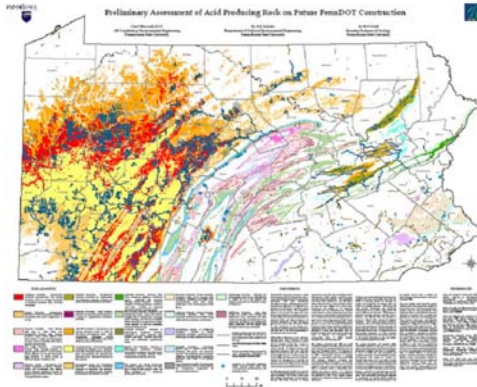

**COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION**

PENNDOT RESEARCH



**PRELIMINARY ASSESSMENT OF ACID PRODUCING
ROCK ON FUTURE PENNDOT CONSTRUCTION**

Final Report

**PennDOT/MAUTC Partnership, Work Order No. 5
Research Agreement No. 510401**

June 8, 2007

By B. E. Scheetz and C. J. Ellsworth

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16. Abstract The objective of this study was to evaluate the geologic formations within the Commonwealth of Pennsylvania as they relate to the potential to form acid rock drainage (ARD). The primary aim of this effort was to assist PennDOT in the avoidance of the potential environmental impacts associated with these pyrite-bearing formations during road construction, as well as the negative impacts upon engineered structures that are often associated with ARD. An ancillary objective was to develop predictive models, where feasible, to forecast the locations and relative severity of ARD and its associated environmentally deleterious effects. Three broad types of potentially acid-producing forming sulfide-bearing groups were identified. The first group, the black shales predominantly of the Valley and Ridge province, may cause ARD and have been observed to swell, leading to heave of engineered structures in some cases. Based on 94 surface samples of the black shales, a preliminary north/south geographic trend in their net neutralization potential has been identified extending between Centre County and Fulton County. A second group, consisting of the mostly flat lying coal bearing successions of Pennsylvanian age, has long been known to contribute to ARD problems. A general trend in decreasing percent sulfur of the coal measures from the southeast to northwest has been perceived based on large amounts of overburden chemical analyses and been attributed to the initial depositional environment of the coals and overburden formations. The third group, a number of isolated sulfide deposits, particularly those associated with dominantly sandstone lithologies, appear to be in part structurally controlled. A preliminary predictive model has been developed and some important geographic trends have been delineated, however the isolated deposits and some of the black shales deserve more attention in order to identify any spatial and temporal relationships allowing for predictive interpretation. Finally, a flowchart has been developed to assist in delineating the potential for significant environmental and engineering impacts based upon the chemical and mineralogical characteristics of the deposit.					
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EXECUTIVE SUMMARY

This report represents the results of an extensive study into the potential for acid rock to impact future Pennsylvania Department of Transportation (PennDOT) construction projects. The principal objective of this study was to evaluate all of the diverse geologic formations within the Commonwealth of Pennsylvania as they relate to the potential to form acid rock drainage (ARD). The primary aim of this effort was to assist PennDOT in the avoidance of the potential environmental impacts associated with these pyrite-bearing formations during road construction, as well as the negative impacts upon engineered structures that are often associated with ARD. An ancillary objective was to develop predictive models, where feasible, to predict the locations and severity of these environmentally deleterious conditions associated with ARD production.

Three broad types of potentially acid-producing, sulfide-bearing groups have been identified during this study and by others on the basis of a variety of interpretive methods including field inspection and geologic mapping, and a range of chemical and physical methods. The first group, the black shales predominantly of the folded Valley and Ridge physiographic province, are known to cause ARD and have been observed to swell, leading to heave of engineered structures in some cases. Based on 94 surface samples of the black shales, two apparent north/south geographic trends in their net neutralization potential (NNP) have been identified, the first of which appears to trend roughly from Centre County south into Fulton County. This trend can be especially well seen on the basis of the black shales of the Marcellus, Mandata, Hamilton, and Antes/Reedsville/Upper Coburn succession. The second, less consistent trend appears to extend approximately from Lycoming County to

Snyder County. The reliability of these perceived trends as predictive models, particularly the latter, could benefit from additional sampling in these areas.

A second group, the mostly flat-lying, coal-bearing successions, have long been known to produce ARD, and have been widely studied and characterized for decades, largely with respect to the economically important mining industry. A general trend in decreasing percent sulfur of the coal measures from the southeast to northwest has been perceived based on large amounts of overburden chemical analyses, and can be well seen in the collective data from the Monongahela Group and Waynesburg Formation, undivided, the Conemaugh Group, and the Allegheny Formation. Although the Pottsville and Llewellyn Formations are known acid producers, there was insufficient data available to identify any spatial or geographic trends in their acid-producing potential.

The third group, a number of isolated sulfide deposits, particularly those associated with dominantly sandstone lithologies, appear to be in part structurally controlled. A basic predictive model has been developed that correlates the presence of the Tuscarora and Bald Eagle sandstones and wind or water gaps with potential sulfide deposits. Some important geographic trends have been delineated which suggest that preexistent fractures may control the deposition of these isolated sulfide deposits.

The overall spatial and temporal acid-producing trends discovered during this study and the associated predictive models that have been developed are thoroughly discussed and presented on maps whenever possible towards their comprehensive illustration. On the basis of this study, and many other available documents and maps, it is possible to effectively predict the potential for ARD and associated hazards in the pre-design phase so as to allow for near complete avoidance of all related problems.

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1.0 INTRODUCTION

The problem of acid drainage is prevalent throughout much of the modern and developing world, but it is perhaps nowhere better illustrated than in the State of Pennsylvania. Not only does Pennsylvania contain a wealth of natural resources, but it has played a significant role in the growth and progress of the United States since the very onset of the Industrial Revolution. The unintended consequences of the modernization of this country have in part been responsible for a considerable adverse affect to the natural environment in such forms as acid rock drainage.

Acid rock drainage (ARD) in Pennsylvania has been occurring since the onset of mining activities in the state going back at least as far as the early 1800s. Naturally occurring low-level acid drainage has also been observed in isolated areas throughout North America for centuries (Brady et al. [eds.], 1998) and has likely been a common occurrence throughout much of geologic history. In fact, a natural level of geodiversity in the form of anomalous and varied environments has been known to lead to the development of biodiversity on an inhomogeneous and changing planet (McConchie, 2003). However, it has not been until more recently that acid drainage has become a widespread problem. Acid drainage affects vast areas of the state, polluting hundreds of waterways along with large quantities of groundwater. In Pennsylvania alone, more than 3,500 miles of streams have been adversely impacted. The increased demand for a variety of natural resources, along with the modernization, mechanization, and industrialization of construction and mining techniques and methods has accelerated the pace of ARD generation and intensified its effects.

The production of acid drainage has not been limited to mining activities, having been produced as an unintended consequence of such large-scale construction projects as roads, large

buildings, and even residential developments. Modern methods of construction in the United States often have done little to integrate structures into the land itself, but rather have taken the approach of altering the land to suit the needs of the project while perhaps paying far too little attention to the limitations presented by the complex geology. As society pushes ever further into once rural areas, land that once would have been left to agricultural or natural purposes is being consumed for various construction projects. The expansion of urban centers coupled with the desire to alter the land regardless of its inherent shortcomings has led to increasingly difficult engineering challenges that can no longer be ignored or diminished.

The problem of ARD in Pennsylvania has recently been brought into the forefront of both governmental and public thought and has proven to be an issue with far-reaching and severe effects to the health of the environment, which must be balanced with the needs of public infrastructure. In 2003 roughly 1 million tons of pyritic rock was unearthed during the construction of a stretch of Interstate 99 at Skytop in Centre County, Pennsylvania (Hammarstrom et al., 2004). Shortly after the pyrite-laced rock was exposed to the atmosphere it began to produce large amounts of metal-leaching sulfuric acid, threatening the quality of nearby watersheds and the drinking water of hundreds of people. The political, geological, and societal issues surrounding Skytop are complex and far-reaching and have proven to be extremely costly financially, environmentally, and socially. The events at Skytop have received considerable attention by both professionals and average citizens alike and are considered in greater detail later in this report.

This study was intended to present a broad and preliminary reference to the problems presented by the presence of sulfide deposits and acid drainage in Pennsylvania, particularly as they relate to road construction. Regardless of whether the production of ARD is from mining or

from the construction of roads and other societal infrastructure, the intention is to present a useful reference for the prediction of the potential for ARD at various locations throughout the state.

Certain areas and particular geologic formations have been examined in depth in order to identify and characterize these and similar sites, and to give some insight into the methods by which one can begin to investigate the potential for ARD. Although this report addresses a wide range of areas and known locations prone to ARD, it should be understood that it is not entirely comprehensive. There are undoubtedly particular acid-producing areas and geologic formations that have not been recognized or are not properly understood at this point in time. There is no substitute for the investigation of any particular site where there is going to be disruption of the subsurface for any mining or construction activity (see Appendix F). Despite hundreds of years of work by geologists, engineers, and other scientists there still remains much to be understood about the geology of Pennsylvania. The numerous challenges that will undoubtedly be presented as we move forward should be viewed as opportunities for further understanding and not barriers or impediments to progress.

1.1 Research Objectives

The objective of this research program was to evaluate all of the geologic formations within Pennsylvania as they relate to the potential to form acid rock drainage. The primary goal of this effort was to assist PennDOT in the avoidance of the potential environmental impacts associated with these pyrite-bearing formations during road construction, as well as the negative impacts upon engineered structures that are often associated with ARD. An ancillary objective

was to develop predictive models, where feasible, to forecast the locations and relative severity of ARD and its associated environmentally deleterious effects.

2.0 LITERATURE REVIEW

The following material reviews relevant publications regarding the consequences of excavating sulfidic materials during construction, the geological processes surrounding the nature and origin of sulfide mineralization, and the complex geochemistry of ARD. This material provides the necessary background information central to an understanding of the complex processes leading to the formation and development of sulfide minerals and the occurrence of ARD.

2.1 Effects of Sulfide-Bearing Materials on Roadway Construction

Although not as well represented in the literature as acid mine drainage issues, the question of what to do with excavated acid-producing materials as it relates to construction has recently received attention in many areas of the world. Some of the primary reasons are that construction methods have become more capable of moving large amounts of earth in short times, and environmental concerns have moved to the forefront of the public consciousness in recent decades. It has become apparent, largely due to a number of environmentally disastrous mistakes and considerable damages incurred to engineered structures, that specific guidelines and approaches to handling acid-producing material during construction are necessary.

Byerly (1990, 1996) writes extensively on the guidelines for handling acid-producing materials during construction. Topics covered include preliminary and design phase actions such as geologic mapping, consideration of climate and local hydrologic conditions, sampling procedures, geophysical methods, and exploratory drilling as well as experimental methods including a variety of laboratory and field chemical type methods such as leaching columns, acid-base accounting, and field tanks. The approaches recommended by Byerly (1990, 1996)

focus mostly upon ideas that have comparatively universal applicability such as encapsulation methods and the addition of interlayers of lime within fill piles. Byerly (1990) also comments on a variety of observed chemical phenomena and concludes that ARD is dependent upon a variety of factors that are highly variable, and remarks on the effectiveness and generally good correlation of laboratory and field methods in predicting phenomena as observed and measured in the field. He also discusses and makes recommendations on excavation procedures, various site considerations, handling of sulfidic material during construction, proper disposal techniques for sulfidic material, and the use of appropriate materials both in terms of quality and quantity.

Orndorff (2001) evaluates the potential for the presence of sulfides and acid drainage in Virginia highway corridors. As has been the case in Pennsylvania, a number of road construction projects and related activities in Virginia have caused localized ARD problems due to intersection with black shales and slates, coal-bearing lithologies, acid sulfate soils, and other sulfide-bearing formations (Orndorff, 2001). Swelling and heave of roads and related structures due to the presence of expansive black shales has also been observed in Virginia (Freeman, 2003). Orndorff (2001) generated a statewide sulfide hazard rating map based upon extensive sampling of rock formations and water from numerous locations throughout Virginia, leading to relative interpretations of risk for specific geologic formations such as the Marcellus and Tabb Formations and physiographic provinces such as the Piedmont and Valley and Ridge provinces. Orndorff (2001) also compares a range of ARD prediction methods on a variety of sulfidic materials, and endeavors to develop a method for predicting the depth to sulfidic sediments in the Coastal Plain of Virginia.

Bryant (2003) writes extensively on the numerous geotechnical problems presented by pyritic materials, provides numerous case histories, and presents several guidelines for

anticipating and avoiding problems. Recommended procedures for anticipating problems include an in-depth review of all available geologic information, site reconnaissance and sampling, geophysical surveys, and a wide range of acceptable chemical tests (Bryant, 2003). Bryant (2003) stresses the importance of interdisciplinary and interregional approaches toward effectively understanding and managing sulfide-related problems, as the issues are complex and encompass a diversity of highly specialized disciplines. These diverse groups are often occupied by those who unfortunately have not had the opportunity to communicate effectively, in many cases resulting in environmentally and socially disastrous consequences.

Barrett et al. (2005) discuss a large-scale endeavor to assess the potential for ARD and metal leaching in several proposed road cuts along the Sea to Sky Highway Improvement Project that extends from Vancouver to Whistler, British Columbia in order to prevent negative environmental impacts. Approximately 70 new rock cuts were proposed and a systematic approach was taken to evaluate the potential for ARD along their extent (Barrett et al., 2005). The assessment used existing geologic maps as a basis for more detailed field mapping, leading to the identification of specific rock units, geologic contacts, and specific details about the rocks in question such as type, mineralogy, structure, and possible alteration (Barrett et al., 2005). Next, an extensive geochemical characterization was undertaken including rock sampling, leach testing, stream sampling, acid-base accounting, and whole rock mineralogical and chemistry analysis (Barrett et al., 2005).

Based upon the variety of field investigations, field and laboratory test methods, and local hydrological considerations, materials that were identified as acid producing were designated to be disposed of in either a mine site whose water discharges were already being treated, or into the ocean where oxidation would presumably be limited (Barrett et al., 2005). Barrett et al.

(2005) recommend, on the basis of this study, that similar assessments should begin early in the design phase of the project, but should be flexible and adaptable to allow for revisions to the plan as construction proceeds, as unexpected difficulties and conditions are likely. Barrett et al. (2005) also recommend a systematic and frequent sampling and monitoring program both during and after construction to ensure that environmental regulations are met, given the complex laterally and vertically variable conditions likely to be encountered on site.

Gold and Doden (2007) have put forth a revised site characterization and assessment scheme for sulfur-bearing rocks and soils that takes into account revisions in the understanding of the nature, composition, origin, evolution, and diversity of sulfide deposits as well as modern investigative methods. Although this assessment was developed in response to I-99 in Pennsylvania, it has broader national implications. Gold and Doden (2007) also summarize the variety of potential hazards and make recommendations regarding appropriate actions for dealing with various types of sulfide deposits during highway construction and related activities. These recommendations include how to best approach preliminary site investigations, excavation, siting and grading/slope concerns, and effective geophysical, chemical, and drilling methods. These recommended procedures, when appropriately followed, lead to a high level of characterization of the site conditions and successful avoidance of potential problems.

2.2 Geology of Sulfide Mineralization

In order to appreciate the geologic conditions that ultimately lead to the formation of ARD, it is important to have an understanding of the conditions leading to and processes surrounding sulfide mineralization. In Pennsylvania there are three main broadly organized groups of sulfides that are distinguished on the basis of their origin and diagenesis, and to a

certain extent, their evolution since their original deposition. The three major groups of sulfides are sedimentary, hydrothermal, and supergene.

The first group includes sulfides of sedimentary origin that are of prime consideration in Pennsylvanian age (290-323 million years before present) coal-bearing strata, which cover roughly one third of the state, as well as in many of the black shales identified and characterized in this report. Sulfides of sedimentary origin have also been termed syngenetic sulfides, meaning that they were deposited and formed in bedded sediments (Gold and Doden, 2007). Syngenetic sulfides are especially common in rocks that have been deposited in anoxic (oxygen-depleted) sedimentary conditions, particularly where there has been a steady supply of both iron from terrestrial sources and sulfur from sea water. Sedimentary pyrite found in differing concentrations in many of the various coal-bearing Pennsylvanian age rocks in Pennsylvania has historically been recognized as a prime contributor to the issue of ARD in the state, both in the western bituminous fields and in the eastern anthracite fields. For this reason, later sections of this report are devoted to the quantification of the potential acidity of various coal-bearing formations, and consider in greater detail specific areas and certain coal seams.

The conditions that persisted in the Pennsylvanian age for millions of years led to the formation of vast quantities of coal and associated pyrite. The most basic ingredients needed for sedimentary pyrite formation in a coal swamp are a reducing environment in which there is a significant supply of sulfate and ferrous iron, along with bacterial populations that assist in the chemical processes leading to the reduction of sulfate. Certain environments of deposition such as estuarine environments in which brackish waters exist can lead to sulfur contents of greater than 10% (Navarro, J.R., Davis, A, 1976). The combination of high sulfide contents found in

marine waters along with the addition of iron from chemical weathering of terrestrial rocks under reducing conditions present the ideal conditions for the formation of sedimentary pyrite.

Pyrite found associated with coal deposits presents a significant difficulty that can be found in many areas of Pennsylvania, most notably in the western plateau regions. Much attention has been paid to this problem in the past several decades and many studies have been carried out in an attempt to characterize the nature of the generation of acid coal mine drainage. Several studies have been devoted to this subject, and so one should refer to more exhaustive studies referenced in this report, such as those carried out by Williams and others (1982, 1985), and Navarro and Davis (1976).

Black shales often contain significant amounts of bedded framboidal pyrite, which was formed in anoxic conditions with a supply of iron and other metals along with reducing organic matter, which often effectively depletes any available oxygen (Gold and Doden, 2007). Sedimentary or syngenetic sulfide minerals found in various black shales have long been known to cause ARD and swelling and heaving problems throughout various parts of North America, but have until recently been largely ignored in Pennsylvania. For instance, black shales in places such as Ohio (Hoover, 2002), Tennessee (Belgeri and Siegel, 1998), Quebec (ACQC, 1999), and elsewhere have led to serious problems with ARD and associated swelling and heave of engineered structures. More recently, black shales of the Devonian Marcellus Formation and Mandata Member have led to costly ARD problems west of Lewistown, Pennsylvania during construction of parts of SR 522. The Marcellus Formation has also caused costly and troublesome heaving problems at the Evangelical Hospital in Lewisburg, Pennsylvania (Hoover, 2002). The geochemical and biological processes leading to sulfide mineralization in black shales are similar to those of coal-bearing formations in that they are both of sedimentary or

syngenetic origin. Although the numerous black shales found in Pennsylvania are only beginning to be viewed as problematic in terms of ARD, it is likely that they will present some of the more complicated challenges in terms of construction projects due to their ability to both produce acid and to swell, leading to volumetric expansion.

The second broad group of sulfide minerals includes those of hydrothermal origin. The processes leading to the formation of hydrothermal sulfide minerals are complex and varied and have been the focus of many studies, as they are often the hosts of economic deposits of lead, zinc, gold, silver, and other important resources. Unfortunately, many hydrothermal sulfide deposits are not only lacking in valuable minerals but are often the sources of large amounts of pyrite and other associated minerals that lead to the formation of ARD. Although the relevance of hydrothermal deposits to ARD in Pennsylvania has historically not been of primary consideration, the unearthing of thousands of yards of hydrothermal pyrite-bearing rock at Skytop has illustrated the harmful potential of such deposits. Ongoing studies may also suggest that hydrothermal pyrite deposits such as those found at Skytop in Centre County, Pennsylvania may be considerably younger than any that formed during Mesozoic times. The Mesozoic era has long been accepted to mark the end of large-scale tectonic influence in eastern North America with respect to those characteristics that are now exposed at or near to the surface of the earth, which makes this age interpretation all the more interesting and mysterious. The events at Skytop have had far-reaching implications and have resulted in huge expenditures of money and time for remediation and further research. Subsequent sections of this report look in detail at the issues surrounding Skytop and provide references for some of the many other studies resulting from this watershed event.

Although pyrite is often a common component of rocks spanning a huge amount of time and space, the mechanisms by which it came to exist within these rocks are numerous, complicated, and not always fully understood. Hydrothermal sulfide deposits can form in a variety of ways but have certain common characteristics. At the heart of most systems is a silicic magma crystallizing at fairly shallow levels within the crust of the earth (Nesse, 2000). As the magma cools over time the process of fractional crystallization leads to the increasing concentration of certain elements while others become preferentially bound up into solid phases.

The heat inherent to these magmatic bodies sets into motion hydrothermal fluids as well as meteoric waters from the surface of the earth. The circulation of these waters into the surrounding host rocks leads to numerous interactions that ultimately result in further mineralization, which depends upon various spatial, temporal, and constitutional parameters (Nesse, 2000). A full and comprehensive discussion of the geology of formation of hydrothermal pyrite was beyond the scope of this research but is nonetheless significant and important in understanding the conditions that lead to ARD.

The third broad group of sulfide-related minerals has been termed supergene deposits, which include both gossan-type minerals and acid sulfate soils. Supergene sulfide deposits are essentially representative of older sedimentary or hydrothermal deposits that have been reworked by a variety of chemical and physical processes. Gossan is a term used to describe the assemblage of often yellow, orange, and red colored, relatively insoluble secondary minerals produced as a result of the oxidation of primary or hypogene sulfide minerals (Nesse, 2000). Gossans are characteristic of what has been termed the “oxidized cap rock,” which is a sulfide-depleted oxidized zone that overlies the reduced rocks below (Gold and Doden, 2007). Supergene processes ultimately result in the production of oxide, hydroxide, oxyhydroxide,

carbonate, and sulfate secondary minerals forming after sulfides have been exposed to near-surface oxidizing environments (Nesse, 2000). Supergene deposits are largely interrelated to the regional ground water table and the level of infiltration of atmospheric oxygen, which are often at the same relative position. Circulating meteoric waters containing dissolved metals and other elements formed in oxidizing conditions may intersect with reduced ground waters, resulting in reprecipitation of sulfides, metallic oxides, and carbonates at or near the water table (Nesse, 2000; Gold and Doden, 2007).

Acid sulfate soils are soils that have been enriched in efflorescent sulfate minerals deposited by migrating groundwater enhanced in dissolved concentrations of salts and acids (Gold and Doden, 2007). Acid sulfate soils are most prevalent in areas such as brackish waters and marshes, mined materials, construction sites, dredged materials, and in regions with limited drainage and sulfate-rich water (Fanning and Burch, 2000). The development and deposition of secondary mineral phases from products of dissolution, as is the case with acid sulfate soils and other supergene deposits, has been termed sulfuricization (Bryant, 2003). Acid sulfate soils were originally identified and studied in coastal areas where both natural and anthropogenic production of sulfidic material led to the development of soils that could no longer effectively sustain agricultural activities (Orndorff, 2001). The problems presented by acid sulfate soils are more prevalent in lower-elevation Coastal Plain regions such as eastern Virginia and parts of Maryland (Orndorff, 2001), but localized areas in Pennsylvania are likely to be host to supergene enrichment.

2.3 Acid-Forming Sulfides vs. Non-Acid-Forming Sulfides

Of the numerous sulfide minerals that are found in varying amounts and forms throughout the Commonwealth of Pennsylvania, only a select few are primary contributors to the formation of acid drainage. Some of the most common sulfide minerals found in Pennsylvania and throughout the world are listed in Table 2.1 and have been designated as either acid forming or non-acid forming. This list is not intended to be comprehensive, but only representative of some of the more common and abundant minerals encountered in many familiar geological settings.

Table 2.1. Examples of common sulfides involved in acid-generating environments.

Acid Forming	Non-Acid Forming
Pyrite FeS_2	Galena PbS
Marcasite FeS_2	Sphalerite ZnS
Pyrrhotite $\text{Fe}_{(1-x)}\text{S}$	Molybdenite MoS_2
Arsenopyrite FeAsS	Millerite NiS
Chalcopyrite CuFeS_2	Chalcocite Cu_2S
Bornite Cu_5FeS_4	Covellite CuS
Pentlandite $(\text{Fe},\text{Ni})_9\text{S}_8$	Enargite Cu_3AsS_4
Tennantite $(\text{Cu},\text{Fe})_{12}\text{As}_4\text{S}_{13}$	Realgar AsS

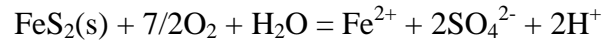
It should be noted that the primary acid-producing sulfides all contain iron in varying amounts, while the non-acid-producing sulfides do not contain any iron. The principal acid producer in most cases is pyrite, along with its polymorphs; however, many of the other minerals present in any given system can contribute to the overall ARD problem. Iron is fundamental to

ARD production because it can exist in multiple oxidization states. The phenomenon known as ferrollysis is a mechanism in which ferric iron reacts with water, iron-bearing sulfides, and non-iron-bearing sulfides, depending upon pH and other environmental conditions, to produce greater amounts of acidity, and which can result in the dissolution of potentially harmful metals such as lead, zinc, copper, and nickel. Ferrollysis is typically contingent upon the initial oxidation of iron containing sulfides such as pyrite and marcasite, in which the reaction proceeds in the presence of water and atmospheric oxygen. These primary reactions will typically lead to the production of ferric iron, which then will often react with the non-iron-containing sulfides. In other words, without the presence of iron-containing sulfides, ARD is not likely to be a problem in most situations even if other sulfide minerals such as galena (PbS), and sphalerite (ZnS) are present, and ARD will likely not commence without the initial oxidation of iron-containing sulfides.

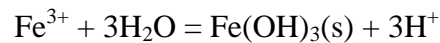
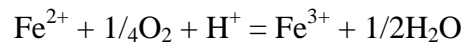
2.4 Geochemistry of Acid Rock Drainage

Acid drainage is a natural process that occurs when water and oxygen react with sulfide minerals, of which the most significant is pyrite, an iron sulfide mineral (FeS_2). The oxidation of pyrite leads to the generation of sulfuric acid (H_2SO_4), which migrates through the subsurface, leaching out various heavy metals such as iron, aluminum, zinc, nickel, and magnesium. Impacted waters are classically seen as having low pH and high levels of dissolved metals and sulfates. There is a predictable correlation between the percentage of sulfur in a rock sample and the maximum acidity that it has the potential to produce. Although there is almost always a discrepancy between predicted values and actual values in the field, being able to effectively predict the potential acidity of a geologic occurrence is considered an indispensable tool in helping to avoid the myriad of problems associated with acid drainage.

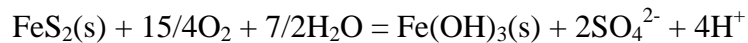
Many in-depth studies have led to the characterization of ARD as it is understood today. Williams et al. (1982), Skousen (1995), and McConchie (2003) have all presented in a comprehensive and thorough fashion, the character and processes of the complex geochemistry of ARD. The fundamental reaction involving the oxidation of pyrite in the presence of water and oxygen is defined as follows:



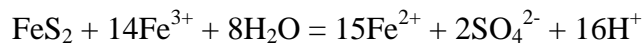
Subsequently it is typically seen that ferrous iron further reacts to produce ferric iron, which is commonly followed in many natural environments by the precipitation of any of a variety of iron hydroxides by the following reactions:



The net reaction of the above equations yields the following:

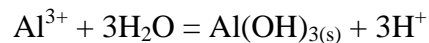
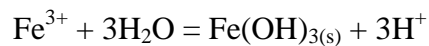


The presence of ferric iron can accelerate further oxidation of pyrite, as seen by:



Although pyrite is the most significant acid producer, there are numerous other ferro-minerals that can not only lead to the production of acid drainage, but can lead to the formation of secondary minerals. The presence and dissolution of other minerals often leads to the liberation of other potentially harmful ions such as iron, aluminum, lead, zinc, copper, and arsenic. In particular aluminum is often a ubiquitous element in most systems and can be toxic to both humans and aquatic ecosystems. The precipitation of iron and aluminum hydroxides is common in many waters affected by acid mine drainage. The yellow to orange red or brown colors of iron hydroxides and the white appearance of aluminum hydroxides stand out in many

impacted watersheds and are the most readily appreciable visual indication of ARD. The following equations represent hydroxide precipitation:



The presence of various hydroxides is not merely an indication of the state of environmental conditions, but has larger implications involving the reactions occurring at the interface of the acid water and the particular substrate that will be presented by the local geology or through emplacement for remediation efforts. After examining and characterizing the local conditions of a site impacted by ARD, it may be possible to incorporate knowledge of a particular substrate in preferentially precipitating hydroxide minerals for a variety of applications. Many treatment methods involve hydroxide precipitation as part of the process and their presence has been viewed as both hindering and helping conditions depending upon the characteristics and goals of the given remediation plan. For instance, limestone aggregate has been widely used as a neutralizing material in passive flow-through treatment systems for acidic metal-laden waters. It has typically been observed that limestone works well in neutralizing the acidic water for a relatively short amount of time until the surfaces become coated with iron hydroxides, which inhibit further reaction at the limestone-water interface.

The processes surrounding the oxidation of pyrite and the subsequent products that are formed are extremely diverse and complex. Since natural environments are highly variable, diverse, and expansive, the processes occurring in any particular locality are unique and depend upon many variables. The kinetics and thermodynamics of the oxidation of pyrite are rather complex and involved, and depend upon the conditions presented by specific localities. Two of the most basic and overarching variable parameters in pyrite redox (reduction-oxidation)

reactions are pH (negative logarithm of the hydrogen ion concentration $[H^+]$) and Eh (oxidation potential measured in volts (V) representative of electron activity), which control the speciation of the various solid phases and dissolved ions found in typical ARD environments. Figure 2.1 illustrates the dependence of pyrite geochemistry upon specific pH and redox conditions.

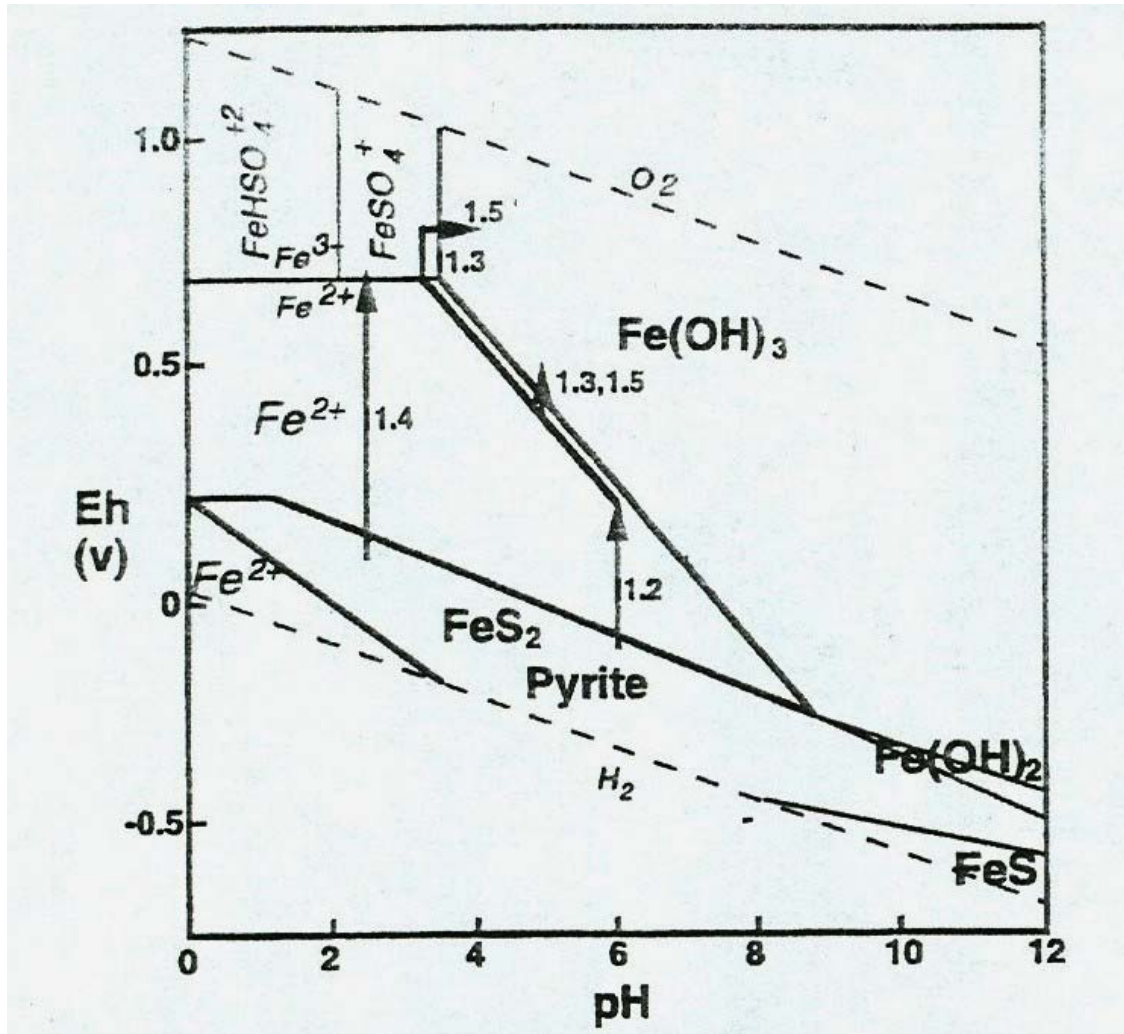


Figure 2.1. Eh-pH diagram for Fe-O-H-S system with activities of Fe=1 mg/L and S=300 mg/L as SO_4 (Brady et al. [eds.], 1998).

Various species of bacteria are known to play a key role in the oxidation of pyrite, as well as in various methods that employ the use of bacteria as an ARD remediation strategy.

Thiobacillus ferro-oxidans have long been known to contribute to the initial oxidation of pyrite as

well as in the later stages where they can catalyze oxidation of Fe^{2+} to Fe^{3+} , which may further accelerate the production of more acid. The effects of these types of bacteria are so significant that in some cases they have the ability to increase the rate of ferrous iron oxidation by as much as 10^6 times (Bryant, 2003). *Thiobacillus ferro-oxidans* seem to thrive at pH values between 2 and 3.5 but are able to continue to function at pH values as low as 1 and as high as 6 (Williams et. al., 1982). Unfortunately for those seeking to alleviate, remediate, or avoid the problems of ARD in any given area, these sorts of bacteria are very common in the majority of geologic settings where pyrite is present (Bryant, 2003). As contrasted with sulfide oxidizing bacteria, there are also sulfate-reducing bacteria, which have the ability to help in effectively lowering the concentration of dissolved metal cations found in drainage waters. Regardless of the role any given bacteria will play in the overall state of conditions surrounding any given ARD environment, their importance cannot be discounted, and if one is to understand and potentially treat a system it is necessary to consider their effects.

The science surrounding ARD is a complicated realm that encompasses chemistry, geology, biology, and various forms of engineering and applied science with regard to prediction, characterization, and remediation. The problem of ARD is widespread and far reaching, and as such it has received a great amount of attention in the form of field and laboratory studies. A wealth of information exists in all areas of this discipline and should be consulted in greater depth in order to engage in preventative or remedial efforts. The discussion of the geochemistry of ARD has been presented here in a greatly abbreviated fashion in order to illustrate and delineate the problem without going into excessive details. Further information should be pursued by individuals seeking more specific information on particular locations and topics as governed by the individual characteristics of the region or site in question.

3.0 EXPERIMENTAL APPROACH

The experimental approach of this study included a methodical consideration of how to properly identify potentially problematic sulfide-bearing formations. The numerous sulfide-bearing lithologies of Pennsylvania that were identified and subsequently characterized by a variety of methods were organized into groups based upon certain common characteristics, and have been described in detail. Important interrelated geological and geotechnical information has also been considered to offer a complete picture of all known factors, considerations, and possible outcomes surrounding these sulfide-bearing units. The recently completed open file report entitled *Geologic Units Containing Potentially Significant Acid-Producing Sulfide Minerals* (Pennsylvania Geological Survey, 2005) was used as a starting point for this study. The different approaches and methods implemented in this study have also been discussed.

3.1 Identification of Potential Sulfide-Bearing Formations

What should typically be the first step and what is perhaps the easiest way to identify potentially problematic geologic formations is to engage in a literature review of known or available published and unpublished relevant works including books, journal articles, graduate theses, maps, and personal communications with both professionals and local residents who have both learned and intuitive knowledge of specific regions. Decades and in some cases centuries worth of information has been accumulated on the geology of certain regions, geologic age groups, stratigraphic successions, and particular formations and phenomena.

The geologic disciplines that may be relevant for a particular formation or region are as diverse and numerous as the types of publications, and include structural geology, stratigraphy, geochemistry, paleontology, mining, and geophysics. An immense amount of work has also

been done in a variety of engineering fields such as engineering geology, environmental engineering, geotechnical engineering, mining engineering, and transportation engineering. All of these disciplines are extremely well represented in the literature, and all may be relevant and should be considered as potential resources of information in the preliminary investigation and design phases of construction projects that may intersect with sulfide-bearing soils and/or lithologies.

It may often be the case that a specific geologic formation that is known or suspected to be present at a proposed or active construction site has been encountered before during other projects, and as such, there may be information available on said formation regarding its inherent physical and chemical properties, as well as any possible negative consequences incurred by excavating the material or using it as fill, subbase, under foundations, etc. If this is the case, it may be concluded on the basis of literature review alone that it is unwise to intersect the given material to use it in certain engineering applications, or that appropriate treatments, mitigations, and precautions should be observed. If potentially problematic formations can be effectively identified, avoided, or accommodated at this early stage of the planning process, it can result in great savings of time, money, and effort in the long term.

3.1.1 Visual Indicators

During preliminary site investigations in areas that have been chosen for roads, buildings, and other large structures an opportunity may exist to recognize certain visual indications that acid-producing sulfides may be present in the subsurface even before any drilling or excavation has taken place. Easily identifiable visual indications that sulfides may be present include the presence of natural ARD, secondary sulfate minerals such as barite (BaSO_4), gypsum

($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), melanterite ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$), and rozenite ($\text{FeSO}_4 \cdot 4\text{H}_2\text{O}$), and secondary oxide, hydroxide, and oxyhydroxide minerals collectively termed gossan. The mineralization associated with a gossan will be typically colored in shades of yellow, orange, red, and brown.

The occurrence of natural ARD in North America has been documented as far back as the 1700s when European settlers first began to colonize the area (Brady et al. [eds.], 1998). Accounts of natural ARD include sulfurous-smelling and metal-rich waters along with iron staining of rocks and stream beds. The visual indications of natural ARD can still be observed today at various locations throughout Pennsylvania. For instance, before excavation at Skytop in Centre County for portions of the I-99 corridor was initiated in 2002, portions of the Bald Eagle Formation exposed along SR 322 were characterized by colorful bright red, orange, and yellow gossan that was thought to have formed as a result of pyrite oxidation. Generations of geology students from Penn State visited the site on field trips to observe this phenomenon, referred to as “rainbow rock” by local residents, in the field (D. P. Gold, Pers. Comm., 2007).

Krohn (1976) relied heavily upon simple visual indicators during portions of his field survey of sections of Bald Eagle Mountain along the Allegheny Front in Central Pennsylvania. In this study, Krohn was looking for apparent relationships between zones of sulfide mineralization, fracture zones, and lineaments in portions of Central Pennsylvania. Numerous mineralized localities were identified on the basis of straightforward field reconnaissance and the identification of limonite gossans, barite, and visible galena and/or sphalerite veins (Krohn, 1976). Krohn (1976) also cites a perceived and expected significant relationship between the majority of the mineralized sites that were visually located in the field with previous geochemical anomalies that were measured by Hsu (1973). The coupling of these two methods seems to comprise an effective preliminary predictive tool that can be employed with a relative

minimum of expense, effort, and time. Consequent drilling and excavation programs can then be more effective in isolating desirable economic mineral deposits for mining operations, or in avoiding objectionable acid-producing deposits during the course of large-scale construction efforts.

3.1.2 Geochemical Exploration

The presence of sulfides and other minerals can often be deduced on the basis of a variety of geochemical exploration methods. These methods rely primarily on manifest surface expressions of geologic conditions that extend into the subsurface where they cannot be seen or reached without more costly and labor-intensive drilling or excavation methods. Geochemical exploration is essentially any method in which one or more chemical properties of a naturally occurring substance (soil, sediment, rock, water, gas, vegetation, etc.) are measured in order to search for the presence of minerals, usually of economic importance (Hsu, 1973). These geochemical exploration methods often serve as a fairly reliable and interpretive primary assessment of relative concentrations of certain minerals and related constituents of interest in both broad and narrow geographic ranges. Based upon these preliminary investigations specific areas may be identified that can later be investigated in greater detail. McConchie (2003) states that naturally generated ARD and its resulting acidic metal-laden waters and soils have been used for years by geologists in the mineral exploration industry.

Hsu (1973) undertook a fairly extensive geochemical exploration study in the Nittany Valley area in central Pennsylvania in which geochemical drainage surveys were employed as a primary reconnaissance method for the presence of a variety of base metals. Lead-zinc mineralization has long been known to exist in isolated areas of central Pennsylvania such as

Milesburg Gap and Sinking Valley (Keystone Mine area) in which economic concentrations of galena (PbS), sphalerite (ZnS), and other related minerals have long been exploited (Smith, 1977). In fact, mines in the Sinking Valley area have yielded important lead and zinc ores as far back as the Revolutionary and Civil Wars (Hsu, 1973).

Methods discussed by Hsu (1973) include chemical analysis of gossan, stream sediments, and stream and ground waters. Some of the more significant or relevant elements that were measured include lead (Pb), zinc (Zn), iron (Fe), barium (Ba), copper (Cu), nickel (Ni), and fluorine (F). Although not analyzed in this particular study, sulfate (SO_4^{2-}) concentrations are also very useful in detecting acid-producing minerals. The geochemical measurements made by Hsu (1973) were subsequently treated statistically in order to obtain proper threshold values to measure anomalies of the various ore indicator elements. Once anomalies are assembled from the large amounts of data necessary to obtain dependable or reliable results (especially for geochemical surveys of large areas), representative values or anomalies can then be mapped along with a variety of related information. Useful information that can be related to and mapped along with any geochemical anomalies may include geological formations, watersheds of varying sizes, and specific streams and springs in order to identify any potential trends and to identify probable source areas in the likely event that sample components have been transported considerable distances from their respective source areas.

It is worth mentioning here that Hsu (1973), Krohn (1976), and others have reported on the presence of a lead-zinc zone of mineralization at Skytop based upon geochemical measurements showing anomalous concentrations of related components in stream waters and straightforward visual indicators such as the presence of gossan. Hsu (1973) and Krohn (1976) also cite various other similar known mineral occurrences in central Pennsylvania such as those

at Milesburg Gap, Sinking Valley, Curtin Gap, and a variety of locations along Bald Eagle Mountain. The host rocks for these numerous occurrences vary by type and age, but most of the mineralized zones seem to be related to regional joints and faults. These zones of relatively high fracture density are especially well suited to the flow of hydrothermal fluids and to the precipitation and growth of the necessary mineral components (Hsu, 1973). The fact that the presence of both economically well-known and smaller, more indefinite deposits have been initially detected and subsequently corroborated by geochemical and field reconnaissance surveys lends further credibility to these methods as being reliable and important preliminary investigative techniques. Furthermore, that the mineralized zone at Skytop was reported numerous times in the literature, albeit not understood or interpreted in any great depth, shows the power of these simple methods as fundamental tools in the avoidance of intersecting potentially acid-producing hydrothermal sulfides during large-scale construction projects.

3.1.3 Geologic Mapping

Geologic mapping has long been considered an essential and primary tool leading to the characterization of both small- and large-scale geographic areas. Due to hundreds of years of work by countless geologists, much of the world and essentially all of the United States has been geologically and topographically mapped, at least at the reconnaissance level. Detailed geologic mapping is especially important if sulfide minerals are known or suspected to be present on site (Gold and Doden, 2007), particularly if the area has not been previously mapped in any great detail.

The first step in any geologic mapping effort is to consult the most current and up-to-date geologic and topographic maps. It may often be the case that many of the existing available

maps were done at the reconnaissance level, and as such will not be extremely precise or detailed to the precision that may be necessary for certain projects or areas. Furthermore, it is usually the case that in the time elapsed since existing maps were made new outcrops have been exposed that will aid in the compilation of new maps. Necessary revisions and additions should be made to the existing maps as more intensive field work is undertaken. All mapping projects are, of course, limited by the number and quality of available outcrops. Pennsylvania is a heavily vegetated state, and so many available outcrops are of anthropogenic origin with the exception of those found along streams, rivers, and resistant ridge tops.

Detailed geologic, structural, and topographic maps may be generated for sites for which there is a distinct possibility for intersection with acid-generating formations. These detailed maps can be effectively used to site highway corridors, building foundations, and other structures so that the potential for acid drainage and/or swelling is avoided or minimized. For instance, precise geologic maps can be used to make decisions regarding the location of road corridors and adjustments of grades or slopes to avoid un-oxidized pyritic materials. Other relevant information can also be mapped separately or superimposed onto the geologic maps including geochemical, geophysical, and hydrological information and data. All of this information can have important consequences for a site in terms of the potential for ARD and the methods by which it may be avoided, minimized or mitigated both before and during active construction phases. Modern mapping techniques including the use of geographic information systems software and other complementary programs have greatly simplified and accelerated the pace of many mapping efforts.

3.1.4 Geophysical Surveys

Geophysical surveys collectively form a reliable and non-invasive preliminary investigative approach to discovering a variety of important metallic elements, whether of economic importance or of acid-producing predisposition. A variety of geophysical methods exist with different approaches being suited to a variety of conditions found in the field. Geophysical surveys are especially important when there is a lack of exposed rock outcrops necessary for good quality geologic mapping (Gold and Doden, 2007) or in remote or inaccessible areas where drilling equipment may be especially difficult to transport or maneuver on site.

Orndorff (2001) discusses the use of an induced polarization survey that results in a metal factor based on polarizability and resistivity measurements. The metal factor can enable a quantitative estimate of the relative level of risk associated with certain areas or formations. Gold and Doden (2007) cite both induced polarization and self-potential as reliable non-invasive geophysical survey methods that are capable of identifying small concentrations of pyrite and related minerals, and recommend that if high chargeability values are obtained then acid-base accounting methods should be utilized. Bryant (2003) also refers to induced polarization and self-potential methods as being common and reliable methods to detect metallic and electronically conductive minerals such as pyrite and other related acid-producing sulfides.

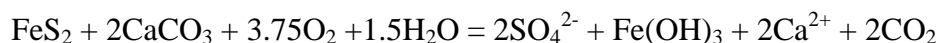
3.1.5 Chemical Methods – Acid-Base Accounting

One of the most traditional methods of subsurface geological exploration involves drilling into the subsurface to obtain soil and rock samples. The method of acid-base accounting (ABA) has been used in conjunction with drilling of test bores for decades as a reliable and fairly

inexpensive and quick way of helping to chemically characterize a variety of rock or overburden types including coal, shale, sandstone, limestone, and others.

ABA is a method that has been developed and used extensively to measure the acid-producing potential along with the acid-neutralizing capacity of rock or overburden materials. The ABA account essentially consists of two main parts, total or pyritic sulfur and neutralization potential. One of the first step-by-step field and laboratory methodologies developed for the ABA procedure was put together by Sobek et al. (1978), and although this frequently cited document has well withstood the test of time, numerous revisions and approaches have been suggested and debated in the years following.

The main components of the ABA account are the maximum potential acidity (MPA), which is calculated on the basis of a measured value for percentage of sulfur (%S), and the neutralization potential (NP), which is a measure of the neutralizing capacity of the sample. %S values may be for total sulfur, which includes all sulfide sulfur, organic sulfur, and sulfate sulfur, or for sulfide sulfur only. The use of total sulfur is easier, less expensive, quicker, and more often reported but may result in an overestimate of the actual level of acid production. %S values are typically determined by high-temperature combustion methods, although other methods may be used (Brady et al. [eds.], 1998). MPA is calculated by multiplying the %S value by 31.25, a number that is based upon the stoichiometry of the following equation, which describes the reaction of pyrite (FeS_2) with calcium carbonate (CaCO_3) in the presence of oxygen and water:



The units of MPA are given in pounds per 1,000 pounds of calcium carbonate (CaCO_3) [lb/1,000 lb of CaCO_3]. Although the determination of MPA based upon the above equation

involves many assumptions and is an oversimplification, the results have been found to be reasonably accurate and reliable.

The neutralization potential of a sample is typically found by boiling the sample with a known volume and normality of hydrochloric acid (HCl) and back-titrating the solution with a known volume and normality of sodium hydroxide (NaOH). The normality of acid and base used in the determination of the NP is based upon the fizz rating of the sample, which is a qualitative measure of how much a sample fizzes when one or two drops of 25% HCl are added, due to the reaction with neutralizing minerals present in the sample. The units of NP are also given in lb/1,000 lb of CaCO₃. NP values of less than 30 and %S values of greater than 0.5 have been recognized as general threshold values representative of potentially acid-producing formations based largely on empirical evidence (Brady et al. [eds.], 1998).

The net neutralization potential (NNP) of the sample is found by subtracting the MPA value from the NP value. A NNP value of less than zero is generally considered to represent a potentially acid-producing sample; however, samples with NNP values ranging from approximately 0 to 12 have been observed to lead to variable water quality in some cases (Brady et al. [eds.], 1998).

For additional detailed and thorough information on the ABA procedure as well as other important analytical chemical procedures useful in the prediction of acid rock drainage, one should refer to one of the many excellent and key publications written on the subject, such as Sobek et al. (1978), Steffen Robertson and Kirsten (B.C.) Inc. (1989), Morrison et al. (1990), Bradham and Caruccio (1995), Lawrence and Scheske (1997), Skousen et al. (1997), and Brady et al. [eds.], 1998.

The approximately 100 black shale samples taken from throughout much of the Valley and Ridge province of Pennsylvania as part of this study (see Section 4.1) were tested using standardized ABA methods (see Appendix B) by Mahaffey Laboratories in Grampian, Pennsylvania, a PaDEP-certified facility (D. Barrett, Pers. Comm., 2007). The black shales sampled during this study were tested for fizz rating, %S, and NP, from which MPA and NNP values were derived (see Appendix C). The ABA procedure was also used to analyze the huge volumes of overburden data provided by the PaDEP (K. Brady, Pers. Comm., 2006) analyzed during the course of this investigation (see Appendix B).

3.2 Selection of Sulfide-Bearing Units

Numerous sulfide bearing geologic units have been identified throughout Pennsylvania. These geologic units have been broadly categorized as black shales, coal measures, sandstones, and isolated deposits. Stratigraphic columns have been included in Appendix A to help illustrate the spatial and temporal relationships among the sulfide bearing units.

3.2.1 Black Shales

The black shales, which although known in many cases to produce acid drainage and lead to swelling, have not been studied on a regional basis in terms of their propensity to cause sulfide related problems. Although the stratigraphy of these black shales and their associated units have been studied in depth, little has been done in order to systematically understand and interpret their ability or likelihood to lead to environmental and engineering problems in Pennsylvania. Unlike the bituminous and anthracite coal measures, which have been extensively drilled and

sampled for years in association with mining operations, the black shales have received comparatively little attention except when they have already led to considerable problems.

As a major component of this study, many of the problematic black shales were identified based upon literature reviews and personal communications. Once the problematic black shales had been identified, an extensive regional sampling effort was undertaken. Robert Smith, a geologist retired from the Pennsylvania Geological Survey, aided in the identification of many of the rock outcrops that were sampled in this study. Approximately 100 outcrops were sampled, the majority of which were road and railroad cuts, active and inactive quarries, and borrow pits. Among the shales sampled in this study were the Marcellus, Mandata, Antes/Reedsville/Upper Coburn, Needmore, Mifflintown, Burket, and Mahantango. It should be noted that while every effort was made to properly identify individual formations or members in the field, in certain cases it became apparent that in order to assign a specific name or designation to certain members more detailed regional mapping would be required, an important but extremely time-consuming effort that was beyond the scope of this study. Furthermore, the difficulty of detailed mapping of this type is further compounded by the lack of outcrops, and therefore such an effort may be impractical without resorting to drilling.

The difficulty in assigning precise stratigraphic names to some outcrops was especially obvious where formations lack certain unequivocally defining features, as is the case with the Tioga ash beds at the base of the Marcellus. This is also the case where formations have been considerably weathered or altered, or where clearly defined stratigraphic boundaries were not present, as when boundaries are gradational as opposed to abrupt. Although in these cases the precision of stratigraphic identification has been diminished, the data are still useful in the broader context of certain formations and groups, principally when the target formations

comprise only a small percentage of a larger unit. It may also be the case that when gradational as opposed to abrupt transitions are present at the site, the stratigraphic interval that may be potentially problematic may become less clearly defined, both in terms of its ease of identification and its potential to produce ARD. In other words, the stratigraphic zone or interval containing significant amounts of sulfide may be less clearly defined when the boundaries of the sulfide-bearing units are not clearly defined either. Further compounding the problem is the lateral variability of the group, formation, or member in question, and the lateral variability of sulfides present within the rock. Both vertical and lateral complexity should be assumed, and each site must be treated as a distinct and unique locality.

Many of the sampling localities were identified and located using USGS topographic maps, and a great deal of time was spent pinpointing the rock outcrops in the field. A few outcrops were identified in the field in the process of searching for previously identified sites. Upon finding each individual outcrop, a systematic course of action was taken to characterize and sample each locality. Each site was photographed and grab samples were taken and retained for later analysis. The latitude and longitude of each site was recorded in the field using global positioning systems for later mapping purposes. Specifically, a Garmin brand GPS model 12CX 12-channel personal navigator was used. This particular model has a position accuracy of up to 15 m (49 ft) depending upon the quality of weather conditions, which is more than adequate for the map scales used in this report. The map datum used in this study was the North American Datum of 1927 (NAD 27).

3.2.1.1 Limitations of the Field Sampling Program

There were two main limitations with regard to the field sampling effort. The first limitation was in the identification of the outcrops themselves. Since most of Pennsylvania is either vegetated or urbanized, it was necessary to rely on limited outcrops as a means to characterizing each shale. As such, the density of sampling locations is variable with some of the shales being better represented than others. For instance, the Antes Member of the Reedsville Formation and the underlying upper Coburn were sampled more extensively than the Mandata shale. This is simply a function of available and identified outcrops, and not a measure of preference for any particular formation. Similarly some geographical areas are better represented by the data than others. Again, this is a function of identified rock outcrops and not a measure of preference or any particularly likelihood for a certain strata to be problematic or not.

The second main limitation of the field sampling process is that many, if not most of the outcrops that have been sampled are somewhat weathered, having been exposed to the atmosphere for, in some, cases several years. In order to obtain fresh rock samples it would be necessary to either drill or excavate, a costly and time-consuming effort beyond the scope of this study. Since many of the outcrops have been weathered to varying degrees, the chemical analysis of the rock samples, namely the acid-base account, was carried out under the assumption that any pyrite, carbonate, or other relevant minerals present have been subjected to various degrees of weathering and oxidation. That being the case, the chemical analyses associated with this study should be considered as conservative estimations, assuming that some of the pyritic sulfides present have been oxidized to sulfates and perhaps leached out of the sample. Therefore, it is likely in some, if not all cases, that a fresh and un-oxidized sample of the same

representative rock would be more problematic in terms of its ability to produce acid drainage. That being said, it is interesting that even some of the more weathered samples are still suggesting a strong tendency towards producing acid drainage. For more information on the acid-base accounting procedure, refer to Section 3.1.5.

3.2.1.2 Black Shale Mapping Methodologies

Each black shale unit that was sampled in the field and analyzed by the Acid Base Accounting (ABA) method for percentage of sulfur, fizz rating, and neutralization potential has been mapped independently in order to spatially or geographically depict the data. ArcGIS geographical information systems software version 9.1 was used to construct all of the maps used in this report. For each shale, the sampling locations have been mapped and the corresponding data, specifically the net neutralization potential, has been displayed. In order to assist in the portrayal of some of the spatial or geographical trends that have arisen as a result of this mapping, Surfer 8, a contouring and 3D surface mapping program, was used to construct isopach lines for individual data sets. Among the black shales sampled and mapped were the Marcellus, Mandata, Antes/Reedsville/Upper Coburn, Needmore, Mifflintown, Burket, Hamilton Group (unknown members), and Mahantango (see Section 4.1).

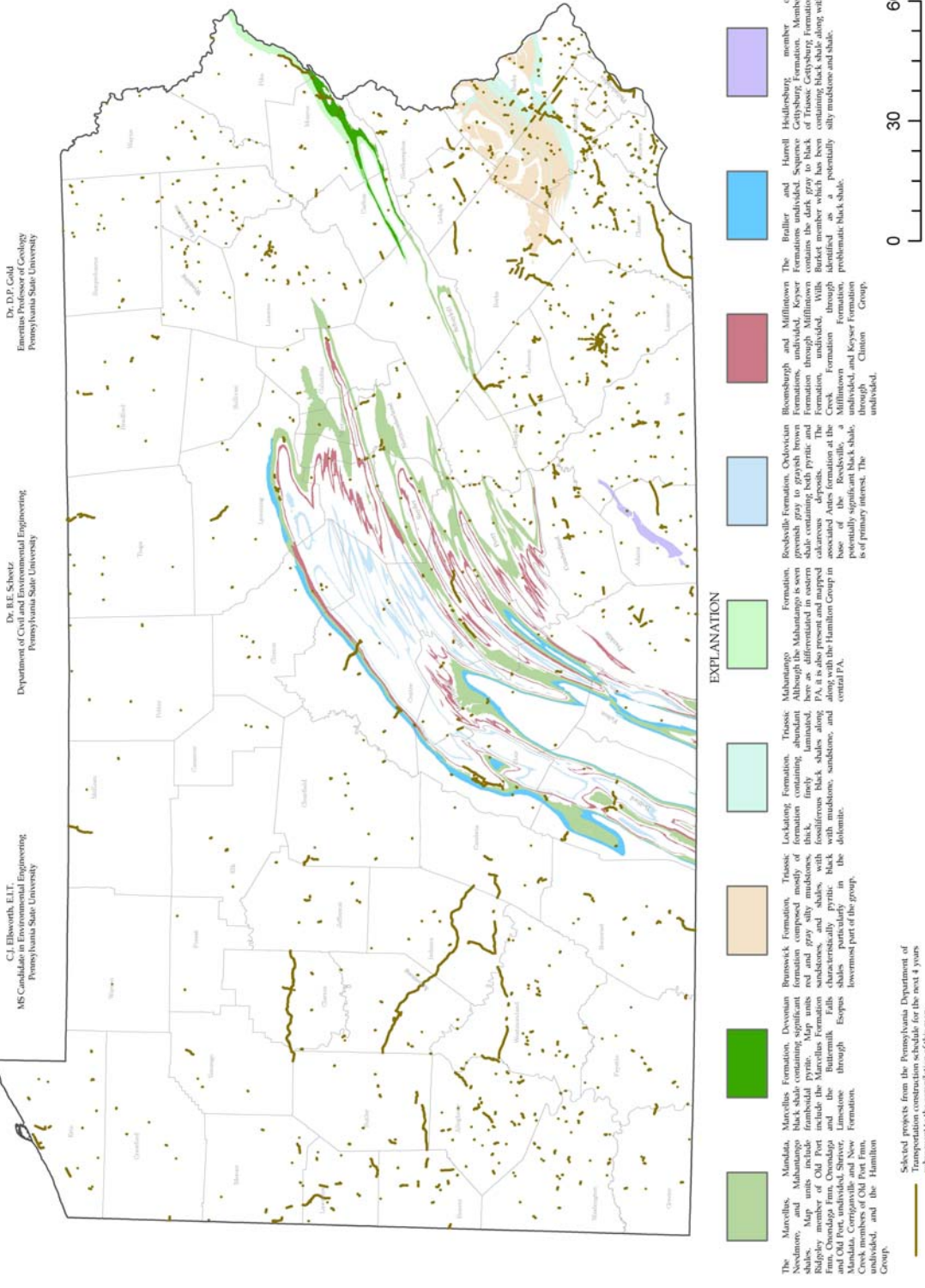
Some of the individual black shales are far better represented than others in terms of the number of sample locations and associated data. For instance, the sampling points representative of the Antes, Reedsville, and Upper Coburn lithologies are especially well represented or distributed geographically. As a consequence of being associated with Ordovician carbonates that are widely exploited in quarrying operations for both construction aggregate and for raw material used in the production of lime, the Antes member has been exposed as well in several

instances. Similarly, the Reedsville Formation has been exploited in several areas as a relatively easily worked and convenient material in borrow pits for use as a low-quality substrate in privately owned drives, primitive roads and the like. Since the sampling of the black shales in this study was limited primarily to surface exposures, quarries and borrow pits presented some of the freshest and most easily accessible sources of rock formations, which otherwise are rarely seen exposed outside of road cuts. The included geological formations with more limited data sets could benefit from additional sampling if more complete geographical or spatial characterization is desired. Such complete spatial characterization of each individual formation was, however, beyond the scope of this project, and would require more detailed and prolonged investigations focused upon the specific formation(s) of interest. Figure 3.1 shows the spatial distribution of all of the individual black shales described in the following sections, although not all of the black shales shown have been sampled for chemical analysis.

3.2.2 Descriptive Geology of the Selected Black Shales

The black shales and black shale-bearing units described here have been included in this report due to their known or suspected tendency to contain sulfide minerals or to produce ARD, or in some cases simply due to the fact that they are thought to have been deposited under the environmental conditions that are known to promote the formation of sulfide minerals as a component. Figure 3.1 shows the geographic distribution of the individual black shales described in the following sections.

Black Shales of Pennsylvania



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Figure 3.1. Geographic distribution of the black shales of Pennsylvania with PennDOT's projected construction projects overlaid.

3.2.2.1 Brunswick Formation

The Brunswick Formation is a Triassic and Lower Jurassic aged deposit composed predominantly of “reddish-brown shale, silty mudstone, siltstone, and sandstone, commonly cyclic” with “less abundant, cyclic, gray or black shale and red to gray siltstone and silty mudstone,” which were deposited in lacustrine environments of the Newark basin (Geology of Pennsylvania, 1999, p. 184). The Brunswick along with the Lockatong, Stockton, Hammer Creek, Gettysburg, and New Oxford Formations make up the Newark Supergroup. Although the black shales present in the lowermost part of the Brunswick Group are “characteristically pyritic, lack lacustrine fossils, and contain evaporate pseudomorphs in their upper parts, reflecting elevated salinities” (Smoot and Olsen, 1994), they are not known to have caused any acid drainage within Pennsylvania. Although the Brunswick Formation is not known to have caused any significant acid drainage and was not sampled in this study, it has nonetheless been included for the sake of completeness in terms of recognition of all black shales.

3.2.2.2 Heidlersburg Member of Gettysburg Formation

The Heidlersburg Member of the Gettysburg Formation is a Triassic aged strata that “also contains traceable black shales in cycles similar to those in the lowermost part of the Brunswick Group” (Geology of Pennsylvania, 1999, p. 187). The Gettysburg Formation is somewhat similar to the Brunswick Formation in terms of its environment of deposition and general sedimentary sequence. The Heidlersburg Member is not known to have caused any significant acid drainage and was not sampled in this study, but like the Brunswick and Lockatong it has been included for the sake of completeness. One possible explanation as to why the black shales within the Brunswick, Lockatong, and Heidlersburg Formations have not led to acid drainage is

that they were deposited in fresh water environments, which typically have much lower sulfur concentrations than saline waters. Another possible reason is that since these formations were at times subjected to arid and subaerial environmental conditions, as evidenced by pseudomorphs after evaporate minerals such as gypsum and other indicators (Geology of Pennsylvania, 1999, p. 190), the necessary anoxic or euxinic conditions that so often lead to sulfide formation were never sufficiently developed.

3.2.2.3 Locketong Formation

The Locketong Formation is a Triassic aged formation deposited in a lacustrine environment that is composed predominantly of mudstone and carbonates and that underlies the Brunswick Formation (Geology of Pennsylvania, 1999, p.197). Although the Locketong contains some black shales, during much of its deposition it was subject to subaerial conditions in an arid climate (Geology of Pennsylvania, 1999, p. 200). As with the Brunswick and Heidlersburg, the Locketong is not likely to be acutely problematic in terms of ARD but has been included because of its black shale content. Despite the presence of black shales, the Locketong is not known to cause ARD and was not sampled as part of this study.

3.2.2.4 Burket Member of the Harrell Formation

The Burket Member, where present, constitutes the lower portion of the Harrell Formation, which is a “dark-colored organic-rich shale” that typically shows a “chippy weathering pattern” in outcrop (Geology of Pennsylvania, 1999, p. 121). The Harrell Formation forms the basal component of the Upper Devonian Fingerlakian Stage of the stratigraphic column in much of Pennsylvania (Geology of Pennsylvania, 1999, p. 112). The Upper Devonian

has been broken into five facies in the western Appalachian basin based upon lithology and depositional environment. The Harrell Formation and the Burket Member are part of the first facies, which has been defined as “dark-gray to black, somewhat calcareous, pyritic, sparsely fossiliferous shales” that are thought to have formed in “anoxic bottom muds of the basin proper (shallow or deep water)” (Geology of Pennsylvania, 1999, p. 121). The Burket has often been seen to be greatly deformed by folding and faulting in many field outcrops and has been observed to be typically on the order of 100 ft in thickness (Colton, 1967).

3.2.2.5 Mahantango Formation

“The Mahantango Formation is a complex series of interbedded shales, siltstones, and sandstones ranging from 1,200 to 2,200 ft thick in central and eastern Pennsylvania” (Geology of Pennsylvania, 1999, p. 117). In parts of Pennsylvania the Mahantango Formation has been further subdivided into various members, including the Clearville, Frame, Chaneyville, Gander Run, Sherman Ridge, Montebello, Dalmatia, and Turkey Ridge Members (Geology of Pennsylvania, 1999, p. 111). The Mahantango, along with the underlying Marcellus and overlying Tully limestone (which may or may not be differentiated), comprise the Middle Devonian Hamilton Group. “The Mahantango Formation formed as a prograding marine shoreline during early Catskill delta building” (Geology of Pennsylvania, 1999, p. 125). Parts of the Mahantango contain the “grayish-red, oolitic, calcareous, and often chamositic hematite ores of the ‘Clinton type’” (Geology of Pennsylvania, 1999, p. 559). Although these oolitic hematite deposits can be found in the upper parts of the Mahantango in Perry, Juniata, and Dauphin Counties, they have historically been mined only in Perry County (Geology of Pennsylvania, 1999, p. 562).

3.2.2.6 Marcellus Formation

“The Marcellus consists of 75 to 800 ft of dark-gray to black, highly fissile, homogeneous, carbonaceous shales containing locally abundant pyrite and few fossils” (Geology of Pennsylvania, 1999, p. 117). The Marcellus, along with the other Devonian black shales, were deposited in anoxic environments, which, although deep in relation to the rest of the surrounding epicontinental seas, were perhaps as shallow as less than 150 ft (Geology of Pennsylvania, 1999, p. 125). It is possible that stratification of the water column led to the anoxic bottom conditions as opposed to the deep water hypothesis, but at this point it is not clear (Geology of Pennsylvania, 1999, p. 126). The Marcellus, where present, constitutes the base of the Hamilton Group of the Middle Devonian age.

“The Tioga ash zone, a series of at least six layers of brown, yellowish-brown, or brownish-gray micaceous shales of volcanic origin, marks the approximate boundary between the Onesquethawan and Cazenovian Stages of the Middle Devonian” (Way and Smith, 1985). The Tioga ash beds are the expression of active volcanism occurring in association with the Acadian orogeny. Not only do the Tioga ash beds aid in the identification of the Marcellus shale, as it may often superficially resemble other Devonian black shales in the field or drill cores, but the ash beds or bentonites may also present a third engineering challenge (in addition to sulfide-induced heave and acid rock drainage) in that they increase the potential for landslides in cut slopes (Gold and Doden, 2007).

The Marcellus shale has already proven to be extremely troublesome with regard to a variety of large-scale engineering and construction projects. The first and most fundamental problem involves the oxidation of the framboidal pyrite in the Marcellus, which typically leads to ARD. The second problem is that the Marcellus has been observed to lead to sulfide-sulfate-

induced heave of engineered structures. The factors leading to structural heave are more complex than the occurrence of ARD but are no less important, as both have led to millions of dollars of remediation expenses in Pennsylvania alone (see sections 5.2 and 5.3). A fourth potential problem with the Marcellus has also been observed. Due to elevated uranium concentrations in the black shale, high radon levels are locally present in areas underlain by this formation (Geology of Pennsylvania, 1999, p. 792).

3.2.2.7 Needmore Shale

The Needmore Shale is “a medium-gray to black, calcareous, commonly fossiliferous shale between 100 and 150 ft thick” in central Pennsylvania (Geology of Pennsylvania, 1999, p. 116). The Needmore, which is part of the Lower to Middle Devonian Onesquethawan Stage, grades into the Huntersville Chert and/or Selinsgrove Limestone, which together comprise the Onondaga Formation throughout much of Pennsylvania (Geology of Pennsylvania, 1999, p. 111). The Needmore lies disconformably on the Ridgeley Sandstone (Geology of Pennsylvania, 1999, p. 116). The Needmore Shale, like the Marcellus and Mandata, was deposited as mud in stagnant and anoxic waters (Geology of Pennsylvania, 1999, p. 125). The Needmore Shale has been recognized as contributing to acid drainage problems in parts of Virginia (Orndorff, 2001) and is suspected to be problematic in Pennsylvania as well.

3.2.2.8 Mandata Shale

The Mandata Shale is representative of anoxic bottom conditions of the Appalachian basin floor during the Early Devonian Helderbergian Stage (Geology of Pennsylvania, 1999, p.124). The Mandata, where present, is underlain by the Corriganville Limestone and overlain

by the Shriver Chert or Licking Creek Limestone in parts of Southwestern Pennsylvania (Geology of Pennsylvania, 1999, p. 111). The data collected in this study imply that the Mandata often has considerable neutralization capacity; however, certain areas do show a strong potential for ARD. The potential for swelling is more difficult to predict but the Mandata Shale appears to have all of the necessary characteristics for heave, including appreciable amounts of sulfur and carbonate not only within the member itself, but within direct proximity.

3.2.2.9 Mifflintown Formation

“The Middle Silurian succession in central Pennsylvania is represented by the Rose Hill, Keefer, and Mifflintown Formations” (Geology of Pennsylvania, 1999, p. 98). “The Mifflintown Formation is composed of interbedded shallow marine mudrocks and limestones” (Geology of Pennsylvania, 1999, p. 98). In western Pennsylvania the Middle Silurian is represented by the Clinton Group. “The dominant unit in these strata is the Rochester Shale, which consists of a variably fossiliferous, gray mudstone and numerous interbedded carbonates” (Brett, 1983). The Rochester is sometimes interpreted as a member of the Mifflintown Formation in central Pennsylvania (Berg, McInerney, and others, 1986). The analysis performed on the Mifflintown Formation and Rochester Shale as part of this study shows that these strata may have a limited potential to cause ARD in localized areas and the potential for swell and related phenomena is uncertain.

3.2.2.10 Reedsville Formation

The Reedsville Formation is an Upper Ordovician succession of shale, sandstone, and minor limestone found in Central and Western Pennsylvania. The Reedsville is on the order of 1,200 ft thick in central Pennsylvania and has been described by Krohn (1976) as a “dark olive-

green shale with thin fossiliferous beds of impure limestone near the top.” The sandstones within the Reedsville “become thicker, burrowed, and more abundant upward” and have been described as “lenticular, crossbedded, and hummocky bedded, (with) erosional upper surfaces, and in some places are size graded” (Geology of Pennsylvania, 1999, p. 83).

The lower sections of the Reedsville Formation are more likely to be problematic than the upper sections since the dark shales are typically found lower in the section, while the sandstones and minor limestones are found higher in the section. The predominance of the samples taken from the Reedsville in this study were from the lower part of the formation (near the Antes Formation), where it often appears as a fissile dark-gray shale, often with pencil-type cleavage in outcrop. The exact boundary between the Antes and Reedsville may be somewhat elusive in outcrop, particularly if the two formations share a gradational contact. Some of the lower components of the Reedsville may cause ARD in some areas, and the potential for swell is possible but unclear and more difficult to quantify or predict.

3.2.2.11 Antes Member

The Antes Formation is a relatively thin carbonaceous black shale of Upper Ordovician age present in parts of Central and Western Pennsylvania. The Antes is sometimes omitted from more simplified stratigraphic columns altogether, partially because it is thin (as thin as a few feet in places) and possibly because it is not always present along with its bounding stratigraphic units. The Antes Formation is underlain by the Coburn Formation and overlain by the Reedsville Formation (Geology of Pennsylvania, 1999, p. 79), both of which are also potentially sulfide-bearing lithologies. The data acquired in this study suggest that the Antes Formation has the

potential to produce ARD in some areas and may also present a swelling problem due to its significant carbonate content.

3.2.2.12 Upper Coburn Formation

The Coburn Formation comprises the top portion of a thick sequence of Middle and Upper Ordovician limestones in Central and Western Pennsylvania, many of which are important sources of construction aggregate and raw material for the manufacture of lime. The Coburn is a transitional formation from the underlying limestones to the overlying siliciclastic formations such as the Antes and Reedsville Formations (Geology of Pennsylvania, 1999, p. 79). It has been said that the Coburn and underlying limestone formations are “commonly dark gray to black, extensively bioturbated, and in some places fetid and carbonaceous” (Geology of Pennsylvania, 1999, p. 79). It is thought that the Coburn Formation, like many of the other black shales, is representative of deep-water anoxic environments. The interbedded fine-grained limestones and black shales that are characteristic of the Coburn Formation are thought to be deposited as a result of “lateral transport of shelf carbonate onto a clay-floored basin by turbidity currents” (Geology of Pennsylvania, 1999, p. 80). The Upper Coburn is a hydrocarbon-rich formation in places, containing significant amounts of both organic matter and sulfur. The data gathered during this study suggest that the Coburn likely does not have the potential to cause acid drainage, owing to the fact that it typically is highly calcareous and therefore has significant neutralization capacity. However, the combination of significant percentages of pyritic sulfur and appreciable carbonate in the Coburn make it a possible candidate for swelling. The Coburn Formation is also prone to sinkholes in the Ridge and Valley province, along with other

underlying Ordovician carbonates such as the Stonehenge, Larke, Nittany, Benner, Nealmont, and Salona Formations (Geology of Pennsylvania, 1999, p. 718).

3.2.3 Coal Measure Data Methodologies

The Pennsylvanian and Permian age bituminous coal measures of western Pennsylvania, as well as the anthracites of eastern Pennsylvania, have been mined extensively for more than one hundred years. In more recent times, in order for coal mining operations to be viable from both an economic and environmental perspective, an extensive characterization of each specific site must be undertaken. Typically this involves geologic mapping of the site and drilling of the coals and their bounding strata for the purpose of acid-base accounting. From the acid-base account and other considerations of site hydrology, regional land use, and the economic promise of the site, it will be determined whether the site is feasible for mining operations or not.

The Pennsylvania Department of Environmental Protection (PaDEP) typically supervises the drilling efforts and helps to determine to what extent certain procedures and practices must be followed to avoid negative environmental consequences as a result of the proposed mine. Several PaDEP offices have participated in contributing data from their regional jurisdiction to a comprehensive coal overburden ABA analysis database. This coal overburden database was provided by Keith Brady (Pers. Comm., 2006) for the purposes of this study. The portion of the data base used in this study consisted of 47,866 individual sets of ABA data. Each set of data or each sampling point contained information on the given name of the drill hole, sample ID, surface elevation, depth, rock type, coal seam names (where present), county name, municipality name, latitude, longitude, total sulfur, fizz rating, neutralization potential, and in certain cases, the percentage of pyritic sulfide.

The ABA data are essentially representative of four main stratigraphic or lithologic groups from the bituminous coal field, the Pottsville Formation, the Allegheny Formation, the Conemaugh Group, and the Monongahela Group and Waynesburg Formations, undivided. No overburden data for the anthracite coal fields were available. Each drill hole was classified and grouped based upon the coal seam(s) that it contained. As would be expected, some of the drill holes straddled the boundary of two of the aforementioned groups, and some of the drill holes could not be unequivocally classified due to the fact that no distinguishing coal seam was found to be present within.

The overburden ABA data were sorted first by county and then by specific drill hole. Then each drill hole was classified into one of the four groups based upon the coal seam(s) present. It should be noted that some, if not many, of the latitude and longitude values listed in the data are incorrect due to typographic errors or due to the fact that one was never provided in the first place. Furthermore, it is likely that different coordinate systems were used by a variety of sources and therefore any given latitude and longitude measurement should be not considered as being precise. For this reason the use of the municipality designation is more reliable and for the purposes of this study excessive levels of accuracy in terms of pinpointing the drill holes were not necessary, as the focus has been placed more upon county and statewide distributions and spatial trends in the data.

In order to distill down the huge amount of data into a more presentable form, a method was used by which the worst-case scenario in terms of the acid-base account could be used to uncover any possible geographical trends or variations. To this end, two drill holes were selected from each representative county for each of the four groups (Pottsville Formation, Allegheny Formation, Conemaugh Group, and the Monongahela Group and Waynesburg

Formations, undivided). The two drill holes were selected based upon having the highest percentage of sulfur out of all the given drill holes in that particular county. The upper end decided upon as the worst-case percentage of sulfur was taken to be 6%, assuming that any value greater than 6% is likely representative of a situation in which a certain drill core hit an area of anomalous pyrite concentration, not representative of the overall coal seam or of the bounding strata. Some of the overburden data showed percentage of sulfur concentrations as high as 18%, an unreasonably high value for the purposes of statewide regional characterization. The upper limit of 6% was decided upon after consultation with Keith Brady of the PaDEP, who has extensive experience and knowledge of the Pennsylvanian coal fields (Keith Brady, Pers. Comm., 2006).

3.2.3.1 Descriptive Geology of the Selected Coal Formations

Many of the Pennsylvanian aged coal-bearing formations found in Pennsylvania have long been known to be acid producers due to the widespread occurrence of acid mine drainage across much of the bituminous and anthracite coal fields. The geographic distribution of the known problematic acid-producing coal measures can be seen in Figure 3.2. The coal-bearing groups and formations discussed below have been listed from stratigraphically youngest to oldest.

3.2.3.1.1 *Llewellyn Formation*

The Llewellyn Formation is an Upper Pennsylvanian to Permian aged succession located entirely in the anthracite regions of eastern Pennsylvania, although the certainty and degree to which it extends into the Permian is debated. The Llewellyn has been measured to be as thick as

3,500 ft, is composed predominantly of conglomerate and sandstone with lesser amounts of shale, siltstone, and primarily nonmarine limestones, and is a structurally complex formation as contrasted with the majority of the bituminous coal measures. The structural complexity of the anthracite region, manifested in hundreds of reverse and thrust faults and a variety of folds, makes the region relatively difficult to map and interpret, with sedimentary sequences being overturned and repeated in some areas (Geology of Pennsylvania, 1999, p. 460). There are on the order of 40 significant and named coals in the Llewellyn, several of which have long been economically important in the development of Pennsylvania and United States as some of the key fuel sources used in the industrial revolution (Geology of Pennsylvania, 1999, p. 159). The Llewellyn has been known to cause acid drainage throughout much of its geographical extent.

3.2.3.1.2 *Waynesburg Formation*

The Waynesburg Formation, which directly overlies the Monongahela Group, is a Pennsylvanian to Permian aged transitional sequence which contains the economically important Waynesburg coal at its base (Geology of Pennsylvania, 1999, p. 472). The exact delineation of the Pennsylvanian-Permian boundary is still debated, and therefore for this and other reasons, the Monongahela and Waynesburg have been mapped and grouped as undifferentiated in this report. The Waynesburg coal itself is typically 2 to 4 ft in thickness and has been found to have a high sulfur content (Geology of Pennsylvania, 1999, p. 478).

The Waynesburg Formation comprises the lower portion of the Dunkard Group and prior to 1963 was included as part of the Washington Formation (Geology of Pennsylvania, 1999, p. 172). The Waynesburg is between approximately 85 to 210 ft thick and is composed of varying amounts of sandstone, shale, claystone, siltstone, with lesser amounts of limestone and coal, which are entirely of non-marine origin (Geology of Pennsylvania, 1999, p. 174). The Waynesburg Formation has been known to cause acid drainage in many parts of its geographic coverage.

3.2.3.1.3 *Monongahela Group*

The Monongahela Group is an Upper Pennsylvanian aged succession that varies in thickness from approximately 270 to 400 ft thick, and crops out in parts of southwestern Pennsylvania (Geology of Pennsylvania, 1999, p. 473). Several coal seams are found in the Monongahela including, from oldest to youngest, the Pittsburgh, Redstone, Fishpot, Sewickley, and Uniontown. Some of the coals of the Monongahela Group are of economic significance and

have been mined extensively, the majority of the other economic coals found in Pennsylvania being located in the Allegheny Formation (Geology of Pennsylvania, 1999, p. 472).

The Monongahela Group is a completely nonmarine sequence that has been divided into the Pittsburgh and Uniontown Formations and generally thickens from west to east (Geology of Pennsylvania, 1999, p. 156). The Monongahela is composed predominantly of limestone, dolomitic limestone, shales, calcareous mudstone, siltstone, and laminites, with some coal seams, and with relatively little sandstone except at its base (Geology of Pennsylvania, 1999, p. 156). Despite its nonmarine depositional history and the presence of significant amounts of limestone and other calcareous strata found in the Monongahela, it still has the capacity to produce acid drainage in many areas.

3.2.3.1.4 Conemaugh Group

The Conemaugh Group is a middle Pennsylvanian aged succession containing many coals, few of which are economic, along with varying amounts of sandstone, shale, siltstone, claystone, and minor limestones that are better developed in the upper portions of the group (Geology of Pennsylvania, 1999, p. 154). The Conemaugh Group is composed of two subunits, the lower Glenshaw Formation and upper Casselman Formation. The major coals found within the Conemaugh Group are, from lowest to highest, the Mahoning, Brush Creek, Lower and Upper Bakerstown, Harlem, Federal Hill (Duquesne), Barton (Elk Lick), Wellersburg, Lower and Upper Clarysville, Lonaconing, Franklin, and Little Pittsburgh (Geology of Pennsylvania, 1999, p. 472).

The Conemaugh Group, which outcrops principally in southwestern Pennsylvania, ranges from around 520 to 890 ft in thickness with an apparent thickening of the unit from west to east

(Geology of Pennsylvania, 1999, p. 154). Although the Conemaugh Group is not as problematic as other coal-bearing lithologies, it has nonetheless led to the formation of acid drainage to in many areas.

3.2.3.1.5 *Allegheny Formation*

The Allegheny Formation is a Middle Pennsylvanian aged succession that contains several important economic coal seams such as the Brookville, Clarion, Kittanning, and Freeport coals (Geology of Pennsylvania, 1999, p. 472). The Allegheny Formation has been mined extensively for decades due to its several valuable coal seams within a relatively short stratigraphic interval of approximately 270 to 330 ft in thickness, and was in fact particularly defined to include all of the economic coals in that part of the Pennsylvanian succession (Geology of Pennsylvania, 1999, p. 473).

The Allegheny Formation is composed of frequently repeating successions composed of coal, limestone, claystone, shale, and sandstone that are of both marine and nonmarine origin (Geology of Pennsylvania, 1999, p. 154). The non-marine Upper Kittanning and Freeport coals are less problematic than the underlying marine coals, but the entire formation has been known to cause acid drainage throughout much of its geographical and vertical extent (Geology of Pennsylvania, 1999, p. 154).

3.2.3.1.6 *Pottsville Formation*

The Pottsville Formation is a Lower Pennsylvanian aged unit that lies unconformably on Mississippian units throughout much of Pennsylvania and conformably on the Mississippian Mauch Chunk Formation in other parts of the state. The Pottsville that is present in both the

bituminous and anthracite coal fields of Pennsylvania, contains several coal seams including the Sharon, Quakertown, and Lower and Upper Mercer coals (Geology of Pennsylvania, 1999, p. 472). In addition to coal, the Pottsville has also been exploited in some areas for sandstone aggregate and clay (Geology of Pennsylvania, 1999, p. 616).

In the bituminous region of Pennsylvania the Pottsville lies unconformably on Mississippian aged strata and is composed dominantly of sandstone and conglomeratic sandstone with varying amounts of shale, siltstone, coal, and minor limestones in localized areas. In western Pennsylvania the Pottsville ranges from approximately 20 to 250 ft in thickness (Geology of Pennsylvania, 1999, p. 151).

In the anthracite region of Pennsylvania, the Pottsville ranges from 1,500 ft thick in parts of the southern fields to less than 100 ft in the northern field and is predominantly composed of conglomerate and sandstone, with lesser amounts of siltstone, shale and coal (Geology of Pennsylvania, 1999, p. 459). Calcareous minerals are not common in the Pottsville and therefore there is little natural buffering capacity within the formation itself.

3.2.4 Descriptive Geology of the Selected Sandstones

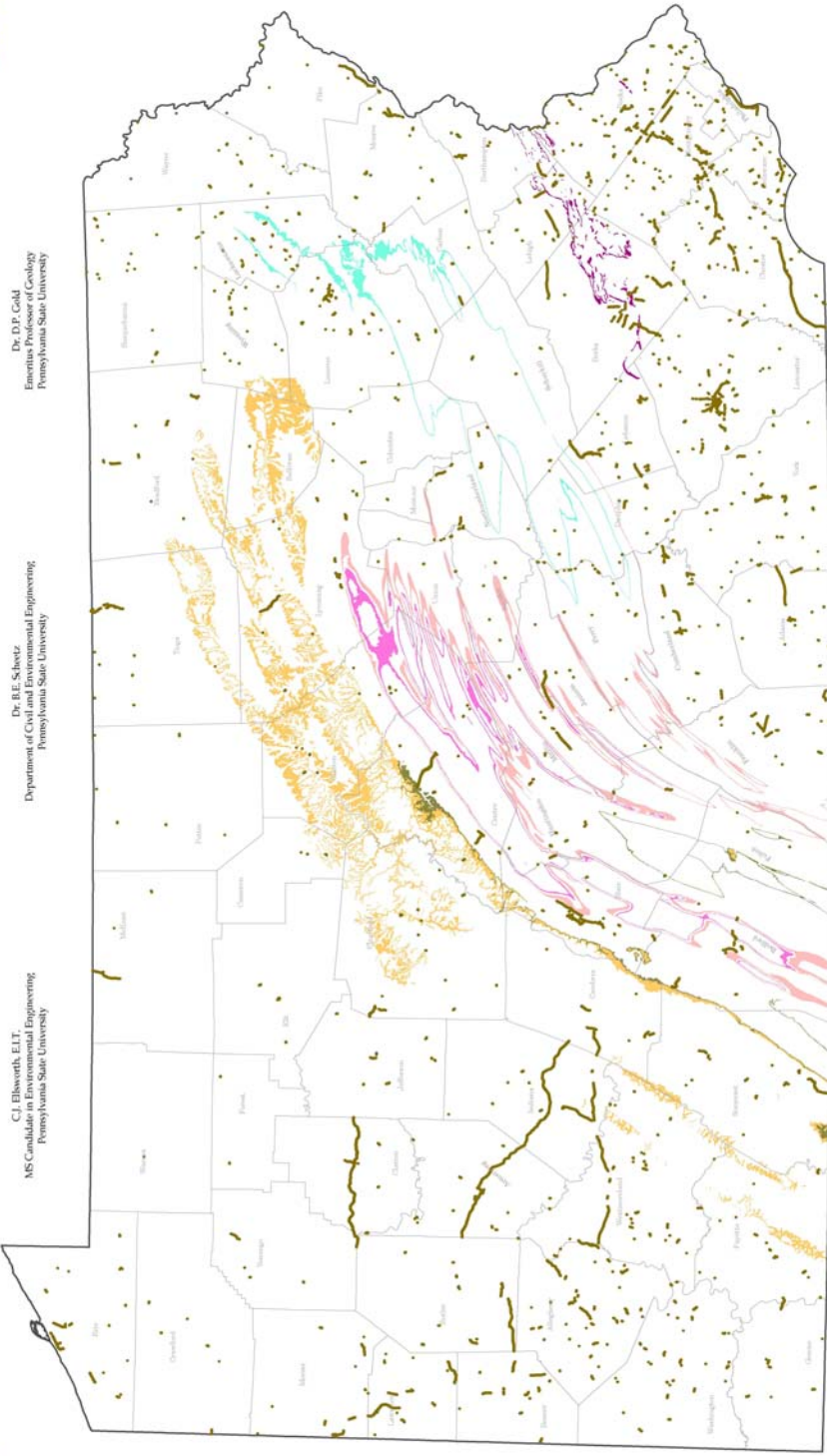
The geologic units included in this section are dominantly composed of sandstones, but also contain other stratigraphic components of varying type such as conglomerates, coals, and shales. It should be understood that the sandstone components of these formations have been observed in many cases to contain sulfides of a secondary hydrothermal or epigenetic origin as opposed to sedimentary or syngenetic. However, it may also be possible that the minor shale or coal components found in some of these “sandstones” may contain some undetermined amount

of sedimentary or syngenetic sulfide deposits. The geographic distribution of the sandstone units that may contain potential acid-producing sulfides can be seen in Figure 3.3.

3.2.4.1 Burgoon Formation

The Burgoon Formation is a Mississippian age succession predominantly of medium- to coarse-grained cross-bedded sandstone with some minor conglomerates at its base, which is thought to have been deposited in a braided river environment (Geology of Pennsylvania, 1999, p. 133). The Burgoon is a resistant formation composed mostly of light-pinkish-tan to almost white sandstones with lesser amounts of dark carbonaceous shale in some of the upper portions of the formation (Colton, 1967). The Burgoon varies in thickness from on the order of 35 to 210 ft (Colton, 1967). Little is known of the ARD-producing nature of the Burgoon Formation with one major exception. During construction of Interstate 80 in Centre County during the 1960s the Burgoon Formation was cut through in the vicinity of a stream named Jonathan Run. Large nodular pyrite was unearthed in the Burgoon at this time resulting in major ARD, which virtually decimated the stream and has continued until this day. It is unclear how much of the Burgoon contains similar nodular sulfide deposits, but it is likely that there are other potentially problematic areas and so the formation as a whole should be approached with caution.

Potentially Acid Producing Sandstones & Associated Strata



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EXPLANATION

- Burgess Formation. Mississippian sandstone with minor conglomerate at its base.
- Tequesta Formation. Lower Silurian sandstone with exceptionally resistant ridge forming sandstone. Many sulfide deposits have been located in Centre and Huntingdon Counties, and it is likely that other similar deposits occur elsewhere.
- Rockwell Formation. Devonian to Mississippian sandstone composed mostly of sandstone with some black shale, siltstone, and coaly zones. Underlies the Burgess Formation.
- Old Eagle Formation. Ordovician sandstone with greenish gray sandstone. Several known sulfide deposits are located along Bald Eagle Mountain in Centre County such as the consequential deposit at Shlytop.
- Specht-Kopf Formation. Devonian to Mississippian sandstone dominated by sandstone with other minor components including siltstone, shale, conglomerate, mudstone, and coal.
- Hardyston Formation. Early Cambrian sandstone with a variety of conglomerates, sandstones, and shales.

Selected projects from the Pennsylvania Department of Transportation construction schedule for the next 4 years subsequent to the compilation of this map.

0 25 50 MI

Figure 3.3. Geographic distribution of the potentially acid-producing sandstones with PennDOT's projected construction projects overlaid.

3.2.4.2 Rockwell Formation

The Rockwell Formation is a Devonian to Mississippian transitional unit composed of relatively resistant sandstone, shale, siltstone, and some thin coals deposited in both marine and alluvial environments. The Riddlesburg Member found in the middle of the Rockwell contains brownish-gray to grayish-black marine shales (Geology of Pennsylvania, 1999, p. 135). The level of risk associated with the Rockwell Formation is unclear but it should be approached with caution due to the possible presence of both black shale and minor coal. There may also be a possibility for localized secondary sulfide occurrences in the Rockwell along some of the resistant ridges, particularly in areas of high fracture density.

3.2.4.3 Spetchty Kopf Formation

The Spetchty Kopf Formation is a Devonian to Mississippian transitional succession composed mostly of sandstone with minor siltstone, shale, laminate, conglomerate, mudstone, polymictic diamictite, and coal (Geology of Pennsylvania, 1999, p. 131). The Spetchty Kopf may be up to 1,280 ft thick in many places but in other areas may be missing stratigraphically (Geology of Pennsylvania, 1999, p. 132). The Spetchty Kopf is believed to have formed in a variety of fresh water lacustrine and fluvial settings (Geology of Pennsylvania, 1999, p. 132), and therefore the minor coals are not likely to present much difficulty when present, as would be the case with coals deposited in marine and estuarine-type environments. Although the Spetchty Kopf Formation has not been known to be problematic it is possible that in some areas, particularly along major lineaments, it may be a host rock to secondary sulfide emplacement.

3.2.4.4 Tuscarora Formation

The Tuscarora Formation forms the base of the Silurian lying unconformably on the Upper Ordovician Juniata Formation, and is present throughout much of central Pennsylvania where it can often be seen exposed along the many ridge tops of the Valley and Ridge province. In much of central Pennsylvania it ranges from around 492 to 656 ft in thickness while thinning to the northwest to as little as 200 ft (Geology of Pennsylvania, 1999, p. 93). The Tuscarora is composed predominantly of light-colored quartzose sandstones with other minor sandstone, siltstone, and shale components that have been interpreted as alluvial plain facies (Geology of Pennsylvania, 1999, p. 96). Along with the underlying Juniata and Bald Eagle Formations, the resistant Tuscarora holds up many of the prominent ridges that help to characterize much of the Appalachian Mountains in central Pennsylvania.

Although the Tuscarora is an extremely hard, dense, and resistant ridge-forming strata it has nonetheless been greatly deformed, extensively folded and faulted throughout the Valley and Ridge province. For instance, well-defined kink folds have been observed in the Tuscarora both at Skytop during excavation of part of the I-99 corridor and north of Lewistown, Mifflin County adjacent to the Laurel Creek Reservoir (Geology of Pennsylvania, 1999, p. 272). Alleghenian deformation is responsible for most of the structural features characteristic of the Tuscarora and Valley and Ridge as seen today. The brittle and ductile deformation that resulted in the creation of many of the known folds and faults also created ideal pathways for the later migration of hydrothermal fluids. It is from these hydrothermal fluids that many of the localized sulfide deposits in the Tuscarora are thought to have originated. Many of these deposits are known to exist in Centre County along Bald Eagle Ridge and seem to be located mostly in wind and water gaps. The sulfide deposit at Skytop is one such deposit and is an overt example of the

significance of these localized hydrothermal cross-strike sulfide occurrences. Although many of the known localized occurrences have been included in this report, it is extremely likely that many others exist and have not yet been documented in the literature. It is for this reason that the Tuscarora should be approached with caution, particularly along major lineaments.

3.2.4.5 Bald Eagle Formation

The Bald Eagle Formation is an Upper Ordovician unit composed predominantly of greenish-gray sandstone with lesser amounts of siltstone and basal conglomerate (Geology of Pennsylvania, 1999, p. 82). The Bald Eagle along with the overlying Juniata and Tuscarora Formations is one of the significant resistant ridge formers in the Pennsylvania Valley and Ridge province. The Bald Eagle has also historically been called the Oswego Formation.

The potential threat for acid drainage in the Bald Eagle, as in the Tuscarora, is related not to primary sedimentary processes, but to secondary hydrothermal process in which fluids migrate through fractures in the sandstone leading to the deposition of sulfides and other accessory minerals such as quartz. As Skytop has proven, the threat associated with the Bald Eagle Formation is extreme in certain localized areas, while in other areas it may be nonexistent. The cross-strike vein type deposits seen at Skytop likely originated in the mantle, and although the events leading to their emplacement are not clear at this time, it is extremely likely that other similar deposits exist in localized areas throughout much of the Bald Eagle. These localized occurrences seem to be concentrated in zones of high fracture density, along fault zones and along major lineaments. Many localized occurrences can be found in wind/water gaps along the ridge tops and it seems likely that both the gaps and the sulfides owe their existence to a common

set of physical processes. Like the Tuscarora, the Bald Eagle should be approached with caution, especially along lineaments and in the vicinity of wind and water gaps.

3.2.4.6 Hardyston Formation

The Hardyston Formation is an Early Cambrian aged unit that comprises the basal portion of the Reading Prong Section of the New England physiographic province and unconformably overlies the Proterozoic crystalline basement rocks in eastern Pennsylvania and which is part of the Chilhowee Series (Geology of Pennsylvania, 1999, pp. 70, 421). The Hardyston, which ranges from 60 to 800 ft, typically consists of “arkosic conglomerate at the base and passes upward into arkosic sandstone, orthoquartzite, carbonate-cemented sandstone, silty shale, and jasper” (Geology of Pennsylvania, 1999, p. 47). There are also zones of arkosic conglomerate and arkose within other parts of the Hardyston, not being limited only to the base of the formation (Geology of Pennsylvania, 1999, p. 47). Although some general stratigraphic trends may be visible in many parts of the Hardyston, it is often a horizontally and vertically variable unit, frequently varying over relatively short distances (Miller et al., 1941).

The Hardyston Formation has historically been an important source of sand, aggregate and dimension stone for surrounding communities, and has also been mined extensively for limonite iron (Geology of Pennsylvania, 1999, p. 601). The limonite iron ores seem to be located principally within the shale layers in the upper portions of the Hardyston, which often appear to be interbedded with minor amounts of chert and sandstone (Miller et al., 1941).

Miller and others (1941) state that significant numbers of euhedral pyrite crystals can be found disseminated throughout many of the arkosic sandstone beds found in the Hardyston, along with some feldspars and a few zircons. Although there is little information available about

previous occurrences of ARD resulting from the Hardyston, the presence of pyrite and limonite in certain stratigraphic intervals suggests that there is a distinct possibility for ARD to occur. The primary potential for ARD within the Hardyston seems to be restrained principally to its basal and lower stratigraphic layers where disseminated pyrite grains have been observed.

3.2.5 Localized Deposit Methodologies

Numerous localized sulfide deposits exist throughout Pennsylvania that are principally of hydrothermal origin. Although there are specific geologic formations such as the Tuscarora that often host these deposits, the localized occurrences in most if not all cases were deposited after their respective host rocks. In other words, the localized occurrences represent a secondary emplacement event that should be considered apart from those sulfide deposits that formed along with their respective host rocks. These localized occurrences often are cross-strike in nature as opposed to bedded deposits of the type seen in coal measures. These types of deposits are also often called vein-type deposits, a designation that pays homage to their cross-strike hydrothermal origins. As such they should be treated differently from bedded sulfides in terms of their interpretation and approach in construction activities insofar as they may not be strictly stratigraphically controlled as are the sulfides typically found in the coal measures and black shales.

The localized sulfide occurrences identified in this report and on the relevant accompanying maps have been identified from a variety of sources. The predominance of the deposits have been identified based upon literature reviews, while many deposits have also been identified through personal communications with a variety of independent sources. A few deposits have also been identified in the field during the course of this study. Smith (1977) has

meticulously listed and described most of the known lead and zinc deposits of Pennsylvania. Many of these sulfide deposits contain significant amounts of iron-bearing, potentially acid-producing sulfide minerals, and have therefore been included in this report. Similarly Geyer and others (1976) have identified numerous mineral deposits in their book *Mineral Collecting in Pennsylvania*, many of which are iron sulfide-bearing deposits.

Krohn (1976) and Hsu (1973) have also identified several deposits in central Pennsylvania based upon field reconnaissance. Krohn (1976) relied heavily on the identification of gossan, a colorful, often red mixture of pseudomorphs replacing pyrite and other primary minerals. Hsu (1973) employed geochemical exploration methods in which anomalous concentrations of indicator elements were identified in stream sediments, along with stream, spring, and well waters. The presence of anomalous concentrations of such elements as lead, zinc, nickel, and copper has proven to be useful in locating mineral deposits along with considerations of watersheds and drainage patterns. Krohn (1976) and Hsu (1973), both Penn State graduate students, focused their studies in the areas surrounding the university, which accounts for the identification of numerous localized occurrences in central Pennsylvania. It seems reasonable to assume that a statewide extension of these sorts of studies would likely yield more discoveries, particularly in similar host rocks and geologic settings.

It is known that certain localized sulfides have been deposited along and in relation to large-scale structural lineaments. There is a distinct possibility that many of the localized sulfide occurrences are genetically related, having been formed as a result of common events. It may be possible to spatially and temporally correlate many of these deposits, allowing the possibility for increased understanding of the nature of the deposits and perhaps leading to predictive models for discovering other cross-strike localized mineral occurrences.

3.2.5.1 Descriptive Geology of the Selected Isolated Sulfide Deposits and Other Miscellaneous Formations

Numerous isolated or localized sulfide deposits have been observed and documented in Pennsylvania. The many localized occurrences included in this report are based upon information from several publications, personal communications, and field observations. The localized or isolated occurrences, with the exception of the Pickering Gneiss, are typically secondary hydrothermal or epigenetic-type sulfide deposits, having been emplaced long after the deposition of their various respective host rocks. Figure 3.4 shows the isolated or localized sulfide occurrences included and discussed in this report.



Localized Sulfide Occurrences of Pennsylvania

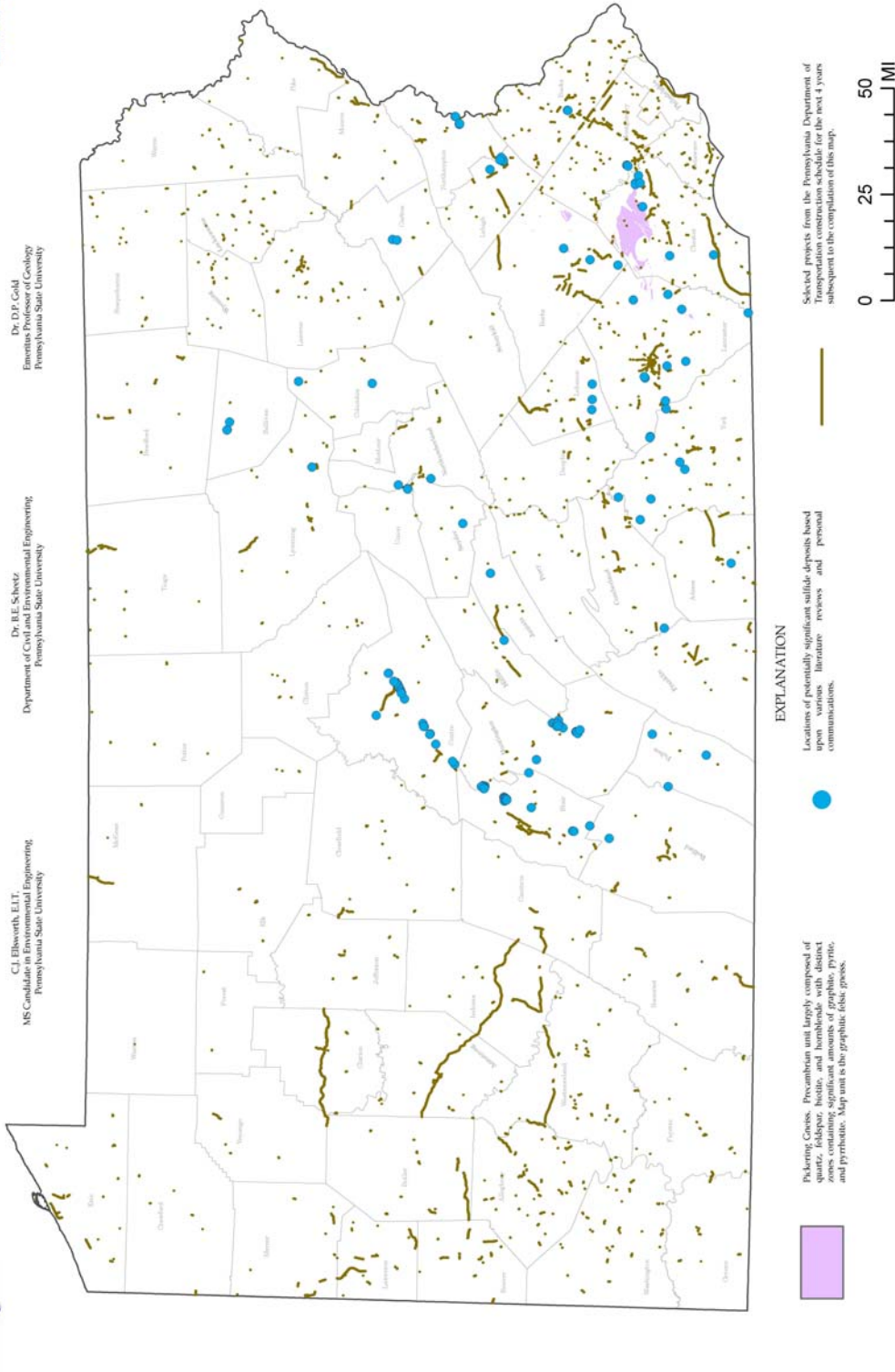


Figure 3.4. Localized or isolated sulfide deposits of Pennsylvania with PennDOT’s projected construction projects overlaid.

3.2.5.1.1 *Pickering Gneiss*

The Pickering Gneiss is a Precambrian aged formation located predominantly in Chester County but also crops out in parts of Lancaster, Berks, and Lebanon Counties. Considerable amounts of coarse flake and foliated graphite have been mined from portions of the Pickering Gneiss since at least the 1800s. The Pickering Gneiss is composed of varying amounts of quartz, feldspar, biotite, graphite, and hornblende as well as associated pyrite and pyrrhotite (Geology of Pennsylvania, 1999, p. 647). The significant amounts of graphite present indicate that some of the rocks that were ultimately metamorphosed into the Pickering Gneiss were organic rich, and may have initially been similar to some of the organic-rich black shales described in this report and elsewhere. The Pickering Gneiss was not sampled or analyzed as a part of this study and the extent to which the sulfides in the formation present the possibility for ARD or swell is unclear and deserves further attention. For this reason, the Pickering Gneiss should be considered as potentially problematic.

3.2.5.1.2 *Localized Deposits*

Several localized mineral occurrences have been identified throughout Pennsylvania, many of which contain significant amounts of sulfides such as pyrite, marcasite, sphalerite, galena, and others. The majority of these deposits appear to owe their origin and genesis to hydrothermal and related events, as opposed to primary sedimentary processes. Therefore, these types of deposits are more difficult to predict and interpret in terms of their likelihood of occurrence in any particular strata, whether it is characterized on the basis of its age or lithology. Furthermore, although many of the deposits are related in terms of their origin and genesis, many

are not related, further compounding the difficulty of identifying any trends or development of predictive models.

It is known that several of the localized mineral occurrences, whether or not they contain acid-producing sulfides, are related to lineaments (Krohn, 1976). It is likely that many of the known deposits are structurally and genetically related, but it is unclear at this point to what extent, and specific details regarding many of the deposits are limited. It is also likely that several unknown localized secondary sulfide emplacements exist throughout Pennsylvania, particularly along major lineaments (see Section 3.3).

The localized occurrences that have been included in this report have been identified primarily through a series of literature reviews, personal communications, and some field reconnaissance work. The occurrences included here, while representative of the current understanding of the nature and quantity of such deposits, are not presumed or intended to be comprehensive. It can be said with certainty that other unidentified deposits exist. Many of these occurrences contain acid-generating sulfides in significant enough quantities to cause major ARD problems if disturbed during construction activities. Conversely, some of the occurrences may not contain substantial quantities or morphologies of acid-producing sulfides that cause major problems when disturbed. The host rock in which the secondary or localized occurrence has been emplaced is also of primary interest. In some cases, naturally occurring rocks such as limestone and dolomite may be present in sufficient quantities to neutralize any acid that may be generated if a deposit is encountered during construction, while in other cases such neutralizing materials may be entirely absent. It is for these reasons that each deposit or site must be approached and treated individually on the basis of its genetic, compositional, and morphological

characteristics as well as the characteristics and properties of the surrounding country or host rock.

3.2.6 PennDOT Four-Year Construction Schedule Methodologies

The geographic information systems (GIS) shape file originally supplied to the authors contained 6,389 individual rows of data representing shape file segments for the numerous construction projects throughout the Commonwealth of Pennsylvania for the next 4 years. Each segment or row of data contained information about the nature of the construction project, including the project classification, title, identification number, length in miles, and district, along with a range of other information. On the basis of the nature of the project classifications it became possible to distill the number of individual segments down to 1,696 individual rows of data, thus greatly abridging the overall GIS layer. The project classifications that were chosen to be omitted were selected on the basis or likelihood that large-scale subsurface excavations or disruptions would take place during the course of construction. Such earth-disturbing activities carried out during the course of construction would present the possibility for intersection with reduced sulfide minerals, thus leading to a significant risk for acid drainage in the presence of certain rock formations and mineral occurrences. For instance, projects classified as Home Town Streets (HTS) projects involve such activities as beautification efforts, primarily of an aesthetic nature, not likely to involve subsurface disruption into underlying reduced bedrock. These types of projects were omitted from the revised GIS layer due to the unlikelihood for any production of acid drainage associated with construction activities. Conversely, many construction projects do present a significant possibility for associated large-scale subsurface excavations or disruptions of the type that may lead to intersection with reduced bedrock of the

type that may lead to the formation of acid drainage. For instance, projects classified as New Alignments (NALGN) would be of the type that may classically involve subsurface excavation into reduced rocks, and as such, these sorts of projects have been included in the revised GIS layer. The categories used in this report are detailed in Table 3.1.

One of the main limitations of the GIS data representative of the 4-year PennDOT construction schedule provided as part of this study is that many of the projects included in the data had already commenced or had been completed by the time the data were analyzed, and by the time the report was completed. There was therefore limited opportunity to use any of the results and conclusions of the study to assist in many of these projects. To assist in the prediction of the likelihood for acid drainage and associated problems at future projects, it would be greatly beneficial to get further ahead of the construction schedule in order to allow more complete assessments of areas or regions that are to be subjected to construction activities. In doing so, it may become possible to incorporate the site assessments into the preliminary designs, allowing for an increased and more effective plan to avoid and circumvent any potential problems.

3.2.7 Aggregate Map Methodologies

The aggregated map seen in Figure 3.5 is a compilation of all of the known or suspected potentially acid-producing and/or potentially swelling sulfide-containing geologic formations, members, or successions found located in Pennsylvania. The foundation upon which this aggregate map was built was the open file map entitled *Geologic Units Containing Potentially Significant Acid-Producing Sulfide Minerals*, which was developed through the cooperation of the Bureau of Topographic and Geologic Survey of the Department of Conservation and Natural

Resources, the Department of Environmental Protection, and the Pennsylvania Department of Transportation (Pennsylvania Geological Survey, 2005).

Table 3.1. PennDOT project classifications included in report GIS layer

Classification	Abbreviation	Originally Present?	Included in Layer?
Additional Lanes	ADDLN	Yes	Yes
Air Quality	AIRQ	Yes	No
Bicycle/Pedestrian	BKPED	Yes	No
Bridge Preservation – State Funded	BPRS	Yes	No
Bridge Pres. – Federally Funded	BPRSF	Yes	No
Bridge Replacement	BRPL	Yes	Yes
Bridge Restoration	BRST	Yes	No
Congestion Reduction	CNGST	Yes	No
Design/Construction	DSCON	No	No
Disaster	DSTR	Yes	No
Transportation Enhancement	ENHNC	Yes	No
Equipment	EQUIP	No	No
General Maintenance	GMNT	Yes	No
Highway Reconstruction	HRCT	Yes	Yes
Highway Restoration	HRST	Yes	No
Home Town Streets	HTS	Yes	No
Interstate Capacity Adding	ICA	No	No
Interstate Maintenance Program	IMP	Yes	No
Intelligent Transportation System	ITS	Yes	No
Land Acquisition	LAND	No	No
Reserve Line Item	LNITM	No	No
New Alignment	NALGN	Yes	Yes
New Bridge	NBRDG	Yes	Yes
Planning	PLAN	No	No
Planning/Research /Administration	PRA	Yes	No
Preventive Maintenance	PRVMT	Yes	No
Public Transit	PT	No	No
Rail Highway Grade Crossing	RAILG	Yes	No
Bridge Removal	RBRDG	Yes	No
Rest Area / Welcome Center	REST	No	No
Rail Freight Const& Maintenance	RF	No	No
Rail Freight Construction	RFC	No	No
Rail Freight Maintenance	RFM	No	No
Safety Improvement	SAFE	Yes	No
Secondary Route	SECRT	No	No
Safe Routes to School	SR2S	Yes	No
Study Phase of Project	STUDY	No	No
Waterline	WATER	No	No

Many of the colors and basic themes used in the map released by the Pennsylvania Geological Survey were incorporated into the aggregate map generated for the purposes of this report in order to maintain consistency and to build upon an existing strong foundation of knowledge and research. The colors used for any given formation or isolated deposit are not meant to imply relative levels of risk, but are meant to only differentiate among different stratigraphic or geologic units. Additional formations and localized occurrences have been added on the basis of literature reviews, field sampling and subsequent chemical analysis, field observations, and personal communications with a variety of people. It is worth mentioning here that the term “potentially acid producing” associated with so many of the geologic occurrences included in this assessment is meant to signify that there can be no substitute for detailed investigations at the site-specific level for any area that is to be involved with construction or related activities. Although very useful and accurate predictions and interpretations can be made about whole rock units, due to the great amount of three-dimensional variability among geologic materials and successions, predictions are just that, and cannot replace detailed investigations in the field at the site-specific level.

3.3 Importance of Lineaments

The complex geology of Pennsylvania has come about as a result of immeasurable physical and chemical processes and incorporates a wide variety of structurally controlled features. Although the tectonic nature of the east coast is that of a passive continental margin, this area has been repeatedly shaped and reshaped by powerful tectonic forces over millions of years. Numerous mountain-building events and their associated erosional and depositional processes have led to an extremely complex, diverse, and distinctive set of features. Among

these features are numerous folds, faults, igneous intrusions, zones of mineralization, and larger-scale features that have been termed lineaments.

Although the precise definition of a lineament is subject to debate, they are generally considered to be large-scale (visible on the map scale), relatively straight linear features that reflect large-scale tectonic processes and events occurring upon the earth's crust, and are thought to represent subsurface phenomena to some extent (Southworth, 1986). Gold (1999) in Chapter 22 of *The Geology of Pennsylvania* comprehensively illustrates the location, nature, and significance of numerous lineaments throughout the state. Large-scale lineaments can be either parallel or transverse to the regional structure. Not only do lineaments have large ranges as seen on a map, it has been inferred that they extend to great depths below the surface of the earth, giving them a fundamentally three-dimensional nature. The implications of their subsurface nature are various, and lead to controls on the tectonics of a region, as well as its hydrology, engineering viability or stability, and presence of potentially economic mineral resources.

The large scale of lineaments lends itself to the usage of remote sensing instruments in order to identify and map such features in any given locality. The ability of satellites to accurately survey the surface of the Earth with a great deal of precision has led to extremely detailed maps of the surface of the Earth, from which lineaments can in effect be visually deciphered by the trained eye. Using accurate aerial maps, lineaments can be compiled from the apparent alignments of features such as streams, alterations in vegetation or soils, wind and water gaps, and anomalous flows of water or gas. In addition to the more apparent visual indicators, there are often non-visual expressions of lineaments as seen manifested by earthquake epicenters and magnetic or gravity irregularities, which often show trends after accumulation of data from multiple seismic events over long periods of time (Shultz, 1999, p. 307).

Krohn (1976) used a series of satellite photos to correlate the presence of lineaments as seen from the air with the existence of sulfide deposits and fracture zones along Bald Eagle Ridge in central Pennsylvania. This study illustrates the apparent relationship between large-scale lineaments and zones of sulfide mineralization. What this study in part implies is that certain sulfide deposits are controlled to some degree by the presence of the lineaments, which seem to promote or accommodate pathways for the circulation of hydrothermal fluids and subsequent sulfide deposition in a variety of host rocks. The presence of sulfides along lineaments may be inferred by one or a combination of several different methods such as geochemical surveys of water and sediments, visual indicators such as gossan, geomagnetic and other geophysical surveys, and subsurface exploration.

Of special interest here is the apparent relationship between lineaments and zones of mineralization, particularly sulfide mineral emplacements commonly of the lead-zinc variety,

which have often been recognized to contain considerable amounts of associated pyrite, marcasite, pyrrhotite, chalcopyrite, and other acid-producing minerals. Lineaments that are cross-strike are typically representative of high fracture zones that not only potentially present sufficient pore space for mineralization, but may accommodate the transportation and circulation of the necessary hydrothermal fluids due to increased permeability.

Geochemical surveys of the Nittany Valley area in central Pennsylvania revealed as early as 1955 and upon subsequent investigation in 1973 that there are distinct zones showing anomalous levels of metal content, sulfate concentrations, pH and conductivity measured in water and sediment samples. The objectives of studies carried out by Hsu (1973) and Krohn (1976) were to determine and characterize the relationships between anomalous geochemical measurements, the presence of sulfide mineralized zones, and structural features such as faults and lineaments. In many cases they were able to conclude with reasonable levels of confidence that at minimum, there appears to a fundamental connection between many hydrothermal sulfide mineral deposits and lineaments.

For instance, Krohn (1976) discusses several well-known and widely studied sulfide occurrences that have yielded economic quantities of galena, sphalerite, and other minerals. These deposits appear to be structurally controlled to a large extent by faults and related features. Moreover, the mineral-bearing veins often cut across the bedding of multiple formations, implying that the mineralization could have occurred during or after the structural deformation, and is of a hydrothermal origin having less in common with the original depositional environment of the host rock than with subsequent events. Gold, in Chapter 22 of *The Geology of Pennsylvania*, refers to the Perkiomen Creek lineament in eastern Pennsylvania as an example of a lineament with several known mineral deposits containing zinc, lead, and copper distributed

along its length. Krohn (1976) submits that the Tyrone-Mt. Union lineament, one of the larger and better-known lineaments crossing Pennsylvania, contains no less than seven lead-zinc occurrences that are found in vein-type deposits in three different types of host rock along this lineament's approximately 75-mile traceable length.

Perhaps the most remarkable example of the unintended consequences of the excavation of sulfide mineral deposits along a lineament has manifested itself at Skytop along the I-99 corridor in central Pennsylvania. Although pyrite was long suspected to be present and was detected before and during excavation of the highway corridor through an existing gap on Bald Eagle Mountain at Skytop in 2002, its quantity and detrimental qualities were not adequately predicted or understood until it had caused millions of dollars of damage and countless lost man and machinery hours. Furthermore, the fact that anomalous levels of metals were detected at this location decades before construction began shows the potential importance and effectiveness of these types of surveys and analyses in helping to predict the presence of unseen pyrite and the potential for ARD.

Krohn (1976) cites several anomalous geochemical measurements made in the vicinity of Skytop in 1955, those at the Milesburg Gap – Treziyulny Mountain area north of Bellefonte, Pennsylvania, and south of Julian, Pennsylvania near the road known as the Julian Pike. And additional mildly anomalous measurements were made at Blue Spring Hollow, a stream south of Port Matilda, Pennsylvania, and the unnamed stream at Skytop. Hsu (1973) also discusses many previously known sulfide occurrences that occur near areas with higher-than-background concentrations of metals and other ions known to be associated with sulfide deposits. Notably, Hsu states that “Another reported lead-zinc mineralized area is located on the crest of Bald Eagle

Mountain near Skytop, about 2.3 miles from the junction of U.S. Route 220 with Route 322, (which contains) abundant pyrite in the Bald Eagle formation.”

Pennsylvania is crossed by literally hundreds of known and yet unrecognized lineaments of varying size, orientation, and significance. It has long been accepted that lineaments allow for the transport of a variety of fluids and gases, and the emplacement of an array of minerals, some of which may have the distinct capability of producing large amounts of acid drainage and associated environmental damage. The identification and interpretation of the presence, extent, and orientation of lineaments has great importance in hydrogeology, economic geology, and in a variety of engineering applications. Of particular interest here is the known capacity or tendency of some lineaments to contain significant amounts of acid-producing sulfides. By identifying and characterizing the numerous known and unknown lineaments it may become possible to avoid intersecting them during construction, thus preventing potential harmful environmental effects.

The cross-strike nature of many lineaments means that they frequently transverse multiple geologic formations. For this reason, a particular formation or rock type that is not characteristically considered to be problematic in terms of primary or sedimentary sulfides may nonetheless be host to significant secondary or hydrothermal sulfides. Consequently, without some level of consideration of the presence and implications of lineaments and associated zones of mineralization there can be a danger of acid drainage regardless of the host rock. Apart from the acknowledgement of a lineament or a known mineral deposit, few deterministic models exist at this point for predicting the likelihood of acid-forming minerals along any lineament. Therefore, each location must essentially be considered independently, and site-specific

investigations coupled with literature reviews and personal communications are of paramount importance with respect to identifying zones of mineralization associated with lineaments.

Figure 3.7 helps to illustrate the relationships among lineaments, numerous documented localized sulfides, and sandstones. Although many of the localized occurrences are hosted by sandstones found within formations such as the Tuscarora or Bald Eagle, many are also hosted by carbonate rocks as well. Note especially the sandstone-hosted isolated sulfide occurrences found located in the Valley and Ridge province that visually plot along the large and prominent northwest to southeast trending lineament known as the Tyrone – Mt. Union lineament (see Figure 3.6).

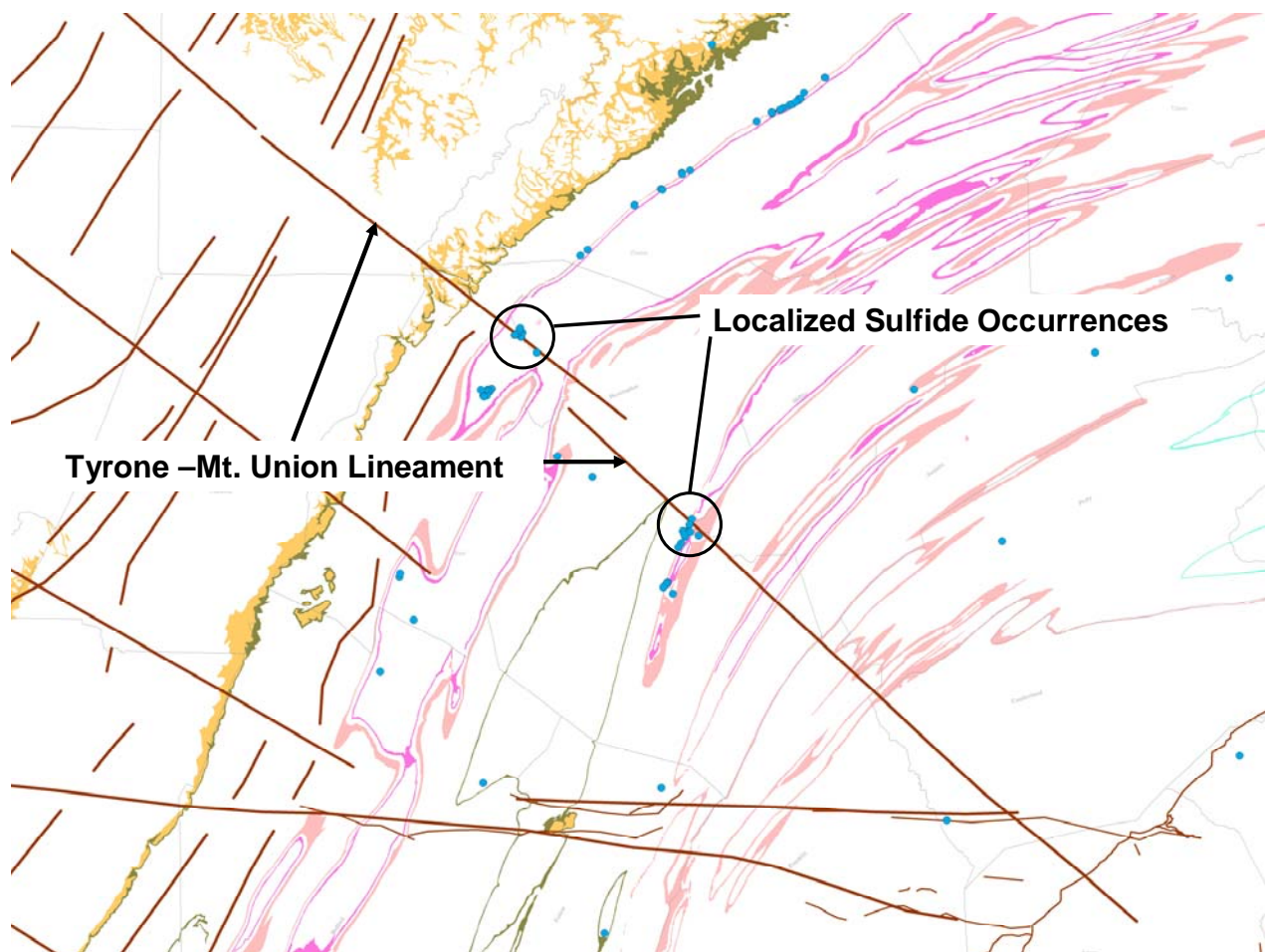


Figure 3.6. Isolated sulfide deposits occurring along the Tyrone – Mt. Union lineament.

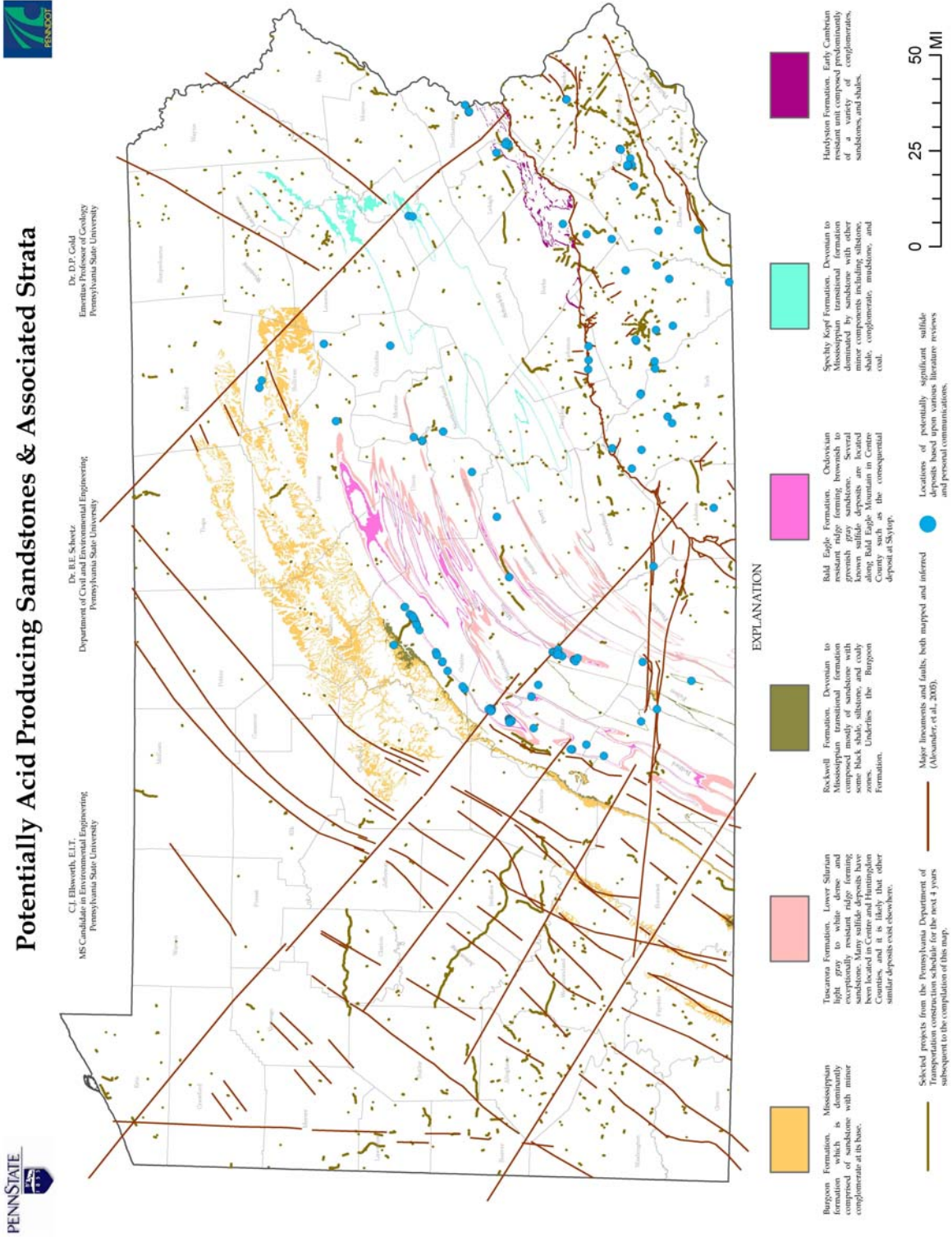


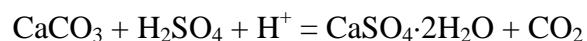
Figure 3.7. Map showing the relations among lineaments and isolated sulfide deposits.

3.4 Geotechnical Considerations – Swelling and Heave

Although the consequences and processes leading to the generation of acid rock drainage have been studied for decades, relatively little attention has been directed towards the problems occurring from the volumetric expansion that can often occur in certain sulfide-bearing formations. The negative effects of swelling and subsequent heave have been observed in numerous geotechnical engineering projects, ranging from schools, homes, and hospitals to mines, dams, and roads. Worldwide, countless millions of dollars of damage has been incurred as a result of the degradation of various structures due to heave.

The initiation of swelling begins with the onset of acid drainage brought about by the introduction of oxygen and water to sulfide-bearing lithologies. Several common construction activities can establish the necessary conditions to begin and sustain the process of swelling and heave, including excavation, blasting, and lowering of the water table, all of which may assist in the establishment of the oxidizing conditions necessary for the inception of ARD. With the onset of ARD comes the generation of sulfuric acid (H_2SO_4), which is elemental to the initiation of swelling.

One of the most fundamental reactions leading to swelling is seen as follows:



In many cases, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) has been interpreted as one of the most important contributors to the volumetric expansion of the swelling rock or fill. Gypsum is a relatively soft although fairly insoluble mineral which has a variety of crystal habits and which is typically colorless or white but may take on shades of gray, yellow, red, brown, or blue (Nesse, 2000). The solubility product (pK_{sp}) of gypsum is given as 4.59 (Gold and Doden, 2007). Gypsum has about two times the molar volume of calcite (Gold and Doden, 2007) and often results in

significant heaving forces exerted upon engineered structures such as footings, floor slabs, and roads. Heaving forces have been calculated to characteristically be at least 1.499 ksf (71.8 kPa) (Quigley and Vogan, 1970), but have been measured up to 12.53 ksf (600 kPa) and more (Hoover et al, 2004). Gypsum crystals have been identified in expansive shales responsible for the heaving of numerous engineered structures such as the Evangelical Hospital in Lewisburg, Pennsylvania (Hoover, 2002), the Johnson City Public Library in eastern Tennessee (Belgeri and Sigel, 1998), the Old Airport Road in Bristol, Virginia (Freeman, 2003), numerous residential dwellings in Quebec, Canada (ACQC, 1999), and the Llandough Hospital in Cardiff, Wales, United Kingdom (Hawkins and Pinches, 1987). All of the aforementioned cases have involved black calcareous mudstones and shales of varying geologic ages used as either fill materials or as a base for foundations, walls, floors, roads, and other structural building components. Gold and Doden (2007) have listed and discussed several other cases involving swelling and heave in various settings and conditions, and have also tabulated molar volumes of numerous minerals and the volume increases related with several relevant reactions.

An added risk is coupled with the formation of gypsum when sulfuric acid reacts with calcite. The associated production of carbon dioxide (CO₂) along with gypsum may, under certain circumstances, present a significant hazard to people. If enough CO₂ is allowed to accumulate in restricted or closed areas with a lack of proper ventilation, as may often be the case in certain types of temporary and permanent structures, an apparent risk of asphyxiation exists to anyone who may be working in such conditions (Bryant, 2003).

Although it appears that the oxidation of pyrite and subsequent reaction of sulfuric acid and calcite to produce gypsum is often the primary and most significant reaction in many cases of swelling and heave, there are numerous other reactions involving a variety of primary and

secondary minerals that are often contributing factors in many situations. For instance, Bryant (2003) distinguished between two broad types of heave, namely sulfide-induced and sulfate-induced. Sulfide-induced heave takes place when heave occurs from the oxidation of sulfides to produce sulfates, while sulfate-induced heave results from the reaction of sulfates to produce other troublesome sulfates (Bryant, 2003). A few examples of the other expansive minerals that have been documented in a variety of locations are jarosite ($\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$), alunite ($\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$), melanterite ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$), and ettringite $\text{Ca}_6[\text{Al}(\text{OH})_6]_2(\text{SO}_4)_3 \cdot 26\text{H}_2\text{O}$ (Bryant, 2003). The chemical and physical processes and parameters surrounding these two modes of heave are intricate and varied, and will be unique at any given geographic location or construction site.

It has been suggested that as little as 0.1% sulfide is sufficient to lead to destructive swelling in some cases (Hoover, 2002; Bryant, 2003). This sulfur value is an oversimplification, however, as numerous complicated factors are in play in any given situation or geographic location, and it is likely that this value is not a reliable threshold value or lower end, as it has been based mostly on limited empirical studies and on little theoretical analysis (Hoover et al., 2004).

It may take years before significant signs or effects of swelling are noticed, and once it begins it may continue for decades at varying rates dependent upon local conditions (Bryant, 2003). On the whole, swelling has proven to be difficult to accurately predict, simulate, and model despite years of attention by scientists and engineers and despite several retroactive case studies. Therefore, the potential for swell should be interpreted and analyzed before construction activities begin through such measures as literature review, analysis of similar or nearby

situations with common geological and engineering factors, and detailed geologic mapping and testing of rock cores for chemical and physical properties.

If the potential for swell is strongly implied or suspected on the basis of preliminary investigations, measures should be taken to avoid its onset. Several actions can be taken to help avoid swelling. The first and most basic way to avoid swelling and heave of engineered structures is to simply avoid rock and soil formations that are known or strongly suspected to be problematic based upon previous knowledge and/or preliminary site investigations. The avoidance of such units can be achieved by making new site selections when possible, as may be the case with highway corridors. This can also be accomplished by complete excavation and removal of the stratigraphic units with swell potential in order to expose more stable or un-reactive units for use as a bedrock foundation. These measures are not always practical, however, and if large amounts of pyritic material are excavated and removed to avoid swelling it may present acid drainage problems, resulting in trading one problem for another.

Another simple measure that should be employed whenever possible is to avoid using pyritic fill materials such as calcareous black shales as backfill against walls, or beneath floor slabs, roads, and other structures. The high surface area of crushed fill materials makes them especially prone to swelling when exposed to oxidizing conditions (Hoover, 2002, 2004; ACQC, 1999).

Another important consideration in the avoidance of swelling involves the use of calcareous materials such as limestone, dolomite, lime kiln dust, and bag house lime. Limestone and dolomite are often used as aggregates for sub-base, concrete and asphalt and have seen wide use in many engineering applications. Lime kiln dust and bag house lime are often used as cheap and readily available materials for use in alkaline addition to pyritic materials in order to prevent

acid drainage. Although these measures may prevent acid from forming, they may greatly increase the potential for swell if mixed with pyritic materials (Hoover, 2004; Bryant, 2003). Since calcium is a primary constituent in all of these materials, and since it plays a significant role in the formation of gypsum and other expansive minerals in the presence of sulfuric acid, their use should be avoided if swelling potential is known or suspected. If it is necessary to use pyritic materials that are to be subjected to alkaline addition, one strategy that has been suggested is to allow the mixture of pyritic and alkaline material sufficient “mellowing time” to chemically and physically react, in which expansive minerals have the opportunity to grow in an unconfined environment before being used as fill or as sub-base (Bryant, 2003).

An additional strategy to limit oxidation and help prevent swelling is to use any of a variety of spray-type sealants to prevent oxygen from interacting with pyritic rock. However, the use of spray sealants may be unrealistic in many situations, especially in wet working conditions or where various construction activities throughout the course of the project may compromise the integrity of the seal (Hoover, 2004). Where spray-on sealants are unrealistic, thin concrete “mud slabs” have been used as an alternative method to seal off bedrock from water and oxygen (Hoover, 2004). In some cases, designs have incorporated engineered void spaces beneath floor slabs in order to allow some amount of swelling to take place without incurring any of its detrimental effects (Belgeri and Siegel, 1998).

In many cases pre-stressed rock bolts have been successfully used in order to effectively restrain stratigraphic successions from expanding (Belgeri and Siegel, 1998). Rock bolting is best suited for moderately loaded structures such as floor slabs and other structures with relatively limited pressures of less than 475 kPa (Belgeri and Siegel, 1998). The pressure exerted by the use of rock bolts should reflect values inferred from laboratory or field tests upon

the particular geologic formation in question, and the bolts should be designed to extend beyond the expansive strata into underlying layers (Hoover, 2004).

Regardless of the methods used to predict, avoid, mitigate, or remediate particular sites affected by expansive geologic materials, measures should always be taken if there is a likelihood for swelling to avoid the problem up front. It is always easier to deal with a potentially expansive material before and during construction activities than it is to engage in costly and time-consuming remediation efforts after damage to a structure has already taken place.

4.0 RESULTS AND INTERPRETATIONS

This chapter will present the relevant and central information and will discuss the results and interpretations of the data gathered and brought together during the course of this study. Topics included in the results and interpretations section will include the black shales, coal-bearing lithologies, and isolated sulfide deposits.

4.1 Black Shale Formations

Numerous black shales of varying age are found in Pennsylvania. In general these black shales were deposited in anoxic or euxinic relatively stagnant and deep water environments in which a lack of oxygen and an influx of organic matter, dissolved iron, and sulfate ultimately led to the precipitation of acid-producing sulfide minerals such as pyrite and marcasite. The following discussions summarize key points and trends of individual black shales sampled as part of this study. A total of 94 black shale samples were gathered, chemically analyzed, and plotted (see Figure 4.1). Recall that the values for neutralization potential, NP, and net neutralization potential, NNP, have been given in units of tons of calcium carbonate (CaCO_3) equivalent per thousand tons of material.

All of the sampled black shales below, which have been listed from youngest to oldest, when taken as a whole show some general statewide trends in terms of the variation in NNP values. For all of the black shales with inferred contoured isopach NNP ranges, the red lines show regions that have been interpreted on the basis of the relevant data to be acid producing while the black lines show areas that have been interpreted to be non-acid producing. Two north/south trending zones in which acid production appears to be more likely can be observed: the first trends roughly from Centre County south into Fulton County, and a second, less

consistent trend appears to extend approximately from Lycoming County to Snyder County (see figure 4.2). Also, when viewing the NNP distributions for the individual black shales discussed below, the same north/south trends can be seen, which are characterized by lower NNP values and what appears to be in general a high probability for ARD. The ostensible north/south trend can be seen rather well in the Mandata Shale and the Hamilton Group and to a lesser extent in the Reedsville/Antes/Upper Coburn succession. The potential trend is further supported by the data of the Marcellus and Mahantango Formations.

4.1.1 Burket Member of the Harrell Formation

The Burket member was sampled at 10 different locations during the course of this study and was found to be acid producing at 6 of the 10 locations. Percentage of sulfur (%S) values range from 0.04 to 1.74, neutralization potential values range from 0.5 to 39.25, and net neutralization potential values range from -41.63 to 34.25. Figure 4.4 shows the field sampling locations for the Burket along with respective NNP values for each location. Figure 4.5 shows the contoured distribution of NNP values within the Burket inferred on the basis of the 10 data points.

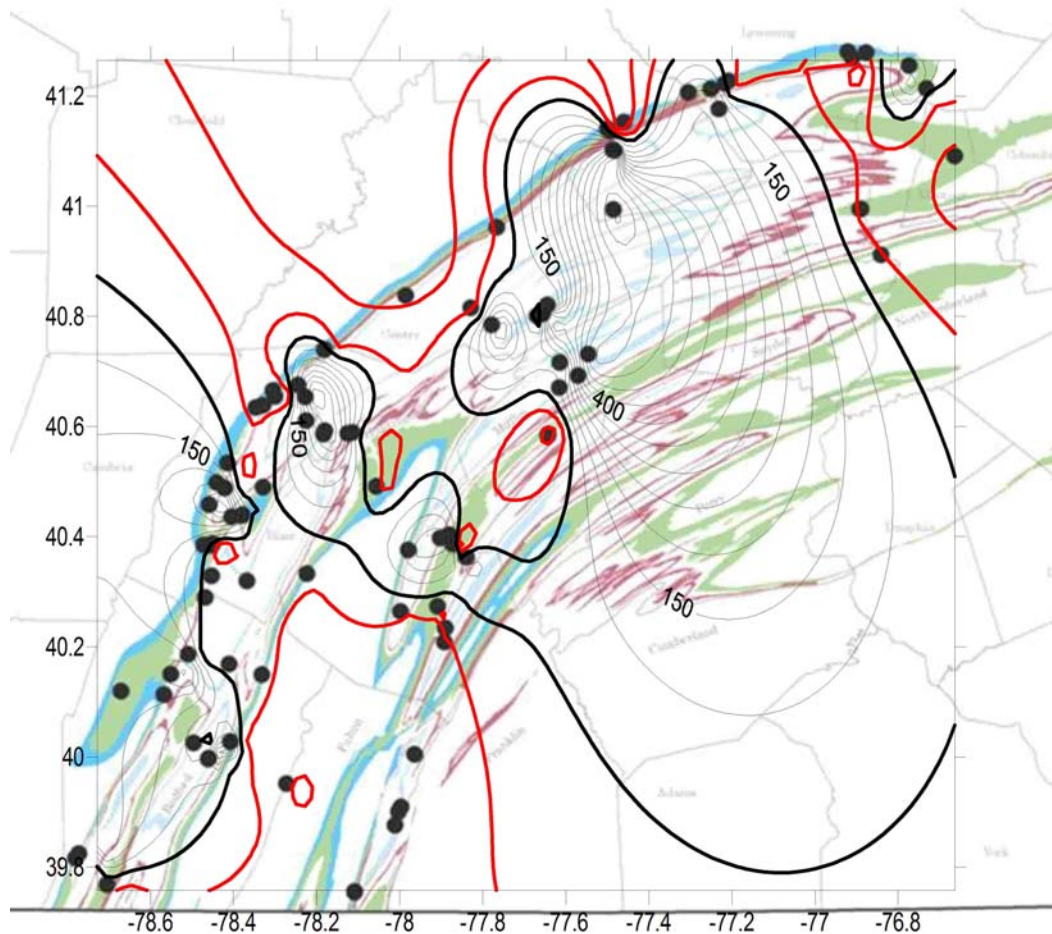


Figure 4.2. Inferred contoured isopach NNP ranges for all sampled black shales.

Little has been documented outside of the data presented here about the Burket member's potential to produce ARD or to swell. However, the data presented here suggest that the Burket has a strong potential to produce ARD over much of its extent. The potential of the Burket to swell is basically unknown, but it should be noted that light-colored whitish efflorescent minerals of an unknown variety (see Figure 4.3) were observed in the field at the Lockport sampling locality (lat 41.1415, lon -77.4444), which suggests that swelling may be possible under certain conditions. The Burket member should be approached with caution during

construction and should be sampled to determine if it has the potential to cause ARD at a given site under consideration for excavation.



Figure 4.3. Burket member showing the presence of encrusting efflorescent minerals.

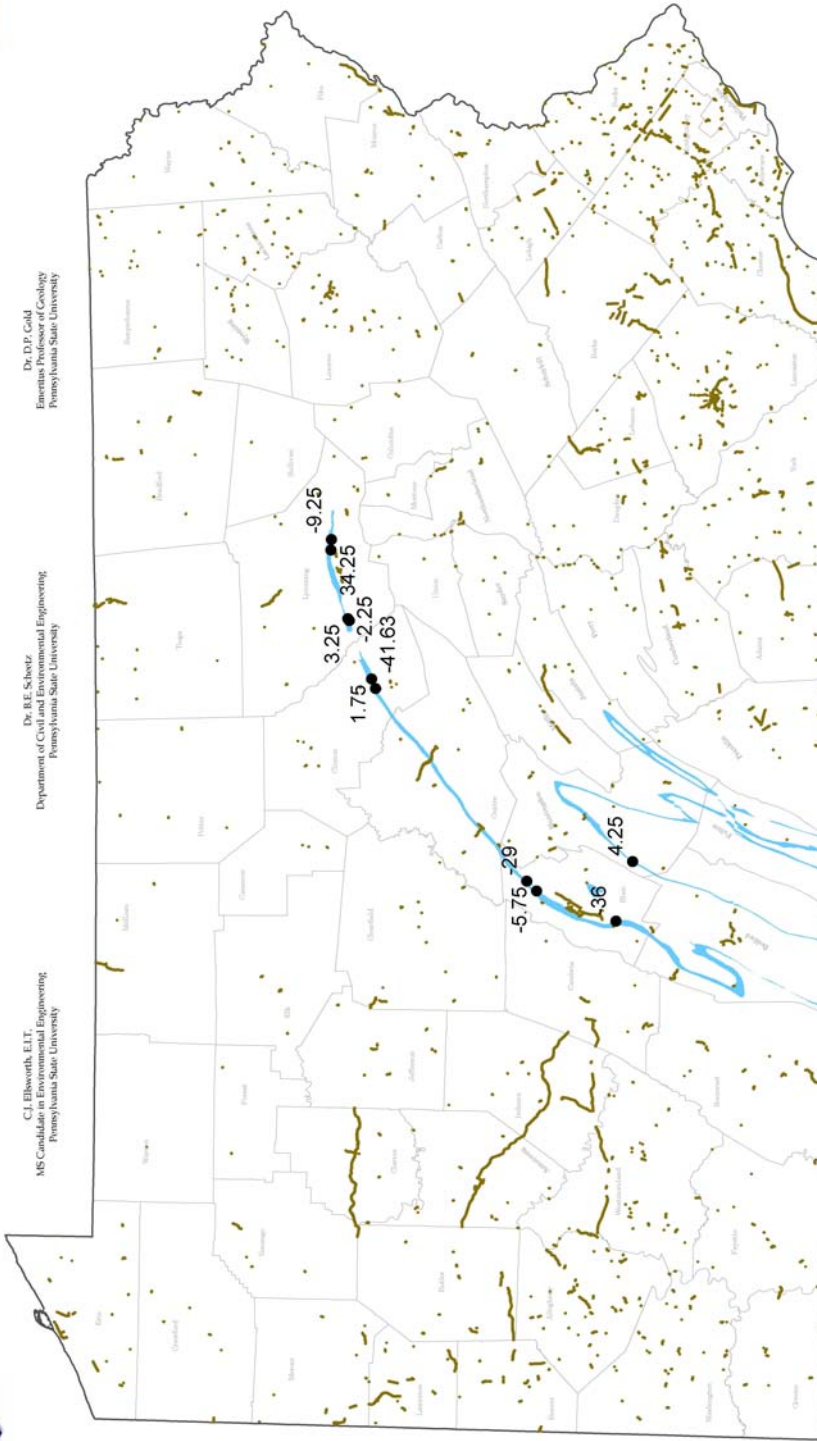
NNP of the Burket Member of the Harrell Formation



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EXPLANATION



The Butler and Harrell Formations undivided. Sequence contains the dark gray to black Burket member which has been identified as a potentially significant black shale.



Selected projects from the Pennsylvania Department of Transportation construction schedule for the next 4 years subsequent to the compilation of this map.



Locations of field sample collection based upon previously identified outcrops of potentially acid producing formations.

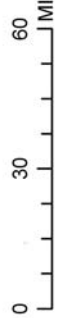


Figure 4.4. Distribution of the Burket member showing respective sample NNP values with PennDOT's projected construction projects overlaid.

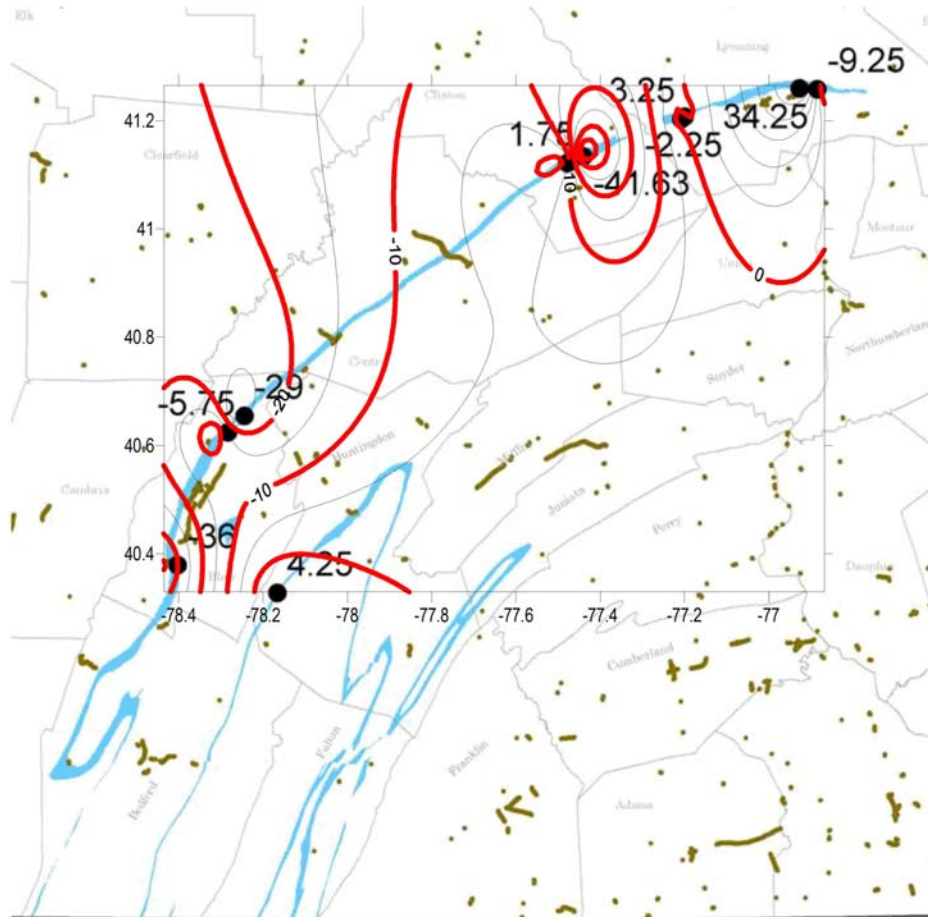


Figure 4.5. Inferred contoured isopach NNP ranges for the Burket member with PennDOT's projected construction projects overlaid.

4.1.2 Mahantango Formation

The Mahantango Formation was sampled at only four locations during this study but was determined to be acid producing at all four sites. %S values range from 0.32 to 1.16, NP values range from -3.75 to 8, and NNP values range from -29.5 to -2. Figure 4.6 shows the field sampling locations for the Mahantango along with respective NNP values for each location. Figure 4.7 shows the contoured distribution of NNP values within the Mahantango inferred on the basis of the four data points. With only four data points this particular NNP distribution for

the Mahantango should not be considered as being extremely accurate, but has been presented nonetheless.

Little is known about the potential of the Mahantango Formation to produce ARD or swell. At this point it is unclear as to the level of risk associated with the Mahantango both in terms of ARD and swelling potential; however, the limited amount of data obtained during this study suggests that portions of the formation will produce ARD, specifically the dark shale components. For this reason, the Mahantango should be approached with caution wherever it may be encountered.

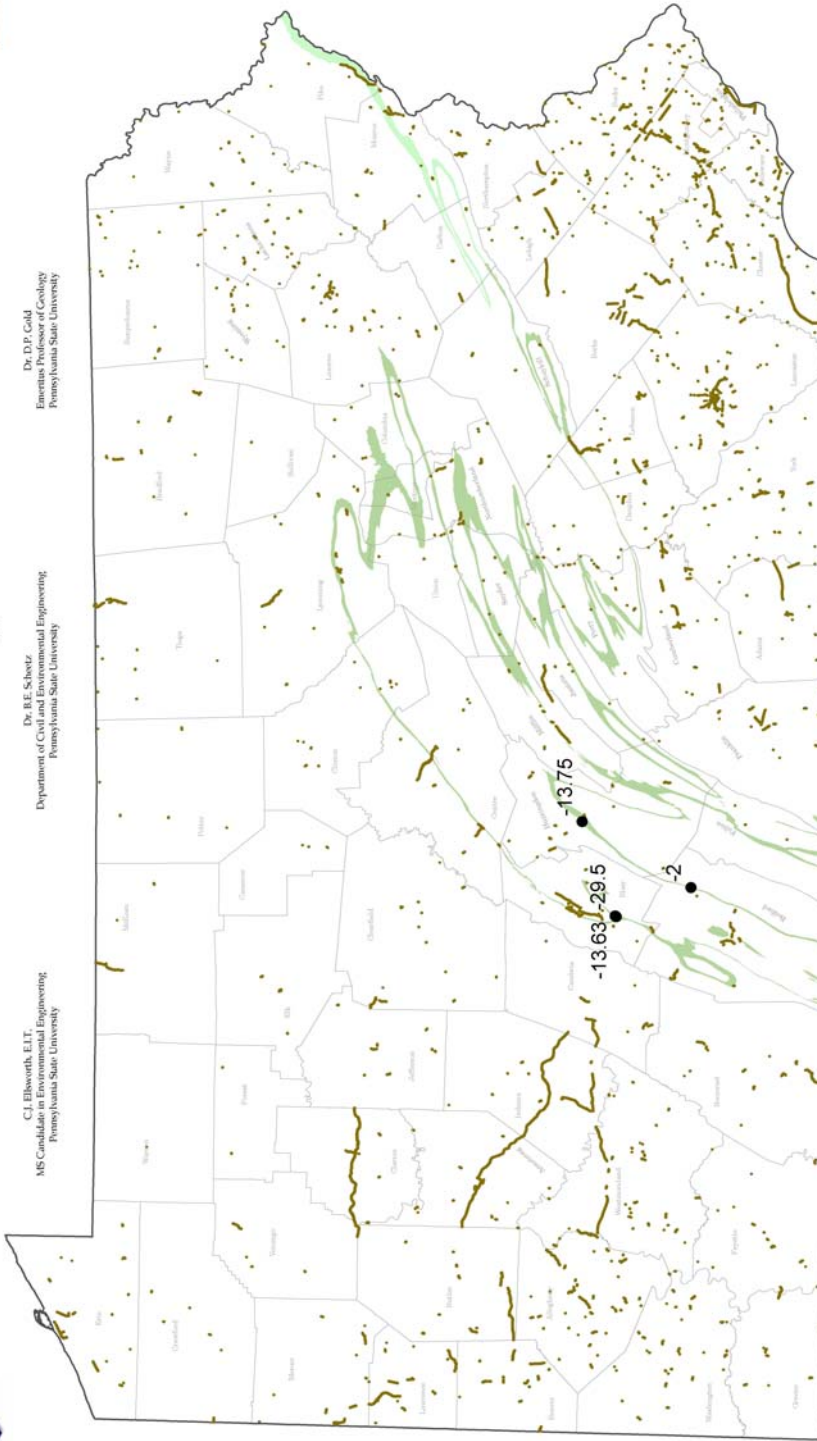
NNP of the Mahantango Formation



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EXPLANATION



-  The Mahantango Formation. Mapped unit is the Hamilton Group. The Hamilton Group is a series of shales, siltstones, and sandstones found in central and eastern Pennsylvania.
-  Selected projects from the Pennsylvania Department of Transportation construction schedule for the next 4 years subsequent to the compilation of this map.
-  Locations of field sample collection based upon previously identified outcrops of potentially acid producing formations.

Figure 4.6. Distribution of the Mahantango Formation showing respective NNP values with PennDOT's projected construction projects overlaid.

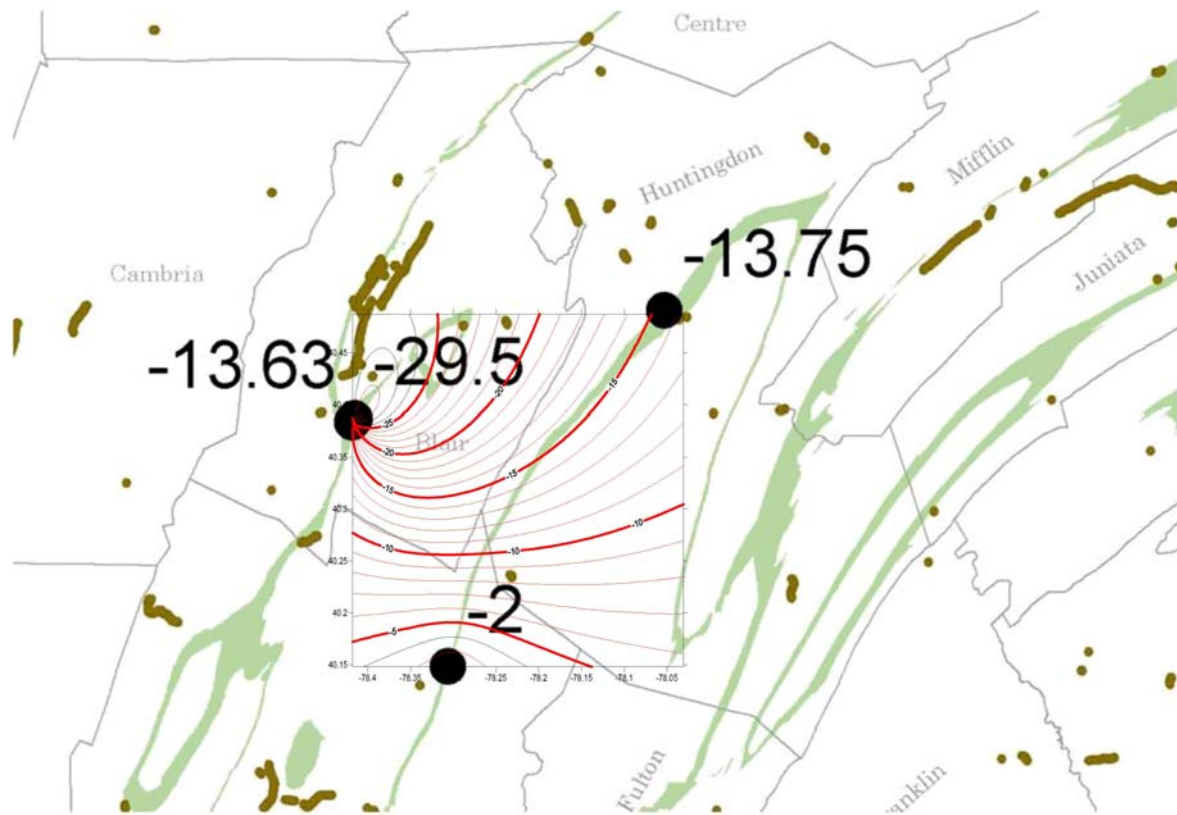


Figure 4.7. Inferred contoured isopach NNP ranges for the Mahantango Formation with PennDOT's projected construction projects overlaid.

4.1.3 Marcellus Formation

The Marcellus Formation was sampled at 10 different locations during the course of this study and was determined to be acid producing at all sampling sites. %S values range from 0.06 to 3.68, NP values range from -42.25 to 47.25, and NNP values range from -101.5 to -2.13. Figure 4.8 shows the field sampling locations for the Marcellus along with respective NNP values for each location. Figure 4.9 shows the contoured distribution of NNP values within the Marcellus inferred on the basis of the 10 data points.

The Marcellus Formation has been widely cited by numerous sources as being a major source of ARD in Pennsylvania and elsewhere (Orndorff, 2001; Hoover, 2002; Gold and Doden, 2007) and has also been extensively documented to cause significant swelling and heave of engineered structures (Hoover, 2002, 2004, 2005) (see Section 5.2). The Marcellus has already caused problems during the course of highway construction along Route 522 near Lewistown, Pennsylvania (see Section 5.3), and along Route 209 near Marshalls Creek, Pennsylvania, leading to costly and time-consuming remediation efforts. The Marcellus is widely distributed throughout much of Central and Eastern Pennsylvania and is likely to be encountered in a variety of construction projects in the future. Data provided by Keith Brady of the Pennsylvania Department of Environmental Protection (Pers. Comm., 2007) show ranges in percent sulfur values of the Marcellus for samples taken from both Route 522 and Route 209 (see Figure 4.10).

It seems likely based upon the data acquired in this study and during numerous other investigations that the Marcellus will cause ARD anywhere it is encountered. Furthermore, there is also a distinct possibility for swelling of the Marcellus Formation depending upon other local factors and depending upon how the excavated material is treated. It is highly recommended that the Marcellus be avoided whenever possible for the aforementioned reasons. If excavation into un-oxidized portions of the Marcellus is deemed necessary or unavoidable all necessary precautions should be taken to mitigate ARD and the formation should not be used as a foundation material whether left as competent bedrock or as fill material. Similarly, the Marcellus should not be used as fill material in any proportion due to the extreme likelihood of associated swelling problems.

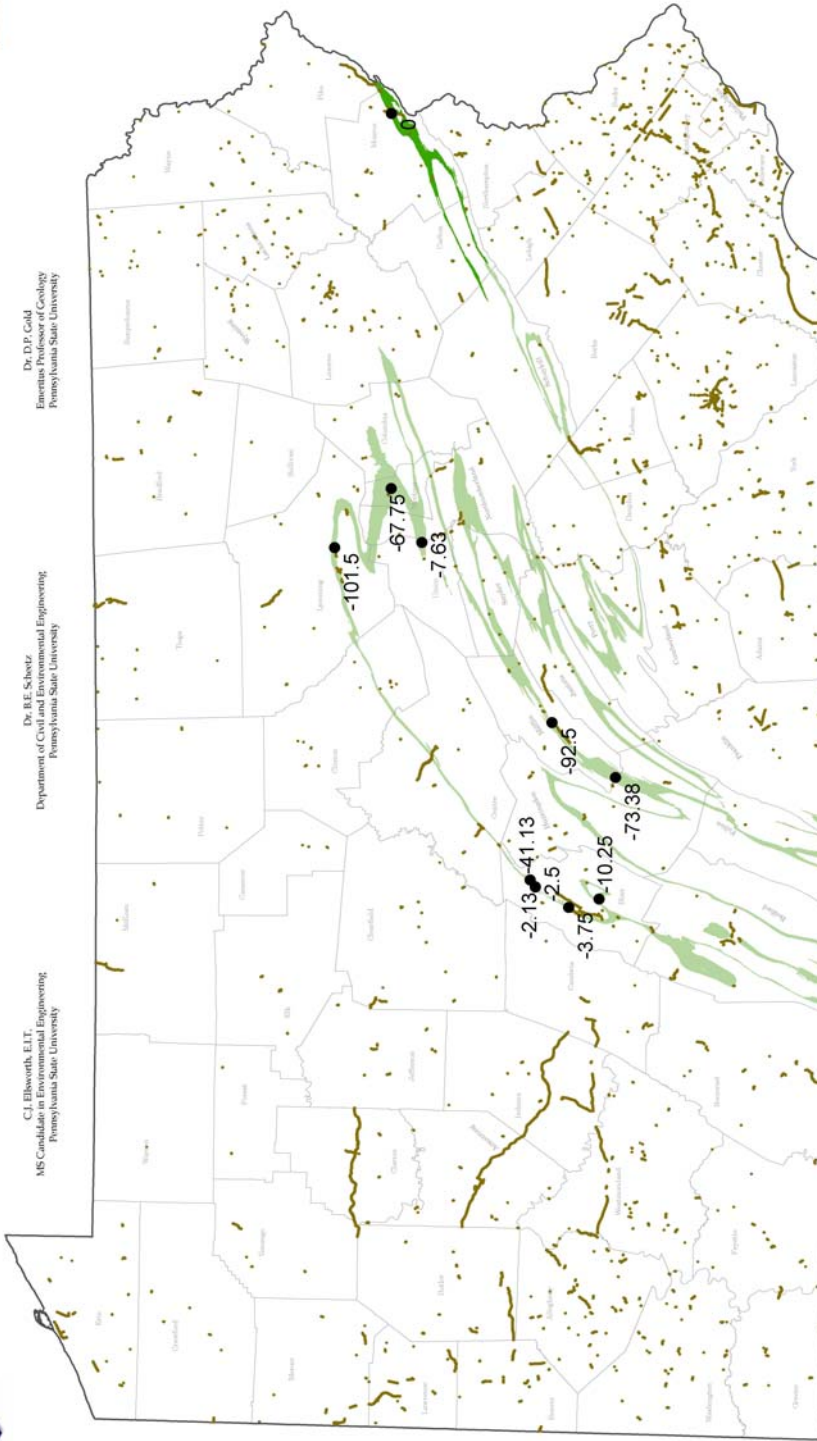
NNP of the Marcellus Formation



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EXPLANATION

-  The Marcellus Formation. Map units include the Hamilton Group, Onondaga Formation, Seneca Group, and the Escopus, Baitermilk, and Falls Formations, undivided.
-  The Marcellus Formation, Devonian black shale containing significant framboidal pyrite, and the Escopus, Baitermilk, and Falls Limestones through Escopus Formation.
-  Selected projects from the Pennsylvania Department of Transportation construction schedule for the next 4 years subsequent to the compilation of this map.
-  Locations of field sample collection based upon previously identified outcrops of potentially acid producing formations.

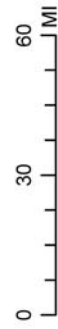


Figure 4.8. Distribution of the Marcellus Formation showing respective NNP values with PennDOT's projected construction projects overlaid.

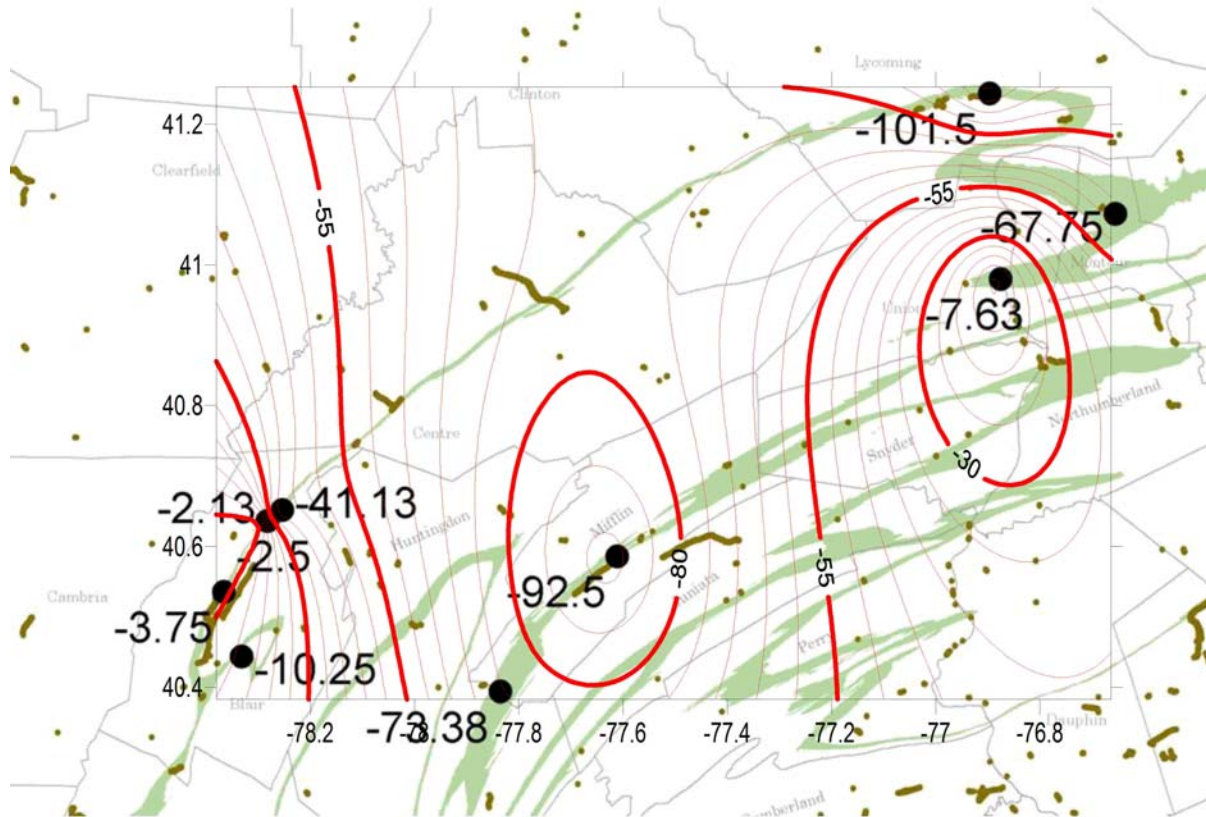


Figure 4.9. Inferred contoured isopach NNP ranges for the Marcellus Formation with PennDOT's projected construction projects overlaid.

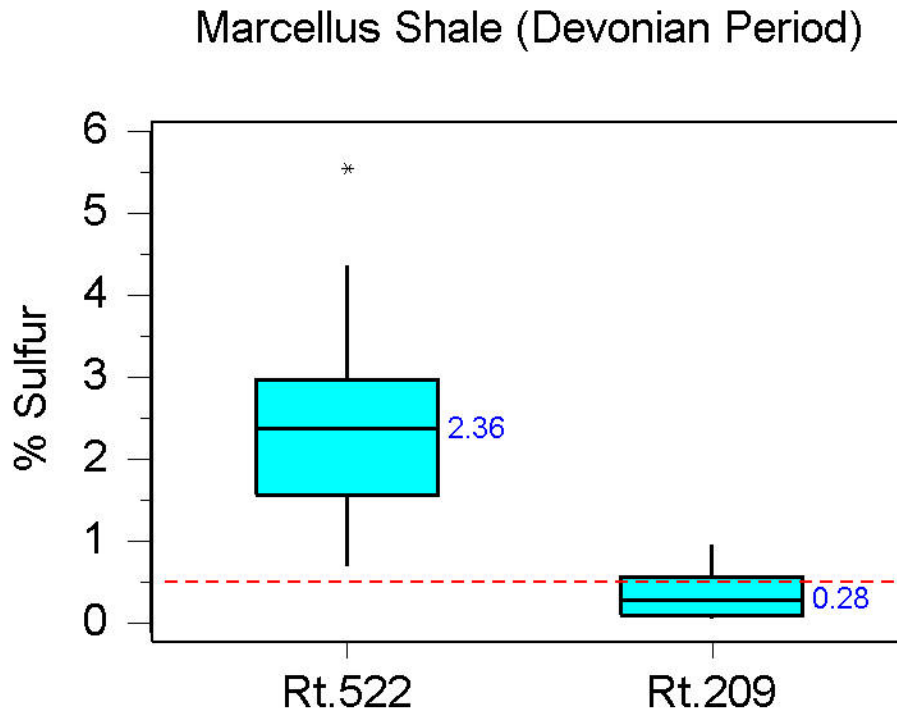


Figure 4.10. Measured ranges in %S of the Marcellus Formation taken from Routes 522 & 209 (Brady, Pers. Comm., 2007).

4.1.4 Hamilton Group

The Hamilton Group was sampled at nine different locations during the course of this study and was determined to be acid producing at five of the sampling sites. %S values range from 0.06 to 0.8, NP values range from -2.75 to 227.5, and NNP values range from -9.0 to 214.38. Figure 4.11 shows the field sampling locations for the Hamilton along with respective NNP values for each location. Figure 4.12 shows the contoured distribution of NNP values within the Hamilton inferred on the basis of the nine data points.

The nine samples taken from the Hamilton Group during this study are representative of black shales of unknown designation. The Hamilton Group includes the Marcellus and

Mahantango Formations, discussed previously. The nine samples taken from the Hamilton Group may be from the Marcellus, Mahantango, or other unidentified shales from this stratigraphic unit. The time constraints of this study did not allow for the detailed and involved mapping that would be necessary to conclusively identify from which shale these nine samples were acquired, and so they have been stratigraphically confined with a reduction of precision to the designation of the Hamilton Group.

It is known that the Marcellus and Mahantango formations are both problematic, and the results for the Hamilton Group further underscore the potential hazards associated with this Middle Devonian stratigraphic interval. There appears to be a distinct potential for ARD and swell within much of the Hamilton Group, and as such the whole interval should be approached with caution as it may lead to both ARD and swell.

NNP of the Hamilton Group, Unknown Black Shales



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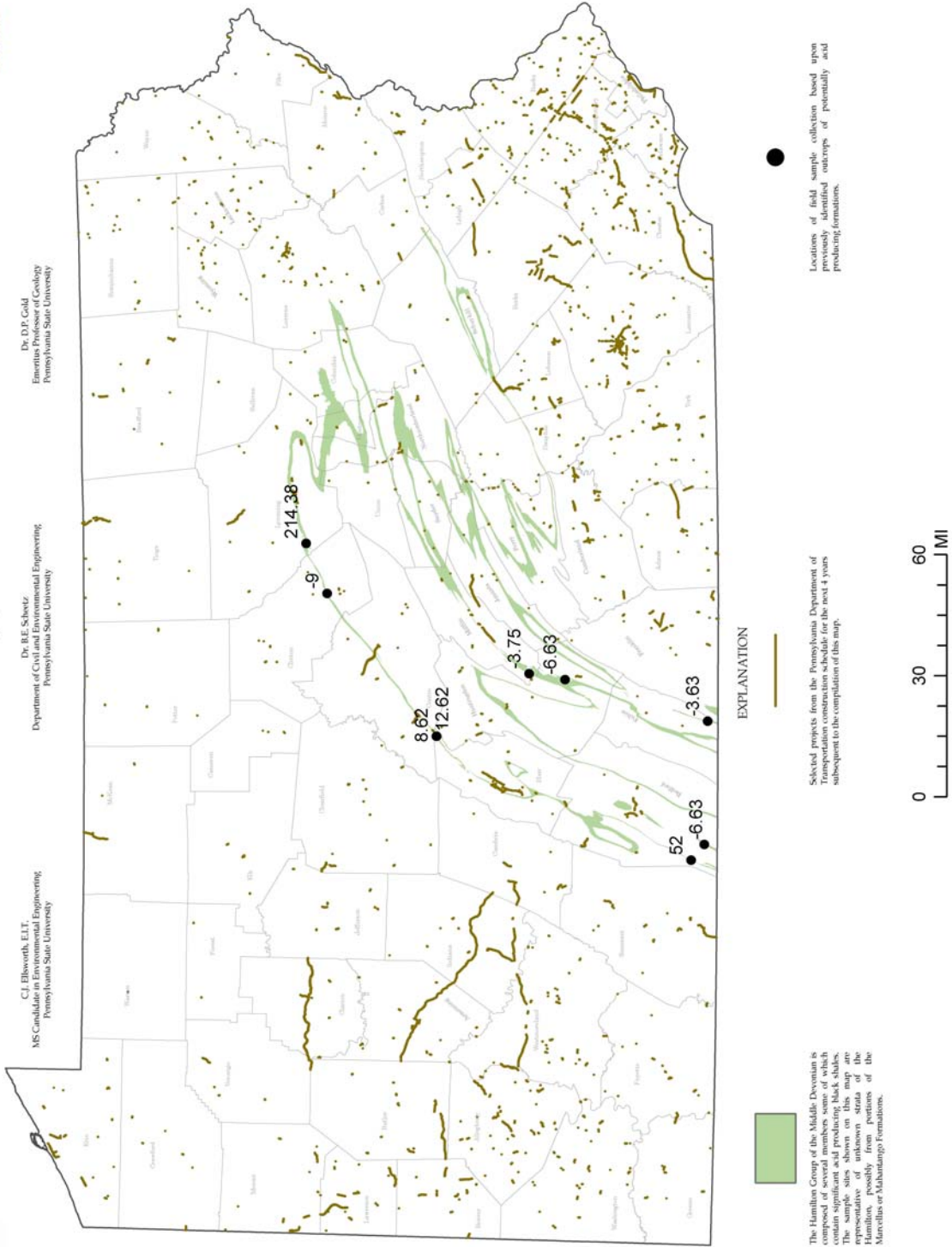


Figure 4.11. Distribution of the Hamilton Group showing respective NNP values with PennDOT’s projected construction projects overlaid.

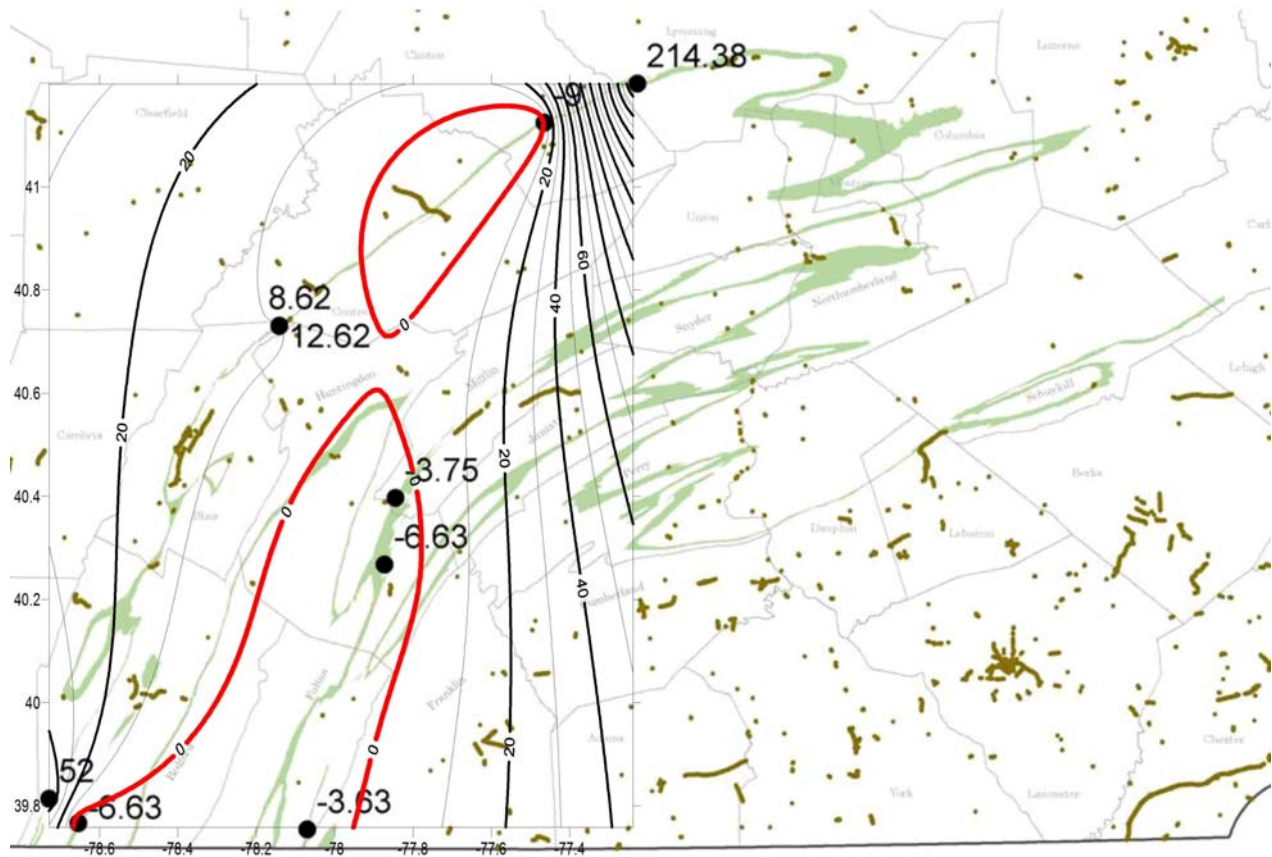


Figure 4.12. Inferred contoured isopach NNP ranges for the Hamilton Group with PennDOT’s projected construction projects overlaid.

4.1.5 Needmore Shale

The Needmore was sampled only in two places during this study and was not found to be significantly acid producing at either site. %S values range from 0.16 to 1, NP values range from 6 to 250, and NNP values range from 1 to 218.75. Figure 4.13 shows the field sampling locations for the Needmore along with respective NNP values for each location. A figure of the contoured distribution of NNP in the Needmore was not generated due to the limited number of samples obtained during the course of this study.

The paucity of data gathered for the Needmore Shale here or elsewhere in Pennsylvania makes it extremely difficult to comment on any trends or general likelihood for the shale to produce ARD or to swell. The Needmore, however, is known to be problematic in parts of nearby Virginia, where it has been found to be a problematic acid producer (Orndorff, 2001). Based on this fact and the significant amounts of sulfur detected in the two samples listed here, the Needmore Shale deserves more attention in Pennsylvania and should be approached with caution during any excavation that is to be sited through it.

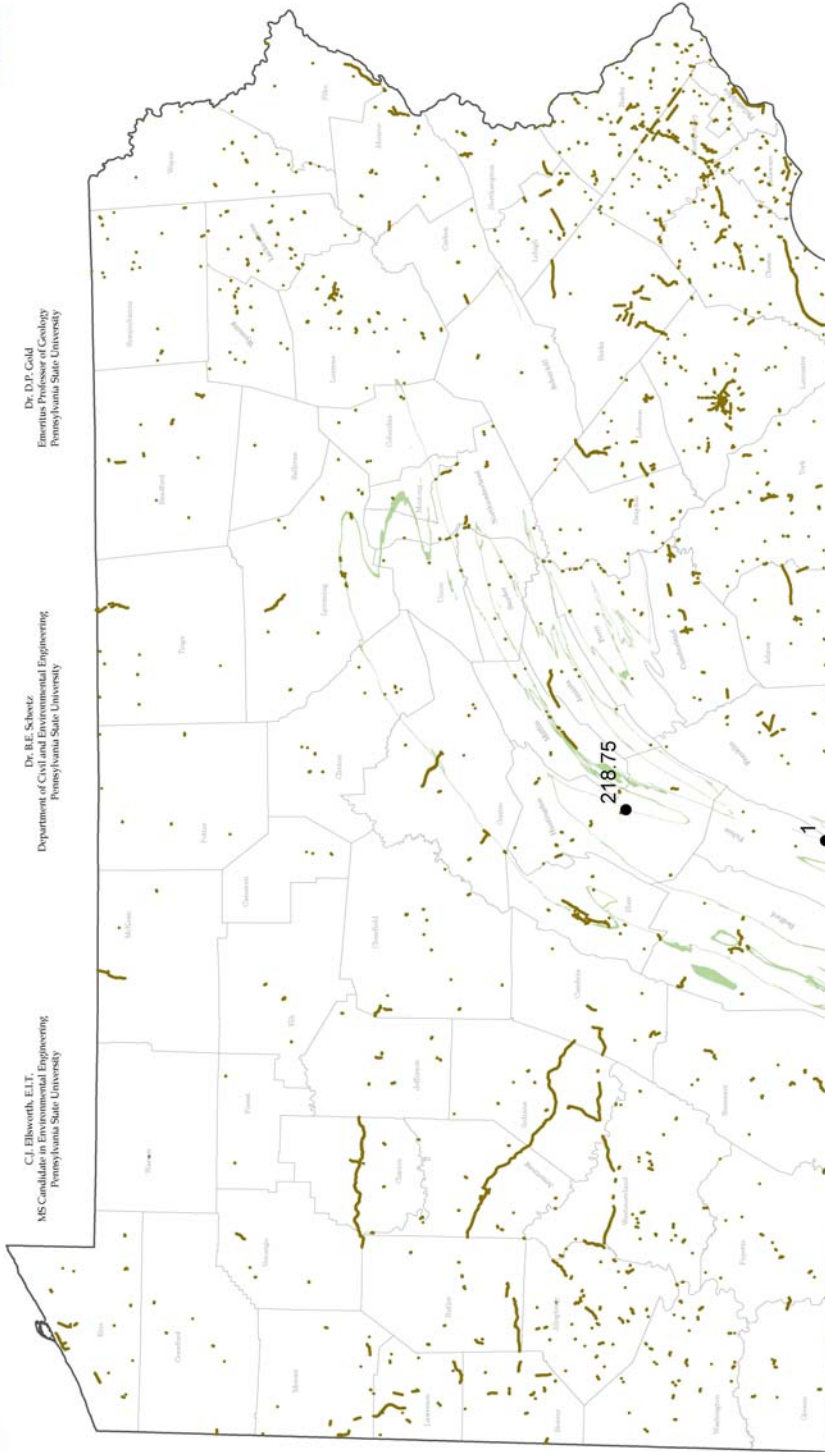
NNP of the Needmore Shale



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EXPLANATION

- The Needmore Shale. Map units include the Onondaga Formation and the Onondaga and Old Port Formations, undivided.
- Selected projects from the Pennsylvania Department of Transportation construction schedule for the next 4 years subsequent to the compilation of this map.
- Locations of field sample collection based upon previously identified outcrops of potentially acid producing formations.

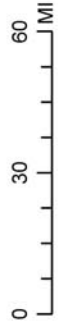


Figure 4.13. Distribution of the Needmore Shale showing respective NNP values with PennDOT's projected construction projects overlaid.

4.1.6 Mandata Shale

The Mandata member, also sometimes referred to as the Mandata Shale, was sampled at 15 locations during this study and was generally not found to be acid producing with the exception of two locations. %S values range from 0.1 to 2.32, NP values range from -38.25 to 471.25, and NNP values range from -86.38 to 444.37. Figure 4.15 shows the field sampling locations for the Mandata along with respective NNP values for each location. Figure 4.16 shows the contoured distribution of NNP values within the Mandata inferred on the basis of the 15 data points.

All of the sample locations with the exception of the two that appear to be acid generating appear to have a significant calcareous component as evidenced by the generally high fizz ratings and neutralization potentials. One of the samples that does show the potential for acid production was observed in the field in a road cut along Route 30 north of Everett, Pennsylvania, to be completely unvegetated and prone to erosion, presumably due to its production of ARD (see Figure 4.14). Several of the samples that show high fizz and NP values also show significant %S values. For this reason it seems that the Mandata may have the distinct possibility to swell under certain conditions, although such a situation has not been documented thus far. Although the Mandata is a relatively thin black shale, it should be treated with caution in all situations in which it is encountered. The Mandata is known to cause ARD in some areas, is suspected to have the necessary components to lead to swelling, and has been generally observed in the field to be a muddy, friable, and incompetent stratum that would typically be unsuitable as a foundation for any size structure.



Figure 4.14. The Mandata member exposed along portions of Route 30 north of Everett, Pennsylvania.

NNP of the Mandata Shale

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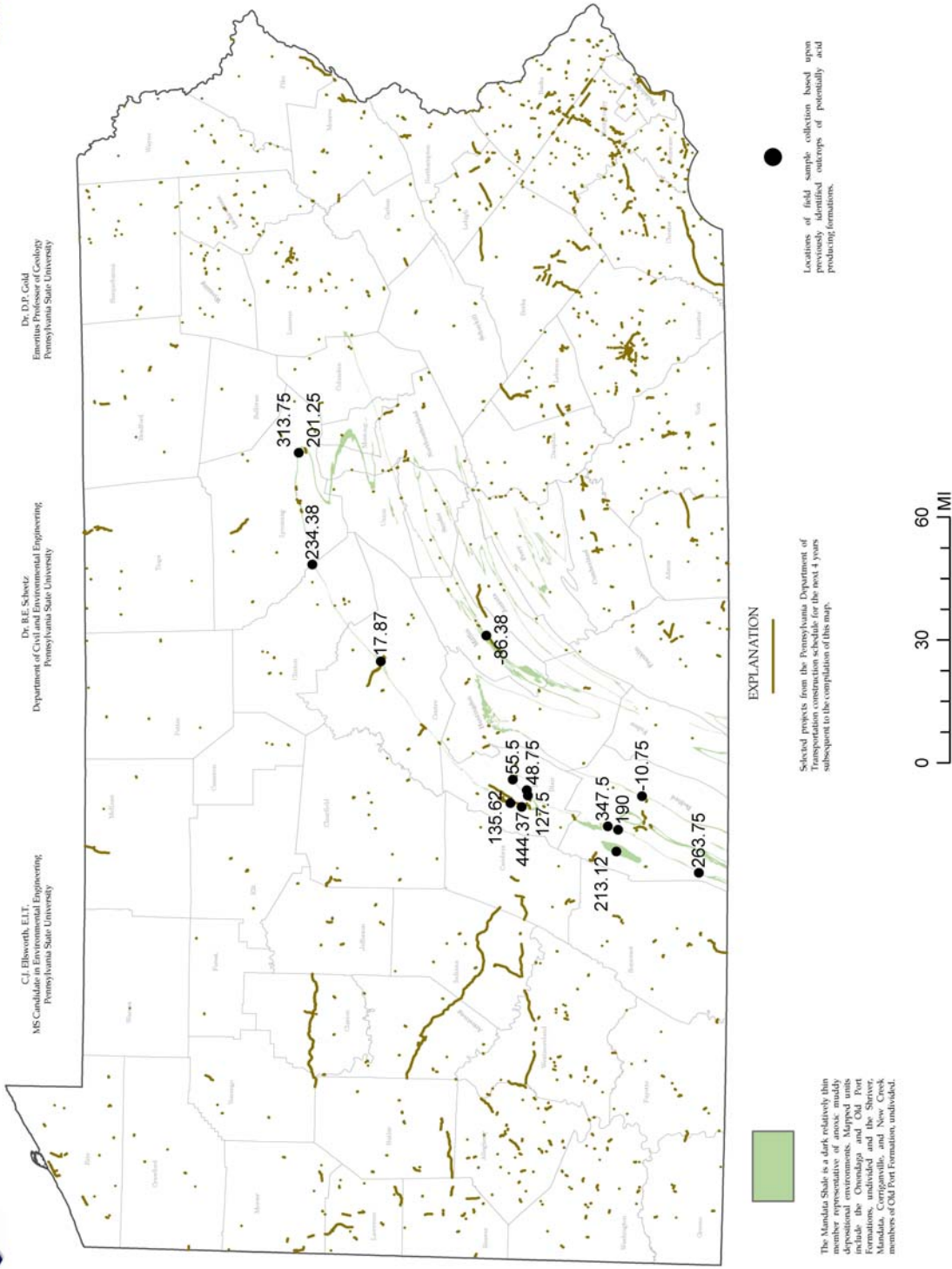


Figure 4.15. Distribution of the Mandata Shale showing respective NNP values with PennDOT's projected construction projects overlaid.

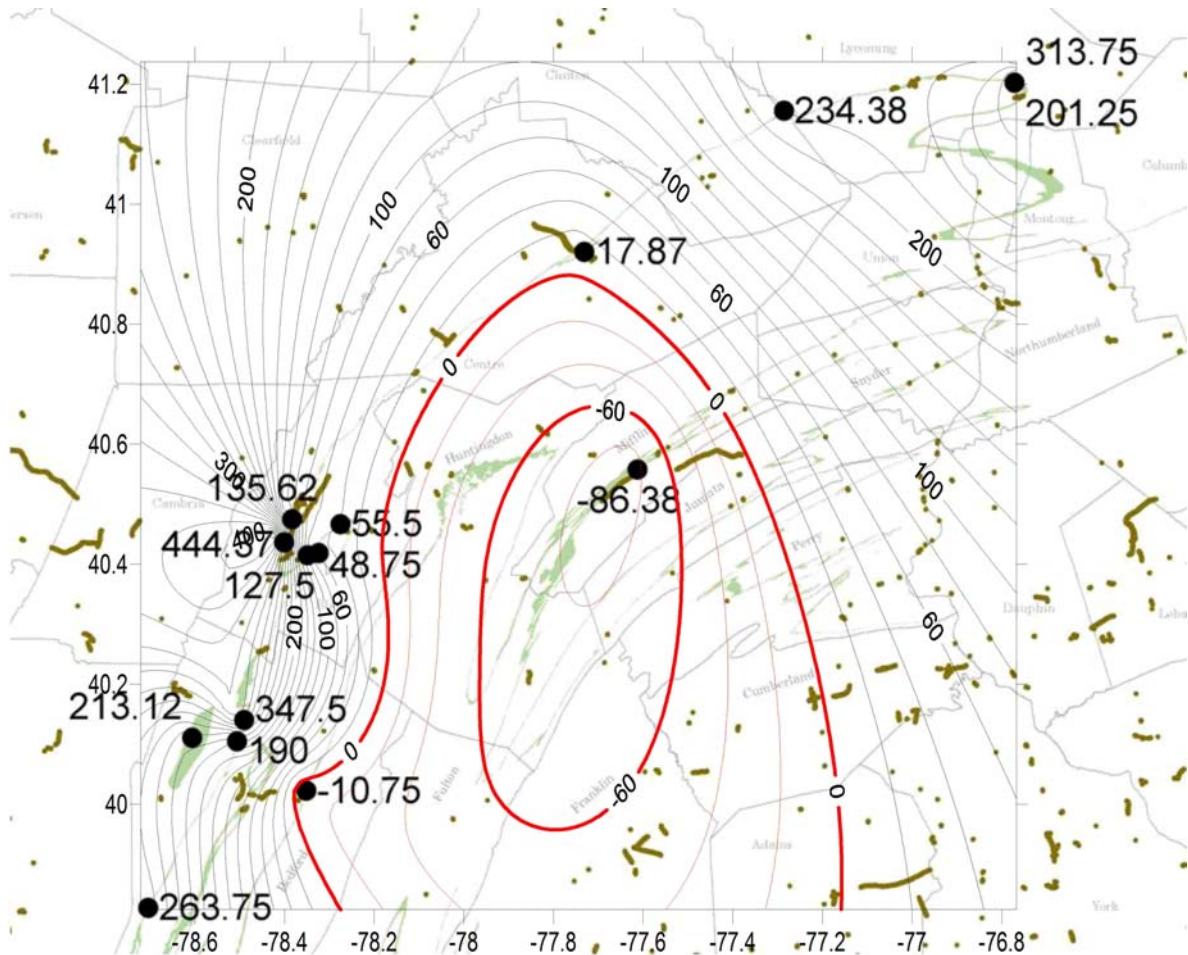


Figure 4.16. Inferred contoured isopach NNP ranges for the Mandata Shale with PennDOT’s projected construction projects overlaid.

4.1.7 Mifflintown Formation

The Mifflintown Formation was sampled at six locations during this study and was found to be acid producing in only one instance. %S values range from 0.1 to 0.86, NP values range from 0.5 to 267.5, and NNP values range from -26.38 to 148.75. Figure 4.17 shows the field sampling locations for the Mifflintown along with respective NNP values for each location. Figure 4.18 shows the contoured distribution of NNP values within the Mifflintown inferred on the basis of the six data points.

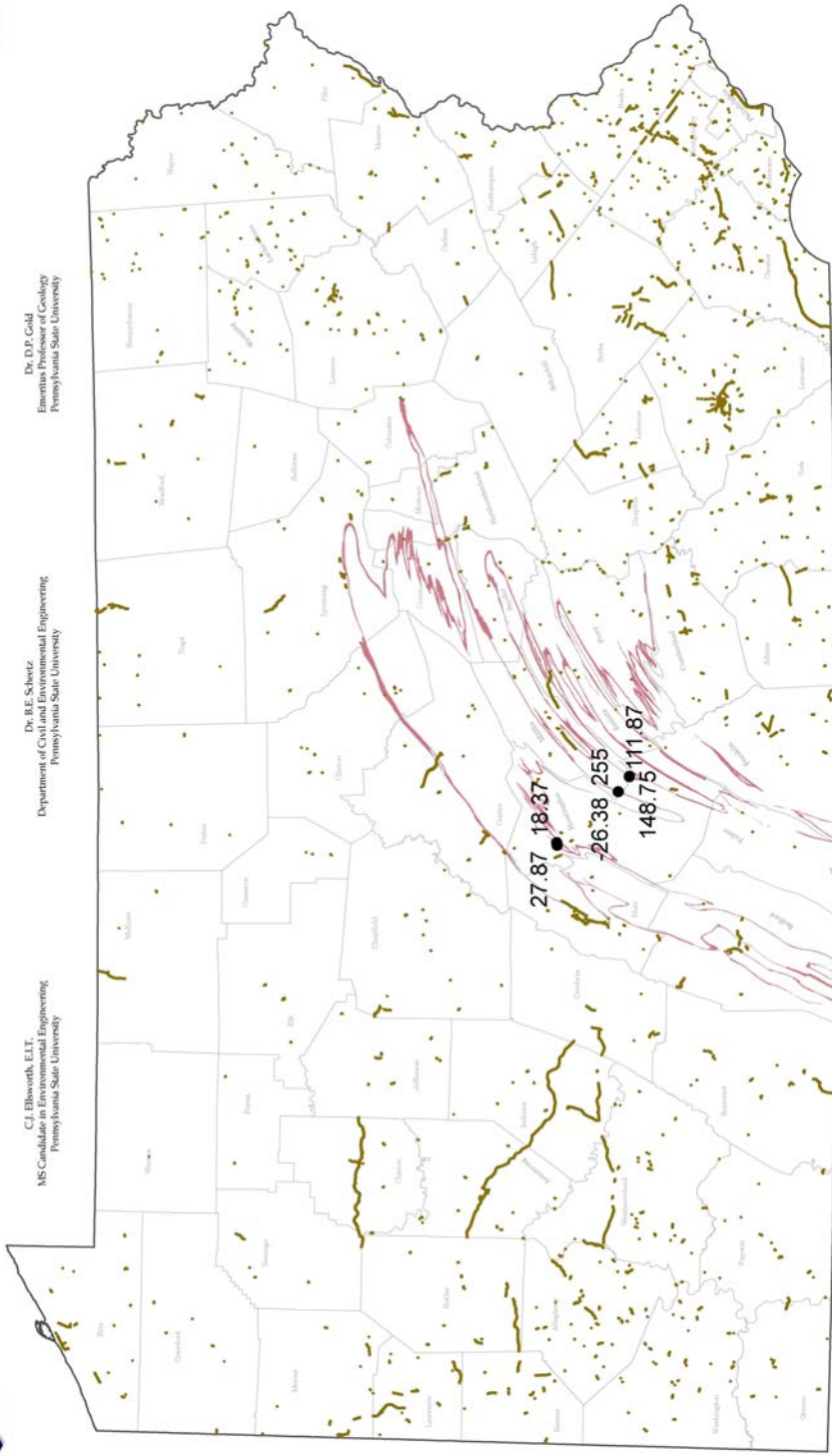
The limited amount of data acquired for the Mifflintown Formation suggests that it may have the potential to produce ARD in certain localized areas, but in general appears to have sufficient buffering capacity to neutralize any acid. The potential for swell and related phenomena is unclear based on the limited amount of data. Although the Mifflintown Formation does not appear to be a high-level risk based upon a limited amount of data, care should be taken to investigate its nature at any location at which it is to be excavated.

NNP of the Mifflintown Formation

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The Mifflintown Formation. Map units include the Kroyer Formation through the Mifflintown Formation, undivided, the Wills Creek Formation through the Mifflintown Formation, undivided, Blossburg and Mifflintown Formations, undivided, and Kroyer Formation through Clinton Group, undivided.

EXPLANATION

-  The Mifflintown Formation. Map units include the Kroyer Formation through the Mifflintown Formation, undivided, the Wills Creek Formation through the Mifflintown Formation, undivided, Blossburg and Mifflintown Formations, undivided, and Kroyer Formation through Clinton Group, undivided.
-  Scheduled projects from the Pennsylvania Department of Transportation construction schedule for the next 8 years subsequent to the compilation of this map.
-  Locations of field sample collection based upon previously identified outcrops of potentially acid producing formations.

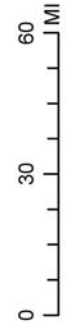


Figure 4.17. Distribution of the Mifflintown Formation showing respective NNP values with PennDOT's projected construction projects overlaid.

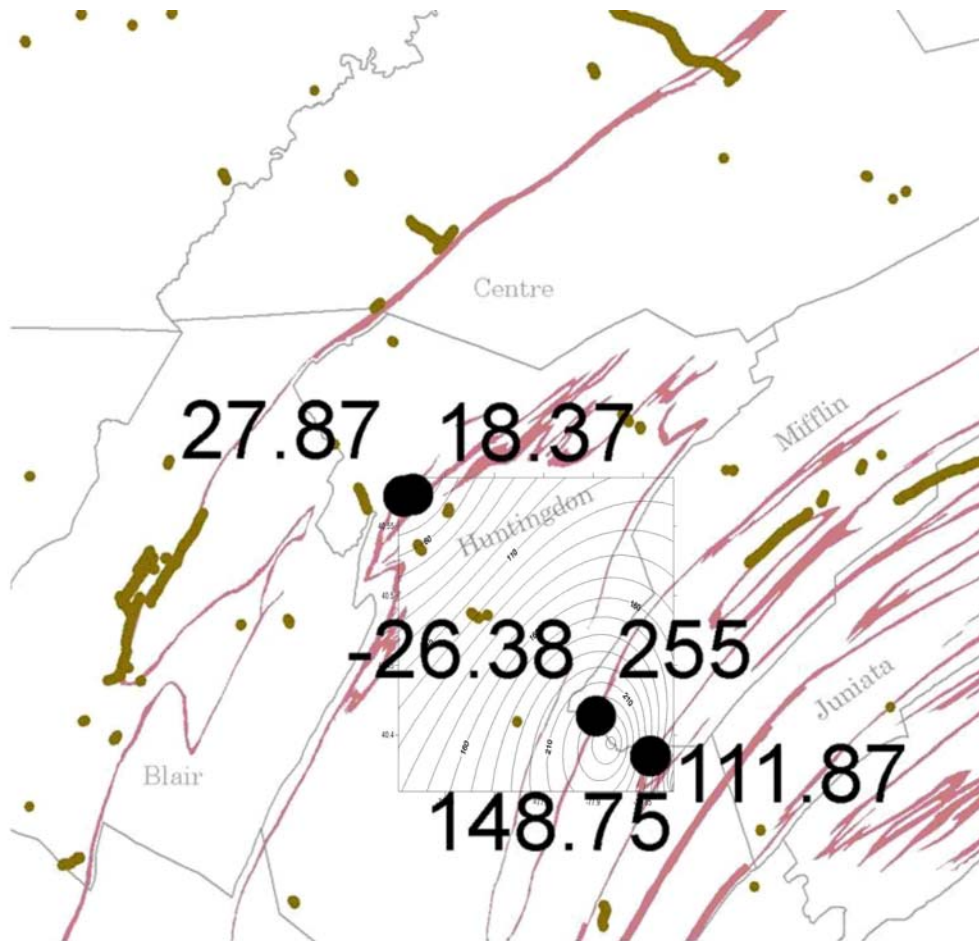


Figure 4.18. Inferred contoured isopach NNP ranges for the Mifflintown Formation with PennDOT's projected construction projects overlaid.

4.1.8 Reedsville Formation / Antes Member / Upper Coburn Formation

The Reedsville Formation, Antes member at the base of the Reedsville Formation, and underlying the Upper Coburn Formation were collectively sampled at 38 locations during this study. %S values range from 0.04 to 2.7, NP values range from -8.5 to 782.5, and NNP values range from -52.88 to 777.5. Figure 4.19 shows the field sampling locations for the Reedsville/Antes/Upper Coburn along with respective NNP values for each location. Figure 4.20 shows the contoured distribution of NNP values within the Reedsville/Antes/Upper Coburn inferred on the basis of the 38 data points.

Collectively, the Reedsville, Antes, and Upper Coburn do not in general appear to have a high potential to produce ARD with the exception of the sample of the Antes member taken from Skytop, a sample of lower Reedsville from the Colyer Lake area east of State College, Pennsylvania, and a group of four samples from the lower Reedsville or Antes member collected in eastern Fulton County. When taken together these six samples show a north/south trending zone running through the middle of Pennsylvania that appears to show a high probability for ARD. The swelling nature of the Reedsville/Antes/Upper Coburn succession is essentially unknown at this point, although the necessary components are all there, namely considerable amounts of sulfur along with substantial calcareous components. The Reedsville/Antes/Upper Coburn succession should be approached with an awareness that there is a distinct potential for ARD, particularly in the perceived north/south trending zone mentioned above, as well as a distinct possibility for swelling and related hazards.

NNP of the Antes Mbr., Reedsville Fm., & Upper Coburn Fm.

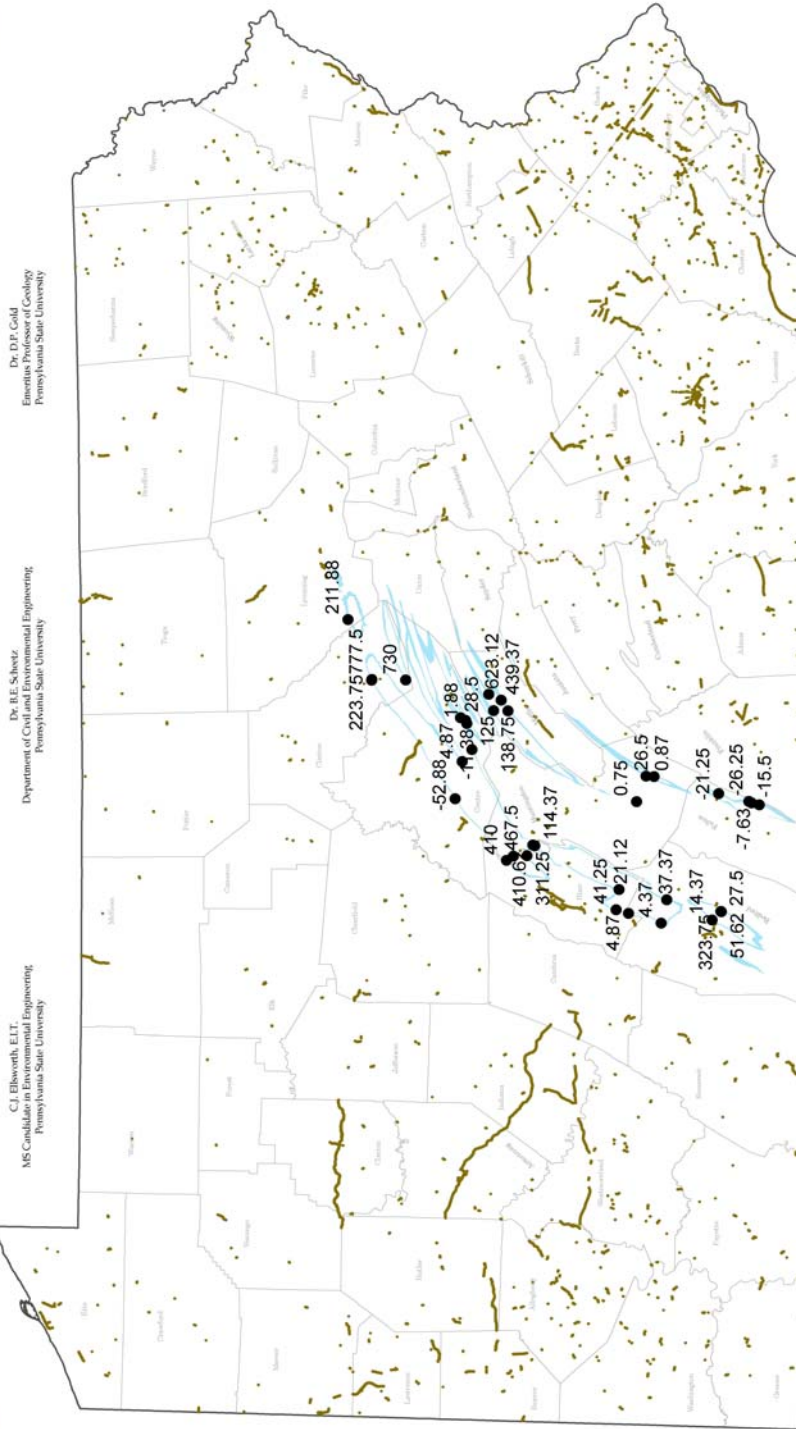


Figure 4.19. Distribution of the Reedsville/Antes/Coburn showing respective NNP values with PennDOT's projected construction projects overlaid.

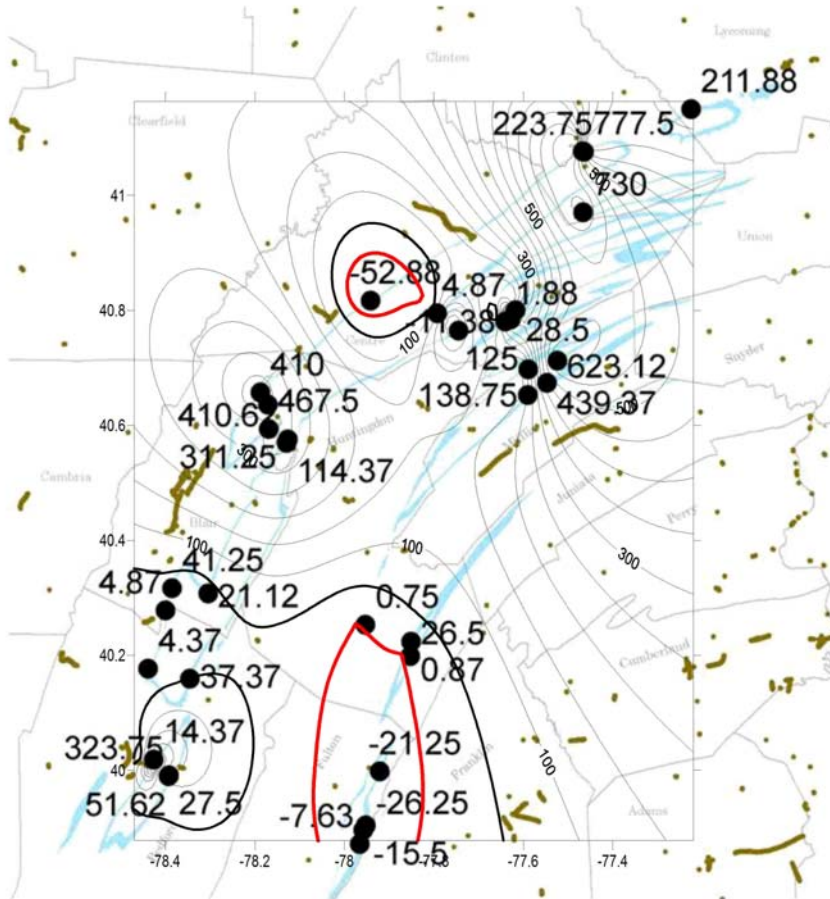


Figure 4.20. Inferred contoured isopach NNP ranges for the Reedsville/Antes/Coburn with PennDOT's projected construction projects overlaid.

4.2 Coal Formations

The coal-bearing formations covered in this section are organized from stratigraphically youngest to oldest. All of the coal measures discussed here are relatively flat-lying units from the bituminous fields that have been extensively mined. The great amounts of overburden data (see Appendix D) provided by the PaDEP (Keith Brady, Pers. Comm., 2006) have been used to identify trends in sulfur content of these units, which can be used to help predict the relative potential for ARD.

4.2.1 Monongahela Group and Waynesburg Formation, undivided

The Monongahela Group and Waynesburg Formation, which crop out in southwestern Pennsylvania, show a strong southeast to northwest trend in percentage of sulfur based upon the data plotted from Fayette, Green, Indiana, Somerset, Washington, and Westmoreland Counties. The percent sulfur values visually decrease from around 6% in the southeast to around 3.6% in the northwestern portions of the extent of the stratigraphic succession.

Figure 4.21 shows the geographic distribution of the Monongahela Group and Waynesburg Formation, undivided and shows the locations and corresponding values of the high-end percent sulfur values taken from the PaDEP overburden database. Figure 4.22 shows the contoured distribution of percent sulfur values within the Monongahela Group and Waynesburg Formation inferred on the basis of the eight plotted data points.

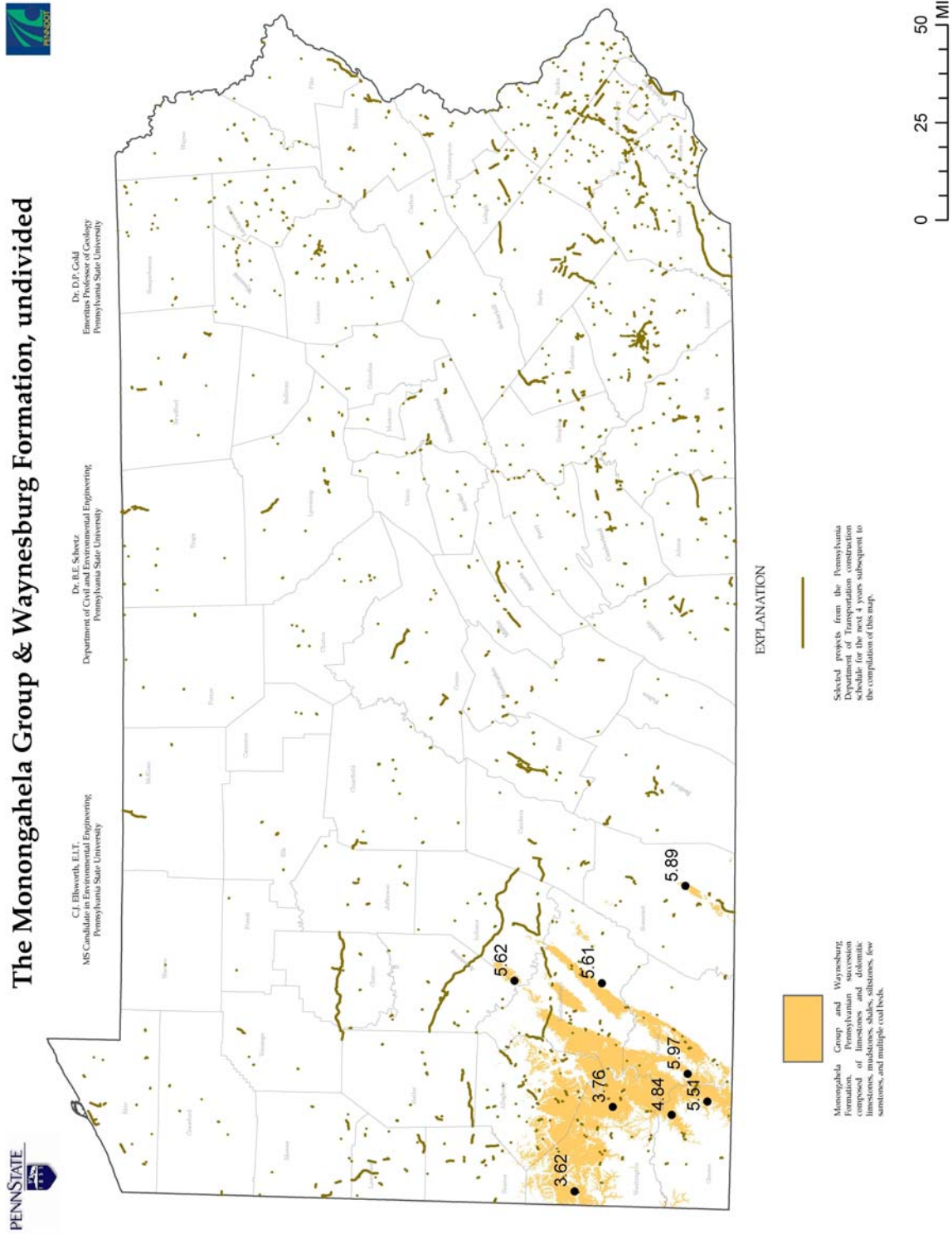


Figure 4.21. Distribution of the Monongahela Group and Waynesburg Formation, with % values and PennDOT's projected construction projects overlaid.

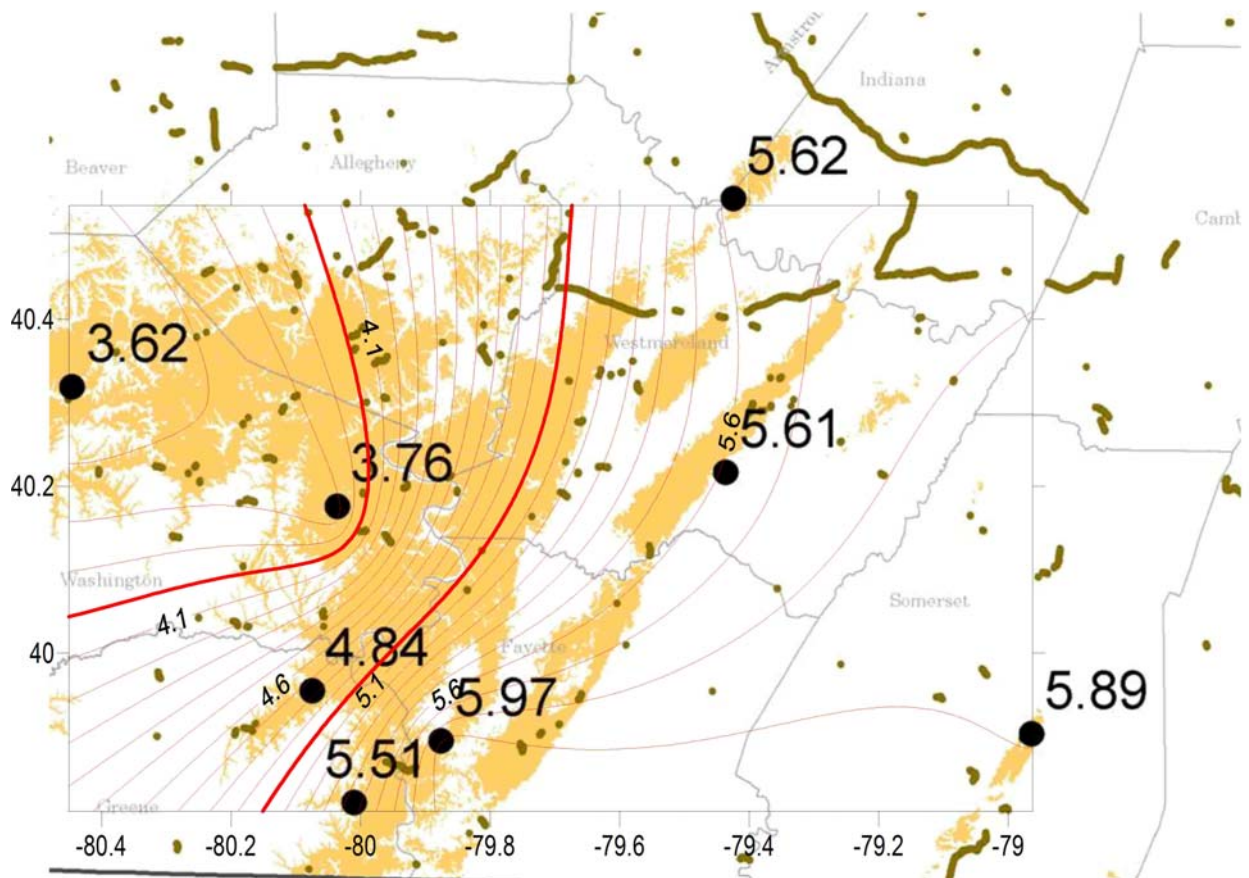


Figure 4.22. Inferred contoured isopach %S ranges for the Monongahela Group and Waynesburg Formation, undivided with PennDOT’s projected construction projects overlaid.

4.2.2 Conemaugh Group

The Conemaugh Group, which crops out in southwestern and west central Pennsylvania, shows a fairly clear southeast to northwest trend in sulfur values based upon the data plotted from Cambria, Clearfield, Fayette, Indiana, Somerset, and Westmoreland Counties. The percent sulfur values decrease from around 5.5% in the southeast to 2.5% in the northwest.

Figure 4.23 shows the geographic distribution of the Conemaugh Group and shows the locations and corresponding values of the high-end percent sulfur values taken from the PaDEP

overburden database. Figure 4.24 shows the contoured distribution of percent sulfur values within the Conemaugh Group inferred on the basis of the 12 plotted data points.

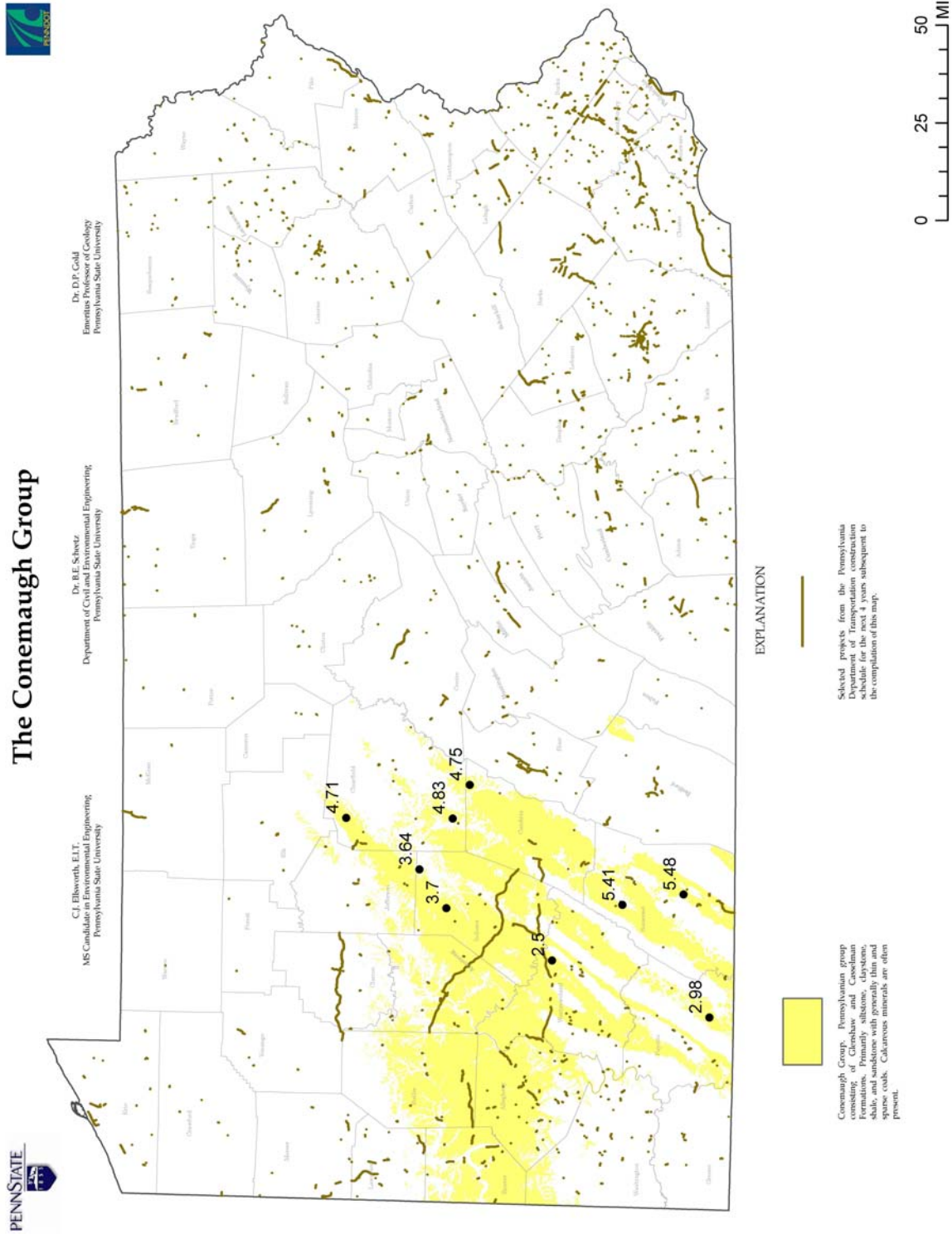


Figure 4.23. Distribution of the Conemaugh Group with respective %S values and PennDOT's projected construction projects overlaid.

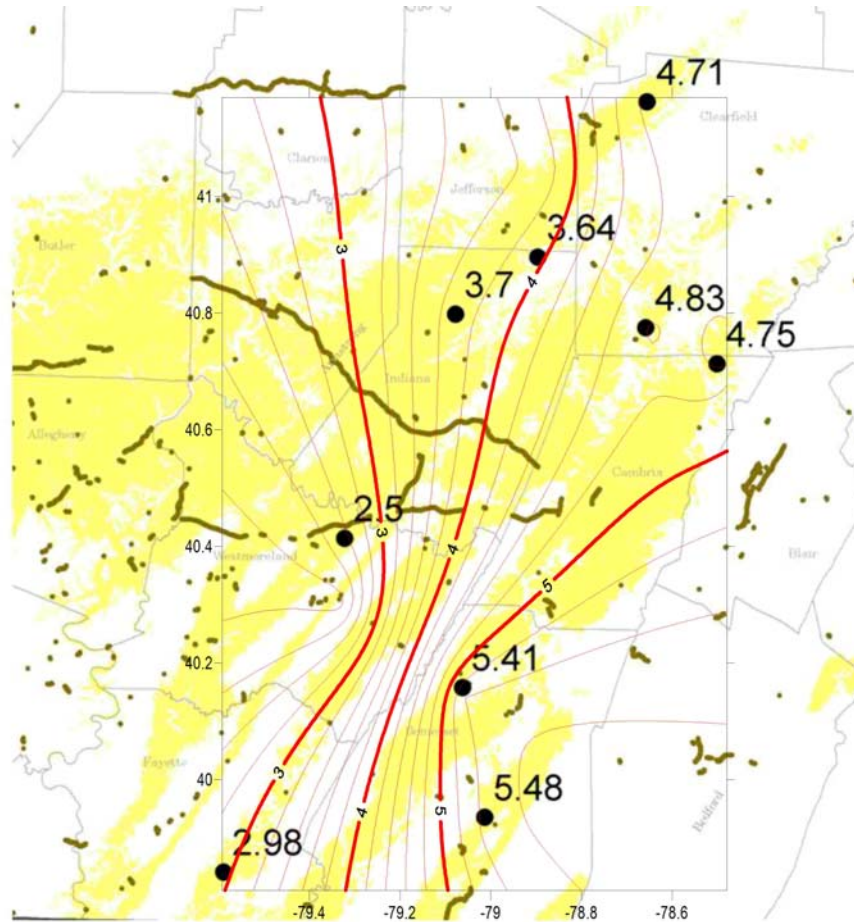


Figure 4.24. Inferred contoured isopach %S ranges for the Conemaugh Group with PennDOT's projected construction projects overlaid.

4.2.3 Allegheny Formation

The Allegheny Formation, which is exposed throughout much of western Pennsylvania, is, of the coal measures discussed here, the best represented in terms of quantity and spatial distribution of data. The main reason the Allegheny is so well represented is that it is a widely sought after and frequently mined formation due to its numerous economically important coal seams. The data plotted for the Allegheny Formation from Armstrong, Beaver, Butler, Cambria, Centre, Clarion, Clearfield, Clinton, Elk, Fayette, Indiana, Jefferson, Lawrence, Somerset, Venango, and Westmoreland Counties show a net overall average decrease in percent sulfur

values from the east to the west, with some lower values also being displayed in portions of its northeastern coverage.

Figure 4.25 shows the geographic distribution of the Allegheny Formation and shows the locations and corresponding values of the high-end percent sulfur values taken from the PaDEP overburden database. Figure 4.26 shows the contoured distribution of percent sulfur values within the Allegheny Formation inferred on the basis of the 30 plotted data points.

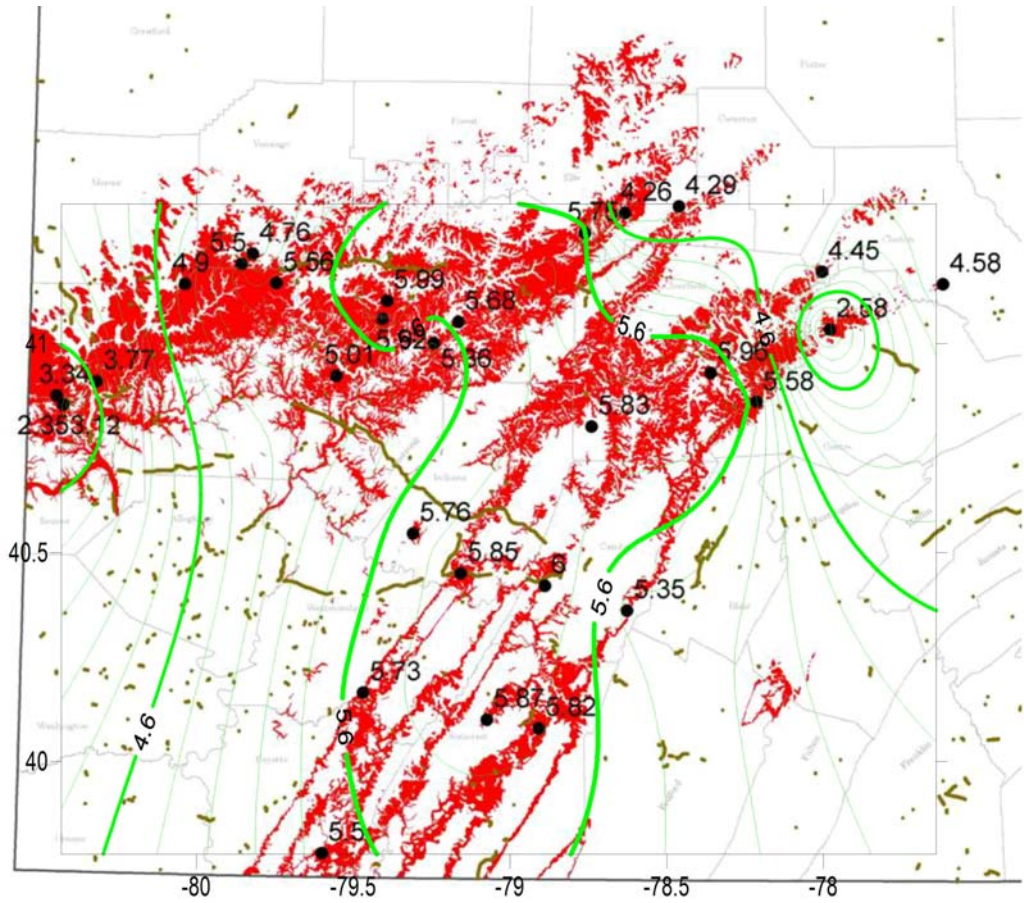


Figure 4.26. Inferred contoured isopach %S ranges for the Allegheny Formation with PennDOT's projected construction projects overlaid.

4.2.4 Pottsville Formation

The Pottsville Formation is exposed mostly in northwestern Pennsylvania and to a lesser extent in parts of southwestern Pennsylvania. The data plotted for the Pottsville Formation from Clarion, Clearfield, Fulton, Jefferson, Lawrence and Somerset Counties show a sulfur distribution that is rather different from the other coal units discussed above. The overall quantity and spatial distribution of data for the Pottsville was rather limited and so it seems that the addition of more data sets would likely change the apparent distribution of percentage of sulfur. The Pottsville Formation has also been mapped in the eastern Pennsylvania anthracite fields as well, but no overburden data were provided for this area.

Figure 4.27 shows the geographic distribution of the Pottsville Formation and shows the locations and corresponding values of the high-end percent sulfur values taken from the PaDEP overburden database. Figure 4.28 shows the contoured distribution of percent sulfur values within the Pottsville Formation inferred on the basis of the eight plotted data points, which, as discussed above, are comparatively rather limited in their quantity and spatial coverage.

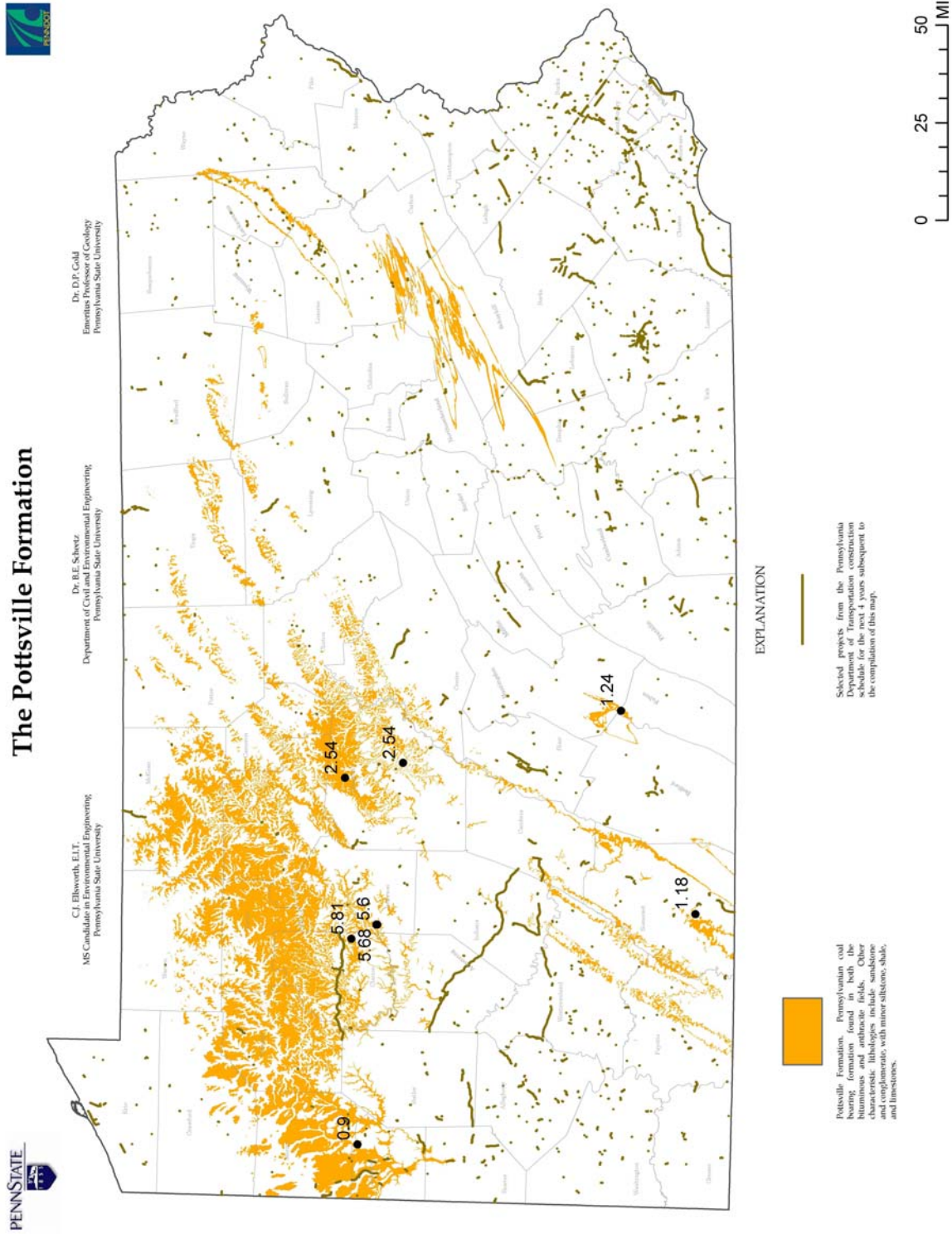


Figure 4.27. Distribution of the Pottsville Formation with respective %S values and PennDOT's projected construction projects overlaid.

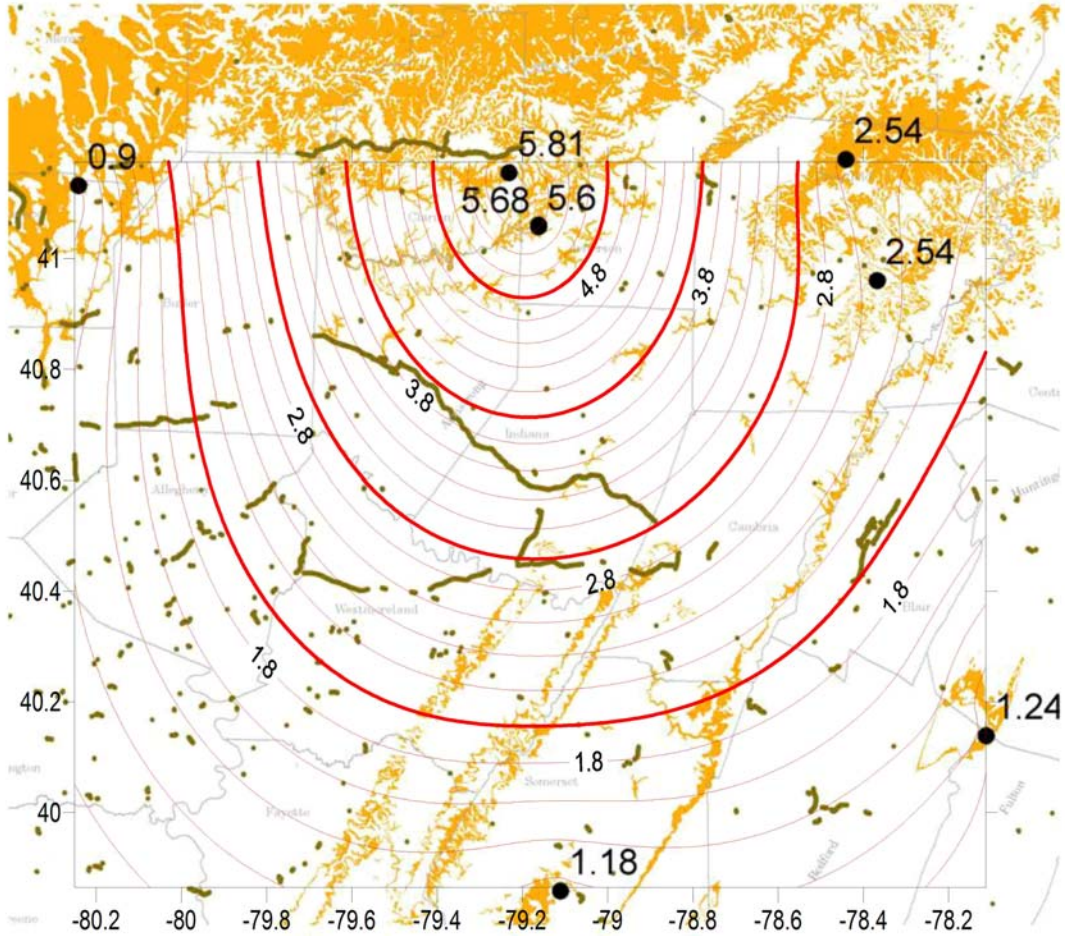


Figure 4.28. Inferred contoured isopach %S ranges for the Pottsville Formation with PennDOT’s projected construction projects overlaid.

4.2.5 Discussion of Geographic Trends in the Coal Formations

A number of predictive studies have been undertaken in an attempt to delineate the occurrence and quantity of sulfidic materials over very large geographic areas and to assess the potential for difficulties related to ARD with respect to coal mining. A considerable amount of work has been done seeking to physically and chemically characterize the dominantly Pennsylvanian aged coal-bearing formations. Reyes-Navarro and Davis (1976) have related the forms and distribution of pyrite in three coals of western Pennsylvania to their respective interpreted environments of deposition. The environment of deposition of coal and its bounding

stratigraphic units has significant controls not only on the form and composition of the coal itself, but upon the type and morphology of the sulfides found within the rocks and how they are likely to behave upon excavation. Reyes-Navarro and Davis (1976) stress the importance of coal swamp settings ranging from marine, brackish, non-marine, and terrestrial as being a primary factor leading to the amount of sulfur present in coal measures and provide examples of sulfur distribution in specific coals across broad geographic ranges of western Pennsylvania.

Reidenour and others (1967) relate the distribution of sulfur in selected coals from western Pennsylvania to the ancient paleotopography existing during their deposition. Reidenour et al. (1967) discuss the importance of such factors as water circulation (or lack thereof), oxidation-reduction potential, the supply of ferrous iron and clay particles, and bacterial processes, particularly as these factors relate to paleoenvironments, which can be interpreted with a considerable amount of detail in western Pennsylvania. It has been suggested that paleotopographic depressions or lows are particularly important for pyrite formation, as the necessary redox potential as well as the plentiful supply of detrital components are contemporaneously in effect (Reidenour et al., 1967).

Hornberger and others (1981) and Hornberger (1985) discuss the acid drainage potential of the Pottsville and Allegheny Groups of western Pennsylvania based on a variety of factors including the topography, structure, stratigraphy, paleontology, and hydrogeology of these geologic units. Of particular interest is the apparent relationship between the occurrence or presence of large calcareous intervals such as the Vanport Limestone and other carbonates, and measured water quality parameters such as pH, alkalinity, sulfate, and conductivity as well as the number of mines in a given area and various paleoenvironmental interpretations (Hornberger et al., 1981). The importance of naturally occurring limestones, dolomites, and calcareous shales,

along with the calcareous glacial till found in portions of northwestern and northeastern Pennsylvania in neutralizing ARD, although not consistently effective, cannot be understated (Hornberger et al., 1981).

Williams and others (1982) report on the multitude of factors that surround the formation of ARD, including pH, alkalinity, oxygen, pyrite quantity and morphology, biological processes, temperature, environment of deposition, and the effects of additional trace elements present in the system. Each case of ARD, although similar to others in a number of respects, is very much a unique circumstance due to the great diversity of settings and parameters at play in any given situation. This notion is important not only in seeking to characterize a given example of ARD, but is especially relevant if ARD is sought to be avoided or mitigated, as effective avoidance and treatment techniques are often very much site-specific depending upon local conditions.

Williams et al. (1982) also portray a variety of geographic trends based upon their study, including the distribution of the relative acid-producing potential of select Pennsylvanian aged intervals based upon the numerous factors mentioned above. These perceived trends not only allow for a level of qualitative pre-excavation predictive interpretation, but also serve to illustrate the end product of a procedure by which one can work toward such predictive techniques.

Williams and others (1982, 1985) discuss the importance of the environment of deposition of the coals and associated lithologies in terms of inherent composition and potential to produce acid. It has been found that coals deposited in brackish conditions typically have a high potential to cause acid drainage, due to the terrigenous input of iron and the uniformly sulfate-rich sea waters. Coals deposited in marine waters often have a significant potential to produce AMD, but typically not to the extent of those deposited in brackish conditions. And lastly, coals deposited in fresh water conditions normally have a relatively moderate or low acid

production potential (Williams et al., 1985). Also of great significance to the potential for acid production and with regard to the environment of deposition is the presence or absence of carbonate minerals, often in the form of limestones, dolomitic limestones, or calcareous mudstones and shales. Although the presence of calcareous or carbonate minerals often has the ability to lessen the severity of acid drainage, their occurrence will often not limit acid production enough to avoid significant environmental impact.

Rimmer and others (1985) write upon the environments of deposition of the Lower Kittanning coal seam of the Allegheny Formation in Pennsylvania and Ohio as they relate to the mineralogic, petrographic, and chemical characteristics of the coal seam. Again, of prime importance is the nature of the environment of deposition in terms of its proximity to the land and open water, or in other words, whether it is of marine, brackish, or non-marine origin (Rimmer et al., 1985). Williams et al. (1985) further underscore this concept as they discuss the distribution of sulfur and carbonate minerals in Pennsylvanian rocks and their estimated levels of acid production, especially as related and correlated to specific paleoenvironmental controls.

A considerable volume published by the Pennsylvania Department of Environmental Protection entitled *Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania* (Brady et al. [eds.], 1998) represents the culmination of decades of research by some of the most well-known researchers from government, academia, and private practice contributing to the growing collection of knowledge surrounding acid drainage. This comprehensive, interdisciplinary work covers virtually all aspects of ARD as it relates to coal mining in Pennsylvania covering important topics on the generation, effects, characteristics, prediction, reclamation, prevention, and control. The diversity of knowledge and experience represented in

this publication allows for a sophisticated level of pre-mining predictive interpretation, and offers numerous options for the effective avoidance and treatment of ARD.

One common theme among all of the reports that have been written about coal-bearing lithologies is that the environment of deposition is an extremely significant control upon the amount of sulfur present in the coals and associated rocks, as well as the presence of carbonates and other components that are integral to the overall ARD process. Although sulfur in coal measures occurs in three main forms—namely organic sulfur, pyritic sulfur, and sulfate sulfur—the most important form in terms of the potential to produce ARD is pyritic sulfur principally occurring as pyrite and marcasite (Reyes-Navarro and Davis, 1976). Based upon a careful investigation into the various parameters contributing to the overall character of a coal measure, it may be possible to effectively predict the potential for ARD at a given site.

All of the reports and studies discussed above relate the chemical and physical properties of the coal measures to the original environment to deposition. All of these studies suggest that during Pennsylvanian time the depositional basin of the coals consisted of a near shore, marginal marine brackish water environment in the southeastern portion of what is now the Pennsylvania coal fields, which gradually transitioned to a more open and deeper marine channel in what is now the central portion of the coal fields. In turn, the northwestern portion of the basin gradually sloped back into shallower water and presumably more brackish conditions once again.

This depositional basin has repeatedly been interpreted to be roughly northeast to southwest trending (Williams et al., 1982, 1985; Rimmer et al., 1985). This notion, which is repeatedly discussed throughout the literature, is supportive of the perceived southeast to northwest trend in decreasing percent sulfur values presented in this study. It should be remembered that the data used in this study were taken from the entire coal-bearing formation or

group in question, and so during the long intervals of time on the order of several millions of years that a formation or group was deposited, the paleotopography and ancient shorelines would have migrated significantly. The various investigations discussed above were done on a more fine scale, investigating only individual coal seams for which the paleoenvironmental conditions would have remained relatively static.

What has not been reconciled is the inconsistency between the notion that a smaller brackish water environment parallel to and separated from the southeastern brackish water environment has been interpreted in the northwestern portion of the depositional basin. If this was the case, the trends in percentage of sulfur found in this study for the Monongahela and Waynesburg, Conemaugh, and Allegheny would be expected to increase again in the northwest. This discrepancy may be explained upon the relatively limited number of data points from the overburden data in the northwest, or it may be possible that there existed as yet not understood marked differences in the nature of the two distinct brackish water environments, such as differences in water depth, circulation, and quantity and character of detrital sediments from the differing terrigenous sources believed to be present on either side of the depositional basin.

4.3 Isolated Sulfide Deposits and Sandstone Formations

The isolated deposits have been integrated together with the sandstone formations in this section for the purposes of interpretations due to the fact that the current understanding supposes that the potentially acid-producing nature of the sandstones included in this report is inextricably linked to the isolated sulfide deposits in nearly all cases. However, it is important to remember that not all of the isolated deposits are found in sandstones, as the reality is quite the opposite. Despite this fact, a great number of isolated sulfides have been found in sandstones such as those

of the Bald Eagle and Tuscarora Formations, particularly in areas of high fracture density, and it appears as though there is a discernible relationship between many isolated sulfides and certain sandstone units.

The numerous isolated or localized sulfide occurrences that have been identified in the course of this study (see Appendix E) are widely varied in terms of their origin, genesis, host rock, overall mineral composition, quantity, quality, and extent. The localized sulfide minerals can be grouped into four fundamental categories based upon their overall potential or likelihood to cause ARD when excavated (see Figure 4.29). The four categories have been summarized in Table 4.1. Although each occurrence that has been extensively documented and characterized on the basis of its mineralogy, host rock, size etc. can be relatively easily categorized in terms of its potential to produce ARD, those deposits that have not been extensively studied, particularly in the subsurface, often remain shrouded in mystery and may be potentially hazardous. Furthermore, it is safe to assume that many undocumented and virtually unknown deposits exist throughout Pennsylvania.

It has been concluded that many of the known isolated sulfide deposits found in Pennsylvania owe their existence in part to structural controls as governed by lineaments (see Section 3.3). Although some of the identified deposits can be unequivocally linked with known lineaments, the origin of many of the others is at this point rather unclear. Through further investigations attempting to link known and unknown lineaments, the related high fracture density of certain sandstone and carbonate units, and localized hydrothermal or epigenetic type sulfide occurrences, and other factors it may become possible to develop predictive models that can help to reveal the probability of encountering a localized sulfide occurrence in a given area.

Table 4.1 Localized Sulfide Deposit Categorization Scheme

Category	Designation	Evidence/Reasoning
1 (red)	ARD Forming	Acid-forming minerals as a major component
2 (yellow)	Potentially ARD Forming	Acid-forming minerals as a minor/trace component
3 (green)	Non-ARD Forming	Acid-forming minerals not present
4 (black)	Unknown	Insufficient information or data unavailable

Any known localized or isolated sulfide deposit should be approached with caution if it is expected to be encountered during construction, particularly if the acid-producing sulfides are known or suspected to be present. Resistant ridge-forming sandstones have been found to often contain isolated sulfide deposits, particularly in areas of high fracture density along faults and lineaments. Any deposit in question should be interpreted upon a number of factors to assess its potential to produce ARD, including its mineral composition, the mineral composition of the host rock (i.e., whether or not acid-neutralizing minerals or lithologies are present), the lateral and vertical extent of the deposit, and the level to which the zone of oxidized material extends below the surface to be excavated.

Potentially Acid Producing Sandstones & Categorized Isolated Sulfide Deposits

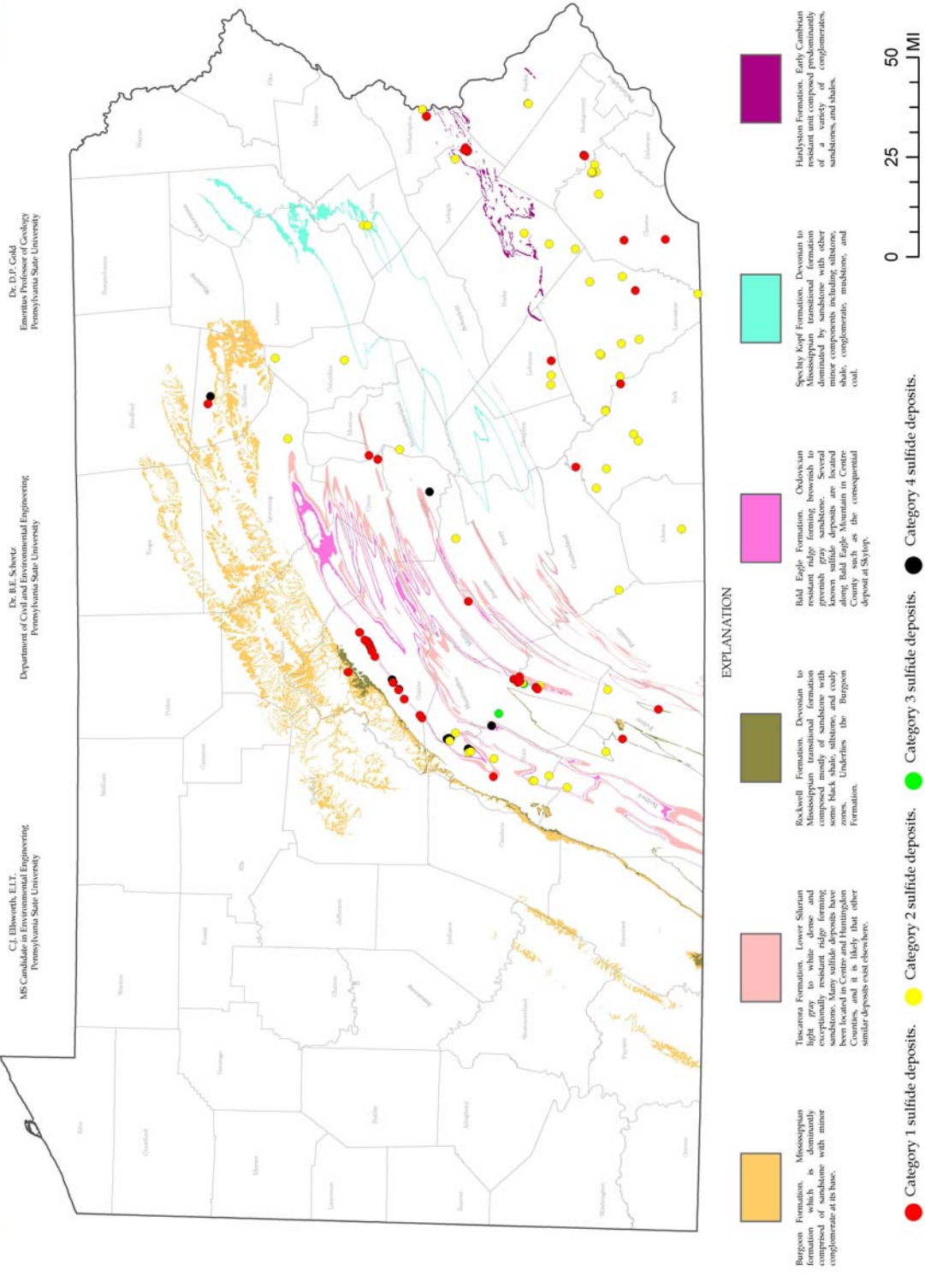


Figure 4.29. Categorized isolated sulfide deposits and potentially acid-producing sandstones.

4.4 Hazards Rating Approach

Based upon the overall assessments regarding the quantity, age, distribution, physical and chemical properties of the various types of sulfide-bearing formations or lithologies known to be present in Pennsylvania, a straightforward and all-embracing hazards rating approach or scheme has been developed. The proposed hazards rating approach is discussed in detail below and has been schematically portrayed in the flow chart depicted in Figure 4.30.

If a sulfide-bearing lithology is identified, the first step toward identifying its relative hazard rating is to determine if pyrite (FeS_2) or other known acid-producing minerals are present, as established upon the basis of determination of the percentage of sulfur present and the following Maximum Potential Acidity (MPA) value. If no pyrite or other acid-producing sulfides are present, then there is no possibility of ARD.

If pyrite or other acid-producing minerals are found to be present in a given lithology, then it must be determined if the lithology in question is carbonate bearing based upon a determination of the neutralization potential, NP. If the NP value is low or negligible, indicating a lithology without sufficient acid-buffering capacity due to the presence of carbonates, then there will be a high potential for ARD to occur. If the NP value is found to be sufficiently high so as to neutralize all of the acid that may be generated, then the potential for ARD will be low. However, under certain circumstances a lithology that has been determined to contain both acid-generating sulfides and carbonates, while it may not be prone to cause ARD, may likely present a high potential for volumetric expansion or heave.

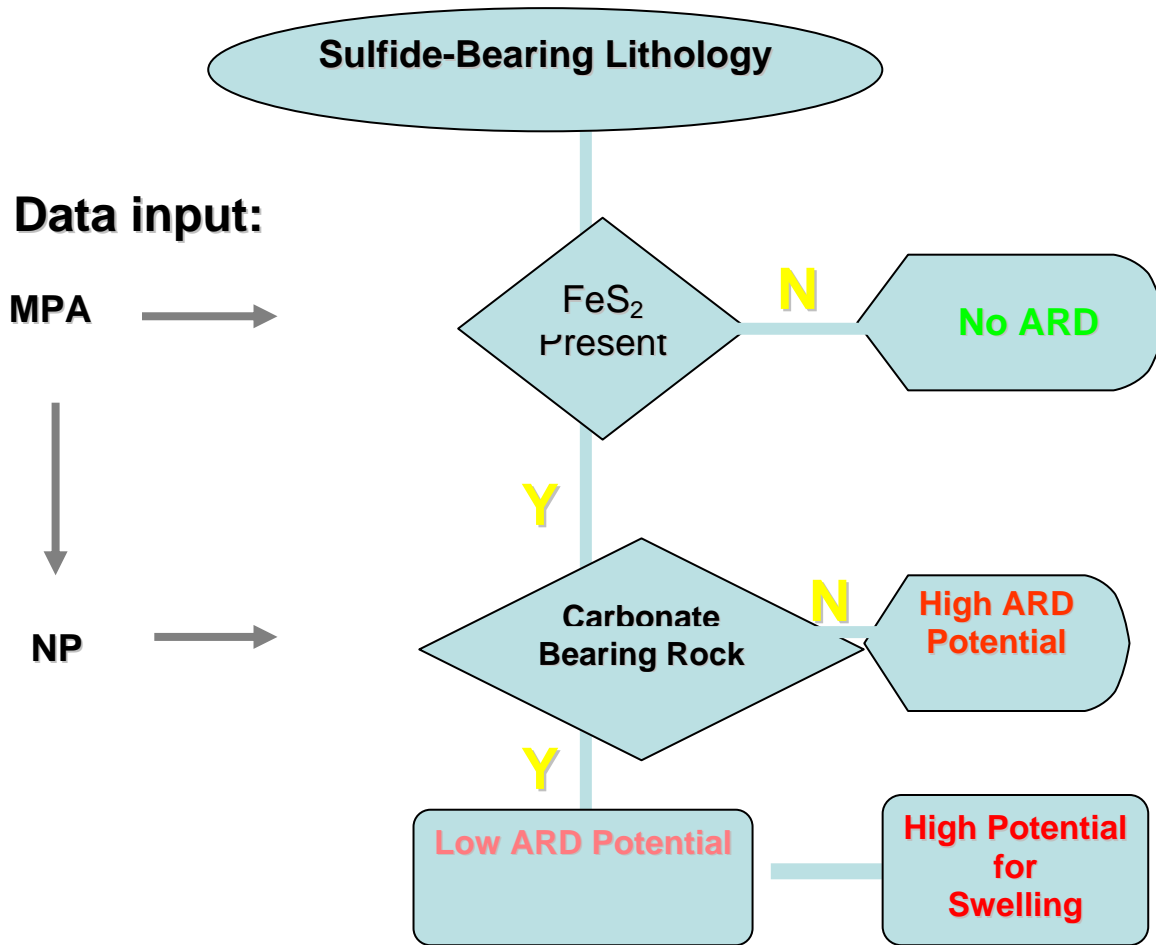


Figure 4.30. Flow chart depicting the recommended approach to sulfide-related hazards rating or assessment.

5.0 CASE STUDIES

The following case studies have been included primarily to provide insight into the diversity, severity, and magnitude of sulfide-related hazards in Pennsylvania. The case studies briefly discussed here serve to illustrate the range of negative consequences that can easily result from the excavation of pyritic materials during construction, and help to demonstrate the importance of taking careful and methodical precautions when these materials are known or suspected to be present at a proposed construction site.

5.1 Central Susquehanna Valley Thruway – Successful Predictive Avoidance?

The Central Susquehanna Valley Thruway (CSVT) is a large-scale highway project that will incorporate a massive bridge spanning the west branch of the Susquehanna River between Union and Northumberland Counties, as well as several miles of new thruway including 4-lane limited access roads and several new interchanges (SEDA-Council of Governments, 2006). This substantial project, which is expected to cost roughly \$75 million and will take a number of years to complete, is a forward-looking venture that is intended to alleviate traffic congestion, promote safety, and support expected increases in population and an increase in development in the region (SEDA-Council of Governments, 2006).

The CSVT project provides an excellent example of a situation in which preliminary aspects of this report and other related studies have been effectively considered and applied at the design phase in order to avoid severe and costly side effects of unearthing sulfide-bearing lithologies during highway construction. The potential environmental and economic implications presented by the variety and amount of sulfides that are suspected to be present at this site based

upon preliminary investigations are enormous. The opportunity to avoid another costly incident similar to Skytop or Route 522 has been clearly presented at the CSVT project.

Many of the known sulfide-related hazards are present at the proposed CSVT site, including the presence of potentially acid-producing and expansive black shales and what appear to be hydrothermal or secondary sulfides and related minerals. Several black shales that are known to be problematic are located within the proposed siting limits of the future thruway, including the Mandata member of the Old Port Formation, the Needmore Shale of the Onondaga Formation, and the Marcellus and Mahantango Formations of the Hamilton Group, all of Devonian age (see Figure 5.1). The presence of the Marcellus is especially troubling, as it has caused extensive swelling damage at the nearby Evangelical Hospital in Lewisburg, Pennsylvania and has caused costly acid drainage issues near Lewistown, Pennsylvania during construction of portions of route 522. Projected sections of the thruway have also been sited through portions of the Lower Silurian Tuscarora Formation, which is a known host of secondary sulfide minerals in various localized occurrences throughout Pennsylvania (see Figure 5.1). Preliminary drilling cores taken from the Tuscarora at this location have revealed the presence of sulfide minerals along with accessory minerals such as quartz in what appears to be a hydrothermal vein-type deposit, which may be superficially similar to the deposits found at Skytop and other areas (D.P. Gold, Pers. Comm., 2007).

The expected presence of significant amounts of acid-producing and swelling sulfide minerals at the CSVT has been acknowledged well in advance of the beginning of any construction activities at the site. The identified problematic formations and occurrences have been recognized early enough to be integrated into the design phase of the project, thus allowing the opportunity to avoid the type and intensity of problems encountered at all too many other

sites. The investment of additional time and the implementation of special measures taken up-front during design and in both preliminary and active construction phases in this and similar situations will pay great dividends in the long run, as costly and time-consuming mitigation and remediation efforts may be largely or entirely avoided.

For instance, a segment of road that has been sited through portions of a linear ridge supported and underlain by the Tuscarora Formation on the east side of the Susquehanna River could be adjusted for grade in order to avoid deep excavations into un-oxidized rocks (K. Petrasic, Pers. Comm., 2007). By adjusting the local grade or slope of the thruway in this portion of the road alignment, it becomes possible to remain within the oxidized cap rock layer, thus avoiding any major intersection with reduced sulfide-bearing rocks of the Tuscarora, as was the case at Skytop. Another design consideration that has been contemplated at this site involves the flooding of any reduced black shales encountered or excavated in the course of the project, thus maintaining reducing conditions until they can be covered again (K. Petrasic, Pers. Comm., 2007).

Although the easiest way to avoid acid rock problems at any construction site is to site roads and other engineered structures away from sulfide-bearing rocks entirely, it is not always possible to make realignments in order to completely avoid problematic formations. All relevant aspects of the design and construction activities must be implemented in full consideration of the known problems. More deliberate designs and adjustments to designs made in full consciousness of the site geology and hydrology are necessary to avoid, mitigate, and remediate any potential problems. Only through a complete acknowledgement of the challenges and difficulties present at the site will the CSVT and other future projects successfully avoid the consequences of acid formation.

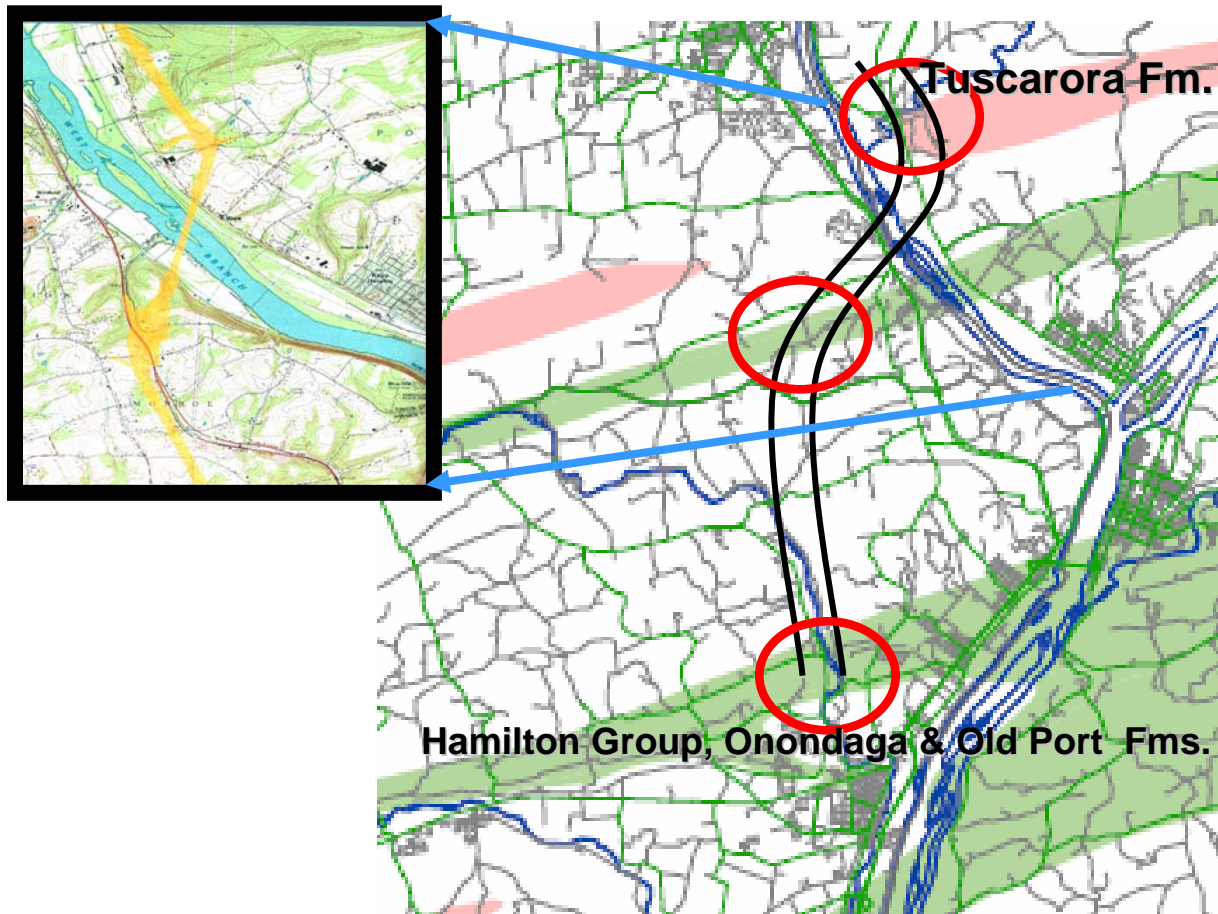


Figure 5.1. Proposed corridor of CSVT (SEDA-Council of Governments, 2006) and problematic geologic units present on site.

5.2 Evangelical Hospital, Lewisburg, Pennsylvania

The Evangelical Hospital located in Lewisburg, Pennsylvania is an excellent example of the negative consequences of swelling and subsequent heave of engineered structures built upon expansive black shales. Large parts of the hospital were built upon relatively flat-lying portions of the Marcellus Shale, a Middle Devonian aged calcareous shale containing significant amounts of sedimentary framboidal pyrite. The Marcellus Formation is part of the Hamilton Group, which contains other potentially problematic black shales in some areas. As discussed earlier in this report, the Marcellus shale should now be considered as a known producer of ARD, but the

problems involving the acid-producing and swelling nature of this formation have not been considered until recently, particularly with the onset of the problems at the Evangelical Hospital.

Visual inspection of the swelling fill materials revealed both the presence of white/translucent minerals as well as yellowish-orange colored minerals. X-ray diffraction analysis carried out at Penn State's Materials Research Institute has shown the presence of gypsum crystals (Hoover, 2002). Gypsum (CaSO_4) is a sparingly soluble mineral that has approximately twice the molar volume of its parent minerals (Gold and Doden, 2007), resulting in significant heaving pressures of at least 1.499 ksf (71.8 kPa) (Quigley and Vogan, 1970). Although gypsum is certainly not the only mineral acting in most systems subjected to swelling, it has often been identified and blamed as one of the principal instigators of significant volumetric expansion and consequent swelling pressures in many instances where an affected structure has been studied.

The original structure that comprised the hospital was opened in 1953, and major additions were built in 1982 and 1993. It has been reported that within 3 months of construction of the 1982 addition, problems with swelling and heave of concrete floor slabs were initiated (Hoover, 2002). The heave of the concrete floor slabs (see Figure 5.2), which were built upon fill composed in part of the Marcellus Formation, was measured as having vertical displacements of up to 6 inches in some areas, and other portions of the hospital built upon natural bedrock have swelled as much as 4 inches (S.E. Hoover, Pers. Comm., 2002). It seems likely that the swelling of the compacted fill beneath the concrete floor slabs has been intensified by the increased surface area brought about by the excavation of the original bedrock. The increased surface area of the fill as opposed to undisturbed bedrock greatly multiplies the area over which water and oxygen can act, thus increasing the rate and magnitude of volumetric expansion.

However, the swelling of undisturbed bedrock can be equally destructive, as expansive minerals typically have less void space in which to grow, forcing them to displace the bounding shale layers. During construction of the addition the local water table was lowered in order to accommodate the structure and to allow work to commence. It is likely that the lowering of the water table was instrumental in ushering in the oxidizing conditions necessary to initiate the production of acid and the subsequent swelling of the rock beneath portions of the hospital.

Some structural members of the hospital, which are mostly underlain by relatively undisturbed bedrock, have not shown the same intensity of heave to date. To what extent the vertical pressures exerted by the structural footings are counteracting any swelling pressures due to sulfate mineralization in the undisturbed bedrock is difficult to know for certain. However, the fact that these structural members were built upon bedrock as opposed to fill could be a contributing factor in their ostensible resistance to significant amounts of heave thus far. The damage to the structure has led to a large-scale remediation scheme in which the existing spread footings are to be underpinned to prevent any further major structural deformations, and to avoid the extremely costly measure of their replacement. The replacement floor slabs will also be built over void space as opposed to slab on grade in order to prevent future heave.

The presence of framboidal pyrite as well as localized nodular pyrite in the Marcellus Formation in this area along with the inherent calcareous nature of the shale made it predisposed to problems (see Figure 5.3). The long and complex geological history subsequent to the deposition of the Hamilton Group in Devonian time has resulted in significant amounts of the Marcellus being situated near the ground surface in much of the marginal areas of the Valley and Ridge province. Although Lewisburg and surrounding areas have been traditionally rural, the likelihood of current and future developments in this area to intersect unoxidized strata of the

Marcellus is great as inspection of geologic maps will reveal. The problems at the Evangelical Hospital should serve as a warning to the potential hazard not only in the immediate vicinity, but anywhere where the Marcellus and other similar black shales are encountered. Although certainly not uniform across its geographic or stratigraphic extent, the Marcellus has proven to be problematic in virtually every instance it has been encountered. It is likely that other projects that have intersected the Marcellus recently may begin to see problems in the coming years as the slow but insidious problem of swelling advances.



Figure 5.2. Visible heave of the floor slab built upon portions of the expansive Marcellus Formation at the Evangelical Hospital in Lewisburg, Pennsylvania.



Figure 5.3. Pyritic black shale samples taken from beneath heaved floor slabs at the Evangelical Hospital in Lewisburg, Pennsylvania (S.E. Hoover, Pers. Comm., 2007).

5.3 Route 522, Lewistown, Pennsylvania

In 2005 major construction work on portions of Route 522 west of Lewistown, Pennsylvania inadvertently intersected pyrite-bearing lithologies, particularly on the semicircular portion of one interchange. The most problematic strata present at this site were the Middle Devonian Marcellus Formation (see Figure 5.4) at the base of the Hamilton Group and the Lower Devonian Mandata member of the Old Port Formation, which led to considerable local ARD problems, as well as slope stability concerns due to their failure to effectively support vegetation. Also observed to be present at this particular locality during a site visit in 2006 were portions of

the Shriver Chert, Ridgeley Sandstone, Needmore Shale, and Selinsgrove Limestone, in ascending order. All of the aforementioned formations are of Devonian age.

The structural geology of this site proved to be very complex, with many of the beds being near vertical to overturned, and showing signs of severe deformation including small-scale chevron-type folds. There was also evidence for faulting in some of the exposed outcrops. Several of the Tioga ash beds at the base of the Marcellus Formation were clearly exposed on site (see Figure 5.5). Pyrite was observed on site to be both finely disseminated as framboids and also in larger localized nodules within the Marcellus Formation. Several euhedral quartz crystals were also found on site, suggesting a later high-temperature hydrothermal event subsequent to the original depositional sequence. Efflorescent minerals were also observed to be growing on localized surfaces of the Marcellus, having formed in the relatively short time following excavation at the site. Whitish colored minerals taken from the site were identified as boehmite ($\text{AlO}(\text{OH})$) crystals using X-ray diffraction techniques at the Penn State's Materials Research Laboratory (B.E. Scheetz, Pers. Comm., 2007).

Remedial efforts undertaken at the site included collection and treatment of the acidic runoff caused by the presence of the pyritic black shales, efforts to intercept and divert water away from the black shales, the use of paraffin-derived spray sealants to attempt to seal off the surface of the Marcellus from atmospheric oxygen and water, and the removal and mixing of the waste rock with alkaline additions in order to help neutralize its acid-generating capacity (D.J. Sokoloski, Pers. Comm., 2006).

In addition to ARD caused by the Marcellus and Mandata pyritic black shales, the workers on site also encountered problems with portions of the Ridgeley Sandstone. The Ridgeley Sandstone, an important source of high-quality pure silica sand, had been historically

mined in underground shafts in this area. A portion of one of these old abandoned mine shafts was visible on site, and it was reported that the workers were having difficulty sealing off the shaft after an incident of blowout during heavy rains. All told, the various unanticipated problems encountered on site set the construction schedule back considerably and led to overall remedial expenses in the millions of dollars (D.J. Sokoloski, Pers. Comm., 2006).



Figure 5.4. Photograph showing the black shales of the Marcellus Formation (center of photograph) exposed during construction along Route 522 west of Lewistown, Pennsylvania.



Figure 5.5. Photograph showing exposure of the near vertical black shale of the Marcellus Formation and one of the light colored Tioga ash beds exposed during construction along Route 522 west of Lewistown, Pennsylvania.

5.4 Interstate 99 at Skytop, Pennsylvania

Construction along Interstate Highway 99 beginning in 2002 exposed approximately one million cubic yards of sulfide-bearing rock from a large road cut through a section of Bald Eagle Mountain at Skytop between Port Matilda and State College (see Figure 5.6). Large quantities of pyrite-bearing rock were moved to several fill piles and large quantities of the rock were used as fill material and as a subbase for the construction of sections of I-99 roadway just west and east of the road cut. Within only a few months of construction the rock began to leach highly acidic runoff with pH values regularly measured below 3 and with high concentrations of toxic

dissolved metals such as aluminum, arsenic, copper, cobalt, iron, nickel, and zinc (Hammarstrom et al., 2004).

Construction of the section of Interstate 99 at Skytop was put on hold after the magnitude of the ARD problem became clearly evident. Once the Pennsylvania Department of Environmental Protection realized the severity and magnitude of the problem, the Department mandated that remedial efforts be undertaken in order to protect the surrounding environment. The site lies in close proximity to two important watersheds, that of Spring Creek and Bald Eagle Creek. Both of these streams, particularly Spring Creek and its tributaries, are of high quality and are of great importance to the local population and economy for recreation, sport fishing, and a variety of other uses. These waterways eventually feed into the Susquehanna River and the Chesapeake Bay watershed, which is already considered to be in environmental danger, and has recently been the focus of a large-scale effort to decrease organic and inorganic contaminants in an effort to restore the once great status of the Chesapeake Bay, an important commercial fishing waterway that also has great importance in navigation for shipping of various commodities.

The lithologies present at Skytop include the following, in ascending order: the Ordovician Coburn, Antes, Reedsville, Bald Eagle, and Juniata Formations as well as the Silurian Tuscarora and Rose Hill Formations. The structural geology of Skytop is rather complex and is characterized by the presence of several folds, joints, and faults of varying size and orientation, with some of the beds ranging from moderately dipping to overturned in places. The structure of some of the rocks at Skytop presented serious engineering challenges, particularly west of the main road cut along the Allegheny Front where a series of kink or chevron-type folds were observed in the Tuscarora Formation. The orientation of these chevron folds with respect to the highway corridor led to large landsliding problems, which were not

anticipated in the original highway design (D.P. Gold, Pers. Comm., 2007). The unexpected slope instability existing at this location led to a modification in the original design of the road, resulting in a bifurcation of the opposing lanes in order to buttress the hillside. In addition, large amounts of material originating from the main road cut were essentially piled against the unstable portions of the slope. Although these measures were effective in stabilizing the slope, the use of highly pyritic rock as both a sub-base for the road and to buttress the slope further compounded the ARD problems at the site. For a more detailed and comprehensive discussion of the stratigraphy, structure, and overall geological conditions present at Skytop, one should refer to the *Geological Report on the Skytop Road Cuts* written by Gold and Doden (2005).

There are a variety of sulfides and other related minerals present at Skytop in addition to the pyrite. Sulfides found at the site include pyrrhotite, marcasite, sphalerite, galena, and chalcopyrite. Other associated minerals include quartz, barite, and such secondary iron oxide and iron oxyhydroxide weathering products of pyrite as limonite, goethite, jarosite, and hematite. The pyrite occurs as both euhedral crystals and in filiform or whisker morphologies, the latter of which have proven to be highly reactive due to their relatively high surface area. With the exception of some primary pyrite observed in parts of the Reedsville Formation, the predominance of the pyrite present at the site occurs in cross-strike veins (see Figure 5.7) and veinlets that are concentrated primarily in the Bald Eagle Formation, and to a lesser extent in parts of the Tuscarora and Juniata Formations (Gold and Doden, 2005).

Previous to the construction at Skytop there were no visible veins of pyrite at the site, however the presence of sulfides was long suspected due to the exposed secondary gossan minerals and anomalous concentrations of sulfates in local groundwater supplies (Gold and Doden, 2005). The gossan minerals are representative of the oxidized portion of rock present at

the site, which had presumably been slowly forming for millions of years. The large road cuts effectively intersected the underlying reduced zones of rock below the oxidized cap rock.

Although the extent of sulfide mineralization was unanticipated, had the reduced zone been avoided through such measures as highway grade (slope) adjustments and/or realignments, many of the problems encountered at Skytop may have been effectively avoided.

Subsequent to construction activities and after the process of ARD had been given a chance to commence for several months, a variety of secondary efflorescent sulfate minerals were observed in both the cut faces and fill piles. Notable efflorescent sulfates that have been documented at Skytop include melanterite, gypsum, halotrichite, copiapite, alunogen, and rozenite (Hammarstrom et al., 2004). All of the aforementioned minerals, with the exception of gypsum, are extremely soluble in water, and unless sheltered will not endure through a rain event (Gold and Doden, 2005). These efflorescent sulfates have been observed to “bloom” during dry periods and will readily dissolve during rainy spells, releasing pulses of acidity into the surrounding ground and surface waters (Hammarstrom et al., 2004). Not only do many secondary sulfates effectively act as a sort of stored acidity that is quickly released upon contact with water, but since their molar volume is often significantly greater than the original sulfide minerals, they have the ability to not only physically break apart their host rock, but may result in the heaving of engineered structures built upon both bedrock and fill materials.

The ARD at Skytop threatens local groundwater quality for potentially hundreds of private and commercial uses. Elevated levels of contaminants such as sulfate, iron, and aluminum have been measured in several local wells, necessitating the use of bottled water in certain cases. It is unclear at this stage how many wells could be potentially affected, as the transport of contaminants through regional-scale aquifers is often a rather slow and

discontinuous process, which is difficult to accurately model without the costly installation of monitoring wells and the like.

The costs of cleaning up the ARD problem at Skytop have now greatly exceeded the initial cost of the construction of that section of road and number in the tens of millions of dollars. The long delays of the original highway construction schedule have also resulted in great political and social tensions. The problems at Skytop have demonstrated the severity of the hazards of not engaging in a thorough investigation into the geological, hydrological, and engineering characteristics of specific localities that will be subjected to large-scale subsurface disruptions. The immense costs associated with remediation of ARD and related problems in this and other instances have motivated large amounts of research into the prediction for the potential occurrence of sulfide mineralization throughout the state, particularly in areas that will intersect with future construction projects.



Figure 5.6. Aerial photograph of the main road cut at Skytop, Pennsylvania (D.P. Gold, Pers. Comm., 2007).

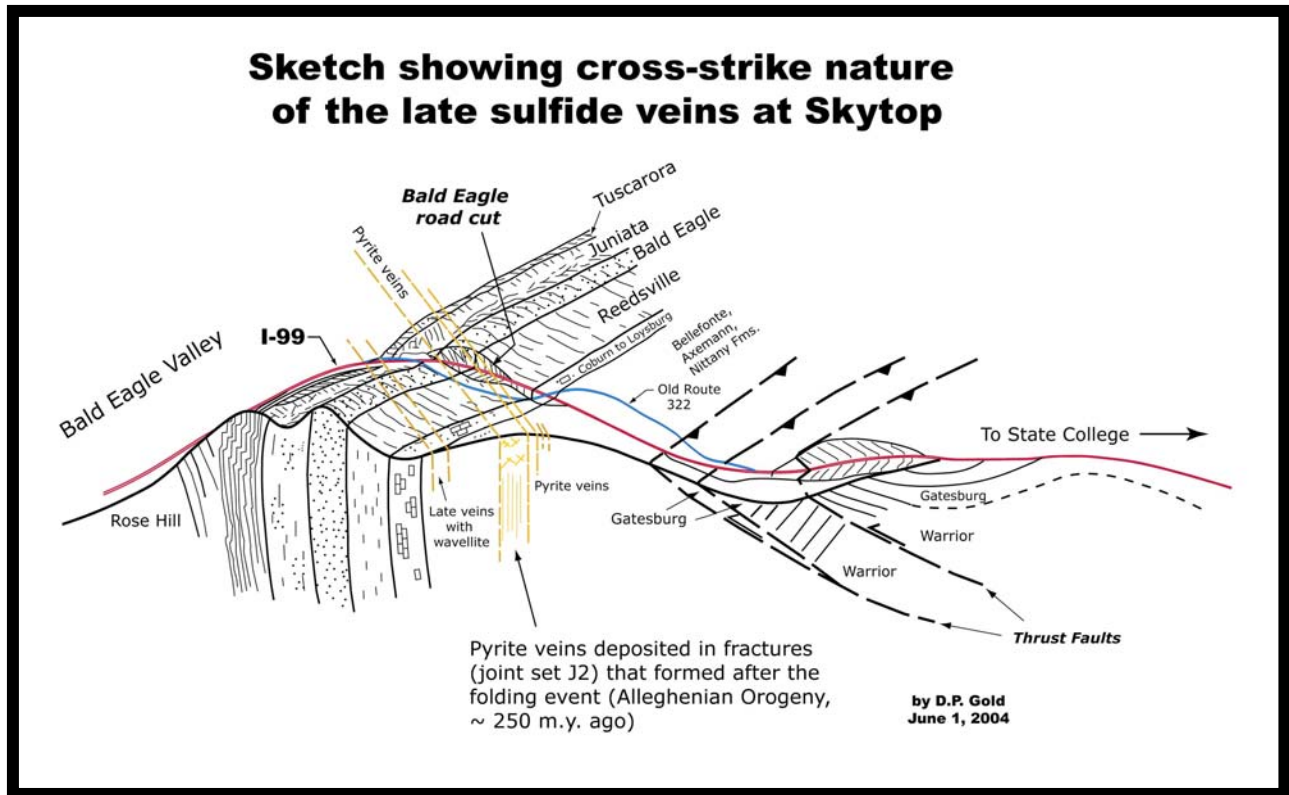


Figure 5.7. Sketch showing cross-strike nature of the late sulfide veins at Skytop (D.P. Gold, Pers. Comm., 2007).

6.0 CONCLUSIONS

Iron-bearing sulfide minerals, primarily pyrite and marcasite (FeS_2), have been identified as the main contributors to ARD in Pennsylvania. Although other sulfides such as galena (PbS) and sphalerite (ZnS) are often found along with iron-bearing sulfides, these sulfides, which do not contain iron, will not result in the formation of ARD. While the non-iron-containing sulfides are not primary contributors to the generation of acid, their presence can result in the dissolution and release of potentially harmful metals such as lead, zinc, arsenic, and copper to the overall ARD system.

Three broad types of potentially acid-producing, sulfide-bearing groups were identified on the basis of a variety of interpretive methods. The first group, the *black shales*, predominantly located in the folded Valley and Ridge physiographic province, are known to cause ARD and have been observed to swell, leading to heave of engineered structures in some cases. Based on 94 surface samples of the black shales, a preliminary north/south geographic trend in their net neutralization potential, NNP, has been perceived that extends roughly between Centre County and Fulton County. The existence of this apparent trend is supported by NNP values from at least four of the individual black shale units sampled. The reasons for the existence of this apparent trend are not clear at this time and could benefit from further sampling efforts.

A second group, consisting of the generally flat-lying *coal-bearing* successions of Pennsylvanian age, has long been known to contribute to ARD problems throughout much of the Appalachian coal region. A general trend in decreasing percentage of sulfur of the coal measures from the southeast to northwest has been perceived based on vast amounts of overburden acid-base accounting chemical analyses. This perceived trend has been attributed to the initial

depositional environment of the coals and overburden formations, especially as it relates to near-shore brackish water environments and open marine water environments and the differing chemical and geological components found in both settings.

The third group, a number of *isolated sulfide deposits*, particularly those associated with predominantly sandstone lithologies such as the Bald Eagle and Tuscarora Formations, appear to be in part structurally controlled. The ability to predict the locations of these deposits, as witnessed by the I-99 Skytop deposit, is limited at this point; therefore, this class of deposits likely represents the highest level of risk to PennDOT construction activities.

A preliminary predictive model has been developed that identifies the coexistence of wind or water gaps with the Bald Eagle and Tuscarora Formations. Wind and water gaps formed from the more rapid weathering of rocks associated with cross cutting lineaments are believed to be permeable conduits for the potential movement of mineralized fluids. This basic predictive model has been observed to a limited extent, but has not been fully empirically tested.

The isolated deposits and some of the black shales, particularly those with a lack of sampling density, deserve more attention in order to identify and substantiate any spatial and temporal relationships allowing for more certain predictive interpretations.

Finally, a straightforward flowchart has been developed to assist in qualitatively evaluating the potential for ARD and significant environmental and engineering impacts based upon the chemical and mineralogical characteristics of the unit or deposit in question.

7.0 FUTURE STUDIES

The environmental and societal problems resulting from acid-generating sulfide minerals in Pennsylvania and elsewhere have long been studied and for the most part are fairly well understood due to decades of attention by a variety of workers in a wide range of disciplines. It is critical that the best available methods and approaches by which potentially acid-producing formations can be identified and avoided before and during construction projects are used in order to minimize or entirely circumvent extensive related problems.

Of the three main groups or types of sulfide bearing formations familiar in Pennsylvania, namely the coal measures, black shales, and localized occurrences, most of the previous work and accumulated knowledge has been regarding the coal measures. A great wealth of information exists regarding all aspects of the coal measures including, but not limited to, their environments of deposition, stratigraphy and structure, chemical and physical properties, as well as several important predictive interpretations for the various coal-bearing formations and specific seams that allow those who expect to excavate these rocks to have a fairly clear idea of the sorts of problems that may be expected in any given area. Much of this work has been motivated by and for the large and economically important coal mining industry in Pennsylvania and in several neighboring states, with relatively little attention being directed toward issues surrounding highway construction or other large geotechnical engineering projects.

Although large amounts of geological interpretations have been made regarding the black shales, comparatively little work has been directed toward understanding their inherent geotechnical and engineering properties. In other words, although the environments of deposition stratigraphy and structure of many of the black shales of Pennsylvania and other areas have been investigated in depth, fairly little is known about their potential to lead to ARD

problems or swelling during construction projects. Only recently have the black shales found in Pennsylvania, such as those of the Devonian aged Marcellus Formation, been elevated to the level of importance that is necessary to avoid significant and costly problems. This report, as well as work by Hoover (2002, 2004, 2005), Gold and Doden (2007), and others has taken necessary steps toward the geological, chemical, and physical characterizations necessary to predict and avoid the hazards related to pyritic black shales.

The localized sulfide occurrences, principally of hydrothermal origin, remain comparatively misunderstood as a group. Although numerous individual localized mineral occurrences have been identified and documented throughout the years, little is known about any relationships that may exist between these deposits. Since a unified theory regarding the origin of these deposits does not exist at this time, it is difficult to predict the likelihood of a localized mineral occurrence, economic or otherwise, to exist in any given location. The lack of predictive tools surrounding these localized occurrences makes it difficult to know ahead of time if a proposed construction site is likely to intersect a localized or secondary acid-generating deposit unless the occurrence has already been extensively exploited (i.e., mined) or documented. However, many localized mineral occurrences of hydrothermal origin are not well documented in the literature, and it is likely that numerous sites have not been documented at all. The lack of knowledge of the origin and relationships among these types of deposits, coupled with the clearly demonstrated hazards linked with their excavation or intersection, makes this group especially important for further study.

Future investigations of the localized sulfide deposits, principally of secondary hydrothermal origin, would benefit from linking these deposits to other measurable surface and subsurface phenomena. It is possible that the presence of localized mineral occurrences can be

correlated with other geological and hydrological trends such as may be facilitated by an increased understanding of the presence of other factors that may be inextricably tied to these localized occurrences. If this is the case then it may become possible to develop predictive methods as to the nature, origin, and likelihood of intersection with these types of deposits over large geographic areas.

8.0 REFERENCES

ACQC, 1999. Pyrite and Your House: What Home Owners Should Know About Swelling Backfills. Montreal, Quebec. Association des Consommateurs pour la Qualite dans la Construction. www.consommateur.qc.ca/acqc/PyriHouse.pdf. pp. 1-48.

Alexander, S. S., Cakir, R., Doden, A. G., Gold, D. P., and Root, S. I. (compilers), 2005. Basement depth and related geospatial database for Pennsylvania. *Pennsylvania Geological Survey*, 4th ser., Open-File General Geology Report 05-01.0, www.dcnr.state.pa.us/topogeo/openfile.

Barrett, D., Pers. Comm., 2007. Mahaffey Laboratory Ltd., P.O. Box L – Main St., Grampian, PA 16838. Email: <dabarrett@mahaffeylaboratory.com>

Barrett, S., Verburg, R., Bertrand, V., Ross, C., Fillipone, J., and Munday, D., 2005. Assessing the Potential Environmental Impact of Acid Rock Drainage and Metal Leaching for the Sea to Sky Highway Improvement Project between Vancouver and Whistler, British Columbia. 2005 Highway Geology Symposium, Wilmington, NC, 16 pp.

Beck, L.A., Pers. Comm., 2007. Marshall Miller and Associates, 3913 Hartzdale Drive, Suite 1306, Camp Hill, PA, 17011. Email: <labeck@earthlink.net>

Belgeri, J.J., and Siegel, T.C., 1998. Design and Performance of Foundations in Expansive Shale. Ohio River Valley Soils Seminar XXIX, Louisville, Kentucky.

Berg, T.M., McInerney, M.K., Way, J.H., and MacLachlan, D.B., 1986. Stratigraphic Correlation Chart of Pennsylvania, 2nd Printing, Revised. *Pennsylvania Geologic Survey*, 4th ser., General Geology Report 75.

Bradham, W.S., Caruccio, F.T., 1995. *Sensitivity Analysis of Laboratory Based Mine Overburden Analytical Techniques for the Prediction of Acidic Mine Drainage*. Submitted to Mr. Eric Perry, U.S. Department of Interior/OSM, 10 Parkway Center, Pittsburgh, PA, 15220.

Brady, K.B., Pers. Comm., 2006. Bureau of Mining & Reclamation, Department of Environmental Protection, 400 Market St., P.O. Box 8641, Harrisburg, PA, 17105. Email: <kbrady@state.pa.us>

Brady, K.B., Smith, M.W., and Schueck, J. (eds), 1998. *Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania*, Pennsylvania Department of Environmental Protection, Harrisburg.

Brett, C.E., 1983, Sedimentology, Facies and Depositional Environments of the Rochester Shale (Silurian; Wenlockian) in Western New York and Ontario. *Journal of Sedimentary Petrology*, v. 53, pp. 947-971.

Bryant, L.D., 2003. Geotechnical Problems with Pyritic Rock and Soil. M.S. Thesis in Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 242 pp.

Byerly, D.W., 1990. *Guidelines for Handling Excavated Acid-Producing Materials*. Report No. FHWA-FL-90-007, U.S. Department of Transportation, Federal Highway Administration, Federal Lands Highway Programs, Washington, D.C. 20590.

Byerly, D.W., 1996. Handling Acid-Producing Material During Construction. *Environmental & Engineering Geoscience*, Vol. II, No. 1, Spring 1996, pp. 49-57.

Colton, G.W., 1967. *Surface Structure Map of Parts of Lycoming, Clinton, Tioga, and Potter Counties, Pennsylvania*. Commonwealth of Pennsylvania Department of Environmental Resources, Bureau of Topographic and Geologic Survey, Map 14.

Fanning, D.S., and Burch, S.N., 2000. Coastal Acid Sulfate Soils. In *Reclamation of Drastically Disturbed Lands*, eds., R.I. Barnhisel, R.G. Darmody, and W.I. Daniels. Agronomy, No. 41, pp. 921-937.

50th Annual Field Conference of Pennsylvania Geologists, 1985. *Central Pennsylvania Geology Revisited*. Commonwealth of Pennsylvania Department of Environmental Resources, Bureau of Topographic and Geologic Survey, Harrisburg, PA, 290 pp.

Freeman, T.E., 2003. *Forensic Investigation of Pavement Distress: Old Airport Road in Bristol, Virginia*. Final Report for Virginia Transportation Research Council, Charlottesville, Virginia. VTRC 04-R6, 15 pp.

Geyer, A.R., Smith, R.C., and Barnes, J.H., 1976. *Mineral Collecting in Pennsylvania*. Commonwealth of Pennsylvania Department of Environmental Resources, Bureau of Topographic and Geologic Survey, 260 pp.

Gold, D.P., Pers. Comm., 2007. Department of Geosciences, The Pennsylvania State University, University Park, PA, 16802. Email: <gold@ems.psu.edu>

Gold, D.P., and Doden, A.G., 2007. *Final Report on The Age, Depth, and Nature of Acid-Generating Mineralization Along Segments of I-99 on Bald Eagle Ridge*, Submitted to Bureau of Planning and Research, Pennsylvania Department of Transportation, Harrisburg, PA, 59 pp.

Gold, D.P., and Doden, A.G., 2005. Geological Report on the Skytop Road Cuts. At Web Site <<http://www.geosc.psu.edu/news/features/gold/skytop.html>>

Hammarstrom, J.M., Brady, K., and Cravotta, C., 2004. *Acid-Rock Drainage at Skytop, Centre County Pennsylvania*, 2004, U.S. Geological Survey, 43 pp.

Hawkins, A.B., and Pinches, G.M., 1987. Cause and significance of heave at Llandough Hospital, Cardiff – a case history of ground floor heave due to gypsum growth. *Quarterly. Journal of Engineering Geology*, London, v. 20, pp. 41-57.

Hoover, S.E., Pers. Comm., 2007. (CMT Laboratories, Inc., 2380 Commercial Blvd., State College, PA 16801. Email: <shoover@cmtlabs.net>

Hoover, S.E., Dempsey, B.A., and Wang, M.C., 2005, Hydrous Sulfate Precipitation in Pyritic Shales, Abst.

Hoover, S.E., Wang, M.C., and Dempsey, B.A., 2004. Structural Damage Induced by Pyritic Shale. *Proc, Fifth Int. Conf. on Case Histories in Geotechnical Engineering*. New York, N.T. Paper #7.02, 7 pp.

Hoover, S., E., 2002. Swelling Behavior of Pyritic Shales in the Marcellus Formation. M.S. Thesis in Civil Engineering, The Pennsylvania State University, 84 pp.

Hornberger, R.J., 1985. Delineation of Acid Mine Drainage Potential of Coal-Bearing Strata of the Pottsville and Allegheny Groups in Western Pennsylvania. M.S. Thesis in Geology, The Pennsylvania State University, 558 pp.

Hornberger, R.J., Parizek, R.R., and Williams, E.G., 1981. *Delineation of Acid Mine Drainage Potential of Coal-Bearing Strata of the Pottsville and Allegheny Groups in Western Pennsylvania*. The Pennsylvania State University, Prepared for the Office of Water Research and Technology, U.S. Department of the Interior, 359 pp.

Howe, S.S., 1988. *Locations and Descriptions of Mineralized Rock Samples from Mississippi Valley-Type Lead-Zinc Occurrences in Central Pennsylvania*. United States Department of the Interior, Geological Survey, Open-File Report 88-250, 37 pp.

Hsu, Fu-Tzu, 1973. Geochemical Exploration in the Nittany Valley Area, Centre County, Pennsylvania, M.S. Thesis in Geochemistry, The Pennsylvania State University, 108 pp.

Krohn, M.D., 1976. Relation of Lineaments to Sulfide Deposits and Fractured Zones along Bald Eagle Mountain: Centre, Blair, and Huntingdon Counties, Pennsylvania. M.S. Thesis in Geology, Department of Geosciences, The Pennsylvania State University, 104 pp.

Lawrence, R.W., and Scheske, M., 1996. A Method to Calculate the Neutralization Potential of Mining Wastes. *Environmental Geology* 32 (2), September 1997, pp. 100-106.

Legget, R.F., and Karrow, P.F., 1983. *Handbook of Geology in Civil Engineering*. McGraw-Hill Book Company, New York, New York, 1308 pp.

Letterman, R.D. (ed), 1999. *Water Quality and Treatment: A Handbook of Community Water Supplies*. American Water Works Association, McGraw-Hill Book Company, New York, New York.

McConchie, D., 2003. The Management of Sulphidic Waste Rock and Tailings, and the Treatment of Acid Rock Drainage: New Solutions for Old Problems. Presented October 2003 for Virotec International & Terraplus, 36 pp.

McMillan, N.J., Embry, A.F., Glass, D.J. (eds), 1988. *Devonian of the World, Proceedings of the Second International Symposium on the Devonian System, Calgary, Canada. Volume I: Regional Synthesis*, Canadian Society of Petroleum Geologists, Calgary, Alberta, Canada, 795 pp.

Miles, C.E., Whitfield, T.G., Kuchinski, J.G., and others, 2001. Bedrock Geology of Pennsylvania. *Pennsylvania Geological Survey*, 4th ser., scale 1:250,000, modified from T.M. Berg and others, 1980, Geologic Map of Pennsylvania, *Pennsylvania Geological Survey*, 4th ser., Map 1, 2nd ed., scale 1:250,000, 3 sheets.

Miles, C.E., 1995. Late Wisconsinan Glacial Border 1:1,000,000, *Pennsylvania Geological Survey*, scale 1:1,000,000.

Miller, B.L., Fraser, D.M., Miller, R.L., Willard, B., Wherry, E.T., 1941. Lehigh County, Pennsylvania. *Pennsylvania Geological Survey*, Harrisburg, Bulletin C39, pp. 138-186.

Morrison, J.L., Scheetz, B.E., Strickler, Williams, E.G., Rose, A.W. Davis, A., Parizek, R.R., 1990. Predicting the Occurrence of Acid Mine Drainage in the Alleghenian Coal-Bearing Strata of Western Pennsylvania: An Assessment by Simulated Weathering (Leaching) Experiments and Overburden Characterization. Geological Society of America Special Paper 248, pp. 87-99.

Nesse, W.D., 2000. *Introduction to Mineralogy*. Oxford University Press, New York, New York, 442 pp.

Orndorff, Z.W., 2001. Evaluation of Sulfide Materials in Virginia Highway Corridors. Ph.D. Thesis in Crop and Soil Environmental Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 175 pp.

Palmer, A.R., and Geissman, J., (compilers), 1999. *1999 Geologic Time Scale*. Geological Society of America, <http://www.geosociety.org/science/timescale/timescl.htm>.

Pennsylvania Geological Survey, 2005. Geologic Units Containing Potentially Significant Acid-Producing Sulfide Minerals. *Pennsylvania Geological Survey*, 4th ser., Open-File Report OFMI 05-01.1, 9 pp., Portable Document Format (PDF).

Petrasic, K., Pers. Comm., 2007. Pennsylvania Department of Transportation, Bureau of Construction and Materials, 211 Materials Lab, Harrisburg, PA 17120. Email: [<kpetrasic@state.pa.us>](mailto:kpetrasic@state.pa.us)

Quigley, R.M., and Vogan, R.W., 1970. Black Shale Heaving at Ottawa, Canada. *Canadian Geotechnical Journal*, Vol. 7, pp. 106-115.

Reidenouer, D., Williams, E.G., Dutcher, R.R., 1967. The Relationship Between Paleotopography and Sulfur Distribution in Some Coals of Western Pennsylvania. *Economic Geology*, Vol. 62, pp. 632-647.

Reyes-Navaro, J., and Davis, A., 1976. *Pyrite in Coal: Its Forms and Distribution as Related to the Environments of Coal Deposition in Three Selected Coals From Western Pennsylvania*. Coal Research Section, The Pennsylvania State University, 141 pp.

Rimmer, S.M., Kuehn, D.W., Allshouse, S.D., Davis, A., 1985. Environments of Deposition of the Lower Kittaning Seam in Pennsylvania and Ohio and Their Influence Upon Coal Petrographic, Mineralogic, and Chemical Compositions. 50th Annual Field Conference of Pennsylvania Geologists, 1985. *Central Pennsylvania Geology Revisited*. Bureau of Topographic and Geologic Survey, Harrisburg, PA, 290 pp.

Scheetz, B.E., Pers. Comm., 2007. Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA, 16802. Email: <bscheetz@enr.psu.edu>

SEDA-Council of Governments, 2006. Central Susquehanna Valley Thruway Bridge – Open House, March 16, 2006, Sponsored by: PennDOT, Route 15 Coalition, and SEDA-COG, 22 pp.

Shultz, C.H., Ed., 1999. *The Geology of Pennsylvania*. Pennsylvania Geological Survey, Harrisburg, & Pittsburgh Geological Society, Pittsburgh, 888 pp.

Skousen J.G., and Ziemkiewicz, P.F., 1995. *Acid Mine Drainage Control & Treatment*. West Virginia University and the National Mine Land Reclamation Center, Morgantown, West Virginia, 255 pp.

Skousen, J., Renton, J., Brown, H., Evans, P., Leavitt, B., Brady, K., Cohen, L., and Ziemkiewicz, P., 1997. Neutralization Potential of Overburden Samples Containing Siderite. *Journal of Environmental Quality*, Vol. 26, No. 3, May-June 1997, pp. 673-681.

Smith, R.C., Pers. Comm., 2007. Mechanicsburg, PA, 17050.

Smith, R.C., 2003. Lead and Zinc in Central Pennsylvania. In Way, J.H. and others (eds.), *Geology on the Edge: Selected Geology of Bedford, Blair, Cambria, and Somerset Counties*, Guidebook, 68th Annual Field Conference of Pennsylvania Geologists, Altoona, PA, pp. 63-72.

Smith, R.C., 1977. Zinc and Lead Occurrences in Pennsylvania. Pennsylvania Topographic and Geologic Survey-Fourth Series, Harrisburg, 317 pp.

Smoot, J.P., and Olsen, P.E., 1988. Massive Mudstones in Basin Analysis and Paleoclimatic Interpretation of the Newark Supergroup, in Manspeizer, Warren, (eds.), Triassic-Jurassic Rifting-Continental Breakup and the Origin of the Atlantic Ocean and Passive Margins, *Developments in Geotectonics*, v. 22, pp. 201-237.

Sobek, A.A., Schuller, W.A., Freeman, J.R., and Smith, R.M., 1978. *Field and Laboratory Methods Applicable to Overburdens and Minesoils*. West Virginia University in Cooperation with the West Virginia Geological and Economic Survey, Morgantown, West Virginia, 203 pp.

Sokoloski, D.J., Pers. Comm., 2006. Pennsylvania Department of Transportation, 1130 West 4th St., Suite 1, Lewistown, PA, 17044. Email: <dsokoloski@state.pa.us>

Southworth, C.S., 1986. *Cross-Strike Structural Discontinuities and Lineaments of the Central Appalachians*. U.S. Geological Survey, Miscellaneous Field Studies Map MF-1891.

Steffen Robertson and Kirsten (B.C.) Inc, 1989. *Draft Acid Rock Drainage Technical Guide*. Prepared for the British Columbia Acid Mine Drainage Task Force, BiTech Publishers Ltd., Vancouver, B.C.

Way, J.H., and Smith, R.C., 1985. Tioga Ash Zone: 6 or More Ash Beds in the Valley and Ridge of Pennsylvania [abs.], *Geological Society of America Abstracts with Programs*, Vol. 17, No. 1, p. 68.

Williams, E.G., Rose, A.W., Waters, S.A., and Morrison, J., 1985. The Distribution of Sulfur and Carbonate Minerals in Pennsylvanian Rocks and Their Significance in Predicting Acid Mine Drainage. 50th Annual Field Conference of Pennsylvania Geologists, 1985. *Central Pennsylvania Geology Revisited*. Bureau of Topographic and Geologic Survey, Harrisburg, PA, 290 pp.

Williams, E.G., Rose, A.W., Parizek, R.R., and Waters, S.A., 1982. *Factors Controlling the Generation of Acid Mine Drainage*. The Pennsylvania State University in Submission to the Bureau of Mines, U.S. Department of the Interior, 265 p.

Appendix A: Geologic Time Scale & Stratigraphic Columns

A.1 Geologic time scale (Palmer and Geissman, 1999).

A.2 Table of formations for central Pennsylvania (D.P. Gold, Pers. Comm., 2007).

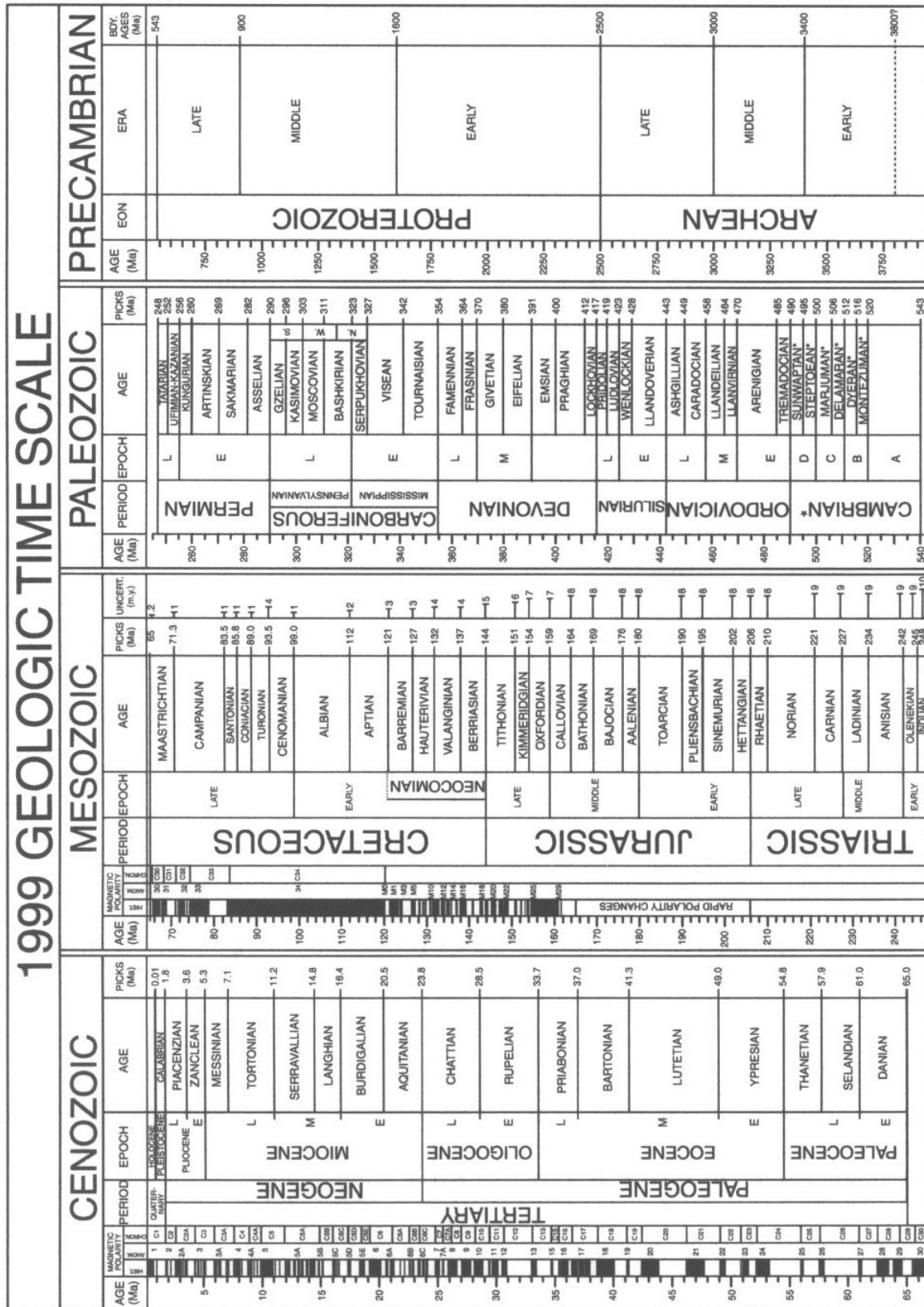
A.3 Generalized stratigraphic correlation chart for Pennsylvania - Cretaceous to Upper Devonian (Shultz [ed.], 1999).

A.4 Generalized stratigraphic correlation chart for Pennsylvania – Middle Devonian to Precambrian (Shultz [ed.], 1999).

A.5 Stratigraphic correlation chart of Lower and Middle Devonian rocks in Pennsylvania (Shultz [ed.], 1999).

A.6 Stratigraphic correlation chart of Middle and Upper Devonian rocks in Pennsylvania (McMillan et al., 1988).

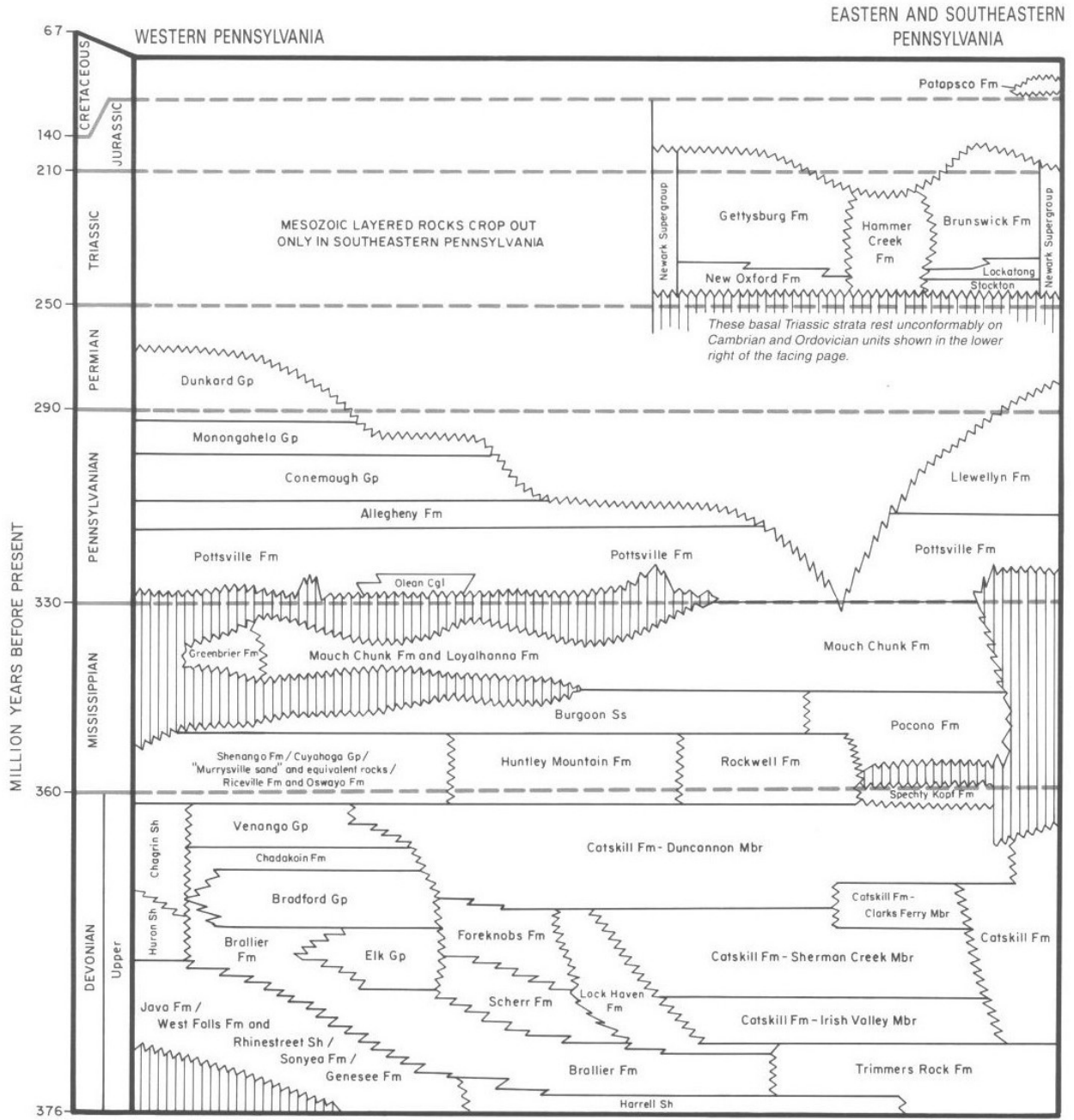
A.1 Geologic time scale (Palmer and Geissman, 1999).



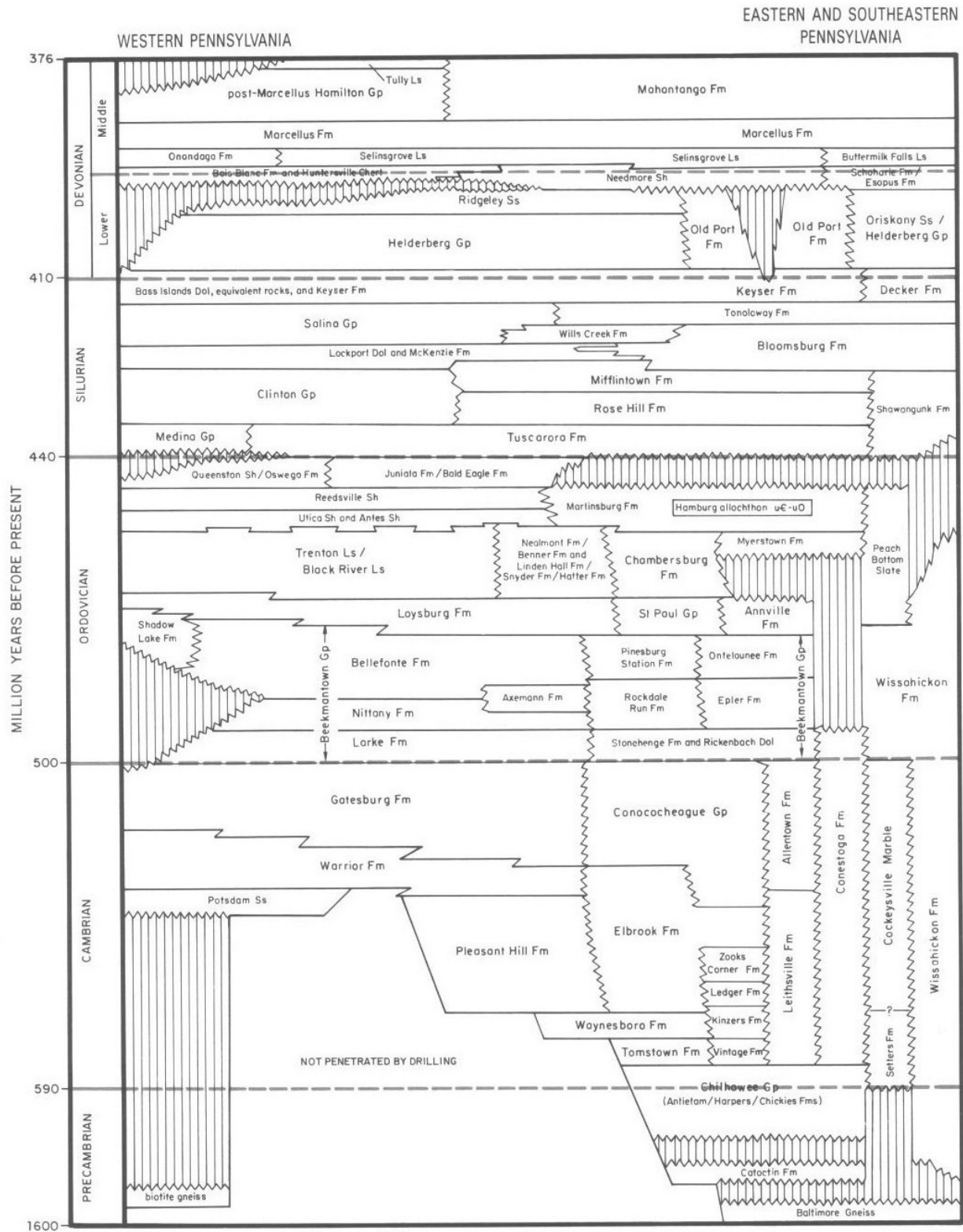
A.2 Table of formations for central Pennsylvania (D.P. Gold, Pers. Comm., 2007).

TABLE OF FORMATIONS FOR CENTRAL PENNSYLVANIA						
	WEST	Feet	CENTRAL	Feet	EAST	Feet
Permian 290 Ma	Dunkard Group					
	Monongahela Group		Monongahela Group			
Pennsylvanian 330 Ma	Conemaugh Fm		Conemaugh Fm		Llewellyn Fm	
	Allegheny Fm		Allegheny Fm			
	Pottsville Fm		Pottsville Fm		Pottsville Fm	
	Loyalhanna Fm		Mauch Chunk		Mauch Chunk	
Mississippian			Burgoon Fm		Pocono Fm	
			Huntley Mtn Fm		Rockwell Fm ; Spechy Kopf Fm	
			Catskill Fm - Duncannon Mbr		Catskill Fm - Duncannon Mbr	
			Lock Haven/Catskill Fm		Catskill Fm - Sherman Creek Mbr	
			Lock Haven/Catskill Fm		Catskill Fm - Irish Valley Mbr	
			Brallier Fm		Trimmers Rock	
			Harrell Shale- Burkett Mbr		Trimmers Rock	
376 Ma			Tully Limestone		Mahantango	
			Hamilton Group	900	Mahantango	
	Marcellus Fm		Marcellus Fm	70	Marcellus	
	Onondaga Fm		Selingsgrove Limestone	135	Buttermilk Falls Fm	
			Needmore Fm		Esopus Fm	
Devonian			Ridgeley Sst	75	Helderberg Group: Oriskany Sst	
			Old Port Group - Schreiber Chert	100+	Helderberg Group	
			Old Port Group - Mandata Black Shale	6-20	Helderberg Group	
			Old Port Group - Coeymans, New Scotland Lst		Helderberg Group	
410 Ma	Three Islands Dolostone		Keyser Fm	200	Decker Fm	
	Salina Group		Tonoloway Fm	400-820	Tonoloway Fm	
Silurian			WillsCreek/Bloomsburg Fms	85-800	Bloomsburg Fm	
			Bloomsburg Fm		Bloomsburg Fm	
	Lockport/McKenzie	200	Mifflintown (Keefe, Rochester, McKenzie)	625	Pocono Island and Bossardville Lst	100
440 Ma	Clinton Group		Rose Hill Fm	600-950	Shawangunk Fm	
	Medina Group	200	Tuscarora Fm	400-650	Shawangunk Fm	
Ordovician			Juniata Fm	700-1400	Hamburg allochthon: Martinsburg Fm	
	Queenstown Sh/Oswego Fm		Bald Eagle Fm	600-800	Hamburg allochthon: Martinsburg Fm	
		1100	Reedsville: Interbedded shale, sst, minor limestone (coquinas). Shallow water, x-bedded burrowed increasingly common upward	700-1000	Martinburg: shale and calc turbites	10,000*
	Reedsville Fm				Upper: f-g, x-bed massive sandstone	
	Utica/Antes Shale		Antes :black graptolitic shale		Middle: fan channel turbidite flysch	
Cambrian		0-350			Lower: graptolitic, pelagic calc shale	1500-2000
	Trenton Group		Coburn Fm	200+	Chambersburg Fm	0
	Trenton Group		Salona Fm	200	Chambersburg Fm	
	Trenton Group		Nealmont Fm	76	Chambersburg Fm	
	Black River Group		Linden Hall Fm	150	Chambersburg Fm	
	Black River Group		Snyder Fm	96	Chambersburg Fm	
	Black River Group		Hatter Fm	100	Chambersburg Fm	
	Loysburg Fm		Loysburg Fm	240	St Paul Group	
	Shadow Lake Fm		Bellefonte Fm	1000	Pinesburg Fm	
	Nittany Fm		Axemann Fm	0-360	Rockdale Run Fm	
	Nittany Fm		Nittany Fm	1000-1200	Rockdale Run Fm	
	Nittany Fm		Stonehenge/Larke Fm	630	Stonehenge/Rickenbach Dolostone	
500 Ma	Gatesburg Fm		Gatesburg Fm	1800+	Conococheague Group	
	Warrior Fm		Warrior Fm	600+	Elbrook Fm	Zooks Corner Fm
	Potsdam Sst		Pleasant Hill Fm			Ledger Fm
590 Ma			Waynesboro Fm			Kinzers Fm
	Grenville Gneiss		Tomstown Fm			Vintage Fm
			Grenville Gneiss?			Chilowee Group

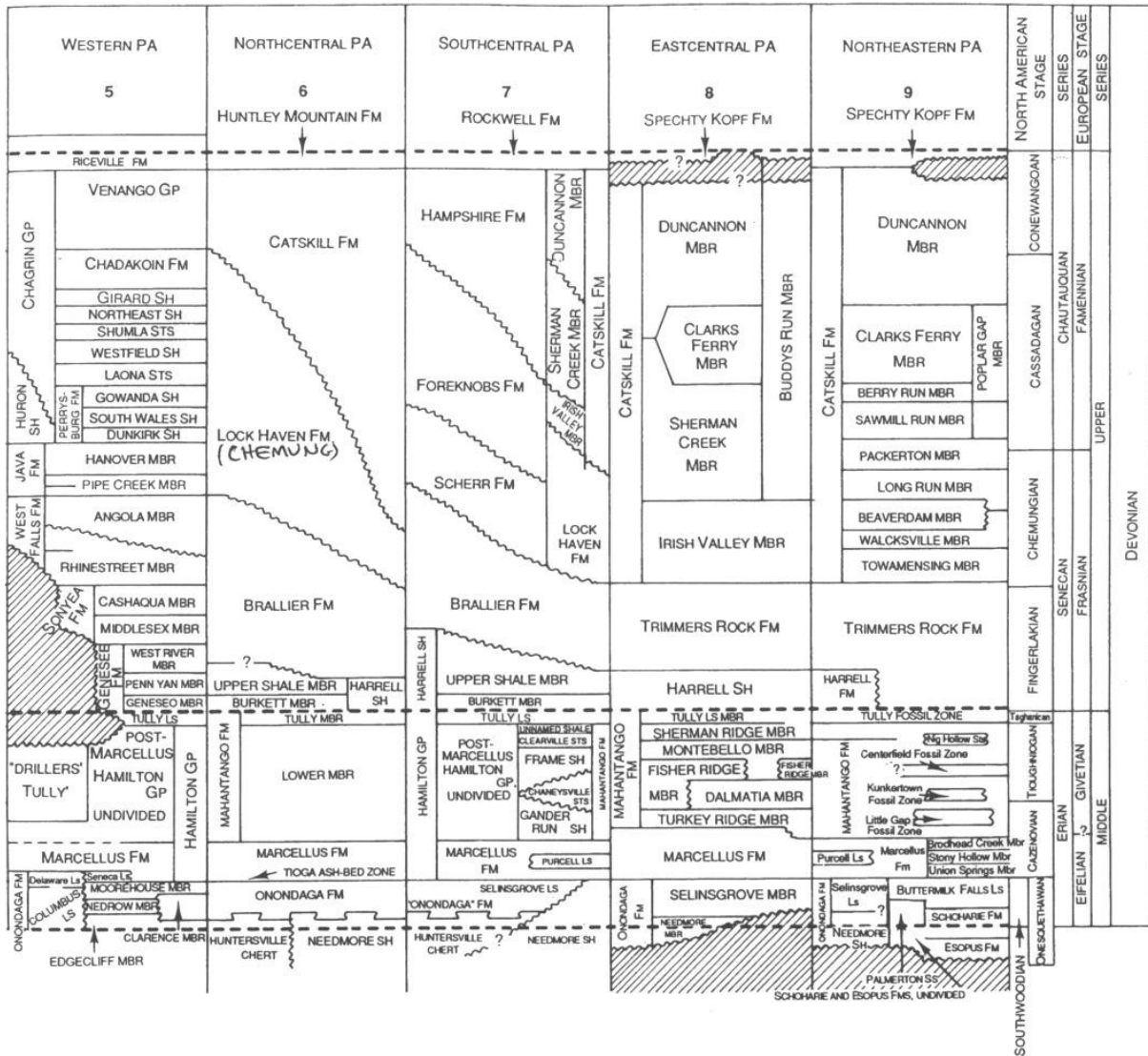
A.3 Generalized stratigraphic correlation chart for Pennsylvania - Cretaceous to Upper Devonian (Shultz [ed.], 1999).



A.4 Generalized stratigraphic correlation chart for Pennsylvania – Middle Devonian to Precambrian (Shultz [ed.], 1999).



A.6 Stratigraphic correlation chart of Middle and Upper Devonian rocks in Pennsylvania (McMillan et al., 1988).



Appendix B: ABA Standard Operating Procedures

B.1 SOP Total sulfur (Barrett, Pers. Comm., 2007)

B.2 SOP Neutralization potential (Barrett, Pers. Comm., 2007)

B.1 SOP Total sulfur (Barrett, Pers. Comm., 2007).

SOP Total Sulfur

METHOD - ASTM D - 4239

All instruments and supplies can be found in the OVERBURDEN AREA unless otherwise stated.

**** Use heavy duty gloves when handling the furnace ****

***** Information such as the method and instructions for the furnace and titrators is located in a white binder found on the desk in the Sample Prep Area.

The solutions needed for this procedure and how to make them up are as follows:

- 0.05N NaOH - Mix 1 Acculute to 2000 mL deionized water
- H₂O₂ Solution - Mix 70 mL H₂O₂ to 2000 mL deionized water
- H₂SO₄ Solution - Mix 3 drops concentrated H₂SO₄ to 20 mL deionized water
- Methyl Purple Indicator

*Concentrated Solutions- H₂O₂, H₂SO₄ found in Acid Area Lower Shelf - MAIN CHEM AREA

Furnace

The Preiser/MINECO Combustible Tube Furnace should be heated to 1325 °C. Usually the oven is already on and you just need to push the function button to heat the oven to the correct temperature. If the oven is not turned on, turn the red switch in the front of the oven to the on position. The fine and course adjustments should be set to 3.

Turning On and Adjusting the Oxygen

The titrator closest to the furnace is called the Leco titrator and the next one is called the Mineco titrator (which will need turned on before use). The oxygen will need to be turned on for both of these titrators if both are to be used. The oxygen tank in the corner is for the Mineco titrator. Open the valve on top of the oxygen tank, then slowly turn clockwise, (turning in) the large regulator knob-valve and watch the flow meter for that particular titrator and adjust to the following level. For the flow meter for the Mineco, the small black ball needs to be between 1/2 to 2/3 of the way up the flow meter tube. Open the side valve until the ball indicator in the gas flow meter (located on the titrator) is between 2.2 - 2.4. The next oxygen tank is for the Leco titrator. Open the valve on the tank, then slowly open the side valve until the ball indicator in the gas flow meter (located on the wall next to the furnace) is approximately two thirds the way up the meter. (Follow the tubing from the titrators, through the furnace, and to the oxygen tanks, making sure the tanks didn't get switched.)

Filling the Burets

To fill the buret for the Leco titrator, press down on the silver knob on the front, then squeeze the bulb, and continue squeezing, until the buret is filled. The buret will automatically zero itself. To fill the buret for the Mineco titrator, press the "fill buret" button on the side of the titrator until the buret is filled. The buret will automatically zero itself.

Filling and Preparing the Bubblers

Before filling up the bubblers, close the valves at the bottom of both bubblers. To fill up the bubbler for the Leco, hold your finger over the silver knob on the front (do not press down because doing so would fill the buret), then squeeze the bulb, and continue squeezing, until the bubbler is filled to the mark. To fill up the bubbler on the Mineco, press the "fill bubbler" button on the side of the titrator until the bubbler is filled to the black mark. Next, add 12 drops of methyl purple to the solution in the bubblers. Then, add 2 drops of H₂SO₄ solution. The solution should be purple at this point. Titrate until the solution turns bright green - with the Leco, use the fine and coarse knobs; with the Mineco, use the "titrate" button on the side of the titrator. Refill both burets.

Conditioning the System

Add a small amount of QC - Found by yellow Sartorius scales- (Usually use Canspecs 51: 1.26) to two ceramic boats. Being careful, remove the plug from one of the tubes on the left side of the furnace. Place a boat in the tube and push it into the tube using the poker with the orange plexiglass at the base. This poker has a mark on it which designates the middle of the furnace. Only push the boat in about half way to the mark, replace the plug, making sure it is in snug enough to allow the oxygen to travel to the bubbler. Make sure to hold onto the tube with a gloved hand, while replacing the plug, because this tube is hot and it is loose in the furnace. Do the same with the other boat and other tube. Set the timer for 3 minutes. After 3 minutes, remove the plug and push the boat farther into the tube to the mark on the poker, and replace the plug. Do the same with the other boat. Set the timer for another 3 minutes. Once the 3 minutes are up, titrate both until a bright green.

Running QCs, Samples, and Dups

(All QCs, samples, and dups use 0.5000 gms. Weigh out using the yellow Sartorius scales.) Start with the QC. Measure out 0.5000 gm of QC in two boats, one for each titrator. Run the same as above (conditioning the system). When done titrating, record the answers on the "Quality Control - Sulfur Standards" log, an example of this log is shown in Appendix 1. This log is located on the desk in the Middle Work Area in a blue binder. If answers are acceptable, continue with the samples. Weigh out 0.5000 gm for each sample. Remember which sample is in which titrator. Run a dup every 20 samples. Record all answers on the "Quality Control - Duplicate Samples" log, an example of this log is shown in Appendix 2. This log is located on the desk in the Middle Work Area in a blue binder. Every 10 or so samples, especially if the previous samples contained a lot of sulfur, drain the solution in the bubbler and refill and recondition the same as above. It is a good idea to run another QC after this step.

If using the Mineco titrator, use the table hanging on the wall above the oxygen tanks. This table shows adjustment values if the answer is 1.50 or higher. If a sample has a high amount of sulfur, redo the sample with half the amount (0.2500 gm) and multiply this answer by 2.

When done with the samples, remember to drain the bubblers, shut off both oxygen tanks, and turn off the Mineco titrator.

Cleaning Boats

When sulfur boats are cool, use a screwdriver to scrape loose sample out.

Cleaning Titrators

- LECO titrator glass tube above the bubbler should be cleaned with soap and water periodically, especially if the tube is blackened.

* There are 3 copies of this document. The QC Technician will hold one on top of the QC file cabinet-FIELD OFFICE. The Main SOP Notebook will hold all SOP Documents on the top shelf of the MERCURY STANDARDS AREA by the WET AREA. The working SOP copy will be found on the desk in the OVERBURDEN AREA. The SOP will be reviewed yearly. If revisions are made, the QC copy and Working copy will be cut in half and destroyed by the laboratory director or QC technician. The Main copy will be kept in the QC file cabinet-FIELD OFFICE- for 5 years. It will then be cut in half and destroyed by the laboratory director or QC technician.

B.2 SOP Neutralization potential (Barrett, Pers. Comm., 2007).

SOP Neutralization Potential

Method: Part 2: Analytical Procedures Section II: Neutralization Potential; Pennsylvania DER Overburden Sampling and Testing Manual, Contract No. ME 86120

Information regarding the method is located in a red folder on the desk in the Sample Prep Area.

***** Some samples arrive already geologically logged, meaning they have already been marked as to how they should be combined according to certain physical attributes. Other samples need to be logged by us. Use the "Overburden Key" (located on the desk in the blue binder in the Middle Work Area) to aid in doing so. An example of this key is shown in Appendix 1.

The samples need to be combined and layed out to dry. When they are dry, they need to be ground to a 60 mesh.

(A). Solutions

1. Hydrochloric Acid 0.1 N (located on the counter in the Sample Prep Area)
2. Hydrochloric Acid 0.5 N (located under the counter in the Sample Prep Area)
3. Hydrochloric Acid 25% - for fizz test (located on the table in the Middle Work Area)
4. Sodium Hydroxide 0.1 N (located under the counter in the Sample Prep Area)
5. Sodium Hydroxide 0.5 N (located on the table next to the entryway)

(B). Determine the Fizz Rating

One of the main reasons for the fizz rating test is to ensure that the addition of acid to the sample, (during the neutralization potential test), is sufficient to react with all the calcium carbonate present.

This is accomplished by first placing approximately 0.5 g of sample on an aluminum dish. Then adding one or two drops of 25% HCl to the sample, a bubbling or audible "fizz" will be heard and/or seen in the presence of CaCO₃. This is rated on the following scale: none, slight, moderate, or strong .

(C). Weigh 2.00 grams of sample and transfer to a 150 ml beaker (located in the Wash Area).

(D). Add the quantity of HCl to sample indicated in the following table, according to fizz rating. 0.1 N HCl is also in a manual dispensette located on the counter in the Sample Prep Area. This dispensette is set at 10 mls. Use this for samples that need 20 or

40 ml of 0.1 N HCl, dispensing either 2 pumps or 4 pumps, depending on the fizz rating. This plunger should be checked first to make sure it is set correctly. Add the 0.5 N HCl using a graduated cylinder.

<i>Fizz Rating</i>	<i>Volume of HCl</i>	<i>Normality of HCl</i>
None	20 ml	0.1 N.
Slight	40 ml	0.1 N.
Moderate	40 ml	0.5 N.
Strong	80 ml	0.5 N.

(E). Add deionized water, using a graduated cylinder, to make approximate volume of 100 ml.

(F). Place beakers on the yellow hot plate (located in the Heating Area), set at about 6. Cover with watch glasses (located in the Wash Area). Boil gently for 5 minutes.

(G). Using gloves, carefully remove beakers from the hot plate and line them up on the table in the Middle Work Area. Allow to cool to room temperature.

(H). The pH meter (located in the Sample Prep Area) will need to be calibrated. Remove probe from storage solution. Rinse and dry. Pour fresh 7.0 buffer (located on the shelf in the Sample Prep Area) into beaker and add a magnetic stirring bar. Do the same with 4.0 buffer (located on the shelf in the Sample Prep Area). Place the beaker with 7.0 buffer on the magnetic stirrer and turn on. Carefully place probe into beaker. Adjust meter to read 7.0 using appropriately marked knob. Remove probe, rinse and dry. Place the beaker with 4.0 buffer on the magnetic stirrer. Carefully place probe into beaker. Adjust meter to read 4.0 using appropriately marked knob. Remove probe, rinse and dry. Go back and read the 7.0 buffer again and record meter reading in the "Daily pH Meter Calibration" log (located on the desk in a blue binder in the Middle Work Area). An example of this log is shown in Appendix 2. Do the same with the 4.0 buffer (don't forget to record the reading). If either of these readings fall out of the (+/-) 0.1 range, recalibrate the meter.

(I). If the sample has a "none" or "slight" fizz rating, use the digital buret (located in the Sample Prep Area) which contains 0.1 N NaOH. Turn digital buret on. Switch to fill. Place a waste container under the tip and crank the knob down a little to get air bubbles out then crank the knob the whole way up until full. Switch back to titrate. Place a magnetic stirrer in the sample beaker and place on the magnetic stir plate. Turn the stir plate on. Place the probe into the beaker. Titrate up to a pH of 7.0. Follow the "Neutralization Potential Guide" sheet when titrating (hanging from the shelf in the Sample Prep Area). An example of this sheet is shown in Appendix 3.

If the sample has a "moderate" or "strong" fizz rating, use the manual buret (located next to the digital buret, Sample Prep Area). Fill the buret with 0.5 N NaOH to above the 25 ml line then slowly let some out (into a waste container) until the meniscus falls on the 0 line. Place a magnetic stirrer in the sample beaker and place on the magnetic stir plate.

Turn the stir plate on. Place the probe into the beaker. Titrate up to a pH of 7.0. Follow the "Overburden Fizz Rating" sheet when titrating (hanging from the shelf in the Sample Prep Area). An example of this sheet is shown in Appendix 3.

(J). Duplicate samples are run every 20 samples. Duplicate results need to be written in the "Quality Control - Duplicate Samples" log (located on the desk in the blue binder in the Middle Work Area). An example of this log is shown in Appendix 4.

(K). "QC-A" NEEDS TO BE RUN EACH DAY THAT 0.1N HCl AND 0.1N NaOH ARE USED FOR N.P. ANALYSIS. "QC-B" OR "QC-C" NEEDS TO BE RUN EACH DAY THAT 0.5N HCl AND 0.5N NaOH ARE USED FOR N.P. ANALYSIS. ALTERNATE "QC-B AND QC-C" EACH SEPARATE DAY THAT 0.5N SOLUTION IS USED IN ANALYSIS. IF MORE THAN 100 N.P.S ARE RUN PER DAY, RUN AN ADDITIONAL "QC-A".

(QC-A) 0.10 gms - 40 mls of 0.1 N HCl = N.P. of 50.0 [(+/-) 2.5]

(QC-B) 1.00 gms - 40 mls of 0.5 N HCl = N.P. of 500 [(+/-) 25.0]

(QC-C) 2.00 gms - 80 mls of 0.5 N HCl = N.P. of 1000 [(+/-)50.0]

The QC results should be written in the "Quality Control - Calcium Carbonate Standards" log (located on the desk in the blue binder in the Middle Work Area). An example of this log is shown in Appendix 5.

* There are 3 copies of this document. The QC Technician will hold one on top of the QC file cabinet-FIELD OFFICE. The Main SOP Notebook will hold all SOP Documents on the top shelf of the MERCURY STANDARDS AREA by the WET AREA. The working SOP copy will be found on the desk in the Middle Work Area of the OVERBURDEN AREA. The SOP will be reviewed yearly. If revisions are made, the QC copy and Working copy will be cut in half and destroyed by the laboratory director or QC technician. The Main copy will be kept in the QC file cabinet-FIELD OFFICE- for 5 years. It will then be cut in half and destroyed by the laboratory director or QC technician

Appendix 1



MAHAFFEY LABORATORY LTD.

362 MAIN STREET, P.O. BOX L

GRAMPIAN, PA 16838

814-236-3540 FAX 814-236-1284

<http://www.mahaffeylaboratory.com>

Company:
Hole Number:

Job:
Date Logged & Remarks:

OVERBURDEN KEY

Combined Depths - Sample #	"Before Combination" Fizz	Depth	Description of Sample	Color Of Sample	Hardness Scale
Depths of sample with similar "before combination" fizz, color, hardness and geological rock/mineral type are combined (up to 3 feet)	None - No Reaction	Feet below surface (ex. 0-1 would be a sample collected from the surface to 1 foot below the surface)	Most dominant geological rock/mineral is stated last (ex. Clay-Shale means there is both clay and shale in the sample, but there is more shale than clay)	Visible appearance If two colors are listed for the same sample, the most dominant color is stated last	Soft Medium-Soft Hard-Soft
	Slight - Minimal Reaction				Soft-Medium Medium Hard-Medium
	Moderate - Active Bubbling				Soft-Hard Medium-Hard Hard
	Strong - Very Active Bubbling				
	Each foot will receive a fizz rating so as not to cover or dilute out a detected fizz.				
	Note: A detected "before combination" fizz rating can be different than the reported fizz recorded after combination and pulverizing of sample				

NEUTRALIZATION POTENTIAL GUIDE

Fizz Rating	Instructions For Using The Amount Of NaOH In mLs. In Analyzing and Calculating The Neutralization Potential (N.P.)
<p>NONE (2,000 grams) 20 mLs of 0.1 N - HCl</p>	<p>Range of mLs of NaOH 0.1 to dispense: 8 - 20 mLs. N.P. Range Negative to 30.0 Titrate No Less Than 8 mLs. for it would produce an N.P. Of greater than 30. If less than 8 mLs titrated gave a pH of 7.0, rerun the sample as a "Slight Fizz Rating".</p> <p>Titration More Than 20 mLs. will produce a Negative N.P., which is usually questioned. This does occur sometimes at the top of the overburden hole. For example a titration of 20.8 mLs gives an Negative -2.00</p>
<p>SLIGHT (2,000 grams) 40 mLs of 0.1 N - HCl</p>	<p>Range of mLs of NaOH 0.1 to dispense: 4 - 28 mLs. N.P. Range 30.0 to 90.0 Titrate No Less Than 4 mLs. for it would produce an N.P. of greater than 90. If less than 4 mLs titrated gave a pH of 7.0, rerun the sample as a "Moderate Fizz Rating".</p> <p>Titrate No More Than 28 mLs. for it would produce an N.P. of less than 30. If you need to titrate more than 28 mLs to reach a pH of 7.0, stop and rerun the sample as "None Fizz Rating".</p>
<p>MODERATE (2,000 grams) 40 mLs of 0.5 N - HCl</p>	<p>Range of mLs of NaOH 0.5 to dispense: 2 - 34 mLs. N.P. Range 75.0 to 475.0 Titrate No Less than 2 mLs. for it would produce an N.P. of more than 475. If less than 2 mLs titrated gave a pH of 7.0, rerun the sample as a "Strong Fizz Rating".</p> <p>Titrate No More Than 34 mLs. for it would produce an N.P. of less than 75. If you need to titrate more than 34 mLs to reach a pH of 7.0, stop and rerun the sample as "Slight Fizz Rating".</p>
<p>STRONG (2,000 grams) 80 mLs of 0.5 N - HCl</p>	<p>Range of mLs of NaOH 0.5 to dispense: 0 - 44 mLs. N.P. Range 450.0 to 1000.0 Since the "Strong Fizz Rating" is the highest level, you do not have to be concerned about titrating too small of an amount. Just use the small number of mLs in the calculations and report the result. There can be samples in which you do not add any titrant. If you place your probe into the sample and it reads a pH of 7.0, the N.P. will be 1000. If the pH reads greater than 7.0, the N.P. will be marked as ">1000".</p> <p>Titrate No More than 44 mLs. for it would produce an N.P. of less than 450. If you need to titrate more than 44 mLs to reach a pH of 7.0, stop and rerun the sample as "Moderate Fizz Rating".</p>

Amount And Normality Of HCl Acid To Add Due To Fizz Intensity

<p>(20 mLs. - 0.1N for NONE) (40 mLs. - 0.1N for SLIGHT) (40 mLs. - 0.5N for MODERATE) (80 mLs. - 0.5N for STRONG)</p>
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Formula For Calculating The Neutralization Potential (N.P.)

<p>(mLs. of HCl acid added minus mLs NaOH base added) x 25.0 x Normality = N.P. Example: (20.0 mLs. - 9.4 mLs.) X 25.0 x 0.1 = 26.5, This would be acceptable for a NONE</p>
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Appendix C: Black Shale ABA Data

C.1 Burket Member of the Harrell Formation

C.2 Mahantango Formation

C.3 Marcellus Formation

C.4 Hamilton Group

C.5 Needmore Shale

C.6 Mandata Shale

C.7 Mifflintown Formation

C.8 Reedsville Formation / Antes Member / Upper Coburn Formation

C.9 Percent Pyritic Sulfur Values of Selected Black Shales

C.1 Burket Member of the Harrell Formation

Locality	Formation	Latitude	Longitude	%S	MPA	Fizz	NP	NNP
Lockport: River Rd. opposite Park	Burket Shale	41.1415	-77.444472	1.74	54.375	None	12.75	-41.625
Canal Rd., Flemington	Burket/Harrell	41.129583	-77.484388	0.04	1.25	None	3	1.75
NE of Antes Fort	Burket?	41.209305	-77.204305	0.44	13.75	None	17	3.25
NE of Antes Fort	Burket?	41.213611	-77.195888	0.08	2.5	None	0.25	-2.25
Montoursville	Burket?	41.2645	-76.911916	0.16	5	Slight	39.25	34.25
Fairfield Shale Quarry	Burket?	41.262444	-76.868277	0.48	15	None	5.75	-9.25
Raystown Dam/Entricken Rd.	Burket	40.330019	-78.1928	0.16	5	None	9.25	4.25
Newry, Rte 220 road-cut	Burket/Harrell	40.380888	-78.435166	1.36	42.5	None	6.5	-36
Grazierville	Burket/Harrell	40.659555	-78.273722	1	31.25	None	2.25	-29
Tipton, I mile SW on railroad track	Burket/Harrell	40.629638	-78.31375	0.2	6.25	None	0.5	-5.75

C.2 Mahantango Formation

Locality	Formation	Latitude	Longitude	%S	MPA	Fizz	NP	NNP
Rte 22, Huntingdon	Mahantango	40.487027	-78.030916	0.32	10	None	-3.75	-13.75
Rte 36, 3 miles S of Hollidaysburg	Mahantango	40.383138	-78.414583	1.16	36.25	None	6.75	-29.5
Rte 36, 3.5 miles S of Hollidaysburg	Mahantango	40.380277	-78.417611	0.46	14.38	None	0.75	-13.63
Hopewell area	Mahantango	40.148194	-78.298083	0.32	10	None	8	-2

C.3 Marcellus Formation

Locality	Formation	Latitude	Longitude	%S	MPA	Fizz	NP	NNP
Route 522 road-cut, Lewistown	Marcellus	40.58025	-77.627388	1.64	51.25	None	-41.25	-92.5
Hollidaysburg; NESL Quarry	Marcellus	40.433805	-78.345555	0.48	15	None	4.75	-10.25
Montoursville Quarry near School	Marcellus	41.252916	-76.902305	3.08	96.25	None	-5.25	-101.5
Grazierville/Charlotts ville	Marcellus	40.649555	-78.268638	2.18	68.13	None	27	-41.13
Tipton, NW of Dysart Cemetery	Marcellus	40.632833	-78.296694	0.08	2.5	None	0	-2.5
Tipton, NW of Dysart Cemetery	Marcellus	40.633194	-78.297527	0.06	1.88	None	-0.25	-2.13
Altoona; 6th St Gravel Pit	Marcellus	40.528444	-78.380305	0.16	5	None	1.25	-3.75
Newton/Hamilton railroad cut	Marcellus	40.383027	-77.851388	2.42	75.63	None	2.25	-73.38
Lewisburg Hospital	Marcellus	40.980861	-76.88825	0.54	16.88	None	9.25	-7.63
(K. Brady) 209 Marshalls Creek	Marcellus	41.0448	-75.12379	0.28	8.75			
(S. Hoover) Washingtonville PPL Project	Marcellus	41.07386	-76.6635	3.68	115	Slight	47.25	-67.75

C.4 Hamilton Group

Locality	Formation	Latitude	Longitude	%S	MPA	Fizz	NP	NNP
Canal Rd., Flemington	Hamilton	41.125555	-77.476833	0.2	6.25	None	-2.75	-9
Jersey Shore; off Rte 44	Hamilton	41.199666	-77.238138	0.42	13.125	Moderate	227.5	214.375
Rte 522, 1.96 S of Shileysburg	Hamilton	40.271305	-77.886944	0.14	4.38	None	-2.25	-6.63
Dickeys Mtn, Fulton County	Hamilton	39.758555	-78.081	0.18	5.63	None	2	-3.63
Hyndman	Hamilton	39.816333	-78.728611	0.8	25	Slight	77	52
Koon Lake	Hamilton	39.7695	-78.655055	0.26	8.13	None	1.5	-6.63
Fielders Rd. Quarry?	Hamilton	40.39975	-77.85975	0.24	7.5	None	3.75	-3.75
Bald Eagle, Rte 322 near California Rd.	Hamilton	40.733583	-78.153194	0.1	3.13	None	15.75	12.62
Bald Eagle, Rte 322 near California Rd.	Hamilton	40.733722	-78.153194	0.06	1.88	None	10.5	8.62

C.5 Needmore Shale

Locality	Formation	Latitude	Longitude	%S	MPA	Fizz	NP	NNP
Ridgeley Quarry off Rte 966	Needmore	40.372777	-77.95575	1	31.25	Moderate	250	218.75
Dickeys Mtn, Fulton County	Needmore?	39.757666	-78.080194	0.16	5	None	6	1

C.6 Mandata Shale

Locality	Formation	Latitude	Longitude	%S	MPA	Fizz	NP	NNP
Route 522 road-cut, Lewistown	Mandata	40.578694	-77.628277	1.52	48.13	None	-38.25	-86.38
Canoe Creek Quarry	Mandata	40.48561	-78.29569	0.96	30	Slight	85.5	55.5
St Clairsville	Mandata	40.148111	-78.510388	1.12	35	Moderate	382.5	347.5
New Paris Quarry	Mandata	40.117194	-78.626583	0.1	3.13	Moderate	216.25	213.12
Altoona Bible Church quarry	Mandata	40.493222	-78.405333	0.5	15.63	Moderate	151.25	135.62
ElDelardo Quarry	Mandata	40.453277	-78.423027	0.86	26.88	Moderate	471.25	444.37
Hollidaysburg/Rte 2	Mandata	40.431972	-78.369888	1.2	37.5	Moderate	165	127.5
Hollidaysburg; NESL Quarry	Mandata	40.435583	-78.344472	2.32	72.5	Moderate	121.25	48.75
80 road-cuts near Milesburg Gap	Mandata	40.953527	-77.746166	1.3	40.63	Slight	58.5	17.87
I-99 near Cessna	Mandata	40.111694	-78.525666	0.72	22.5	Moderate	212.5	190
Rte 30 road-cuts, north of Everett	Mandata	40.027416	-78.370472	0.2	6.25	None	-4.5	-10.75
Jersey Shore area	Mandata ?	41.193583	-77.291805	0.1	3.125	Moderate	237.5	234.375
Lime Bluff Quarry, Muncy	Mandata (upper)	41.2375	-76.767222	1.16	36.25	Moderate	237.5	201.25
Lime Bluff Quarry, Muncy	Mandata (lower)	41.237388	-76.767194	0.96	30	Moderate	343.75	313.75
Hyndman	Mandata	39.824666	-78.720333	0.6	18.75	Moderate	282.5	263.75

C.7 Mifflintown Formation

Locality	Formation	Latitude	Longitude	%S	MPA	Fizz	NP	NNP
Barree railroad cut	Rotchester	40.582583	-78.097583	0.38	11.88	Slight	39.75	27.87
Leading Ridge Anticline	Rotchester	40.584305	-78.086166	0.1	3.13	None	21.5	18.37
Road cut 6 miles east of Mt Union	Mifflintown	40.359472	-77.820444	0.04	1.25	Moderate	150	148.75
Road cut 6 miles east of Mt Union	Mifflintown	40.359805	-77.818888	0.86	26.88	Moderate	138.75	111.87
Across river on Rte 22; Mt Union	Mifflintown	40.394333	-77.880416	0.4	12.5	Moderate	267.5	255
Rte 522, 3.09 m N of Shileysburg	Mifflintown	40.394333	-77.880416	0.86	26.88	None	0.5	-26.38

C.8 Reedsville Formation / Antes Member / Upper Coburn Formation

Locality	Formation	Latitude	Longitude	%S	MPA	Fizz	NP	NNP
Morris Hts. Rd.	Antes	40.587222	-78.151277	0.18	5.63	Moderate	381.25	375.62
Grier School, Birmingham	Antes	40.648305	-78.197805	0.2	6.25	Moderate	473.75	467.5
Nealmont	Antes	40.67	-78.214805	0.24	7.5	Moderate	417.5	410
Skytop	Antes	40.830805	-77.961333	1.42	44.38	None	-8.5	-52.88
S. Wrights well, Hungry Hollow	Antes/Coburn	40.581166	-78.15425	0.7	21.88	Moderate	432.5	410.62
Bill Foster shale pit	Antes	40.581166	-78.15425	0.1	3.13	Moderate	117.5	114.37
East Back Mtn. Road (Milroy)	Antes	40.709972	-77.599194	1.12	35	Moderate	160	125
Reedsville Exit	Antes	40.665027	-77.601277	1.72	53.75	Moderate	192.5	138.75
Ski Mont Road	Upper Coburn	40.778416	-77.758638	2.7	84.38	Moderate	471.25	386.87
Skyline View Dr/Route 322	Reedsville	40.797444	-77.639	0.08	2.5	Strong	651.25	648.75
Musser Quarry, Egg Hill	Reedsville	40.813527	-77.62775	1.28	40	Slight	68.5	28.5
Mt. Nittany Quarry	Reedsville	40.80875	-77.807944	0.46	14.38	None	19.25	4.87
Ashcom Quarry	Antes	39.996166	-78.421694	0.54	16.88	Slight	68.5	51.62
Bedford area	Antes	40.025333	-78.455972	0.42	13.13	None	27.5	14.37
Salona Quarry	Antes/Reedsville	41.090694	-77.467972	0.76	23.75	Moderate	247.5	223.75
River Bank, w. of Salona Quarry	Antes/Reedsville	41.090888	-77.470972	0.16	5	Strong	782.5	777.5

Coyler Lake area	Reedsville	40.793555	-77.652611	0.58	18.125	None	6.75	-11.375
Roaring Spring: Plum Creek Rd.	Antes? Reedsville	40.793555	-77.652611	0.1	3.125	None	5	1.875
Nippenose Valley	Antes/Reedsville	41.163916	-77.219722	1.22	38.125	Moderate	250	211.875
Orbisinia, McMann farm	Reedsville	40.207444	-77.870888	0.22	6.88	None	7.75	0.87
Orbisonia Quarry area	Reedsville	40.232694	-77.8695	0.84	26.25	Slight	52.75	26.5
McLucas Farm, Knobville	Antes/Reedsville	40.005333	-77.94075	0.72	22.5	None	1.25	-21.25
Ayr Township Quarry, Cito area	Antes/Reedsville	39.902472	-77.978555	0.56	17.5	None	2	-15.5
Cito, 3 miles S of McConnellsburg	Antes/Reedsville	39.878083	-77.986694	0.78	24.38	None	16.75	-7.63
Cito, Mike Hill farm	Antes/Reedsville	39.910722	-77.972916	0.88	27.5	None	1.25	-26.25
Old Womans Gap	Reedsville	40.262361	-77.973277	0.08	2.5	None	3.25	0.75
Martinsburg, Rte 167	Reedsville	40.316583	-78.333083	0.1	3.13	None	24.25	21.12
Loysburg road cut on Rte 36	Reedsville	40.16725	-78.374583	0.1	3.13	Slight	40.5	37.37
Rte 867, west of New Enterprise	Reedsville	40.184638	-78.469527	0.1	3.13	None	7.5	4.37
Leach farm, west of Ore Hill	Reedsville	40.2865	-78.4305	0.06	1.88	None	6.75	4.87
Roaring Spring	Reedsville	40.325833	-78.41575	0.76	23.75	Slight	65	41.25
Ashcom Quarry, NE High wall	Antes	39.997972	-78.421111	0.2	6.25	Moderate	472.5	466.25
Arch Spring Area	Antes	40.605555	-78.196055	0.04	1.25	Moderate	312.5	311.25
Ashcom Quarry, high on east wall	Coburn	39.996194	-78.42175	0.64	20	Moderate	343.75	323.75

Ashcom Quarry, high on east wall	Antes	39.997166	-78.421277	1.6	50	Moderate	77.5	27.5
Honey Creek	Coburn/Antes	40.686083	-77.556694	0.14	4.38	Moderate	443.75	439.37
Harrop Farm 2 km s. of Siegerville	Antes	40.724611	-77.53275	0.22	6.88	Strong	630	623.12
Lamar Fish Hatchery (S.Hoover)	Antes?	40.98448	-77.47173	0.12	3.75	Strong	733.75	730

C.9 Percent Pyritic Sulfur Values of Selected Black Shales

Locality	Formation	Latitude	Longitude	%Pyritic Sulfur
Lamar Fish Hatchery (S.E.Hoover)	Antes?	40.984481	-77.471739	0.16
Washingtonville, PA PPL Project (S.E. Hoover)	Marcellus	41.073864	-76.663503	3.31
Route 522 road-cut, Lewistown	Marcellus	40.58025	-77.627388	2.16
Grazierville/Charlottesville	Marcellus	40.649555	-78.268638	1.67
Ashcom Quarry, high on east wall	Antes	39.997166	-78.421277	0.49
Newton/Hamilton railroad cut	Marcellus	40.383027	-77.851388	2.3
Lewisburg Hospital	Marcellus	40.980861	-76.88825	0.42

Appendix D: Coal Measure ABA Data

D.1 Monongahela Group and Waynesburg Formation, undivided

D.2 Conemaugh Group

D.3 Allegheny Formation

D.4 Pottsville Formation

D.1 Monongahela Group and Waynesburg Formation, undivided

lat	lon	Lithology	Coal	County	Municipality	% S	Fizz	NP
39.8861	-79.8692	Coal	Pittsburgh	Fayette	German Twp	5.97	0.00	0.89
39.8106	-80.0006	Coal	Waynesburg A	Greene	Greene Twp	5.51	0.00	6.06
39.9422	-80.0686	Coal	Waynesburg A	Greene	Morgan Twp	4.84	0.00	1.77
40.5364	-79.4350	Limestone		Indiana	Conemaugh Twp	5.62	3.00	165.83
39.9061	-78.9628	Coal	Morantown	Somerset	Brothersvalley Twp	5.89	0.00	1.87
40.2956	-80.4503	Coal	Pittsburgh	Washington	Cross Creek Twp	3.62	0.00	2.03
40.1614	-80.0375	Coal	Waynesburg	Washington	Somerset Twp	3.76	0.00	-1.56
40.2114	-79.4394	Shale		Westmoreland	Mount Pleasant Twp	5.61	0.00	13.79

D.2 Conemaugh Group

lat	lon	Lithology	Coal	County	Municipality	% S	Fizz	NP
40.7114	-78.4792	Coal	Mahoning	Cambria	Reade Twp	4.75	0.00	-2.50
40.7736	-78.6431	Shale		Clearfield	Chest Twp	4.83	0.00	11.56
41.1694	-78.6439	Sandstone		Clearfield	Huston Twp	4.71	2.00	95.23
39.8097	-79.5925	Coal	Mahoning	Fayette	Wharton Twp	2.98	0.00	1.02
40.8956	-78.8939	Coal	Mahoning	Indiana	Banks Twp	3.64	0.00	8.44
40.7936	-79.0819	Shale		Indiana	East Mahoning Twp	3.70	3.00	83.50
40.1389	-79.0556	Coal	Mahoning	Somerset	Jenner Twp	5.41	0.00	1.90
39.9122	-79.0019	Clay		Somerset	Brothersvalley Twp	5.48	0.00	13.94
40.3978	-79.3297	Coal	Brush Creek	Westmoreland	Derry Twp	2.50	0.00	0.00

D.3 Allegheny Formation

lat	lon	Lithology	Coal	County	Municipality	% S	Fizz	NP
41.0008	-79.2461	Shale		Armstrong	Redbank Twp	5.36	0.00	7.08
40.9200	-79.5506	Coal	Middle Kittanning	Armstrong	Washington Twp	5.01	0.00	1.53
40.8369	-80.4083	Clay		Beaver	Big Beaver Boro	2.35	0.00	5.64
40.8361	-80.4083	Shale		Beaver	Darlington Twp	3.12	0.00	2.70
41.1386	-79.7453	Coal	Clarion #1	Butler	Allegheny Twp	5.56	0.00	-4.73
41.1319	-80.0336	Shale		Butler	Mercer Twp	4.90	0.00	11.61
40.3664	-78.6314	Coal	Middle Kittanning	Cambria	Portage Twp	5.35	0.00	-3.37
40.4239	-78.8881	Coal	Lower Freeport	Cambria	Jackson Twp	6.00	0.00	0.00
41.0406	-77.9978	Coal	Upper Kittanning	Centre	Snow Shoe Twp	2.58	0.00	-3.00
40.8678	-78.2297	Coal	Lower Kittanning	Centre	Rush Twp	5.58	0.00	14.78
41.1008	-79.3958	Shale		Clarion	Monroe Twp	5.99	0.00	8.44
41.0583	-79.4092	Coal	Lower Kittanning	Clarion	Porter Twp	5.92	0.00	1.28
40.9367	-78.3739	Carbonolith		Clearfield	Boggs Twp	5.96	0.00	0.50
40.8067	-78.7467	Coal	Upper Kittanning	Clearfield	Bell Twp	5.83	0.00	1.56
41.1789	-78.0239	Coal	Middle Kittanning	Clinton	West Keating Twp	4.45	0.00	0.00
41.1481	-77.6406	Coal	Clarion #1	Clinton	Bald Eagle Twp	4.58	0.00	0.00
41.3342	-78.4772	Shale		Elk	Jay Twp	4.29	0.00	-1.09
41.3172	-78.6461	Coal	Anthracite (Unknown)	Elk	Fox Twp	4.26	0.00	23.00
39.7778	-79.5700	Coal	Upper Kittanning	Fayette	Wharton Twp	5.50	0.00	2.85
40.5458	-79.3028	Shale		Indiana	Young Twp	5.76	0.00	-1.15
40.4514	-79.1519	Coal	Upper Freeport	Indiana	Burrell Twp	5.85	0.00	-3.55
41.2681	-78.7736	Sandstone		Jefferson	Snyder Twp	5.75	0.00	-13.99
41.0533	-79.1703	Coal	Bituminous (Unknown)	Jefferson	Beaver Twp	5.68	0.00	0.60
40.8944	-80.3047	Coal	# 8	Lawrence	Wayne Twp	3.77		-1.25
40.8583	-80.4306	Coal	# 8	Lawrence	Little Beaver Twp	3.34	0.00	0.00
40.0833	-78.9025	Shale		Somerset	Quemahoning Twp	5.82	0.00	-0.70
40.1028	-79.0644	Coal	Middle Kittanning	Somerset	Jenner Twp	5.87	0.00	1.36
41.1831	-79.8561	Shale		Venango	Clinton Twp	5.50	1.00	29.70
41.2078	-79.8219	Siltstone		Venango	Scrubgrass Twp	4.76	4.00	118.00
40.1633	-79.4511	Shale		Westmoreland	Mount Pleasant Twp	5.73	0.00	-3.16

D.4 Pottsville Formation

lat	lon	Lithology	Coal	County	Municipality	% S	Fizz	NP
41.1456	-79.2414	Coal	Bituminous (Unknown)	Clarion	Limestone Twp	5.81	0.00	0.32
41.1747	-78.4508	Coal	Mercer	Clearfield	Lawrence Twp	2.54	0.00	0.00
40.9589	-78.3756	Coal	Mercer	Clearfield	Boggs Twp	2.54	0.00	0.00
40.1494	-78.1186	Shale		Fulton	Wells Twp	1.24	0.00	1.54
41.0503	-79.1697	Coal	Bituminous (Unknown)	Jefferson	Beaver Twp	5.60	0.00	-1.25
41.0533	-79.1703	Coal	Bituminous (Unknown)	Jefferson	Beaver Twp	5.68	0.00	0.60
41.1069	-80.2503	Coal	Mercer	Lawrence	Washington Twp	0.90	0.00	2.13
39.8669	-79.0992	Coal	Quakertown	Somerset	Summit Twp	1.18	0.00	0.58

Appendix E: Isolated Sulfide Deposit Data

E.1 Category 1 Deposits

E.2 Category 2 Deposits

E.3 Category 3 Deposits

E.4 Category 4 Deposits

E.1 Category 1 Deposits

lat	lon	Location	Category	Reference
40.415556	-77.918333	Hares Valley Area, Huntingdon Co.	1	Smith 1977
40.407778	-77.922222	Hares Valley Area, Huntingdon Co.	1	Smith 1977
40.399444	-77.926944	Hares Valley Area, Huntingdon Co.	1	Smith 1977
40.398889	-77.927778	Hares Valley Area, Huntingdon Co.	1	Smith 1977
40.395556	-77.930556	Hares Valley Area, Huntingdon Co.	1	Smith 1977
40.392500	-77.929167	Hares Valley Area, Huntingdon Co.	1	Smith 1977
40.335000	-77.958056	Hares Valley Area, Huntingdon Co.	1	Smith 1977
40.332778	-77.961111	Hares Valley Area, Huntingdon Co.	1	Smith 1977
40.328889	-77.965556	Hares Valley Area, Huntingdon Co.	1	Smith 1977
39.843889	-75.847222	Coatesville, Chester Co.	1	Smith 1977
40.699167	-75.229444	Bushkill Drive, Northampton Co.	1	Smith 1977
40.017778	-76.523889	Kline's Quarry, York Co.	1	Smith 1977
40.017222	-76.525000	Kline's Quarry, York Co.	1	Smith 1977
40.559722	-75.398333	Correll or Saucon Mine, Lehigh Co.	1	Smith 1977
40.554444	-75.405000	New Hartman Mine, Lehigh Co.	1	Smith 1977
40.559444	-75.399444	New Hartman Mine, Lehigh Co.	1	Smith 1977
40.552778	-75.400833	Old Hartman Mine, Lehigh Co.	1	Smith 1977
40.560833	-75.386389	Triangle Mine, Lehigh Co.	1	Smith 1977
40.565556	-75.397778	Ueberoth Mine, Lehigh Co.	1	Smith 1977
40.904444	-76.865833	Winfield Quarry, Union Co.	1	Smith 1977
41.518889	-76.586944	Millview, Sullivan Co.	1	Smith 1977
40.132222	-75.437778	Perkiomen Mine Area, Montgomery Co.	1	Smith 1977
40.130556	-75.439444	Perkiomen Mine Area, Montgomery Co.	1	Smith 1977
40.128056	-75.441944	Perkiomen Mine Area, Montgomery Co.	1	Smith 1977
39.993994	-75.845939	Coatesville, Chester Co.	1	Geyer et al., 1976
40.184314	-76.913333	French Creek mines, Chester Co.	1	Geyer et al., 1976
39.957200	-76.083731	Gap nickel mine, Lancaster Co.	1	Geyer et al., 1976
40.267794	-76.408392	Cornwall Magnetite Mine, Lebanon Co.	1	Geyer et al., 1976
41.518508	-76.586369	Millview, Sullivan Co.	1	Geyer et al., 1976
40.394000	-77.907014		1	Beck, Pers. Comm., 2007
40.579267	-77.548722		1	Beck, Pers. Comm., 2007
40.399000	-77.920981		1	Beck, Pers. Comm., 2007
40.400069	-77.933197		1	Beck, Pers. Comm., 2007
39.888978	-78.062178	Meadow Grounds, Fulton, Co.	1	Scheetz, Pers. Comm., 2007
40.936417	-76.845675	CSVT	1	Gold, Pers. Comm., 2007
41.017450	-77.883700	Jonathan run	1	Scheetz, Pers. Comm., 2007
40.395861	-77.931083	Rte 22, Near Motel 22	1	Ellsworth/Gold, 2007
40.488444	-78.382833	Logan Town Center Mall	1	Ellsworth/Gold, 2007
40.749722	-78.103333		1	Krohn, 1976
40.757222	-78.091111		1	Krohn, 1976
40.814444	-78.013333		1	Krohn, 1976
40.834722	-77.969167		1	Krohn, 1976
40.855278	-77.934167		1	Krohn, 1976
40.920556	-77.809167		1	Krohn, 1976
40.931389	-77.784167		1	Krohn, 1976
40.934167	-77.770278		1	Krohn, 1976
40.941389	-77.749722		1	Krohn, 1976

40.946667	-77.738611		1	Krohn, 1976
40.948889	-77.738611		1	Krohn, 1976
40.956944	-77.730000		1	Krohn, 1976
40.975833	-77.695000		1	Krohn, 1976
40.904444	-76.865833	Faylor Quarry	1	Smith, Pers. Comm., 2007
40.395556	-77.930556	Hares Valley	1	Smith, Pers. Comm., 2007
40.931111	-77.784167	Milesburg Gap	1	Smith, Pers. Comm., 2007
40.019300	-78.202300	Breezewood Tunnel	1	Scheetz, Pers. Comm., 2007

E.2 Category 2 Deposits

lat	lon	Location	Category	Reference
40.398056	-77.926667	Hares Valley Area, Huntingdon Co.	2	Smith 1977
40.384444	-77.936111	Hares Valley Area, Huntingdon Co.	2	Smith 1977
40.334722	-77.958889	Hares Valley Area, Huntingdon Co.	2	Smith 1977
40.321111	-77.949722	Hares Valley Area, Huntingdon Co.	2	Smith 1977
40.700000	-75.233056	Chestnut Hill, Northampton Co.	2	Smith 1977
40.700556	-75.231111	Chestnut Hill, Northampton Co.	2	Smith 1977
40.713056	-75.196667	Chestnut Hill, Northampton Co.	2	Smith 1977
40.086944	-76.386389	Bamford Mine, Lancaster Co.	2	Smith 1977
40.090000	-76.380000	Bamford Mine, Lancaster Co.	2	Smith 1977
40.072500	-76.646944	Billmeyer Quarry, Lancaster Co.	2	Smith 1977
40.074167	-76.651389	Billmeyer Quarry, Lancaster Co.	2	Smith 1977
40.121667	-76.037222	Blue Ball Quarry, Lancaster Co.	2	Smith 1977
40.699444	-75.229167	Bushkill Drive, Northampton Co.	2	Smith 1977
40.003056	-76.016111	Gap Northeast Prospect, Lancaster Co.	2	Smith 1977
39.955833	-76.793333	Medusa West, York Co.	2	Smith 1977
40.018611	-76.488889	N. Manor Hill, Lancaster Co.	2	Smith 1977
39.972500	-76.762778	York Co.	2	Smith 1977
40.626944	-78.175556	Keystone Mine, N Sinking Valley, Blair Co.	2	Smith 1977
40.355833	-75.801667	Oley Valley, Berks Co.	2	Smith 1977
40.486389	-78.296667	Canoe Creek Quarry, Blair Co.	2	Smith 1977
40.093333	-75.485833	Jug Hollow Mine, Chester Co.	2	Smith 1977
40.105000	-75.525556	Montgomery Co. mine, Chester Co.	2	Smith 1977
40.328889	-75.185556	New Galena, Bucks Co.	2	Smith 1977
40.327500	-75.186667	New Galena, Bucks Co.	2	Smith 1977
40.088056	-75.519444	Pennypacker Mine, Chester Co.	2	Smith 1977
40.171389	-75.881389	Grace Mine, Berks Co.	2	Smith 1977
39.802000	-77.212361	Teeter Quarry, Adams Co.	2	Geyer et al., 1976
40.079640	-78.262810	Sherman Valley, Bedford Co.	2	Geyer et al., 1976
40.266514	-75.854261	Dyer Quarry, Berks Co.	2	Geyer et al., 1976
40.345689	-78.400942	Roaring Spring, Blair Co.	2	Geyer et al., 1976
40.570450	-78.263464	Sinking Valley, Blair Co.	2	Geyer et al., 1976
40.579283	-78.268333	Sinking Valley, Blair Co.	2	Geyer et al., 1976
40.649033	-78.212314	Sinking Valley, Blair Co.	2	Geyer et al., 1976
40.940156	-75.742208	Carbon Co.	2	Geyer et al., 1976
40.925042	-75.745606	Carbon Co.	2	Geyer et al., 1976
40.100942	-75.520683	Phoenixville, Chester Co.	2	Geyer et al., 1976
40.103642	-75.520503	Phoenixville, Chester Co.	2	Geyer et al., 1976
40.104942	-75.518133	Phoenixville, Chester Co.	2	Geyer et al., 1976
40.081836	-75.624211	Graphite Locality, Chester Co.	2	Geyer et al., 1976
41.271614	-76.371886	Cu-U localities, Columbia Co.	2	Geyer et al., 1976
40.073672	-77.968975	Ft. Littleton, Fulton Co.	2	Geyer et al., 1976
40.624578	-77.247706	East Salem, Juniata Co.	2	Geyer et al., 1976
40.011708	-76.333850	H.R.Miller LS Quarry, Lancaster Co.	2	Geyer et al., 1976
39.946764	-76.315569	Pequea Silver Mine, Lancaster Co.	2	Geyer et al., 1976
39.730467	-76.106594	Wood Chromite Mine, Lancaster Co.	2	Geyer et al., 1976
40.271006	-76.522844	Carper Magnetite Mine, Lebanon Co.	2	Geyer et al., 1976
40.268881	-76.477575	H.J.Smith LS Quarry, Lebanon Co.	2	Geyer et al., 1976

40.600106	-75.439236	Allentown, Lehigh Co.	2	Geyer et al., 1976
41.230628	-76.761136	Lime Bluff LS Quarry, Lycoming Co.	2	Geyer et al., 1976
40.713936	-75.196792	Easton Serpentine, Northampton, Co.	2	Geyer et al., 1976
40.904450	-76.863964	Winfield, Union Co.	2	Geyer et al., 1976
40.110850	-77.015017	Dillsburg Fe Mines, York Co.	2	Geyer et al., 1976
40.017381	-76.525072	Klines Quarry, York Co.	2	Geyer et al., 1976
40.073008	-76.923633	Rossville, York Co.	2	Geyer et al., 1976
41.020000	-76.387222	Almedia Mine	2	Smith, Pers. Comm., 2007
40.825000	-76.820000	Doughty Mine	2	Smith, Pers. Comm., 2007
40.648889	-78.212778	Keystone Mine area, northern Sinking Valley	2	Smith, Pers. Comm., 2007
40.341111	-78.402222	Roaring Spring area	2	Smith, Pers. Comm., 2007
40.286944	-78.378333	Soister Mine	2	Smith, Pers. Comm., 2007
40.570833	-78.263889	Southern Sinking Valley	2	Smith, Pers. Comm., 2007
40.220556	-78.433056	Woodbury	2	Smith, Pers. Comm., 2007
40.031667	-77.498611	Old Clippinger Bank	2	Smith, Pers. Comm., 2007

E.3 Category 3 Deposits

lat	lon	Location	Category	Reference
40.378611	-77.940833	Hares Valley Area, Huntingdon Co.	3	Smith 1977
40.469444	-78.082778	Thompson Lead Mine	3	Smith, Pers. Comm., 2007

E.4 Category 4 Deposits

lat	lon	Location	Category	Reference
41.509153	-76.551486	Millview, Sullivan Co.	4	Geyer et al., 1976
40.833625	-77.966700		4	Hsu, 1973
40.858356	-77.920475		4	Hsu, 1973
40.934625	-77.770086		4	Hsu, 1973
40.930697	-77.783250		4	Hsu, 1973
40.853875	-77.934017		4	Hsu, 1973
40.495289	-78.140858		4	Hsu, 1973
40.948450	-77.735839		4	Hsu, 1973
40.975450	-77.694619		4	Hsu, 1973
40.646492	-78.201339		4	Hsu, 1973
40.646389	-78.202511		4	Hsu, 1973
40.652217	-78.199539		4	Hsu, 1973
40.650389	-78.207872		4	Hsu, 1973
40.650872	-78.208503		4	Hsu, 1973
40.654769	-78.203142		4	Hsu, 1973
40.656219	-78.204897		4	Hsu, 1973
40.658528	-78.203322		4	Hsu, 1973
40.580833	-78.250381		4	Hsu, 1973
40.579661	-78.257042		4	Hsu, 1973
40.575383	-78.255872		4	Hsu, 1973
40.576903	-78.254342		4	Hsu, 1973
40.577661	-78.256322		4	Hsu, 1973
40.577661	-78.260283		4	Hsu, 1973
40.571522	-78.258572		4	Hsu, 1973
40.571936	-78.264153		4	Hsu, 1973
40.944450	-77.743622		4	Hsu, 1973
40.931111	-77.783056		4	Krohn, 1976
40.936667	-77.764444		4	Krohn, 1976
40.940278	-77.754444		4	Krohn, 1976
40.717500	-77.023333	Mt. Pleasant Mills	4	Smith, Pers. Comm., 2007

Appendix F: Disclaimer

F.1 Disclaimer

F.1 Disclaimer

The interpretations, characterizations, and assertions contained herein have been made upon review of large amounts of data and many reports from a variety of peer-reviewed journals, university theses, professional communications, governmental publications and information from individuals in private practice as well as data acquired specifically for the purposes of this study. Although every effort to accurately portray, depict, and describe the potential of numerous geological formations and phenomena to produce acid drainage has been made based upon the large amounts of available data, written information, and personal communications, the information presented is not intended to be entirely conclusive in the sense that there may be geologic materials or geographic areas that have the potential to cause acid drainage and associated phenomena that have not been included or identified in this report. Similarly, the geologic materials and areas recognized by this report as being problematic on the basis of any amount of data or information may not inevitably lead to acid drainage or related occurrences in all cases.

There is no substitute for careful, systematic, and deliberate investigations at the site-specific level pending the proposal or design of any construction project regardless of its purpose, magnitude, capacity, or extent. The information presented here is meant as a detailed and thorough predictive foundation and first reference upon which further investigations may well be built as necessitated by the numerous factors presented at any given construction site.