REGIONAL DEPOSITIONAL TRENDS IN THE DEVONIAN
GENESEO/BURKET BLACK SHALE BASED ON GAMMA RAY-
DENSITY CHARACTERISTICS

A Thesis in
Geosciences
by
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ABSTRACT

Gas shales are becoming increasingly important as new technologies are applied to enhance their production of natural gas. The Barnett, the Fayetteville, and the Haynesville have all been successful gas shale plays in North America. In addition, the Marcellus has recently stimulated a boom in Pennsylvania shale-gas production. The Geneseo-Burket is a Middle Devonian black shale of the Genesee Group that overlies the Tully Limestone and Hamilton Group, which includes the Marcellus Black shale. It is currently unclear whether it is prospective as a gas shale or not. This study seeks to examine the commercial value of the Geneseo-Burket Shale through the characterization of the relationship between density and organic matter. This relationship, in conjunction with thickness trends in a sequence stratigraphic framework, can be used as an exploratory tool for gas shale reservoirs in the Appalachian Basin.

This study uses 280 well logs used to conduct a petrophysical evaluation of the Geneseo-Burket Shale in Pennsylvania and New York. Gamma ray and bulk density well logs, supplemented by well cuttings, are used to derive isopach/structure maps, density-gamma ray trends and the spatial distribution of organic matter. The relationships among these characteristics and the mechanisms that produce their regional patterns are also explored. Distinctive density patterns can be observed in well logs of the Geneseo-Burket throughout the basin. Density vs depth trends illustrate considerable deviation from normal shale sections. Observed lower densities in the Geneseo-Burket are a likely indicator of increased organic matter. Density data are compared with gamma ray logs to
quantify the relationship between density and organic content. They are correlated with a Pearson product-moment correlation coefficient ($R^2$) equal to 0.65. Organic matter percentages in the Geneseo-Burket are calculated and range from 2-18 percent by volume. An empirical relationship is developed to convert organic matter in volume percentages to total organic carbon in weight percent. The spatial distribution of organic matter is mapped and increasing concentrations in western Pennsylvania suggest a decrease in clastic dilution. Also, the variation in formation thicknesses is illustrated by construction of an isopach map. The Geneseo-Burket extends throughout the northern Appalachian Basin and thicknesses exceed 150 feet in eastern Pennsylvania.

The internal stratigraphy of the Geneseo-Burket is defined in terms of its well log (density, gamma ray) character. Locally, the interval is characterized by at least 4 gamma ray maxima and density minima that correlate. These patterns are repeatable throughout northern Pennsylvania and west-central Pennsylvania and ultimately demonstrate the extent and structure of the basin. Regional variations in the interval of the Geneseo-Burket are identified, defined and summarized into a depositional sequence, using a sequence stratigraphic framework. Finally, the distribution of systems tracts in the Geneseo-Burket, Lodi limestone and Penn Yan Members of the Genesee Group suggest that these units are analogous to the Union Springs, Cherry Valley, and Oatka Creek members of the Marcellus Formation in Hamilton Group.
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Chapter 1

Introduction

Although Devonian shales from the Appalachian Basin (Pennsylvania, Ohio, West Virginia, Kentucky) were a target of modest natural gas production for over 100 years, they recently became more economical to produce due to the combination of rapid decline in conventional gas production and advanced production techniques. Some of these techniques, which include horizontal drilling and massive slickwater fracturing, are currently being used in the Marcellus and Dunkirk-Huron shale play. The Marcellus gas shale has the potential to be one of the most promising natural gas resources in the United States. Natural gas producers have recently invested billions in Pennsylvania in lease and land acquisition, new well drilling, infrastructure development, and community partnerships. There is an even greater investment expected in the future. Commercial gas production has been reported from the Rhinestreet, Levanna and Marcellus shales of the Appalachian Basin (Van Tyne, 1983). The Geneseo-Burket shale, along with the Marcellus is one of the most highly radioactive of the Devonian shales, yet there is no known gas production where the Geneseo-Burket is the explicit target, although comingled production is likely.

The Geneseo-Burket was incorporated into previous assessments that included isopach maps (de Witt and Colton, 1978; Piotrowski and Harper, 1979; Schmoker, 1980; Lash, 2007), but the maps are either limited to a portion of Pennsylvania or examine an
undifferentiated Devonian shale section (Figures 1-4). The differences between these maps are striking and deserve explanation.

The main goal of this research is to examine some characteristics that will ultimately allow an assessment of the commercial value of the Geneseo-Burket Shale. We hypothesize that trends in bulk density are driven by variations in organic content, which is preserved mainly as a function of varying dilution rates. Specifically, this study will examine: 1) the relationship between density and organic matter 2) thickness trends and 3) a sequence stratigraphic model.

Development of the Geneseo-Burket’s internal stratigraphy is critical to understanding the evolution of the Appalachian Basin and future exploration opportunities. Well logs have previously been used for sequence stratigraphic analysis, including identifying elements such as: depositional sequences, system tracts, sequence boundaries and surfaces (Partington et al., 1993; Emery and Myers, 1996). In this way, basin fill can be organized into bounded packages of strata that provide framework for reservoir assessment (Lash and Engelder, in press).
Figure 1. Isopach map showing thickness of Geneseo Shale Member in feet (de Witt and Colton, 1978).
Figure 2. Isopach map of Burket-Geneseo-Renwick shale facies (Piotrowski and Harper, 1979).
Figure 3. Thickness in feet of organic rich Devonian-shale facies with organic rich defined as organic content of 2% or more by volume (Schmoker, 1980).
Figure 4. Isopach map of the Geneseo Shale, thickness in feet (Lash, 2007).
1.1 Nomenclature

The Burket Shale member of the Harrell Formation in Pennsylvania is correlative to the Geneseo Shale of the Geneseo Formation of New York (Butts, 1918). The Geneseo-Burket contains an Upper Givetian conodont fauna characterized by the *disparilis* Zone, which places it in the Middle Devonian (Over, 2007). The Burket and Geneseo are lithology very similar and they occupy the same stratigraphic position above the Tully Limestone (de Witt et al., 1993). The assumption that they are lithostratigraphic-equivalents will be further validated by correlation in gamma ray and bulk density logs. Thus, in this work, this interval is referred to as Geneseo-Burket Shale and follows the convention that the Geneseo is a formation in the Genesee Group (Van Tyne, 1983).

1.2 Geologic background

1.2.1 *Stratigraphic background*

The stratigraphic unit that includes the Geneseo-Burket shale and Tully limestone has been discussed in great detail (Grabau, 1917a; Heckel, 1966; de Witt and Colton, 1978; Ettensohn, 1985;). The depositional sequence is characterized by the basal Tully limestone (Figure 5). A sequence-boundary unconformity and flooding surfaces caps the limestone and is
Figure 5. Middle and Upper Devonian stratigraphy of western New York, showing major black shale units; not to scale (modified from Van Tyne, 1983). Photo taken at the entrance of Taughannock State Park in Trumansburg, NY.
succeeded by dark shale-dominated strata that in general coarsen upward to the base of
the overlying sequence (Ver Straeten and Brett, 1995).

The Tully Limestone is one of two major carbonate units in the Devonian clastic wedge,
the other being the Onondaga Limestone. In general, the Tully is a dark gray to black,
fossiliferous limestone, composed of lime silt and fine mud. The grains of non-uniform
shape/size, along with their mono- and polycrystalline structures, are interpreted as
skeletal lamellae (Heckel, 1966). Because fossils in the Tully calcilutites are whole and
show no signs of abrasion, they could not have contributed a significant amount of lime
or mud (Grabau, 1917). Syn-orogenic structures that prevented the clastic influx from
overwhelming the carbonate shoal in the east, westward thinning of the Tully, and
increasing shale content in the south, suggests the lime mud was derived from an algal or
coral reef in the north (Heckel, 1966).

The interval characterized by deposition of the Tully limestone was terminated in the
western basin by either lack of sedimentation or subsequent uplift and erosion of it. The
organic-rich deposits of the Geneseo-Burket onlapped the Tully Limestone throughout
the basin. The Geneseo-Burket Shale is primarily composed of grayish-black, brownish-
black and black shales. Dark-medium gray, laminar to wavy bedded siltstone layers that
range from 0.25-10 inches occur sparingly.
The number of siltstone beds in the Geneseo-Burket increases towards the east in the vicinity of Keuka Lake, NY (de Witt and Colton, 1978). The unit grades upward into a prograding wedge of deltaic clastics. Previous maps (de Witt and Colton, 1978) indicate that the Geneseo-Burket’s thickness ranges from 130 ft, near Cayuga Lake to 44 ft in western New York. East of Cayuga Lake, the Geneseo-Burket interfingers the Tully limestone in a zone that increases up to 15 feet thick. This zone consists of 1-6 inches of brownish-black, slightly calcareous shales, intercalated with 3-18 inches of argillaceous, brownish-black nodular limestones (de Witt and Colton, 1978). In contrast, the Geneseo-Burket lies unconformably above the Tully in the west (Ettensohn, 1985).

1.2.2 Tectonic background

The Middle-Upper Devonian black shales, including the Marcellus and Geneseo-Burket have been interpreted as a direct manifestation of the Acadian Orogeny (Ettensohn, 1985). Pulses of crustal loading caused rapid subsidence and black shale (Figure 6) was deposited in four stages (Ettensohn, 1985). The first stage was initiation of tectonic loading and formation of a basin through rapid subsidence. These deep, basinal black shales are characterized as a transgressive systems tract. Stage two was characterized by southern migration of deformation and a decrease in subsidence rate along the eastern and western side of the basin (Ettensohn, 1985). This deposits a regressive systems tract and clastic influx increases. During stage three, additional collision and widespread uplift creates a regional disconformity in association with a peripheral bulge (Ettensohn, 1985). Stage four consists of a period of tectonic quiescence.
Figure 6. Four tectophases associated with black shale deposition (Ettensohn, 1994).
with widespread carbonate deposition. In the absence of stage four, the depositional cycle returns to stage one (Ettensohn, 1985).

The Middle and Late Devonian are divided into four intervals called “tectophases” (Ettensohn, 1985). The first is represented by the Needmore and Esopus black shales, as well as the Onondaga limestone. The second tectophase is represented by the Hamilton Group which is composed of the Marcellus and other siltstone and shale units (Figure 7). The Tully limestone, which directly underlies the Geneseo-Burket, is representative of the last stage in the second tectophase, while the Geneseo-Burket marks the beginning of the first stage of the third depositional cycle (Ettensohn, 1985). This third tectophase began with stage one, where tectonic loading was re-initiated. This stage is characterized by the black Geneseo-Burket Shale, and is related to a period of global transgression and cratonic submergence (Sloss and Speed, 1974; Johnson, 1970; Baird and Brett, 2003).

1.3 Sequence Stratigraphy

The application of sequence stratigraphic methods to basin evolution studies permits chronostratigraphic subdivision of the rock record into cyclic, unconformity bound, genetically related, successions of strata (Van Wagoner et al., 1988). A depositional sequence is the fundamental unit of sequence stratigraphy. They are coherent packages of strata that are bound at the bottom and top by unconformities or their correlative conformities (Mitchum et al., 1977). Sequences are formed by cyclic changes in relative
Figure 7. Upper and Middle Devonian stratigraphy of western and west-central New York showing major black shale units. (Van Tyne, 1983).
sea level through interaction of tectonics, eustasy, and sedimentation (Allen and Allen, 1990). They are divided into system tracts: Lowstand (LST), Transgressive (TST) and Highstand (HST), composed of smaller sequences (parasequences) deposited during a transgressive-regressive cycle.

A transgressive-regressive cycle (T-R cycle) is characterized by sedimentary rocks deposited during the time between the beginning of one deepening event and the beginning of the next (Johnson et al., 1985). Twelve post-Lochkovian T-R cycles have been recognized and dated using standard conodont zonations. Evidence from three mid-continent areas demonstrates that these deepening events are simultaneous in several or all of the following five regions: western US, western Canada, New York, Belgium and Germany (Johnson et al., 1985). The Geneseo-Burket and underlying Tully limestone belong to the TR cycle referred to as IIa and correlate with the Taghanic Onlap (Johnson, 1985). T-R cycle IIa is associated with a strong-sustained transgression.

Surfaces most beneficial to identifying depositional and T-R sequences are: subaerial unconformities, shoreface ravinements, and the maximum flooding surface (Embry 2002). The marine flooding surface defines the change from the TST to the RST (highstand systems tract), which is not necessarily a record of the base level maximum. Base level rise-induced transgressions are characterized by associated increased accommodation space, reduced clastic influx and may correspond with a condensed section (Emery and Myers, 1996; Van Wagoner et al., 1988; Partington et al., 1993).
Condensed sections are spatially extensive, can have high total organic carbon (TOC) and authigenic/diagenetic minerals such as phosphatic, glauconitic, or pyritic material (Sarg 1988; Liro et al 1994; Emery and Myers, 1996). Transgressive system tract deposits, especially the condensed section, have great source rock potential (Emery and Myers, 1996; Vail, 1987). The reduced clastic flux that is associated with a base level high favors concentration of oil-prone organic matter (Creaney and Passey, 1993).

In this study, a sequence stratigraphic framework is adopted to investigate the regional variation of the Geneseo-Burket and adjacent formations. A model that includes log signatures (bulk density, gamma ray) to describe and identify depositional sequences, their associated system tracts and sequence boundaries surfaces is developed.

1.4 Geophysical Well logs

Many geophysical well logs could be used to evaluate the petrophysical characteristics of the Geneseo-Burket shale, including; resistivity, sonic, neutron porosity, gamma ray, and density logs. For this study, bulk density and gamma ray logs were primarily used due to their wide availability.
1.4.1 *Gamma ray logs*

Gamma ray logs are used to measure the natural radioactivity of a formation. Various rock types are inferred, because specific gamma ray intensities are known for each of the major sedimentary rock classes. In general, shales have higher gamma ray values than sandstones and limestones. The Geneseo-Burket’s typical gamma ray signature is prominent in well logs, as it usually exceeds 180 API units. In addition, there is a gamma ray spectrum tool that records total gamma ray counts as well as individual contributions from potassium, thorium and uranium. While all of these radioactive elements significantly contribute to the total gamma ray count, it has been shown that in black shale sections, variations in uranium correlate best with variations in the total gamma ray count. For example, the gamma ray spectral log response in the Geneseo-Burket interval, Allegany County, NY, shows excessive uranium concentrations (Figure 8). Organic compounds within a rock play a significant role in uranium accumulation (Fertl and Chilingar, 1988). The precipitation of uranium from seawater onto the surface of organic particles under anoxic or euxinic conditions may be governed by several factors, including carbonate content, sedimentation rate, and primary uranium content of the seawater (Lüning and Kolonic, 2003). Marine shales generally contain 15-60 ppm uranium and within a given formation, large amounts of organic matter are found in the rocks containing the most organic matter (Mckelvey and Nelson, 1949). Devonian shales of the Appalachian Basin are a prime example of this association (Guidry et. al. 1990; Leventhal and Goldenhaber, 1978). Therefore, gamma ray logs in Devonian shales are an estimate of organic richness.
Figure 8. Geneseo-Burket log from Allegany, NY showing Uranium, Potassium, Thorium and gamma ray association (Fertl and Chilingar, 1988).
1.4.2 Bulk density logs

The bulk density log is a measure of overall formation density. This “formation” density measurement includes the solid matrix and the fluid enclosed in pores. The Geneseo-Burket interval is characterized by several low bulk density layers (Figure 9). If the bulk density only depends on matrix density and fluid density, then porosity is inferred. The Geneseo-Burket shale has other constituents, namely organic matter and pyrite, which affect the bulk density. A porosity curve (sonic, bulk density, neutron porosity) cannot be exclusively used to estimate organic richness, because it is impossible to distinguish the porosity response from the organic matter response, without assuming constant porosity throughout the interval (Passey et al., 1990). To make quantitative total organic carbon (TOC) estimations, measured TOC values must be available for calibration. Once the volume of organic matter is calculated, the correct bulk density reading is obtained and calculation of the corresponding porosity is possible.

1.5 Other geophysical data

Although the Tully limestone is laterally discontinuous, it serves as a very prominent reflector in seismic data (Figure 10). The reflector is characterized by a strong acoustic impedance contrast that signifies the contact between the Tully and the overlying shales of the Geneseo-Burket (Scanlin and Engelder, 2003).
Figure 9. Gamma ray and Bulk density logs of Geneseo, Hornell quadrangle, NY.
Figure 10. Cross section through Fayette Anticline within Upper Devonian section (Scanlin and Engelder, 2003).
1.6 Organic Content

The significance of organic content in gas production is supported by the common division of shale into black and gray facies (Schmoker, 1980). The darker shales, with higher organic content are usually more productive than the lighter (gray) shales.

Organic matter is the source of natural gas in the Devonian shales (Schmoker, 1980). Also, organic content affects the design/effectiveness of well stimulations and concentrates trace metals of economic and environmental importance. For these reasons, it is useful to examine the spatial distribution of organic matter. This was achieved previously in Ohio, Kentucky and West Virginia using aggregated organic rich zones of the western Appalachian basin (Schmoker, 1980). Continual exploration and production in the basin over the past 20 years have led to better well control, including more wireline logs. Here we focus on the Geneseo-Burket and expand the organic matter analysis to the northern Appalachian Basin, specifically Pennsylvania.
Chapter 2
Methods

This study uses over 280 well logs from Pennsylvania and New York (Figure 11) to obtain gamma ray, density, thickness and stratigraphic characterizations of the Geneseo-Burket shale. The well log files were downloaded in raster and digital formats from the Empire State Oil and Gas Information System (ESOGIS) and Pennsylvania Internet Record Imaging System (PAIRIS). Specifically, the study area includes well logs from 11 counties in south-central New York and 32 counties of Pennsylvania, west of the Allegheny Front. PETRA Software was utilized to manage well data, including calibration, digitization, construction of cross sections and maps.

2.1 Bulk density

In examining the well logs, a distinctive relationship between bulk density and gamma ray was observed: the maximum gamma ray value in the Geneseo-Burket interval usually corresponds to the minimum bulk density value (Figure 9). In an effort to investigate the frequency, statistical significance, and driving mechanism of these occurrences, maximum gamma ray and corresponding bulk density values are recorded from well logs and analyzed. Bulk density vs depth trends are investigated first, followed by the spatial distribution of bulk densities and last, we examine the correlation (or lack thereof) of bulk density with gamma ray intensities. The bulk density vs gamma ray plots were constructed using the LogCrossplot module of PETRA.
Figure 11. Study area and well control, including 280 wells throughout New York and Pennsylvania.
We explore the spatial trends in bulk densities, both spatially and vertically. To observe these depth trends, minimum bulk densities within the Geneseo-Burket interval were picked and plotted with their respective depths. These same bulk density values were plotted in their geographic location to examine the spatial trends. This was to test whether the effect of compaction on bulk density could be distinguished from organic content. Bulk densities were also plotted with their respective gamma ray (organic matter proxy) values to verify that organic matter influences bulk density.

To further test the effect of organic content on bulk density, gray shale (organic lean) bulk densities are also plotted with their respective depths. The bulk density values were chosen in the Harrell Shale Formation, approximately 50 feet above the Geneseo-Burket interval.

The logging tool that measures bulk density requires a constant borehole diameter. As the size of the hole (as measured by the caliper) increases, the bulk density readings become anomalously low. For this reason, the bulk density log was only used when the caliper indicated that the borehole had not become enlarged by breakouts or washouts.

2.1.1 Maximum burial depths

Since the formation of the Appalachian Basin during the middle Ordovician Period, it has subsequently been uplifted and eroded. The associated unloading could mask the effect of overburden compaction on the bulk densities. In an effort to understand this, burial
curves were examined for calculating maximum burial depths. Fluid inclusion data shows that the Middle Devonian Shale section of the Appalachian Basin has been buried to a maximum burial depth of approximately 5 km in the central Appalachian Plateau and 4 km in northern West Virginia (Evans, 1995). Also, vitrinite reflectance data shows that the Geneseo-Burket shale was buried over 2 km at Lake Erie and approximately 5 km at the Finger Lakes District (Lash, et al., 2002). The latter burial history is more consistent with the study area and thus was utilized to estimate maximum burial depths. Burial was assumed to increase in a regular manner; from northwest to southeast. Well locations were projected onto the linear model to calculate total burial. These depths were also plotted with bulk density to find any observable trend.

2.2 Organic Content

Bulk densities are used to estimate the organic content of the Geneseo-Burket shale. Gamma ray values are an estimate of organic matter because organic matter preferentially concentrates uranium, but this is only a qualitative measure of organic richness. The volume percent of organic matter within the Geneseo-Burket shale interval can actually be calculated using the Schmoker Method developed for Devonian shales of the Appalachian Basin (Schmoker, 1979). Black shales are modeled as a four-component system whose formation density consists of: rock matrix (\( \rho_m \)), interstitial pores (\( \rho_i \)), pyrite (\( \rho_p \)), and organic matter (\( \rho_o \)). The bulk density log is significantly affected by pyrite since it is a heavier mineral. This association is translated into an equation that reflects a linear increase of pyrite with organic matter (Strahl et al., 1955; Brown 1956). Geochemical
data taken from Devonian shales in the central Appalachian Basin confirm this relationship (Leventhal and Goldhaber, 1978). Also, the gamma ray intensity versus bulk density crossplot can be examined to determine the general applicability of the Schmoker Method (Schmoker, 1979). A linear relation between bulk density and gamma ray signal demonstrates that bulk density variations are caused by variations in organic content; confirming the fundamental assumption of the Schmoker Method. Bulk density vs gamma ray intensities were plotted for one well in several counties throughout the study area to show the relation (Figures 12-15). For this study, $R^2$ serves as a statistical measure of how well a regression line approximates real data points; an $R^2$ of 1.0 (100%) indicates a perfect fit.
Figure 12. Crossplots for counties of Pennsylvania showing linear relation between density and gamma ray intensity. Wire-line data are averaged over intervals of 20 feet.
Figure 13. Crossplots for counties of Pennsylvania showing linear relation between density and gamma ray intensity. Wire-line data are averaged over intervals of 20 feet.
Figure 14. Crossplots for counties of Pennsylvania showing linear relation between density and gamma ray intensity. Wire-line data are averaged over intervals of 20 feet.
Figure 15. Crossplots for counties of Pennsylvania showing linear relation between density and gamma ray intensity. Wire-line data are averaged over intervals of 20 feet.
2.2.1 Schmoker Method

The formation density ($\rho$) is expressed by densities and fractional volumes of the four components:

$$\rho = \rho_o \phi_o + \phi_p \rho_p + \phi_i \rho_i + (1 - \phi_o - \phi_p - \phi_i) \rho_m$$  \hspace{1cm} (1)

We assume -

1. $\phi_p = 0.135 \phi_o + 0.0078; R^2 = 0.72$ (Strahl et al., 1955; Brown, 1956)
2. $\rho_p = 5.0 \text{ g/cc} \pm 0.02$
3. $\rho_o = 1.0 \text{ g/cc}$ (Smith and Young, 1964) $\pm 0.25$
4. $\rho_m = 2.69 \text{ g/cc} \pm 0.02$

So, the fractional volume of organic matter is calculated using:

$$\phi_o = (\rho_B - \rho_{log})/1.378$$  \hspace{1cm} (2)

where,

$\rho_B =$ bulk density if no organic matter present (gray shale density)

$\rho_{log} =$ black shale bulk density

We further explore assumptions and simplifications of the Schmoker Method to address the associated uncertainties.
Pyrite and organic matter

The linear equation relating pyrite and organic matter of the Schmoker Method is based on earlier work in Devonian shales (Strahl et al., 1955; Brown, 1956). For normal marine sediments (deposited in oxygenated water of more-or-less normal salinity), the assumption that pyrite linearly increases with organic matter, likely holds true. However, this relation is subject to change with chemical composition of bottom waters. Organic carbon and pyrite sulfur burial also take place under euxinic conditions (bottom waters which are anoxic and contain dissolved H$_2$S) Because anoxic conditions exist over much of the water column in euxinic basins, freshly killed organic matter settling from surface waters can be used for bacterial sulfate reduction both in the water column and on the bottom (Sweeny and Kaplan, 1980). As a result, more organic matter is consumed by sulfate reduction than is the case for normal marine sediments. In this way more H$_2$S per unit of carbon deposited is available for pyrite formation in euxinic basins (Berner and Raiswell, 1983) and the pyrite can form before, as well as after, burial. In fact, formation before burial can occur whether or not local organic matter is available. Then euxinic sediments likely exhibit higher S/C ratios than normal marine sediments, resulting in a steeper slope for the pyrite-organic matter relationship.

Concentrations of redox-sensitive proxies indicate some oxygen deficiency during deposition of the Geneseo-Burket. Mn concentrations suggest that anoxic conditions were relatively short lived and values for DOP (depth of pyritization) suggest pervasively oxic conditions or rapid siliciclastic sedimentation under euxinic conditions (Sageman et al., 2003). In general, the mean condition was probably closer to suboxic. Since the S/C
ratios vary from about 0.3-1 for normal to euxinic sediments (Berner and Raiswell, 1983), we use 0.5 for organic matter calculation in the Geneseo-Burket as well.

**Density of organic matter**

The density of organic matter in the Schmoker Method was assumed constant 1.0 g/cc based on previous specific gravity measurements (Smith and Young, 1964). However, the Appalachian Basin has been buried and the density of organic matter changes as a function of depth (maturity). With respect to the maturity range of oil and gas generation: prior to and during the early phase of petroleum generation, kerogen densities range between 1.18 g/cc and 1.25 g/cc, during peak and late stage petroleum generation, densities increase to 1.35 g/cc (Van Krevelen, 1961). To see the variation in organic matter percentages based on changes in maturity, we use $\rho_o = 1.18$ g/cc and 1.25 g/cc for organic matter calculation in the Geneseo-Burket as well.

**Interstitial pores**

The fractional volume and density of the interstitial pores were assumed constant for a given location in the Schmoker method. This assumption neglects variation of gas content gas found in pores of the Geneseo-Burket. In Devonian black shales, gas generally occurs as “free” gas in the pores or in the natural fracture system and adsorbed onto the organic matter or clay minerals (Lane et al., 1989). A series of reports published in the early 1980’s (Kuuskraa et al., 1983, 1984) indicate that adsorbed gas may account for up to 85% of the gas stored in the Devonian shales. In addition, recent reservoir assessments of the Marcellus estimate 50% adsorbed gas. Thus the current study assumes
that the gas filled porosity is relatively constant and changes in gas content occur from changes in the strong adsorption component.

The above modifications were included in wells where digital data was available (Figure 16), these organic matter percentages were calculated every 0.5 feet. Values were averaged over the interval and plotted in their geographic location. To observe regional trends, PETRA software was used to contour a map. PETRA uses the data to construct a gridded surface whose size is estimated from the data. The grid contains regularly spaced values which have been interpolated from the original data by locally fitting various mathematical functions to the data (GeoPLUS, 2005). In this case, a least squares algorithm was employed, as it tends to produce connected features.

2.2.2 Well Cuttings

In contrast to the Schmoker Method which uses density logs to estimate organic content values from bulk density data, total organic content (TOC) can be accurately calculated using rock samples derived from the well. Well cuttings are rock chips cut by a bit in the process of well drilling and removed from the hole by pumping of drilling fluids. They are collected at closely spaced intervals, providing a record of the sediment layer penetrated. Twelve boxes of well cuttings were obtained from the Pennsylvania Geological Survey and 1 sample was collected from Taughannock Falls of
Figure 16. Highlighted circles represent wells that have density data that was used to calculate organic matter in volume percentages.
Trumansburg, NY. Each well had cutting samples from throughout the entire well. They were divided into intervals of 10, 20, 30 feet and were labeled accordingly. The cutting interval of interest were selected by first matching the Geneseo-Burket interval on the corresponding well log (gamma ray and bulk density). The cuttings circulate up the well and are often times mixed over the specified interval. So the cuttings from well log interval, along with two samples from above and below it were visually inspected. In this way, the transition between lithologies was observable: gray, very-fined grained samples marked the gray shale formation overlying the Geneseo-Burket, black-very fine grained samples were an indicator of the Geneseo-Burket interval and samples with white-gray coarse-grained sediment (identified as limestone using HCl) marked the Tully limestone, which underlies the Geneseo-Burket. Finally, the cuttings sample with the (darkest) black very fine-grained sediment was selected for shipment to Weatherford Laboratories for geochemical analyses. See Appendix for photographs of well cuttings from Geneseo-Burket interval.

At Weatherford, the Rock Eval (RE/REII)/Pyrolysis method was used to determine the geochemical make up of the shale samples. This includes qualitative determination of:

\[ S_1 = \text{the amount of free hydrocarbons (gas and oil) in the sample (in milligrams of hydrocarbon per gram of rock).} \]

\[ S_2 = \text{the amount of hydrocarbons generated through thermal cracking of nonvolatile organic matter.} \]
\( S_3 = \) the amount of \( \text{CO}_2 \) (in milligrams \( \text{CO}_2 \) per gram of rock) produced during pyrolysis of kerogen.

\( T_{\text{max}} = \) the temperature at which the maximum release of hydrocarbons from cracking of kerogen occurs during pyrolysis (top of \( S_2 \) peak).

TOC = Total Organic Carbon of the sample obtained by oxidizing the residual organic carbon.

2.2.3 Calibration

It is important to note that there are uncertainties in comparison of the lab-derived organic content and log-derived organic content due to several factors such as: hole quality, sampling rate, drilling rate and whether the cuttings are high-graded for analyses (Passey et al, 1990). These all affect how representative the cuttings are of the true downhole lithology. To increase the quality of comparison, the caliper was inspected to ensure good hole conditions, and cuttings were collected and analyzed at approximately every 10 feet. Lab values of TOC are measured in weight percent, while log-derived organic content is measured in volume percent. For comparison of these organic richness parameters, an empirical relation is derived using the TOC from well cuttings and log-derived organic content from their associated well logs. Samples with TOC (wt %) were multiplied by 1.3 to obtain organic matter (wt %). Since 7 of the 12 wells were unusable due to inaccuracies with the density log and the well cutting interval, the remaining 5 were employed in the regression. This relation can be extrapolated to other wells in the dataset to convert log-derived organic matter values to TOC, which is an industry standard.
2.3 Thickness

2.3.1 Criterion for picking formation tops

Bulk density and gamma ray logs were used to pick the top and base of the Geneseo-Burket shale. It is bounded above by gray shales of the Harrell Shale Formation in Pennsylvania or in New York, gray shales of the Penn Yan Formation. In central New York, the Lodi Limestone (of the Genesse Group) rests above the Geneseo-Burket. Throughout New York and Pennsylvania, the Tully limestone underlies the Geneseo-Burket. The Tully is prominent in well logs with the exception of western areas where it is less than 10 feet thick. Characteristically, it is blocky, rectangular, and 50-100 feet thick. This is observable at the outcrop scale (Figure 5) as well as in gamma ray and density logs. The Tully limestone usually registers around 20 API units on the gamma ray log and 2.65-2.7 g/cc on the bulk density log. In general, limestones have lower radioactivity than shales due to lower amounts of uranium (organic matter). This corresponds to lower gamma ray values. The “gray shale baseline” is defined as the point where all units to the left of it are gray shale, while units on the right are black shale. In the Appalachian Basin, it lies between 140 and 160 API gamma ray units (Figure 17). Thus in the gamma ray log, the base of the Geneseo-Burket is easily observed by the top of the Tully; an abrupt “kick” to the left (lower values), relative to the black shales. Contrasts in rock types are also visible in the bulk density log as limestone whose major component is calcite has a higher bulk density than shale whose major component is clay. Although organic matter is a minor component (~1%) of shale, its low-density can have
Figure 17. Detailed view of gamma ray log, including gray shale baseline (dashed), and formation names.
significant affects on the bulk density. In the absence of the Lodi limestone, the top of the Geneseo-Burket is defined at the base of the overlying gray shales; Penn Yan and Harell in New York and Pennsylvania, respectively. The usually occur near or on the grayshale baseline. In this way, the gamma ray and bulk density logs were used in conjunction to define the top and base of the Geneseo-Burket.

Formation tops were determined to obtain formation thicknesses of the Geneseo-Burket Shale. After formation tops were selected, they were entered into PETRA® software. PETRA® subtracts depths of formation tops to calculate thickness values and utilizes a grid to map isopachs of the Geneseo-Burket.

2.4 Internal Stratigraphy

In an effort to understand the internal stratigraphy of the Geneseo-Burket, the present study develops a stratigraphic framework. Marker beds (black shale, limestone tops) are correlated by gamma ray and bulk density logs to map lithostratigraphic units. Because the depositional setting is an epicontinental sea, these time stratigraphic marker beds can be traced across the basin.

PETRA’s cross section module was used to map lithostratigraphic units of the Geneseo-Burket in the subsurface. The units are correlated across the study area and examined for their defining features, including: system tracts, sequence boundaries and surfaces.
Cross sections that are constructed west-east are roughly parallel to paleoflow of Middle-Upper Devonian marine sediments (Figure 18). Average paleocurrent directions from sedimentary structures in the Portage lithofacies of central and eastern Pennsylvania/New York show average current direction is west (McIver, 1970). Directional features include: sole marks, flute casts, and a variety of substratal grooves and striations.
Figure 18. Average paleocurrent directions of Upper Devonian marine sediments (McIver, 1970)
Chapter 3

Observations

3.1 Type logs

The Geneseo-Burket interval is characterized by regional variations in the bulk density and gamma ray logs. In this study, we recognize six type logs of the Geneseo-Burket interval. These type logs illustrate how gamma ray and bulk density signatures vary with location in the northern Appalachian Basin. The complete section of the Geneseo-Burket and encompassing units can be observed at Taughannock Falls, NY (Figure 19).

In west-central New York, the Geneseo-Burket is 20 feet thick (Figure 20). The gamma ray intensities exceed 200 API units. The bulk density values decrease to 2.45 g/cc. In contrast, the overlying (Lodi) limestone is at a minimum of less than 5 feet, with gamma ray values of approximately 100 API units and a corresponding bulk density of about 2.60g/cc. The Akzo 9455 core from west-central New York shows Mo concentrations that mirror organic content (Murphy et al., 2000). In central New York, there is a sharp contrast between the Lodi limestone and the Geneseo-Burket (Figure 21). In the Geneseo-Burket interval, the gamma ray values significantly increase to a range of 150-200 API units. The bulk densities show a corresponding decrease to 2.50-2.55 g/cc. Here, the Lodi is at its minimum gamma ray intensity (80 API units) and its maximum thickness of about 20-30 feet. In contrast, the thickness of the Geneseo-Burket is twice of that. Towards the east, the limestone pinches out into gray shales of the Penn Yan formation. The gamma ray
Figure 19. Complete Middle Devonian section at Taugannock Falls, NY.
Figure 20. Well API 3112115219. Type well with density and gamma ray logs. Corresponding sections from (de Witt and Colton, 1978; Murphy et al., 2000)
Figure 21. Well API 3100315253. Type well with density and gamma ray logs.
intensities of the gray shales range from 140-160 API units, while the densities are approximately 2.60 g/cc (Figure 22). The Geneseo-Burket is approximately 100 feet thick. This is close to the maximum thickness of 150 feet. The high gamma ray signature is lost as the peak is around 200 API units and the Lodi has disappeared. Regardless of whether there are gray shales or limestone that overlie the Geneseo-Burket, there is a distinguishable transition into the Geneseo-Burket interval. Near the middle of the basin, in central Pennsylvania, the thickness of the Geneseo-Burket reaches 60 feet (Figure 23). The gamma ray intensities have increased to 250 API units. The Lodi limestone is 30 feet thick with lower gamma ray values. In southwest Pennsylvania, gamma ray intensities of the Geneseo-Burket increase to slightly above moderate to 250 API units and has thinned to less than 10 feet (Figure 24). The Lodi limestone is present but is only 10 feet thick and has an increased gamma ray signature (100 API units). Its density is about 2.70 g/cc, while the Geneseo-Burket’s is less than 2.5 g/cc. In the western most basin, near the vicinity of the Pennsylvania-Ohio border, gamma ray intensities exceed 250 API units (Figure 25). Here, bulk densities decrease to 2.35 g/cc and the Geneseo-Burket thins to less than 15 feet. Throughout the Appalachian Basin, with the exception of areas where it is severely eroded, the Tully Limestone is present below the Geneseo-Burket. It is characterized by gamma ray intensities of 20 API units and bulk density values of 2.71 g/cc.
Figure 22. Well API 311012301. Type well with density and gamma ray logs. Corresponding section from (de Witt and Colton, 1978)
Figure 23. Well API 3703520375. Type well with density and gamma ray logs.
Figure 24. Well API 3706327489. Type well with density and gamma ray logs.
Figure 25. Well API 3707320056. Type well with density and gamma ray logs.
3.2 Bulk density vs gamma ray signal

The type logs described above are constructed next to gamma ray intensity vs bulk density plots (Figures 21, 23-25). Throughout all of the type logs, bulk density vs gamma ray is plotted for the Geneseo-Burket interval exclusively and little to no correlation observed. The $R^2$ values range from 0.01 to 0.60 (upper plots). However, when the same plots are constructed for a larger interval (100 feet above the base of the Tully), a stronger relation is observed consistently. $R^2$ values have a range of 0.66 to 0.84.

A more distinctive pattern is witnessed when the parameters are selected at a given depth. In each well with available bulk density data, maximum gamma ray values within the Geneseo-Burket interval are also plotted against their corresponding bulk densities. Values are shown in Table 1. There is some scatter but the relationship is inversely proportional and has an $R^2$ value of 0.80 (Figure 26).

The correlation between radioactivity and density in Devonian shale is the primary feature that permits an analysis of the internal stratigraphy of the Geneseo-Burket and the Marcellus black shales. Wells in Allegany are used to refine an understanding of the Geneseo-Burket relative to its more famous partner, the Marcellus black shale. To anticipate results from a regional look at the Geneseo-Burket, gamma ray and bulk density logs from five wells in Allegany County, NY were plotted.
Figure 26. Minimum density vs maximum gamma ray. Points represent minimum density and corresponding gamma ray value within each well. $R^2 = 0.65$
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<th>Geneseo-Burket min RHOB (g/cc)</th>
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on one track (Figure 27). 875 feet of each log is displayed with the log pinned to the top of the Tully so that 700 feet above the Tully is displayed.

Figure 27 is a cross section of logs from five wells in north-central Allegany County: 31-003-11978, 31-003-14253, 31-003-20128, 31-003-23531, and 31-003-21115. The gamma ray log track covered 200 API units between 80 and 280 with a shading cutoff at greater than 180 API units. The bulk density log covered the range between 2.35 g/cc and 2.85 g/cc with a shading cutoff at less than 2.60 g/cc. The gamma ray and bulk density cutoffs were placed so that minimum bulk density and maximum gamma ray signals were accented with no overlap between shading. Note that for analysis of the Geneseo-Burket black shale later in this thesis, the bulk density range is shifted downward to between 2.3 g/cc and 2.8 g/cc with a shading cutoff at less than 2.55 g/cc. Line of section is shown in Figure 28.

Formations within four stratigraphic groups of the Middle and Upper Devonian Catskill Delta are identified in the five logs from Allegany County including, from top to bottom, the West Falls, the Sonyea, the Genesee, and the Hamilton Groups (Figure 7). The westward prograding Catskill Delta is evident by the gradual east to west thinning. The Tully limestone has a sharp upper contact and the formation thins westward. Three regional black shales are evident in each of the Allegany County logs as gamma ray highs and bulk density lows. The base of the Penn Yan constitutes a fourth black shale which is of local extent. The
Figure 27. Cross section of logs from five wells in north-central Allegany County. Arrows show younger black shale units.
Figure 28. Line of section for Figure 27.
Geneseo-Burket black shale is the most prominent whereas the Middlesex and Rhinestreet are indicated by arrows. The Geneseo is the only black shale sitting directly on regional limestone, the Tully. Like the Penn Yan above, the Lodi limestone is considered local. Two other prominent but local limestones are the Tichenor and Genundewa. All three regional black shales display the highest gamma ray signal and lowest bulk density signal in the westernmost log. Both the Middlesex and Rhinestreet gamma ray signals weaken to the east. In both cases, however, the bulk density signal remains strong to the extent that the base of the Rhinestreet is unambiguous only in the density log from the easternmost well. This characteristic weakening of the gamma ray signal relative to the bulk density signal will become evident further east in the Geneseo-Burket black shale as well.

3.3 Bulk density vs depth

The bulk density vs present day depth plot (Figure 29) shows that bulk densities in the Geneseo-Burket range from approximately 2.30-2.60 g/cc over a depth range of 1500-6000’ below sea level. The maximum burial plot (Figure 30) has the same bulk density range, but the depth range increases from about 6000 ft-14,000 ft below sea level. The geographic distribution of bulk densities has a distinctive pattern. They are lower in the west-northwest, where the basin is shallower and increase towards the southeastern, deeper part of the basin (Figure 31).
Figure 29. Geneseo-Burket Density vs present day depths. Points represent minimum density within each well.
Figure 30. Points represent minimum density within each well. Density vs present day depths shown in blue; density vs maximum burial depths shown in pink.
Figure 31. Geographic distribution of minimum bulk densities from Geneseo-Burket (one per well).
The gray shales from ~50 feet above the Geneseo-Burket, have bulk densities that range from 2.57-2.72 g/cc over the 4500 feet present day depth range; a noticeably smaller range than the Geneseo-Burket densities. There are no apparent trends (Figure 32). When plotted with Geneseo-Burket minimum bulk densities and the Athy curve, the gray shale densities follow the Athy trend more closely (Figure 33). The spatial distribution of gray shale densities are such that the highest bulk densities occur on a northeast-southwest trend (Figure 34).

3.4 Organic content

3.4.1 Log-derived organic content

Trends in the distribution of log-derived organic matter can be observed by looking at the PETRA-generated map in Figure 35 and Table 2. The organic matter (volume percentages) range from 2-18% with the highest values in the west-northwest and they decrease along a southeastern-northwestern axis. Organic matter values in volume percent are converted to TOC values in weight percent using an empirical relationship described by the following (Figure 36):

\[
\text{log organic matter (vol\%) = 1.05[lab organic matter (wt\%)] + 3.26 \quad R^2 = 0.79} \tag{3}
\]

TOC values range from less than 0.5% to approximately 10% throughout the study area.
Figure 32. Minimum bulk densities versus depth for gray shale interval above Genesee-Burket.
Figure 33. Present day density vs depth for Geneseo-Burket (blue diamonds), gray shale interval (orange circles) and Athy (1930) curve (red squares).
Figure 34. Spatial distribution of gray shale bulk densities.
Figure 35. Map of log-derived organic matter in volume percent.
<table>
<thead>
<tr>
<th>Well API</th>
<th>County</th>
<th>Max GR</th>
<th>Min RHOB</th>
<th>Calculated organic matter (vol %) ± 0.23</th>
<th>Calculated TOC (wt %) ± 0.50</th>
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</thead>
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<td>37005213540000</td>
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</table>

Table 2. Organic matter and TOC values calculated using equations (2) and (3), respectively.
Figure 36. Empirical relationship derived between lab derived organic matter (wt %) and log-derived organic matter (vol %) for regular parameters of Schmoker Method ($\rho_o = 1$, p:o = .5).

\[ y = 1.0525x - 3.2565 \]

\[ R^2 = 0.7916 \]
3.4.2 Lab-derived organic content

Trends in the lab-derived organic carbon distribution are similar to the log derived organic matter: the maximum values are in the north and west; while the minimum values appear on a northeast-southwest axis (Figure 37). The TOC values (weight percentages) range from 0.22-5.33%. Geochemistry data is in Table 3.

3.4.3 Uncertainty Analysis on Schmoker Method

Organic matter values were calculated using modified parameters in the Schmoker Method (Table 4, 5). Calculations were performed on (5) wells with log and lab data available. The density of organic matter (maturity) was varied according to different phases of petroleum generation and the linear relationship between pyrite and organic matter (p:o) was adjusted to values more consistent with what is observed in Geneseo-Burket core.

With the regular Schmoker Method parameters ($\rho_o=1.0 \text{ g/cc}, \ p:o = .3$) the absolute error between log-derived organic matter and lab derived organic matter values average 1.3. The corresponding TOC’s have an absolute average error of 0.66. The increase in slope for the pyrite-organic matter relationship ($\phi_p = 0.5\phi_o$), causes the organic matter values to increase on average, by approximately 10 volume percent. The absolute error increases by more than two times the original values to ~8. Note the TOC absolute error is constant. Organic matter densities are increased so they correspond to early ($1.18 \text{ g/cc}$)
Figure 37. Map of lab-derived total organic carbon in weight percent.
<table>
<thead>
<tr>
<th>API</th>
<th>Well Name</th>
<th>Top Depth (ft)</th>
<th>TOC</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>Tmax (°C)</th>
<th>HI</th>
<th>OI</th>
<th>Pi</th>
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<tr>
<td>37039204620000</td>
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<td>3370.00</td>
<td>2.17</td>
<td>1.43</td>
<td>4.72</td>
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<td>7400.00</td>
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<td>76.09</td>
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<td>18.05</td>
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Table 3. Geochemistry data determined from Weatherford Laboratory
<table>
<thead>
<tr>
<th>County</th>
<th>( \rho_o = 1, \ p:o = .3 )</th>
<th>( \rho_o = 1, \ p:o = .5 )</th>
<th>( \rho_o = 1.18, \ p:o = .5 )</th>
<th>( \rho_o = 1.25, \ p:o = .5 )</th>
<th>lab values (om in vol %)</th>
</tr>
</thead>
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Table 4. Organic matter values calculated using modified parameters in the Schmoker Method

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<th>Log-derived TOC</th>
<th>Log-derived TOC</th>
<th>Log-derived TOC</th>
<th>Log-derived TOC</th>
<th>Lab-derived TOC (wt %)</th>
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<td>1.49</td>
<td>1.49</td>
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Table 5. TOC values calculated using modified parameters from Table 4 in the Schmoker Method
and peak (1.25 g/cc) petroleum generation. The volume percentages of organic matter increase as the densities increase. The most significant deviation is over 60 volume percent. Although the organic matter values change greatly with these parameters, the log-calculated TOC values show little variation. The TOC values maintain accuracy, with an $R^2$ of approximately .80 (Figures 38-40) when compared to values obtained in the lab. The log-derived TOC values are precise, as they deviate from the lab values consistently by approximately 0.66 average weight percent.

3.5 Local Trends

3.5.1 Cross sections

We also explore spatial trends in lithologies and their gamma-bulk density characterizations throughout the study area for the Geneseo-Burket. Local trends are examined by observation of several cross sections that span one or two counties (Figure 41). An east-west cross section that spans Cattaraugus and Allegany Counties shows well logs with striking similarities in the bulk density and gamma ray logs (A-A’, Figure 42). All of the gamma ray logs are characterized by intensities that exceed 250 API units in the Geneseo-Burket. The second Allegany county well has gamma ray values that reach 350 API units. The gamma ray logs also have several maxima that occur within the Geneseo-Burket interval. There are at least 4 peaks that can be traced across the two counties.
Figure 38. Empirical relationship derived between lab derived organic matter (wt %) and log-derived organic matter (vol %) for $\rho_o = 1$, $p:o = .5$. 

The equation of the line is $y = 2.9624x + 9.1615$ with $R^2 = 0.7916$. 

Figure 39. Empirical relationship derived between lab derived organic matter (wt %) and log-derived organic matter (vol %) for $\rho_o = 1.18$, $p:o = .5$. 

$y = 4.5841x + 14.475$

$R^2 = 0.7918$
Figure 40. Empirical relationship derived between lab derived organic matter (wt %) and log-derived organic matter (vol %) for $\rho_o = 1.25$, p:o = .5.
Figure 41. Map of cross sections
Figure 42. Cross section through Cattaraugus and Allegany counties
Corresponding minima in the bulk density interval are also evident. Thicknesses average 20-25 feet. Although variations in the Geneseo-Burket are consistent in this cross section, the adjacent formations demonstrate considerable variation. The overlying Lodi limestone thickens from about 2 feet to greater than 10 feet in this local area. Similarly, the underlying Tully limestone thickens from about 5 feet to about 40 feet in a distance that spans approximately 25 miles.

The cross section that spans 9 miles of eastern Allegany County (B-B’, Figure 37), is comparable to the previous one. The interval of the Geneseo-Burket has at least 4 major gamma ray maxima/bulk density minima that are easily traced across the county. Its thickness increases to an average of 35 feet. The Lodi limestone is always present above the Geneseo-Burket. A slight increase in gamma ray intensity appears in the middle of the limestone. The peak shows increasing radioactivity towards the east, approaching 150 API units. A corresponding bulk density trough is visible. The profile and structure of the Tully limestone in gamma ray and bulk density logs is unchanging in this portion of the county.

To the south, the internal variation of the Geneseo-Burket changes drastically. The north-south trending cross section that spans Allegany and Potter counties (C-C’, Figure 44) shows the same 4 peaks in the gamma ray and density logs but the peaks become less frequent and begin to separate. The last two wells of this 20 mile section show 2-3 peaks at the base of the Geneseo-Burket and 1-2 peaks at the top. This character, causes an
Figure 43. Cross section through Allegany county
Figure 44. Cross section through Allegany and Potter counties
increased thickness of about 100 feet. A general thickening of the Lodi limestone occurs towards the south, while the Tully limestone’s thickness is maintained.

The northeast-southwest trending cross section from Potter County (D-D’, Figure 45) shows the Geneseo-Burket interval with its characteristic peaks in the gamma ray and bulk density logs, but like the previous cross section, the major peaks are spread along the vertical extent of the black shale. The two-tiered Geneseo is more prominent, as it extends and thickens the 20 mile section throughout Potter County. The Lodi demonstrates consistent thicknesses of about 20 feet. The Tully reaches nearly 100 feet in the northeast.

The northernmost cross section from Allegany and Steuben counties (Figure 46) is the longest. Some of the internal variation from the previous sections are observed here. This includes the westward thickening of the Lodi limestone and Geneseo formations. However, the increased thickness of the Geneseo-Burket occurs without the expanded peaks. Only subtle increases are evident in the far east.

3.5.2 Internal stratigraphy

The internal stratigraphy of the Geneseo-Burket includes more than one tongue of coarsening upward shale, with the uppermost tongue extending furthest to the west. The Geneseo-Burket is punctuated by lower gamma ray troughs indicative of layers a few cm to half a meter thick (Figures 42-46). These individual sheets are consistent in thickness of the troughs and thickness of intervening shale throughout central New York,
Figure 45. Cross section through Potter county
Figure 46. Cross section through Allegany and Steuben counties
including Cattaraugus, Allegany, and Steuben Counties and Potter County of Pennsylvania.

3.6 Thickness

The isopach map (Figure 47) shows how the Geneseo-Burket’s thickness varies across the basin. The thickness ranges from over 150 feet in the east to less than 30 feet thick in the west. It is present throughout Pennsylvania and south-central New York. The Geneseo-Burket depositional basin appears to have two depocenters. The first one includes east-central New York and eastern Pennsylvania. Here, the thicknesses range from 20-140 feet. The second depocenter is in southwestern Pennsylvania and is less pronounced. Thicknesses average a smaller range of 20-40 feet. In the western counties of Pennsylvania, the Geneseo-Burket becomes extremely thin (<5 feet).
Figure 47. Isopach map of Geneseo shale, contour interval 20 feet.
4.1 Shale compaction (density vs depth)

The Geneseo-Burket bulk density versus depth relations are not consistent with what is expected for a normally compacted shale section. Normal shales should have bulk densities that differ only with the depth of burial (Athy, 1930). Mathematically, this can be expressed as a logarithmic curve, where bulk density increases with depth (Figure 48). The bulk density data collected from the Geneseo-Burket shale does not exhibit this Athy-like compaction. The bulk densities vary over range of about 0.30 g/cc, within a 4500 feet interval. This is twice as wide as the range for gray shales of the same section and Athy-like compaction (Figure 33). The Geneseo-Burket includes more lower bulk densities and thus deviate more from the predicted response to compaction exhibited by the gray shale. There are several factors that cause density anomalies by compaction disequilibrium, including but not limited to: cementation, overpressure and organic matter.
Figure 48. Density vs depth curve modified from Athy (1930).
4.1.1 Cementation

Calcareous shales are much denser and less porous than pure shales because of the high density calcium carbonate and more cementing material. X-ray diffraction techniques that provide mineralogical data for the Geneseo-Burket shale of the Fingerlake District, New York demonstrate a minimal amount of calcite (Towarak, 2006). This suggests that relatively little cementation occurred and changes in density (or porosity) are a result of increased pressures. Thus density (or porosity) is a measure of the compaction the shale has undergone. Also, cementation would result in abnormally high density values, when the opposite trend is observed.

4.1.2 Overpressure

There are a number of mechanisms that cause abnormal pore pressures, but it usually develops during compaction when hydrostatic pressure cannot be maintained as a result of pore water draining too slowly (Engelder and Oertel, 1985). This is called “compaction disequilibrium.” Plots of shale density or porosity versus pore pressure show that undercompaction correlates with abnormal pore pressures (Magara, 1976; Sclater and Christie, 1980). The bulk density anomalies observed in the Geneseo-Burket can be interpreted as high porosities, as a result of sediment that is undercompacted as a consequence of abnormal pore pressure during burial. Pore pressure estimates are usually based on wireline logging methods and analysis of drilling parameters. Since changes in the log response or drilling rate may result from changes in lithologies as well, the
accuracy in pore pressure estimations is uncertain. For example, North Sea shales showed no significant differences in log density-derived porosities between normal and overpressured stratigraphic units (Teige et al., 1998). Conversely, measurements of compaction in conjunction with the distribution of joints in the Catskill Delta, suggest overpressure in the black and gray shales, including the Geneseo-Burket (Engelder and Oertel, 1985). The current study only incorporates bulk density logs, which are sensitive to porosity changes as well as low density organic matter. It is impossible to distinguish the signal using density logs alone. Therefore, the low density signature is necessary but not sufficient evidence for paleo-overpressure.

4.1.3 Organic matter

Organic material in the Devonian shales has a density near 1.0g/cc and the average grain density of shale is 2.7 g/cc (Smith and Young, 1964). Thus changes in organic content produce significant changes in formation density. This is evident in Figure 26. The plot of gamma ray vs bulk density shows a significant correlation. As previously discussed, gamma can be used as a proxy for organic matter. Then the highest gamma ray values with lowest densities correspond to the intervals of Geneseo-Burket that are organic rich. Similarly, the lowest gamma ray values with highest densities correspond to the Geneseo-Burket intervals that are organically lean. The values in the bulk density vs depth plot of the gray shale demonstrate a density trend closer to the predicted (Athy) trend (Figure 33). So it is the addition of organic matter that shifts the shale towards lower density
values. Calculated organic matter values shown in Table 2 confirm this. The geographic distribution of bulk densities increase from northwest to southeast, implying that if organic matter is driving the density patterns, then the spatial distribution of TOC should mirror the bulk density distribution.

4.2 Bulk density vs gamma ray

The maximum gamma ray values and their associated bulk densities have a prominent relationship. As the gamma ray values increase, the bulk density values decrease. This is a manifestation of the uranium-bearing organic matter and its influence on the bulk density and the gamma ray. This dependence of the two variables is quantified by a correlation coefficient of 0.65. The gamma ray logs and bulk density logs, together are an indicator of organic richness. These qualitative trends are confirmed by the calculated organic matter values. Places where there is scatter in the data represent well logs where the maximum gamma ray doesn’t correlate to the minimum bulk density. The bulk density values that appear far from the predicted trend (lateral uncertainty) can be attributed to pyrite. It doesn’t significantly affect the gamma ray log, but causes increases in the density log, where otherwise organic matter would produce a lower bulk density value. The vertical uncertainties are likely a result of poorly calibrated gamma ray logs. The well logs were obtained from multiple (at least 6) different companies, some of which were over 20 years old. We observe similar structure/frequency of gamma ray variations with magnitudes that vary up to 70 API units over less than a 1 mile distance.
Geologic, geochemical, etc changes are unlikely to vary so significantly over such a short distance.

The range of lithologies is also interpreted from the bulk density vs gamma ray plots (Figures 21, 23-25). When a linear trend is visible the lithologies can be differentiated as follows: the lowest cluster of data points with high densities (2.65-2.70 g/cc) and low gamma ray intensities (100 API and less) correspond to the limestone unit(s). The middle cluster of points with moderate densities and gamma ray intensities, (2.55-2.665 g/cc; 150-180 API) represent the sections of gray shale. The highest cluster of data points with low densities (2.35-2.45 g/cc) and high gamma ray values (190 and above) represent the Geneseo-Burket black shale. This is why there appears to be a better correlation in one-well plots that include more lithologies than one-well plots that only include the Geneseo-Burket. Unless specific depths are used (ie- maximum gamma ray and associated density, minimum density and associated gamma ray, etc), the general correlation between all bulk density points and all gamma ray values for one lithology (per well) is not strong. This is likely due to the other factors influencing gamma ray and density logs within a specific interval, for example variations porosity, minerals, geochemistry.
4.3 Organic content

It is widely accepted that there are three factors fundamental to the formation of most organic carbon-rich facies: primary photosynthetic production, bacterial decomposition and bulk sedimentation rate/dilution (Arthur and Sageman, 1994). Despite this consensus, the relative importance of these factors is still debated. For this study, the dataset allows relative and qualitative measurement of dilution rates. Although present day production and decomposition rates vary, there are currently no known techniques to estimate past rates. For the purposes of this study, they are assumed constant. There are some uncertainties associated with this assumption but a detailed geochemical analyses of Devonian black shales (including Geneseo-Burket) show a systematic range of variation that ultimately suggest dilution was the predominant control on organic carbon burial flux (Sageman et al., 2003). The trends in the distribution of log-derived organic content (Figure 35) are considered accordingly. The Mo concentrations that closely follow organic content in the Akzo core suggest that bottom water conditions during Geneseo-Burket deposition were not pervasively euxinic (Murphy et al., 2000).

The lower concentration of organics in the east and south is representative of a heavy clastic influx, which demonstrates proximity to the load (Acadian mountains). The clastic sediments overwhelmed the organic material, largely indicated by lower gamma ray intensities. Likewise, in the western and northern portions of the basin, far from the load, the concentration of organics are relatively high. This represents a decrease in the clastic influx, as indicated by relatively thin units. As a result, the organic signature was
preserved. These variations in dilution are validated by the isopach map as the two
diluted (low organic matter) patches correlate with the two “thick patches.”

The lab-derived TOC measurements serve as an independent indicator of organic
richness. Similar trends in the spatial distribution of TOC give confidence to calculated
organic matter and the dilution hypothesis. These trends in TOC are opposite of the
density trends. Minimum TOC values occur towards the east and south along with
maximum density. This substantiates the aforementioned influence of organic matter on
density trends.

The lab derived TOC value of 3.5 weight percent in Blair County is not consistent with
the dilution hypothesis. It is among the highest values and occurs in the east. This
indicates that although dilution serves as the major control, there are other factors that
influence burial/preservation of organic matter. For example, a localized area of nutrient
upwelling could allow for enhanced organic matter, despite high dilution rates.

The uncertainty in the TOC values derived from the organic content can be evaluated by
comparing with the TOC values from Weatherford. Figure 49 and Table 6 show the
comparison, where all 5 samples have calculated TOC’s within an average 0.66 of the lab
TOC.

Sensitivity of the Schmoker Method is evaluated by exploring different parameters and
observing the effect on calculated organic matter values. The organic matter values
Figure 49. Log-derived TOC vs lab-derived TOC for Schmoker Method.
<table>
<thead>
<tr>
<th>County</th>
<th>Weatherford Lab derived TOC (wt%)</th>
<th>Average TOC calculated from logs (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bradford</td>
<td>0.22</td>
<td>0.51</td>
</tr>
<tr>
<td>Cambria</td>
<td>0.83</td>
<td>2.12</td>
</tr>
<tr>
<td>Elk</td>
<td>5.37</td>
<td>5.71</td>
</tr>
<tr>
<td>Fayette</td>
<td>2.37</td>
<td>2.79</td>
</tr>
<tr>
<td>Potter</td>
<td>2.81</td>
<td>1.49</td>
</tr>
</tbody>
</table>

Table 6. Calculated TOC vs cuttings-derived TOC values. Cuttings average 10 foot intervals.
increase significantly with increasing density of organic matter (maturation). The increase in organic matter density is manifested as a relative volume reduction. The increasing density contrast between residual kerogen and its mobile products during progressive maturation results in an increase of total volume of organic matter (Dueppenbecker et al., 1991). This considerable volume expansion of organic matter is likely the cause of pressure build-up in the pore system of source rocks and may be a driving force for petroleum expulsion. Organic matter values also increase with the slope of the pyrite-organic matter relationship. In sediments with high sulfate reduction rates, the deposition of larger quantities of the more reactive organic compounds also means that more total organic matter is initially deposited (Berner and Raiswell, 1983). Likewise, more total organic matter is eventually buried once all sulfate is consumed at depth. The opposite is true for sediments with low sulfate reduction rates. In contrast, greater concentrations of pyrite accompany greater concentrations of buried organic matter and the positive correlation between organic matter and pyrite observed in the data results. The consistent and significant change in organic matter values shows great sensitivity of the method to the density and pyrite parameters. Nevertheless, the amount of variation from log derived TOC values and lab derived values does not vary significantly (Tables 5). Figure 49 is applicable to all 5 samples, with regular and modified parameters. The log TOC values are based on an empirical relationship where the organic matter values vary significantly, but systematically. So, the individual organic matter values may change, but their deviation from lab values remain constant. For the lower (<2%) TOC values, the (0.66) error may become substantial.
While Bradford, Elk and Fayette county samples have calculated TOC’s that are within 0.4 of the lab values, samples from Potter and Cambria county significantly deviate (~1.2) from the lab TOC values. The first sample that has considerable deviation, is from Cambria county and is an overestimate. This can be attributed to inconsistencies in the bulk density log. From visual inspection, the bulk density minima occur with the gamma ray maxima (black shale) but the bulk density log doesn’t significantly increase to show the change in lithology for the interbedded gray shale/siltstone. The second sample from Potter county has a calculated TOC that is substantially underestimated. This is likely due to uncertainties in the methods, including organic matter calculation and/or conversion to TOC. In general, once the organic matter is calculated using the Schmoker Method, TOC is determined by virtually cutting it in half.

In a previous chemical analysis of Devonian rocks, samples of the Geneseo-Burket found at Newton Hamilton, Pa had organic matter values of ~0.95 volume percent (Swain, 1958). This value is comparable to quantities obtained in this study.

4.4 Thickness

From the isopach map in Figure 47, we observe the Geneseo-Burket’s main depositional center (area of maximum thickness) lies in northwestern Pennsylvania. The Geneseo-Burket was deposited in the Appalachian Basin during its creation via tectonic loading. The time interval corresponds to maximum Acadian subsidence in the third depositional
cycle of the Acadian orogeny (Ettensohn, 1985). The Geneseo-Burket thins monotonically to the west, with a steep gradient located in Tioga County, PA. This is the first depocenter. The second depocenter is oriented roughly, northwest-southeast. The average thickness of 30 feet that spans two counties is of much smaller magnitude. Despite varying sizes and thickness patterns, both depocenters correspond to highest “patches” of dilution in the map of organic matter (Figures 35, 47). Differences in the depocenters are likely result of well control. The larger depocenter has encompasses a much denser set of well data, over the area. There are approximately 150 wells in New York alone. Better well control in southwestern New York would capture more of the thickness variations in the second depocenter. The general westward thinning pattern is interpreted as a response to flexural loading, with the thickest portion of the formation closest to the Acadian Mountains. The thickest portion of the Geneseo-Burket is also coincident with the thickest portions of the Silurian-Devonian carbonate sequence, and specifically, evaporite bed “F” as mapped by Rickard (1969). Halite units “D” and “F” (Figure 50) show a southeastward shift in their overall distribution and areas of maximum thickness (Mesolella, 1978). The western progression and orientation of the salt basins appear to mirror those in the Devonian black shale basins. More work needs to be done to quantify this relationship and supply a link between evaporites of the Salina Group and the Geneseo-Burket basin.
Figure 50. Distribution of Salina evaporate units (Mesolella, 1978).
4.5 Local trends

4.5.1 Cross sections

Within the northern Appalachian Basin, near the vicinity of west-central New York and northern Pennsylvania, the Tully limestone is 40-50 feet thick, but thickens towards the east and rapidly thins west of Allegany county. The well log character is one of low gamma ray intensity and high bulk density. The contact between the Geneseo-Burket and the Tully remains sharp. The uniform thickness and consistent well log response of the Tully is interpreted to indicate that it was deposited on a relatively flat surface. The overlying Geneseo-Burket has several tongues that show changes in relative and/or eustatic sea level (Figures 42-46). The peaks represent transgressive surfaces of two separate flooding events that place deeper, marine facies far landward. They are separated by thin gray shale intervals representing progradation (Figure 44). The two tongues apparent in Potter County, the most southwestern of the study area, come from an area that is interpreted to be more proximal. As the basin deepened towards the north and west (Figures 42, 46), the two gamma ray peaks amalgamate. Also evident at the local scale are correlatable log signatures at the foot scale that show and systematic changes in thickness. They are interpreted to be high frequency cycles. The Lodi limestone thins westward and eventually pinches out in Cattaraugus County. The maximum thickness is reached in Potter County. Internal changes are visible in Allegany County. In general, we see the retrogradation of a carbonate shelf landward.
4.6 Regional Trends

In New York, the Tully limestone is in unconformable contact with gray shales of the underlying Windom Member of the Moscow Formation (Baird and Brett, 2003). Although not visible in well logs, this surface has been previously interpreted as the Taghanic Unconformity that is present west of the Appalachian Basin. The flexural response of the crust associated with Acadian thrust loading offers a possible explanation for this unconformity that developed during the Taghanic age on the west side of the Appalachian basin. Flexural modeling predicts upwarp in central and western New York, western Pennsylvania, and eastern Ohio, and offers a plausible explanation for this unconformity (Rollins et al, 1984). The unconformity is prominently developed along the Waverly, Cincinnati, and Kankakee arches in Ohio, Kentucky and Indiana, respectively. This character suggests that the unconformity is related to a reactivation of the arch system and tectonic in origin (Hamilton-Smith, 1993). The surface does not correspond to the character of a stratigraphic sequence boundary resulting from eustatic sea level fall, because it is better developed in the cratonic interior and disappears at the margin (Sloss, 1963). Even so, the Taghanic Unconformity is interpreted as the lowermost sequence boundary. The LST is not well preserved although sharp erosive bases of thin, fossiliferous carbonate beds that indicate shallow water environments may reflect this tract (Baird and Brett, 2003). This can be seen as jagged edges in the gamma ray logs of the Tully toward the east.
During the Middle-Upper Devonian, basin expansion and deepening caused by the Acadian Orogeny, coupled with eustatic sea level rise, resulted in a regional onlap across the North American interior (Johnson, 1970). This major marine onlap, called the Taghanic (Cooper, 1942) allowed for widespread carbonate accumulation in the north-central Appalachian Basin. The Tully Limestone is interpreted as a transgressive systems tract, because the onset of deposition correlates to the onlap of marine units in the Middle \textit{varcus} Zone (Baird and Brett, 2003). Major faunal fluctuations in the Tully record diverse brachiopod associations in the lower Tully to dysoxic biofacies in the upper Tully. This supports the Taganic deepening. The well log character of this trangressive systems tract has a blocky, gamma ray profile. This ‘boxcar’ trend, denoted by low gamma ray intensities and sharp boundaries is indicative of retrogradational deposition during rapid sea level rise. The TST that includes the Tully limestone thins basinward. The transgression causes onlap of sea level and sedimentation onto the basal (Taghanic) unconformity of the underlying sequence.

The sharp Tully-Geneseo-Burket contact is interpreted as a maximum flooding surface. Evidence includes a documented faunal turnover marking the transition from the TST to the HST. Most of the Hamilton fauna became extinct within the Appalachian Basin during deposition of the overlying Geneseo-Burket shale and its shelf facies (Williams, 1913). The gamma ray character of this surface is a dramatic increase from about 20-40 API units to gamma ray intensities that exceed 200 API units. There is a corresponding decrease in bulk density values from 2.71 g/cc to less than 2.40 g/cc. This gamma ray
peak/bulk density at the base of the Geneseo-Burket extends farthest towards the east, which is interpreted as the farthest landward extent of deep-water facies.

Although the contact represents a significant regional unconformity in New York and Pennsylvania, there is some debate as to whether the contact is a disconformity that represents subaerial erosion, marking a new sequence boundary, or a surface of submarine nondeposition. The base-Geneseo-Burket contact can be interpreted as a flexural, tectonic disconformity (Baird and Brett, 2003), where the unconformity at the top of the Tully records the existence of a Middle-Upper Devonian forebulge. Then onlap of the Geneseo-Burket extended over the topographically positive area responsible for erosion of the Tully Limestone, especially along a north-south-trending axis coincident with that region of greatest erosion of the underlying Moscow Shale (Lash, 2007). In contrast, at Taughannock Falls the contact is abrupt but nearly conformable (Baird and Brett, 2003). West and east of this location, the base of the Geneseo-Burket is disconformable and a thin, lenticular pyrite-bone bed (the Leicester Pyrite), rests on truncated Tully or the underlying Moscow shale (Brett and Baird, 1986). This marine, transgressive lag deposit is reworked, redeposited, acid-resistant and dominated by a wide range of pyritic clasts in the absence of carbonate grains that required high-energy but low-oxygen conditions at pycnocline depths in a subaqueous marine setting (Formolo and Lyons, 2007). The Leicester Pyrite can be interpreted as residual deposits on a surface of long-term non-deposition. Fine detrital muds were either carried past or not transported this far. The pyrite contains various fossil grains, phosphorite ooids, glauconite and authigenic barite (Heckel, 1966) which are consistent with a condensed
section. The condensed section is interpreted as a sediment-starved interval that was caused by the trapping of terrigenous sediments during times of relatively rapid sea-level rise and marine flooding. Here, the slow accumulation of sediment characterized by a thin (less than 10 feet) Tully, represents the same amount of time as the Tully that thickens up to 100 feet towards the east.

In the southern and eastern portions of the basin, the character of the marine flooding surface changes. Here, the Tully-Geneseo-Burket contact, which is now composed of interbedded limestones and shales (Heckel, 1966), is interpreted as a conformable contact. It is not sharp but gradational; a transitional lithology appears in between the two formations. The transitional nature of the dark limestones and shales allow them to be placed as either part of the upper Tully or part of the lower Geneseo-Burket. The predominance of the carbonate composition demonstrates more lithiologic similarities to the Tully, in comparison to the darker, and nearly non-calcareous Geneseo-Burket shale (Heckel, 1966). This upper transitional member of the Tully Limestone gets up to 30 feet thick in central New York.

The Geneseo-Burket interval is interpreted as a highstand systems tract (HST) that formed during the late stage of eustatic sea level rise. Evidence includes an aggradational to progradational set of parasequences that overlies the maximum flooding surface. This is observed in Potter county, where the Geneseo-Burket has two black shale tongues that interfinger with gray shales and siltstones. Tongues onlap and are separated by a progradational gray shale. The gray shale is interpreted as a parasequence bounded by
two marine flooding surfaces, above which black shale were deposited. The well log signature of this HST is two distinct gamma ray maxima/bulk density minima. Gamma ray intensities increase up to 250 API units, while densities decrease down to 2.5 g/cc. In the southern and eastern portions of the basin, only the upper tongue exists. Also, the Geneseo-Burket contains framoidal pyrite and little evidence of bioturbation (Sageman et al., 2003). Geochemical evidence does not indicate euxinic depositional conditions, although minimum Ti/Al levels that correlate with the initiation of enhanced organic matter accumulation at the base of the Geneseo-Burket (Sageman et al., 2003).

The surface at the top of the Geneseo-Burket interval indicates the end of highstand conditions, and a sequence boundary above which the LST is not preserved. Directly overlying this surface in central New York is the Lodi limestone. The well log character of this interval is similar to that of the Tully limestone, with lower gamma ray values and higher densities. In addition, the Lodi is more organic rich towards the east, as gamma ray intensities average 80-100 API units. The densities average 2.65 g/cc. East and west of central New York, the Lodi pinches out into gray shales. The Lodi is interpreted as a TST because as the calcareous pelagic intercalation in the earliest Penn Yan Shales (Ebert, 1993), it represents relatively deep water.

The surface that overlies the Lodi Limestone is interpreted as a marine flooding surface because overlying black and gray shales of the Penn Yan formation represent an abrupt increase in water depth and likely denote a highstand systems tract.
4.7 Marcellus Analogue

The Geneseo-Burket black shale is roughly comparable to the Union Springs Member of the Marcellus Formation in duration of deposition and thickness, with the thicker portion of both units found in the eastern portion of the northern Appalachian Basin and both pinching to the west in the vicinity of the regional Devonian forebulge (Lash and Engelder, 2007). Both the Geneseo-Burket and Union Springs are capped by a limey shale or limestone, the Lodi and Cherry Valley, respectively. The basal portion of the Penn Yan Formation above the Lodi limestone is a black shale by gamma ray signature (i.e., API > 180). Hence it is fair to presume that it serves as an analogue to the Oatka Creek of the Marcellus. Similarly, the Genundewa limestone caps the Geneseo-Lodi-Penn Yan sequence just like the Stafford limestone caps the Union Springs-Cherry Valley-Oatka Creek sequence (Figure 27). The specific members that are associated are listed in Table 7.
<table>
<thead>
<tr>
<th>Geneseo-Burket section</th>
<th>Marcellus section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penn Yan (black and gray shales)</td>
<td>Oatka Creek Black shale</td>
</tr>
<tr>
<td>Lodi Limestone</td>
<td>Cherry Valley Limestone</td>
</tr>
<tr>
<td>Geneseo-Burket Black shale</td>
<td>Union Springs Black shale</td>
</tr>
</tbody>
</table>

Table 7. Geneseo, associated formations and possible Marcellus analogues.
Chapter 5

Conclusions

Bulk densities within the Geneseo-Burket black shale have a range that is not consistent with normal shale sections when plotted with their respective depths. The range is twice as large (0.30 g/cc) as the overlying gray shale trend and the predicted trend. This expanded range in the Geneseo-Burket includes a higher amount of anomalously low values. This increased quantity of low bulk densities is attributed to higher quantities of organic matter. The hypothesis that trends in bulk density are driven by variations in organic content is confirmed and statistically significant, as the relationship is characterized by a correlation coefficient of 0.65.

While high (>180 API) gamma-ray intensities in the Geneseo-Burket are a qualitative indicator of increasing organic content, it is also examined in a quantitative sense. The Schmoker method is used to calculate organic matter and values range from 2-18% by volume throughout Pennsylvania. Higher concentrations in northwest and lower concentrations in the southeast, suggest that clastic dilution rates were a major control on organic matter preservation in the Geneseo-Burket. TOC values measured independently show similar trends, confirming the varying dilution rates. An empirical relationship developed between log-derived organic matter and lab-derived organic matter allows TOC estimates to be made in the Geneseo-Burket from organic matter calculated from logs. TOC values in weight percent are about half of the organic matter in volume percent.
The Schmoker Method is sensitive to changes in the equation parameters, namely the density of organic matter and fraction of pyrite/organic matter. This is evident in organic matter values that vary up to 10 volume percent and calculated TOC values that vary up to 2 weight percent. While these errors are substantial when evaluating the accuracy of the method, qualitative trends are still preserved. Likewise, although the organic matter values vary, they do so systematically such that the extrapolated TOC values remain a good approximation.

Lack of well control caused major discrepancies in isopach maps from previous years. In this study, a new isopach map of the Geneso-Burket reveals the thickest patterns of the formation. The first depocenter occurs in the east, where the thickest shale exceeds 150 feet. In the second southwestern depocenter, thicknesses average 30 feet before thinning to less than 5 feet near the Pennsylvania-Ohio border. These thickness trends are consistent with the tectonic model (Acadian Orogeny) that defines the distribution of the Catskill Delta deposits and the relative dilution rates inferred from the spatial distribution of organic matter. Although general thickness trends support the varying dilution rates as a major control on the preservation of organic content, more detailed observation of the trends, such as area of the depocenters in comparison to area of the most diluted sediment, may suggest other minor controls on organic matter preservation.

The internal stratigraphy of the Geneseo-Burket is defined in terms of its well log character. The interval is characterized by several (at least four) gamma ray mimima and
bulk density maxima that correlate. These patterns are repeatable throughout northern Pennsylvania and west-central New York. The fluctuations represent interbedded limestones or siltstones that occur in the upper Geneseo-Burket.

In central New York and northern Pennsylvania, the Geneseo-Burket is bounded above and below by limestones. The Tully reaches its maximum thickness in the east and thins towards the west. Although thickness patterns are consistent with model predictions for forebulge-erosion, it is also consistent with sedimentological evidence indicating the western Tully is a condensed section. This evidence includes: pyrite, glauconite and phosphorite and a transgressive lag indicating a surface of submarine nondeposition. The Lodi is thickest in the central portion of the study area. Its subsequent disappearance in the east and west represents a depositional pinchout.

The well log signatures of the section that includes the Geneseo-Burket may be used as an analogue for the Marcellus. The gamma ray and density characterizations of the low-density, organic rich shale bounded above and below by high density, low organic formations are present in both intervals. The patterns and consistency in the Geneseo-Burket can be used in future investigations of the Marcellus.

The regional (northern Appalachian Basin) variation in the Geneseo-Burket is summarized as the lower part of the depositional sequence composed of the Tully limestone, overlying Geneseo-Burket, Lodi Limestone and Penn Yan shales as they occur throughout the northern Appalachian Basin. The basal bounding surface of the sequence
is the Taganic Unconformity. The lowstand system tract of the sequence is not preserved, with the exception of erosive bases of thin, shallow water carbonate beds. The transgressive systems tract consists of the Tully limestone. The maximum flooding surface occurs at the base of the Genesee-Burket. The Tully-Genesee-Burket contact also represents a surface of non marine deposition. The Genesee-Burket itself, comprises the early highstand, as indicated by an overall coarsening-upward trend to the upper member, which is associated with late highstand conditions of siliclastic progradation. In the vicinity of Potter county, the Genesee-Burket is divisible into two fining upward successions. The tops of the successions are capped by a sharply defined flooding surface. The Lodi limestone represents another transgressive system tract. It is overlain by a flooding surface and the gray shales of the Penn Yan likely represent another highstand systems tract.

Well log characterizations of the Genesee-Burket defining, organic content and bulk density trends, show hickness, and stratigraphic trends that are traceable locally patterns and allow development of a regional interpretation of the depositional processes. Ultimately, the trends can be used to develop models for future assessments of the Genesee-Burket. The current study shows potential for the Genesee-Burket as a viable exploration target. In addition, the framework can be extrapolated to other sedimentary basins where black shale facies need to be characterized.
References


Chave, K.E., 1964, Skeletal durability and preservation, in Approaches to paleoecology: New York, John Wiley & Sons, Inc., p. 377-387


Fertl, W.H. and Chilingar, G.V., Total organic carbon content determined from well logs. SPE 15612 (1986).


Lash and Engelder, in press. Thickness Trends and Sequence Stratigraphic Stratigraphy of the Middle Devonian Marcellus Shale, Appalachian Basin: Implications for Acadian Foreland Basin Evolution, American Association of Petroleum Geologists Bulletin


Appendix A. Photographs of well cuttings

Well API No. 37005233380000, Armstrong County.
Well API No. 37039204620000, Crawford County
Well API No. 37047203340000, Elk County
Well API No. 37051202510000, Fayette County
Well API No. 37105205520000, Potter County
## TOTAL ORGANIC CARBON, PROGRAMMED PYROLYSIS DATA

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<th>Client ID</th>
<th>Well Name</th>
<th>Occurrence</th>
<th>Depths (ft)</th>
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<th>Sample Date</th>
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<th>LTO %</th>
<th>TOC %</th>
<th>ROC %</th>
<th>TN %</th>
<th>TIC %</th>
<th>TIC/TOC</th>
<th>TVOC %</th>
<th>S/ULOC</th>
<th>PHL</th>
<th>Notes</th>
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### Notes:
- "LTO" = Low Temperature Oxidation
- "SRC" = Source Rock
- "SRC RE" = Source Rock Residence
- "TVC" = Total Volatile Carbon
- "TVOC" = Total Volatile Organic Carbon
- "S/ULOC" = Slow/Unextractable Organic Carbon
- "PHL" = Polynuclear Aromatic Hydrocarbon
- "EXT" = Extracted
- "MOCS" = Mineral Oil Contamination
- "H" = Heavy
- "L" = Light

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KEROGEN TYPE AND MATURITY (Tmax)

Company: PENN STATE UNIVERSITY
Project #: BH-46224 / 10-107-A
KEROGEN QUALITY PLOT

Company: PENN STATE UNIVERSITY

Project #: BH-48224/10-10-A

REMAINING HYDROCARBON POTENTIAL (ST. MF. CMD. eq)

TOTAL ORGANIC CARBON (TOC, wt. %)

REMAINING HYDROCARBON POTENTIAL (ST. MF. CMD. eq)

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0

18 16 14 12 10 8 6 4 2 0

TYPE IV
TYPE III
Type II
Type I

Mixed TYPE II
oil-prone
gas-prone

Organic Lean