Genesee	41.836706	-77.681499	Potter	West Pike	29.51	3.94
105-90065	4747	4766	Genesee	41.871842	-77.618853	Potter	Sabinsville	32.24	1.59
105-90155	4875	4902	Genesee	41.845598	-78.009861	Potter	Coudersport	32.99	7.13
117-00040	3000	3078	Genesee	41.925172	-77.268647	Tioga	Elkland	28.75	1.25
117-20016	4940	4950	Genesee	41.697728	-77.420681	Tioga	Tiadaghton	26.91	1.34
117-20019	4410	4420	Genesee	41.8869612	-77.5987199	Tioga	Potter Brook	31.16	2.76
117-20036	4310	4320	Genesee	41.689685	-77.310645	Tioga	Antrim	28.78	0.34
117-20037	5011	5133	Genesee	41.591522	-77.532047	Tioga	Lee Fire Tower	27.80	3.11

Well Permit Number	Top Sampled Interval (ft)	Bottom Sampled Interval (ft)	Formation Name	Latitude (NAD83)	Longitude (NAD83)	County	Quadrangle (1:24,000)	Quartz (wt %)	Calcite (wt %)
117-20043	4420	4430	Genesee	41.986142	-77.514392	Tioga	Potter Brook	26.73	14.47
117-20056	6140	6150	Genesee	41.629346	-77.298292	Tioga	Antrim	26.98	2.50
117-20057	4690	4720	Genesee	41.689400	-77.546656	Tioga	Marshlands	25.64	3.03
117-20062	5250	5260	Genesee	41.549307	-77.596173	Tioga	Lee Fire Tower	27.58	1.35
117-90001	3637	3662	Genesee	41.870654	-77.507586	Tioga	Sabinsville	31.65	1.76
121-22166	4020	4050	West Falls	41.248091	-79.969368	Venango	Barkeyville	34.19	0.95
121-25224	4110	4130	West Falls	41.224763	-79.947519	Venango	Barkeyville	34.70	0.73
123-20150	3698	3763	West Falls	41.653913	-79.368939	Warren	Cobham	31.59	0.00
123-20281	3964	3978	Genesee	41.671663	-79.373390	Warren	Cobham	28.09	16.30
123-20609	3010	3160	West Falls	41.770610	-79.069264	Warren	Clarendon	35.36	0.10
123-90000	3809	3871	West Falls	41.643622	-79.422996	Warren	Tidioute	32.43	1.19
123-90001	3160	3350	West Falls	41.933087	-79.028309	Warren	Scandia	34.94	0.00
123-90004	3264	3375	West Falls	41.880000	-79.465975	Warren	Lottsville	35.73	0.00
123-90004	3399	3408	Genesee	41.880000	-79.465975	Warren	Lottsville	36.63	0.00
123-90007	3301	3380	West Falls	41.774796	-79.581382	Warren	Spring Creek	31.37	0.41

RESULTS and DISCUSSION

Plots

TOC versus Gamma-Ray

Marine black shale deposits commonly show a strong correlation of uranium (high gamma-ray American Petroleum Institute [API] measurement on a geophysical log) and TOC content (Lüning and Kolonic, 2003). Many researchers have observed a direct correlation between TOC and gamma-ray signature in the Middle Devonian Marcellus shale (e.g., Boyce and others, 2010; Bank and others, 2012; Zagorski and others, 2012). This correlation is generally associated with low sedimentation rates (Lüning and Kolonic, 2003; Lash, 2008) and is not found in all organic-rich shale deposits. For example, TOC and gamma-ray measurements show no correlation in the spectral gamma-ray logging done on Utica/Point Pleasant cores (Patchen and Carter, 2015).

The Upper Devonian Genesee and West Falls samples analyzed in this study do not exhibit any apparent correlation between TOC content and gamma-ray values (Figure 6). In particular, the Genesee weight percent TOC and gamma-ray values are scattered, with TOC ranging from 1.14 to 5.88 percent and gamma-ray values ranging from 60 to 460 API units. In contrast, the relatively narrow range of gamma-ray values from the West Falls Formation (127 to 250 API units) could be a result of the sampling bias from researchers choosing intervals with high gamma-ray

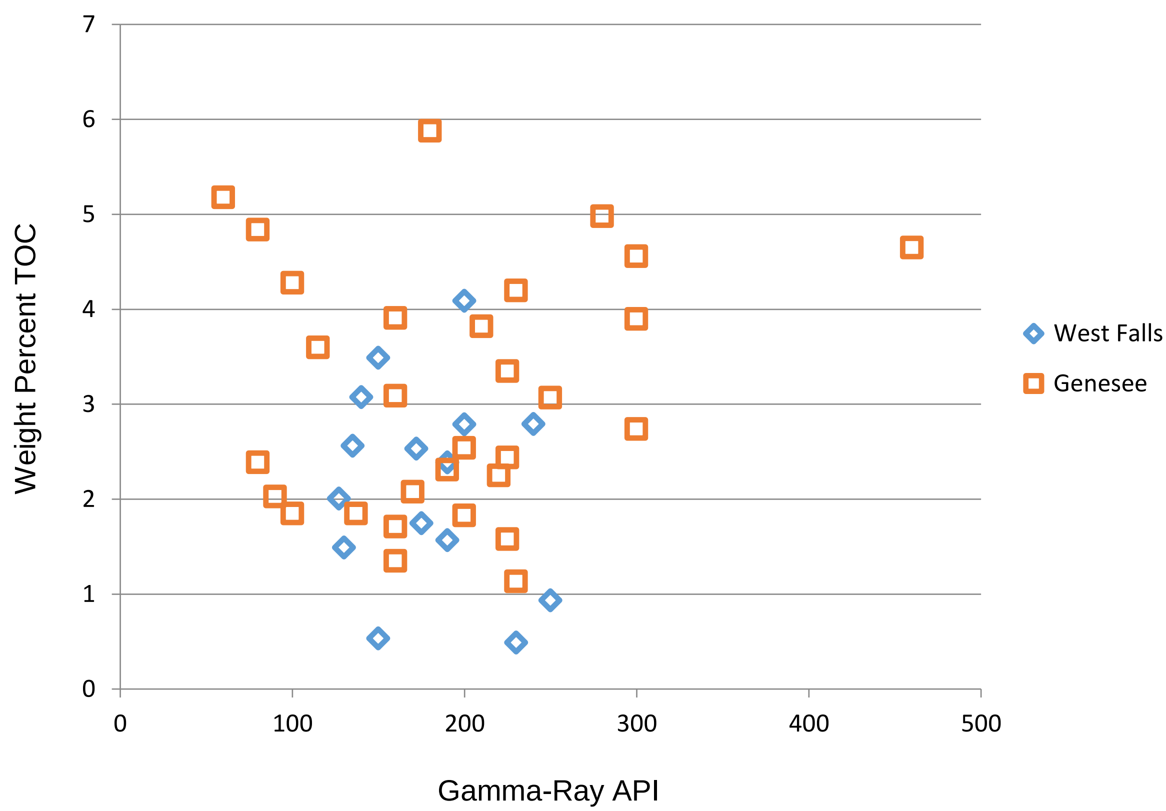


Figure 6: TOC versus gamma-ray API value for the Genesee and West Falls Formations.

measurements for analysis. Despite this narrow range of gamma-ray values, TOC concentrations for the West Falls Formation range from 0.49 to 4.09 percent.

In such situations, formation density is a better proxy for organic content than gamma-ray because organic-rich shales will always exhibit low density readings even when they do not record high gamma-ray values (Lash, 2008). Devonian shales analyzed by the Kentucky Geological Survey exhibited correlation between laboratory-measured bulk density and TOC (Brandon Nuttall, oral commun. 2015). Unfortunately, bulk density data were not available for this study.

Depth versus R_o

The authors used calculated R_o values to assess the thermal maturity of the analyzed samples. The thermal maturity of sediments tends to become greater with increasing pressures and temperatures (Tissot and others, 1971). Because of this, samples from stable settings associated with deeper burial depths may be expected to have higher thermal maturities than less deeply buried samples. The West Falls samples suggest a positive relationship between average measured depth below the surface and calculated R_o values (Figure 7) with the shallowest sample (1,340 ft [408.4 m]) having an R_o of 0.81 and the deepest sample (5,970 ft [1,819.7 m])

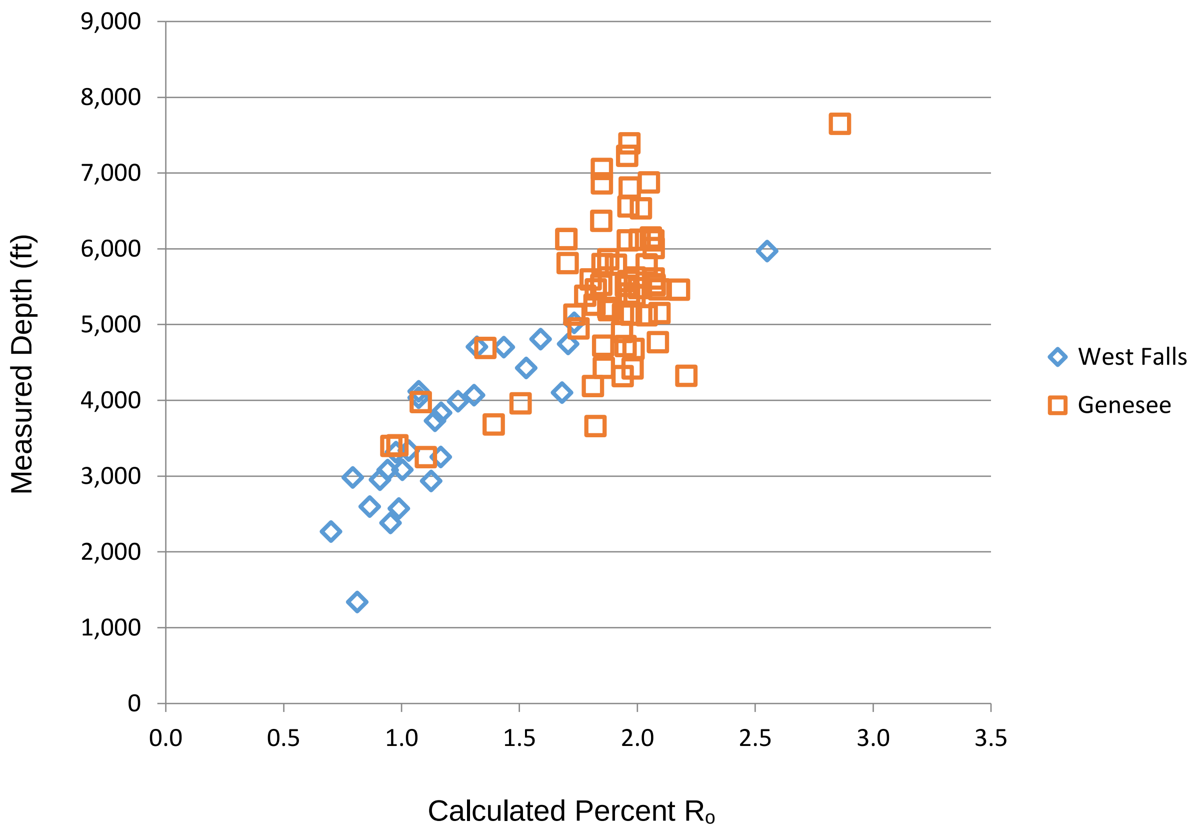


Figure 7: Depth versus calculated R_o value for the Genesee and West Falls Formations.

having an R_o of 2.55. The calculated R_o values for the West Falls Formation range from 0.70 to 2.55.

With respect to the Genesee Formation, measured R_o values do not show as strong of a trend. Samples with R_o values of about 1.50 or less seem to follow a trend similar to the West Falls samples. These samples have depths ranging from 3,250 ft (990.6 m) to 4,690 ft (1,429.5 m) and R_o values ranging from 0.96 to 1.51. The deepest sample from the Genesee Formation also falls along this trend. It is from southwestern Pennsylvania and has a depth of 7,650 ft (2,331.7 m) and a R_o value of 2.86. R_o values from the remaining samples seem to cluster around the R_o value of 2. The remaining samples have a depth range of 3,662 ft (1,116.2 m) to 7,390 ft (2,252.5 m) and a R_o range of 1.70 to 2.21. Some of these Genesee values are higher than expected for the measured depth and some are lower as compared to the trend implied by the West Falls samples. Mapping revealed that the lower values are mostly located close to the Allegheny Front. The higher values are located mostly in north-central Pennsylvania. More study is needed to determine the cause of these abnormal R_o values.

Quartz versus TOC

Figure 8 plots quartz content and TOC for the Genesee and West Falls samples. The apparent positive trend between these two parameters supports a biogenic source for the quartz in these organic-rich shales (Wang and Carr, 2013; Jarvie, 2014), as opposed to an alternative source such as sand particles derived from aeolian transport. Samples from the Genesee Formation have TOC concentrations ranging from 0.35 to 5.88 percent and quartz concentrations ranging from 18.59 to 42.47 percent. West Falls Formation samples have TOC concentrations ranging from 0.20 to 4.09 percent and quartz concentrations ranging from 24.06 to 40.34 percent.

Biogenic quartz gives the rock structural rigidity (Blood and Lash, 2014) because it is a recrystallized, more stable form of quartz and its lipoid-like (lipid/fat-like) algal cell-wall component is highly resistant to chemical and bacterial degradation (Schieber and others, 2000). The presence of biogenic quartz also improves the propagation of fractures during hydraulic stimulation (Blood and others, 2013). The differences in the apparent trends shown by the two formations may reflect different depositional environments with different biota.

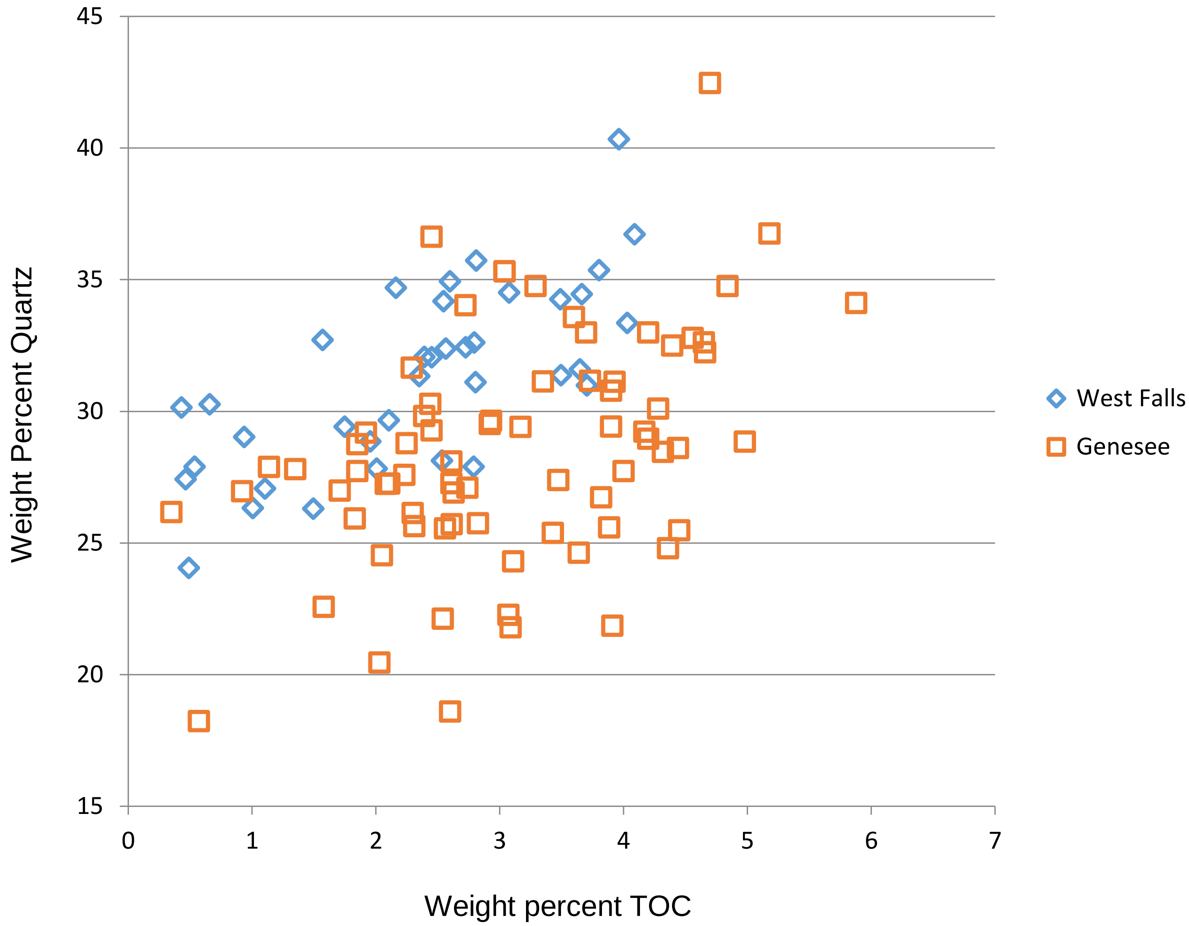


Figure 8: Weight percent quartz versus weight percent TOC for the Genesee and West Falls Formations.

Major Geologic Structures

Allegheny Front

The Allegheny Front (Faill, 1999, 2011) is a structural boundary in Pennsylvania that was created during the Alleghanian orogeny. It roughly coincides with the physiographic feature also called the Allegheny Front. Structurally, it marks a transition zone between the highly folded and faulted Ridge and Valley and relatively flat-lying Appalachian Plateaus provinces (Sevon, 2000). It is the western limit of significant décollement (basal detachment) tectonism and overthrusting of Cambrian through Middle Ordovician carbonates (Faill and Nickelsen, 1999). Ramping of Cambrian through Upper Silurian strata occurred east of the Allegheny Front, producing numerous folds at the surface, whereas most Plateau folds west of the front originate in the Upper Silurian salts of the Salina Group (Faill, 1999). Other minor décollement zones occur in Cambrian shales and shales of the Upper Ordovician Reedsville Formation (especially the basal Antes Shale) near the front.

Lineaments

Lineaments are regional linear features on the landscape, such as linear stream courses or aligned volcanoes, that are usually surface expressions of underlying geological structures such as a fault or series of faults, fracture zone, or shear zone (Hobbs and others, 1976, p. 267; Neuendorf and others, 2011). In Pennsylvania, most lineaments are zones of fracture concentration with little or no cumulative displacement along them (Gold, 1999). The expression of lineaments in subsurface formations may not lie directly in line with the mapped trend of the lineaments due to two factors: 1) lineaments may have a narrow band of morphological expression on the surface and a much broader expression in the subsurface due to processes such as *en echelon* faulting—a series of faults that occur in an overlapping or step-like arrangement (Canich and Gold, 1985); and 2) lineaments are not necessarily vertical features, which means that their expression may be offset at depth. All of the lineaments included in this report are considered CSDs—broad transverse zones of structural disruption in fold and thrust belts (Southworth, 1986).

Various Appalachian basin studies have observed influence of lineaments on organic-rich shale deposition and/or maturation (e.g. Repetski and others, 2008; Lash and Engelder, 2011; McClain, 2014). The speculated depositional systems of Sevon and Woodrow (1981) coincide with Harper's extended lineaments (1989) from the Plateau into central Pennsylvania. These lineaments could represent different depositional systems, as each pair of lineaments bound a separate fluvial system which could have had some control on TOC transport and deposition. Reactivation of the lineaments during the Acadian orogeny may also have controlled TOC deposition (Lash and Engelder, 2011). Flow of hydrothermal fluids (Coyle, 2003) or reactivation during the Alleghanian orogeny may have increased thermal maturities along the lineaments. Repetski and others (2008) reported higher thermal maturities in the Devonian shales along the Pittsburgh-Washington and Tyrone-Mount Union lineaments (respectively shown as E and K on the plates). Repetski and others (2008) studied all organic-rich shales of Devonian age and did not focus on specific intervals as the authors have done in this report. McClain (2014) showed the effects of lineaments on TOC distribution in the Ordovician Utica Shale.

Rome Trough

The Rome trough is a failed rift zone that formed when the Iapetus Ocean opened approximately in the Early to Middle Cambrian (Gao and others, 2000) to possibly Late Cambrian (Ryder, 1987). This feature extends from north-central Pennsylvania south through West Virginia to south-central Kentucky in the Appalachian basin (Shumaker, 1996). Many researchers dispute the exact location of the Rome trough in Pennsylvania; it may be a more subtle feature in Pennsylvania than it is in states to the south (Harper and Laughrey, 1987; Harper, 2004). Interpretations of the Rome trough's location in the state vary significantly. Many reports have the trough trending northeast from Greene County to Potter County (e.g. Root, 1977; Riley and others, 1993; Shumaker, 1996; Beardsley and others, 1999). Others have the trough trending farther to the west from West Virginia (e.g. Dennison, 1985; Harper, 1989, 2004). Repetski and others (2008) show the Rome trough trending southeast of these two interpretations with the northeastern tip of the trough approaching the Scranton gravity high in Susquehanna and Wyoming Counties. These multiple interpretations may, in fact, be correct if the trough bifurcates as it passes through Pennsylvania (Harper, 1989).

The location of the Rome trough should be taken into account when mapping TOC concentrations in Devonian organic-rich shales because of the trough's potential controls on the deposition and preservation of organic material. The basin created by the Rome trough could have created anoxic subbasins favorable for the preservation of organic matter (Curtis and Faure, 1997). In Pennsylvania, for example, the distribution and thicknesses of the Marcellus and Rhinestreet organic-rich shales vary across the hypothesized location of the Rome trough and lineaments in western Pennsylvania (Harper, 1989).

Maps

Common Features

Each map displays structural features such as the Allegheny Front, the approximate location of the Rome trough, and lineaments. Because the exact location of the Rome trough in Pennsylvania is uncertain, the authors display the approximate location of the trough (Alexander and others, 2005; Repetski and others, 2008) with fuzzy edges and the speculated western edge of the trough (Harper, 1989, 2004) as a dashed line. Based on the speculative nature of the western edge of the Rome trough, some of the following interpretations, by necessity, are inferred. The lineaments of this study are related to basement structures that may have been reactivated during the Acadian and/or Alleghanian orogenies. The authors coded the names of the depicted lineaments for map representation. Table 3 provides references for locations of these lineaments.

Table 3: Lineament codes used on contour maps in this study. Locations for lineaments E, G, I, K, Q, T, and U are based on shapefiles from Alexander and others (2005).

Lineament Code	Lineament Name	Source of Location
A	Unnamed	Harper (1989, 2004)
B	Greene County	Harper (1989, 2004)
C	Unnamed	Harper (1989, 2004)
D	Washington County	Harper (1989, 2004)
E	Pittsburgh-Washington	Alexander and others (2005)
F	Unnamed	Harper (1989, 2004)
G	Blairsville-Broadtop	Alexander and others (2005)
H	Cross Creek	Harper (1989, 2004)
I	Home-Gallitzin	Alexander and others (2005)
J	French Creek	Harper (1989, 2004)
K	Tyrone-Mount Union	Alexander and others (2005)
L	McAlevys Fort-Port Matilda	Harper (1989, 2004)
M	Unnamed	Harper (1989, 2004)
N	Sinnemahoning Creek	Harper (1989, 2004)
O	Unnamed	Harper (1989, 2004)
P	Unnamed	Harper (1989, 2004)
Q	Lawrenceville-Attica	Alexander and others (2005)
R	Unnamed	Harper (1989, 2004)
S	Unnamed	Harper (1989, 2004)
T	Everett	Alexander and others (2005)
U	Unnamed	Alexander and others (2005)

Total Organic Carbon Content of the Genesee Formation

The authors used 76 data points measuring TOC by average weight percent from cuttings of the basal Upper Devonian Genesee Formation (includes primarily the undifferentiated Geneseo and Burket Shale Members, and to a lesser extent the undifferentiated Genesee and Tully/Harrell Formations) to generate the Genesee TOC map (Plate 1). These data cover 13 counties ranging from southern Allegheny to northwestern Bradford and southeastern Lycoming Counties, with a large data cluster in north-central Pennsylvania and sparse data covering western Pennsylvania. The number and distribution of data points for each county are as follows: Allegheny (1), Armstrong (1), Bradford (1), Cameron (9), Clinton (8), Crawford (1), Elk (11), Lycoming (5), McKean (7), Potter (19), Somerset (1), Tioga (10), and Warren (2). The authors consider the one data point in Armstrong County anomalous (* on the map) because cuttings from the Geneseo Shale and the Tully Limestone were mixed in the provided analysis. It seems likely that there is a low TOC in the Geneseo Shale at this location, but it is probably not as low as the measured value shown in Table 1 or Plate 1. The authors mapped TOC on a contour interval of 1 percent based on overall distribution and the data cluster in Cameron, Clinton, Elk, McKean, Potter, and Tioga Counties. A hachured contour of 2 percent defines a low concentration zone in Elk County, and a closed contour of 5 percent defines a high concentration zone in Cameron and McKean Counties. If more data existed in western Pennsylvania, the contours would probably be as complex as they are in the north-central portion of the state. The approximate western limit of the Geneseo Shale occurs from northern Mercer to northwestern Warren County (Lash, 2007).

The authors examined Lash's isopach map (2007) of the Geneseo Shale to aid in the construction of Plate 1. According to this map, the Geneseo Shale ranges from more than 100 ft (30.5 m) thick in the northeast to 0 ft (0 m) thick in the northwest (Lash, 2007). Most of the high TOC data points in this study fall between the 12-ft (3.7-m) and 36-ft (11-m) contours of Lash's map (2007). In the southwestern part of the state where there was little Genesee data control, the authors incorporated trends from these two contours as mapped by Lash (2007). A justification for using this method is that the highest TOC concentrations are usually found in a condensed section—a thin stratigraphic unit that has been starved of sediment influx (Loutit and others, 1988; Laughrey, 2009; Embry, 2010; Catuneanu and others, 2011; Blood and Lash, 2014). The biogenic material is therefore concentrated in this zone. Consequently, thinner shales may have higher TOC concentrations than thicker shales.

Over most of the mapped extents of the Geneseo Shale, the TOC concentrations measured in these samples are sufficient to have the potential to produce hydrocarbons. This shale is considered to be the source rock for some of the oil and gas encountered in Upper Devonian sandstone and siltstone reservoirs (Harper, 1989; Repetski and others, 2008). TOC concentrations may not be high enough to produce commercial quantities of hydrocarbons in eastern Armstrong County, eastern Westmoreland County, and the area from Somerset County to the Allegheny Front. More data will help better define the boundaries of potentially productive regions for these shales.

Because the authors interpreted the Rome trough to have more of an influence on high TOC concentrations than the lineaments where they approach the Allegheny Front in the center of the state, they constructed the contours parallel to the trough rather than parallel to the lineaments. The Rome trough's speculated western edge (Harper, 1989, 2004) also appeared to have an influence on the northwest shift of a lobe formed by the 3 percent TOC contour in Butler, Clarion, and Venango Counties. Harper (1989, 2004) based this speculated edge of the Rome trough on mapped Cambrian faults and subsurface data from wells. Offset of the trough's speculated edge along the Tyrone-Mount Union (K) lineament was supported by aeromagnetic and gravity data (Lavin and others, 1982) and offset along the Pittsburgh-Washington (E) lineament was supported by subsurface data (Harper, 1989).

The authors also observed the effects of lineaments on TOC distribution. The unnamed M lineament shown on their map separates the high and low TOC concentration zones in Cameron, Elk, and McKean Counties. This and the McAlevys Fort-Port Matilda (L) lineament roughly bracket most of the low TOC area mapped in Elk County. These two lineaments also bracket a thinner zone, 18 to 24 ft (5.5 to 7.3 m) thick, of the Geneseo Shale in southern Elk County on the isopach map constructed by Lash (2007). Lash's map did not show any thickness variations in the region of high TOC concentrations mapped to the north in Cameron and McKean Counties, where the shale is 24 to 36 ft (7.3 to 11 m) thick. Moving farther to the east, the shale thickens to more than 100 ft thick (30.5 m) on Lash's map (2007), and it is uncertain what may have caused the linear east-west feature in southern Potter and Tioga Counties on the authors' map. This feature is parallel to the strike of surface anticlines and synclines.

The speculated western edge of the Rome trough (Harper, 1989, 2004) bisects the high and low concentration TOC zones in Cameron, Elk, and McKean Counties. Also, both of these clusters occur within the limits of the Oriskany "no-sand zone." This Oriskany "no-sand zone" was caused by tectonic doming above the Kane gravity high (Lavin and others, 1982), which either allowed sand to be eroded away or prevented deposition of this blanket sand (Root, 1977). Devonian shales are also thinner in this zone (Root, 1977). The TOC high in Cameron and McKean Counties may be the result of increased nutrient influx from an unknown source on this topographic high. Smith (2014) created a model that describes how increased nutrient flow can lead to higher TOC concentrations. A separate flow system as divided by the M lineament could have prevented this nutrient influx from impacting the southwestern part of this topographic high.

Thermal Maturity of the Genesee Formation

The Genesee R_o map (Plate 2) is based on 65 data points measuring average percent R_o, which represents the thermal maturity of cuttings from the basal Upper Devonian Genesee Formation (including primarily the Geneseo Shale Member, and to a lesser extent the undifferentiated Genesee or Tully/Harrell Formations). These data cover 11 counties ranging from southern Allegheny to western Lycoming and Tioga Counties. The number and distribution of data points for each county include: Allegheny (1), Cameron (9), Clinton (7), Crawford (1), Elk (7), Lycoming (3), McKean (7), Potter (19), Somerset (1), Tioga (8), and Warren (2). The Geneseo's approximate western limit extends from northern Mercer to northwestern Warren County (Lash, 2007). The authors mapped R_o on a contour interval of 0.5 percent due to a clustering of data in the northcentral counties of Cameron, Clinton, Elk, Lycoming, McKean, Potter, and Tioga. A hachured contour of 2.0 percent occurs within this cluster in northeastern Cameron and southwestern Potter Counties. Another hachured contour of 1.0 percent occurs just northwest of the 1.5 percent contour line. The authors inferred the southern part of this 1.5 percent contour because of the sparse data in northwestern Pennsylvania from Beaver to Forest Counties and extrapolated the remaining contours to trend southwest to northeast roughly parallel to the Allegheny Front and the Rome trough.

Thermal maturities of organic-rich shales in the Genesee Formation vary from late in the oil generation window in the north-northwestern portion of Pennsylvania to late in the gas generation window over much of the study area (Table 4). In general, Genesee thermal maturities increase toward the Allegheny Front. All of the measured R_o values greater than 2.0 occur within the Rome trough. This may result from geothermal fluids traveling along faults in the Rome trough, a limited thermal maturity dataset, greater burial depths in this region, or a combination of these factors. The low maturity area mapped in Cameron and Potter Counties may be a result of other structural influences within the trough. The high concentration lobes reaching north in Potter County and east in Lycoming County may be evidence of the Rome trough bifurcating as postulated by Harper (1989), but more data is needed to determine this.

Table 4: R_o values used to determine a source rock's level of thermal maturity (from Peters and Cassa, 1994).

Stage of Thermal Maturity for Oil	%R_o
Immature	0.20–0.60
Early	0.60–0.65
Peak	0.65–0.90
Late	0.90–1.35
Postmature	>1.35

Total Organic Carbon Content of the West Falls Formation

The authors used 45 data points of measured TOC content by average weight percent from cuttings of the basal Upper Devonian West Falls Formation (includes primarily the Rhinestreet Shale Member, followed by the undifferentiated West Falls Formation and correlative Brallier Formation) to create the West Falls TOC map (Plate 3). These data cover 15 counties, ranging from western Beaver to northwestern Bradford County. The number and distribution of data points for each county include: Armstrong (1), Beaver (4), Bradford (1), Clarion (4), Clinton (1), Crawford (6), Elk (4), Erie (4), Forest (2), McKean (5), Mercer (1), Somerset (1), Tioga (1), Venango (3), and Warren (7). The authors mapped West Falls TOC on a contour interval of 1 percent based on a fairly even distribution of data throughout the northwestern portion of the study area. They show the southern ends of the 1 and 2 percent contour lines as dashed lines from Greene to Armstrong and Butler Counties due to lack of data control.

TOC concentrations in the West Falls Formation decrease toward the Allegheny Front. This shale is best developed northwest of the Rome trough (location of trough as interpreted by Alexander and others, 2005; Repetski and others, 2008) due to a westward shift in the basin's depocenter (Piotrowski and Harper, 1979; Figure 4B). With TOC values greater than 1 percent, the authors expect the shale to produce hydrocarbons in the area northwest of the Rome trough in Pennsylvania. The Rhinestreet Shale is considered a potential source rock for Upper Devonian and Mississippian sandstone and siltstone oil and gas reservoirs (Harper, 1989; Repetski and others, 2008). It might also be a source rock for the Oriskany Sandstone in western fields of the Appalachian basin (Repetski and others, 2008).

The authors observed some influence of lineaments in West Falls TOC concentrations, especially the French Creek (J), Tyrone-Mount Union (K), and unnamed (M) lineaments. The low TOC value of 0.49 in Crawford County corresponds to the area of greatest net thickness in the Upper Devonian West Falls Formation (Rhinestreet Shale) in Pennsylvania (Pennsylvania Department of Conservation and Natural Resources, 2009). However, the point with the second greatest net thickness on the map has a high TOC (greater than 2). This net feet map does not seem to show a relationship to the K lineament, but does show a relationship to the J lineament which may be related to data availability at the time of the map's creation.

Thermal Maturity of the West Falls Formation

The authors based the West Falls R_o map (Plate 4) on 30 data points measuring average percent R_o of cuttings from the basal Upper Devonian West Falls Formation (includes primarily the Rhinestreet Shale Member, followed by the undifferentiated West Falls Formation and equivalent Brallier Formation). These data cover 11 counties ranging from western Beaver to southwestern Tioga County. The number and distribution of data points for each county includes: Beaver (4), Clarion (3), Clinton (1), Crawford (5), Erie (3), Forest (1), McKean (2), Somerset (1), Tioga (1), Venango (3), and Warren (6). The authors mapped West Falls R_o on a contour interval of 0.25 percent based on multiple data points spread throughout the northwestern counties of Clarion, Crawford, Erie, McKean, Venango, and Warren, as well as Beaver County. Most of the contours trend southwest to northeast, roughly paralleling the Allegheny Front.

Thermal maturity values measured from the West Falls Formation vary from the peak oil window in the northwest to post-mature near the Allegheny Front (Plate 4). Where TOC contents are sufficient to produce hydrocarbons, the measured thermal maturity values range from the oil generation window to the gas generation window.

The Tyrone-Mount Union (K), McAlevys Fort-Port Matilda (L), and unnamed (M) lineaments exhibited an apparent strong influence on thermal maturities found in the Rhinestreet Member of the West Falls Formation in Crawford, Erie, McKean, and Warren Counties. The authors interpreted this influence over the rest of the map to suggest trends where data are sparse. Coyle (2003) speculated on the transport of hot fluids along permeable pathways formed by the lineaments which potentially elevated the organic maturities along these lineaments during the Alleghanian orogeny.

Depositional Environments

Genesee Formation

Early to Middle Cambrian rifting that created the Rome trough (Figure 3) may have facilitated accommodation space for the organic-rich shales of the Genesee Formation. After uplift and erosion of the underlying upper Hamilton Group strata and Tully Limestone, maximum regional subsidence occurred with onlapping of Genesee strata over older eroded Hamilton strata, heralding the third tectophase of the Acadian orogeny (Ettensohn, 1985, 1987, 1994; Figure 5). Although most of the Middle and Upper Devonian clastics came from the southeast, a shift in depocenter was responsible for a northeast provenance for the lower Genesee members (Piotrowski and Harper, 1979).

Organic material and skeletal remains of pelagic fauna preferentially accumulate in condensed zones when transgressive events advance clastic sedimentation farther inland (Loutit and others, 1988). Maximum flooding surfaces of late transgressive to early regressive systems tracts enriched the Genesee Formation in biogenic silica zones. This transgressive event supplied silica, molybdenum, and nutrients that stimulated productivity in the photic zone (upper 260 ft [79.3 m]) (Blood and others, 2013). Protozoans (Radiolaria) thrived on a diet rich in organic detritus, bacteria, zooplankton, and other phytoplankton (Anderson, 1983; Steineck and Casey, 1990). When food was scarce, symbiotic relationships with algae provided primary nutrition for the radiolarian host and the general area (Kling and Boltovskoy, 2002). In addition to optimal temperature and salinity conditions, radiolarian colonies depend on chlorophyll to survive as large populations are associated with high chlorophyll concentrations (Anderson, 1983).

In the organic-rich shale member of the Genesee Formation, biogenic quartz is the most dominant biogenic mineral second only to calcite (Bohrmann and Stein, 1989). Biogenic quartz fills *Tasmanites* algal cysts and other fossil and interparticle voids. These cysts are dormant spores of the microscopic marine green alga, *Tasmanites* (de La Rue and others, 2009) and are referred to in this discussion as “voids” for vacant cysts after spore release. Early diagenetic silica likely originated from the dissolution of unstable opaline quartz tests of planktonic radiolarians or other microorganisms in bottom intrabasinal waters; dissolution was controlled by harsh temperature and redox conditions, and silicon undersaturation (Schieber and others, 2000; Blood and others, 2013). During conditions of enhanced productivity, the silica reprecipitated as a more stable form at the algal cell wall which enriched buried organic matter to result in an organic-rich deposit (Schieber, 1996; Blood and others, 2013). Schieber (1996) inferred sites of silica infilling not associated with algal voids to form in gas-bubble cavities at the pore-fluid/gas contact in some cases. This new precipitate consequently became part of the clay matrix in mudstones, strengthening the framework to enable a high-modulus medium that is receptive to hydraulic fracture propagation and production (Blood and others, 2013).

West Falls Formation

The Rome trough (Figure 3) may have also initially facilitated accommodation space for the shales of the West Falls Formation and created associated Rhinestreet Member subbasins (Curtis and Faure, 1997). Subsequent thermal history may also depend on other geological factors such as repeated tectonic patterns, hydrothermal fluid activity through fractures, and eustatic sea level changes (Harper, 1989).

Middle and Upper Devonian erosion of the Acadian Mountains contributed to development of the Rhinestreet Member, which originated as fine-grained extensions of the Catskill delta (Faill, 1985; Roen, 1993; Curtis and Faure, 1997). Deposition of the Rhinestreet Shale in a condensed section is supported by a maceral study from Curtis and Faure (1997), which revealed that organic matter accumulated in water above the subbasins with minor amounts of continental material. High TOC values occurred from high biological production during upwelling conditions and/or from enhanced preservation of organic matter in anoxic waters of subbasins above the distal end of a westward thinning clastic wedge as proposed by Schieber (1996). For example, periodic blooms of *Tasmanites* and similar organisms in waters above the subbasins during Rhinestreet and later Huron (in ascending stratigraphic order) deposition helped preserve organic matter (Curtis and Faure, 1997) due to a strong chemical resistance of the algal void wall, presence of clays, and redox conditions at the sediment-water juncture (de La Rue and others, 2009). Smectitic clays also offer a large surface area onto which organic matter may adsorb (Kennedy and others, 2002). Low TOC occurred where organic matter decomposed in oxygen-rich water associated with high sedimentation rates. Mixed marine-continental organic matter is more prevalent in the east near the postulated Catskill delta complex (Dennison, 1985; Woodrow, 1985).

Similar to the Genesee Formation samples, biogenic quartz is important in the West Falls Formation because it furnishes a rigid structural framework for the rock, assists in the preservation of organic matter, and provides insight into the shale's depositional environment. The likely candidate for the source of early diagenetic silica in these sediments is the dissolution of large initial concentrations of unstable amorphous silica such as radiolarian tests or other microfossils, opaline skeletons, and volcanic glass (Schieber, 1996). According to Schieber (1996), recrystallization of the dissolved silica from these opaline skeletons may provide a major component of *in situ* intrabasinal quartz sand in shale sequences as opposed to fluvial or aeolian derived detrital quartz grains of the extrabasins (Blood and others, 2013). Silica-filled voids in lag deposits on erosion surfaces and shale sequence boundaries (Schieber and others, 2000) characterize a sediment-water interface, low sedimentation rates, and the potential presence of biogenic silica in the original sediment (Schieber, 1996).

CONCLUSIONS

Graphs of TOC and R_o values from the Upper Devonian Genesee, Harrell, and West Falls Formations, in concert with other available data, have provided insight into the organic-rich shale members of these formations. Plotting TOC concentrations versus net radioactivity of these shales did not exhibit any relationship, which implies rapid sedimentation rates. Plotting R_o versus sample depth suggests a positive trend for the West Falls Formation, consistent with the documented relationship between thermal maturity and burial depth. The nonlinear relationship between thermal maturity and depth for the Genesee and Harrell Formations is ambiguous and requires further study. The apparent positive relationship between TOC and quartz concentrations suggests a biogenic source for the quartz in these shales. The maximum flooding surface of a transgressive sequence enabled these shales to become enriched in biogenic silica as it stimulated productivity in the photic zone. During this time, the transgression impeded clastic sedimentation, enabling preferential accumulation of stable skeletal remains of pelagic fauna such as radiolarians to form condensed sections within the intrabasins. Likewise, preservation of organic matter was also enhanced by periodic algal blooms of *Tasmanites* and similar organisms in waters above the subbasins.

Mapped TOC for the Genesee and West Falls Formations show areas where organic-rich shales have the potential to produce hydrocarbons. Mapped R_o indicate what hydrocarbon type drillers may expect in potentially productive areas. Organic-rich shales in the Genesee and Harrell Formations have the potential to be productive over much of the study area. Thermal maturity values imply mostly dry gas production from these two formations, with the possibility of some oil or wet gas production in the northwestern portion of the study area. The Rhinestreet Member of the West Falls Formation has the potential to produce oil or wet gas in northwestern Pennsylvania, north of the Rome trough.

The authors' maps reveal the influence of tectonic events and basement structures including the Acadian and Alleghanian orogenies, the Rome trough, and lineaments on Genesee and West Falls TOC and R_o distributions, with some features exhibiting more control on these parameters than others. When comparing these events and structures, the Acadian and Alleghanian orogenies demonstrated the strongest effects on R_o values for both formations, as R_o values increase toward the Allegheny Front. Elevated pressures and hydrothermal fluids associated with the orogenic events could have caused the higher R_o measurements near the front. As a result of westward deepening of the basin, TOC concentrations in the West Falls Formation decrease toward the front. The Rome trough appeared to have had the strongest influence on Genesee TOC concentrations, and less influence on R_o values calculated for either formation. Anoxic subbasins within the Rome trough could have led to the preservation of organic carbon, and faults within the trough may have transmitted hydrothermal fluids that affected R_o values. Due to the westward shift in the basin's depocenter, the Rome trough did not display significant control on TOC concentrations or R_o values measured in the West Falls Formation. Various lineaments appear to have strongly influenced TOC and R_o values associated with the West Falls Formation. Transport of hydrothermal fluids along lineaments during the Alleghanian orogeny may have affected thermal maturities. Variations in TOC associated with the Genesee and Harrell Formations were consistent with some of the mapped lineaments. TOC deposition may have varied across lineaments because each pair of lineaments defined a separate fluvial system or fault block.

ACKNOWLEDGMENTS

The authors wish to thank Robin V. Anthony and Michele L. Cooney for their help and insights as this report was being prepared. The authors also thank Victoria V. Neboga for guidance on initial GIS map construction, and Caron E. O'Neil and John H. Barnes for editorial advice. In addition, they are grateful to Thomas G. Whitfield for final GIS map preparation, Robin V. Anthony for assistance with figure preparation, and Brian J. Dunst, Gary M. Fleeger, Gale C. Blackmer, Kristin M. Carter, John A. Harper (retired, Pennsylvania Geological Survey), and industry reviewers Kathy J. Flaherty (Geologist & Attorney) and Tracee K. Imai for providing valuable technical reviews of this report.

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