ENVIRONMENTAL HEALTH AND SAFETY DYNAMICS OF THE MARCELLUS SHALE IN PENNSYLVANIA

by

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Quantifying the environmental impacts of hydraulic fracturing of the Marcellus Shale in Pennsylvania is critical for identifying high risk activities, and informing the development of engineering and policy practices aimed at risk mitigation. Environmental inspection and incident reports issued by the Pennsylvania Department of Environmental Protection (PADEP) are the most complete and consistent dataset available for analyzing trends in environmental incident rates in the Commonwealth. Overall violation and penalty rates decreased statewide between 2008 and 2011 when scaled to the number of Marcellus completions (1.08 to 14; and .43 to .03, respectively). There are regional differences in inspection practices and violation and penalty issuance between PADEP districts: Based on the assumption that intra-company environmental practices are consistent across drill sites, violation and penalty rates should generally be equivalent between PADEP districts for each driller. However, for 4 major gas companies operating in all 4 PADEP districts, the Northwest District Office issued overwhelmingly more violations and penalties than the other district offices in almost every case. Several important regulatory changes impacting Marcellus exploration activities occurred during the study period. Since many of these changes are activity specific, the overall incident rates were not affected. However, penalties for accidental discharges to stream waters declined from .04 per new completion to .01, following a regulatory change requiring a 150 foot buffer between drill sites and streams. There is generally an inverse relationship between the number of Marcellus drill site inspections, and the number of violations and fine carrying penalties issued. The number inspections increased statewide from 1195 in 2008 to 10,192 in 2011, and the rate of violations and penalties per inspection decreased from .09 to .02; and .03 to .004, respectively. This thesis shows that the relationship between incident reporting, drilling activity, inspection activity, and regulatory changes interact in a dynamic manner. It is recommended that inspection and reporting practices be centralized between PADEP districts, and that incident rates and types continue to be monitored so that regulatory and engineering practices can continue to be targeted to risk bearing activities.

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PREFACE

This thesis is dedicated to the memory of my father, Mark Louis Glosser. Without him, and countless others, this work would not have been possible. I would also like to acknowledge (in no particular order), Caryle Glosser; Jennifer Fagan; the Arnolds; Shane Michael Greentree; Keti Pavic; Ian Ehrlich; Lucy Rose; Bob Dilmore; Kelly Rose; Dan Soeder; Jim Sams; Ale Hakala; Eric Perry; Shannon Granahan; the Burkholders; Sandra Davis; Stasia Miaskiwicz; Jennifer Holt; Ronald Guttierez; Steve Scheinert; and everyone else who I will only realize I left off this list after I hit “submit”.

1.0 INTRODUCTION TO MARCELLUS SHALE DEPOSITION AND ENVIRONMENTAL ISSUES

1.1 INTRODUCTION

The environmental risk of natural gas extraction from the Marcellus formation in via hydraulic fracturing has ignited a great deal of debate and research (Vidic and Brantley 2013) (Kell 2011; Warner, Jackson et al. 2012). In Pennsylvania, where legacy environmental issues from coal mining remain (Hammarstrom 2003) there is particular concern about potential unintended consequences from fracturing. Environmental issues surrounding Marcellus development range from concerns about water contamination (A Vengosh 2011) to ecosystem and vegetation destruction (Adams 2011). The physical processes and mechanisms by which adverse events such as fluid migration (Saiers and Barth 2012), (Rozell and Reaven 2012), blowouts (Jordan and Benson 2009), and spills (Vidic and Brantley 2013) occur are not fully understood. In addition, drilling, completion, and stimulation methods are still being developed (Lee, Herman et al. 2011), making strategies for mitigation of environmental risk an ongoing challenge. Quantifying the environmental risks of Marcellus exploration is a complex task, which can be informed by a comprehensive analysis of existing environmental incidents.

Estimates of recoverable natural gas in the Marcellus formation range from 30 (Lee, Herman et al. 2011) to 282 trillion cubic feet (MSET 2011). The geologic characteristics, including the high organic content, of the Marcellus shale make it an attractive target for development (Wang 2012). Compared to other shales, the Marcellus has high porosity and high permeability (Wrightstone 2011), which enables exploitation of the organic matter through horizontal drilling and hydraulic fracturing. Incorporating the geologic, stratigraphic, and depositional characteristics of the Marcellus into the discussion of Marcellus resource development is necessary to develop a thorough scientific understanding of environmental risk, because these factors control exploration and exploitation of the shale resources.

The geochemistry endemic to the Marcellus shale, and the chemicals and techniques used during hydraulic fracturing have resulted in several highly publicized adverse environmental outcomes. Environmental receptors for Marcellus related contamination include land, surface water, ground water, ecosystem, and air. For example, salinization of freshwater aquifers resulting from contact with high concentrations of TDS, Cl, Na, Ca, Ba, Sr, Ra, and other constituents characteristic of Marcellus flowback waters can harm biota, and create unsafe drinking water (Warner, Jackson et al. 2012). However, to date, the full environmental impact of hydraulic fracturing in Pennsylvania has not been established through scientific study

1.1.1 HYDRAULIC FRACTURING: POTENTIAL ENVIRONMENTAL CHALLENGES

Horizontal hydraulic fracturing is a technique used to release natural gas stored in subsurface geologic formations. During hydraulic fracturing, water and a mixture of proprietary chemicals and propants are injected at high pressure underground to open up small natural fractures in the rock, and release natural gas (Adams 2011). The lifecycle of a horizontal hydraulic well begins at site exploration and ends with disposal of waste, and site remediation (Arthur and Bohm 2008). However, the spatial and temporal scope of potential environmental impacts from hydraulic fracturing spans both on-site and off-site, and near-term and long-term impacts (Figure 1). Even before a well is completed, site exploration activities, and the installation of a well pad can disturb sensitive ecosystems, flora, and fauna (Kargbo, Wilhelm et al. 2010).

The drilling depth of a horizontal well in the Marcellus can be extreme, exceeding 8000 feet below the surface (Arthur and Bohm 2008). Drilling at this depth presents a host of difficulties related to geophysical realities such as increased pressure, rock hardness, and abrasiveness. The temperature of the Marcellus at depth can reach 51 degrees Celsius, and the pressure can exceed 410 bar (Kargbo, Wilhelm et al. 2010). Engineering related difficulties are also encountered, such as problems with efficient disposal of drill cuttings at depth, and maintaining cementing and casing integrity under extreme conditions. In addition, there is a risk of intercepting permeable gas reservoirs or orphan wells, which could lead to an underground blowout.

Perhaps the most commonly discussed environmental incidents occur in the well completion phase (Myers 2013). Following drilling and casing of a well, the well is perforated (Soeder 2013). During perforation, holes are shot through the horizontal component of the well. Then, to stimulate gas production, fluids and propants are injected at a pressure exceeding the combined tectonic forces, and tensile strength of the rock (Kargbo, Wilhelm et al. 2010). The fluids and injected propants are known as “slickwater,” and are often proprietary in nature. It is known that the main constituents in slickwater are sodium and calcium chlorides, however, toxic chemicals are also known to be present in smaller quantities (Adams 2011). The propants – commonly sand – keep shale fractures open, and stimulate the release of gas from formation.

Once a well is completed, some of the slickwater remains in the subsurface, and the rest is returned to the surface as “flowback” for disposal. During the completion and disposal phases, the risk of blowouts, and accidental spills of briney formation water and flowback water is greatest.

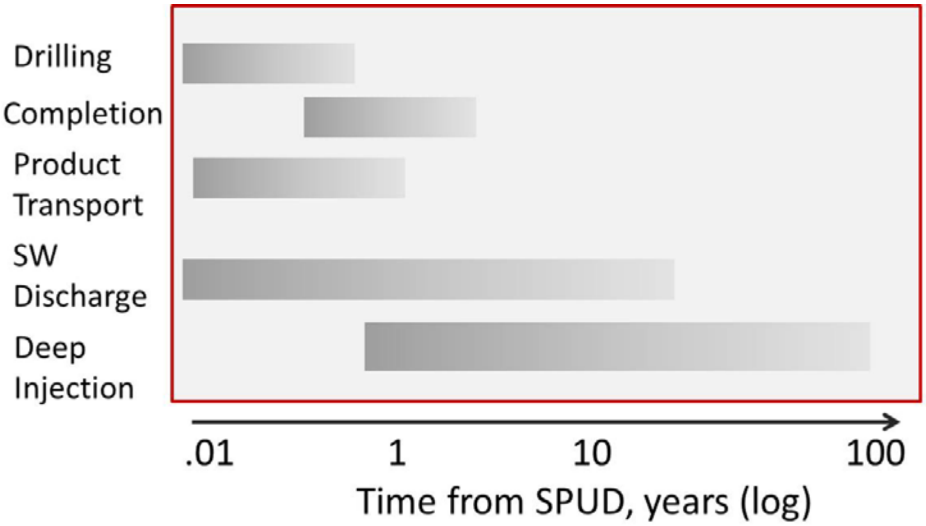


Figure 1 Qualitative representation of the temporal scope of potential environmental risks from hydraulic fracturing.

1.1.2 NEED FOR QUANTIFICATION OF ENVIRONMENTAL RISK

The environmental impact of oil and gas exploration is a topic of fundamental importance to ensuring air, water, ecosystem, and human health (Soeder and Kappel 2009). As shown, natural and engineering related difficulties are known to exist before, during, and after hydraulic fracturing. However, the actual rate of adverse environmental incidents in related to development of the Marcellus Shale in Pennsylvania has not been quantified. And, importantly, the efficacy of targeted regulations aimed at improving shale gas related environmental outcomes in Pennsylvania has not been tested. The objectives of this thesis are to determine:

1. Do overall report rates of environmental health and safety incidents related to Marcellus exploration change in Pennsylvania between 2008 and 2011?
2. How do report rates change when separated by environmental impact?
3. Are there spatial trends in environmental incident report rates in Pennsylvania?
4. Do Pennsylvania regulations aimed at specific Marcellus exploration activities result in fewer adverse environmental outcomes related to those activities?

1.1.3 DATA SOURCES USED FOR CHARACTERIZING ENVIRONMENTAL INCIDENTS

It is necessary to use the most complete and consistent available datasets to describe environmental incidents, particularly early in the resource development process when best management practices are in development. Previous studies of environmental incidents arising out of oil and gas exploration have used data ranging from industry reported incidents (Groat and Grimshaw 2012) to drill site groundwater contamination reports (Kell 2011). The scope and quality of these records vary among studies. In Pennsylvania, the Pennsylvania Department of Environmental Protection (PADEP) issues and produces records of environmental health and safety inspections and inspection outcomes (incident reports). Although the information contained in the reports is often of limited detail, these reports are the most consistent and complete dataset from which to analyze trends in environmental incident rates in Pennsylvania. In this study, PADEP's inspection and incident reports are used to analyze temporal trends in Marcellus related environmental incidents in Pennsylvania between 2008 and 2011. Incident reporting rates are examined in the context of drilling phase, and the regulatory environment, including changes in inspection effort and inspection practices, to assess whether the observed trends may be confounded by these processes. This methodology is further applied to datasets used in a previous study of environmental incident reporting, because efforts to make incident rates directly comparable are essential for contrasting findings among studies.

1.2 THESIS STRUCTURE

This thesis describes the geology of the Marcellus shale in Pennsylvania, and assesses dynamics of environmental incident trends arising out of the development of its shale gas resources. Chapter 2 provides an exposition of the geologic, stratigraphic, and depositional characteristics of the Marcellus shale. It is essential to understand the geology of the shale in order to inform risk assessment, since drilling, and risk therefrom, is dependent on shale geology. Chapter 3 contains the methods, results, and discussion of the incident study. Chapter 4 contains conclusions of this work

2.0 GEOLOGY OF THE MARCELLUS SHALE

2.1 INTRODUCTION TO THE GEOLOGY OF THE MARCELLUS SHALE

The Marcellus shale is a Middle-Devonian shale within the Hamilton group of the Appalachian Basin (Lash and Englender 2011). The areal extent of the Marcellus spans the Allegheny Plateau structural region of North America, including parts of Canada, New York, Maryland, West Virginia, Virginia, New Jersey, Kentucky, Tennessee, and Pennsylvania (Englender and Lash 2009) (Figure 1). A series of tectonic events led to the creation of the Appalachian Basin, which hosts the Marcellus Shale, and several other Devonian aged shales. The Marcellus is typically overlain by the Mahantango formation in Pennsylvania, and underlain by the Onondaga Limestone. The Marcellus is generally considered to be a black shale (Wallace and Roen 1993) (Harper 2008), however, thin sediments in the west consist of finer-grained, organic-rich black shale interbedded with organic-lean gray shale (Soeder and Kappel 2009), and a submember of the shale is primarily a skeletal limestone (NETL 2010). Although there is disagreement among geologists regarding the division of Marcellus members, the formation is generally divided into three formal members in Pennsylvania: the Union Springs member, the Cherry Valley Limestone, and the Oatka Creek Member (Figure 2). Of these members, the Union Spring and Oatka Creek contain the highest organic content, and are typically the targets of exploration (NETL 2010). Trace metal geochemistry of the Marcellus is typically characterized by trace element enrichment of Ag, As, Cd, Cu, Mo, Sr, and Rb (Mosher 2010) (Chapman, Capo et al. 2012), resulting from the unique depositional and tectonic history of the Marcellus Shale .

An enhanced understanding of the structure, stratigraphy and composition of the Marcellus is important for analyzing environmental incidents, because exploitation of the shale (and attendant environmental impact) is dependent on its compositional attributes. The following sections detail the unique geologic history and attributes of the Marcellus Shale.

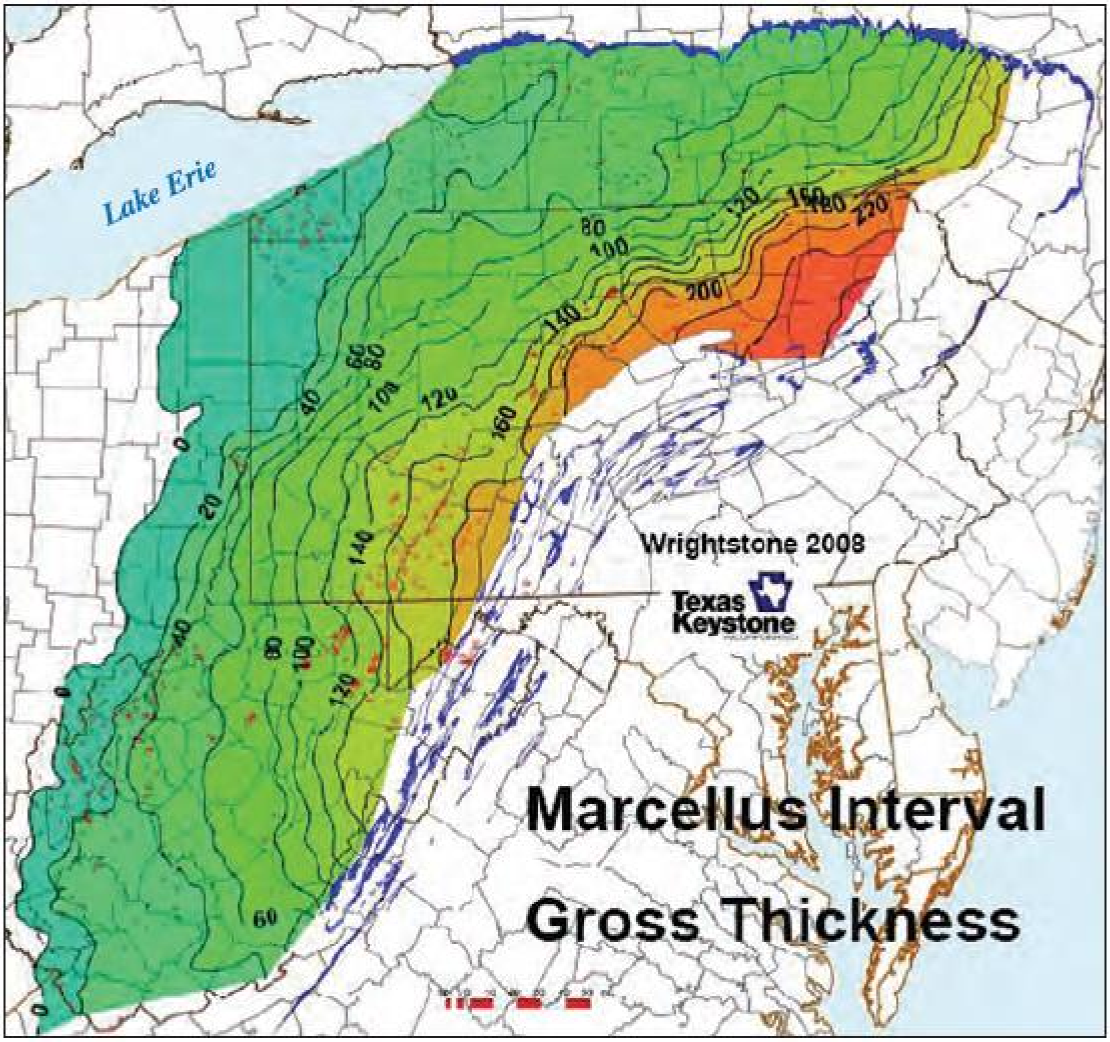
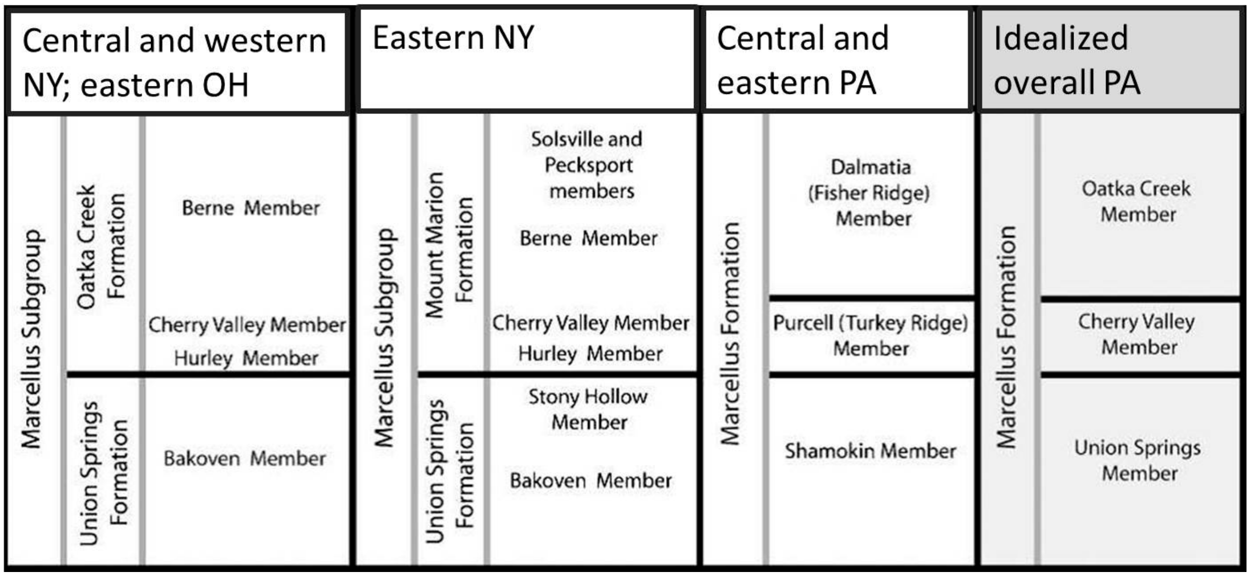


Figure 2 Aerial extent and thickness (in feet) of the Marcellus Shale. The Marcellus is found throughout the Allegheny Plateau region of the Northern Appalachian Basin (NETL 2010).



Central and western NY; eastern OH		
Marcellus Subgroup	Oatka Creek Formation	Berne Member
		Cherry Valley Member Hurley Member
	Union Springs Formation	Bakoven Member

Eastern NY		
Marcellus Subgroup	Mount Marion Formation	Solsville and Peckport members Berne Member
		Cherry Valley Member Hurley Member
	Union Springs Formation	Stony Hollow Member Bakoven Member

Central and eastern PA	
Marcellus Formation	Dalmatia (Fisher Ridge) Member
	Purcell (Turkey Ridge) Member
	Shamokin Member

Idealized overall PA	
Marcellus Formation	Oatka Creek Member
	Cherry Valley Member
	Union Springs Member

Figure 3 Marcellus formation stratigraphy and nomenclature, modified from (Lash and Englender 2011). Grey column at far right shows idealized Marcellus stratigraphic column for Pennsylvania as discussed in this study.

2.2 TECTONIC HISTORY OF THE APPALACHIAN BASIN AND STRUCTURAL CHARACTERISTICS OF THE MARCELLUS SHALE

The Marcellus Shale belongs to a group of eight Devonian aged shales in the Appalachian Basin (Ettensohn 1985). The Appalachian Basin is a foreland basin that covers the areal extent of most of Pennsylvania. The basin development began with the Taconic orogeny. The Taconic orogeny occurred during the middle to late Ordovician period (~480 – 440 mya), and was the first of several important mountain building episodes in the basin. In the Taconic orogeny, an ocean island arc collided with Laurentia, a large continental craton. Following the Taconic orogeny in the Ordovician, the Acadian orogeny began during the middle Devonian, and lasted through the early Mississippian periods. In the Acadian orogeny, a series of minor continental bodies again collided with Laurentia. The mountains which produced most of the sediments which became the Marcellus formed during the Acadian orogeny. Finally, during the late Pennsylvanian period, the Alleghany orogeny formed the Appalachian mountain range when Laurentia and Gondwanaland, another continental craton, collided. The continental collision created many folds and peaks in the Valley and Ridge province of the Appalachian basin, and led to outcropping of the Marcellus in some areas. (Nickelson 1986; Soeder and Kappel 2009; Soeder 2013)

The tectonic history of the Appalachian Basin led to distinct geologic structures in the resulting rocks. Devonian shales, including the Marcellus, are characterized by several bed-normal joint sets (Evans 1994). Two of these joint sets – J1 and J2, are basin wide (Englender and Lash 2009), (Figure 4) and the J1 joints have been shown to extend beyond the Appalachian

Basin (Englender and Whitaker 2006), pointing to a common growth mechanism in the post-Devonian era. The Marcellus is structurally distinguished from other Appalachian shales by the extent of its deformation resulting from the Alleghany orogeny (Englender and Lash 2009). Unlike the New Albany and Antrim shales, which were also part of the Acadian foreland basin, the Marcellus was subjected to a considerable amount of layer parallel shortening (LPS) (Englender and Lash 2009).

2.2.1 J1 FRACTURES IN THE MARCELLUS

Unlike faults, which are rarely systematic, the Marcellus carries two systematic joint sets, noted above (J1 and J2). The J1 joints are something of a geological conundrum. Early interpretations of the joints suggested a neotectonic origin (Evans 1994), possibly from the Pleistocene glaciation. This interpretation was in part based on the J1 joint orientation being nearly identical to that of Appalachian neotectonic joints and the contemporary tectonic stress field (Englender and Lash 2009). The J1 joint set strikes east-northeast, and within a few degrees of maximum horizontal compressive stress (S_{Hmax}) (Lash and Englender 2011). However, the neotectonic interpretation is challenged by the existence of folding along with bedding in the joints. Contemporary geologic evidence strongly suggests that J1 joints in fact formed prior to the Alleghany orogeny folding, surviving the event with minimal deformation. The conundrum of the J1 joints is resolved by several lines of evidence suggesting that the joints are natural hydraulic fractures, which episodically propagated around concretions.

Whether the J1 joints are natural hydraulic fractures instead of tectonic features is an important drilling and environmental consideration. If the J1 features are natural fractures, then tensile failure will occur during hydraulic fracturing. If the features are faults, then shear failure will occur. Shear failure is the intended goal of fracking: It creates good fracture connectivity by increasing the surface area of both the J1 and J2 joint sets. If tensile failure occurs, then some existing fractures will be elongated, while other fractures will close. In this case, not only will wells be less productive, but subsurface leakage of fluids may be more poorly controlled, leading to potential environmental issues.

2.2.2 J2 JOINTS IN THE MARCELLUS

J2 Joints in the Marcellus are common to the gray shale deposits, and are dispersed normal to fold axes along the orocline bend in the Appalachians As a consequence of the cross-fold orientation, the J2 joints retained their vertical orientation during folding (Englender and Lash 2009). They tend to cross cut the J1 joints (Figure 4).

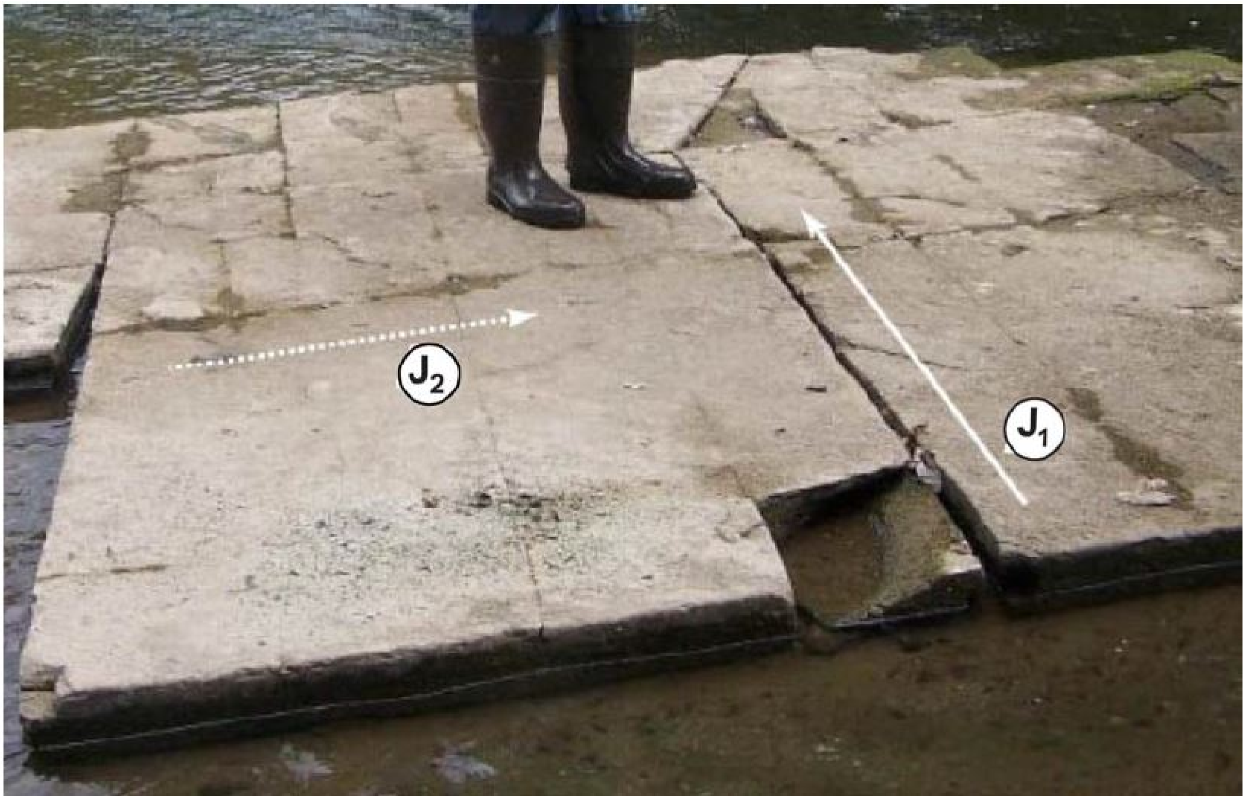


Figure 4 Jointing in the Marcellus Shale (Englender and Lash 2009). J2 joints are common to the grey shale portions of the Marcellus; J1 joints are common to the black shale portions.

2.3 STRATIGRAPHY OF THE MARCELLUS IN PENNSYLVANIA

2.3.1 UNION SPRINGS MEMBER

The Union Springs is the basal member of the Marcellus and is primarily composed of black shale (Lash and Englender 2011). The Union Springs is sometimes referred to as the Bakoven member (Griffing). The thickness of the Union Springs member exceeds 49m in northeastern

Pennsylvania, and is highly radioactive, exceeding 600 API units (Lash and Englender 2011). Interbeds of siltstone occur at the base of the Union Springs member (NETL 2010), and the member is characterized by low clay content, and higher quartz and pyrite content than the other members (NETL 2010; Lash and Englender 2011). Early studies of the Marcellus interpreted the contact between the Union Springs and underlying Onondaga Formation as a regional unconformity, however, later studies determined that the contact is “relatively conformable” across much of the region (Ver-Straeten 2007). Trace elements characteristic of the Union Springs member include Chromium, Manganese, Molybdenum, and Vanadium (Bracht 2010).

2.3.2 CHERRY VALLEY MEMBER

Overlaying the Union Springs member is the Cherry Valley Member. Some geologists refer to this member as the Purcell limestone, particularly in West Virginia (NETL 2010). The thickness of this member ranges from 3m in Western NY (Lash and Englender 2011) to over 43m in Northeastern PA (NETL 2010). The Cherry Valley limestone is characterized by interbedded nodular limestone, shale, and siltstone (Lash and Englender 2011), with thin intervals of organic rich siliciclastic mudstones (Werne, Sageman et al. 2002). Gamma ray and bulk density logs signatures of the Cherry Valley member confirm field studies, and show that the member becomes more arenaceous to the east (Lash and Englender 2011).

2.3.3 OATKA CREEK MEMBER

The Oatka Creek member is the upper member of the Marcellus, and is subdivided into 2 units: a basal black shale similar in organic content to the Union Springs member, and an upper unit comprised of grey shale (NETL 2010). The thickness of this member ranges from 9m in central NY (NETL) to over 168m in central PA (Lash and Englender 2011). The basal unit of the Oatka Creek member is distinguishable from the Union Springs member on gamma-ray logs (Figure 3) Dark grey mudstones in the Oatka Creek member have organic Carbon content ranging from 1-4% (Werne, Sageman et al. 2002). Trace element geochemistry characteristic of the Oatka Creek formation includes Molybdenum, Vanadium, Iron, and diagenetically precipitated Calcium Carbonate, and Silica (Werne, Sageman et al. 2002).

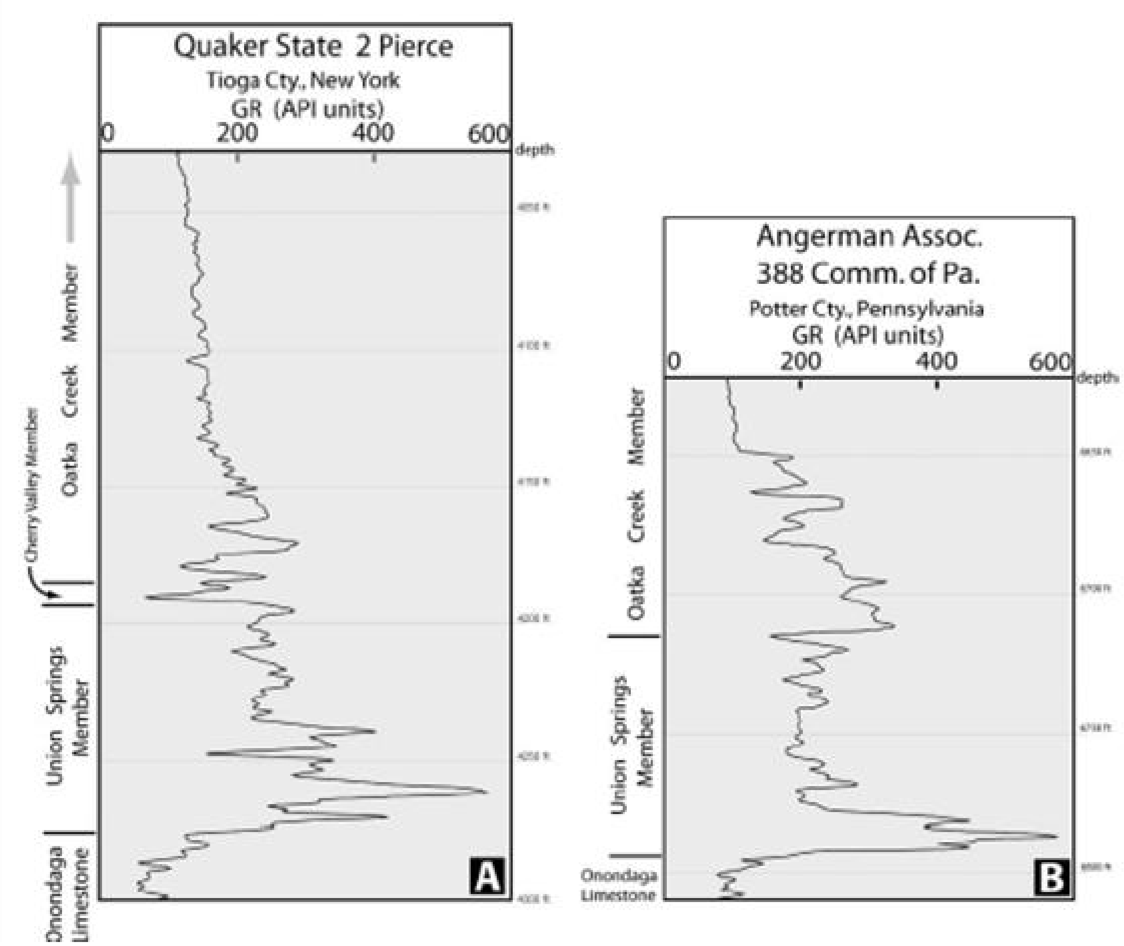


Figure 5 Gamma ray signatures of the Marcellus Shale members, from wireline logs. (Lash and Englender 2011). A) wireline log from Tioga County with all submembers of the Marcellus; B) wireline log from Potter County, where the Cherry Valley member does not extend.

2.4 DEPOSITION OF THE MARCELLUS SHALE

The depositional history of the Marcellus shale is responsible for the high organic content of its members. In general there are three factors identified in the literature that explain controls on organic matter burial and preservation of carbon rich lithology: Primary photosynthetic production; bacterial decomposition; and bulk sedimentation rate (Figure 6). The relative degree to which each of these processes influences the formation and preservation of organic rich facies is not settled in the literature. Early hypothesis explaining the organic content of the Marcellus propose a "preservation only" model (Ettensohn 1985). A "preservation only" model – described in more detail below –posits that the Marcellus was deposited and preserved in fully anoxic conditions under a permanent pycnocline (Sageman and Arthur 1994). However, recent hypotheses based on a more complete stratigraphic and geologic record of the Marcellus, propose that a combination of the three factors explain the high organic content of the Marcellus.

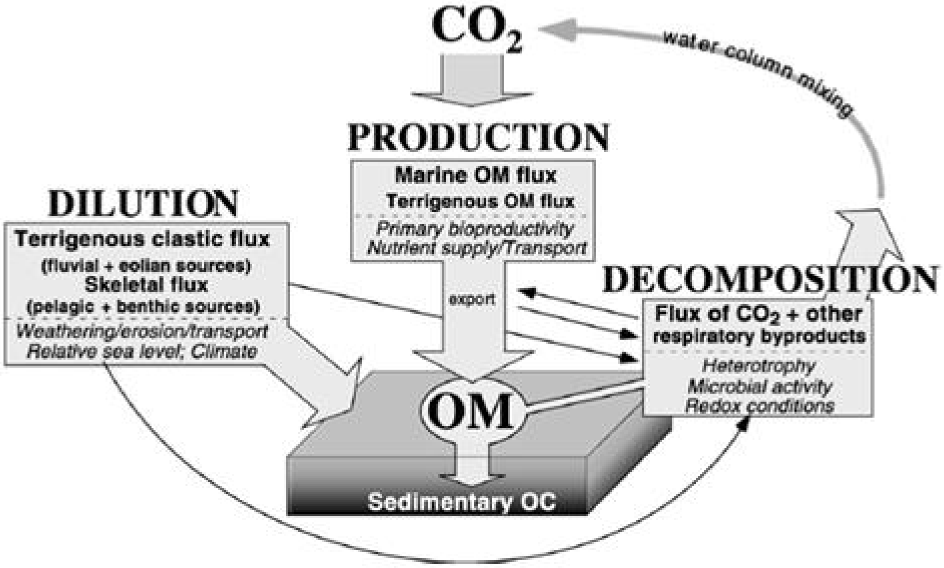


Figure 6 Processes that regulate organic matter content of lithofacies. Primary Production; dilution; and decomposition under anoxic conditions interact to control the burial and preservation of carbon rich lithology (Sageman, Murphy et al. 2003).

2.4.1 LIMITATIONS OF A “PRESERVATION ONLY” MODEL

An early model for the provenance of the high organic content of the Marcellus was a “preservation only” model, where permanently anoxic conditions would have preserved organic matter. Here, evidence of southward migrating deformation of the Marcellus was interpreted as tectono-stratigraphic cycles of subsidence, which were followed by the basin being filled in by uplifted orogen (Ettensohn 1985). In this model, each cycle has a distinctive stratigraphic sequence, which is characterized by black mudstones overlaying shallow water carbonates. These sequences would have been deposited under anoxic conditions beneath a “nearly permanent” pycnocline (Capman and Bustin 1996) and (Sageman and Arthur 1994). However, later work weakens the case for tectonically driven subsidence as the cause of high organic matter in the Marcellus. The case for tectonically driven subsidence is called into question by the existence of a “relatively conformable” section spanning the Hamilton Group, as described above (Werne, Sageman et al. 2002). The case for the “nearly permanent” pycnocline/preservation model is further weakened by the lack of observational evidence (Werne, Sageman et al. 2002), and the fact that sustenance of such permanent stratification of the water column is inherently difficult, especially given geologic evidence of frequent sediment mixing by storms.

Geochemical analysis of the Marcellus suggests an oscillation between oxic and anoxic conditions, and does not support a permanent pycnocline. In the Oatka Creek member, there is a gradual increase in the organic carbon to total phosphorous ratio, which suggests a preferential release of P relative to C, which means that there was a gradual increase in the intensity and duration of anoxic conditions (Figure 7) (Werne, Sageman et al. 2002). More evidence against a permanent pycnocline, and for thermal stratification and fluctuating oxic conditions is found in variations in the organic carbon to nitrogen ratios in the shale. Nitrogen is thought to be preferentially released over carbon during the oxic phase of the oxic-to-anoxic cycle. Geologic evidence also suggests that seasonal mixing from storms in the basin prevented the formation a permanent pycnocline (Wrightstone 2011). In addition there is evidence of sea level fluctuation, sedimentary structures and fossils found in the Marcellus to support sea level fluctuation. Sedimentary structures include bioturbation and shell beds containing benthic fossils, which suggest reworking of the Marcellus from storm currents (Figure 8 and Figure 9) (Griffing) .

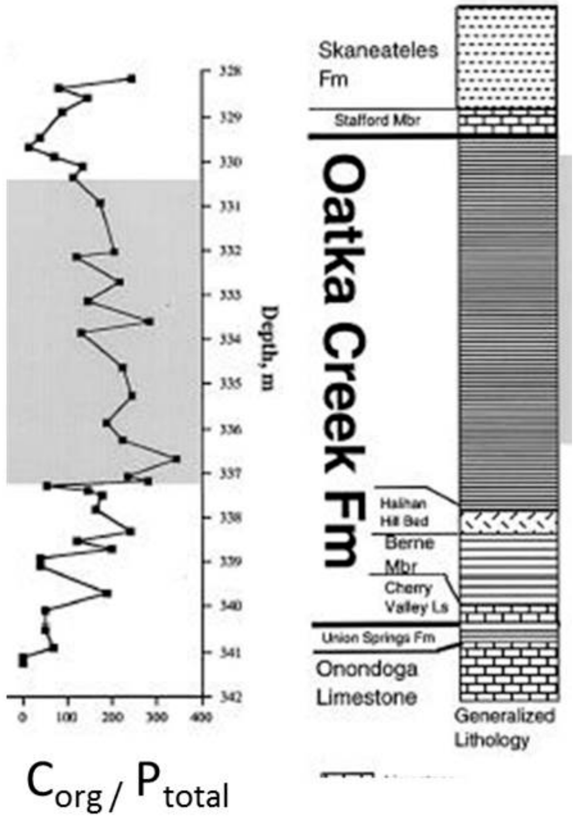


Figure 7 Depth trends of biogeochemical cycling proxies. Increasing C:P ratios suggest increase in intensity and duration of anoxic events, mediated by enhanced nutrient regeneration during anoxia. Fluctuations between oxic and anoxic conditions evident from C:P trends. Modified from (Werne, Sageman et al. 2002).

Figure 8 Brachiopod fossil from Marcellus formation (Dave 2012). Existence of brachiopod fossil suggests oxic conditions suitable for life.

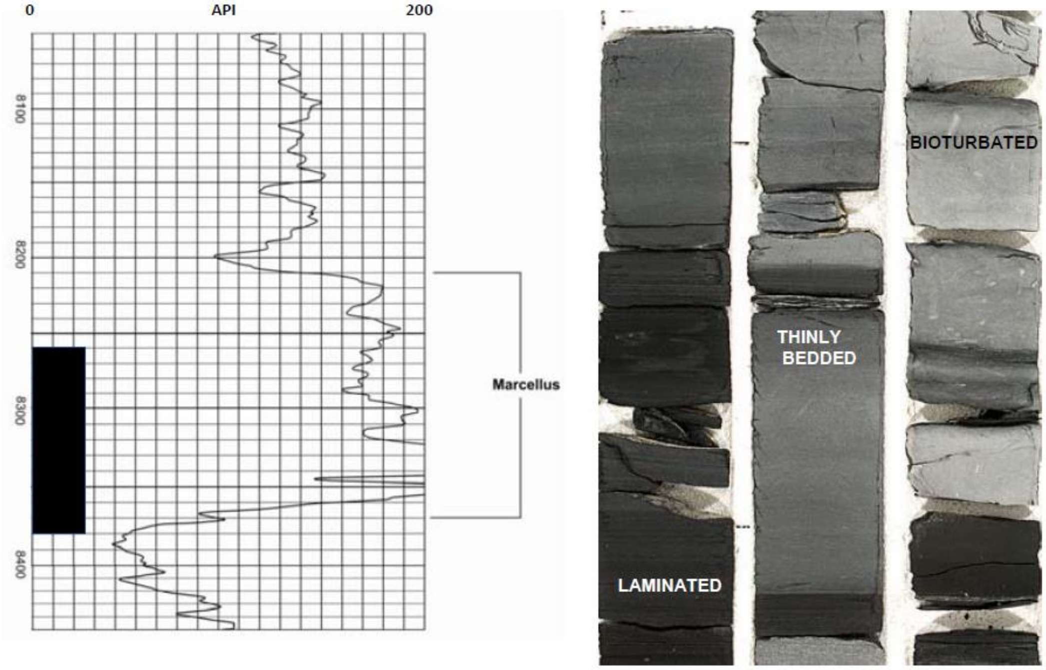


Figure 9 Organic rich intervals of the Marcellus shale, showing bioturbated interval, thinly bedded interval, and laminated interval. Cores are from single wellbore in Jefferson County PA, at varying depth intervals (Laughrey and Ruble 2011).

2.4.2 MODERN DEPOSITIONAL FRAMEWORK FOR THE MARCELLUS: COUPLED PRODUCTIVITY AND PRESERVATION MODEL

Recent depositional models for Middle Devonian shales, including the Marcellus, are based on a more complete stratigraphic and geologic record (Brett, Baird et al. 2011) than earlier preservation only models. Recent studies have recognized the Marcellus encompasses 2 third-order transgressive-regressive sequences (Brett, Baird et al. 2011; Lash and Englender 2011). Stratigraphic evidence for these T-R sequences, including rapid thickening toward the Northeastern region of the basin, is important because it implies greater accommodation space for sediment. As with the "preservation" model, the accommodation space, coupled with close proximity to clastics from the Acadian orogeny, would have influenced the accumulation and preservation of sediment (Lash and Englender 2011). However, the role of primary photosynthetic productivity is also of fundamental importance to the organic content of the Marcellus. Recent paleogeographic reconstruction of the Appalachian basin, and modern geochemical analysis of Marcellus sediment, provides evidence that high primary photosynthetic productivity may have further influenced the accumulation of the Marcellus organic matter.

Paleogeographic reconstruction of the Mid-Devonian Appalachian Basin, suggests that climatic conditions would contribute to high photosynthetic productivity (Figure 10). During the Mid-Devonian, the Appalachian Basin was located in the tropics of the Southern Hemisphere, with some literature proposing between 15° and 30° south latitude (Wrightstone 2011), or and 30° to 35° (Sageman, Murphy et al. 2003). The organic rich portions of the Hamilton Group, including the Marcellus Subgroup, were deposited in a large, nearly enclosed sea – the Marcellus basin (Blakey 2005). The subtropical location of the basin likely enhanced the growth of marine phytoplankton. Marine phytoplankton are the dominant contributor to the Marcellus organic facies (Wrightstone 2011). The paleogeography of the basin during the Mid-Devonian indicates that high primary photosynthetic production was an important factor in the deposition of the high organic content of the Marcellus.

A subtropical setting of the basin is consistent with evidence from sediment showing a storm wave base in the basin. Regional climate cooling occurred during the Middle and Late Devonian (Sageman, Murphy et al. 2003) (Scotese and McKerrow 1990), which would have increased seasonality in evapotranspiration and precipitation, as well as surface water temperature.

As water densities changed during the cool season, a thin mixed layer of surface water would have expanded over a large geographic area, and thermal stratification would have become a factor, with the thermocline potentially dissipating (Sageman, Murphy et al. 2003). The thermal stratification would have further contributed to the seasonal anoxia.

The warm, but seasonably variable, and arid conditions during the Middle Devonian are supported by additional paleoclimatic indicators (Sageman, Murphy et al. 2003).   Thin sections from the Marcellus show maximum silt concentrations in the zone of maximum total organic carbon. These silt grains are subangular with pitted surface textures, suggesting eolian origin. Arid conditions may have contributed to non-eolian sediment starvation (Wrightstone 2011). This is evidenced by the decrease in the flux of non-eolian siliciclastic and carbonate sediment, and the enrichment of eolian silt grains (Werne, Sageman et al. 2002), which would have prevented the dilution of accumulating organic matter. Thus, maximum TOC enrichment and maximum sediment starvation correlate (Sageman, Murphy et al. 2003).

As also described earlier, intervals of sedimentary structures generated by sea currents, bioturbation, and shell beds which contain benthic fossils also suggest episodic sea level fluctuation and changes in sea floor oxygenation. These indicators also support evidence of reworking from bottom currents and also reworking from storm currents (Griffing).

Geochemical proxy evidence also suggest sea level fluctuation. In particular, Mo/Ti, Fe/Ti, organic Carbon, and $\delta^{34}S_{py}$ proxy evidence in other black shales suggests that after the carbonate supply to the basin was cut off, sea level continued to rise, and a threshold in which dominantly anoxic conditions shifted to dominantly euxinic conditions was passed (Werne, Sageman et al. 2002).

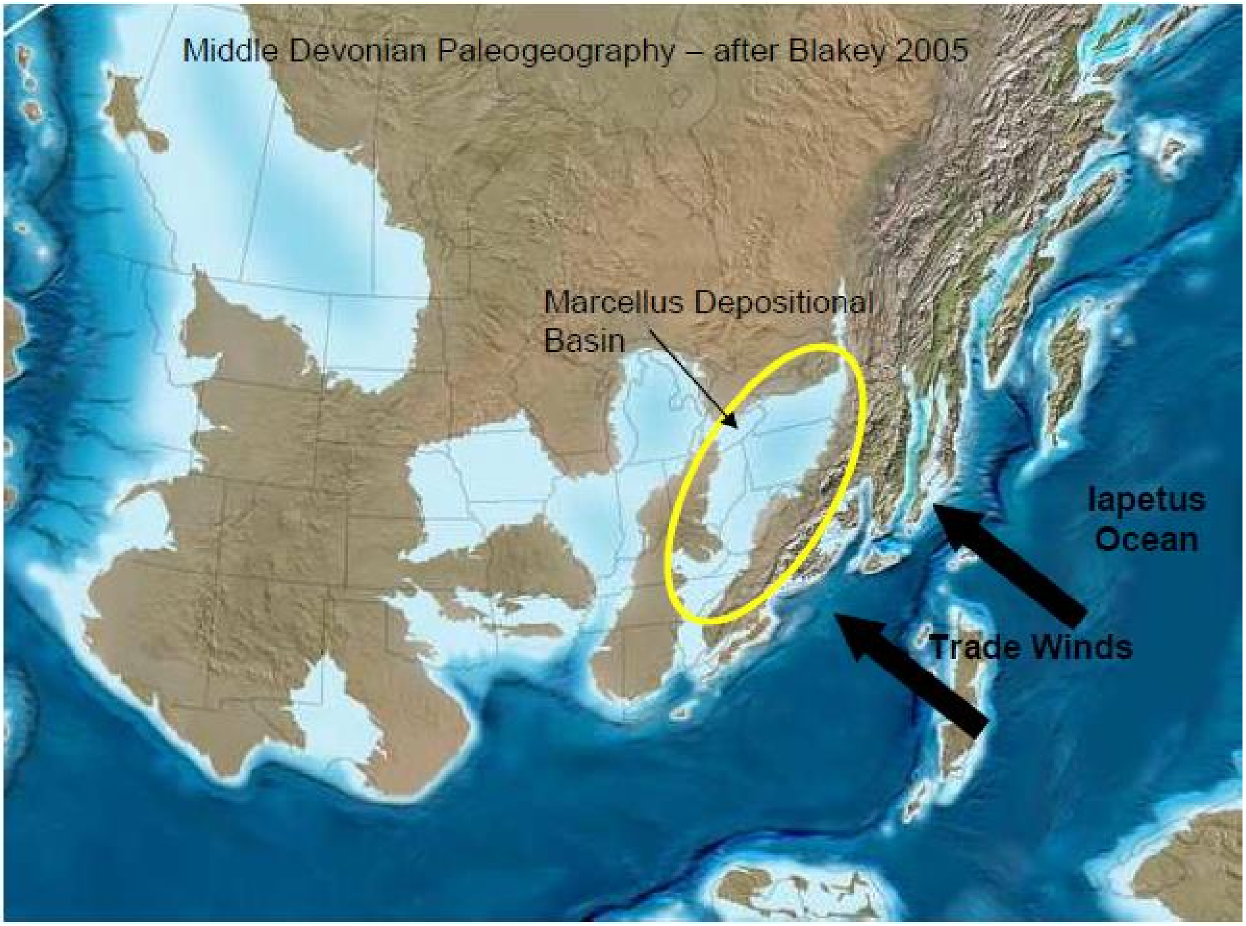


Figure 10 Middle Devonian paleogeographic reconstruction of the Appalachian Basin from (Wrightstone 2011), modified by Wrightstone from (Blakey 2005). Appalachian basin was located south of the equator during time of deposition.

2.4.3 SUMMARY OF MARCELLUS DEPOSITION

The high organic matter content of the Marcellus Shale likely resulted from a “Perfect Storm” of circumstances, primarily driven by high primary photosynthetic production by algal blooms, and subsequent preservation of the organic content by seasonal anoxia associated with thermal stratification (Wrightstone 2011). A subtropical climate would have encouraged the high primary production (Blakey 2005). Arid conditions may have contributed to non-eolian sediment starvation. This is evidenced by the decrease in the flux of non-eolian siliciclastic and carbonate sediment, and the enrichment of eolian silt grains, which would have prevented the dilution of accumulating organic matter. Thus, maximum TOC enrichment and maximum sediment starvation correlate (Sageman, Murphy et al. 2003).

2.5 CONCLUSION OF MARCELLUS GEOLOGY

The present day Marcellus shale is the largest on shore natural gas reserve in the United States (Lee, Herman et al. 2011). It is one 8 of Devonian aged black shales deposited and preserved in the Appalachian Basin, following a series of basin wide tectonic events. In Pennsylvania, the Marcellus is divided into 3 members, the Union Springs, Cherry Valley, and Oatka Creek members, of which the Union Springs and Oatka Creek have the highest organic content, and are common targets for exploration. Important structures in the Marcellus shale include the J1 and

J2 joints. J1 joints are common to the black shale portions of the Marcellus, whereas J2 are endemic to the grey shale components. The unique paleogeographic setting of the Appalachian Basin in the Middle Devonian period assisted the deposition and preservation of the high organic content in the Marcellus Shale. It is critical to understand the geology of the Marcellus Shale, because exploration of its natural gas resources is dependent on its geologic conditions.

3.0 MARCELLUS SHALE ENVIRONMENTAL HEALTH AND SAFETY INCIDENT STUDY

3.1 INTRODUCTION TO MARCELLUS SHALE ENVIRONMENTAL HEALTH AND SAFETY REPORTING IN PENNSYLVANIA

A primary goal of state regulatory agencies is to promulgate and consistently apply rules to protect natural resources (Aunkst, Hines et al. 2011). In Pennsylvania, the Pennsylvania Department of Environmental Protection (PADEP) enforces environmental safety regulations under the authority of the Oil and Gas Act (25 PA Code Section 78.71, 1984; 2011 revisions to PA Oil and Gas Act). PADEP is responsible for issuing oil and gas drilling permits; managing SPUD and completion reports and procedures; establishing drill site specific conditions for drilling and well construction; training oil and gas inspectors; performing drill site inspections; and issuing Notices of Violation (NOVs), penalties, and field orders (PAGA 2011). In other states, state regulatory agencies are responsible for a similar suite of environmental protection and management processes (Kell 2011).

In this study, inspection and incident reports generated by PADEP were used to analyze temporal trends in Marcellus shale related environmental incidents in Pennsylvania between 2008 and 2011. Incident reports were examined relative to regulatory phase (permit, SPUD, and completion), to identify feedbacks between incident rates and processes such as changes in regulation, drilling, and inspection practices. This study's methodology was also applied to previous studies of incident reports in Texas and Ohio, because efforts to make incident rates comparable are essential for contrasting findings among studies.

3.1.1 MARCELLUS SHALE DRILL SITE INSPECTION PROCESS AND POTENTIAL OUTCOMES

Following an initiating event, there are three potential outcomes of a well site inspection: NOV *and* penalty; NOV only; or no NOV and no penalty (Figure 11). According to a PADEP Bureau of Oil and Gas Management policy statement effective in 2002 and revised in 2005 (Pennsylvania Department of Environmental Protection 2005), any violation of oil and gas laws should result at a minimum, in a written notification of the violation in the form of either an NOV, or a copy of the inspection report. A penalty may be issued for serious violations. In making the determination of whether a violation is serious enough to warrant a penalty, factors to be weighed by PADEP include the danger to the public health and welfare, and damage to natural resources as a result of the violation. The violating operator's good faith and violation history is also considered (Pennsylvania Department of Environmental Protection 2002). PADEP enumerates factors, and lays out a severity classification system which PADEP must use to assess the penalty amount, based on the extent of a violation's damage, danger, and the operator's bad faith. For example, violations that result in resource damage to the state's waters are qualitatively classified on a 5 point scale from negligible to severe, as follows:

1. **Negligible**: Violations that do not result in detectible damage or inconvenience, but are considered because preventative interest.

2. **Low**: Minimal damage to the resource and minimal inconvenience to water users;
3. **Moderate**: Minor damage to the resource, or impairment of one or more water uses to the extent that it inconveniences a water user;
4. **Significant**: Considerable damage to the resource, or considerable impairment of one or more water uses;
5. **Severe**: Extensive damage to the resource, or extensive impairment of one or more water uses;

Fundamentally, NOVs and penalties differ in one important respect: Unlike penalties, NOVs are issued at the discretion of the site inspector and do not require administrative approval. Collectively, NOVs and penalties issued by PADEP from Marcellus activities are referred to as "enforcement actions" in this study.

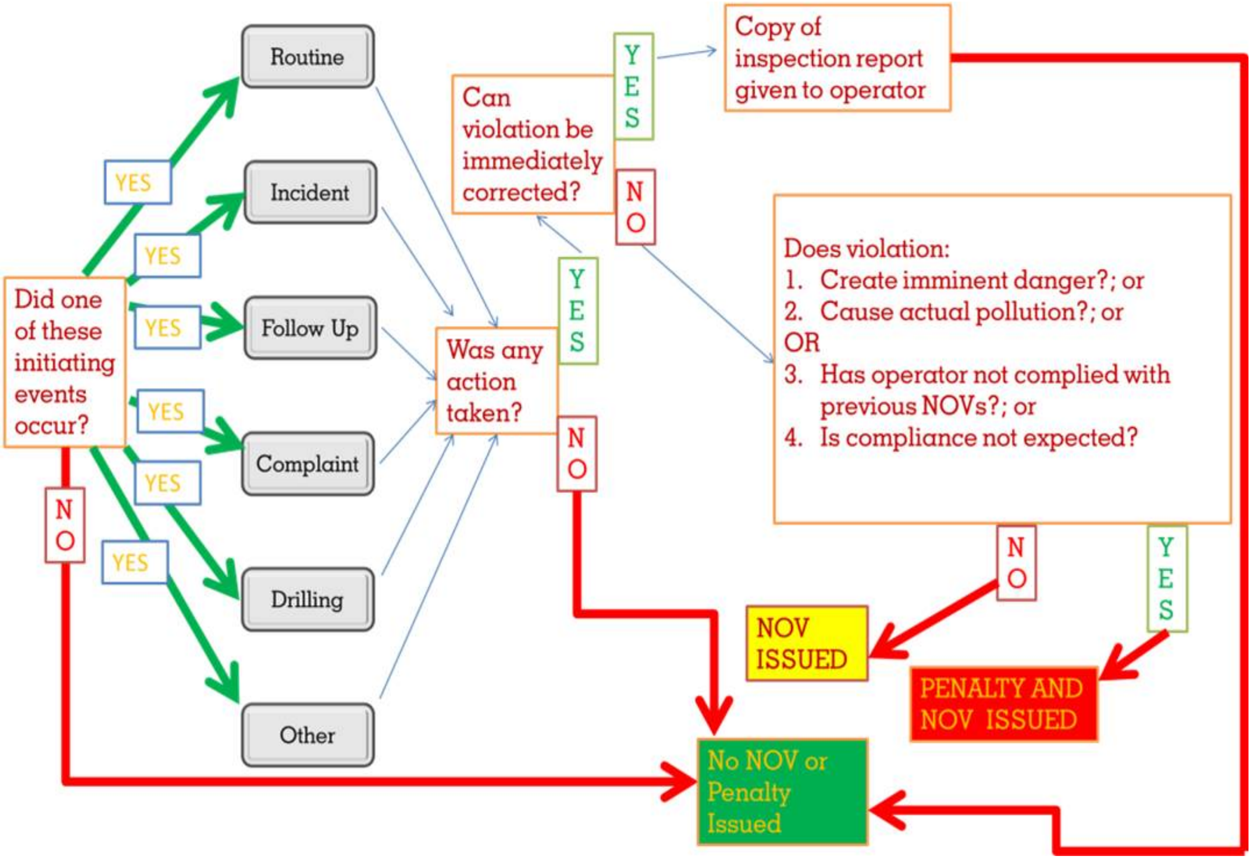


Figure 11 Flow chart of PADEP inspection process and outcomes. Potential outcomes include: Copy of drill report issued to driller as warning; NOV issued; NOV and penalty issued; neither NOV nor penalty issued.

3.1.2 REGULATORY PHASES DEFINED

The three regulated drilling phases examined in this study are permit, SPUD, and completion. “Permits” in this study are drilling permits issued by PADEP to drillers for Marcellus shale wells. “SPUD” is defined as the date a drill bit penetrates the ground (2011 revisions to PA Oil and Gas Act), and in this study are Marcellus well drill bit penetrations reported by PADEP. “Completions,” are Marcellus well completion reports reported by PADEP.

3.2 METHODS

3.2.1 RANKING INCIDENTS BY SEVERITY

In this study, Marcellus Shale related Environmental Health & Safety (EHS) incidents reported by the PADEP between 2008 and 2011 were categorized by severity based on environmental impact. The incident severity classification system is presented in Table 1. As used in this study, an “incident” is a PADEP reported Notice of Violation (NOV) that has been issued a violation code arising out of an inspection of a Marcellus well site. Multiple violation codes arising from a single surface inspection are counted as separate incident reports. Violation codes reference the provision of the regulation, statute, or permit that is violated (Pennsylvania Department of Environmental Protection 2005). Violation codes classified by PADEP as “Administrative” were not included in this analysis. Penalties were not assigned severity rankings. Instead, penalties were treated as a separate dataset for comparative analysis purposes.

Incident reports were assigned a severity ranking based on the amount of polluting material discharged, and the receptor the material was discharged to (Table 1). This information was determined from the violation code of the incident report, and, where available, incident description notes. Incident description notes were available for approximately 50% of the NOV records. Less than 25% of this subset of description notes contained details such as spill quantity or areal extent of the contamination. The violation codes contained in the incident reports generally refer to Environmental Protection portions of the Pennsylvania Code or the Pennsylvania Clean Streams Law. The subsection of the statute or regulation in the incident report often identifies a receptor (e.g. air, pad surface, ground surface, subsurface, potential spill).

Code sections which reference “potential pollution,” or activities that increase risk of pollution but do not result in a spill generally received the lowest severity ranking (i.e. 1) due to the speculative nature of the harm to people or ecosystems. Single spills or discharges to a well pad, stream, or road, where the spill quantity is unknown were automatically assigned a severity ranking of 1. Discharges of materials to the soil surface, or small surface water spills were generally ranked as significant (i.e., 2) because they likely result in transient contamination in the environment that can be contained with minimal expense or effort. Where the code section specified that such spills were not mitigated within 15 days, these events were upgraded to “serious,” (i.e., 3) because the delay in remediation may allow the contamination to spread to a wider geographic area and/or impact a greater number of receptors. Where the code section of an incident report explicitly indicates a subsurface receptor, the violation was issued a ranking of either “serious” or “severe,” (i.e., 3 or 4) depending on contamination amount, due to the risk of contamination to USDWs (underground sources of drinking water), and the considerable effort and expense to contain the contamination. Where incident description notes contained additional information, this data was used to confirm or revise the incident severity ranking that was assigned based on the code section.

Table 1 Severity classification table for EHS NOVs contained in PA DEP incident reports.

Severity	Description	Example
1	Minor	Potential pollution; Improperly installed cement; Inadequate diking; Improper transport of residual waste; pad, ground or surface spill that was immediately contained; spills limited to pad with no leakage; drill cuttings on ground; containment leak; Failure to prevent spill where spill quantity is not known or <20 gallons. Failure to minimize erosion. *Severity Level 1 is the default category for incidents with references to statute or regulations that do not specify a contaminant type or receptor, or where incident notes do not specify a spill amount.*
2	Significant	Discharge of polluting materials between 20 – 100 gallons, multiple spills of any size <100 gallons (or where spill sizes are not noted), or any soil contamination not immediately contained: Examples are stream discharges of industrial waste, brine, silt; Discharge of polluting materials to waters; Spills of mud or drilling fluid on ground surface. Wetland encroachment, due to the protected status of wetlands.
3	Serious	Discharge of polluting materials between 100 and 200 gallons onto ground or streams, or any groundwater contamination, or failure to mitigate spills within 15 days or failure to restore site within 9 months of plugging well;: Examples are diesel fuel, fracking fluid, or sediment discharges into pipeline trenches or groundwater. Dead vegetative zones.
4	Severe	Fluid releases to groundwater or surface water or ground surface over 200 gallons; Well blowouts.

3.2.2 QUANTIFYING TEMPORAL TRENDS OF NOV AND PENALTY RATES

To assess NOV and penalty rates in the context of regulated drilling stage, NOV and penalty reports were normalized by permits, SPUD, and completions. Permit, and SPUD records were sourced from records maintained by PADEP, and accessed from Fractracker.org (RhizaLabs 2013). Well completions were determined from the date and number of Marcellus well production reports maintained by PADEP and reported by the Pennsylvania Department of Conservation and Environmental Resources (Pennsylvania Department of Conservation and Environmental Resources 2013). Unlike permits and completions which can be active across several years, the SPUD date only occurs once, and was counted only in that year. So, when normalizing by permit or completion, the denominator was the accumulation of all records to that point, and when normalizing by SPUD, the denominator represents SPUDs only from that year.

3.2.3 EVALUATING NOVS AND PENALTIES BY INSPECTION EFFORT

To characterize NOV and penalty rates in the context of inspection effort, NOVs and penalties were normalized by the count of PADEP oil and gas inspection reports (Pennsylvania Department of Environmental Protection 2008-2011). To assess inspection effort in the context of drilling stage, inspection reports were compared to the count of permits, SPUD, and completions, respectively. Unlike NOV and penalty reports, inspection reports are not Marcellus-specific; consequently, inspection rates may be inflated.

3.2.4 QUANTIFYING SPATIAL TRENDS IN NOV AND PENALTY ISSUANCE

Because NOVs are issued at the discretion of individual site inspectors and do not require PADEP approval, regional differences in inspection practices may result in inconsistent issuance of NOVs across districts. To test for regional differences in inspection outcomes (and potentially inspection bias), NOV rates per completion were compared between PADEP district offices. Three PADEP district offices reported NOVs during the study period (North Central District Office: NCDO; South West District Office; SWDO, and North West District Office: NWDO) (Figure 20). Average NOV per completion rates were calculated for each district office by dividing the total number of NOVs issued in each district by the total number of Marcellus well completions in that district. In addition, NOV per completion rates within each district office were calculated for individual drillers. Four drillers had operations within each district office. Drillers were anonymized, and only NOVs and completions within each district office were counted in this analysis.

3.2.5 ANALYZING OIL AND GAS VIOLATIONS IN OTHER STATES: REPRODUCING AND EXPANDING ON PAST STUDIES

To compare contemporary Pennsylvania violation trends with historical results in other states, Ohio and Texas oil and gas incidents that resulted in contamination of groundwater (Kell 2011) were normalized by state drilling data. For this analysis, data analyzed and reported by Scott Kell were utilized. Kell (2011) derived Ohio incident determinations from state agency reports and grouped all groundwater contamination incidents occurring between 1983 and 2007 into 5 year bins. Here, Ohio incident data were normalized by SPUD count and by well completion counts reported in Kell's appendix, and then grouped into the same 5 year intervals for analysis. Kell's Texas incident data were also used to examine Texas incident trends between 1997 and 2008. Kell reported groundwater contamination incidents identified by the Texas Railroad Commission (RRC). These data, as well as Texas SPUD and completion data reported by Kell, were used to examine the Texas groundwater incident trends.

3.3 RESULTS

3.3.1 TEMPORAL TRENDS IN MARCELLUS DRILLING, INSPECTION, INCIDENTS, AND PENALTIES IN PENNSYLVANIA

Inspection frequency increased substantially over the study period (Figure 12). However, Marcellus activity also increased during this period: 2010 was the peak year for Marcellus permits and completions (Figure 13a). The number inspections performed at each stage in the process was lower in 2011 than in 2008 when the level of activity is considered (Figure 13b). There is generally an inverse relationship between the number of inspections performed at each regulatory phase (Figure 13b), and the number of enforcement actions per inspection (Figure 12). Between 2009 and 2011, the number of enforcement actions (in particular, penalties) per inspection declined each year, but the number of inspections per permit, SPUD, and completion increased (Figure 13b). During this period, the number of inspectors working for PADEP increased from 97 in 2008, to over 200 by 2010 (Figure 12). So, when more inspectors are performing inspections, fewer enforcement actions are issued relative to Marcellus drilling activity.

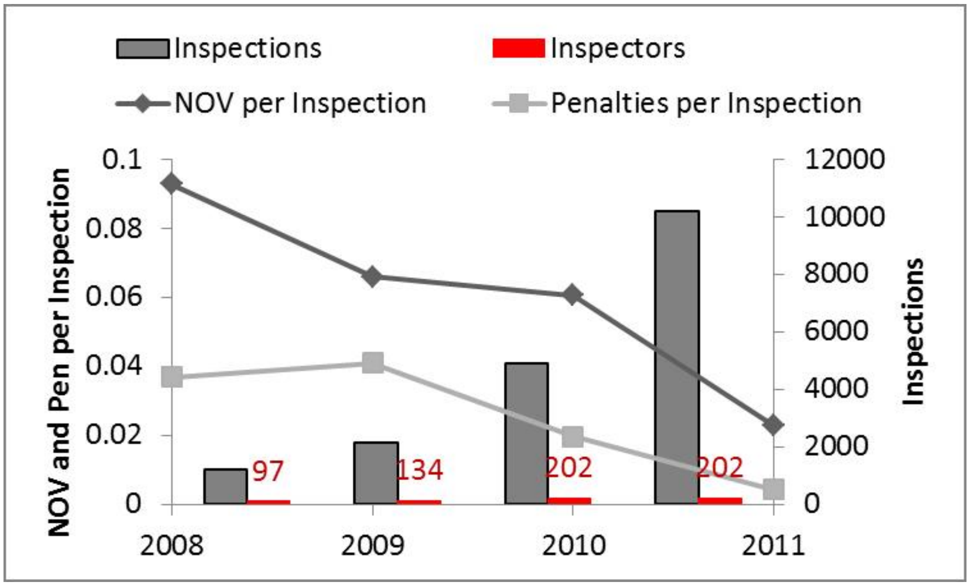


Figure 12 NOVs and penalties per inspection, and the total count of inspections and inspectors per year on secondary axis. Increase in inspectors and inspections correspond with decrease in enforcement actions.

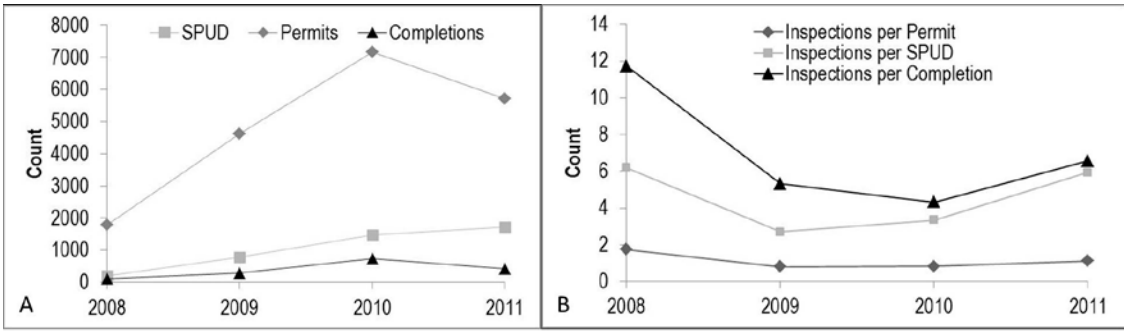


Figure 13 (a) Total number of permits, SPUD, and completions per year and (b) inspections performed per permit, SPUD, and completion per year. In figure (b) permits and completions are accumulated.

3.3.2 BREAKING OUT NOVS BY SEVERITY LEVEL

Rates of both NOVs and penalty actions relative to Marcellus activities were lower statewide in 2011 than in 2008. However, the rate of NOVs of severities 2, 3, and 4 increased over the study at all regulatory stages (Figure 14). Between 2009 and 2011, the difference between the rate of NOVs of severity levels (2) (3) and (4), and the rate of penalties issued per each regulatory phase were not significantly different. $\chi^2(1, N=4)=.99$ $p = .32$ for NOV(2)(3)(4) and penalty rates per permit; $\chi^2(1, N=4)=.98$ $p = .32$ per SPUD; and $\chi^2(1, N=4)=.96$ $p = .33$ per completion.

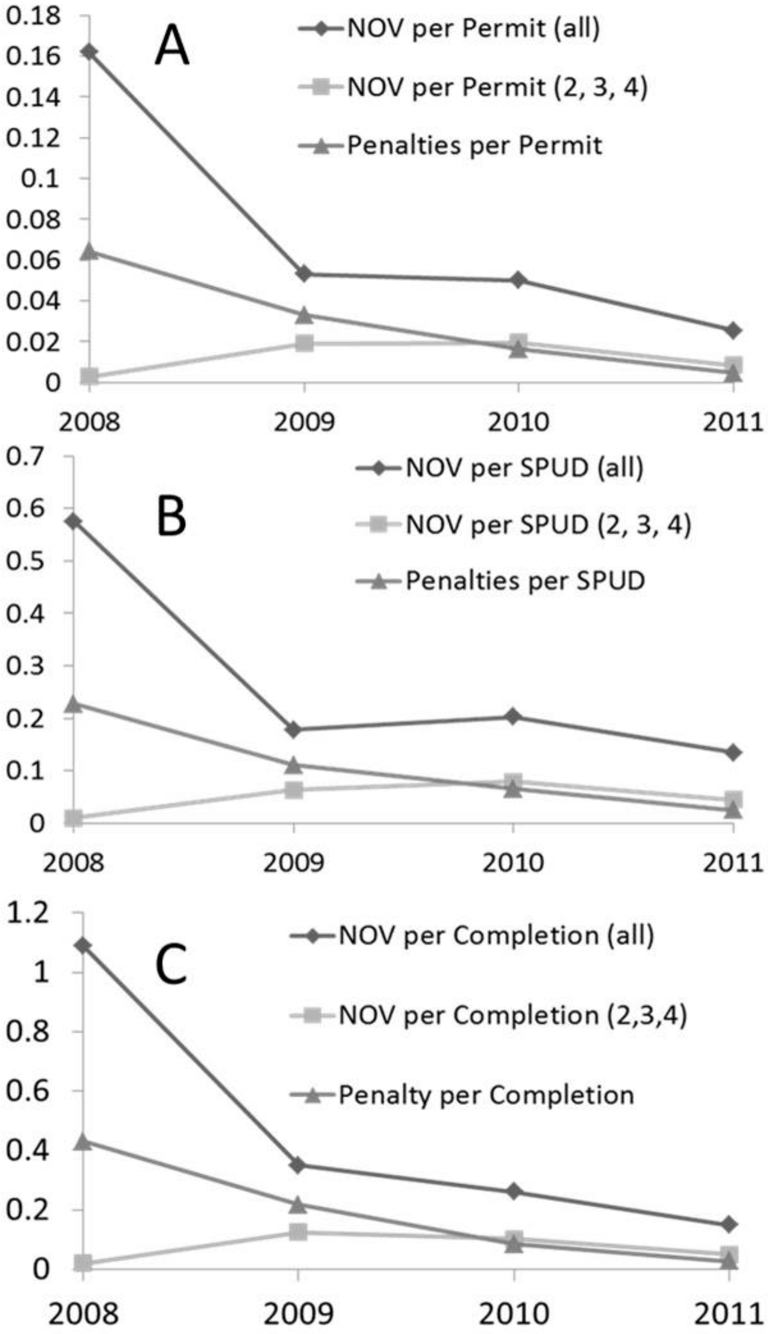


Figure 14(a) NOVs and NOVs of Severity Levels 2, 3, and 4 and penalties per permit (b) SPUD (c) Completion per year. NOVs and penalties decrease over the study period when scaled to drilling activity, except for subset of NOVs(2,3,4) which increase slightly.

3.3.3 REGIONAL DIFFERENCES IN ENFORCEMENT ACTIONS

The relationship between inspection practices and enforcement actions is also reflected in regional differences in rates between PADEP inspection districts. In Pennsylvania, there are clear differences in enforcement action rates between PADEP districts. The Northwest District Office (NWDO) issued, on average, more NOVs per completion than either the NCDO or SWDO (Figure 15a). When broken out by individual driller, the NWDO issued overwhelmingly greater numbers of NOVs and per completion for drillers A, C, and D (Figure 15b), and to a lesser extent, a greater number of penalties per completion for these drillers (Figure 15c). The NCDO issued on average, the fewest NOVs and penalties per completion. And, when broken out by individual driller, the NCDO issued the fewest enforcement actions per completion for drillers A and D (Figure 13b and c).

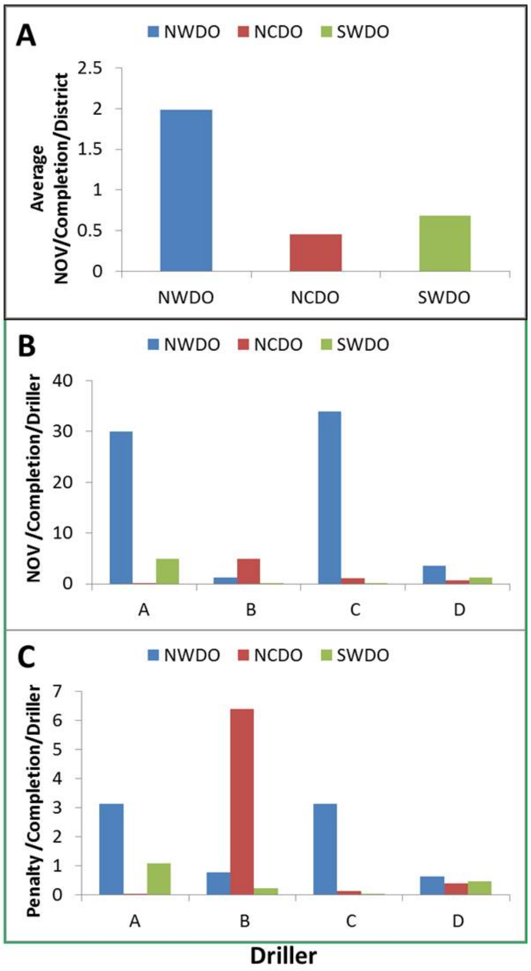


Figure 15 (a) Average number of NOVs per Completion per regional office; (b) NOVs per Completion per drillers (A, B, C, and D) within each regional office; (c) and Penalties per Completion per drillers (A, B, C, and D) within each district office. Substantial differences in number of enforcement actions are evident among districts, suggesting that varying inspection practices substantially influence environmental incident report rates statewide.

3.3.4 REPRODUCTION AND APPLICATION OF METHODOLOGY TO OHIO AND TEXAS GROUNDWATER INCIDENT DATA

Efforts to make incident rates directly comparable are essential for contrasting findings among studies. Here, the present study methodology is applied to studies of groundwater contamination incidents in Ohio and Texas.

A 2011 study showed that the number of Ohio oil and gas incidents that resulted in contamination of groundwater supplies decreased in each 5-year increment between 1983 and 2007 (Figure 16). These data were normalized by SPUD and accumulated completion reports in Ohio during these periods (Figure 16(b) and (c)). When normalized by SPUD, groundwater contamination rates were highest in the five year intervals between 1993-1997 and 1998-2002. When normalized by accumulated completions, the data show a decreasing trend similar to that of the raw incident counts.

Incidents of groundwater contamination reports in Texas also changed, trendwise, when normalized by SPUDs and accumulated completions (Figure 15). Here, the normalization produced more peaks in the reports, particularly when the data were normalized by SPUD.

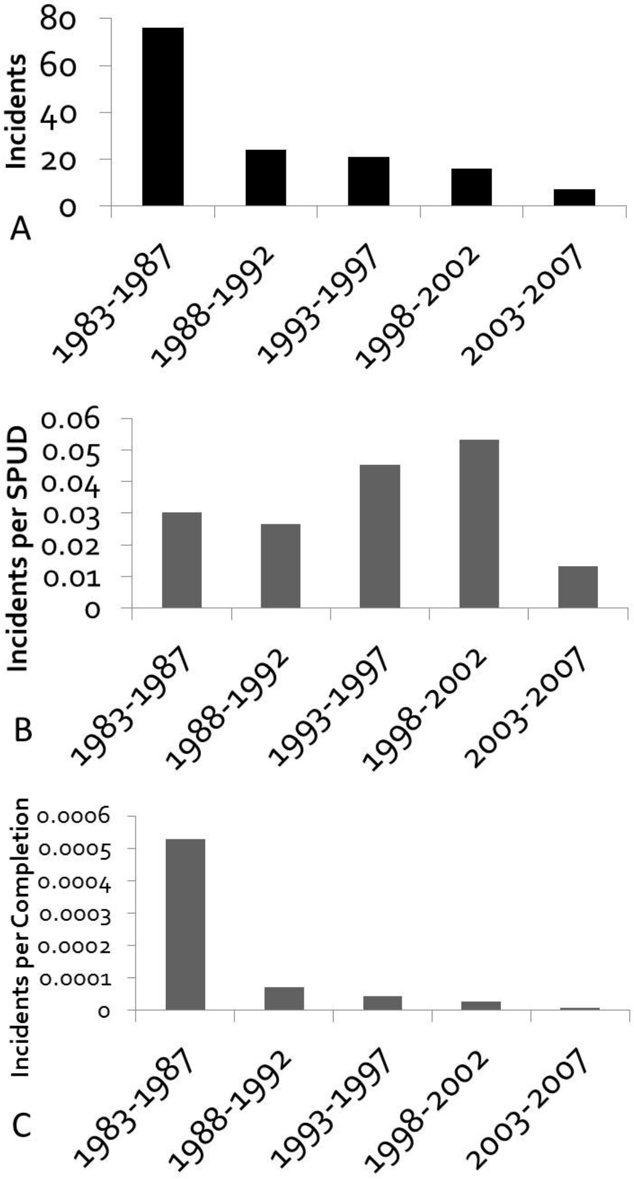


Figure 16 (a) The number of groundwater contamination incidents in Ohio (Kell 2011) (b) normalized by SPUD (c) and accumulated Completions. Contamination incidents increase during study period when scaled to wells SPUDed.

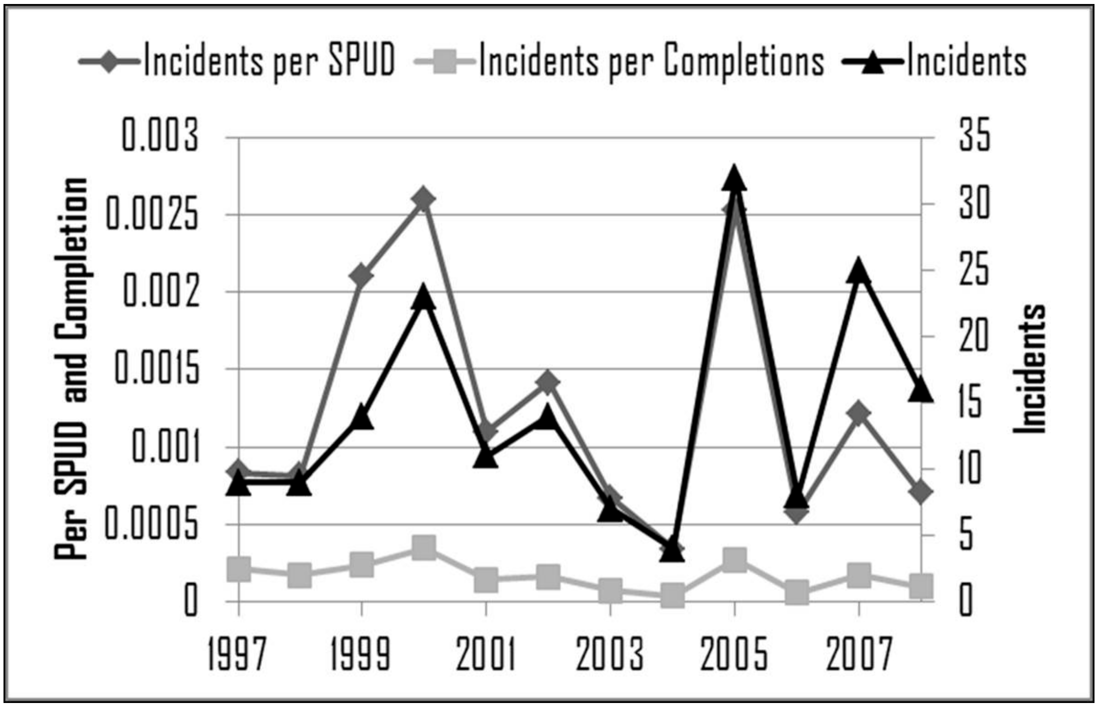


Figure 17 Texas groundwater contamination incidents on the secondary axis (Kell 2011), and incidents normalized by SPUD and accumulated completions on the primary axis.

3.4 DISCUSSION

3.4.1 INCIDENT REPORT RATES ACROSS STUDIES

Several studies have reported declining oil and gas related incident rates over time (Cosidine, Watson et al. 2011; Kell 2011; Groat and Grimshaw 2012) (Table 2). While it is difficult to directly compare this study's results with those of other studies due to contrasting record periods, and scope and quantity of incident records, study methodologies are examined to identify processes responsible for incident trajectories, and discuss how the results of those studies change when the present study's methodology is applied to the data.

3.4.2 TYPE AND QUALITY OF INCIDENT REPORTS IS IMPORTANT

Groat (Groat and Grimshaw 2012) examined incidents in the Pennsylvania portion of the Marcellus Shale between 2008 and 2010, and found that the rates of surface spills declined during the study period. However, the incidents analyzed in Groat's report consisted solely of "spill" incidents self-reported on the shale gas company Talisman's website. Environmental incident citations to Talisman from PA DEP during the study period were not included in the analysis. Further, this study is limited to only Talisman, other producers are not considered. These substantial limitations in study scope limit the application of the reported results to general Marcellus-related activity.

Official data produced by regulatory agencies provide a more comprehensive dataset to draw from. A study by Cosidine (Cosidine, Watson et al. 2011) analyzed Marcellus shale related incidents reported by PADEP in Pennsylvania between 2008 and 2010. This study utilized two-tier severity classification: Violations were aggregated into eight categories, and assigned 4 of the 8 violation categories as serious (major spills; cement and casing; blowouts; stray gas), and 4 as minor (erosion; other spills; water; administrative). Under this classification, spills over 100 gallons of hazardous chemicals, fuel, or produced drilling fluids, were considered to be major spills. Cosidine concluded that a subset of serious incidents (involving cement casing, and blowouts), and other violations (including minor spills and other water violations) increased over the study period when normalizing reports by the number of wells drilled.

This study builds upon Cosidine's work in several important respects: In addition to the NOV dataset, Marcellus penalty reports are also analyzed. Penalty reports, because they require administrative oversight, may be more reliable indicators of incident trends than NOVs. This study also expands levels in the severity classification system for NOVs, and determines incident severity based primarily on environmental receptor and contaminant volume, instead of the activity which led to the violation. In addition, enforcement actions are analyzed relative to all regulated drill phase activities, the importance of which is addressed in the next section.

3.4.3 PUTTING INCIDENT REPORTS IN CONTEXT OF DRILLING IS IMPORTANT

Official regulatory datasets are a necessary, but not sufficient tool for analyzing trends in environmental incidents. Placing incident reports into the proper context is critical for interpreting incident reporting trends.

As shown above (Figure 16 and Figure 17), when Ohio and Texas incident counts were normalized by the number of SPUDs, the temporal trends in reports were changed. Initially, declines in groundwater incidents in Ohio were tied to regulatory enhancements in the state directed at improving oil and gas exploration practices to reduce groundwater contamination (Kell 2011). In particular, the drop in incident reports between 1988-1992 and 1993-1997 intervals was attributed to revised waste disposal rules. The drop in reports between the 1993-1997 and 1998-2002 intervals was attributed to the emergence of an Ohio orphan well program, aimed at plugging abandoned wells in the state (Kell 2011). And, in Texas (Figure 17), the 2005 spike in groundwater incidents was attributed to several factors, including improvements in the complaint tracking process; improved diligence by operators; and an administrative change that resulted in the inclusion of more incidents.

However, when Ohio incidents are normalized by SPUDs, the relationship between regulatory enhancements and groundwater contamination incidents is not apparent (Figure 16). Similarly, changes in the number of groundwater contamination incidents reported in Texas were also not clearly related to changes in Texas regulations, once normalized by SPUD. The SPUD normalized Texas reports show higher incident rates in the late 1990s and early 2000s that do not bear a relationship to regulation changes. And, the noted regulatory changes that occurred in 2005 do not provide an explanation for why incident reports fluctuated after 2005. If a broader definition of “incident” accounted for the 2005 spike, then incident reporting would be expected to stay high after 2005. Instead, incidents, particularly when SPUD normalized, dropped substantially after 2005 (Figure 17).

3.4.4 PENNSYLVANIA MARCELLUS INCIDENT REPORTS PUT INTO CONTEXT

There is a clear declining trend in overall Marcellus shale related EHS report rates between 2008 and 2011. However, when NOVs are broken out by severity level, the subset of NOVs ranked as severity level 2, 3, and 4 did not decline. As shown above, contrasting record periods, data sets, and methodologies make difficult direct comparison of these results with environmental incident trends in other studies (Table 2). State specific processes, such as drilling operations, geology, and environmental regulations, likely interact in a complex manner. In the following sections, it is discussed whether the processes identified in other studies interact with Marcellus environmental report rates. And, Pennsylvania-specific inspection practices, and other processes which may contribute to the decline in Pennsylvania EHS incidents in this study, are discussed.

Table 2 Summary of study design and findings of past research on the evolution and trends in oil and gas incident rates

Author	State	Incident Definition	Period of Study	Study Design	Findings
Cosidine	PA	All NOVs issued by PA.	2008 – 2011	NOVs by severity per 100 wells drilled.	Increase in cement, casing, and blowout incidents. Decrease in minor spills and other water contamination incidents.
Kell	OH	GW contamination from regulated oilfield activities reported by DMRM.	1983 – 2007	GW contamination reports per 5 years.	Decrease in water contamination reports in each 5 year increment between 1983 and 2007.
Kell	TX	GW contamination			

TABLE 2 CONTINUED					
Kell	TX	from legacy and producing wells reported by the Railroad Commission of Texas.	1993 – 2008	GW contamination reports per 5 years.	Incidents of groundwater contamination increased from six in 1997 to 32 in 2005.
Groat	PA	Talisman Corporate Website.	2008 – 2010	Partial count of Talisman surface spills.	Half barrel or larger spills decreased from 415 in 2008 to 109 spills in 2010.

3.4.5 RELATIONSHIP BETWEEN REGULATED DRILLING PHASE AND ENVIRONMENTAL INCIDENTS IN PENNSYLVANIA

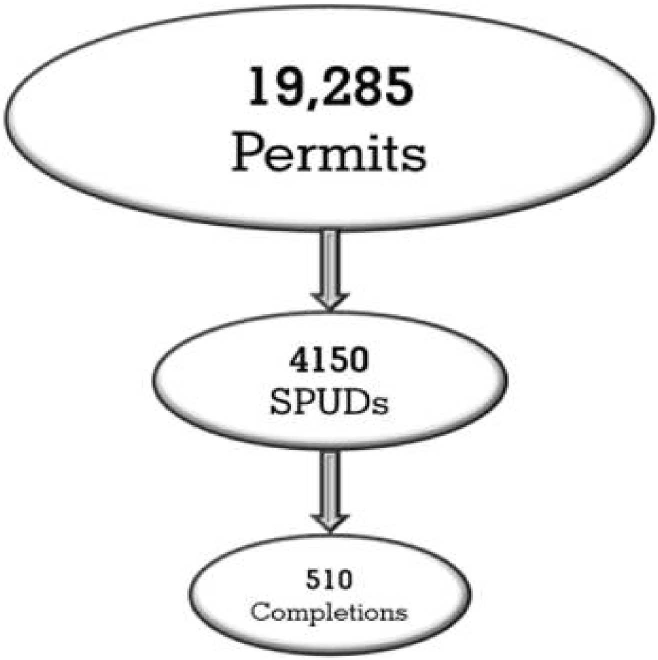


Figure 18 Diagram showing the total number of Marcellus reports in Pennsylvania at each stage in the regulatory process between 2008 and 2011. The vast majority of Marcellus wells permitted did not progress to SPUD or completion phase.

Given the relationship between regulatory phase (Figure 18) and exploration activities with potential environmental impacts, it is critical to consider environmental violations relative to regulated drilling stages in Pennsylvania. In Pennsylvania, prior to drilling a well, an operator must file a permit application with PADEP. With certain exceptions, PADEP must issue a permit within 45 days of the application (25 PA Code Section 78.71, 1984). At this stage in the drilling process, well site exploration activities are likely minimal. Activities likely to occur in the permit stage include site visits, road construction and surveying. Well permit rates bear a strong relationship to inspection effort. The reason for this is twofold. DEP's policy is to inspect well sites at least once upon the issuance of a permit (25 PA Code Section 78.71, 1984). And, permits are often cited in media reports as a direct measurement of Marcellus activity, and, they are considered by the state legislature when allocating funding for DEP to carry out well site inspections (Commonwealth of Pennsylvania 2010). Therefore, the number of permits issued both directly and indirectly impacts inspection effort.

The next stage in the regulatory lifecycle of a well site is the “SPUD” phase. The drill date, or “SPUD” date, is the day that the drilling bit penetrates the land surface (2011 revisions to PA Oil and Gas Act). PADEP considers any well with conductor pipe or casing to be a SPUD well (Pennsylvania Department of Environmental Protection). The potential for exploration activities with adverse environmental impacts increases at SPUD sites relative to permit only sites. For example, erosion and sedimentation would be expected from road and well pad construction (Adams 2011). During the SPUD phase, well site activity is ensured. Subsurface fluid spills and blowouts would be unlikely at a SPUD site, because hydrologic fracturing follows boring of the well. However, drill mud and fuel spills can occur during the SPUD phase.

The next phase of the well construction process is completion. Most SPUD wells have not been completed. A well is considered to be completed, when it is stimulated (Pennsylvania Department of Environmental Protection). Well stimulation is the process by which fluids, chemicals, and proppants are injected into a well at high pressures (480 to 850 bar) to increase production (Vidic and Brantley 2013). A single well can be completed multiple times. It is during the completion phase that exploration activities with the most serious potential for adverse environmental outcomes are expected. When hydraulic fracturing is done, reservoir pressure increases. The resulting pressure differential between different geologic formations can potentially result in subsurface fluid leakage and well blowouts. Significant groundwater, surface water, and contamination of vegetation can are potential adverse environmental results.

3.4.6 THE INFLUENCE OF REGULATION ON INCIDENT REPORT RATES IN PENNSYLVANIA

Regulatory enhancements are one mechanism that has been identified by past studies, which influence environmental incident rates from oil and gas activities. Here, notable regulatory changes in Pennsylvania during the study period are identified, and it is assessed whether the data reflect changes in incident rates concomitant to these changes.

Several important changes in Pennsylvania law occurred during the study period. In 2009, two new PADEP regional offices opened in the North Central and Northeast region of the state. In 2010, a new regulation passed that required drillers to treat wastewater with TDS >500 mg/L. Also in 2010, a 150 foot stream buffer was mandated for new drill sites. And, in 2011, regulations went into effect that required enhanced casing and cementing for Marcellus wells. (Pennsylvania Department of Environmental Protection 2011).

Since many of these regulatory changes are activity specific, overall incident rates will not be affected. However, changes in regulation can alter incident rates arising out of specific activities. Penalties for accidental discharges to stream waters declined in 2010 and 2011 following the 150 foot stream buffer for new drill sites (Figure 19a). And well blowout and venting penalties declined in 2011 following the imposition of stricter casing and cementing requirements for new Marcellus wells (Figure 19b). These results reflect that incident reporting dynamics are influenced by driller compliance with regulations aimed at protecting environmental resources. While the decline in overall environmental penalties in Pennsylvania cannot be fully explained by regulatory changes in the state, the decline in penalties for these subsets of incidents provides evidence that targeted regulation of drilling practices can improve environmental outcomes.

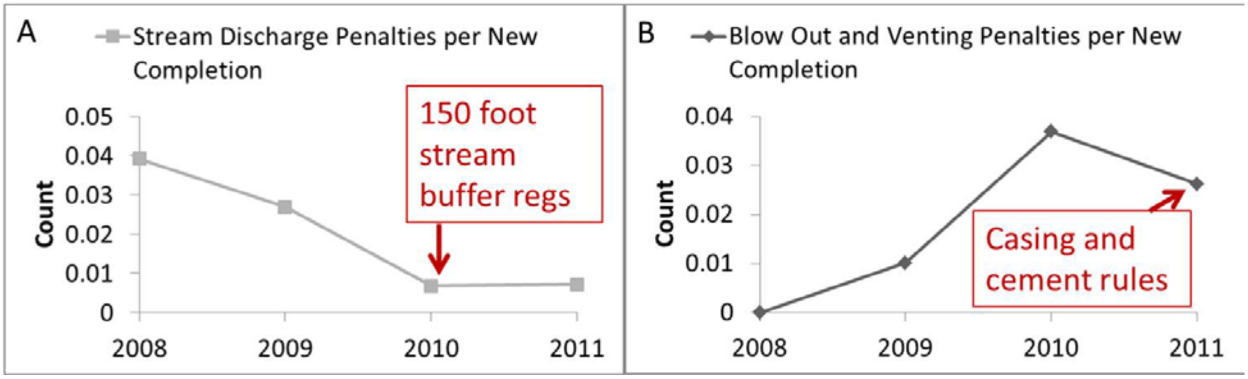


Figure 19 (a) Stream discharge penalties per new Marcellus well completions (b) and Blowout and venting penalties per new Marcellus well completions. Regulatory changes may influence environmental incidents arising from these specific activities.

3.4.7 THE RELATIONSHIP BETWEEN INSPECTION PRACTICES AND INCIDENT RATES

The Pennsylvania incident rate data show both temporal and spatial relationships between inspection practices and enforcement action outcomes (Figure 12, Figure 13, and Figure 14). Temporally, as the number of inspectors (and inspections) increased across the study, the number of enforcement actions declined (Figure 12). Driller compliance due to increased inspection frequency may account for some of the decline in NOVs as inspections increase. Indeed, decreases in NOVs of severity level 1 account for the majority of the decline in NOVs (Figure 14). The bulk of NOV(1) violations in the dataset are "potential pollution" and small spills (Table 1). Scenarios under which these minor violations are issued would be easily avoided by drillers anticipating regular inspections. However, driller compliance is not likely to be the cause of regional heterogeneities in NOV issuance, because NOV rates were consistently higher in certain PADEP districts for most drillers (Figure 15). Inconsistencies in inspector training, and contrasting inspector practices, are proposed as additional mechanisms influencing enforcement outcomes. The following paragraphs provide an overview of PADEP inspector training, and the relationship between inspector practices and regional incident rates.

During the study period, PADEP did not provide a formalized, consistent training program for oil and gas inspectors. Inspector training in Pennsylvania is done “on the job,” and inspectors are trained by their supervisors (Perry 2013). An internal review of inspection practices performed by PADEP in 2011 concluded that three regional differences were noted in the inspections process: 1) The manner in which violations are memorialized and issued to operators; 2) The manner in which violations are cited in eFacts, PADEPs tracking software (http://www.dep.state.pa.us/dep/efacts/); and 3) The inspection form utilized by inspection staff. (Aunkst, Hines et al. 2011). PADEP reached these conclusions following an inspection field exercise with supervisors from all 3 PADEP districts.

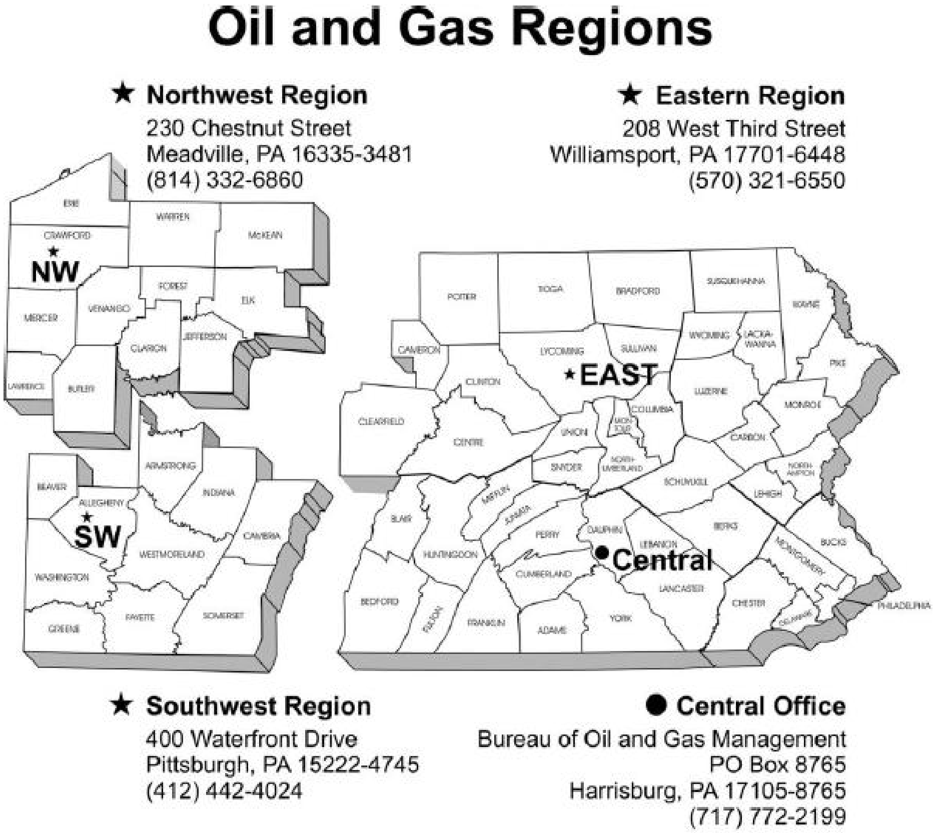


Figure 20 PA DEP Oil and Gas Regions from (Aunkst, Hines et al. 2011).

Based on PADEP's internal review, there are known regional heterogeneities in inspection practices. And, based on our data, there are clear regional heterogeneities in enforcement action rates (Figure 15). Since incident report rates are influenced by multiple processes, average NOV per completion rates within each district office (Figure 15a) may not necessarily reflect contrasting district inspection practices. However it is possible to detect regional inspection bias by comparing enforcement action rates among drillers between PADEP districts (Figure 15b and c). It is likely that drillers with statewide drilling operations are consistent in their ESH operations across the state. Therefore, if most drillers operating statewide have contrasting NOV outcomes between districts, this likely reflects regional practices of inspectors, in terms of a likelihood of issuing an NOV. These results support PADEP's own internal review showing regional differences in the inspection process. Here, it appears that there is a clear tendency of NWDO inspectors to issue NOVs, as compared to the inspectors other PADEP districts. In comparison, there is greater parity between the NCDO and SWDO in terms of NOV outcomes among drillers, when scaled to completions.

In contrast to expectations, penalty reports also appear to reflect regional inspection biases. It is notable that penalty rates are also district dependent (Figure 15c), although to a lesser extent than NOV rates. Since penalties require PADEP approval, regional differences in penalty rates would not necessarily be expected to result from inspector scale practices. However, during the study period, PADEP approval of penalties was done on a district-by-district basis, with each district head approving penalties within that district (Aunkst, Hines et al. 2011). This, coupled with the noted regional differences in inspection forms and the manner in which violations were cited in eFacts, likely contributed to the regional heterogeneities in penalty issuance among districts.

3.5 CONCLUSIONS AND RECOMMENDATIONS

Understanding environmental health and safety incidents related to Marcellus exploration is of critical importance to ensuring that environmental and public health concerns related to exploration are appropriately addressed by industry and by regulators. It is fundamentally important that data used to assess trends in incident reporting are of high quality, and are interpreted in the proper context.

Here, it is shown that overall EHS enforcement actions have declined in Pennsylvania between 2008 and 2011, except for a cumulative subset of NOV reports ranked as “significant,” “serious,” and “severe”. It has been shown that the relationship between incident reporting, drilling activity, inspection activity, and regulatory changes interact in a dynamic manner. And, several important limitations in the inspection process have been identified, which make incident rates an imperfect proxy for assessing environmental outcomes.

Despite the noted limitations in PADEP’s environmental inspection and reporting process, the NOV and penalty datasets provide important insight into temporal and spatial trends in environmental incident rates related to hydraulic fracturing of the Marcellus in Pennsylvania. A possible – though likely erroneous – interpretation of the decrease in enforcement actions following the increase in the number of inspectors (and inspections) is that the increase in Pennsylvania’s budget for PADEP was unnecessary and wasteful. The basis for this interpretation would cite the relative increase in more serious NOVs over the study period, and the decrease in overall inspector activity relative to the number of wells SPUDed and completed. However, the better interpretation of these data is that the budgetary increase was insufficient to keep pace with the explosion in Marcellus drill site activities: As shown, the number of Marcellus wells SPUDed increased at a rate and count greater than the number of inspectors over the study period. Given the known limitations in PADEP's inspector training, it is likely that the inspection and citation practices of individuals inspectors vary greatly, and that inspector discretion in citing smaller environmental violations would confound temporal and spatial reporting trends. This interpretation is also supported by the sharp decrease in overall NOVs over the study period. Most of the decrease in NOVs is due to a drop in those ranked as the least severe. Driller compliance with PADEP regulations likely contributed to this drop (particularly if drillers were aware that the number of inspections performed was rising). In addition, some of this drop could be due to the NOV ranking system used in this study: By default, NOV reports without inspection notes were ranked as minor. Better record keeping by individual inspectors may have led to a vestigial increase in the number of NOVs ranked as more serious in the second half of the study.

Because enforcement action rates display fundamental regional heterogeneities stemming from inconsistent inspection training, practices, and reporting among PADEP districts, the following is recommended:

1. Consistent statewide training of oil and gas inspectors
2. Use of the same inspection form between districts
3. All inspections and violations should be promptly entered into eFacts, with complete inspection notes, and photographs, within 24 hours of an inspection

4. PADEP should publish these data in an accessible fashion electronically on a monthly basis

Despite the noted limitations in the inspection and enforcement action process, it has been shown that targeted regulations can influence driller practices, which in turn can influence environmental incident rates, and environmental safety. It is recommended that the regulators continue to monitor environmental incidents, in particular, once improved inspector training and incident tracking processes are in place. Based on this data, regulators should continue to target specific activities and processes to improve driller practices and better manage environmental outcomes. Identifying and targeting areas of concern is a fundamental requirement for managing risk as Marcellus exploration continues in Pennsylvania.

4.0 CONCLUSIONS

The development of horizontal fracturing technology has led to rapid growth in drilling in the Marcellus shale. The Marcellus shale contains abundant natural gas resources as a result of its unique depositional environment, and its rich geologic history. Understanding environmental incidents arising from development of the Marcellus is of considerable importance to the public, to industry, and to regulators, in order to ensure that environmental and public safety concerns are appropriately addressed.

From a geologic standpoint, the Marcellus shale is a fascinating formation. Geologists are continuing to build an understanding of its unique structure, stratigraphy, and depositional history based on emerging techniques and technology. Understanding the geology of the Marcellus shale will enhance scientific understanding of other oil and gas bearing shales, and this information can be used to target exploration, with the potential for profound economic and political gain. However, exploration of any energy source is not without risk. A collinear exploration of drilling practices, regulation, and environmental impacts is fundamental for ensuring that the welfare of the public and the environment is appropriately addressed.

Environmental incident report rates, analyzed in the context of drilling, inspection, and regulatory practices, indicate that between 2008 and 2011, environmental enforcement actions declined in Pennsylvania. However, substantial limitations in the quality of data, and in regionally heterogeneous inspection training and practices indicate that a necessary effort must be taken in Pennsylvania to improve the inspection and incident reporting process.

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