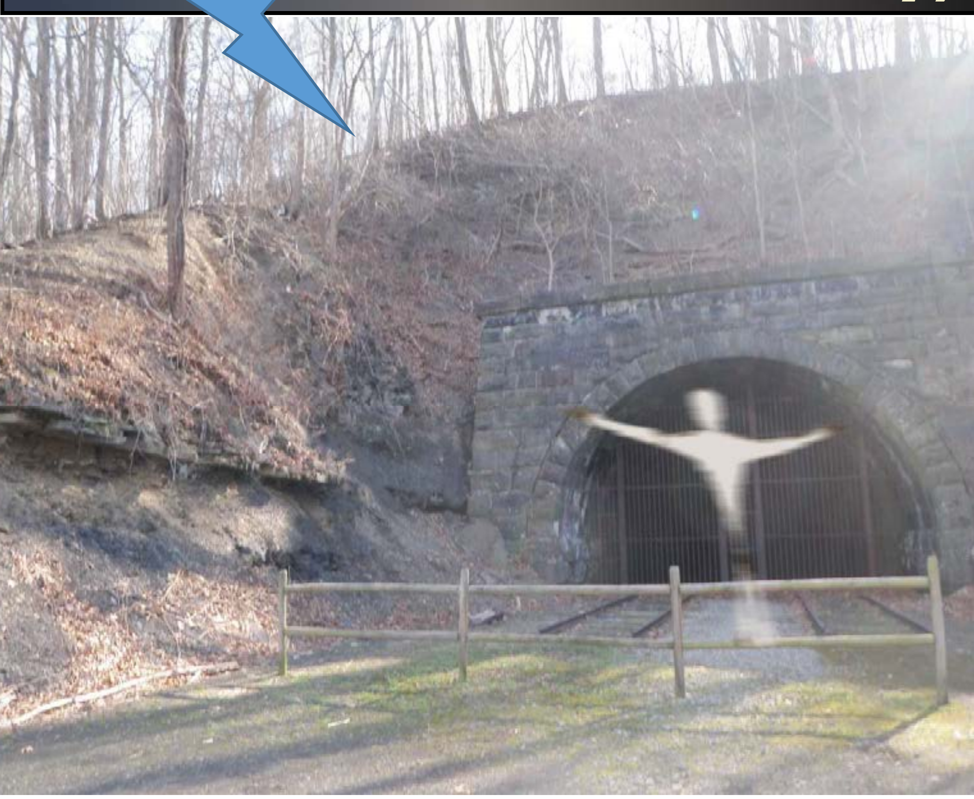
Energy & Environments: Geology in the "Nether World" of Indiana County, Pennyslvania



Hosts:

Pennsylvania Geologic Survey

University of Pittsburgh at Johnstown

Geoscience Department of Indiana University of Pennsylvania

October 6th – 8th 2016

81st Annual Field Conference of Pennsylvania Geologists

SYSTEM	*SERIES*	*GROUP OR FORMATION*	*FORMATION OR MEMBER*	*MAJOR BEDS*
PENN.-PERMIAN	UPPER PENNSYLVANIAN/ LOWER PERMIAN	DUNKARD GROUP (PART)	GREENE FORMATION	
			WASHINGTON FORMATION	Upper Washington limestone Washington coal bed
			WAYNESBURG FORMATION	Waynesburg "A" coal bed Waynesburg coal bed
? PENNSYLVANIAN	UPPER	MONONGAHELA GROUP	UNIONTOWN FORMATION	Uniontown coal bed
			PITTSBURGH FORMATION	Sewickley coal bed Redstone coal bed Pittsburgh coal bed
		CONEMAUGH GROUP	CASSELMAN FORMATION	Morgantown sandstone Skelley marine zone
			GLENSHAW FORMATION	Ames marine zone (prominent) Pittsburgh red shale Noble marine zone (less prominent) Upper Bakerstown coal bed Carnahan Run marine zone (less prominent) Woods Run marine zone (prominent) Lower Bakerstown coal bed Nadine marine zone (less prominent) Pine Creek marine zone (prominent) Brush Creek marine zone (prominent) Brush Creek coal bed Mahoning sandstone (Big Dunkard*) Zone of brackish-water fossils Mahoning coal bed (F)
	MIDDLE	ALLEGHENY FORMATION		Upper (E), Lower (D) Freeport coal beds Upper Kittanning (C') coal bed Johnstown limestone Middle (C), Lower (B) Kittanning coal beds Vanport limestone Clarion (A') and Brookville (A) coal beds
	? LOWER	POTTSVILLE FORMATION		Homewood sandstone (First Salt sand*) Upper, Lower Mercer coal beds Upper Connoquenessing sandstone (Second Salt sand*) Quakertown coal bed Lower Connoquenessing sandstone (Third Salt sand*) Sharon coal bed
MISSISSIPPIAN	UPPER	MAUCH CHUNK FORMATION		Mauch Chunk red beds
			LOYALHANNA MEMBER	Loyalhanna Limestone (Big lime*)
		POCONO FORMATION		Burgoon Sandstone Shenango sandstone

GUIDEBOOK FOR THE

81ST ANNUAL FIELD CONFERENCE OF PENNSYLVANIA GEOLOGISTS

OCTOBER 6 — 8, 2016

ENERGY AND ENVIRONMENTS: GEOLOGY IN THE "NETHER WORLD" OF INDIANA COUNTY, PENNSYLVANIA

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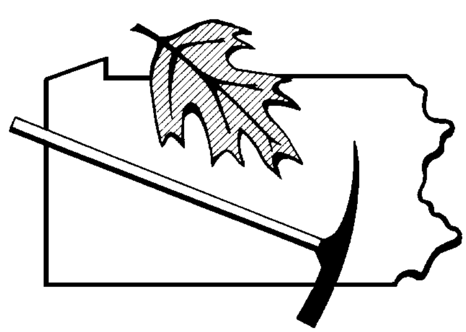
Railroad tunnel through Bow Ridge, near Conemaugh Dam



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and

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IN MEMORIAM

EMERITUS PROFESSOR ULDIS KAKTINS

UNIVERSITY OF PITTSBURGH AT JOHNSTOWN

Uldis Kaktins, long-time attendee of our field conference, passed away at his home on July 2nd after surviving cancer for three years. He was born in war-torn Riga, Latvia, at the height of WWII, and his family made their way to the United States while he was a child. He grew up in Boston where the family put down new roots, and he worked hard to get an education. The Vietnam War interrupted Uldis' graduate studies when he was deployed to Vietnam. He wrote a thesis by hand on the floor of his Bachelor Officer's Quarters. He began teaching in Pitt Johnstown's Department of Earth & Planetary Science in 1975 and retired after a long career in 2008.

Emeritus Professor Uldis Kaktins is a beloved professor who touched the lives of thousands of students and inspired hundreds to pursue careers in geology, hydrology, and other fields in the earth sciences. Hydrology and flood studies were his passions, always focused on fieldwork. He was lead author of a 2013 paper about the 1889 Johnstown flood, published in the Pennsylvania History Journal. His latest paper on the 1889 flood was published in the journal Heliyon on June 16, 2016, the result of more than five years of research. Excerpts from that paper may be found in this conference guidebook. Uldis summarized the findings in an interview with a Johnstown reporter just days before his passing. "You still hear all of the time that there was supposedly so much rain that their dam would've been over-topped no matter what. That's simply not the case – and now we have the scientific facts to prove it."

You will also find in the older 1989 guidebook an article Uldis wrote with the late Hal Fry of UPJ about the three historic floods that have struck Johnstown, in 1889, 1936, and 1977. We will visit the site of the South Fork dam on the second day of the conference to learn more about the latest research on the Johnstown flood of 1889. This year's visit to the Johnstown Flood memorial is dedicated to Emeritus Professor Kaktins.

INTRODUCTION

JOAN HAWK, CME MANAGEMENT LLC

I have been asked why the Field Conference is being held in Indiana, "What of geological significance is there to see in Indiana County?" they ask. The sub-title, "Geology in the Netherworld of Indiana County" is apt…and historically correct. P. Lesley, in his preface to the Report of Progress in Indiana County, volume HHHH (1878) states,

> "Connections between the geology of the Allegheny River, worked out by the first Survey previous to 1841, and the geology of the counties bordering on the Allegheny Mountain and the Maryland State line, have hitherto been unsatisfactory because imperfect; the almost unexplored region of Indiana and West Armstrong counties acting as a barrier over which none of our vague hypotheses of identification could pass either way. Covered as this region is with the Barren Measures, and large parts of it being until recently an almost unbroken forest, mine exposures have always been wanting, and natural exposures difficult to find, and when found hard to collate. The first geological survey of Pennsylvania therefore passed to the right and left of Indiana County, and nothing of account was done in subsequent years to discover its minerals and explain its geology…" The survey now happily completed by Mr. W. G. Platt places the geology of Indiana in clear light".

Several important observations were made to place the stratigraphic units of Indiana County in proper context with those of adjacent counties. One of these observations was that the earlier surveys of Cambria and Somerset counties in 1875-7 had "revealed the startling truth that there were several other important and persistent limestone horizons in the lower coal measures and in the barren measures, not one of which could be made to correspond properly with the Ferriferous Limestone (Vanport) and Buhrstone iron of the Allegheny region" (Lesley, 1878).

The presence of multiple limestone beds had resulted serious stratigraphic miscorrelation between the western and eastern sides of Pennsylvania's third Coal Basin during the First Geological Survey. During the Second Survey, Platt was unable to find the Ferriferous Limestone at its expected position in Indiana County east of the Indiana anticline. Another observation was that of an extensive sandstone "fault" in the Pittsburgh Coal, described by Platt as "representing a line of ancient (stream) erosion in the old swamps and lagoons in which the vegetation for the formation of the coal was collected."

The Pittsburgh Coal outcrops in the valley of the Conemaugh River at Blairsville and on the southern valley wall, above remnants of the Pennsylvania canal, collapsed workings on the Pittsburgh Coal can be seen. The coal is overlain by the massive Pittsburgh Sandstone. The face of the exposed sandstone is coated with an efflorescence of alum that "blossoms" out of the strata that gives the cliff face a pitted and "honeycomb" pattern. This outcrop, known as Alum Hill" is best accessed from the Conemaugh River at Blairsville.

Regardless of Lesley's proclamation, Indiana County retained geologic puzzles into the 20th and 21 centuries and corrections to second survey work were made during subsequent investigations by the Pennsylvania Geological Survey and others. Road cuts, railroad cuts, surface mines, and deep mines exposed stratigraphic enigmas that would not have been otherwise brought to light.

The exploration programs of the former Rochester & Pittsburgh Coal Company and a recent roadcut in Indiana County revealed what shouldn't be—the Upper Freeport Coal transitioning into flint clay and limestone. A buried log jam revealed in the roof of an Upper Freeport Coal deep mine in Indiana County, seen by only a few, remains hidden from view. In adjacent Armstrong County, a similar phenomenon on the Upper Freeport Coal occurs at the surface exposure; however, this outcrop will disappear into the "mists of time" because after this year's field conference views it, the landowner is placing it off limits to further visitations. The Pennsylvania Department of Environmental Protection requires that surface mines are to be backfilled soon after mining ceases and PennDOT has a similar mindset. However, sometimes a particularly striking outcrop, such the Morgantown Sandstone along the ramps at the intersection of Routes 22 and 119 near Blairsville, escapes the plague of crown vetch or other plant that is used as a "cloaking device". Several Indiana County coal mines revealed the presence of Jurassic Age dikes intruding into Pennsylvanian Age coal beds. We won't get to see them because there are no known surface exposures; however, this year's guidebook contains a body of current work that synthesizes the current state of knowledge and photodocumentation that will guide future work.

The theme of energy and environments is appropriate for this year's field conference, although perhaps not in the most obvious way. Indiana County has an abundance of energy resources – coal and gas. At the time of the second survey publication HHH, gas was barely mentioned. If only Lesley could see a map of the gas wells that have been drilled since the publication of Volume HHHH. Coal and gas are one source of energy. The other "energy" is that of the paleoenvironments preserved in the rock record. We will see in outcrop the preserved remnants of high energy paleo-rivers and their associated strata low energy environments. Unfortunately as soon the stratigraphy of the county is exposed, it is almost covered up again, or made inaccessible. The geology of Indiana County has been preserved, uncovered and hidden again—will we ever be able to decipher the geologic past here with only such fleeting glimpses?

Reference

Platt, W.G., 1878, Report of Progress in Indiana County: Pennsylvania Geological Survey, 2nd ser., vol HHHH, 316 p.

STRUCTURAL GEOLOGY OF THE SOUTHWESTERN SECTION OF THE APPALACHIAN PLATEAU

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Introduction

The Appalachian plateau is the westernmost province of the Appalachian mountain belt and stretches from Alabama to New York. The Appalachian plateau is characterized by broad, low, open folds with dips ranging from 20° to less than 5°. Wavelengths of the folds range from 5 to 20 miles and the structural relief can be a few hundred to greater than 3,500 feet. The structural trends show fold amplitudes that decrease from the eastern margin to the western margin. Various structural lineaments, or cross-strike structural discontinuities, cross-cut the Appalachian plateau generally perpendicular to fold axes. The structural development of the Appalachian plateau ranges from Precambrian age, with Grenvillian basement structural features influencing lower stratigraphic levels, to Permian age with Allegheny orogeny development of décollement slip and folds. Much debate has occurred to determine the timing of fold development and the influence of the basement of the Appalachian plateau. This paper will focus on the key structural features of the Appalachian plateau in southwestern Pennsylvania.

General Geology

The Pennsylvania state portion of the Appalachian Plateau can be broken up into several sub-provinces or sections (Figure 1-1). This brief structural geology summary will focus on literature covering the Pittsburgh Low Plateau Section and the Alleghany Mountain Section. The plateau province comprises almost entirely sedimentary rocks in gentle folds with large wavelengths and amplitudes that decrease to the northwest. Most folds are asymmetrical with the steep flank dipping to the southeast. Anticlines commonly have dips ranging from 3° to 12° on their northwestern flanks and from 4° to 20° on their southeastern flanks, however, larger dips have been measured throughout the plateau at scattered localities (Hickok and Moyer, 1971; Harper, 1989; Beardsley et al., 1999). Fold axes are generally arcuate and remain parallel to sub-parallel to the arcuate trend of the Appalachian mountain range seen in central Pennsylvania. Folds generally trend northeast to southwest and plunge 1° to 2° to the northeast (Iranpanah and Wonsettler, 1989). Overall the plateau is characterized by generally level surface with some rolling hills which are at an altitude great enough to permit erosion of deep valleys by streams.

The general stratigraphy is Pennsylvanian through Cambrian sedimentary units deposited on a metamorphic Precambrian basement. Most models of the plateau show anticlines and synclines extending down to a décollement surface within salts of the Silurian Salina Group. The Appalachian plateau is often cited as the type example of broad zone, layer-parallel shortening with subordinate splay faults in the hanging wall of the detachment sheet (Gwinn, 1964; Rodgers, 1964; Scanlin and Engelder, 2003). Layers of rock above the décollement are referred to as the Appalachian plateau detachment sheet and were folded above the décollement by a variety of mechanisms. Using seismic reflection data Scanlin and Engelder (2003) were able to discern the following three-tiered mechanical stratigraphy: a thin basal detachment zone in Upper Silurian strata, an imbrication zone within Upper Silurian through Lower/Middle Devonian strata, and a wedge zone within Upper Devonian and Mississippian strata.

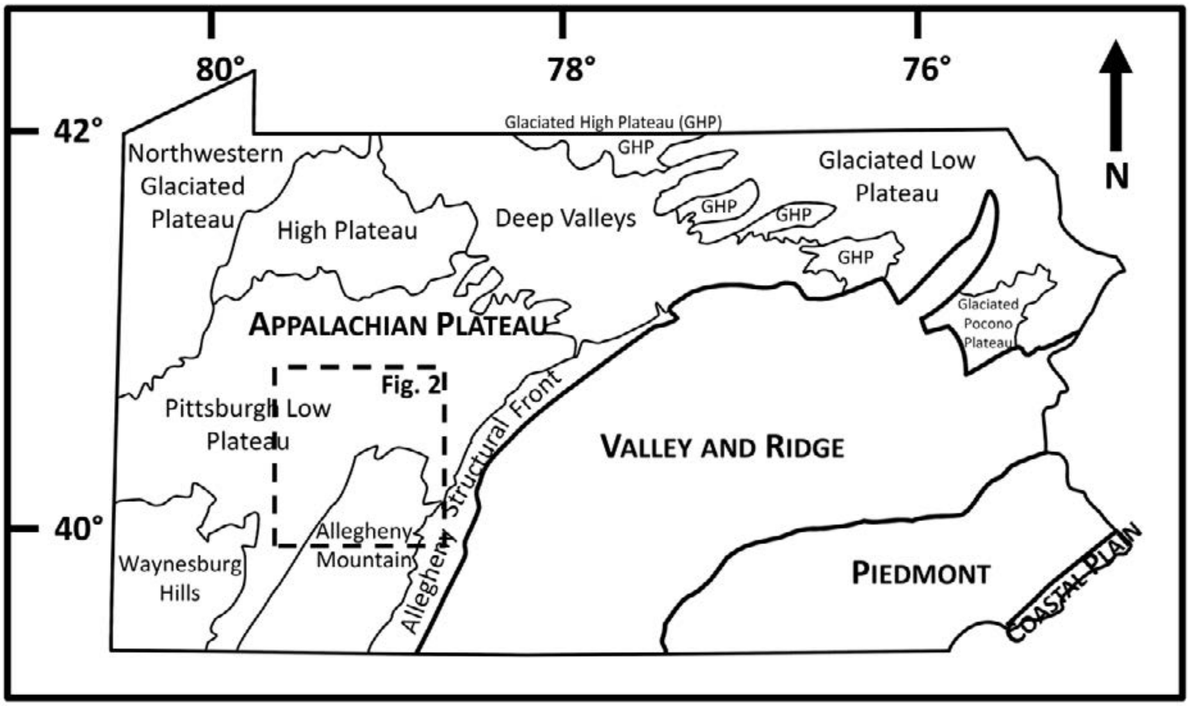

Figure1-1. Generalized physiographic provinces of Pennsylvania with province sections for the Appalachian Plateau (Berg et al., 1980)

Above the detachment zone, at the core of plateau anticlines, seismic data support the presence of imbricated thrusts of splay faults that exhibit fault-propagation folds, fault-bend folds, and kink banding morphology (Scanlin and Engelder, 2003; Gillespie et al., 2015). These imbrications are observed to cut the Lower/Middle Devonian units which are composed of carbonates (Tully, Onondaga, and Helderberg limestones) and interbedded clastics (Marcellus shale and Oriskany sandstone). Above the imbrication zone is an area that exhibits wedge thrusts with a combination of foreland and hinterland thrust directions (Scanlin and Engelder, 2003).

Proximity to the Allegheny structural front and variation of thickness of the salt detachment appears to control the variation of subsurface structural style and structural relief (Wiltschko and Chapple, 1977). Detachment and translation occurred during the Pennsylvanian-Permian Alleghenian Orogeny. Mount (2014) estimated the shortening necessary to create observed structural is approximately 1-2%. However, Scanlin and Engelder (2003) note that movement along the salt décollement alone is insufficient to account for the fold amplitude in the Bedford-Pittsburgh region and that additional mechanisms are required for full anticlinal growth. It is postulated that some salt doming within the Salinas Group has contributed to folding (Wiltschko and Chapple, 1977). When examining the folds within the context of buckle fold mechanisms, relatively modest length to spacing ratios are predicted (Biot, 1961). However, the anticlines of the Allegheny plateau have large aspect ratios which are more akin to forced folds centered on basement involved faulting indicating that there are important footwall structures involved in fold development (Scanlin and Engelder, 2003). Evidence appears to suggest that the evolution of the Appalachian plateau folds are a complex intermingling of mechanisms including:

décollement slip and buckling; hanging wall thrusts, imbrications, and wedging; kink banding; salt doming; pervasive layer-parallel shortening; and footwall faulting in basement rocks.

Formation

The classic model for the Appalachian plateau detachment sheet involves periodic buckling above a detachment in salt (Wiltschko and Chapple, 1977). There are two hypotheses for the formation of the large-scale folds of the Allegheny Plateau: folds are the result of thin-skinned tectonics which deformed the upper layers without basement deformation (Rodgers, 1949, 1953, 1964; Gwinn, 1964); folds are the result of deep basement faulting that passively folded the upper layers (Cooper, 1964).

The Grenvillian basement in the plateau has various décollement ramps, tear faults, and transform faults from the Grenville orogeny (~1 Ga) that were later reactivated to influence folding throughout the plateau (Beardsley et al., 1999). These Grenvillian structures initiated a large graben (the Rome Trough) and growth faults within the overlying Cambrian strata during tensional stress related to rifting in the Cambrian. The Appalachian plateau region was primarily a sedimentary basin during much of the Paleozoic which facilitated deposition of thick sedimentary sequences that were shed from the eastward Taconic and Acadian mountain belts. The Paleozoic sedimentary sequence is occasionally punctuated by limestone units. Throughout the Taconic orogeny (480-440 Ma) the plateau underwent compression stresses which created a series of monoclinal flexures across the old growth-faulted terrane (Beardsley et al., 1999). During the Acadian/Caledonian orogenies (~390 Ma) down-warping of monoclinal flexures occurred. Stresses imposed by the Alleghenian orogeny (~260-340 Ma) pushed strata along a basal detachment creating the Appalachian Plateau detachment sheet and induced thrusting and folding within the detachment sheet creating much of the structure present in the plateau today.

Examination of several types of strain indicators (e.g., deformed fossils, solution cleavage, and mechanically twinned calcite grains), studies have been able to show that there has been approximately 10% layer-parallel shortening throughout the Appalachian plateau (Nickelsen, 1966; Engelder and Engelder, 1977; and Engelder, 1979). Strain indicators are oriented at right angles to the northwestward movement of the orogenic front and suggest that layer-parallel shortening occurred prior to folding (Gillespie et al., 2015). Recent estimates of the shortening needed to create the folding present in the Appalachian plateau are approximately 1-2% (Mount, 2014).

Asymmetry of folds (i.e., shallow northwesterly limbs and over-steepened southeasterly limbs) in the Appalachian plateau has been the source of much debate. This asymmetry in the folds of the plateau is the exact opposite trend seen in the Valley and Ridge province to the east. Sherrill (1934) proposed that the asymmetry was caused by an overall southeasterly regional dip at the time of deformation and the southeasterly thickening of the folded sequence. Others have suggested that the asymmetry was developed by basement-driven, deep-seated underthrusting of northwest limbs by the southeast limbs (Cathcart and Myers, 1934). Gwinn (1964) developed a complex model of splay faulting shearing off the décollement and translating wedges of material northwest into the northwesterly limbs of the folds reducing the northwestern limb dips and over-steepening the southeasterly limbs. Seismic interpretations conducted by Mount (2014) suggest that fold asymmetry is created by mechanically pinched out salt at synclinal locations at the décollement level buttressing the folds and accentuating asymmetry.

Intra-Plateau Structural Front

Gwinn (1964) identified significant decrease in structural relief going toward the foreland which he subdivided into the Inner plateau, to the east, and the Outer plateau, to the west, along an intra-plateau structural front (Figure 1-2). The Intra-Plateau Structural Front is a demarcation within the plateau where a change in the character of folding is apparent. The Intra-Plateau Structural Front is present on the west side strike parallel to the Chestnut Ridge anticline and separates the relatively more intense folding of the southeastern portion of the plateau from the gentler, less intense folding of the northwestern portion of the plateau (Gwinn, 1964). The broad gentle folds of the Outer plateau region commonly have dips less than 5° on their limbs whereas the Inner plateau often has dips from 5° to 20° on their limbs.

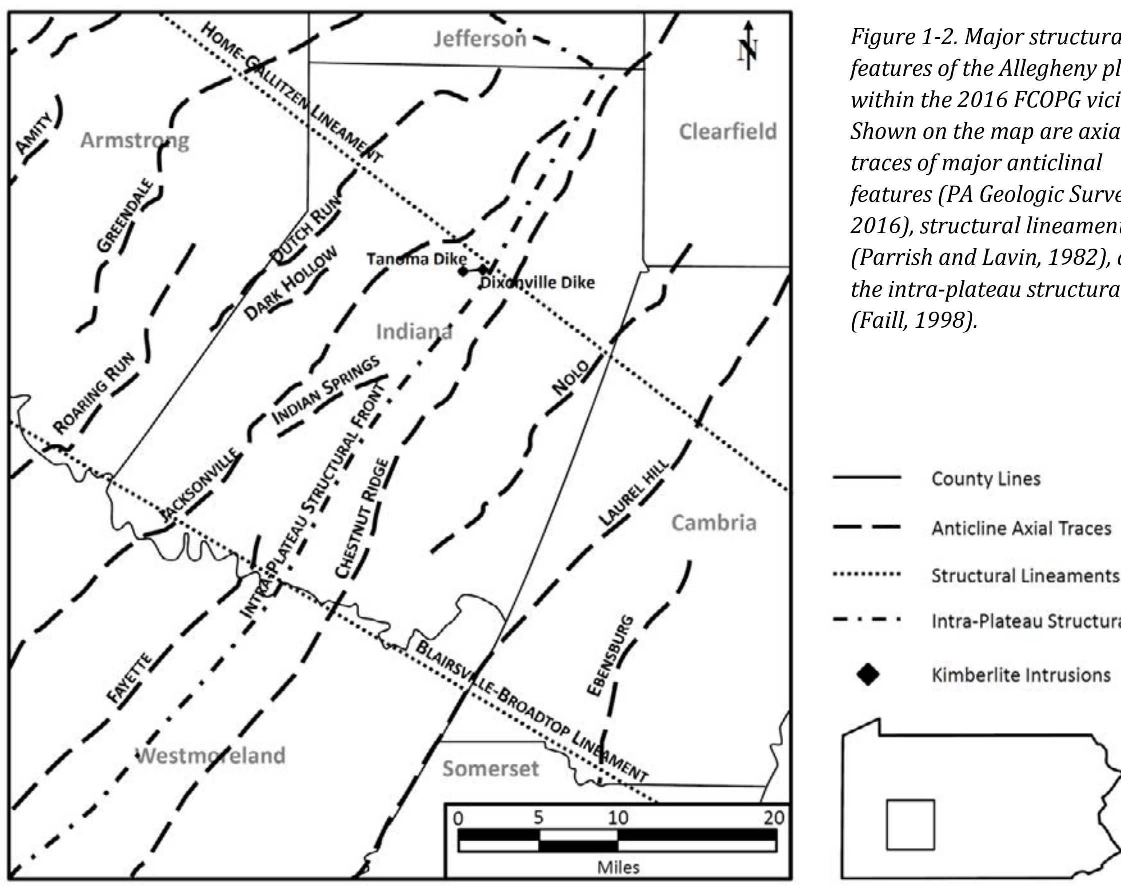

Figure 1-2. Major structural features of the Allegheny plateau within the 2016 FCOPG vicinity. Shown on the map are axial traces of major anticlinal features (PA Geologic Survey, 2016), structural lineaments (Parrish and Lavin, 1982), and the intra-plateau structural front (Faill, 1998).

Silurian Salina Group

Most models for the plateau folds suggest detachment along the Silurian Salina salts with overlying imbrication zones within the incompetent Devonian shales punctuated by limestones, folding the units above. In southwestern Pennsylvania the Salina Group generally consists of: the Vernon formation, a unit of red and green shale, and the Syracuse formation, an interbedded dolomite, anhydrate, and salt. Along with two other minor formations, the Camillus and Bertie formations, the overall thickness of the Salina Group is approximately 650 meters (Heyman, 1977). There are at least six major salt units within the Salina Group designated “A” through “F”. Two notable salt layers within the Syracuse formation, the F-2 and F-3 salts have been measured to exceed 50 meters in thickness. However, the F-2 and F-3 salts are not regionally continuous and therefore are unable to accommodate the full décollement of the plateau (Heyman, 1977). It believed that the Vernon shales must accommodate some of the detachment (Scanlin and Engelder, 2003). In northwestern Pennsylvania the folds die out, this is attributed to a reduction of stress but also the pinching out of the Salina salts (Frey, 1973).

Folds

Numerous folds transect the plateau region (Figure 2) and two major folds within this region, the Laurel Hill anticline and the Chestnut Ridge anticline, are further examined. Both folds are broad, open, slightly asymmetric folds with accurate axial trends that are approximately 030°. The folds plunge 1° to 2° to the northeast and both folds extend for over 125 miles. The Laurel Hill and Chestnut Ridge anticlines lie within the Inner plateau region of the Appalachian plateau with the northwestern margin of the Chestnut Ridge anticline serving as the limits of the Inner plateau region.

Laurel Hill anticline

The Laurel Hill anticline is an open, slightly asymmetrical fold with dip on southeastern limb ranging from 10° to 15° and 8° to 10° on the northwestern limb (Iranpanah and Wonsettler, 1989). The anticline, on average, is 8 miles wide and generally has a flat broad top that can be up to 2 miles wide. The amplitude of the Laurel Hill anticline to the adjacent synclines, the Ligonier syncline to the northwest and the Johnstown syncline to the southeast, is as much as 1,800 ft (Hickok and Moyer, 1971). However, the northwest limb of the Laurel Hill anticline has been uplifted slightly more than the southeast limb giving the northwest limb slightly less structural relief (Hickok and Moyer, 1971).

The Conemaugh River cuts through the Laurel Hill anticline just west of Johnstown creating the Conemaugh Gorge. The creation of the Conemaugh Gorge is thought to be from an antecedent river that existed before the surface expression of the Laurel Hill anticline (Iranpanah and Wonsettler, 1989). The Conemaugh Gorge is approximately 1,500 ft in relief, trends 330° and provides a well exposed cross-section of Pennsylvanian, Mississippian, and Devonian strata (Iranpanah and Wonsettler, 1989).

Scanlin and Engelder (2003) subdivide the subsurface of the Laurel Hill anticline into three tiers: an Upper Devonian wedge zone, a Silurian through Lower/Middle Devonian imbrication zone with central triangle structures, and a Silurian detachment zone. Thrust wedges within the wedge zone of the Laurel Hill anticline have been measured to be approximately 1,400 ft thick (Scalin and Engelder, 2003). There is evidence for basement involved faulting beneath the Laurel Hill anticline in the form of monoclinal bends that show little indication of detachment in seismic reflection, however, the seismic data show some deep high angle faults (Scalin and Engelder, 2003).

Chestnut Ridge anticline

The Chestnut Ridge anticline is an open, slightly asymmetrical fold with dip on southeastern limb are up to 15° to 20° and on the narrower northwestern limb approximately 10° or less (Shumaker, 2002). The anticline is about 8-10 miles wide with a generally flat broad top. Unlike the Laurel Hill anticline, the southeast limb of the Chestnut Ridge anticline has been uplifted slightly more than the northwest limb (Hickok and Moyer, 1971). The asymmetry of uplift provides varied structural relief with respect to the adjacent synclines. On the northwest limb of the Chestnut Ridge anticline, adjacent to the Uniontown syncline, structural relief is as much as 3,400 ft. The southeast limb of the Chestnut Ridge anticline, adjacent to the Ligonier syncline, structural relief is as much as 1,700 ft (Hickok and Moyer, 1971). Approximately 25 miles northeast of Indiana, near Johnsonburg, the Jacksonville anticline (also referenced as the Grapeville-Kinter Hill anticline) merges with the Chestnut Ridge anticline forming a broader Chestnut Ridge anticline which continues another 35 miles northeast.

Subsurface structure of the Chestnut Hill anticline displays the same three tier structure as Laurel Hill anticline as reported by Scanlin and Engelder (2003). Seismic reflection data shows that the Chestnut Ridge anticline has a thickened Upper Silurian section with doubly vergent blind thrusts at the level of the Lower/Middle Devonian section (Scanlin and Engelder, 2003). Passive concentric folding is accommodated above the blind splay faults in the Upper Devonian unit above the Lower/Middle Devonian faulted units. The footwall ramp can be seen in the reflection data cutting the F-2 and F-3 salt of the Syracuse formation at an angle of 25°. Additionally, thickening of the Vernon shale is seen by Scanlin and Engelder (2003) which fills some of the fold volume.

The change in structural styles between the southwest and northeast portions of the Chestnut Ridge anticline correlates to sub-detachment structures. Scanlin and Engelder (2003) used seismic data to suggest that, along the axis, changes in structural styles of the Chestnut Ridge anticline are due to the presence of the Rome Trough in the southwest portion which appears absent in the northeast portion of the Chestnut Ridge anticline. The southwestern portion of the Chestnut Ridge anticline subsurface exhibits extensive wedge thrusting at depth (Scalin and Engelder, 2003). Using a combination of well logs and seismic profiles along the southwest portion Shumaker (2002) identified subsurface structure that is more akin to faulted folds rather than traditional imbrications. The northeast portion of the Chestnut Ridge anticline seismic reflections indicate larger-scale imbrication in the imbrication zone leading to more coherent concentric folding throughout the Devonian section (Scanlin and Engelder, 2003).

Lineaments

Structural lineaments in this area have been identified using gravity, magnetic, structural, and Landsat data and represent fracture zones which penetrate deeply into the crust (Lavin et al., 1982). Using these data sets, several structural lineaments have been identified by observing the following: terminations and displacements in gravity and magnetic surveys; terminations of fold axes; high fracture densities; linear topographic depressions; zones of anomalous hydrocarbon leakage; and valley and stream alignments on Landsat images (Gold, 1999). Additionally, these fracture zones are occasionally visible in the field with the presence of: 0.3 to 1.2 miles wide zones of increased fracture density, geometrically related faulting and jointing, and Pb-Zn and Cu mineralization (Lavin et al., 1982). Where the lineaments intersect plateau folds there is often a rapid decrease in the amplitude of folding, as much as 900 ft in some locations (Parrish and Lavin, 1982). The lineaments may represent fossil transform faults that have been later reactivated (Gold, 1999).

The Allegheny plateau is thought to be part of the Lake Erie-Maryland crustal block. This rectangular crustal block is thought to be approximately 60 miles wide and 350 miles in length and bound in the plateau region by the Tyrone-Mt. Union lineament to the northeast and the Pittsburgh-Washington lineament to the southwest (both trending approximately 320-330°). These two larger lineaments are considered to extend at least into the Precambrian basement, if not into the mantle (Lavin et al., 1982). Displacement along the Pittsburgh-Washington and Tyrone-Mt. Union lineaments has been identified and is thought to be as much as 35 miles left-lateral movement on the Pittsburgh-Washington lineament and 60 miles right-lateral movement on the Tyrone-Mt. Union lineament resulting in northwest translation of the Lake Erie-Maryland block during continental collisions (Lavin et al., 1982).

Two structural lineaments, the Blairsville-Broad Top and Home Gallitzin lineaments (Figure 2), are present within the 2016 Field conference vicinity and are considered to be within the Lake Erie-Maryland crustal block. Gravity and magnetic data for the Blairsville-Broad Top and Home Gallitzin lineament lack strong reflectance which compelled Parrish (1978) to suggest that they are confined to the sedimentary section and upper basement. Additionally, Parrish (1978) found no apparent evidence of major displacement suggesting that they are undisturbed within the block but interrupted or terminated along the deep crustal fractures beneath the bounding lineaments (i.e., the Pittsburgh-Washington and Tyrone-Mt. Union lineaments).

Summary

The structural geology of the Appalachian plateau can be deceptively complex when examining only the subtle features expressed at grounds surface. Debate about the exact mechanisms of deformation has engaged geologists for over a century. The recent wealth of seismic profiles related to increased petroleum hydrocarbon exploration in the plateau is providing the opportunity for more detailed research of subsurface features responsible for the architecture of the Appalachian plateau. As more data becomes available, it is apparent that this region will spur debate for years to come.

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LUCERNE COAL REFUSE SITE

CAMBRIA RECLAMATION CORP – CENTER TOWNSHIP, INDIANA COUNTY RECLAMATION VIA COAL REFUSE FIRED ELECTRIC GENERATION UNITS

SHAWN SIMMERS, PE, ENVIRONMENTAL HEALTH AND SAFETY, CAMBRIA COGENERATION
JEFF ZICK, PE, FUELS MANAGER, CAMBRIA COGENERATION AND IPAC COLVER
TODD COLEMAN, PE, PRESIDENT, MINETECH ENGINEERS INC.
GARY MERRITT, PG, NORTHERN STAR GENERATION SERVICES COMPANY LLC

Executive Summary

Coal Mining was a critical economic factor in the industrial development of Pennsylvania tied directly to the iron and steel industry. As a result, the underground deep mines from the late 1800's through the mid 1980's were directly connected. The metallurgical coal needed to produce coke was a key ingredient to the manufacturing and production of steel.

The Lucerne Coal Mines in Indiana County, Pennsylvania, were developed to support the production of coke. In fact, there were large beehive coking batteries (Lucernemines Coking Works) that were an integral part of their operations.

Associated with the coal mining and coke production activities was the disposal of the waste produced by the coal mining and processing operations. The Lucerne Coal Refuse Site is one example. There were over 8.7 million tons of coal refuse (in the form of coarse rejects and fines/slurry placed on two areas of the property. This material was simply placed on the land with no environmental restrictions (in other words dumped on the land to burn and leach creating air, water and land pollution) at that point in time.

As a result, the Federal Surface Mining Control and Reclamation Act (P.L. 96-87) accomplished two major things: (1) regulated the disposal of coal refuse, and (2) established an Abandoned Mine Land Reclamation Program funded by fees.

In 1978, the Public Utility Regulatory Policy Act (PURPA) was passed. The Act was designed to encourage alternative generation in terms of Qualifying Facilities (either cogeneration or small power produce). This required Utilities to enter into Power Purchase Agreements, which was the financial vehicle to allow these plants to be designed, financed, constructed and operated. The Act and the FERC regulations encouraged the use of alternative fuels including waste fuels. FERC recognized that coal refuse was a waste fuel. These plants were limited in size with the larger small power production facilities capped at about 125 MW.

At this time, there was a new clean coal technology developed in Europe and brought to the United States and improved. The technology allowed for the burning of lower Btu, high ash waste (coal refuse) in a Fluidized Bed Combustor. The emissions were controlled by injecting limestone into the boiler to be fired with the coal refuse to control SO_2 emissions (90% to 95% capture in the boiler), control Filterable Particulate Matter through the use of baghouses, and control NOx through the combustion process and in some cases the use of Selective Non-Catalytic Reduction (SNCR) technology. Mercury has always been controlled to limits below the 1.2 lbs/TBtus.

Coal refuse-fired plants provide an important public-private partnership to address critical pollution and safety issues through removal, remediation and reclamation of polluting coal refuse piles. Acid mine drainage (AMD) from mine affected lands, including coal-refuse piles, is a major source of water pollution in Pennsylvania with over 3,300 miles of streams being impacted. The coal refuse piles have burned (as evidenced by the "red-dog"), are burning and will burn in the future. While burning, these sites emit uncontrolled toxic air pollutants. They are also major contributors of fugitive dust.

In Pennsylvania, coal refuse-fired plants have removed more than 214 million tons of coal refuse for use as fuel and remediated millions more tons of coal refuse through the use of the resulting beneficial use ash. Thousands of acres of land have been remediated and reclaimed through these operations. (See Appendix A)

Land, water and air pollution are permanently eliminated which results in an improved environment and a higher quality of life for all members of the public. Remediation of coal refuse sites has energized local watershed groups to prioritize their clean-up efforts in the same watersheds. Significant local, county and state emergency services costs are avoided by the removal of coal refuse piles.

In general, the coal refuse fired plants have controlled their emissions of SO_2, NOx, and PM. They have been some of the lowest emitters of Mercury and PM. In fact, 8 of the coal refuse fired units were in the EPA floor calculations to determine the emission rate for SO_2.

The ability of these plants to comply with the acid gas aspects of MATS is a function of the sulfur content of the fuel. Plants located in the anthracite area burn low sulfur fuel whereas the sulfur content of the fuel in the bituminous area is high. This allows the plants in the anthracite area to comply with the SO_2 surrogate of 0.2 lb/MMbtu as they only need to capture approximately 90% of the sulfur in the boiler. Whereas, the coal refuse fired units in the bituminous area would have to achieve 98+% capture of the sulfur in the boiler.

The Lucerne site is an old abandoned coal refuse pile where the mining and coal processing wastes from the Lucerne Deep Mines Complex was placed. There was a total of 8.7 million tons of coal refuse of varying quality and size. The quality of the pile varies in Btus from 5000 to 8000 and sulfur content from 1 to 6%

The site was un-reclaimed, discharging acid and iron to Yellow Creek and one of its unnamed tributaries, as indicated by seeps and discharges from the areas where coal refuse was placed. Silt laden runoff was also discharging into the stream. In addition, there have been times when the pile was burning in the past as evidenced by "red dog".

The project mines and blends the coal refuse, ships the material to Cambria and Colver plants as well as shipping some material to Seward. Coal combustion residuals from both Colver and Cambria are returned as part of the site reclamation. Cambria Reclamation permitted and bonded the site and conducts the mining and reclamation operations.

It is projected that upon completion, this should reduce the discharge load to the stream by 261,000 lbs of acidity a year and 59,000 lbs of iron a year.

Pennsylvania's Abandoned Mine Land Problem including Coal Refuse Sites

Pennsylvania's coal miners have extracted approximately 16.3 billion short tons of anthracite and bituminous coal from the state's mines since commercial mining began in 1800. While mines permitted under the 1997 Surface Mining Control and Reclamation Act (SMCRA) are required to be reclaimed after the coal is extracted and processed, many pre-SMCRA mines were abandoned without any reclamation. These sites are referred to as Abandoned Mine Lands (AML).

In Pennsylvania, there are more than 5,000 abandoned, unreclaimed mining areas covering approximately 184,000 acres. The estimated cost to address these problems is between $15 and $16 Billion.

What are the impacts from abandoned, unreclaimed coal refuse sites? There are three basic areas of impact: Land, Water, and Air.

Land

The coal refuse piles are scattered across the landscape next to communities, rivers and streams and sometimes fill entire valleys. These piles are unsightly and scar the landscape and some areas look like moonscapes. The piles also tend to attract dumping and other activities, increasing the potential for nuisances such as starting the coal refuse piles on fire. Abandoned coal mines and coal refuse piles cause many adverse impacts to surrounding land. Unstable coal refuse piles may collapse and threaten the safety of nearby communities and the scenic and recreational quality of the landscape is ruined. Properly reclaimed coal refuse sites can and have returned the land to productive uses including wildlife habitat, recreational opportunities and commercial development.

Water

More than 3,300 miles of streams in Pennsylvania are impacted by Acid Mine Drainage (AMD), according to the United States Geological Survey (USGS). This is the result of AMD from both mine discharges and acid runoff from coal refuse piles. The run-off from precipitation, in addition to being acidic and contaminated by metals, contains silt, which is also a pollutant. This acidic contaminated discharge creates water pollution and negatively affects the ability of a stream to support aquatic life.

Air

Coal refuse sites historically and currently catch fire. Coal refuse fires typically start as a smoldering, oxygen starved fire that produces the necessary oxygen from the generation of steam created by moisture in the coal refuse. Slowly, as the fire continues to develop, avenues for oxygen migration through the refuse expand, resulting in flames. Combustion of the coal refuse emits uncontrolled toxic air pollutants and greenhouse gases into the atmosphere. The toxic air pollutants are a particular health and safety problem in the proximity of the coal refuse fires.

Coal refuse disposal piles have been burning and causing air pollution since coal mining first started (Sussman and Mulhern, 1964).

The oxidation of pyrites produces an exothermic reaction that produces heat, which causes the carbonaceous material in the coal refuse pile to ignite and burn. The temperature within a coal refuse pile (or portions of a pile) will increase when more oxygen is available to cause oxidation but the amount of air circulating in the pile is insufficient to provide for the dissipation of heat. The temperature of the refuse increases until the ignition temperature of the carbonaceous material in the refuse is reached. At this point the coal refuse pile spontaneously combusts, releasing various uncontrolled pollutants into the air of the near-by community.

Pennsylvania Department of Environmental Protection has identified 42 coal refuse piles that are currently burning and at some point will need to be addressed. This does not include underground mine fires.

Pennsylvania was the first state to pass a law to address the air pollution associated with coal refuse disposal, entitled "The Coal Refuse Disposal Control Act, Act of September 24, 1968, P.L. 1040, No. 318." This has allowed the Commonwealth to address active coal refuse pile fires and to attempt to prevent additional coal refuse piles from catching fire. While the efforts have met with success, new coal refuse fires continue to occur.

The EPA (1978 Study) identified the uncontrolled emissions from burning coal refuse piles. The following pollutants were listed:

(1) criteria pollutants (total particulates, respirable particulates, nitrogen oxides, sulfur dioxide, sulfur trioxide, hydrocarbons, carbon monoxide, and mercury);
(2) non-criteria pollutants (ammonia, hydrogen sulfide, polycyclic organic materials); and
(3) trace elements (arsenic, boron, silicon, iron, manganese, magnesium, aluminum, calcium, copper, sodium, titanium, lead, tin, chromium and vanadium)

The money needed to address Pennsylvania's Abandoned Mine Land problems is not available at this time. It was projected that Pennsylvania would receive over $1 Billion from the Federal AML Fund. This represents less than 7% of the money needed to address the problem. Pennsylvania recognized this and has pushed for remining previously mined areas in order to reclaim the land. The remining was tied to the mining of coal, not coal refuse.

There were efforts in the 1980s to have coal refuse piles reprocessed and reclaim the coal mixed in the piles. This had marginal success, but more often than not resulted in many coal refuse sites being partially mined, not reclaimed, which forfeited bonds.

Pennsylvania's Coal-Refuse Fired EGUs became the most effective tool for reclaiming abandoned coal refuse piles. This program has resulted in over 200 million tons of coal refuse fired as fuel and 1000's of acres of land reclaimed. This industry was a result of the Public Utility Regulatory Policy Act of 1978 (PURPA).

PURPA

While it was recognized that the Federal AML Program would not be able to address the AML problem in many of the States, what was unforeseen was the potential of PURPA to help address the problem. PURPA established a program requiring states to contract for power from qualifying facilities (QF). QF status was accorded to types of projects: Cogeneration and/or Small Power Production Facilities.

FERC would certify the facilities as being cogeneration and/or small power production QFs. FERC certified small power production facilities as QFs if the facility was burning waste (coal refuse), and if the waste provided 75% of the heat input to the boiler and had no value. Further, in the case of coal refuse (waste coal), FERC certified the coal refuse fuel sources as waste coal and later established the criteria for coal refuse to be classified as waste in its regulations.

As a result of the QF certification, the Utility in the area was required to enter into contracts for purchasing power from these facilities at their avoided costs.

Pennsylvania Administrations embraced PURPA and more specifically bought into utilizing coal refuse (waste coal) in these facilities. They saw two basic benefits: (1) economic development in these areas that were distressed economically; and (2) environmental remediation and clean up. There were 15 QF facilities in Pennsylvania burning coal refuse, of which 2 have ceased operations. In addition, the Seward Facility (an Electric Wholesale Generator) also burns coal refuse and is larger than the other 4 bituminous coal refuse fired QFs (525 MW vs 320 MW).

The coal refuse fired PURPA QF facilities utilized Fluidized Bed Combustion Technology.

Fluidized Bed Combustion Technology

Fluidized Bed Combustion (Circulating Fluidized Bed Combustion (CFB)) Technology is a clean coal technology developed in Europe. The technology allows low Btu high ash coal refuse to be the fuel (Figure 1).

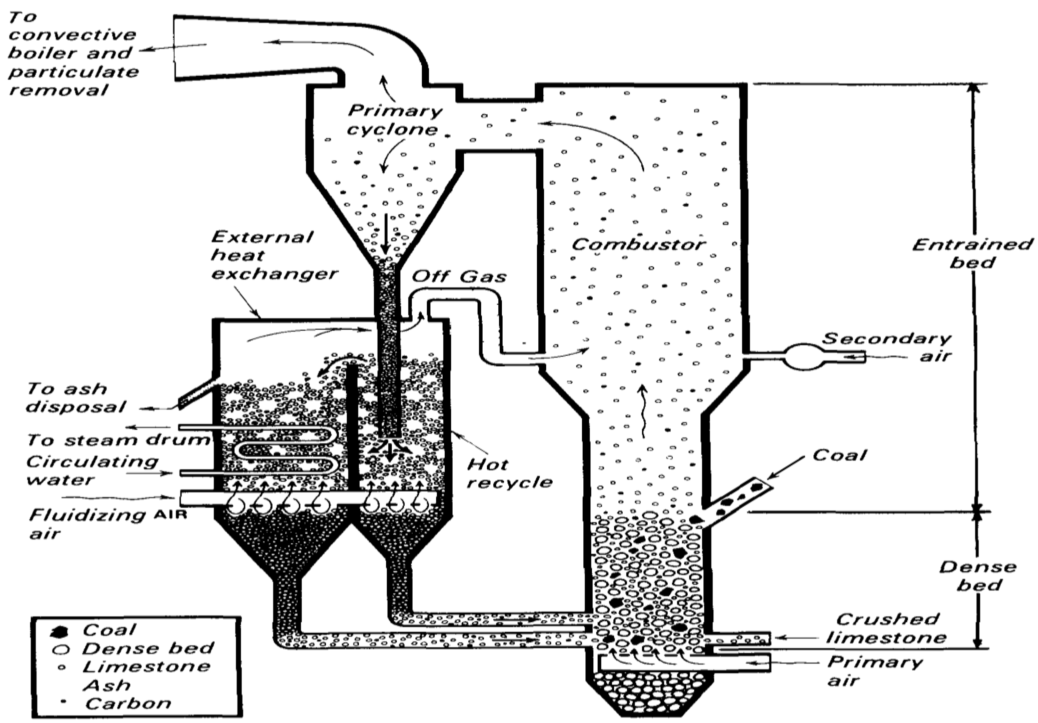

Figure 1. Cross Section of a Circulating Fluidized Bed Combustor

There are four coal refuse fired CFB electric generating units within a 30-mile radius of the site and a total of 14 plants in Pennsylvania (Figure 2). They are: Cambria Cogeneration, IPAC-Colver, Ebensburg Power (which were QFs) and Seward (an Electric Wholesale Generator). These plants vary in size and age. While the CFB Technology is basically unchanged, with design modifications these plants have grown in size (electrical output) and the ability to control their emissions. The basic aspects of a CFB is that the fuel (coal refuse) is co-fired with injected limestone to control SO_2 emissions, use combustion and/or emission control technology to reduce NOx emissions, and bag-house to control particulate emissions.

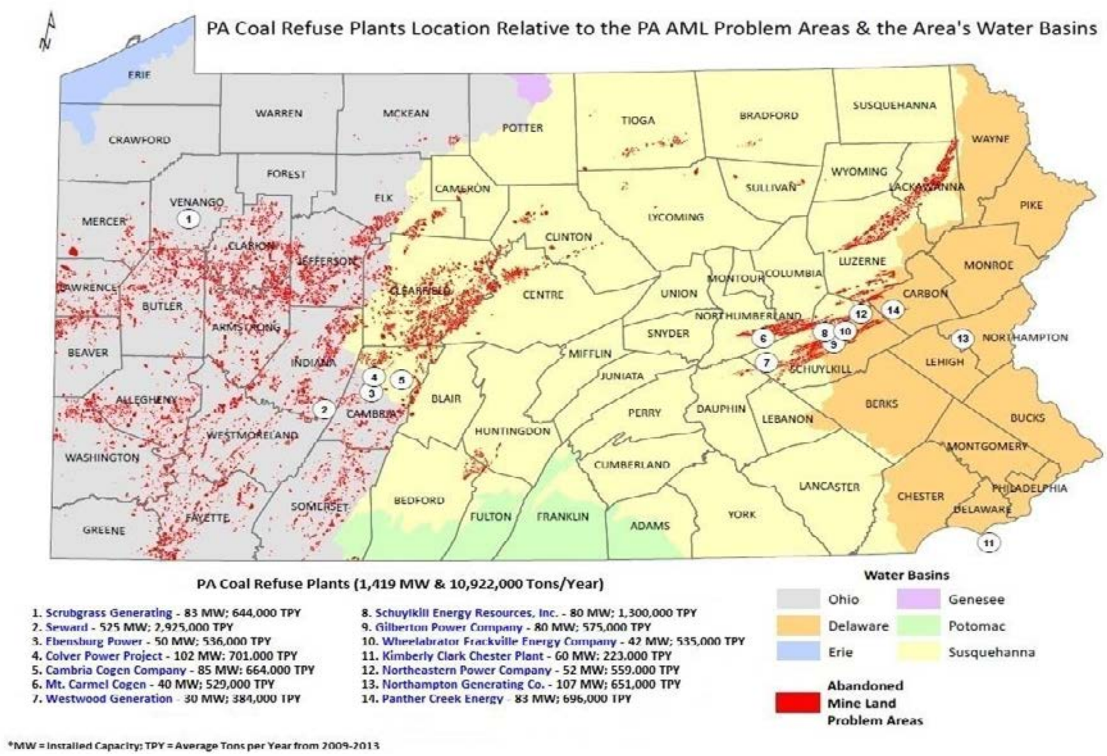

Figure 2. Map Showing Coal Refuse Plant Locations

Unlike coal fired units, these facilities have been controlling their emissions effectively. These facilities control SO_2 emissions from the fuel between 90% and 95%, control their mercury emissions at levels at or below the new EPA standard, and control PM emissions below the EPA standards, while cleaning up the environment by eliminating coal refuse sites as existing and future uncontrolled air emission sources, ameliorating, if not eliminating water pollution, from these sites, and returning the property back to a productive use and establishing vegetation.

These plants are very low emitters of mercury and filterable particulate matter (per the baghouse technology). They have controlled SO_2 emissions from the day operations were commenced. These plants inject both limestone and coal refuse in the boiler. The temperatures in the boiler allow the limestone to calcine and the resulting lime oxide to react with the sulfur dioxide (SO_2) in the boiler, reducing the emissions of SO_2 from 90% to 95%. To achieve the 98% reduction that the Mercury Air Toxic Rule (MATS) will impose on the plants will place a major technical and financial burden on the ability of a coal refuse facility to survive.

The sulfur content of the bituminous coal refuse varies from lows in the 1% range to over 6% and generally falls in the range of 2.5% to 4%. The Lucerne site has this level of variability, whereas anthracite coal refuse is usually around 1%. Thus, coal refuse fired units in the anthracite area have the ability to meet the MATS rule. The bituminous meets all but the SO_2 limits in the MATS rule, but must bring their units into compliance with the acid gas aspects of MATS by April of 2019.

Because of the calcinations of the limestone, fluidized bed combustion units have a higher level of CO_2 emissions than a coal fired boiler.

It should be pointed out that if the coal refuse sites are not used as fuel, they remain un-reclaimed and a source of air pollution (fugitive dust and air toxics from burning); water pollution (silt laden runoff to acid mine drainage); and the land is unproductive (none to minimal vegetation).

Each new generation of CFB coal-refuse fired units has been able to reduce SO_2 emissions by increasing limestone consumption. (It should be noted that the upgrades to the newer plants are not able to be applied to the older plants.) These plants have been able to control their mercury emission significantly (~99% reductions) and are low emitters of mercury per the EPA Mercury and Air Toxics Rule. The plants have used baghouse to control Particulate Matter (PM) emissions at levels below that required by the MATS rule. These plants are either low emitters of PM or are very close to the low emitter limits. They are low emitters of NOx emissions which results from either use combustion control or Selective Non-Catalytic Reduction Technology. Further, these plants are low emitters of Nitrogen Oxides (N_2O). These facilities have a higher footprint for Carbon Dioxide Emissions resulting from burning the coal refuse and the calcining of the limestone to control SO_2 emissions.

The smaller, earlier Coal-Refuse Fired CFB (>130 MW) have a problem meeting the HCl emission rate or its SO_2 surrogate. These units would need to achieve either 98% capture of the HCl or SO_2. The economics of controlling these emissions at that level in today's electric market is problematic let alone having the technology to control or the cost of said technology.

Introduction - Lucerne Coal Refuse site

The Lucerne Coal Refuse Site represents the coal refuse aspect of Pennsylvania's Abandoned Coal Mine Legacy. The Lucerne Coal Refuse Pile resulted from the disposal of coal refuse from the Lucerne Mines that were developed in 1907, with the mines ceasing operations in 1929 (Lucerne Mine No.1), 1943 (Lucerne Mine No. 2) and 1967 (Lucerne Mine No. 3). The mine complex covered over 14,000 acres. Through the years (until 1948), the coal was delivered to the breaker where it was crushed and sized. At the breaker, men were employed to pick slate, rock, and sulfur from the conveyors for disposal. The operations slowly transitioned to mechanical separation with the construction and operation of the Lucerne Coal Cleaning Plant in 1948. (Mountjoy, IUP Website).

The coal refuse disposal was placed on 125 acres of a 397 acre property of which 286 acres have been permitted. The process of coal refuse to energy is leading to the Lucerne site being reclaimed. This process is summarized in Figure 3.

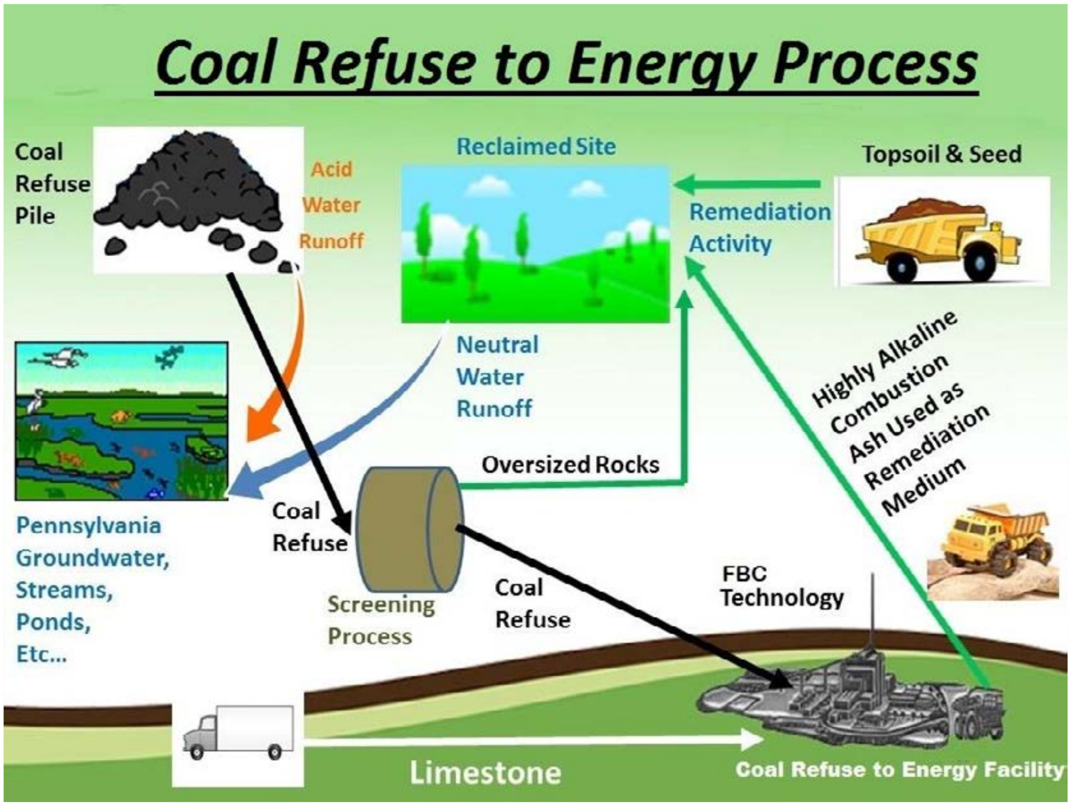

Figure 3. Coal Refuse to Energy Process *(Source - www.wpcamr.org)*

The Lucerne Site has burned in the past, as is evidenced by “red-dog” (burnt coal refuse) present within the pile. The area is unreclaimed with no vegetation, which creates fugitive dust, sediment laden run-off and acid mine drainage pollutional discharges.

Since the site was not permitted (nor required to be permitted) at the time it was in operation, it was subsequently abandoned with no one required to reclaim the site. The reclamation fell to the Commonwealth, but with no funding available to reclaim, it remained in the unreclaimed state.

The Federal AML Program was designed to provide monies for addressing abandoned mine problems in the States through a federal reclamation fee assessed against each ton of coal mined. These monies were to be used to reclaim priority 1 and 2 sites first. In the case of Pennsylvania, most of these sites would fall into either priority 3 or 4. (With Pennsylvania’s AML program needing over $15 Billion to address its AML problem, and projected to receive $1 Billion dollars, with most of the sites being classified as priority 3 or 4, it is doubtful that these sites will be reclaimed.)

As such, the Commonwealth will not be able to fully address its priority 1 or 2 sites so it remains very doubtful that it can address the coal refuse sites.

Lucerne's Location

The Lucerne Coal Refuse pile is located in Center Twp., Indiana County, PA, adjacent to Homer City Borough, and near the communities of Lucerne Mines and Tide, just off US 119 and Township Road T-840 (Tide Road) (Figure 4).

The coal refuse disposal was placed on 125 acres of a 397 acre property of which 286 acres have been permitted. The 125 acres is comprised of two specific areas of the property (Figure 4). Area 1 was primarily coarse coal refuse (the main site for mining operations) and Area 2 (sludge/coal slurry) as the coal cleaning process improved.

The reject from the coal cleaning plant was delivered by conveyor to the Lucerne coal refuse site (Figure 5). There was over 8,700,000 tons of coal refuse placed on the site.

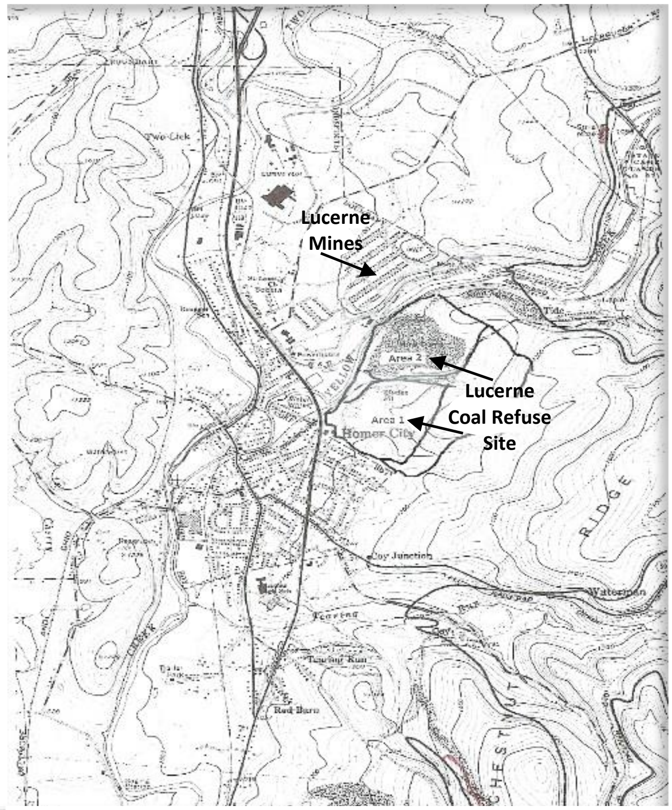

Figure 4. Location of Lucerne Coal Refuse Site (Area 1 & Area 2) and Lucerne mines, Indiana County

Figure 5. Library of Congress Photo showing boney pile (coal refuse) and Conveyor at Lucerne

History of the Lucerne Mine Complex (Mountjoy, IUP Website)

The Rochester and Pittsburgh Coal and Iron Co. (R&P) opened the Lucerne Mines operation and patch town in 1907. Within 15 years, Lucerne had three mine openings, steel tipple, and central power house (Figure 6) making Lucerne one of the largest and most complete mining plants in the United States.

Over the course of the next 60 years, R&P played an important role of electrifying mines when in 1899, R&P began to convert the haulage systems at each of its mines to electric from animal. Starting in 1903, R&P began to construct power plants at its mine with Ernest being one of the first. However, due to the high-line losses, R&P built a centralized power plant at Lucerne and placed it into operation in 1911.

At this time, R&P was testing electric cutting machines at Lucerne which led to R&P electrifying all their mines using electric cutting machines.

With the centralized power plant, R&P began to run power lines to its various mines in Indiana and Armstrong County. The Ernest Mine was the first mine to be powered by the Lucerne Power Plant.

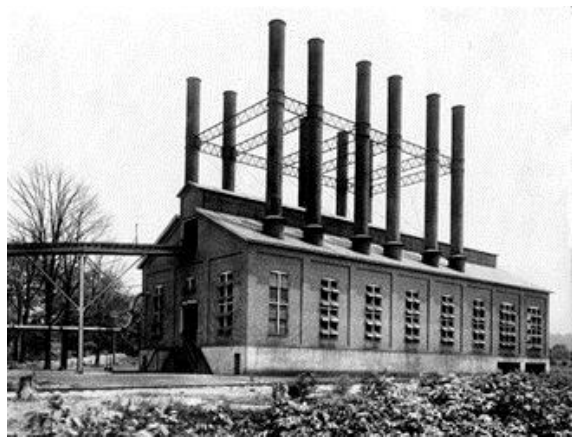

Figure 6. The Lucerne power plant

The Lucerne power house was furnishing electricity to all R&P mines in Indiana County as well as to the Indiana Street Railway system near Lucerne by 1920. The Lucerne Power Plant was modernized by replacing a number of the old boilers with two large ones, building the first tall stack in 1937, and additional turbogenerators were placed in operation 10 years later along with additional boilers and a tall stack.

By 1948, Lucerne had brought on line a new coal cleaning plant which over time was upgraded to improve coal quality. The resulting coal refuse and silt from the cleaning plant were conveyed over to the Lucerne Coal Refuse Site.

In 1952, R&P had a battery of 264 beehive coke ovens built at Lucerne furnishing high quality coke for the iron and steel industry until 1972 (Figure 7).

In 1964, R&P made the decision not to upgrade the power plant and to purchase electricity from the Pennsylvania Electric Company.

Figure 7. General perspective view of coke ovens looking east (264 block beehive ovens) - Lucernemines Coke Works, Coke Ovens, 0.5 mile East of Lucerne, adjacent, Lucerne Mines, Indiana County, PA.

Photos from Survey HAER PA-264-A

The original mines at Lucerne closed down with Lucerne No. 1 Mine ceasing operations in1929; No. 2 closed in 1943 and No. 3 ceased operations after 60 years of production in 1967.

Today, the Lucerne coal refuse site is providing fuel to serve Coal Refuse Fired Circulating Fluidized Bed Facilities resulting in the energy stored in the coal refuse at the site to be utilized to generate electric power. Further, the coal ash produced from a CFB Unit is highly alkaline and meets the State regulatory requirement for its use in mine land reclamation.

Geologic and Groundwater Overview of the Lucerne Coal Refuse Site

This portion of Indiana County is underlain by the Pennsylvania Conemaugh and Allegheny Group (Figure 8).

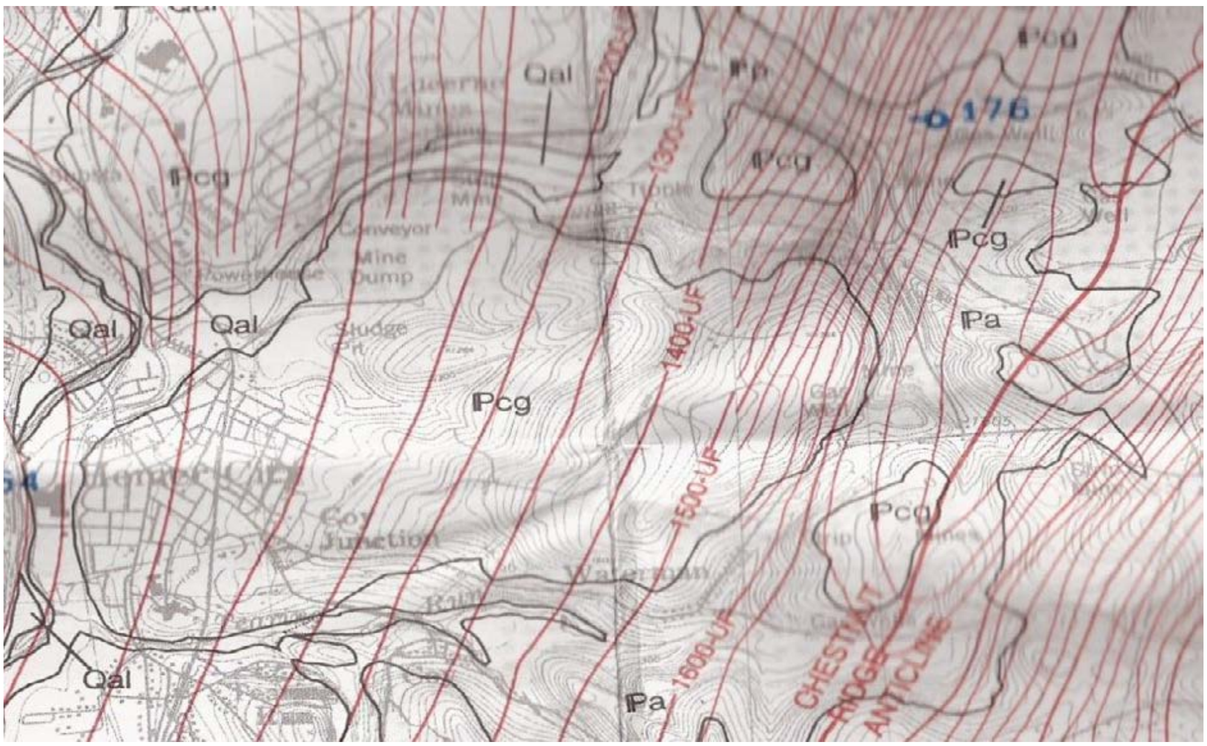

Figure 8. Geologic Map with Structural Contours (Williams and McElroy, 1997)

The Lucerne Coal Refuse Site is located approximately 1.4 miles southeast of the Latrobe Syncline and 2.0 miles northwest of the Chestnut Ridge Anticline. The area beneath the mine site had been extensively deep mined with the mine complex being over 14,000 acres extending from the Lucerne area to the Ernest area.

The coal refuse area (identified as the conveyor mine dump) and the slurry impoundment (identified as the "Sludge Pit") is underlain by the Pennsylvanian Conemaugh Group (the Glenshaw Formation (Pcg)). The Glenshaw Formation has been described as being olive-gray to dark-gray, thinly bedded fossilferous, limestone and clay shales, red claystone, locally massive fine to coarse-grained sandstone near the base, fresh water limestone, and thin, non-persistent coal (Williams and McElroy, 1997).

The Upper Freeport Coal (Allegheny Group) underlies the area and has been extensively deep mined, as was the Upper Kittanning Coal (Allegheny Group) by Rochester and Pittsburgh Coal and Iron Company from 1907 to ~1972. (Bragonier and Glover, 1996) (Figures 9 and 10).

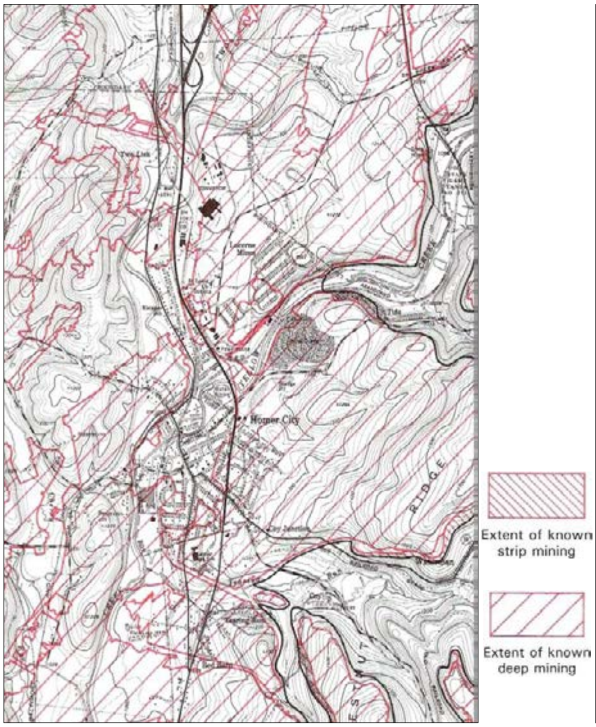

Figure 9. Mining in the Upper Freeport Coal

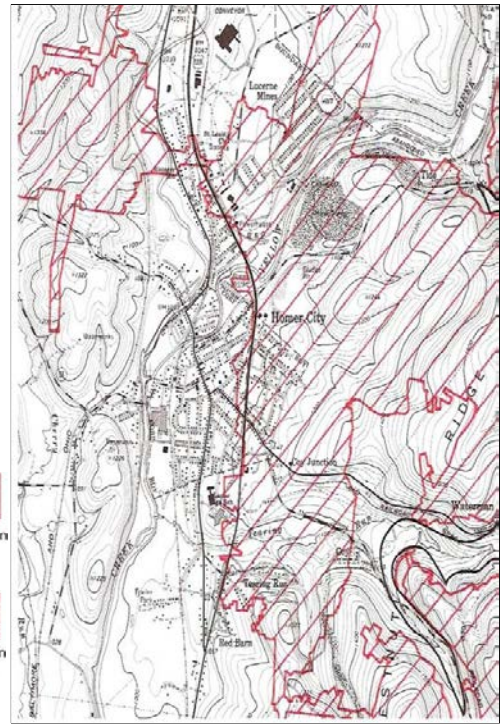

Figure 10. Mining in the Lower Kittanning Coal (Bragonier and Glover, 1996)

The coal refuse was placed on the sites with minimal considerations (not having legislation or regulation dealing with stability or environmental issues. In 1952, the Lucerne Mines constructed and operated a coal preparation and cleaning facility across the stream from the coal refuse site and sludge pit. Waste from the Lucerne Preparation Plant was transported to the coal refuse site, where it was dumped on the ground with minimal compaction. Later, the sludge pits was established to dispose of slurry from the preparation plant. Both the coal refuse site and the slurry sites were placed on the ground surface.

The valley adjacent to the coal refuse site has Quaternary Age Alluvium (Qal) deposits.

The pre-1972 deep mining and coal refuse disposal has impacted groundwater quality and surface water quality in the area. In general, the groundwater system within the permit area consists of one or more perched water tables with the regional water table at the level of Yellow Creek. However, the extensive deep-mining of the Upper Freeport and the Lower Kittanning has had a major impact on ground and surface water in the area. The Upper Freeport Deep Mine is flooded to an elevation of 1040 feet to >1070 feet. The mining in this area has been to the rise, resulting in additional head allowing deep mine discharges at the 1040 and 1070 foot elevation. In addition, the extensive deep-mining has probably led to subsidence issues allowing the mine to dewater the shallow perched water groundwater.

The Lucerne Coal Refuse Site is being remined and used as a fuel source for Cambria, Colver, and Seward. The coal refuse and slurry located on the sites has been certified by FERC as waste coal.

The Mining Operation

There are two distinct areas of mining based on the past coal refuse and coal slurry disposal operations. The intent is to remine the site, using the coal refuse as fuel for the coal-refuse fired electric generating units, eliminate the piles as source of acid mine water and sediment laden runoff, use the alkaline ash beneficially to reclaim the site, eliminate the potential for the site to burn in the future and restore the land to a productive use.

The site has been permitted to be mined. The permit includes a mining plan and abatement plan to reduce or eliminate the pre-existing pollution emanating from the site, as well as full-cost reclamation bonding. A key aspect is burning the coal refuse and replacing it with an alkaline coal ash as a beneficial use in the mine reclamation.

The site will be monitored for a period of 10 years from the day the last coal ash is placed on the site before the site is eligible for final bond release.

The mining operations commenced in Area 1, in order to develop this portion of the site to accept ash when mining coal refuse in Area 2. As part of the development of this portion of the site, some of the slurry/silt was moved and stockpiled on the coarse refuse site. This was needed in order to manage coal ash from the Cambria Cogeneration facility. This coal ash, approved for beneficial use in coal mine land reclamation, is being placed in that area. The active coal refuse mining activities are being conducted on the coarse refuse site (which also has areas of silt/slurry). At this time, no ash is being placed in this area, as the site needs to be developed in a manner that maximizes the recovery of the coal refuse. In mining this area, the variability in fuel quality, based on wide swings in Btus and sulfur percentage, requires the development of 'coal refuse "highwalls"'. The coal refuse is shipped to the plants on a daily basis by trucks loaded with coal refuse from the different highwalls that are mixed and blended at the plants to achieve a more uniform Btu and sulfur content. This procedure:

(1) allows for mining of the coarse refuse to maximize recovery without it being limited by being ash bound,
(2) insures that the acid producing material is burned and neutralized,
(3) the site will not catch fire in the future and
(4) water quality from the site will improve.

The site was un-reclaimed causing acid and iron discharges to Yellow Creek and one of its unnamed tributaries as indicated by seeps and discharges from the areas where coal refuse was placed. There was silt laden runoff that was also discharging to the stream. In addition, there have been times when the pile was burning in the past as evidenced by "red dog". It is projected that upon completion, this should reduce the discharge load to the stream by 261,000 lbs. of acidity a year and 59,000 lbs. of iron a year.

Summary and the Dilemma

In summary, the remining of the Lucerne Coal Refuse Site allows for the coal refuse to be used as a fuel in coal-refuse fired electric generating units in Indiana and Cambria County. As a result of the mining effort, the site will be reclaimed, the potential for future fires eliminated, and in the process eliminate 261,000 lbs. of acidity and 59,000 lbs. of iron from being discharged into Yellow Creek and one of its unnamed tributaries, improving the overall water quality.

The dilemma is that the Coal Refuse Fired EGUs have proven they are able to generate power, meet reasonable environmental regulations, and clean up the piles through the Coal Refuse to Energy Process (Figure 3). In the process, they have minimized or eliminated the mine drainage from these sites, eliminated the future potential of these sites to burn, and returned the land to a productive use with the **vegetation becoming a carbon sink**. Without these sites, there is no economical means to reclaim the sites to standards for regulated coal mining. The dilemma is the need to keep these types of electric generating units operational so that they can continue to be an economic tool in the region and more importantly clean up the pollution associated with the abandoned coal refuse sites.

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For more information on Coal Refuse, see Appendix A.

ROSEBUD MINING AND THE ST. MICHAEL DISCHARGE WATER TREATMENT PLANT, ST. MICHAEL, PENNSYLVANIA – TOPPER RUN DISCHARGE

JACQUELINE HOCKENBERRY P.G., J HOCKENBERRY ENVIRONMENTAL SERVICES, INC.
JACKIE RITKO, CAMBRIA COUNTY CONSERVATION DISTRICT
JOHN ST. CLAIR, ROSEBUD MINING COMPANY

Introduction

The South Fork Branch of the Little Conemaugh River Watershed has been home to a long history of both surface and deep coal mining. For decades, beginning in the early 1900's, the coal mining industry established its presence, created jobs and spurred development of municipalities such as St. Michael, Beaverdale, Sidman, and South Fork located outside of Johnstown, Pennsylvania. This industry in turn supported the steel industry.

The remnants of the past mining have etched many faces on the surface in the form of old company housing, railroads, bony piles, un-reclaimed and reclaimed surface mine areas, mine openings, shafts and mine discharges that were accepted as a part of life and landscape.

For decades, the South Fork Branch and its tributaries have received mine discharges into their corridors from closed or abandoned mines, creating a quagmire of water chemistry and landscapes of brown, red, and white within their channels.

Fast forward to 2010, and mining has a new mission and a new perspective to mining coal in this area. The Rosebud Mining Company presented a proposal to the Pennsylvania Department of Environmental Protection, the United States Environmental Protection Agency, local municipalities and countless other interested parties to substantially remove the acid mine drainage load to the largest pollution contributor within the Little Conemaugh Watershed in exchange for a permit to deep mine coal reserves that were flooded by both past mining and geological conditions.

What has been referred to as "out of the box" thinking, Rosebud has entered into an agreement with the regulatory agencies to substantially reduce the metal loading to the South Fork Branch of the Little Conemaugh River by pumping and treating the worst discharge in the Little Conemaugh Watershed in exchange for the ability to continue mining – Mine 78 (Upper Kittanning – C')

Rosebud Mining Company committed to fund and construct the now functioning $15 million dollar water treatment facility and pay treatment expenses during the active mining of "Mine 78." In addition, Rosebud will contribute another $15 million to establish a fully funded perpetual treatment trust fund. The construction of the treatment plant has been completed the treatment of the water commenced in 2013.

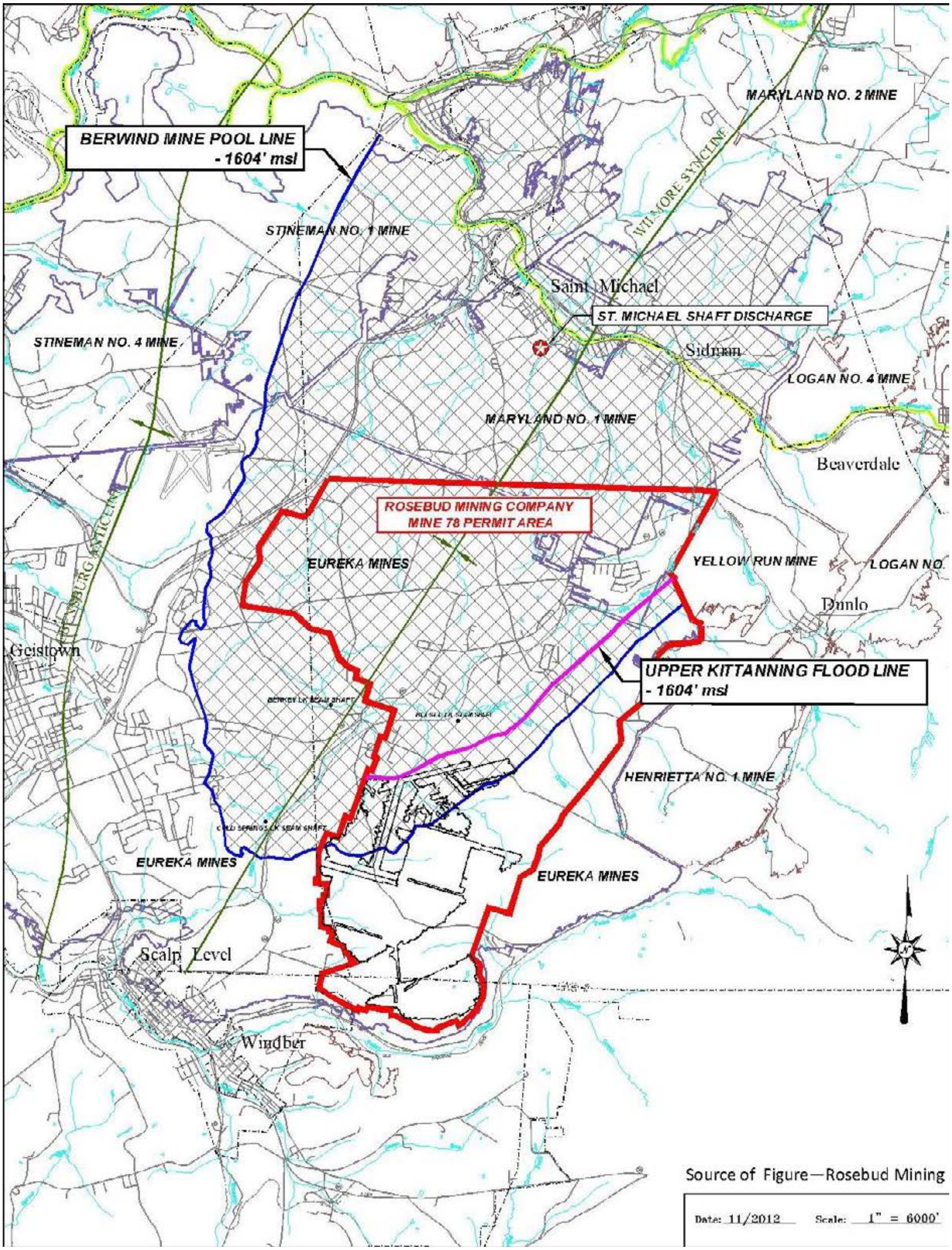

Figure 1. Map showing the geological structure of the area as it relates to the Berwind Mine pool (outlined in blue), limit of flooded area of the Upper Kittanning C–coal seam (pink line), and the St. Michael shaft discharge. The Rosebud Mining Company Mine 78 permit area is outlined in red. Source of figure – Rosebud Mining.

Background History

One of mining companies who established a mine operation in the St. Michael area around the 1900's time was the Maryland Coal Company of Pennsylvania. The company, based out of New York City established the Maryland Shaft & Collieries circa 1908-1910. The mine was established in the Topper Run Watershed (tributary to the South Fork Branch of the Little Conemaugh). When this mine opened, a shaft was constructed 670-ft deep, which at the time was the deepest shaft of all bituminous mines in Pennsylvania. This mine operated under the Maryland Coal Company until 1932 when it was sold to the Berwind-White Coal Company. Berwind operated the mine until 1958 when the mine was closed. Berwind ceased pumping the shaft in July 1962 and the shaft became the infamous discharge in December 1963.

Since that time, the shaft had been discharging untreated acid mine drainage water progressively into Topper Run, to the South Fork Branch of the Conemaugh, Stonycreek River, the Conemaugh, Kiskiminetas River to the eventually to the Lower Allegheny River. The Maryland Shaft (St. Michael) discharge is the largest single source of acid mine drainage pollution within the Little Conemaugh River, producing 29.2% of the total acid mine drainage pollution load on the river. Average flow rates approximate the discharge as 2, 067 gallons per minute to as high a 3,656 gallons per minute. The discharge originates from a 36-inch pipe at the top of the shaft.

The shaft was evaluated for integrity as part of the design for the treatment plant. The shaft was considered to be in good condition despite its construction date of 1908-1910 era.

The "Berwind Mine Pool"

The discharge and subsurface conditions have created the "Berwind Mine Pool" which in the subsurface have flooded substantial areas above the Lower Kittanning "B" prohibiting the mining of the Upper Kittanning coals (C') (Figure 2).

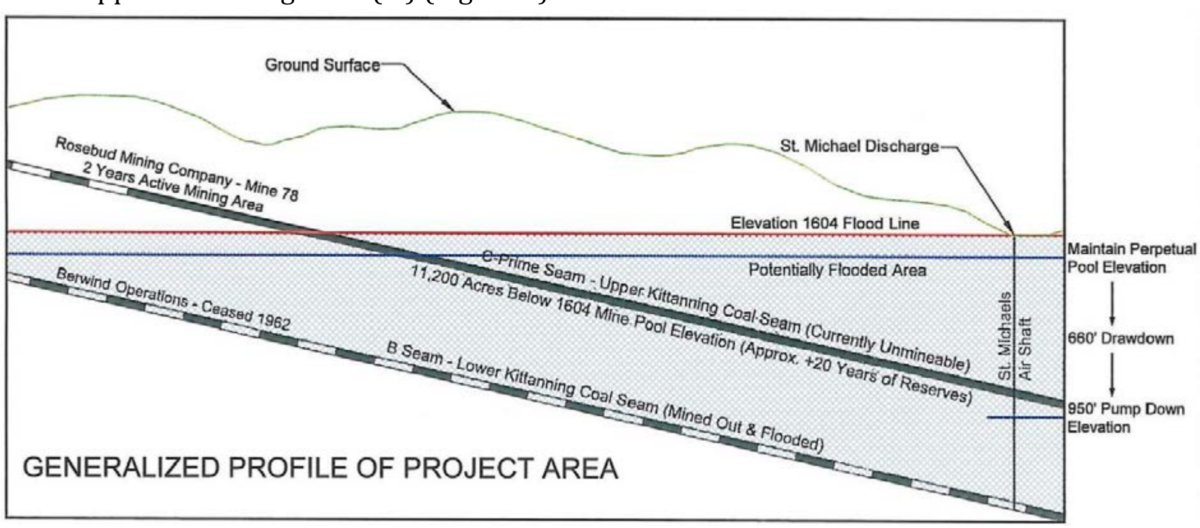

Figure 2. The Upper Kittanning coal seam (seam being extracted by Mine 78) is approximately 100 feet above the Lower Kittanning coal seam (seam extracted in the early 20th century) and they are hydraulically connected. No mining can be conducted at Mine 78 below an elevation of 1604' msl until the area is dewatered by pumping the Berwind mine pool at the St. Michael Shaft. The pumping and treatment facilities will allow 20 plus years of additional mining and eliminate 30% of the AMD loading on the Little Conemaugh Watershed. Upon completion of the mining activities at Mine 78, the mine pool will be allowed to rise but be maintained below the current discharge elevation. Source of figure – Rosebud Mining.

The mine pool developed resultant of the structural geology of the area. Ground water in the vicinity traverses towards the Wilmore syncline, which plunges in the direction of the St. Michael/ Maryland Shaft (Figure 3). The groundwater fills the synclinal feature and the shaft becomes the discharge point for the mine pool. This elevation is approximately 1604 feet. Rosebud will pump the mine pool to an elevation of 950-feet allowing the deep mining of Mine 78 to continue for 20+ years. Upon completion of the mining, the mine pool will rise, but will be maintained below the 1604 discharge elevation. Treatment will continue after mining is completed via use of the established trust funds.

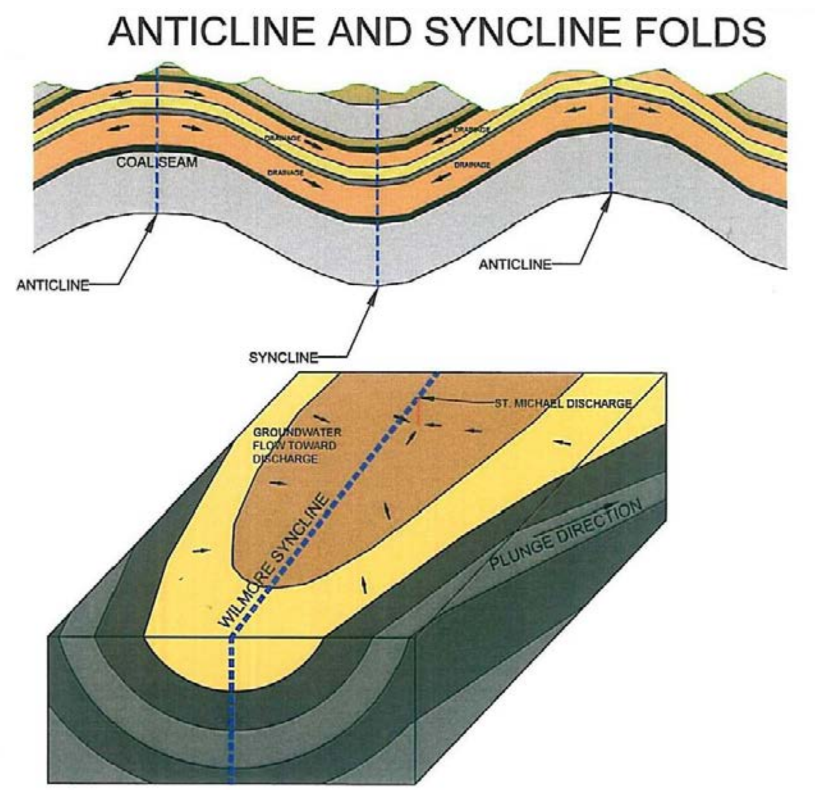

Figure 3. Water enters the subsurface near stratigraphic high areas known as anticlines. Groundwater then travels down gradient toward the axis of stratigraphic lows known as synclines. The Wilmore Syncline plunges toward the St. Michael Shaft where the groundwater fills a bowl-like structure to form the Berwind Mine Pool. St. Michael Shaft is the discharge point of the mine pool. Source of figure – Rosebud Mining.

Topper Run Water Chemistry

Significant interest in this watershed has spurred the initiation of several studies. Many organizations have donated time and resources in attempts to improve the watershed. These studies have sought to identify the discharges that plaque this watershed. Some of these studies commenced twenty to thirty years ago and served as a basis to identify and inventory the discharges in the watershed. The studies were conducted to determine the total impact of the acid mine drainage to the watershed and to observe changes in waterways resultant of other land-use activities. The historic record of inventory and chemical analysis is reflective of the interest in the community to reduce pollution in these waterways. The overall conclusion is that many of these discharge flow rates prohibit any type of treatment except for chemical, which as presented with the St. Michael/Maryland Shaft discharge is very costly.

In a comprehensive watershed study conducted by the Cambria County Conservation District in 2000, Topper Run was recognized as being the largest source of acid mine drainage in the watershed. The study notes that Topper Run is contaminated with 100-150 mg/l ferrous iron with a field pH of 4.91. Comparing the iron content of the discharge with the Pennsylvania Maximum Contaminant Level for drinking water in Pennsylvania of 0.3 mg/l puts the extent of the pollution in perspective.

Other contaminant levels for this discharge included:

Sulfates:	132 mg/l
Manganese:	4.46 mg/l
Aluminum:	0.717 mg/l

This chemistry equates to a load of 31,141 pounds per day and 3700 tons of acid mine drainage annually.

The Rosebud/ St. Michael Water Treatment Project which is now operational treats an average flow rate of 3,656 gallons per minute, and draw down pump capacity is up to 10,000 gallons per minute.

This treatment facility significantly improves the water quality of Topper Run, however, refuse piles located contiguous to the stream, which are situated upgradient of the treatment facility, leach pollution to Topper Run.

Sulfur Creek, another tributary to the South Fork Branch, is ranked as the second most significant acid producer to the South Branch of the Little Conemaugh River, contributing a load of 11,418 pounds per day, and attributes to 10.71 % of the pollution in this watershed. A visit to Sulfur Creek closely depicts the condition of Topper Run prior to the treatment. The Sulfur Creek landscape is dominated by the considerable accumulation of iron mounds, created from the deposition of the iron and other metals. It is a stark display of the magnitude of how acid mine drainage distresses the environment. In addition to the visual characteristics, these affected areas are extremely hazardous, due to the instability of the iron mounding and water chemistry associated with these site(s).

Components of the Treatment Plant

The Rosebud/ St. Michael Water Treatment Project which is now operational treats an average flow rate of 3,656 gallons per minute, and draw down pump capacity is up to 10,000 gallons per minute.

Some of the major components of the treatment facility include:

- Installation of 266-H-piles and 6,560 cubic yards of concrete for the foundation for 2, 210-feet diameter thickener tanks
- Construction of 2-35-diameter tanks, reactor tanks and mixers
- Construction of a 525 ft. long concrete retaining wall
- Construction of a treatment plant building, with 2-120 ton silos, motor control center, lime slakers, sludge transfer pumps, grit bunkers, various pumps and flow measuring devices

- Installation of caissons, steel platform for the installation of 2-800 horsepower mine dewatering pumps
- Installation of the 36-inch discharge piping and outlet structure

Conclusion

Acid mine drainage issues will continue to affect South Fork Branch of the Little Conemaugh River, but this project is a substantial step forward in removing pollution from these waterways.

This project is an effective of how industry and the regulatory agencies can work together to bring environmental and economic outcomes that benefit this area.

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St. Michael Discharge Water Treatment Facility

Rosebud Mining: St. Michael Discharge Water Treatment Plant Power Point Presentation

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http://www.cjmerlo.com/index.php?page=saint-michaels-acid-mine-draining-treatment-plant

Personal Communication:

John St. Clair: Rosebud Mining Company
Jacqueline Ritko: Cambria County Conservation District

A PRELIMINARY ANALYSIS OF AN UPPER PENNSYLVANIAN FLUVIAL CHANNEL COMPLEX OF THE CASSELMAN FORMATION (CONEMAUGH GROUP) EXPOSED ALONG US-22 NEAR BLAIRSVILLE, PA

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Introduction

In 2001 the Pennsylvania Department of Transportation began work on highway improvements to portions of US-22 and US-119 in Indiana County. These improvements included lane widening, straightening and, two miles east of Blairsville, construction of a ramp linking US-22 W to US-119 N (Figure 1). On the north side of this exit ramp an extensive roadcut reveals a complex of fluvial deposits in the Casselman Formation (Conemaugh Group, Virgilian) that measures 300 meters laterally and up to 6 meters vertically (Figure 2). The south side of the ramp offers a similar, but slightly less extensive vantage point. Just below the ramp, the interchange provides more exposures that are nearly orthogonal to the east-west trending sections of the ramp, facilitating a three-dimensional perspective of the unit and its architecture. Accordingly, this represents one of the largest and most accessible outcrops of its kind in Indiana County.

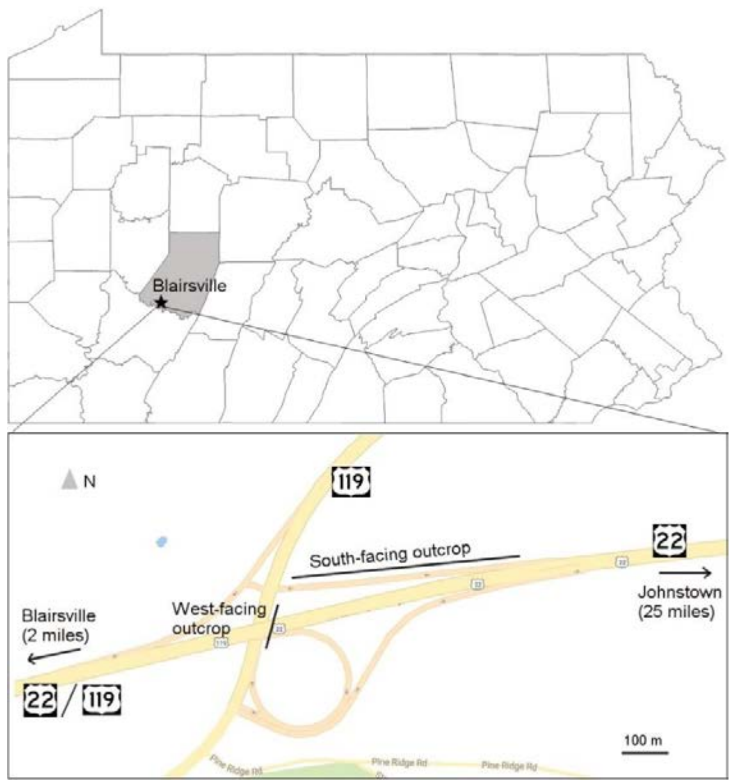

Figure 1. Map of the study locality near Blairsville, Indiana County (highway map from Google Maps)

The locality lies at the western edge of the northeast trending Chestnut Ridge, one of the more prominent structural and geomorphic features of the Appalachian Plateau in western Pennsylvania. This results in structurally controlled dips of around 6.3^{o} (11%) to the northwest (Bragonier and Glover, 1996). Stratigraphic units near the interchange and its vicinity have been mapped as belonging to the Casselman Formation of the Conemaugh Group (Berg and Dodge, 1981).

The Conemaugh Group (Upper Pennsylvania, upper Missourian and Lower Virgilian) is a clastic sequence dominated by siltstone, claystone, shale and sandstone (Edmunds et al., 1999). Early Pennsylvania geologists called this series of rocks the “Lower Barren Measures” due to the lack of economically important coal beds that characterize the underlying Allegheny and the overlying Monongahela series. That changed in 1865 when Franklin Platt renamed it "Conemaugh" after exposures along the Conemaugh River in adjacent Cambria County (Shaffner, 1958). The Conemaugh is bounded by the Upper Freeport coal at the base and the Pittsburgh coal at the top. The Conemaugh Group was divided into the Glenshaw and Casselman Formations by Flint (1965) in his survey of southern Somerset County based on the last occurrence of marine units. The unit dividing the two formations is the marine Ames limestone, which caps the Glenshaw Formation.

Figure 2. A typical section of the south-facing exposure along the US-22 W exit ramp. Sand sheet bodies predominate and generally lie above higher order bounding (erosional) surfaces and silty-sandy overbank deposits. Jacob's staff is 1.83 m in height.

The Casselman Formation is devoid of marine units with the exception of the non-persistent Skelly Marine Zone in the lower Casselman, which in Somerset County to the southeast is represented by a marine shale on the Federal Hill Coal and in Pittsburgh to the west by the Birmingham shale on the Duquesne Coal (Edmunds et al., 1999). By early Virgilian time the sea had retreated completely from this area and the Casselman Formation was deposited as alluvial sediments, often ascribed to upper deltaic environments (Edmunds et al., 1979). Although Pennsylvanian formations are composed of somewhat cyclic sequences of sedimentary lithologies, the concept of an idealized cyclothem as applied to the mid-continent falls apart for the Central Appalachians. Unlike the mid-continent, there is little vertical or horizontal lithic continuity in the Central Appalachians (Edmunds et al., 1979). In fact, the Glenshaw Formation thins from approximately 128 meters (420 feet) in Somerset County to approximately 85 meters (280 feet) in the very western part of Pennsylvania; the Casselman thins in a similar fashion from 148 meters (485 feet) in southern Somerset County to 70 meters (230 feet) in westernmost Pennsylvania. The Casselman Formation is one of the least studied formations of the Pennsylvanian, primarily because of its lack of economic resources and paleontologically significant fossil zone (Edmunds et al., 1999).

Methodology

To begin this reconnaissance study, the authors and several colleagues walked the US-22/US119 interchange and determined the most extensive outcrops were 1) the extensive south-facing roadcut along the US-22 W exit ramp and 2) the west-facing roadcut at the end of the ramp (Figure 1). The outcrops were then each divided into 10-meter sections. Each section was analyzed and photographed at 2.5 meter intervals. Where possible, fresh portions of the outcrop were sampled to observe grain size, color, composition and structure. Where sampling was not possible (due to height), deposit grain size and texture had to be visually inferred.

Determination of stratigraphic position within the Casselman Formation was explored via previously published literature and analysis of logged drill core data from the Rochester & Pittsburgh Coal Company (R&P). These cores were taken between 1.5 and 3 km from the study area. Drill core data also permitted determination of group and formation thicknesses and other local trends.

Casselman Formation in the study area

The Morgantown sandstone occurs in the approximate middle of the Casselman Formation and is often bounded by redbeds; Clarksburg red clay above and the Birmingham shale below (Figure 3). With limited exposures available, Shaffner had estimated the top of the Morgantown sandstone to lie approximately 64 meters (210 feet) below the base of the Pittsburgh Coal. Prior to the construction of the current interchange, Shaffner (1958) documented an occurrence of the Morgantown sandstone located just north of this outcrop along the original alignment of U.S. Route 119. In addition, he found a highly weathered outcrop of the Ames limestone along the original section of US. Route 22 (now Old William Penn Highway) near the current Chestnut Ridge Golf Club (400 m from the interchange) consisting of weathered limestone nodules 6 to 8 inches in diameter. This supports the notion that this outcrop is the Morgantown sandstone.

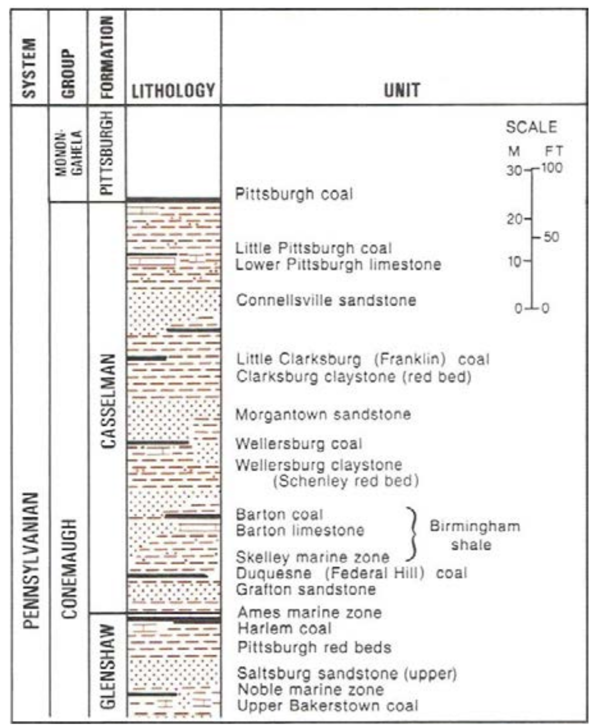

Figure 3. Simplified stratigraphic column for the Casselman Formation (Conemaugh Group) modified from Edmunds et al. (1999)

Three exploration drill holes from the archives of the Rochester & Pittsburgh Coal Company, IND-D-HELN-B0009, IND-D-HELN-B0011 and IND-D-HELN-B0012 show the total thickness of the Conemaugh to be approximately 222 meters (730 feet) with the Glenshaw approximately 375 thick and the overlying Casselman approximately 108 meters (355 feet) thick. These holes lie between approximately 1.5 kilometers (5,000 feet) and 3 kilometers (10,000 feet) from the outcrop. Two of the drill holes (B009 and B0011) were advanced through strata starting above the Pittsburgh Coal in the overlying Monongahela Group and extending through the Lower Kittanning Coal in the underlying Allegheny Group. The third drill hole, B0012, was advanced through strata starting at what is correlated to the Connellsville sandstone. These drill hole logs are included in Appendix (digital guidebook).

The lack of lateral continuity of lithic units comprising the Casselman Formation is illustrated by these drill holes. Correlations among the drill holes indicate that the top of the Morgantown Sandstone lies approximately 60 meters (200 feet) below the base of the Pittsburgh Coal. The base of the Morgantown sandstone lies approximately 40 meters (130 feet) above the top of the Ames limestone. However, 5 meters (18 feet) of sandstone, correlated to the Morgantown sandstone is present at one location, bounded by red shale, whereas at a second location, the sandstone is not present, but its horizon is marked by 11 meters (36 feet) of sandy shale overlain by red shale, and underlain by the fossiliferous dark gray shale of the Skelley marine zone. At a distance of 27 meters (90 feet) above the Ames Limestone in the third hole there is no sandstone or sandy shale, but 9 meters (30 feet) of light grayish green shale bounded by red shale. In this same hole, at a height of approximately 45 meters (150 feet) above the Ames Limestone, there is 6 meters (20 feet) of light grayish green sandy fireclay, directly overlain by the Connellsville sandstone. The intervening strata are composed of shale and thin limestone. This may represent a merging of the Connellsville Sandstone with the representative of the Morgantown Sandstone horizon at this location. At the location where the Skelley marine zone is present there is no Ames fossil zone identified; however, the underlying Harlem coal is present, which is not present in the other holes.

Facies descriptions and interpretations

Primary lithofacies observed were described according to the scheme of Miall (1981), which provides standardized descriptions for commonly encountered fluvial lithologies. Overall, there are seven basic facies that occur throughout the study area (Table 1). The outcrops display a narrow grain size distribution, with nearly all sediment between the silt and medium sand size classes (save for a few, local gravels). The sands predominate over the silts. Horizontal, planar internal stratification (with minor ripple cross-lamination) is most common, with trough cross-stratification also common. In the sand-sized fraction, there is a broad degree of similarity in texture and color throughout the exposures. These sands are strongly quartzose, with some dark clasts, possibly tourmaline, also present (Orsborn, 2015). Mica content is variable, ranging from minor, small clasts to large flecks. The color is consistently medium-light gray with a slight light brown hue (unweathered). In some places, it simply appears to be a sandier gradation of Fl, while in other locations it shows distinct ripple lamination. Contorted strata, overturned strata, and flame structures were observed in this facies and Fl.

Gravels, which are rare on the south-facing outcrop, are common in some particular sand bodies along other exposures. Gravels consist almost entirely of mud rip-up clasts, save for rare isolated pebble conglomerate bodies. Diagenetic siderite concretions are commonly present. There is little evidence of widespread pedogenesis or biological activity in the outcrops examined, aside from some thin (< 1 cm) stringers of woody material/low-grade coal. Small occurrences of bioturbated claystone and coal were observed at the lowest stratigraphic position in the study.

Table 1. Codes and descriptions for basic lithofacies observed in the study (modified from Miall, 1981)

FACIES CODE	LITHOFACIES	SEDIMENTARY STRUCTURES
Fl	Silt (>50%), with some fine sand	Fine lamination (some heterolithic), small ripple cross lamination
Shr	Sand (>50%), fine to med with prominent silt	Horizontal lamination or ripple cross lamination
Fm	Mud	Massive, often with evidence of deformation
Shm	Sand (>80%), fine to coarse, with minor silt	Internal planar, horizontal lamination, sometimes with only thin, discontinuous silt (some appear internally massive on weathered surfaces)
Se	Sand, fine to coarse with intraclasts	Crude cross-bedding and/or massive appearance
St	Sand, fine to coarse	Solitary or grouped trough cross-beds
Sl	Sand, fine	Low angle (<10^{o}) internal cross-stratification

Facies Fl (fine-grained, laminated)

A common unit observed, particularly along the south-facing outcrop, is a dark gray micaceous siltstone that is variably heterolithic, and commonly exhibits (internal) planar to wavy (small ripple) lamination that alternates between the dominant, dark silt size fraction and buff-colored sands of fine to medium size. This facies is designated as 'Fl' (Figure 4.A). In many places this facies is in contact with sandier zones that exhibit similar planar stratification. Disconformities and subtle angular discordances are not uncommon within this facies, particularly at contacts with sandier laminae. Identification of fine, millimeter-scale structures was greatly aided by the remnant blast drill holes used to excavate the cut. This facies commonly occurs in sets that are thick (some exceeding 2 meters) and laterally continuous over tens of meters. Facies Fl is most extensive in the south-facing outcrop in the first 60 meters of the section (much of the rest of the outcrop has a distinctly sandier character). There is little bioturbation or evidence of pedogenesis.

Facies Fl is interpreted as originating from overbank processes. Similar facies have been ascribed to floodplain deposition (see Bridge and Demicco, 2008) and passive fill of abandoned channels associated with overbank sedimentation (Li and Bhattacharya, 2014). Geometry of the body can help differentiate specific sub-environment (see Table 2).

Facies Shr (sandy, horizontal to ripple-laminated)

Facies Fl is closely associated in space/arrangement with a sandier unit (Shr) that exhibits horizontal planar lamination and some current-ripple lamination (Figure 4.B). These sandier bodies may represent particularly high-amplitude flood events (i.e. sheet floods), also in the overbank/floodplain environment. Facies Fl and Shr feather out and are often cut into by channel elements. The micaceous silt fraction was likely deposited from suspension when deeper water conditions prevailed or late in a waning flow, while the fine sands likely represent traction transport produced during strong flows. Current-ripple lamination and preserved 2-D ripples are further evidence that traction transport was occurring.

Soft-sediment deformation is commonly observed in both Fl and Shr, likely the result of strong shear stresses induced by traction currents as overlying sands were laid down. Sometimes this occurs under basal channel scour, such as in the outcrop along US-119. Along the exit ramp, it occurs under trough and low-angle cross-beds (see below).

In these facies, there is a general lack of root casts, bioturbation, and plant fossils with the exception of limited zones of carbonified woody material and thin, low-grade coals. A paucity of pedogenic features indicates soil-forming processes were inhibited by relatively frequent delivery of sediment from active channels. Unfavorable climate conditions for pedogenesis may have also prevailed during this time, although typical arid climate indicators such as desiccation cracks, gypsum pseudomorphs, or adhesion ripples associated with aeolian transport were not observed (Wilson et al., 2014).

Facies Fm (massive mudstone/siltstone)

Another finer-grained facies present is a dark gray siltstone (in places, mudstone) that often does not display evident stratification or significant sand (in a few places it does resemble folded Fl). This facies often possesses an irregular, almost hackly appearance and displays jointed surfaces. It is locally fissile. It most commonly occurs in irregular tabular bodies up to 2 meters in thickness, but is also present in a large lobe and a ribbon body. It almost ubiquitously underlies sandstone deposits of facies Shm and St. This facies is designated as 'Fm' and is most common on the south-facing 'exit ramp' outcrop. (Figure 4.C)

The irregular surfaces of Fm, some perhaps accentuated by late diagenetic jointing, may indicate syndepositional or very early diagenetic deformation. In several outcrops, the beds are noticeably tilted and contain contorted beds. Its occurrence under channel sandstone facies and its geometric relation to channel forms suggests a relation to channel deposition. It is easily denoted (top and bottom) by bounding surfaces, implying three possible scenarios: 1) shear deformation of saturated Fl/Shr facies owing to precipitation and stresses of channel incision (or sheet flows where it occurs under Shr), 2) deposition at the bottom of an (initially) abandoned channel (Li and Battacharya, 2014) or 3) deposition during later-stage channel abandonment. For most of the Fm facies (occurring as irregular tabular bodies) we interpret scenario 1. An extreme case of scenario 2 occurs at the east end of the exit ramp, where a complete channel body is filled with Fm, forming a mud plug (Figure 5). This body is a "ribbon", possessing a width of 60 m and a maximum thickness of 4 m, yielding a W/T = 15 (Gibling, 2006). If the facies is more linear, or perhaps, slightly concave-down in character, scenario 3 is interpreted.

Facies Shm (very sandy, horizontal to faint lamination)

As sand content is further increased and silt becomes a minor component, the laminations become more linear and, in some cases, difficult to distinguish. These overwhelmingly sandy facies are denoted 'Shm' (Figure 4.D). These are often bounded by erosional surfaces and comprise sand bodies a few tens of meters long. This facies is the second most common facies observed (after Shr) and generally occurs in sand bodies bounded by high-order erosional surfaces (often concave-up).

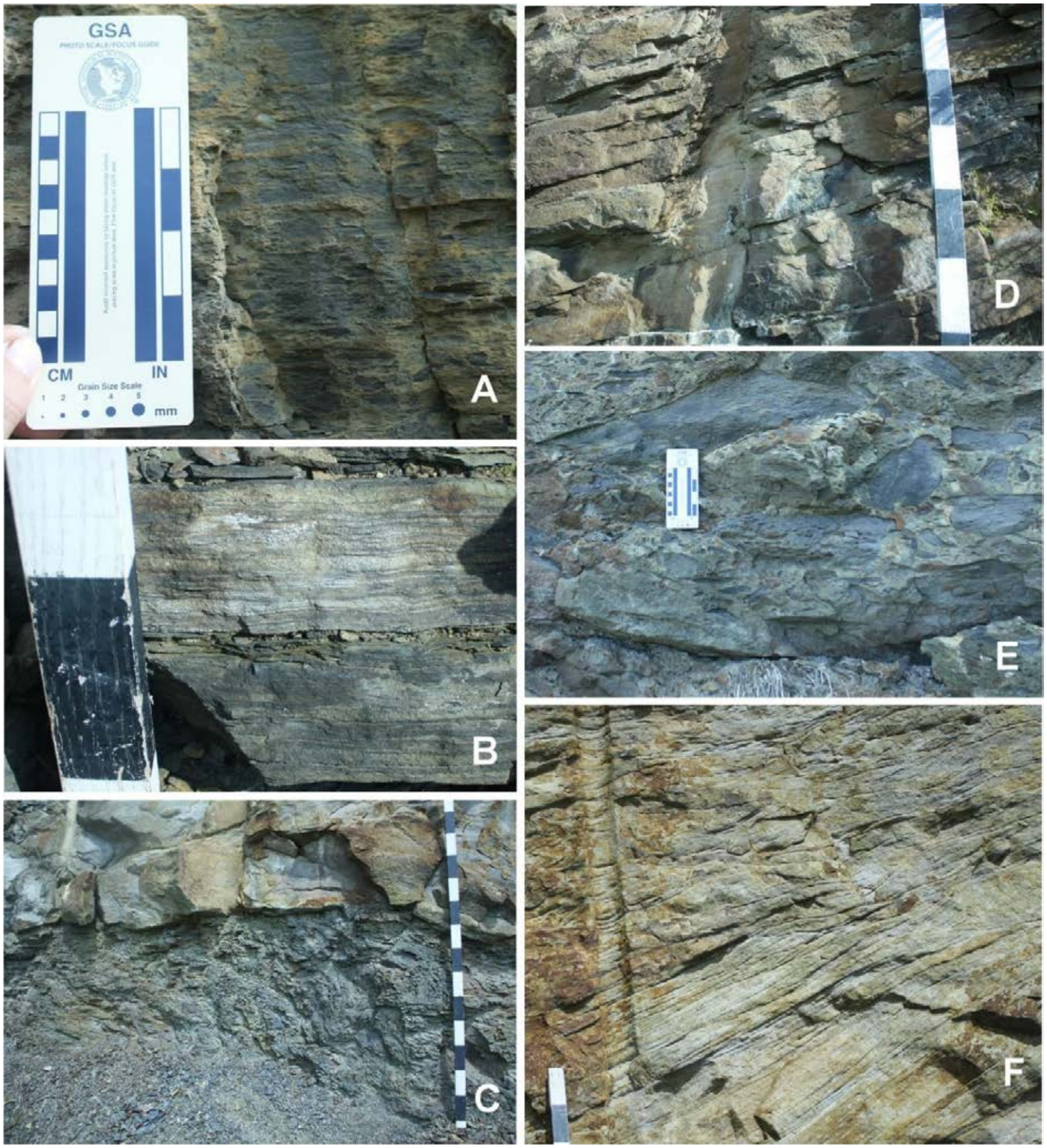

Figure 4. Examples of the primary facies observed: A) Fl, B) Shr, C) Fm, D) Shm, E) Se, and F) St (composed of superposed trough cross-bed sets on larger-scale inclined strata). Jacob's staff marked in decimeter increments.

Facies Shm is prominent in many sand bodies that are bounded by concave-up erosional surfaces. As such, we interpret these as channel bodies. In many of these sand bodies, there is prominent large-scale stratification (decimeter-scale), with the cumulative thickness of the sets generally 1-2 m. Beds are often boundary conformable, or nearly so. Dips are overwhelmingly to the west. Superposed on the larger-scale stratification is internal (mm-cm scale) horizontal stratification and, possibly, some trough cross-bedding.

These channel-fill bodies represent accretion, with several possible styles: vertical, downstream, or lateral. Li et al., (2015) interpreted similar deposits as resulting from channel filling after abandonment. Overbank sedimentation from active channels would supply sediment. Others have interpreted similar boundary-conformable arrangements as related to downstream unit-bar migration (e.g. Lowe and Arnott, 2015). Neither of these interpretations, nor the bulk of the visible outcrop evidence suggest widespread occurrence of lateral accretion elements, such as point bars. Weathering and relative height on the outcrop may be obscuring some of finer-scale features and important diagnostics (see example from Morrison Formation in Miall, 1996).

In some cases, thin (dm-scale) bodies of sand extend laterally from the channel forms. These are interpreted as levee deposits (Gibling, 2006). They are typically composed of Shm, often with only faintly observable silt stringers.

Facies Se (sandy scours with crude bedding and intraclasts)

Many of the sandstones observed along US-119 (the west-facing outcrop) display prominent mud rip-up clasts forming a matrix-supported conglomerate. A number of these rip-ups are composed of facies Fl. Most of the units bearing intraclasts show little/no readily apparent signs of stratification within the sandstone, although the intraclasts do exhibit a preferred long-axis orientation. This facies is designated as 'Se' (Figure 4.E). The geometry of the bodies containing Se is somewhat variable. Along US-119, a concave-up base is formed with lateral tapering with a single channel containing most of the Se facies there. Along the south-facing outcrop, bodies of Se have steep margins that seem to feather into laminated and siltier Shr facies.

Facies Se indicates rapid, sediment-choked flow (Hjellbakk, 1997). An apparent ball-and-pillow structure along US-119 and a sandy, almost massive nature, suggest rapid deposition. Rip-up conglomerates often lie near the base and appear to be sourced from immediately underlying Shm and Fl facies. This denotes avulsion into overbank environments. This close relation to overbank facies, the rather limited overall appearance of Se, and its apparent feathering into siltier Shr facies implies possible crevasse and splay processes.

Facies St (sandy, trough cross-bedding)

Other sandstones, generally sans intraclasts, are cross-bedded (internally). The predominant internally cross-bedded facies is designated as 'St' (Figure 4.F). Larger-scale bedding, several meters in thickness, frequently occurs with nested internal stratification (generally, trough and horizontal). These larger-scale strata are strongly unidirectional and most are oriented broadly to the west. In at least one location (along US-119), festoon trough cross-bedding of sands is visible with set thicknesses of 0.5 - 1 m (Figure 6).

Facies St is interpreted as representing subaqueous dune migration. This likely would occur as a result of lower flow regime currents of moderate depth (Lowe and Arnott, 2016). St was observed from several vantage points. Along the south-facing outcrop, several sets with high-angle dipping beds indicate paleoflow was broadly to the west during that cycle. In other places decimeter-scale sets of trough cross-beds were superposed with oblique flow onto larger-scale, westward dipping accretion surfaces. This one of the few visible indications that compound bar migration was occurring producing lateral or downstream accretion (see Gibling, 2006). Rotating perspective by 110° and looking along the west-facing outcrop, festoon trough cross-bedding indicates a roughly flow-parallel view into the outcrop (east-west paleoflow) related to sinuous mesoform migration (Figure 6).

Figure 5. Abandoned channel mud plug observed at the east end of the US-22 exit ramp. This is a "ribbon" channel body.

Figure 6. Prominent festoon cross-bedding along US-119.

Facies Sl (sandy, low-angle cross-bedding)

Another cross-bedded sandstone is denoted 'Sl' when exhibiting low-angle (< 10°) cross-bedding (Figure 7.A). This facies is not as common as those described above, but is not uncommon along the south-facing cut.

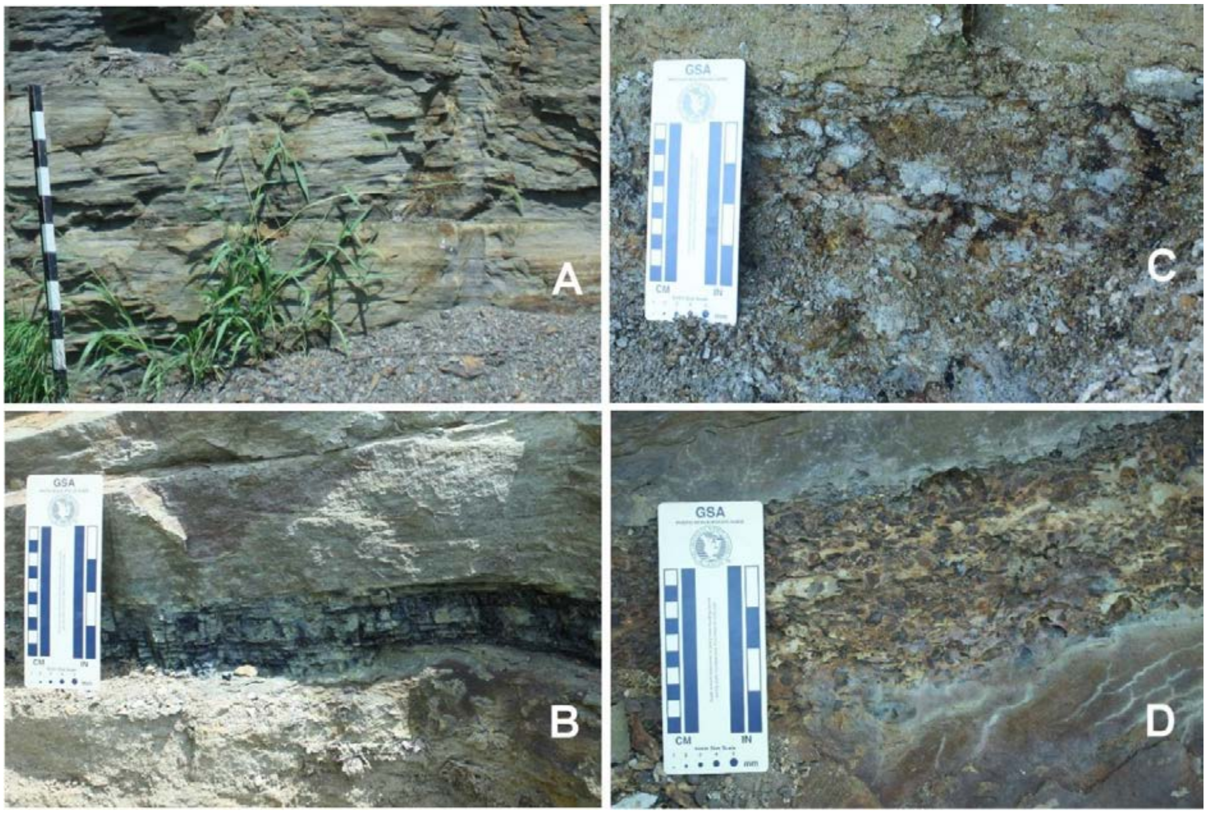

Figure 7. Secondary facies observed in the study area: A) Sl, B) coal, C) bioturbated claystone with apparent carbonized rootlets, and D) ferruginized conglomerate. Note that B-D were found near the bottom of the US-119 outcrop.

In a few places, silt-draped sandy laminae dipped sufficiently (< 10°) to warrant recognition of facies Sl. One interpretation for this facies is antidune/standing wave deposition (Fielding, 2006). This may have occurred on the floodplain with shallow depths promoting upper flow regime conditions, possibly during splaying (Wakelin-King and Webb, 2007). Contorted beds of Shr have been found under this deposit, suggesting rapid deposition and strong shear (Figure 8).

Local coal and claystone

At the lowest stratigraphic position of the pilot study, a 5 cm-thick coal bed was observed (Figure 7.B). In similar position several meters away was a bioturbated gray claystone (Figure 7.C). Just above these was a ferruginized pebble conglomerate. These were unique in that no similar units were found in the overlying 10-meters of sandstone and siltstones (Figure 7.D).

Near the bottom of the succession claystone and a thin coal were observed that suggest a different setting than that portrayed in the overlying sediments if, of course, these deposits are indicative of those in the subsurface. This could record a different fluvial/hydrogeologic regime that favored longer retention of near-surface water and/or a shift in paleoclimate.

Architectural elements:

All of the facies described above occur in association (except the basal coal and claystone). These facies can be further interpreted by recognizing “architectural elements” that “build” the overall system (see Miall, 1996). In this preliminary study, 5 elements were recognized (see Table 2). A typical section is annotated with its interpretation in Figure 9. A corresponding vertical log is provided in Figure 10.

Figure 8. Soft-sediment deformation showing internally contorted strata and overturning. Note that local shear would have been broadly toward the west (left on photo).

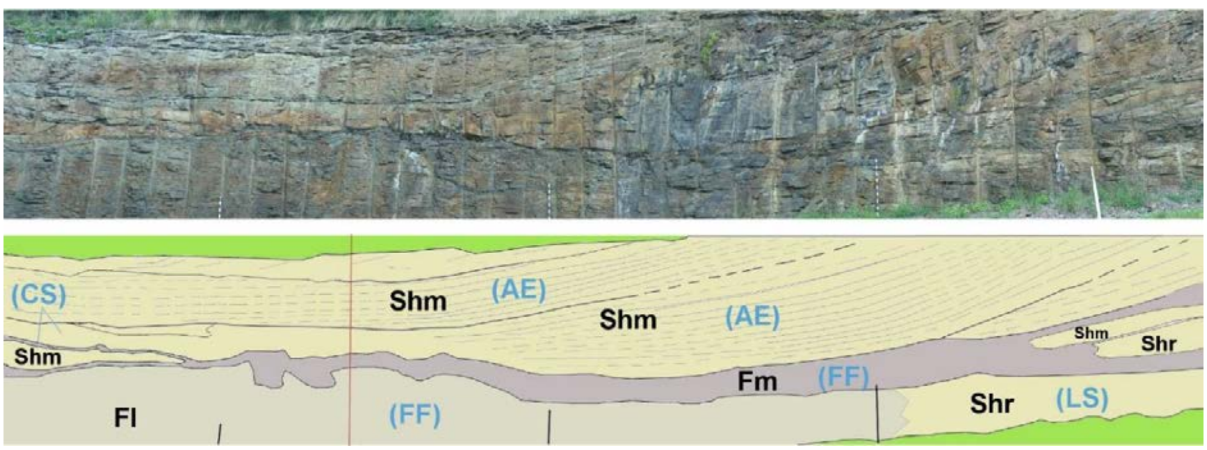

Figure 9. Photo of a section of the south-facing outcrop (top) with interpretation of the lateral profile (bottom). The staffs are 10 m apart. Lithofacies are denoted in black and architectural elements are in blue and parentheses (see Table 2 for element interpretations). The vertical red line denotes the location for the vertical log in Figure 10.

In the absence of other distinguishing criteria, or for simple channel fills, the channel element (CH) is invoked. A prominent CH element is noted at the extreme east end of the exit ramp and is interpreted as an abandoned channel fill (see Figure 5). It possesses a diagnostic concave-up basal surface, infill with muddy sediment (Fm), and lateral pinch-out. The accretion element (AE) is a more specific interpretation of channel deposits and filling. With further detailed observations these may be broken down into vertical (often sandy bedforms), lateral, or downstream accretion elements (Miall, 1996).

The laminated sand sheet (LS), floodplain fines (FF), and crevasse splay (CS) elements are associated with overbank processes (at least relative to the trunk channel).

Table 2. Summary of lithofacies interpretations and architectural elements observed in the study

LITHO-FACIES	INTERPRETATION	ARCHITECTURAL ELEMENT(S)	COMMENTS	REFERENCE(S)
St	Within-channel migration of mesoforms (e.g. dunes)	AE (accretion element)	Generally observed on south-facing outcrop superposed with larger dipping surfaces. Strikes of set surfaces variable	Lowe & Arnott, 2016 Miall, 1996
Shr	Related to overbank traction transport and sheet flooding. Lower flow regime	LS (laminated sand sheet)	Second most common facies. Laterally extensive/unbounded geometry. Soft-sed deformation common	Bridge & Demicco, 2008 Wilson et al., 2014
Shm	Channel belt deposition by accretion	AE (accretion element)	Most common facies on south-facing outcrop. Bounded by concave-up basal surfaces. Note: some Shm are levee deps., denoted as CS elements	Li et al., 2015 Lowe & Arnott, 2016
Sl	Overbank, related to shallow depth promoted upper flow regime and antidune migration	LS (laminated sand sheet)	Grades from Shr. Often overlies soft-sediment deformation	Fielding, 2006 Wakelin-King & Webb, 2007
Se	Sediment dumping in channels. Scours due to avulsion (including crevasse channel cut)	CS (crevasse splay element) CH (channel element)	Intraclastic mud rip-ups and concave-up bases. Frequently exhibits steep margins that interfinger with Shr	Hjellbakk, 1997
Fl	Overbank (floodplain) primarily suspension	FF (floodplain fines element)	Often associated with Shr and laterally extensive/unbounded	Bridge & Demicco, 2008
Fm	Variously deformed/folded muds from floodplain shear and channel abandonment	FF (floodplain fines element) CH (channel element)	Most form thin (<1 m) irregular tabular bodies under channel sands. Prominent channel fill mud plug	Li & Bhattacharya, 2014

Interpretation of fluvial style

The large majority of sediments preserved in the system display evidence of bedload transport. Paleocurrent indicators observed were strongly unidirectional, particularly for larger-scale accretion surfaces, implying possible low sinuosity. Fluvial mechanics are interpreted here as probably that of a sandy bedload system (*sensu* Galloway and Hobday, 1996). Channel fills are dominantly sandy and floodplain deposits exhibit no/little bioturbation or pedogenesis and are sandy-silty in character. Furthermore, the sandy within-channel deposits volumetrically exceed interpreted overbank deposits. The above evidence suggests a medial position within the fluvial distributary system (Nichols and Fisher, 2007). Overall, the system appears to have been aggradational, with sand-body stacking and little evidence for terracing. Given the lateral extent of the sand bodies, it appears the system possessed a mobile channel belt. Braided, low-sinuosity, and meandering streams can occur in sandy, mobile belts (Gibling, 2006). An apparent lack of lateral accretion sets (epsilon cross-bedding), lack of divergent paleocurrent directions, and lack of oxbows or extensive "stable" floodplain seem to suggest the system was not meandering. Broadly similar architectural styles to those recorded at Blairsville have been observed in systems in which a sandy, braided style was interpreted (e.g. Wilson et al., (2014), Li et al., (2015), Lowe and Arnott (2016)). More observations, including more extensive paleocurrent data, are needed to more definitively elucidate fluvial style in the Blairsville outcrop.

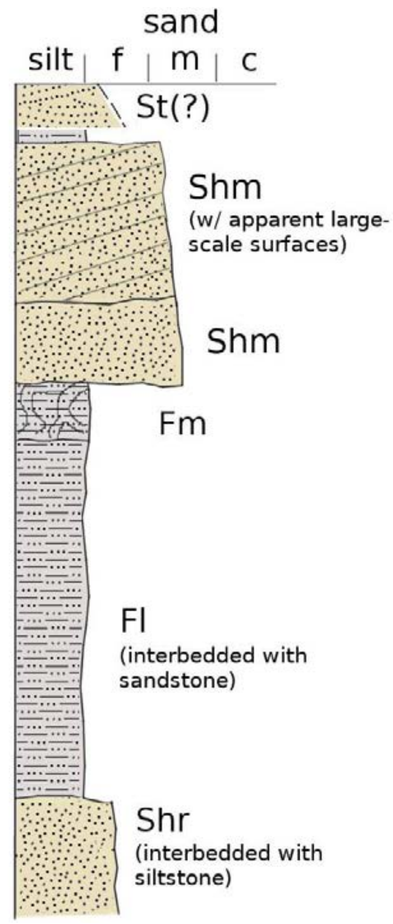

Figure 10. Representative vertical log for the south-facing outcrop. Note that a sandstone unit was present, but not in the outcrop photo in Figure 9.

Gibling (2006), in an exhaustive review of fluvial channel bodies and published literature, asserted that meandering streams appear to represent only a small fraction of styles preserved in the stratigraphic record. Hartley et al. (2015) noted that, in lateral profile, sandy fluvial deposits in the Morrison Formation resembled those often described/modeled as braided in style. This system, however, was exceptionally well-exposed in plan view in the Utah drylands, revealing a meandering planform. The key diagnostic for meandering streams, lateral accretion elements, composed less than 5% of the total outcrop.

The Upper Pennsylvanian Conemaugh Group is generally thought to denote the latter stages of a transition from marginal marine and coastal plain conditions, such as those predominating in the Middle Pennsylvanian, to more alluvial conditions such as those seen in the non-marine Casselman Formation (see Greb et al., 2009). The sandy bedload architecture and aggrading nature of the system preserved near Blairsville indicate at least strong, periodic fluxes of sediment. Whether this was a function of proximity to sediment sources, tectonic forcing, or dry climate (or some combination thereof) remains for further study. A recent study of (lower) Casselman deposits and paleoecology prompted by the discovery of a temnospondyl amphibian (*Fedexia striegeli*, near Pittsburgh) reveals that this period of the Virgilian may have been fairly dry (Berman et al., 2010).

Conclusion

The US-22/US-119 interchange near Blairsville, PA preserves a laterally extensive record of the evolution of a mobile, sandy fluvial belt. The deposits here have been preliminarily assigned to the Morgantown sandstone member of the Casselman Formation. Extensive exposures like those seen at this roadcut offer a 3-D perspective and afford much greater information than data gathered from cores and borehole studies alone. More study of this unit and its correlatives in the region may reveal interesting evidence for basin-scale sedimentation dynamics and possible relations to tectonics, as well as regional paleoclimate.

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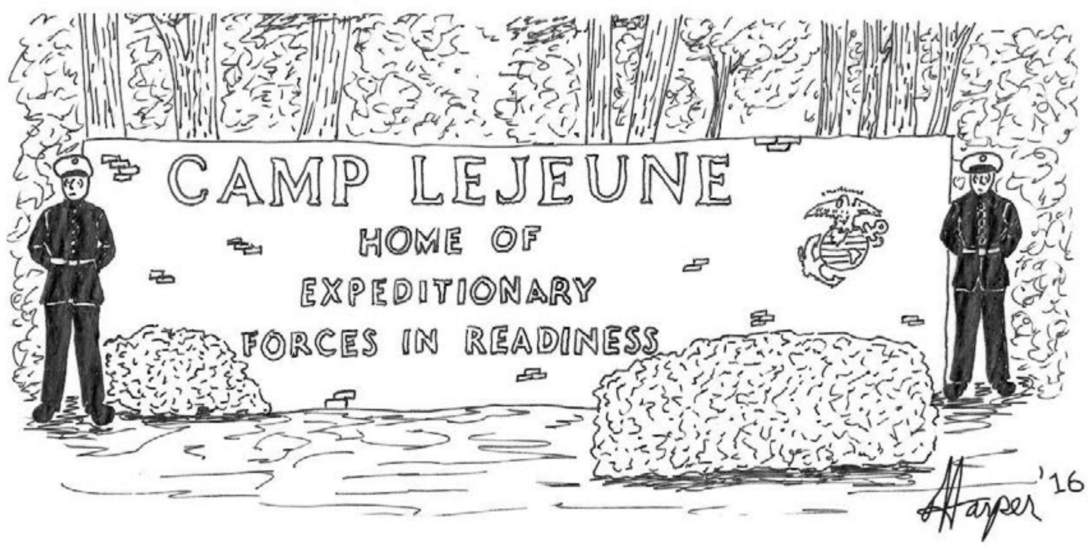
HARPER'S GEOLOGICAL DICTIONARY



MARINE ZONE - a large accumulation of jarheads.

SOME GEOLOGICAL CONSIDERATIONS OF THE MARINE ROCKS OF THE GLENSHAW FORMATION (UPPER PENNSYLVANIAN, CONEMAUGH GROUP)

JOHN A. HARPER, PENNSYLVANIA GEOLOGICAL SURVEY (RETIRED)

The Glenshaw Formation

When the first Geological Survey of Pennsylvania began its work in 1836, the series of rocks we now know as the Conemaugh Group was called the "Lower Barren Coal Measures" because of the perceived lack of economically mineable coal seams. This name remained in place until Platt (1875, p. 8) coined the term "Conemaugh series" to include all the rocks from the base of the coal, which cropped out along the Conemaugh River from Johnstown, Cambria County to Saltsburg, Indiana County. Woolsey (1906) later upgraded the name to Conemaugh Formation, and that nomenclature remained in place throughout most of the Appalachians until Flint (1965) subdivided the interval into a lower Glenshaw Formation, defined by the occurrence of numerous marine units, and an upper Casselman Formation that was mostly devoid of marine rocks. This action upgraded the Conemaugh to a group (although the Pennsylvania Geological Survey had been using that terminology for many years). The top of the marine Ames Limestone is the boundary between the two formations (Figure 1).

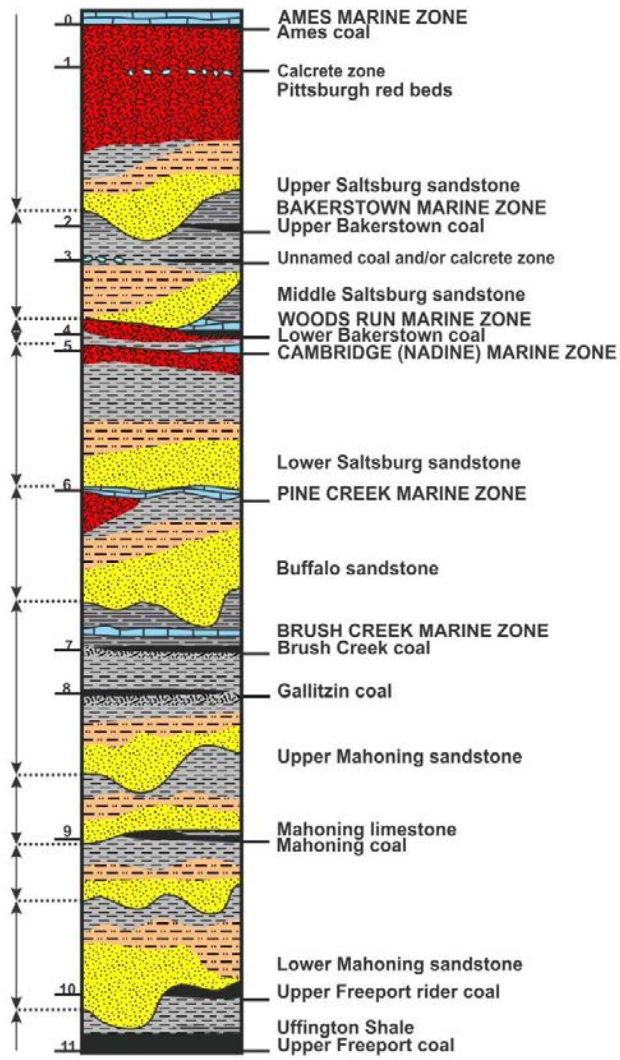


Figure 1. Generalized stratigraphic section of the Glenshaw Formation in western Pennsylvania (based on Busch and Rollins, 1984). The marine zones (in caps) are important marker horizons throughout the formation. Arrows between dashed lines indicate cyclothems based on the classic concept of Wanless and Weller (1932). Numbered intervals indicate transgressive surfaces or climate change surfaces separating 5th-order transgressive-regressive intervals (see Busch and Rollins, 1964).

The Glenshaw Formation in Pennsylvania ranges from about 280 ft (85 m) thick near the Ohio border to more than 400 ft (122 m) thick in Somerset and Cambria counties (Edmunds et al., 1999). It consists primarily of fluvio-deltaic siliciclastics that form a complex mosaic of interfingering channel, levee, overbank, and lacustrine deposits. These nonmarine rocks are punctuated at intervals by thin marine zones of limestone and/or shale (Figure 1) that record six separate marine incursions of an epeiric sea that transgressed from the Midcontinent, probably through a seaway in southern Ohio and Kentucky (Donahue and Rollins, 1974a), onto a shelf formed by the detrital slope of the Appalachian highlands to the east during the Missourian through early Virgillian (late Westphalian D through Middle Stephanian global stages) (Heckel et al., 1998). The Glenshaw Formation contains few economically and stratigraphically important coals, but it makes up for that lack by the presence of the marine limestones, which have been used as key beds in physical (and temporal) correlation of outcrops and cores across western Pennsylvania and adjacent states. Despite a maximum thickness of only 1 to 3 ft (0.3-0.9 m), they are laterally extensive, and are known from western Pennsylvania, eastern Ohio, northern West Virginia, western Maryland, and even eastern Kentucky (Chesnut, 1981) (Figure 2). Two of the marine units, the Brush Creek and the Ames, tend to have the most continuous distribution of any sedimentary sequence within the Glenshaw. Because of their regional extent, unique lithologies, and fossil faunas, they are important marker beds for stratigraphic correlations within the Upper Pennsylvanian Series.

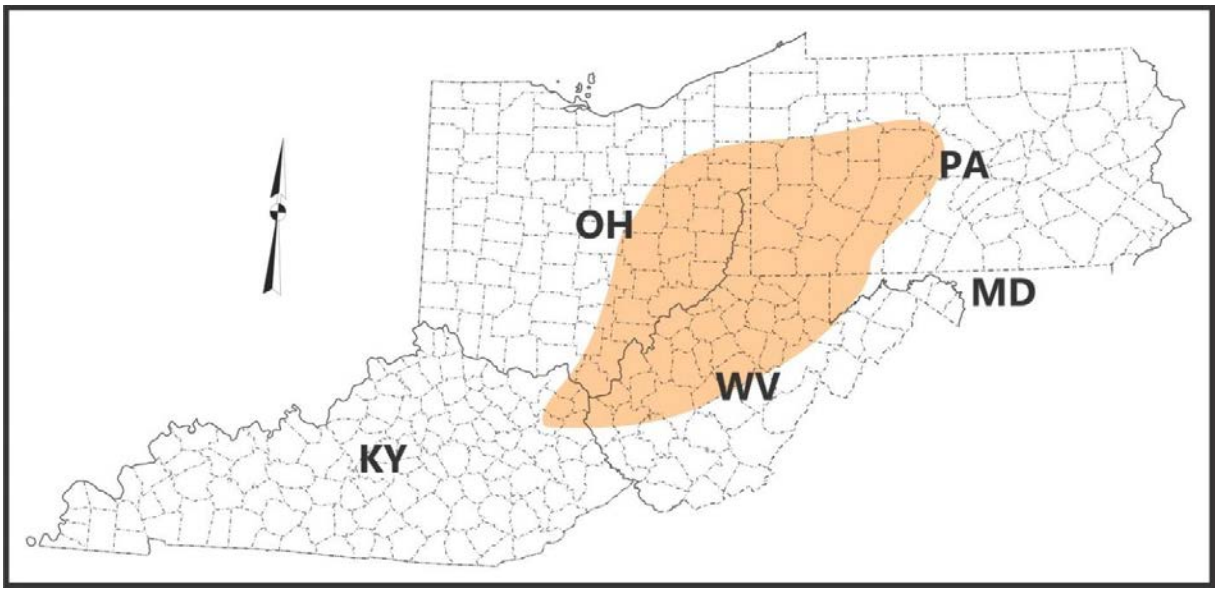


Figure 2. The sand-colored area denotes the approximate extent of the Glenshaw depositional basin (based on Busch and Rollins, 1984, and Martino, 2004).

Glenshaw Cyclothems: Allocyclicity versus Autocyclicity

Ever since the early 1930s, geologists have recognized cycles of deposition (cyclothems) throughout the Pennsylvanian strata of North America. Figure 3 illustrates an "ideal cyclothem" for the Appalachian Basin (compare Figure 3 with the cyclothem sequences in Figure 1). Twenty-six years after Wanless and Weller's classic paper on cyclothems (Wanless and Weller, 1932), Myron Sturgeon recognized eight cycles in the lower half of the Conemaugh Formation in Ohio (Sturgeon, in Sturgeon et al., 1958; Sturgeon and Hoare, 1968). Wanless and Shephard (1936)

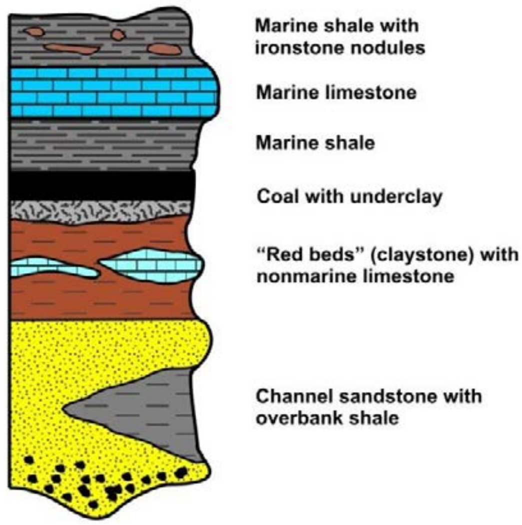


Figure 3. "Ideal cyclothem" for the Glenshaw (based on Donahue and Rollins, 1974a).

attributed these types of cycles to global sea level changes caused by glaciations in the southern hemisphere. Although not generally accepted at first, this concept became the standard explanation for the Appalachian Pennsylvanian cyclothems until the late 1960s and 1970s when work on depositional systems within the basin led some researchers to interpret Appalachian cyclothems as autocyclic, rather than allocyclic (e.g., Beerbower, 1964; Williams, 1964; Ferm, 1975; and others). Competing views of allocyclic versus autocyclic origins for Appalachian cyclothems were batted back and forth throughout the 1980s and 1990s. Busch (1984; also Busch and Rollins, 1984), Busch and West (1987), and Heckel (1995) among others, favored the allocyclic origin. In contrast, Klein and Willard (1989) and Klein and Kupperman (1992), among others, regarded Appalachian-type cyclothems as occurring in response to episodic thrust loading during orogenic events. According to this model, thrust loading caused the foreland basin to become deeper, generating transgressive facies in the basin. Regressive facies resulted when orogenic uplift caused increased sedimentation. More recently, Greb et al. (2008) found that, although glacial eustasy influenced Pennsylvanian deposition across the Appalachian Basin, the depositional cycles were influenced by changing paleoclimate, sediment flux, and changing rates of tectonic accommodation as well. So, the question of whether Pennsylvanian cyclothems are the result of allocyclic or autocyclic influences can be answered simply and succinctly: "yes!"

As marine units situated within a primarily terrestrial succession, the Glenshaw marine zones are valuable in assessing sea level cycles (e.g., Donahue and Rollins, 1974a; Busch and Rollins, 1984) and for use in correlating eustatic events between the Appalachian Basin and Carboniferous basins in Illinois and the Midcontinent (e.g., Heckel et al., 1998; 2011) (see below). Each of the Glenshaw marine intervals represents a sea level rise that inundated the deltaic margin and deposited marine shales and argillaceous limestone on the more typical fluvio-deltaic sandstones, non-calcareous shales, paleosols, and thin coals characteristic of Late Pennsylvanian sedimentation in the Appalachian Basin.

Martino et al. (1996; also Lebold, 2005) considered four of the Glenshaw marine zones, the Brush Creek, Pine Creek, Cambridge (Nadine), and Ames (Figure 1), to be widespread, major transgressions. Such transgressions established a variety of marine facies within the Appalachian Basin, allowing for numerous stratigraphic, sedimentologic, and paleoecologic studies since the late 1960s (Brant, 1971; Donahue et al., 1972; Donahue and Rollins, 1974a; 1974b; Shaak, 1975; Rollins and Donahue, 1975; Carother, 1976; Rollins et al., 1979; Al-Qayim, 1983; Brezinski, 1983; Busch, 1984; Saltsman, 1986; Caudill, 1990; Fahrer, 1996; Martino et al., 1996; Lebold and Kammer, 2006; Klasen, 2007; Heckel et al., 2011; and many others). Although the current stratigraphic framework is based on key beds (laterally persistent coal seams and marine zones), several studies attempted to establish a sequence stratigraphic framework (Martino, 2004; Klasen, 2007).

Glenshaw Marine Zones

Busch (1984) recognized eight marine zones within the Glenshaw Formation in the Appalachian Basin. The lower two of these, apparently marine zones associated with the Upper Freeport and Mahoning cyclothemic sequences (Figure 1), are rarely, if ever, preserved and exposed in Pennsylvania, although they are exposed at places in Kentucky, Ohio, and West Virginia. Busch (1984) and Shaulis (1993) recognized a shale bearing lingulid brachiopods (brackish to marine) and plant fossils overlying the Mahoning coal near Lavansville, Somerset County. Busch (1984) referred to this as the "Uffington Shale". The type Uffington of West Virginia, however, is nonmarine and, where exposed, lies between the Upper Freeport coal and Lower Mahoning sandstone (Figure 1). The confusion results from a series of repeated misinterpretations: 1) Stevenson (1871) described, but did not name, a dark-colored, fine-grained, argillaceous shale containing marine fossils, identified by F. B. Meek, overlying the Upper Freeport coal; 2) White (1903), in describing and naming the Uffington, reported Meek's list of invertebrate fossils, even though he actually found only plant fossils in the formation, implying that Stevenson's shale and the Uffington were one and the same; and 3) until 1917, some authors (e.g., Raymond, 1910 and 1911) simply continued to consider the Uffington to be marine. Although Price (1917; also Hennen and Gawthrop, 1917) confirmed that the type Uffington was nonmarine, and that Stevenson's (1871) marine zone was actually Brush Creek, erroneous reports of the Uffington being a marine zone continued (e.g., Busch, 1984). Busch also made the error of placing the Uffington above the Mahoning coal, rather than above the Upper Freeport coal. If a marine zone actually associated with the Upper Freeport coal does exist, it apparently does not occur in Pennsylvania, and neither this nor the Mahoning marine zone will be addressed further here. The remaining six marine zones are widespread and typically preserved in many outcrops. In western Pennsylvania, these include, in ascending order, the Brush Creek, Pine Creek, Nadine, Woods Run, Bakerstown, and Ames.

Brush Creek Marine Zone

White (1878) named the Brush Creek limestone for a sequence of marine rocks exposed along Brush Creek in Cranberry Township, Butler County. He described it as:

> At times it is a black calcareous shale, 4 to 5 feet thick, and again we see it a very compact limestone, 1 to 2 feet thick. It often has a peculiar slaty and arenaceous aspect, and sometimes contains so much iron as to be used as an ore. It is usually fossiliferous, and the following species have been seen in it: *Chonetes mesoloba, Spirifer cameratus, Edmondia Aspenwalensis, Bellerophon montfortianus, Productus Prattenanus, P. longispinus, Nautilus occidentalus, and Lophophyllum proliferum*. (White, 1878, p. 34)

The names of those fossils have changed over the years, but all are recognizable to anyone who has collected Pennsylvanian fossils in the Appalachians. Plates 1 to 3 illustrate many of the marine invertebrate fossils that can be found in the Brush Creek and other Glenshaw marine zones in Pennsylvania. Busch (1984) described the Brush Creek as primarily black, gray, or olive marine shales containing common fossils and ironstone nodules. There is also a highly fossiliferous, dark gray, argillaceous wackestone-packstone facies present within the shales at many localities, and in other localities the limestone is present but the marine shales are not.

For many years, any Glenshaw marine limestone sandwiched between dark-colored marine shales was considered to be the Brush Creek. Several classic localities in Allegheny (Sewickley locality), Armstrong (Cadet Restaurant locality), and Indiana (Shelocta locality) counties provided great fossil collecting opportunities for both weekend paleontologists and students anxious to write a Master's or Doctoral thesis on any number of paleobiological or paleoecological topics. Alas, many of these sites are now known to be Pine Creek localities, making the data and conclusions of those theses suspect. Some of the sites are now off limits, and others have been destroyed. In addition, certain localities in Fayette and Somerset counties considered Brush Creek because of appearance and fossil content (Piccolomini Strip Mine locality in Fayette County; Ursina locality in Somerset County) turned out to be Woods Run instead. This leads to the inevitable conclusion that, just because it looks like a duck, walks like a duck, and quacks like a duck doesn't mean it's a duck! Other "Brush Creek" localities (e.g., Donahoe and Youngwood in Westmoreland County) will remain Brush Creek until proven otherwise.

Pine Creek Marine Zone:

White (1878) named the Pine Creek limestone for exposures on the hill between Gourdhead Run and Pine Creek at Allison Park, Hampton Township, Allegheny County. The limestone was found on the property of J. A. Herron, lying 162.5 feet above Pine Creek (White, 1878, p. 161) (Figure 4). Some workers (e.g., Busch, 1984) and at least one website (Evans, 2003) mistakenly cited a classic exposure of the limestone on PA Route 8 in Etna, about 5 miles south of Allison Park, as the type locality, but White (1878) was quite specific.

The Pine Creek is a dark gray, argillaceous and arenaceous, fossiliferous wackestone that often carries phosphate granules (Busch, 1984). Like the Brush Creek, it commonly is sandwiched between dark gray or black marine shales carrying a well-preserved fauna. To the east, the Pine Creek grades into a dark gray, somewhat oolitic calcilutite surrounded by buff to reddish-colored clay shales with a few marine fossils. This phase of the Pine Creek marine zone is referred to as the Meyersdale red beds.

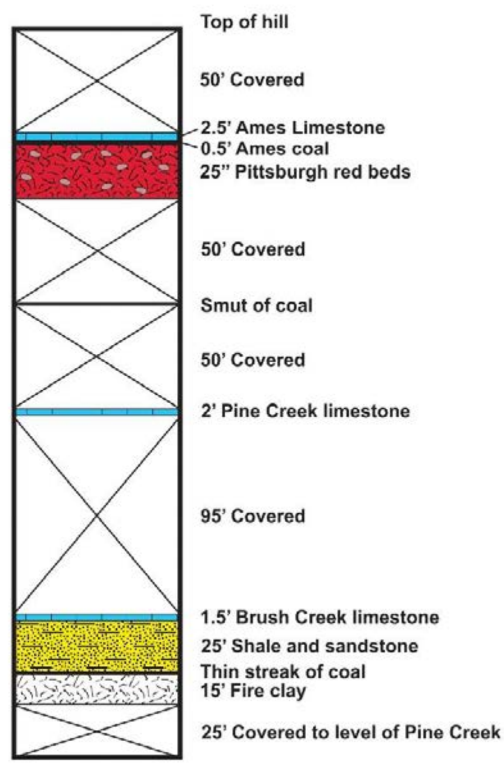


Figure 4. I. C. White's type section of the Pine Creek limestone near Allison Park, Allegheny County (modified from White, 1878).

The Pine Creek is also well known for including some large biogenic "mounds" in the New Kensington, Westmoreland County area, the Sewickley "Brush Creek" locality in Allegheny County (Figure 5A), and near Glouster, Ohio (Carothers, 1974a, 1974b, 1974c; Norton, 1974a). The lithology of the Pine Creek limestone within each mound is very similar to the intermound limestone beds (Figure 5B), except for vertical, bifurcating burrows in the central part of the mound. Carothers found the burrows in thin section were filled with either: 1) fossil fragments having a micritic or spar cement and 20 to 3 percent clay and silt-sized quartz; or 2) a drusy calcite fill with a micrite boundary separating the burrowed and unburrowed portions of the limestone. Both the unburrowed mound limestone and the intermound limestone have high clay and silt contents and contain fossils of foraminiferans, bryozoans, brachiopods, gastropods, and crinoids. The mounds typically are ice cream cone-shaped (Figure 5B), and display multiple truncation surfaces (compare Figures 5A and B). The highest truncation surface can be traced laterally into the intermound limestone throughout the outcrop. Carothers (1974c) and Norton (1974b) provided conflicting interpretations of the depositional environments for the mounds, but agreed that the burrows probably resulted from the activities of burrowing crustaceans.

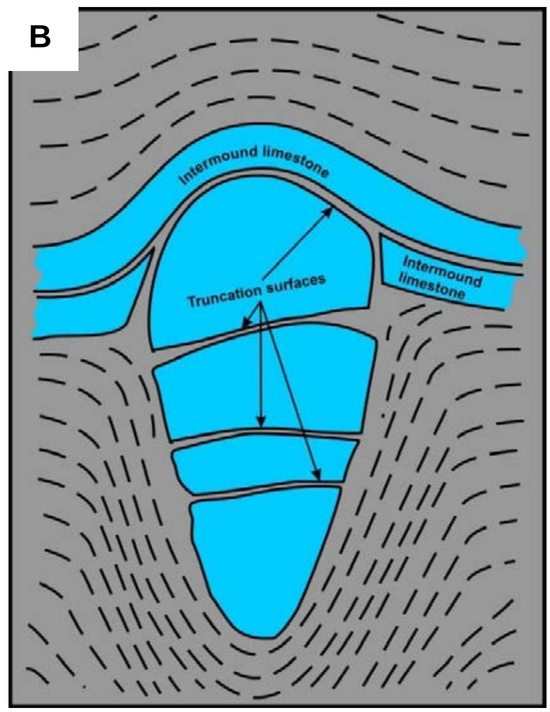


Figure 5. Pine Creek mounds. A – Photo of the mound at the Sewickley, Allegheny County, locality. This mound is now covered by talus and vegetation. B – Morphology of a typical mound (modified from Carothers, 1974c). The mound on which this was based was 10 ft (3 m) tall and consisted of a gray limestone cut by four truncation surfaces.

Cambridge (Nadine) Marine Zone

Andrews (1873) named the Cambridge Limestone, presumably for the abundant and excellent exposures in the Cambridge, Guernsey County, Ohio, area. For many decades, the Cambridge and Pine Creek were considered to be correlative (see below). Burke (1958) named the Nadine Limestone for a relatively pure, light to dark gray limestone 4 to 15 in (10 to 38 cm) thick that occurs on Allegheny River Boulevard near the intersection with Nadine Road in Allegheny County about 10 mi (16 km) northwest of downtown Pittsburgh. Previously, Johnson (1929) had noted the occurrence of this limestone, which he called the "lower bed" of the Woods Run limestone, in several places around the Pittsburgh area. Busch (1984, p. 34) described the Nadine as a thin, medium gray, crinoidal wackestone-packstone bearing allochthonous phosphate granules and *in situ* phosphate nodules. Olive-colored marine clay shales occurring both above and below the limestone contain bivalve and chonetid brachiopod fossils. Burke (1958) noted the presence of "*Chonetina flemingi plebia*" (now *Chonetinella plebia*), and suggested it was a distinctive brachiopod within the fauna. Sturgeon and Hoare (1968) give the range for this brachiopod in Ohio as Brush Creek to Cambridge, so its presence in the Nadine, previously considered younger than Cambridge, should have been problematic. Now that we know the Nadine and Cambridge are the same marine zone, the brachiopod's presence in the Nadine should be expected.

Woods Run Marine Zone

Raymond (1910) named the Woods Run limestone for a fossiliferous marine limestone lying between the Pine Creek and Ames that, at one time, apparently was well exposed within the channel of Woods Run and along the roads in what is now the Woods Run neighborhood of Pittsburgh about 3 mi (5 km) north of the downtown area. He noted that the few fossils found in the limestone were common but low in diversity, with the horn coral *Lophophyllum* (now called *Stereostylus*) often the only fossil present in the rock.

Almost 50 years later, Burke (1958) named the Carnahan Run Shale for a 5-ft (1.5-m) thick, dark gray, fossiliferous shale cropping out in the vicinity of Carnahan Run, Parks Township, Armstrong County about 0.7 mi (1.1 km) north of the town of North Vandergrift. He stated that it was separated from the Woods Run limestone by 21.5 ft (6.6 m) of reddish-brown shale carrying plant fragments. Wells (1983), however, determined that the Carnahan Run was merely a shale facies of the Woods Run.

Busch (1984) described the Woods Run as an argillaceous, ferruginous wackestone, packstone, or grainstone with occasional phosphate granules and abundant macrofossils and microfossils. Dark gray to dark olive, platy shales with marine fossils commonly overly it. In Allegheny County, the few Woods Run outcrops I've seen were more mudstone than carbonate. In Fayette and Somerset counties, however, it often consists of a well-developed limestone sandwiched between dark colored shales (e.g., the Piccolomini Strip Mine and Ursina localities, respectively). It looks so much like typical Brush Creek that several reports erroneously used that name (Flint, 1965; Donahue et al., 1972) for what are now recognized as Woods Run outcrops.

Bakerstown Marine Zone

The Bakerstown marine zone is one of those anomalous units that went unrecognized for decades. It consists essentially of red, green, or black, platy to fissile shale with siderite nodules and a sparse marine or brackish water fauna (Busch, 1984) that lies above the Upper Bakerstown coal in a few places in western Pennsylvania. There are few or no occurrences of a bedded marine limestone associated with the zone in Pennsylvania, unless they occur in coal cores taken in the westernmost part of the state. The correlative Noble Limestone of Ohio (Murphy and Picking, 1967) is a white to gray, nodular limestone that is interbedded with greenish-gray, calcareous marine shales. In Ohio, the Noble itself grades laterally into a freshwater-to-brackish facies called the Rock Riffle Limestone, and to a calcrete zone called the Ewing Limestone.

Ames Marine Zone

Andrews (1873) named the Ames Limestone for exposures of a fossiliferous limestone, 1 to 5 ft (0.3 to 1.5 m) thick in Ames Township, Athens County, Ohio. This unit was, for many years, called the "crinoidal limestone" because of the abundance of crinoid ossicles, primarily columnals, scattered throughout. The Ames is a greenish-gray, argillaceous wackestone, packstone, or grainstone carrying abundant macrofossils. It is occasionally replaced by a dark gray to black, platy to fissile shale with wackestone nodules and a somewhat sparser fauna, but overall it is the most recognizable marine unit in the Glenshaw Formation. The Ames is, arguably, the most fossiliferous stratum in the Upper Pennsylvanian of western Pennsylvania. It has provided a plethora of familiar forms representative of most of the Late Paleozoic invertebrate phyla, as well as the occasional fish fossils (mostly "shark" teeth) and some species never before reported from Pennsylvania (Harper, 1986). A locality in northeastern Allegheny County, along PA Route 28 (the Allegheny Valley Expressway – Figure 6), in particular, provides a wealth of invertebrate fossils collected in a relatively short time (Harper, 1989).

Figure 6. Outcrop of Ames Limestone and Pittsburgh red beds along PA Route 28 near Creighton, Allegheny County.

The Ames has often been correlated with the Mill Creek Limestone of the anthracite area of northeastern Pennsylvania (e.g., White, 1903; Chow, 1951; Busch, 1984), but more recent analyses of the Mill Creek's conodont fauna indicates it is actually correlative with the Bakerstown/Noble marine zone (Merrill and Wentland, 1994; Heckel et al., 2011) (see below).

A Note on Casselman Formation Marine Zones

Two other marine zones occur above the Ames in the Appalachian Basin, within the lower Casselman Formation. The lower Gaysport marine zone does not occur in Pennsylvania, unless it is found in coal cores in the westernmost part of the state, but it probably correlates to the nonmarine Duquesne shale of the Pittsburgh area. The upper Skelley marine zone occurs in the Pittsburgh area as a brackish to marginal marine zone within the upper third of the Birmingham shale. Raymond (1909) first reported this from the railroad tracks below Kennywood Amusement Park in West Mifflin, Allegheny County, about 9 mi (14.5 km) southeast of downtown Pittsburgh. He found crinoid columnals, brachiopods, bivalves, gastropods, and a cephalopod at this locality, and mentioned the presence of fossils in this interval in several localities around the city, with the most common and best preserved at Kennywood, across the Monongahela River in East Pittsburgh, and farther east in Wilmerding. Brachiopods have also been found in the Birmingham shale in Washington County and in an outcrop adjacent to the Armstrong Tunnels beneath Duquesne University in Pittsburgh (H. B. Rollins, personal comm., 1970s). Price (1970) documented marine fossils in what he called the "green siltstone facies" at many localities in the Birmingham shale. He interpreted the fauna as representing a restricted marine environment and noted that, although he did not find the “green siltstone facies” at all of the localities he visited, he believed that the restricted marine horizon was present over the entire study area.

Problems and Resolutions of Identity and Correlation

Of the six widespread Glenshaw marine units (Figure 1), the Brush Creek and Ames are the most recognizable in Pennsylvania, although, as pointed out above, several of the well-known Brush Creek localities are actually Pine Creek or Woods Run. These typically have well defined limestones sandwiched between dark-colored marine shales. The Cambridge (Nadine) has not been recognized in many places in Pennsylvania. It is often very thin with relatively small amounts of associated shale. The Woods Run in Allegheny County and adjacent areas is most often a punky brown, calcareous, argillaceous rock. The Bakerstown marine zone most often occurs as a dark-colored shale containing a few brackish-water fossils and rare truly marine species. One needs to have a very good handle on the stratigraphy of any particular sequence of Glenshaw rocks to have any chance of correctly identifying a marine zone.

Correlation of the marine zones across state lines has created even more numerous problems over the decades. In eastern Ohio, the Brush Creek was for many years considered to be divided into two parts of a single interval. Condit (1912), for example, described the Brush Creek limestone as consisting of two limestone units separated by 25 to 30 ft (7.5 to 9 m) of fossiliferous shale, resulting in a continuous series of fossiliferous beds 30 to 45 ft (9 to 14 m) thick. “Since the upper and lower limestones are so closely related it is best that they be included under the same name.” (Condit, 1912, p. 49). As such, the limestones have been called Lower Brush Creek and Upper Brush Creek in Ohio and West Virginia for many years; these names were formalized by Sturgeon (in Sturgeon et al., 1958). A large part of the confusion resulted from White’s (1903) referring to the Brush Creek and Pine Creek limestones in West Virginia with the names “Lower Cambridge” and “Upper Cambridge”, respectively. Stevenson (1906) retained the name Brush Creek for the lower limestone but called the upper one Cambridge. Since the Cambridge Limestone had priority over Pine Creek, the name Pine Creek was abandoned in Ohio and West Virginia (and even in some parts of Pennsylvania – e.g., Butts, 1906). Although Pennsylvania retained the name Pine Creek, it was still considered to be correlative with the Cambridge Limestone for decades (e.g., Donahue and Rollins, 1974a; Carothers, 1976; Rollins et al., 1979). In fact, this was considered dogma until Busch (1984; also Busch and Rollins, 1984) showed the Pine Creek correlated with the Upper Brush Creek and the Cambridge correlated with the Nadine limestone (Figure 1). Thus, the Lower and Upper Brush Creek of Ohio and West Virginia are, respectively, the Brush Creek and Pine Creek of Pennsylvania.

The Friendsville marine zone of western Maryland, also once considered to be Cambridge (and therefore Pine Creek) equivalent (Swartz et al., 1919), is now correlated with the Woods Run, as is the Portersville marine zone of Ohio.

The Mill Creek Limestone of the anthracite area of northeastern Pennsylvania traditionally had been correlated with the Ames Limestone (White, 1903; Chow, 1951; Busch, 1984). Based on conodont content, however, Merrill and Wentland (1994) suggested that the Mill Creek correlated instead with the Noble Limestone of Ohio. Their analysis of Mill Creek conodonts showed that the fossil population was evolutionarily older than the conodont population found in the Ames. They concluded that the Mill Creek definitely is not equivalent with the Ames, and was, in fact, actually older than the Noble Limestone in eastern OH. Although Merrill and Wentland (1994) determined that the Mill Creek could not be definitively correlated to any marine zone anywhere else in the Appalachian Basin, Heckel et al. (2011, p. 260) concluded that the dominance of *Streptognathodus firmus* in the Noble confirmed the correlation of that limestone with the Mill Creek.

In fact, the identification of conodonts in the Pennsylvanian marine zones of the Appalachian Basin has resolved most of the problems of identification that have cropped up over the last 120 years. Figure 7 illustrates our current understanding of the correlation of Upper Pennsylvanian marine zones from the Midcontinent to the Appalachian Basin, and Table 1 shows the conodont zonation of the Glenshaw Formation and correlative units. Any confusion of marine zones that might occur now and in the future should be able to be resolved by someone with enough expertise to sample for and identify the conodonts that occur within the Glenshaw marine zones.

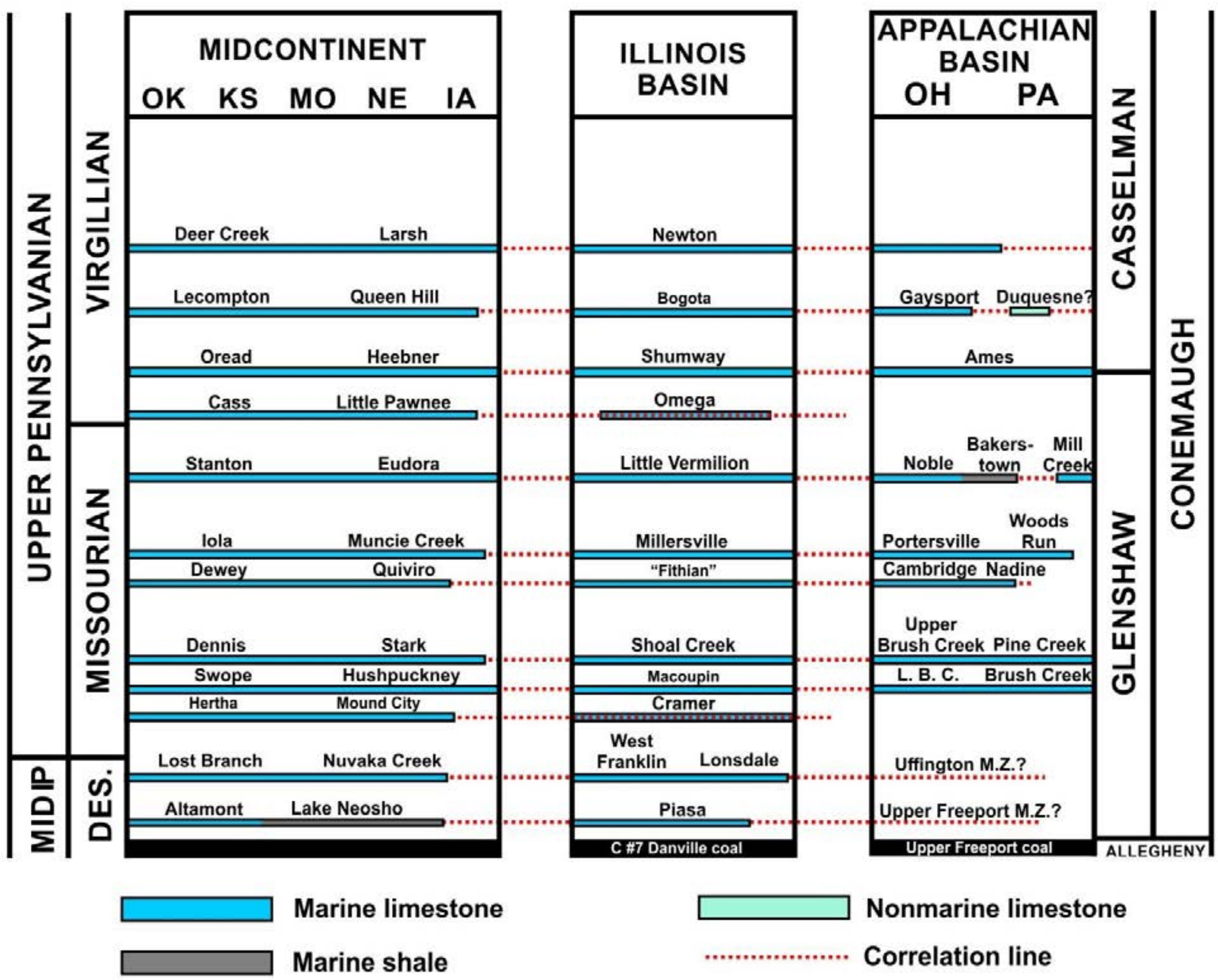


Figure 7. Correlation of Glenshaw marine zones with marine rocks in the Midcontinent and Illinois Basin (based on Heckel et al., 1998).

Table 1. Conodont zones associated with the Midcontinent and Illinois Basin marine zones and correlation with Glenshaw marine zones in the Appalachian Basin (from Heckel et al., 2011).

MIDCONTINENT	ILLINOIS BASIN	APPALACHIAN BASIN (Conemaugh Marine Units)	CONODONT ZONES
Oread/Heebner	Shumway	Ames	***Idiognathodus simulator***
Cass/Little Pawnee	"Omega"	?	***Streptognathodus zethus***
Stanton/Eudora	Little Vermilion	Bakerstown/Noble	***Idiognathodus eudoraensis***
Iola/Muncie Creek	Millersville	Woods Run/Portersville	***Streptognathodus gracilis***
Dewey/Quiviro	"Filian"	Nadine/Cambridge	***Streptognathodus gracilis***
Dennis/Stark	Shoal Creek	Pine Creek/Upper Brush Creek	***Idiognathodus confragus***
Swope/Hushpuckney	Macoupin	Brush Creek/Lower Brush Creek	***Idiognathodus cancellosus***
Hertha/Mound City	Cramer	"Mahoning"?	***Idiognathodus turbatus***
Lost Branch/Nuvaka Creek	West Franklin/Lonsdale	Upper Freeport?	***Idiognathodus eccentricus***

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Plates

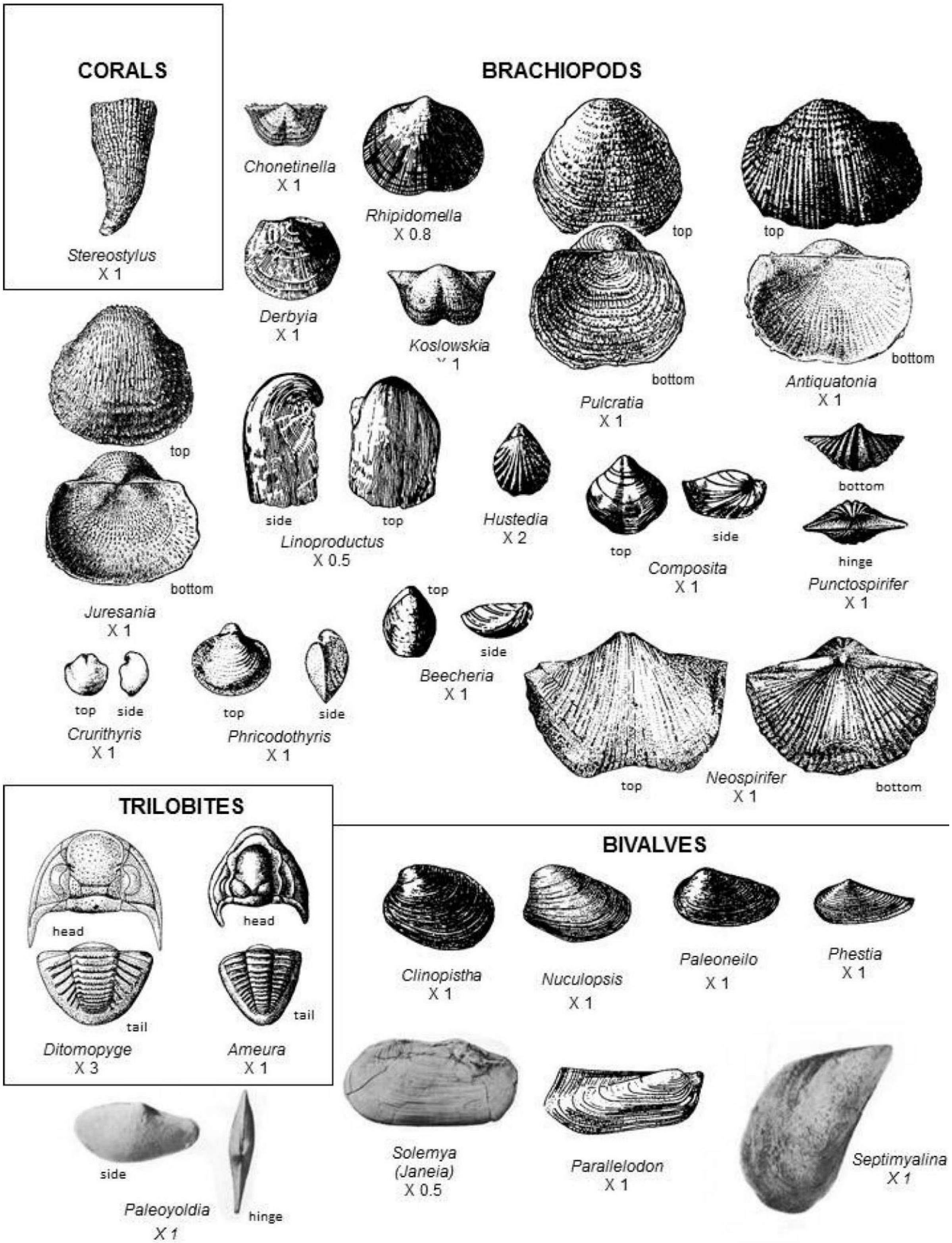

Plate 1. Illustrations of some fossils commonly found in the marine rocks of the Glenshaw Formation (from Moore et al., 1952; Hoskins et al., 1983; and a variety of other sources).

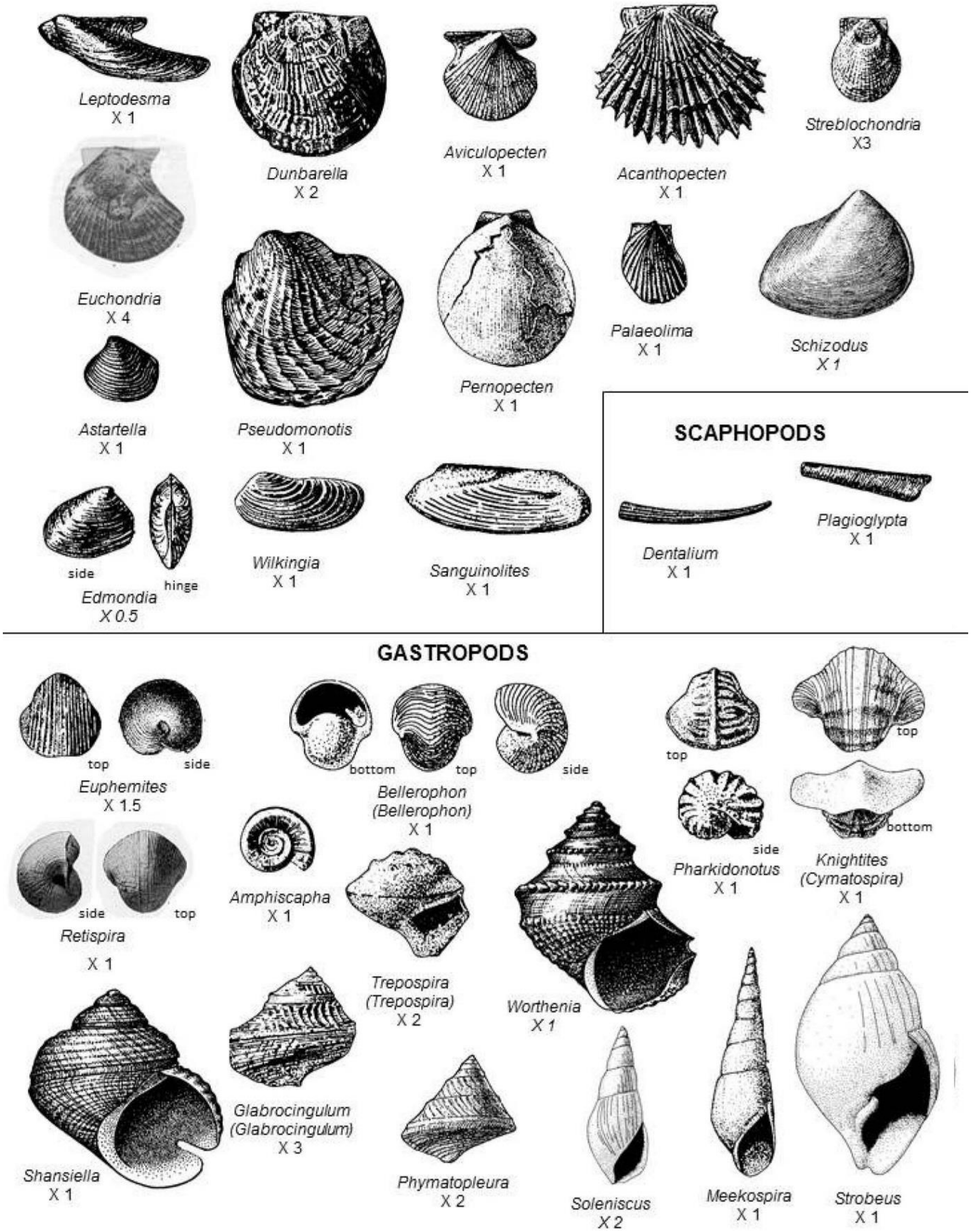

Plate 2. Illustrations of some fossils commonly found in the marine rocks of the Glenshaw Formation (from Moore et al., 1952; Hoskins et al., 1983; and a variety of other sources).

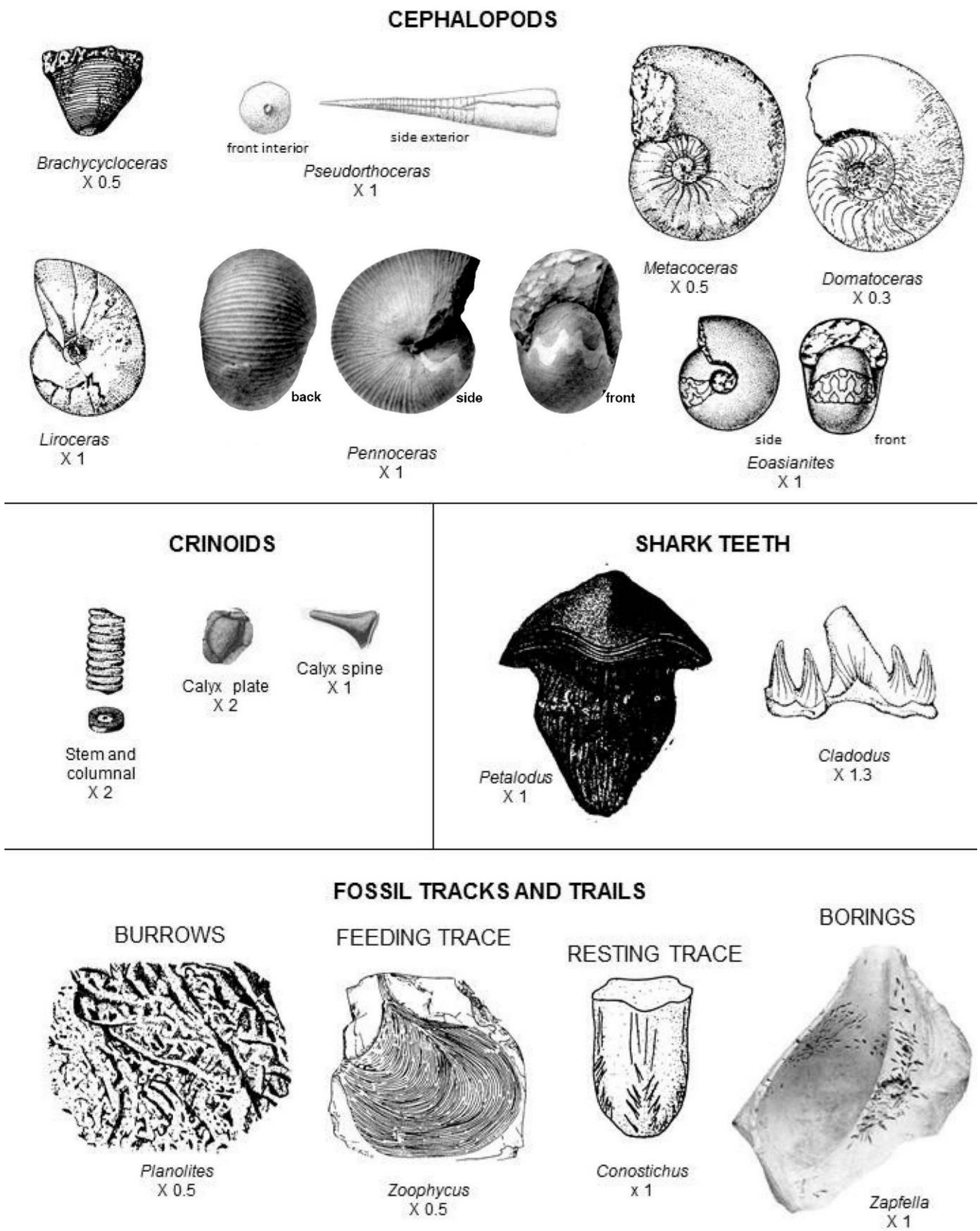

Plate 3. Illustrations of some fossils commonly found in the marine rocks of the Glenshaw Formation (from Moore et al., 1952; Hoskins et al., 1983; and a variety of other sources).

PINE CREEK MARINE ZONE, US 422 BYPASS, KITTANNING

JOHN A. HARPER, PENNSYLVANIA GEOLOGICAL SURVEY, RETIRED
BILL BRAGONIER, COAL GEOLOGIST, RETIRED

CAUTION: US 422 is a heavily traveled, high-speed, divided highway. Although, for the Field Conference, the stop will be protected by relatively wide berms and Flagger Force, caution should be taken while studying the outcrops and collecting fossils. Stay as far off the road and as close to the roadcuts as you can.

Introduction

Stop 5 occurs on the onramp from PA 28/66 (from New Bethlehem) to US 422 East (Figures 1 and 2A). This stop will give conferees the opportunity to examine the Pine Creek marine zone and its adjacent strata, as well as view other Glenshaw marine zones above and below the Pine Creek. A nearby outcrop, along the onramp from PA 28/66 to US 422 West, also exposes the Pine Creek marine zone at a lower level (Figure 2B), but the sharp curve of the onramp prohibits safe viewing.

Figure 1. Location of Stop 5 at the US 422 bypass around Kittanning and other locations mentioned in the text.

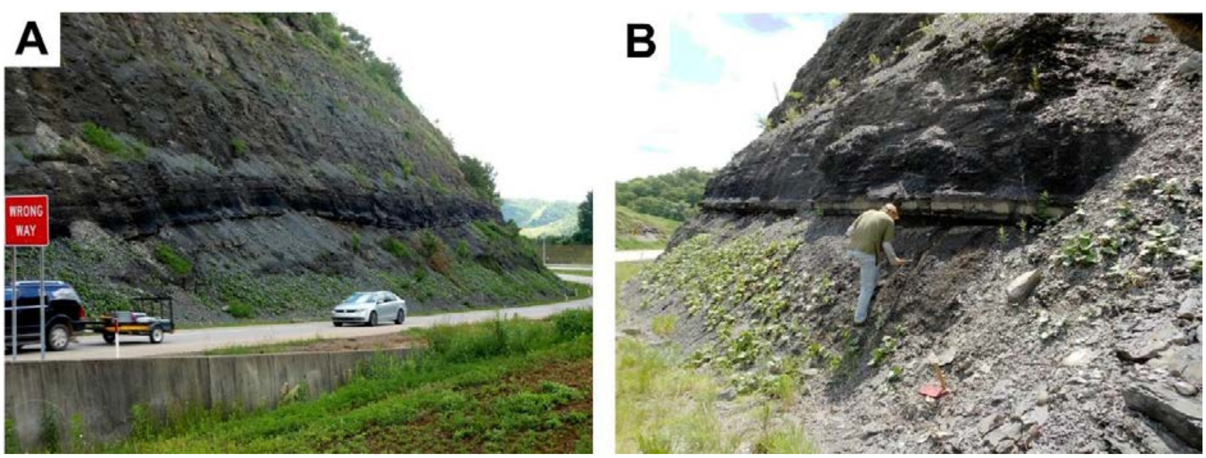

Figure 2. Photos at Stop 5 of the Pine Creek limestone and associated rocks. A – Outcrop along the onramp to US 422 East showing paleotopography beneath the limestone. B – Outcrop along the onramp to US 422 West.

In the 1970s, US 422 bypasses were built around New Castle, Kittanning, and Indiana. Sections of the Indiana bypass remained incomplete until 1995 and the Kittanning bypasses were completed in 2000. In 1982, the Kittanning Bypass opened from the Allegheny Valley Expressway (PA 28) to PA 66 and a median installed from there to Kittanning. The project cost $39 million and opened on December 13, 2001. Officials from state and local agencies as well as PennDOT and Federal Highway Administration officials cut the ribbon signaling the opening of the highway.

> "This is truly a monumental day for Armstrong County and it is a great pleasure for me to share in this celebrated opening of the A-15 Kittanning Bypass with you," said Pennsylvania Secretary of Transportation Bradley L. Mallory. "It is days like today that make this job worthwhile. And sharing these moments with hardworking Americans like the people of Armstrong County reminds me of why this country is great." (Kitsko, 2016).

Glenshaw Formation

The rocks exposed in the roadcuts at Stop 5 are part of the Glenshaw Formation, the lower unit of the mostly Late Pennsylvanian Conemaugh Group (Figure 3). Platt (1875, p. 8) first used the name "Conemaugh series" to include all the rocks from the base of the Pittsburgh coal to the top of the Upper Freeport coal. The Conemaugh later became a formation (Woolsey, 1906) and that nomenclature remained in effect throughout the Appalachian Basin until Flint (1965) subdivided it into the lower Glenshaw Formation and the upper Casselman Formation. Flint delineated the Glenshaw by the occurrence of numerous marine units, whereas the Casselman is mostly devoid of marine rocks. The top of the marine Ames Limestone is the boundary between the two formations. Although Busch (1984; also Busch and Rollins, 1984) recognized eight marine zones within the Glenshaw, the lower two are so rarely exposed that for all intents and purposes the Glenshaw has six regionally extensive marine zones. In Pennsylvania, these include, from oldest to youngest, the Brush Creek, Pine Creek, Cambridge (also called Nadine), Wood Run, Bakerstown, and Ames. The Casselman Formation also contains two marine zones, the Gaysport and Skelley, mostly restricted to eastern Ohio.

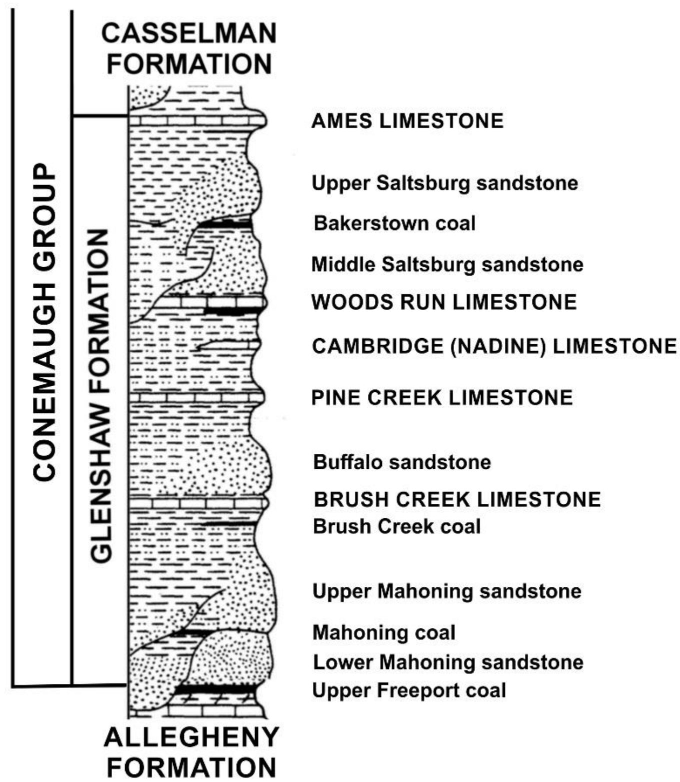

Figure 3. Generalized stratigraphic section of the Glenshaw Formation in western Pennsylvania. The marine intervals (in caps) are important marker horizons throughout the formation (modified from Harper and Laughrey, 1987).

The rocks exposed at Stop 5 include the Pine Creek marine zone and adjacent rocks. The Brush Creek marine zone (essentially, just the limestone) occurs near the base of the section along the bypass between the two onramps, and the Woods Run marine zone occurs near the tops of the higher knolls above the Pine Creek (see below).

Pine Creek Marine Zone

White (1878) named the Pine Creek limestone for a dark arenaceous and fossiliferous limestone bed about 2 ft (0.6 m) thick that crops out of the hillside between Gourdhead Run and Pine Creek in Allison Park, Allegheny County, PA. He described it as:

> "… quite variable; sometimes it is a compact light dove colored rock, and burns readily into a tolerably fair lime; but more generally it is quite arenaceous, and earthy, without close inspection would often be very readily mistaken for a stratum of sandstone. It is always fossiliferous, and generally more or less brecciated. In it were seen *Productus longispinus, P. Nebrascensis, Athyris subtilita, Chonetes mesoloba, Nautilus occidentalis, Orthoceras cribrosum,* and many stems and fragments of crinoids." (White, 1878, p. 32-33)

The names of the fossils have changed over the years, but the fossils themselves will be familiar to anyone who has collected from the Glenshaw marine zones around the Appalachian Basin. In its most recognizable form, the Pine Creek marine zone typically is a richly fossiliferous, shallow marine argillaceous limestone sandwiched between calcareous marine shales of various thickness.

Despite a maximum thickness of only about 3 ft (0.9 m) (Seaman, 1941), the Pine Creek limestone is laterally extensive. It is well known from western Pennsylvania, eastern Ohio, northern West Virginia, and western Maryland (Busch, 1984). It is possible that the Pine Creek also occurs in eastern Kentucky, as marine rocks above the Brush Creek and below the Ames occur there (Chestnut, 1981), but that particular name apparently has not been used. Because of its regional extent, lithology, and fossil fauna, it is an important marker bed for stratigraphic correlations within the Upper Pennsylvanian. As a marine unit situated within a primarily nonmarine succession, it also is valuable in assessing sea level cycles (e.g. Busch & Rollins, 1984) and for use in correlating allocyclic (eustatic) events between the Appalachian Basin and Carboniferous basins in the mid-continent (e.g. Heckel et al., 1998; 2011).

Correlation

White (1903) applied the names "Lower Cambridge" and "Upper Cambridge" to the two lower Conemaugh marine limestones in West Virginia. Stevenson (1906), realizing the lower of the two was the same as the Brush Creek of Pennsylvania, retained that name and restricted the name Cambridge to the higher of the two. Since the Cambridge Limestone, named by Andrews (1873, p. 262) for outcrops in Cambridge, Guernsey County, Ohio, had priority over the Pine Creek (White, 1878), the name Pine Creek was dropped in Ohio and West Virginia (and even in some parts of Pennsylvania; Butts, 1906, for example, called the marine zone "Cambridge (Pine Creek)" here in the Kittanning area). In fact, the Pine Creek was considered to be nothing more than Pennsylvania's name for the Cambridge Limestone for decades (e.g., Donahue and Rollins, 1974a; Carothers, 1976; Rollins et al., 1979) until Busch (1984) demonstrated that the Cambridge actually correlated with the Nadine Limestone, an otherwise insignificant marine zone above the

Pine Creek (Figure 3). The Pine Creek correlates instead with what Ohio and West Virginia call the Upper Brush Creek (see Harper, this guidebook, for additional details).

Lithology

The lithology of the Pine Creek marine zone varies considerably around the Appalachian Basin. It often occurs as a gray to greenish gray, argillaceous, sometimes arenaceous, skeletal mudstone and wackestone bearing allochthonous phosphate granules, and with the limestone sandwiched between dark gray to black, calcareous, clay shales containing marine fossils and siderite nodules. On a fresh surface the limestone typically is dark gray, whereas the weathered surface commonly is a buff color (Figure 4). Where it has been leached, sand grains can be so abundant that the rock seems to be more sandstone than limestone (Richardson, 1932). We measured the limestone on the US 422 West onramp adjacent to Stop 5 where it occurs at road level. The limestone was at 12 in (30.5 cm) thick, although it appears to vary across the outcrop. Internal stratification of the limestone, although not always readily apparent, is very apparent here. In most of the Glenshaw marine limestones, several layers can be discerned based on the presence of phosphatic nodules (lag deposits) and the presence of corals. At this locality, at least four separate layers can be distinguished within the Pine Creek limestone, separated on the basis of bedding, fissility, and frequency of fossils (Figure 5).

Figure 4. Pine Creek limestone at Stop 5 showing its weathered surface. U.S. quarter for scale.

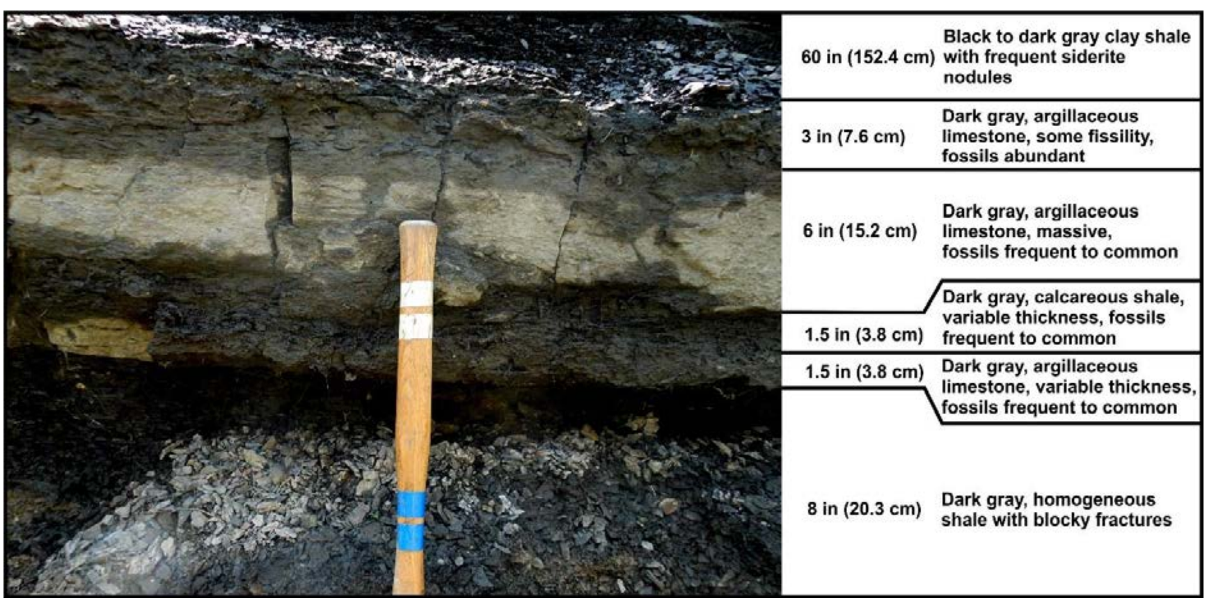

Figure 5. Details of the lithology of the Pine Creek marine zone at Stop 5. Hammer handle for scale; distance between blue and white tape = 6 in (15.24 cm).

The calcareous marine shales associated with the limestone can include compact nodules and sand lenses as well as siderite nodules and fossils. Besides the typical dark gray to black clay shales, other lithologies occur in different places. In Somerset County, for example, pale red- to buff-colored, platy to fissile clay shales occurring above and below the limestone, called the Meyersdale redbeds, grade laterally into typical Pine Creek lithologies farther west. Meyersdale shales can also occur in areas of "typical" Pine Creek. In southeastern Ohio, the shales are replaced locally by buff-colored spiculites (Busch, 1984). In many places, the lower marine shale interval is thin or absent and the limestone lies directly on the Buffalo sandstone interval. At Stop 5, the Buffalo interval consists of about 25 ft (7.6 m) of predominantly gray, silty shale containing thin layers of siderite nodules (Figure 6A). A thin, 2 ft (0.6 m) ledge of sandstone occurs at the top of this, followed by 22 in (55.9 cm) of light grayish green claystone (Figure 6B) and 8 in (20.3 cm) of dark gray, homogeneous shale displaying a blocky fracture pattern. The claystone is an underclay, but all evidence of coal is missing at this locality. Shaak (1975) measured the Pine Creek interval in the hillside behind the Cadet Restaurant, about 2,000 ft (610 m) south-southeast of Stop 5, where he documented a coal 22 ft (6.7 m) below the limestone (Figure 7), thereby showing one of the effects of paleotopography on the Pine Creek-Buffalo interval in the Kittanning area.

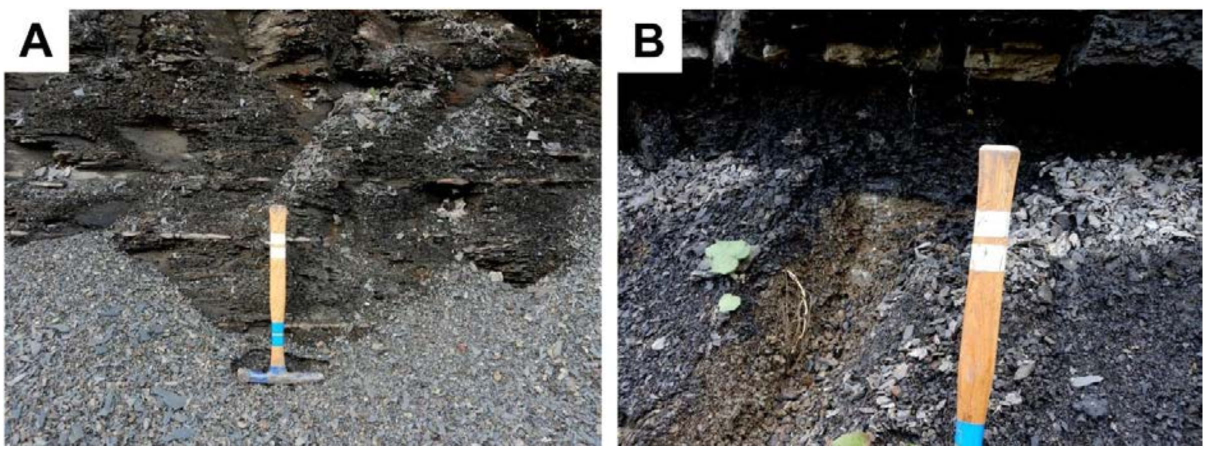

Figure 6. Photos of the rocks below the Pine Creek limestone at Stop 5. A - Siderite nodules are quite common in both the marine and nonmarine shales and siltstones above and below the limestone. B – Underclay 22 in (55.9 cm) thick occurs about 8 in (20.3 cm) below the limestone, but there is no evidence of coal. Hammer handle for scale; distance between blue and white tape = 6 in (15.24 cm).

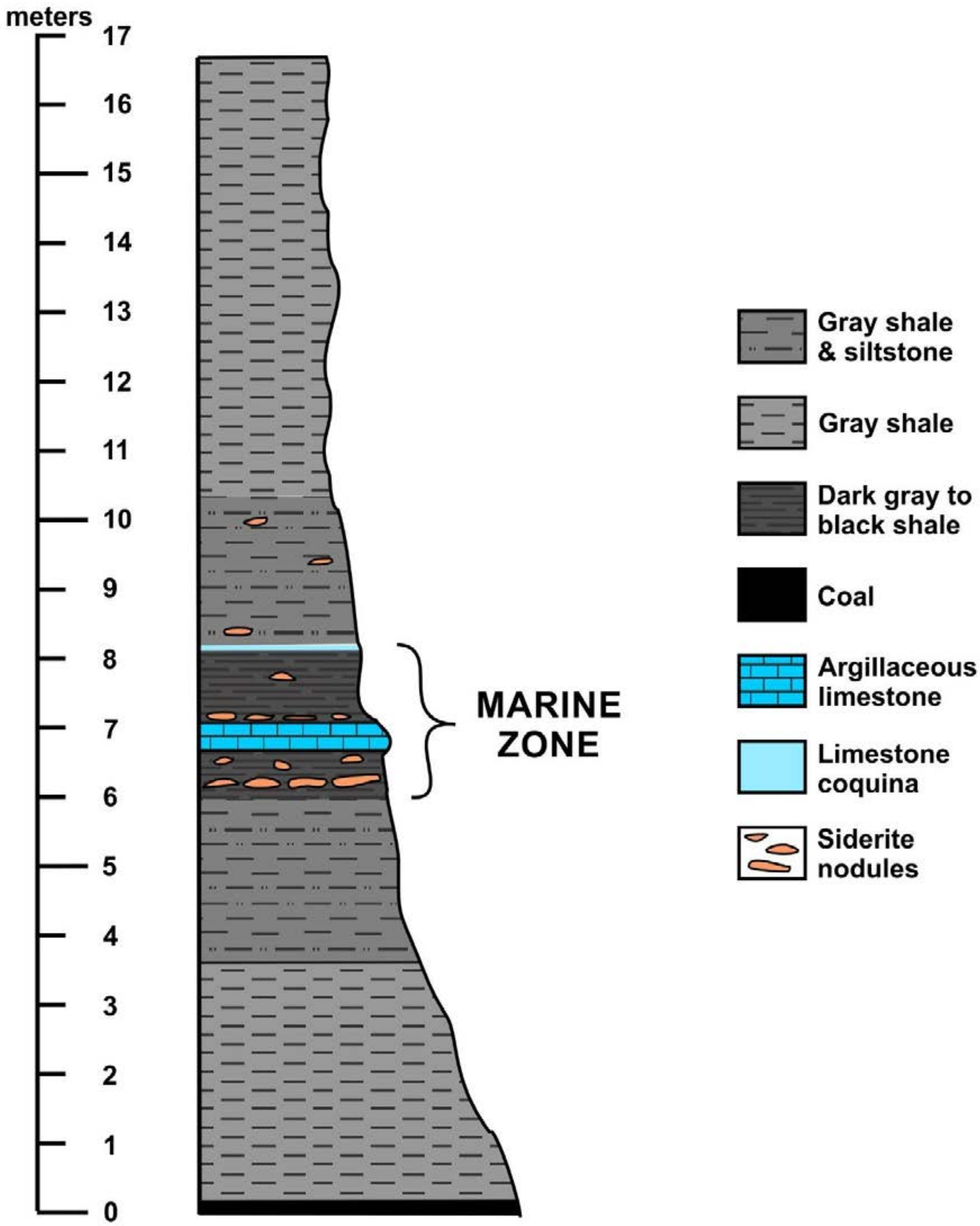

Figure 7. Stratigraphic column of Pine Creek and associated rocks exposed in the hillside behind the Cadet Restaurant on US 422 about 2,000 ft (610 m) SSE of Stop 5-2 (redrawn from Shaak, 1975; Shaak called this section Brush Creek).

Fossils

The Pine Creek marine zone can be a prolific fossil producer, yielding numerous excellent specimens, although no one group is dominant (Seaman, 1941). Where it is fossiliferous, the limestone commonly contains horn corals (*Stereostylus*), crinoid debris, a variety of brachiopods, some cephalopods, and other fossils that lived in an open marine environment. Although some of the molluscs, particularly the gastropods (for example, *Meekospira, Amphiscapha, Shansiella*) and bivalves (for example, *Nuculopsis, Phestia, Astartella*), can be found in the limestone, they are far more commonly found in the shales because most were shallow water dwellers. *Meekospira*, in particular, appears to have been a mud snail that plowed through intertidal sediments looking for detrital organic material. Petalodontiform (*Petalodus*) and cladoselachid "shark" teeth (*Cladodus*) are not common, but they typically are found in the lower shales. Trace fossils also occur within the marine zone, including resting traces such as *Conostichus* and assorted burrows. We found a nice example of what appears to be *Asterosoma* (Figure 8A) lying along the side of the road at Stop 5. *Asterosoma* consists of bulbous to elliptical burrow chambers radiating out from a central burrow tube, probably made by some kind of worm or crustacean. Those with microscopes or good hand lenses might also be able to find ostracodes or agglutinating foraminifers attached to shells. Plates 1-4 illustrate many of the genera that have been found in Conemaugh marine deposits around the Appalachian Basin. Perhaps a few of these can be found at this locality (upon walking up to the outcrop at Stop 5 for the first time, Harper found two good specimens of the gastropod *Shansiella* just begging to be pulled out of the matrix. It took a few minutes to locate specimens of the brachiopod *Chonetinella* (Figure 8B), the resting trace *Conostichus*, and several badly preserved bivalves).

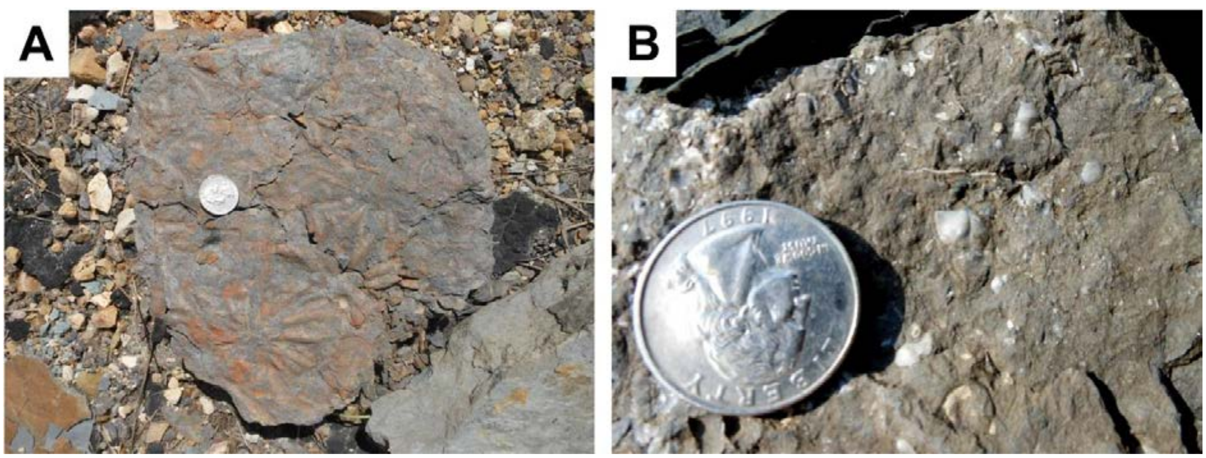

Figure 8. Photos of some Pine Creek fossils found at Stop 5. A – The trace fossil Asterosoma. B – Specimens of the brachiopod Chonetinella plebeian. Notice the white material on the rock. This is aragonite or high-magnesium calcite preserved by high organic content and hypoxic conditions in the rocks. US quarters for scale.

Some of the specimens lying around on the ground also showed evidence of preservation of original or near pristine shell material. The Pine Creek and, especially, Brush Creek marine zones are well known for having shell material preserved in near-pristine condition as primary aragonite and high-magnesium calcite (Cercone and others, 1989; Harper, 1992). Aragonite, a form of calcium carbonate that, in particular, most molluscs use to form their shells, is unstable under normal conditions. It tends either to recrystallize to calcite or dissolve completely after burial, resulting in internal and external molds. In unusual cases, however, such as in some Brush Creek and Pine Creek localities where the rock has a high organic content, the aragonite may be preserved in its original form and structure. Where abundant aragonitic shell material occurs in the Brush Creek or Pine Creek, there exists strong evidence for high organic content and hypoxic conditions in the original muds. But the degree of preservation is not uniform across western Pennsylvania. At many localities the metastable carbonate components have undergone the normal stabilization to low-magnesium calcite. Whether the aragonitic shell material of molluscs at Stop 5 has been preserved will need to be tested. Keep an eye peeled. You might find some here.

Other Marine Zones

Although we will not be stopping to examine and collect from the other Glenshaw marine zones exposed at this stop, they deserves some mention. The Brush Creek limestone is exposed at the lower (northern) end of Stop 5 (Figure 9A) and along the west side of PA Route 66 just above road level south of the exit ramp to US 422 Eastbound (see Figure 1) where it is almost entirely obscured by talus. White (1878) named the Brush Creek limestone for 4 to 5-ft (1.2 to 1.5-m) thick sequence of fossiliferous, black, calcareous shale and 1 to 2-ft (0.3 to 0.6-m) thick, argillaceous or arenaceous, often ferruginous, and highly fossiliferous limestone. The Brush Creek quickly became so recognizable by its lithology and fossil content that, for many years, any Glenshaw marine limestone sandwiched between dark-colored marine shales was considered to be the Brush Creek, especially if only a limited section was exposed. Several classic "Brush Creek" localities in Allegheny, Armstrong, and Indiana counties provided numerous fossils used for a variety of paleoecological MS and PhD theses, but as it turned out these localities actually expose Pine Creek rather than Brush Creek, making the data and conclusions of those theses suspect. Where exposed in the vicinity of Stop 5, the Brush Creek limestone contains a relatively sparse marine fauna, mostly fragmented corals, crinoids, and brachiopods. The corals typically are exposed in either transverse or longitudinal cross section, and so are unmistakeable. Unlike most Brush Creek localities, the limestone is not sandwiched between dark-colored marine shales containing lots of fossils.

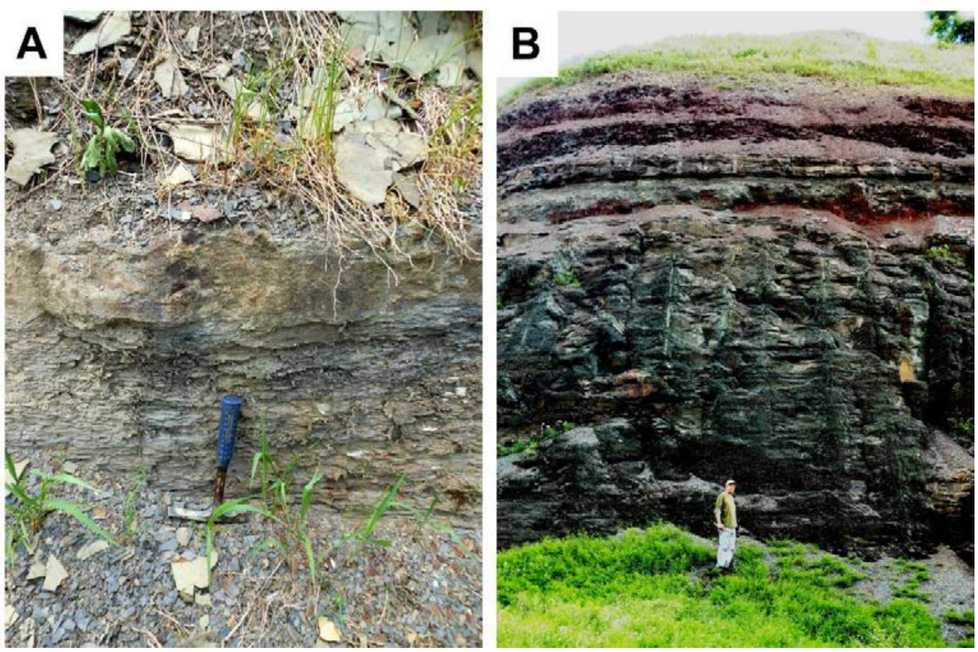

Figure 9. Other Glenshaw marine zones exposed at Stop 5. A – The Brush Creek limestone is exposed at the lower (northern) end of the onramp. Estwing rock hammer for scale. B – The Woods Run marine zone is exposed near the top of the roadcut, too high to get an accurate measurement. Notice the reddish or reddish-brown beds both above and below the limestone and its dark-colored marine shales. Geologist, 6 ft 2 in (1.9 m) tall, for scale.

In addition to the Brush Creek and Pine Creek marine zones, the Woods Run marine zone is also exposed near the top of the roadcut at Stop 5 (Figure 9B). Raymond (1910) named the Woods Run limestone for a fossiliferous marine limestone lying between the Pine Creek and Ames (Figure 1). He found only a few species of fossils in the limestone dominated by the coral *Stereostylus*. Busch (1984) described the Woods Run as an argillaceous, ferruginous limestone with occasional phosphate granules and abundant fossils. It is commonly overlain by dark gray shales with marine fossils. Burke (1958) named the Carnahan Run Shale for 5 ft (1.5 m) of dark gray, fossiliferous, marine shale separated from the Woods Run limestone by 21.5 ft (6.6 m) of reddish-brown shale carrying plant fragments. Wells (1983), however, determined that the Carnahan Run was merely a shale facies of the Woods Run. As you will see at Stop 5, the Woods Run marine zone is both underlain and overlain by reddish or reddish-brown beds (Figure 9B), probably the same beds Burke (1958) described as separating the Woods Run and Carnahan Run units.

On The Nature of Lower Conemaugh Unconformities

The on- and offramps to US 422 at Stop 5 provide an excellent three-dimensional exposure of the Pine Creek marine zone. One of the most significant features at this site is the undulating surface over which marine transgression strata were deposited. Immediately below the marine interval is a well-developed paleosol soil horizon that displays a high degree of lateral variability over a short distance. At the paleotopographic summit on the north end of the onramp, the clay is mottled red, green, and gray and contains abundant calcite nodules, mostly oriented parallel to the well-developed slickenlines within the clay. The red and green color disappears down the paleotopographic slope to the south, fading into light gray, but calcite nodules, still mostly aligned on slickensided surfaces, exist in the gray paleosol for some distance before disappearing downslope. In the lowest paleotopography visible at the site, the paleosol is a medium gray color and contains no visible calcite and minimal slickensides.

The mottled red and green and translocated calcite deposits are indicative of vertisols formed in dry-subhumid to semiarid climates (Cecil, 2003). Some degree of rainfall seasonality is required to form the slickensides. However the local paleotopography has obviously influenced paleosol development (i.e., a *paleocatena*). A paleocatena is a group of paleosols on the same buried land surface whose original soil properties differ owing to their different original landscape position and soil water regimes (Valentine and Dalrymple, 1975). The lateral changes in paleosol properties observable at this stop are best explained by lateral changes in soil moisture controlled by landscape position. Similarly, Fedorko (1998) equated lateral variations in Late Pennsylvanian organic and mineral paleosols over a 79-mi (127-km) long transect in northern West Virginia to a paleocatena. The underclay beneath the Pine Creek marine zone at Stop 5 fits the definition of a paleocatena on a micro scale, as well as the definition of a *toposequence*. A toposequence is a type of catena in which the differences among the soils result almost entirely from the influence of topography because the soils in the sequence all share the same parent material and have similar conditions regarding climate, vegetation, and time. The catena concept is similar to that of a toposequence, except that in a catena the member soils may or may not share a common parent material.

The maturity of soil development over an established paleotopographic surface prior to the Pine Creek transgression hints that Lower Conemaugh unconformities are temporally substantial. In eastern Ohio, where the Mahoning coal has been extensively mined, it is common to see the undulating surface of the Brush Creek marine zone in pre-law Mahoning surface mines. The typical interval between the Mahoning and Brush Creek horizons is approximately 50 to 60 ft (15 to 18 m). However, drilling by the East Fairfield Coal Company in eastern Carroll and northern Jefferson Counties, Ohio, demonstrates the extreme variability of this interval. Figure 10 shows this interval in four closely spaced drill holes from northern Jefferson County where it varies from 60 ft (18 m) to over 100 ft (30.5 m). A 100-ft (30.5-m) Brush Creek-to-Mahoning coal interval requires the deposition and subsequent erosion of at least 40 ft 12 m) of sediment. In addition, as illustrated, one of the eroded deposits was a red paleosol over 13 ft (4 m) in thickness and another was a thin marine/brackish transgressive unit known as the Rock Camp marine zone. Additionally, Tim Miller, geologist for the East Fairfield Coal Company (personal communication), has mapped the Brush Creek-to-Mahoning interval immediately to the west of the cross section in Figure 10 and found that the interval *decreases* to as little as 19 ft (5.8 m), revealing a local relief of over 80 ft (24 m) after compaction and lithification.

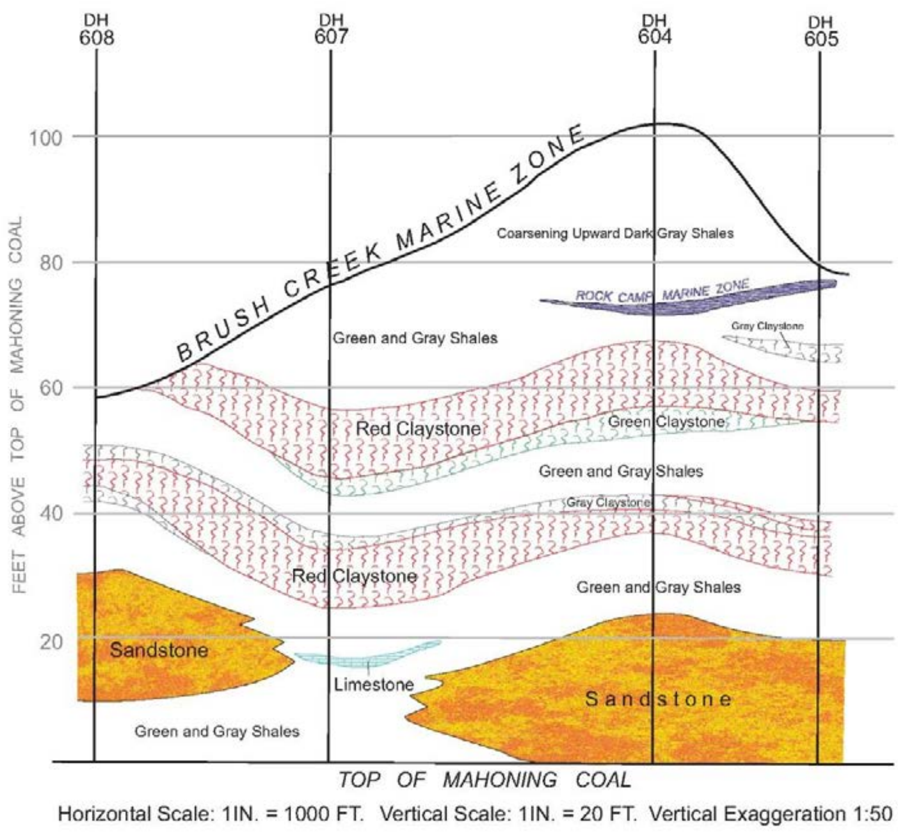

Figure 10. Cross-section defined by four diamond drill holes in Northern Jefferson County, Ohio, where the Brush Creek marine zone-to-Mahoning coal iterval increases from a normal interval of 50 to 60 ft 15 to 18 m) (DH 608) to over 100 ft (30.5 m). The uncomnmonly high interval exposes stratigraphic units normally eclipsed, suggesting the unconformable surface immediately beneath the Brush Creek transgression has substantial temporal significance.

The point of this discussion is that at least the two lowermost Glenshaw marine zones have transgressed over very mature erosional surfaces. The amount of relief on the Brush Creek surface in Ohio indicates that a formidable amount of material, including a thick soil horizon, was deposited and eroded. It is suggested that the temporal interval involved was quite substantial. This insight is only possible due to the local “lifting off” of the Brush Creek marine zone, exposing rarely seen strata. What is not known, of course, is how much more strata were deposited and eroded for which there is no record.

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STRATIGRAPHY, LITHOLOGY, AND SEA-LEVEL HISTORY OF THE BRUSH CREEK MARINE DEPOSITS OF THE GLENSHAW FORMATION

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Introduction and History

The Brush Creek Limestone is a richly fossiliferous, shallow marine carbonaceous limestone in the Glenshaw Formation of the Conemaugh Group (Upper Pennsylvanian, Missourian). The unit and its associated calcareous marine shales are often known as the Brush Creek marine zone, which has a total thickness of around 15 feet (4.6 m) (White, 1878). This marine zone generally overlies the Brush Creek coal, which is a thin (1-2 feet), occasionally mined coal. As sea level receded in the basin, a terrestrial sandstone and siltstone unit, the Buffalo sandstone, was deposited. In some locations another marine unit, the Pine Creek limestone, is encountered directly above the Buffalo sandstone, indicating a relatively rapid return to marine conditions and the completion of a high-order (eustatic) transgressive-regressive cycle.

Despite a maximum thickness of only around 1 foot (0.3 m), the Brush Creek limestone is laterally extensive, as is the Pine Creek limestone (known as the upper Brush Creek limestone in Ohio and West Virginia), which attains thicknesses of several feet. These marine zones are known from western Pennsylvania, eastern Ohio, northern West Virginia, western Maryland (Wilmarth, 1938), and even eastern Kentucky (Chestnut, 1981) (Figure 1). Because of their regional extent, unique lithologies, and fossil faunas, they are important marker beds for stratigraphic correlations within the Upper Pennsylvanian Series. As marine units situated within a primarily terrestrial succession, they are also valuable in assessing sea level cycles (e.g. Busch & Rollins, 1984) and for use in correlating allocyclic (eustatic) events between the

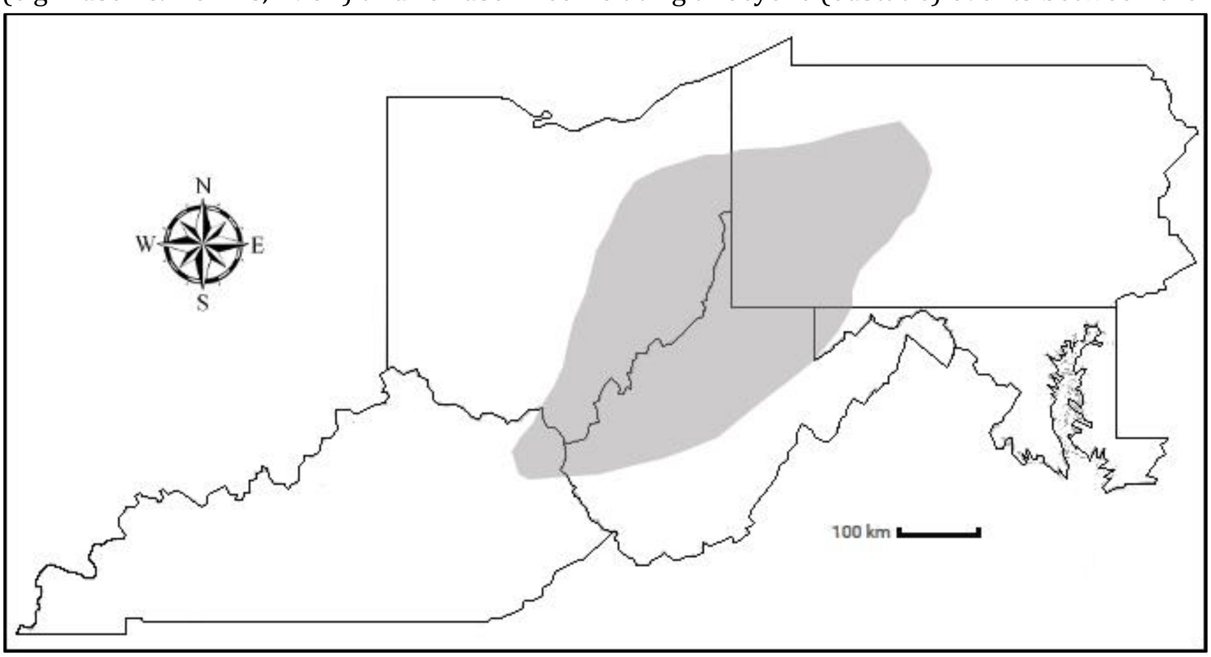

Figure 1. Shaded area denotes the approximate extent of the basin containing the Glenshaw Formation and Brush Creek and Pine Creek marine zones (after Busch & Rollins (1984) and Martino (2004)

Appalachian Basin and Carboniferous basins in the mid-continent (e.g. Heckel et al., 1998). Additionally, the units are prolific fossil producers, yielding relatively pristine gastropod fossils, including some that are still aragonitic (see discussion in Cercone and Taylor, 1989). The deposits also yield numerous bivalves and cephalopods.

The Brush Creek and Pine Creek limestones were first named by Israel Charles White in 1878, during the Second Geological Survey of Pennsylvania (White, 1878). White performed his mapping in the "Beaver River district" encompassing parts of Butler, Beaver, and Allegheny Counties. The Brush Creek limestone was described from an outcrop along Brush Creek in Cranberry Township, Butler County. The limestone and associated calcareous shales of the marine zone were all described within the "Lower Barren Measure Series". Franklin and William G. Platt, in a survey report from Cambria and Somerset Counties the previous year (1877), also delineated the "Lower Barren Measures" and within it described a Philson limestone. The Philson limestone correlates to the stratigraphic position of the Brush Creek limestone and has been synonymized with the Brush Creek limestone (although, technically 'Philson' has taxonomic priority). An underlying Gallitzin coal reported by Platt and Platt has, ultimately, been largely regarded as synonymous with the Brush Creek coal, after some uncertainty regarding a possible correlation to the isolated Humbert coal in southern Somerset County (see discussion in Shaulis, 1993). Both White and the Platts defined the Lower Barren Measures as all units occurring above the Upper Freeport coal and below the "Pittsburg" coal (in the second survey publications, Pittsburgh was spelled as 'Pittsburg'). Later, this section came to be known as the Conemaugh Formation (Woolsey, 1906) and, eventually, Conemaugh Group (see Wilmarth, 1938).

Later studies (Flint, 1965) divided the Conemaugh Group into the Glenshaw and Casselman Formations, with the Glenshaw extending from the upper contact of the Upper Freeport coal to the top of the Ames Limestone (Figure 2). The Brush Creek marine zone is the lowest marine unit in the Conemaugh Group. Flint (1965) noted the similarity of lithofacies between the Brush Creek shales and those associated with the Ames marine zone.

Moving up-section before one encounters the Pine Creek Limestone (White, 1878). In Ohio, a lower Brush Creek and upper Brush Creek limestone separated by around 20 feet of siliciclastic shale and sandstone have been recognized, along with the overlying Cambridge limestone (Wilmarth, 1938). Heckel et al (2011), using conodont relations, report that the Brush Creek limestone of Pennsylvania is biostratigraphically correlated to the lower Brush Creek limestone in Ohio, while the Pine Creek limestone is correlated to the upper Brush Creek limestone. The Cambridge limestone is not correlated to the Pine Creek/upper Brush Creek limestone.

Lithology and Petrology

The Brush Creek marine zone is composed of two basic carbonate lithofacies that overlie a 1-2 foot seam of bituminous coal. White (1878) described the lithologic heterogeneity in the carbonates overlying the coal, noting that "[a]t times it is a black calcareous shale, 4 to 5 feet thick, and again we see it a very compact limestone, 1 to 2 feet thick." The total thickness of the coal and carbonates is typically around 5 meters. In some localities (e.g. several road cuts in Indiana County), the coal is absent under the carbonates.

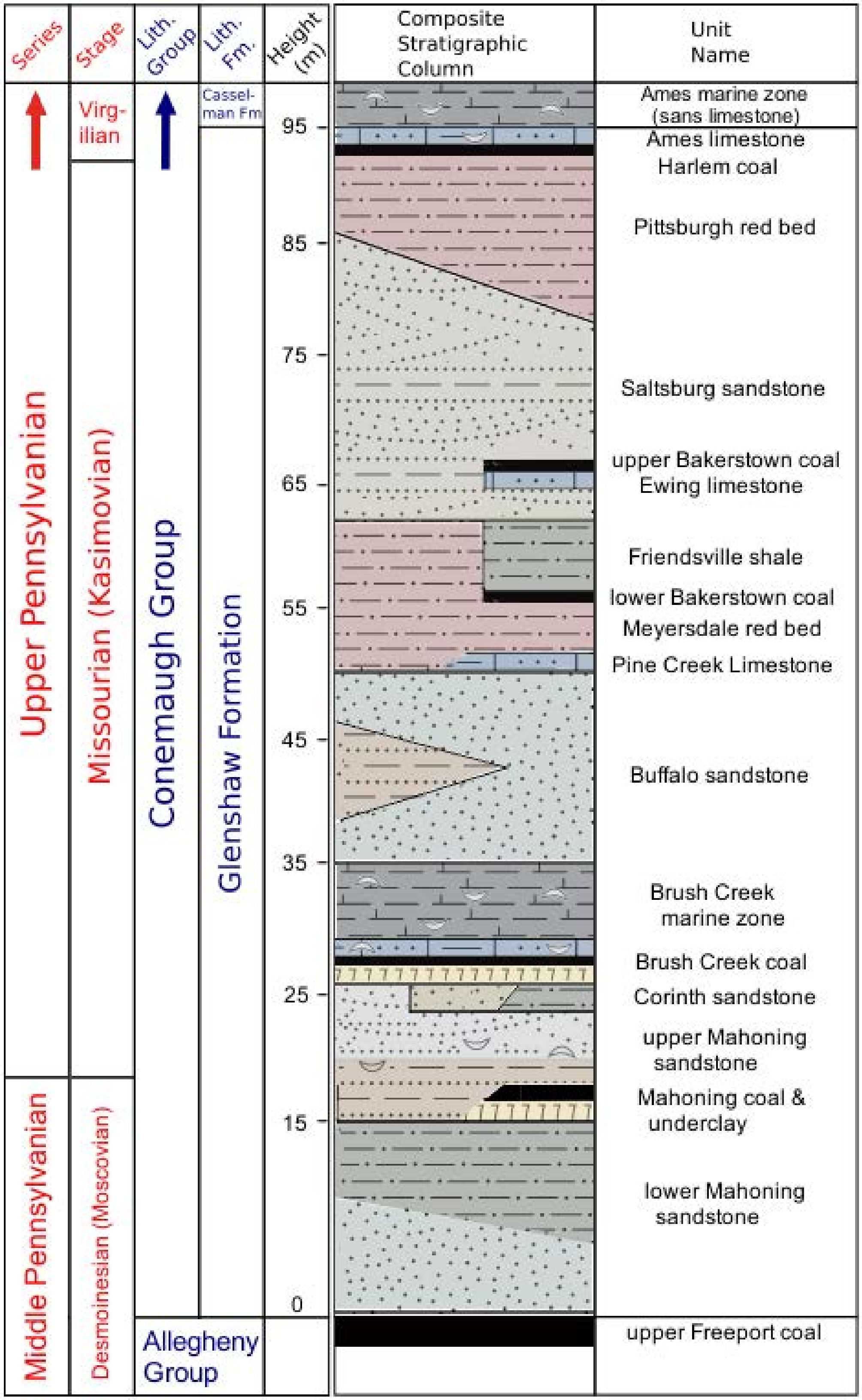

Figure 2. Composite stratigraphic column of the Conemaugh Group (for Cambria County) references: (White, 1878), (Phalen, 1910), and (Flint, 1965). Lithology symbols are those of USGS.

The Brush Creek limestone facies is a carbonaceous, often nodular limestone and its color at outcrop is dark gray (Munsell: Gley 1 3/N), with the calcareous shale facies being of similar color. The measured thickness of the limestone in the Johnstown area is 9-14 inches. Where it directly overlies the coal, it often forms an irregular, 'hummocky' contact. Stratification of the limestone, although not always readily apparent in situ, does become more apparent in broken hand sample. Thin, sub-mm, sub-parallel laminae are often present and the unit exhibits rather thick, flaggy partings under moderate shear (e.g. tapping with a hammer) that parallel the laminae. Few trace fossils are present in the marine zone.

Cutting and polishing of the limestone reveals several features not readily observed at outcrop. Numerous biogenic clasts become more visible (appear white when polished) that exhibit a wide variation in size (from sub-mm to several mm's). Photomicrographs reveal a biogenic clast-supported structure (Figure 3). Most of these clasts are fragmented mollusk shells that are sized as fine-medium sands. Overall, the Brush Creek limestone facies (as sampled in Johnstown) would be classed as a biomicrite in the Folk (1962) scheme and a packstone in the Dunham (1962) classification. In other localities, such as eastern Ohio, a wackestone lithology is also present (Klasen, 2007). Additionally, zones of golden colored iron sulfide become apparent. This is consistent with diagenetic pyritization observed in some gastropods collected in the unit. Iron is also present in other forms in the marine zone. Payne et al. (1981), working from thin sections, reported "many equant magnetite or titanomagnetite grains, generally less than 2 μm across." These were used in a paleomagnetic study that placed the magnetic pole during Brush Creek deposition in the area of the Yellow Sea (between the Korean Peninsula and China) (Payne et al., 1981).

Figure 3. Photomicrographs of polished hand sample of the Brush Creek limestone revealing biogenic clast-supported structure, iron sulfide zones (e.g. top, center), and dark, organic-rich matrix. The inset reveals the location of the photomicrograph at right.

The dark matrix that lends the shale and limestone its dark color is composed of significant terrigenous material, although micrite is also a component. Analysis of broadly similar "dirty" marine limestone and shale intervals from the Late Carboniferous of Nova Scotia revealed highly variable total organic content (several percent to over forty percent) that was primarily vitrinite and sporinite (Gibling and Kalkreuth, 1991), indicating input from relatively proximal forests/swamps. It is important to note that this does not denote a high influx of detrital sediment; in fact, the pyritization and skeletal make-up of the limestone (and to lesser degree shale) suggest sediment starvation and a period of slow deposition not affected by pulses of sediment from the Appalachian Highlands to the east that typify the period (Heckel, 1994).

The shale facies of the marine zone is fissile to platy and varies slightly in color from medium to dark gray. It overlies the limestone and in many outcrops also underlies it. The contact between the units is fairly abrupt. The shale facies possesses greater clay mineral content, and has calcareous mud content that is broadly similar in character, if not concentration, to the limestone. As with the limestone, marine gastropods, bivalves, and cephalopods are fairly common in the shales, although a rigorous comparison of the community compositions in the two facies has yet to be performed. Morris et al. (1973) reported the first known occurrence of a nearly complete ophiuroid (echinoderm) from the Upper Carboniferous (in Murrysville, PA). The specimen was found in the shale facies and the associated fauna there was described as "low in diversity". Overall, the shale indicates a deeper depositional setting than the limestone, with low energy and low oxygen waters. Unlike other basins in which these shales are more phosphatic, it appears that the Appalachian Basin shales were too shallow to allow the development of a pycnocline (usually at depths greater than several hundred meters) that would promote the accumulation of phosphates (Heckel, 1994).

Nodules are present in both the limestone and shale. Seaman and Hamilton (1950) report these as "clay-ironstone" concretions containing siderite, variable barite or calcite, pyrite, chalcopyrite, and several previously unknown polymorphs of the mineral Wurtzite (ZnS) present in shrinkage cracks (reported from near Shelocta, PA). Nodules are generally intermittent, but can form nearly linear (meters long) strands in the shales.

Discussion of sea-level and regional events

The Brush Creek limestone is the culmination of a high-order transgression that likely spanned only a few hundred thousand years and resulted from widespread glacially-driven changes in sea level, perhaps related to Milankovitch cyclicity (e.g. Bodek, 2006). An ideal example occurs at the outcrop exposed in Richland Township (behind Giant Eagle, along Eisenhower Blvd). A simple (high-order) transgressive-regressive (T-R) cycle typical of the Glenshaw Formation (but often obscured by talus or overburden) can be observed moving from the upper Mahoning sandstone to the Buffalo Sandstone. Moving up-section one encounters 1) interbedded sandstones and siltstones (regression/lower sea level), 2) underclay and coal, 3) the limestone and marine shales (transgression and highstand), and 4) the overlying siltstone and sandstone (regression).

This sequence mirrors, in fundamental form, the cyclical sedimentation described by Weller (1930) and Wanless and Weller (1932) during the development of the original cyclothem model. In fact, Weller (1930) makes explicit mention of the Brush Creek sediments and places units 1-3 from the cycle above within a 'cyclic formation' (later, 'cyclothem'). The cyclothem development was first thought to be controlled by uplift/tectonic processes, although competing ideas that controls were related to fluctuations in global sea level were proposed soon after (see discussion in Heckel, 1994).

Later workers developed an alternative cyclic sedimentation model using the concept of a "punctuated aggradational cycle" (PAC) (Goodwin and Anderson, 1980; Busch and Rollins, 1984). A PAC is a rather abrupt, but low amplitude transgression that follows a period of relative stillstand and shallows upward (Goodwin and Anderson, 1985). The PAC concept was extended to relate to complete transgressive-regressive (T-R) units and cyclothems by the "cyclothemic PAC" model (Anderson and Goodwin, 1982). A cyclothemic PAC begins with the surface denoting the onset of transgression, often taken as the base of a widespread coal. The transgressive maximum is denoted by a marine limestone and the subsequent regression denoted by overlying marine mudstones and non-marine sandstones.

For example, units 2-4 (from the Johnstown outcrop) comprise a cyclothemic PAC, beginning with the base of the Brush Creek coal and terminating at the top of the marine zone shales. The Pine Creek limestone marks the beginning of the subsequent sequence. Busch and Rollins (1984) identified eleven cyclothemic PAC sequences in the Glenshaw Formation. The PAC hypothesis states that these represent time-stratigraphic units and allocyclic events that can be used for widespread correlation. Allocyclic controls denote mechanisms that originate outside of the basin, such as tectonic effects, climate change, or eustatic change, thus, occurrence of these events is of widespread chronostratigraphic significance. For example, with the aid of conodonts, the Brush Creek cyclothemic PAC (T-R unit) has been correlated to the Macoupin cyclothem in the Illinois Basin and the Swope cyclothem in the Midcontinent Basin (Heckel et al., 2011). Cyclothemic units with periods of several hundred thousand years are often ascribed to orbitally-driven (Milankovitch) changes in eustasy.

In considering transgressive-regressive processes, it is important to recall the hierarchical nature of stratigraphic cycles and their relevance in sequence stratigraphy (Figure 4). Temporal control is

Tectono-Eustatic/ Eustatic Cycle Order	*Sequence Stratigraphic Unit*	Duraction (my)	*Relative Sea Level Amplitude (m)*	*Relative Sea Level Rise/Fall Rate (cm/1,000 yr)*
First		>100		<1
Second	Supersequence	10-100	50-100	1-3
Third	Depositional Sequence Composite Sequence	1-10	50-100	1-10
Fourth	High Energy Sequence, Parasequence and Cycle Set	0.1-1	1-150	40-500
Fifth	Parasequence, High-Frequency Cycle	0.01-0.1	1-150	60-700

(From SEPM#40)

Figure 4. Stratigraphic cycle orders with corresponding duration and relative sea level parameters. From sepmstrata.org, reproduced from SEPM shortcourse notes by Kerans and Tinker (1997).

necessary for this task. Recent chronostratigraphic work places the Brush Creek units near the base of the Missourian Stage (ICS Kasimovian Stage) Ma (see summary in Greb and Chestnut, 2009). The Ames limestone at the top of the Glenshaw Formation is estimated at 301.5 Ma and the top of the upper Freeport coal is estimated at 305.5. Following Busch and Rollins (1984) in assuming 11 cyclothemic PACs in the Glenshaw Formation, the average duration of each cycle is then about 275,000 years. The Brush Creek marine zone then denotes a transgressive maximum within a 4th order T-R cycle (Figure 5). Using the definitions of Figure 3, Appalachian Basin cyclothems originally described by Weller (1930) are 4th order cycles (note that order definitions are not standardized).

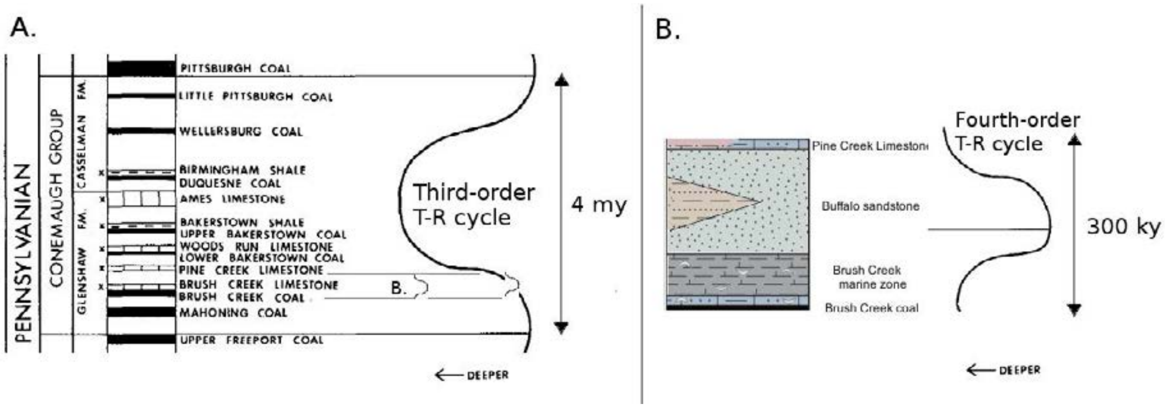

Figure 5. A. Depiction of the allocyclic (subsidence-controlled) third-order cycle of the Conemaugh Group (after Busch & Rollins, 1984). B. The allocyclic (eustatic-controlled) fourth-order cycle that is expressed between the Brush Creek coal and the Pine Creek Limestone.

The Brush Creek to Pine Creek 4th order interval can also be interpreted in terms of systems tracts (units defined by their deposition within a particular phase of sea level rise, fall, or relative stillstand). Systems tracts are the stacked depositional units that make up sequences. One model is that of a sequence composed of four systems tracts that span a complete T-R cycle (Figure 6). The four systems tracts are: lowstand systems tract (LST), transgressive systems tract (TST), highstand systems tract (HST), and falling stage systems tract (FSST). In many cases, however, delineating so many systems tracts and their boundaries is problematic at outcrop or with otherwise limited data. Accordingly, many workers group the HST, FSST, and LST into a single "regressive systems tract" (RST) (e.g. Johannessen et al., 1995).

Klasen (2007) performed a sequence stratigraphic analysis of the upper to lower Brush Creek interval in Ohio. The base of the Brush Creek coal, along with the underlying clay and upper Mahoning sandstone, is ascribed to a period of lower sea level, but with the overlying Brush Creek limestone, denotes a transition to marine facies. These units are interpreted to form the TST of sequence 1. It is thought deposits of the LST would not occur in the Appalachian Basin, but in correlatives in more westward basins (Klasen, 2007). Combined with the lithologic evidence of sediment starvation, the limestone has been interpreted as representing a condensed section where sedimentation rates were very low (often under 1 mm/yr) (Heckel, 1994). Condensed sections typically occur near the end of a TST as the rate of sea level rise and accommodation creation decrease, but water remains relatively deep.

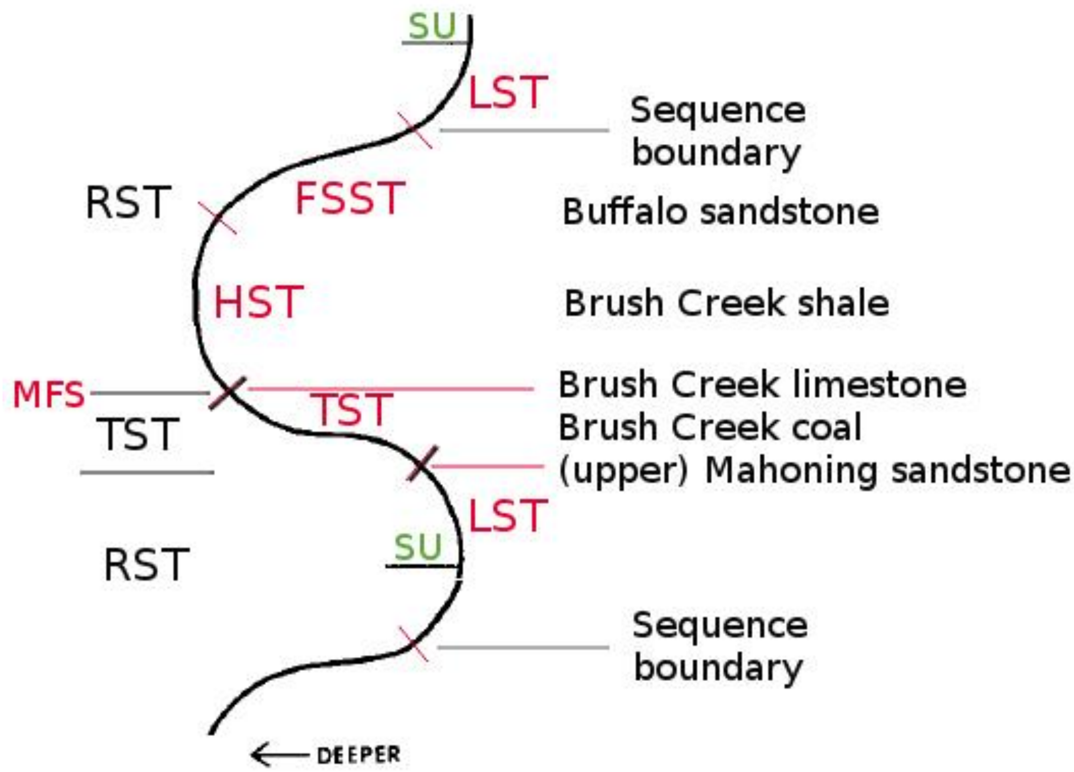

Figure 6. Model demonstrating systems tracts and their relation to relative sea level with approximate positions of the units of the lower Glenshaw Formation denoted. RST = regressive systems tract, TST = transgressive systems tract, MFS = maximum flooding surface, LST = lowstand systems tract, HST = highstand systems tract, FSST= falling stage systems tract, and SU = subaerial unconformity.

A maximum flooding surface (MFS), when sedimentation rates were very similar to the rate of increase in sea level (and accommodation), generally caps a condensed section and forms the boundary between the TST and HST. Accordingly, the MFS lies in the Brush Creek limestone. The transition to deeper marine calcareous shales is then ascribed to a HST (Klasen, 2007). This is the beginning of the RST. Sediment accumulation, while not very great here, exceeded the rate of sea level rise and creation of accommodation space, which become nearly zero. Subsequent to this was a period when sea level and accommodation space were decreasing and, eventually, reach a stillstand. This results in a seaward migration of depositional systems and, eventually, the onset of subaerial exposure, erosional surfaces, and sediment bypassing. Martino (2004) analyzed the Glenshaw Formation in a sequence stratigraphic framework, employing paleosols as important markers for systems tracts. The part of the RST corresponding to this “forced regression” would begin in the lower portions of the Buffalo sandstone, which does denote a prograding upper deltaic/fluvial system.

Martino (2016) notes that the Buffalo sandstone (in West Virginia) contains an incised valley fill cut during the RST and filled by the subsequent TST. This is consistent with Klasen (2007) in placing the Buffalo sandstone (and equivalents) within the RST. The overlying Pine Creek (or upper Brush Creek) limestone was not incised by this event, while some of the fill deposits aggrade up to the limestone (Martino, 2016). This indicates that the TST and the beginning of the next sequence is represented by the Pine Creek limestone. Thus, the TST of sequence 1 contain the upper Mahoning sandstone, the Brush Creek coal, underclay, and Brush Creek limestone. The RST of the sequence is composed of the Brush Creek shales and the Buffalo sandstone. Similar to the Brush Creek limestone, the Pine Creek limestone is thought to represent a condensed section and contain the maximum flooding surface.

The transgression represented by the Brush Creek deposits is nested within a larger transgressive trend that culminated in the thicker Ames limestone, and may represent a slower cycle related to foreland subsidence in that part of the basin (e.g. Ettensohn, 2008). Within the Conemaugh Group, the Ames marine zone is the thickest and most laterally extensive marine unit and is thus attributed to maximum transgression within the group. This transgression was preceded by the regressive maximum at the base of the upper Freeport coal and succeeded by the next regressive maximum at the base of the Pittsburgh coal. These coals are noted for having been locally removed by valley incision around times of low stand and subsequently filled (in part) with fluvial-estuarine sediments (see Martino, 2016 and discussion in Bragonier et al., 2007). The well-developed paleosols and fireclays underlying the coal also point to regression and long periods of subaerial exposure. Approximately 4 million years separate the upper Freeport coal from the Pittsburgh coal, thus, this interval represents a complete 3rd order T-R cycle (see Figure 5).

Interestingly, in Phalen's 1910 Johnstown Folio for the USGS, the author moves directly up-section from the Brush Creek (Gallitzin) coal to the Buffalo sandstone member with no mention of the Brush Creek marine zone above the coal, despite its known occurrence in the area, including the field stop in Richland Township (Phalen, 1910). Richardson (1936) noted the Brush Creek marine zone was almost entirely absent in quadrangles (Butler and Zelienople) neighboring the type locality of the Brush Creek Limestone. These episodic absences of the unit may be typical of high-shelf deposits that were dissected by erosion during subsequent high-order (4th order) regressions (Heckel et al., 1998).

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Yes, but look at the bright side, Martha—
we don't live anywhere near Mt. St. Helens!

EVIDENCE OF A SINGLE-EVENT DEPOSIT OVERLYING THE UPPER FREEPORT COAL SEAM IN CENTRAL WESTERN PENNSYLVANIA

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Abstract

The Toms Run Mine is a deep coal mine on the Upper Freeport coal seam operated by Rosebud Mining Company in southeastern Indiana County, Pennsylvania. A portion of the reserve area is overlain by *draw rock*, or rock in the immediate roof that falls as the coal is mined or soon after. The draw rock varies in thickness from nothing to over ten feet and the thickness has been mapped using available drill hole data and in-mine measurements. The draw rock is a clayey siltstone that typically has a churned, non-bedded appearance with a crude, color banding upward and contains numerous vitrainized plant fossils interpreted as logs and branches. Genetically, the argument is made herein that draw rock was emplaced catastrophically as a single depositional event. Paleontological and sedimentological evidence are provided to support the single-event hypothesis. The possibility of a more regional distribution of the draw rock, and, by extension, of the catastrophic single event, is also considered.

Introduction

The term *draw slate* or *draw rock* is a coal mining term that refers to an out-of-seam rock type which is usually a shale, coaly shale or bony shale in the immediate roof of a coal mine that falls either immediately or soon after the coal seam is mined. This is an undesirable type of roof rock since it becomes a contaminant in the run-of mine coal product and necessitates the need for coal beneficiation. The term commonly refers to rock less than two feet in thickness (McGraw-Hill, 2003) and the contact between coal and the overlying roof shale is often gradational.

Rosebud Mining Company's Toms Run Mine is a underground mine on the Upper Freeport coal seam located in Burrell Township, Indiana County Pennsylvania northeast of the town of Blairsville (Figure 1). The mine entrance is a drift off of the coal crop located on the northwest flank of the Chestnut Ridge anticline. The Upper Freeport coal averages approximately 50 inches in thickness over the reserve area. Most of the mining is slightly south and west of the mine entrance and extends down dip past the axis of the adjacent Latrobe Syncline, where the Upper Freeport coal acquires a cover of over 800 feet. Dips on the flank of the anticline exceed 10o but the coal is relatively flat on either side of the synclinal axis. Structural elevations within the mine range from 1160 feet to near 400 feet above mean sea level.

Figure 1 shows the final mine workings for the Tom's Run Mine. There is a large no-coal area west and slightly south of the mine defined by drill holes labeled *Flint Clay Area-No Coal*. The purple stippled area illustrates the extent of draw rock overlying the Upper Freeport coal in the Tom's Run reserve area. The area is largely defined by drill holes but also intersected by mine workings in several places.

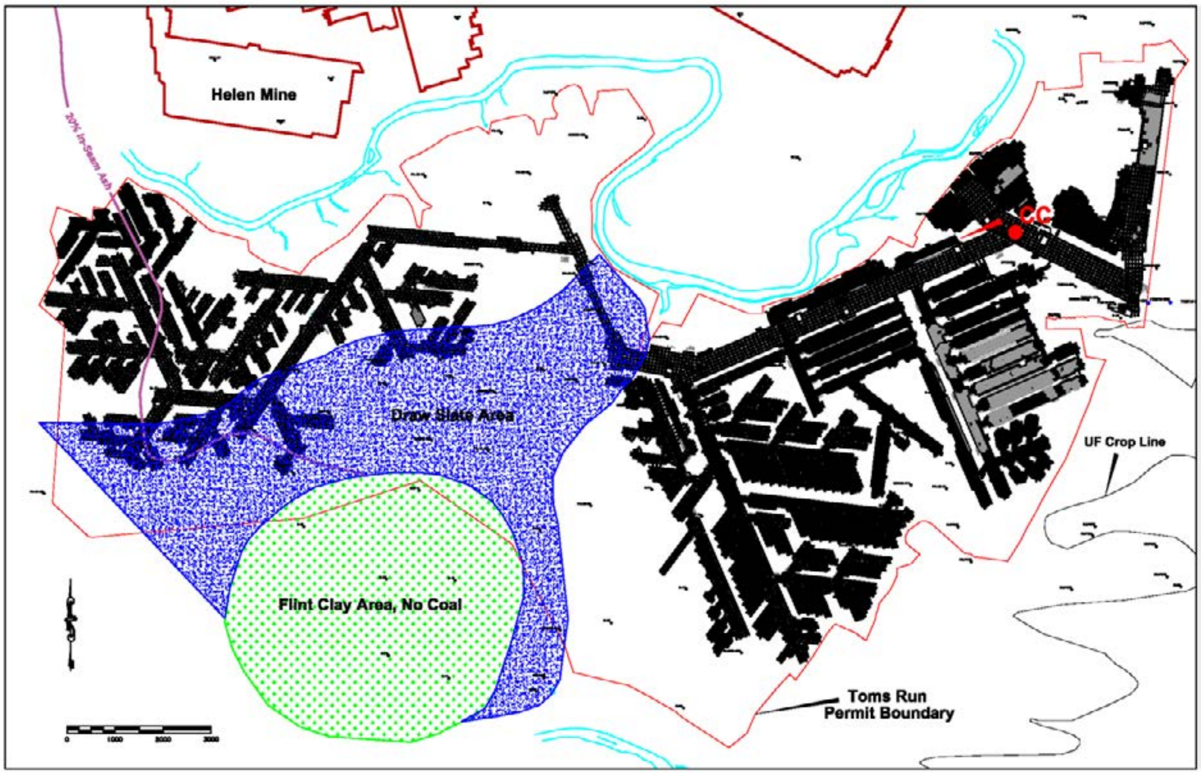

Figure 1. Map of Toms Run Mine showing the extent of the draw rock occurrence, the no coal (flint clay) area and areas of high (greater than 20%) in-seam ash.

Draw Rock Characteristics

Thickness Distribution

Figure 2 illustrates the thickness distribution in feet of the draw rock in the Tom's Run reserve area. The isopach map was constructed from drill hole data and in-mine thickness measurements. Several features are noteworthy. The distribution of the draw rock is geographically limited within the reserve area but thickens dramatically over short distances and achieves a maximum thickness of over 10 feet. Further, the draw rock thickness distribution appears center around the no-coal area south west of the Tom's Run reserve area.

Influence on Mining

The result of mining difficulties under the draw rock may be observed in the northeast corner of Figure 2. Note that the number of north-northwest trending mine headings under the draw rock has been reduced to three. The draw rock achieves a maximum thickness of over five feet above the mine workings as indicated on the isopach map. The heading reduction is due to the fact that the draw rock could not be supported and fell out immediately after the coal was mined and was consequently loaded with the coal. This area, designated as 'E Mains', was mined simply to provide an access to the coal on the northern side of the draw rock.

As noted above, draw rock is typically under a foot thick and commonly results from an upward gradational change from coal to shale. Figure 3 is a photograph taken in the eastern-most of the three headings in E Mains. The photo is facing northwest (i.e., inby). The contact between the coal and the overlying draw rock is obscured by rock dust but is visible on the right side of the photograph about half way between the top and bottom of the entry. Note that the contact is ***not*** gradational, but a sharp line that separates the darker toned coal from the overlying lighter draw rock. The entry is approximately 18 feet wide and 10 feet high. The solid roof shale is shown at the top of the photograph and is supported with roof bolts.

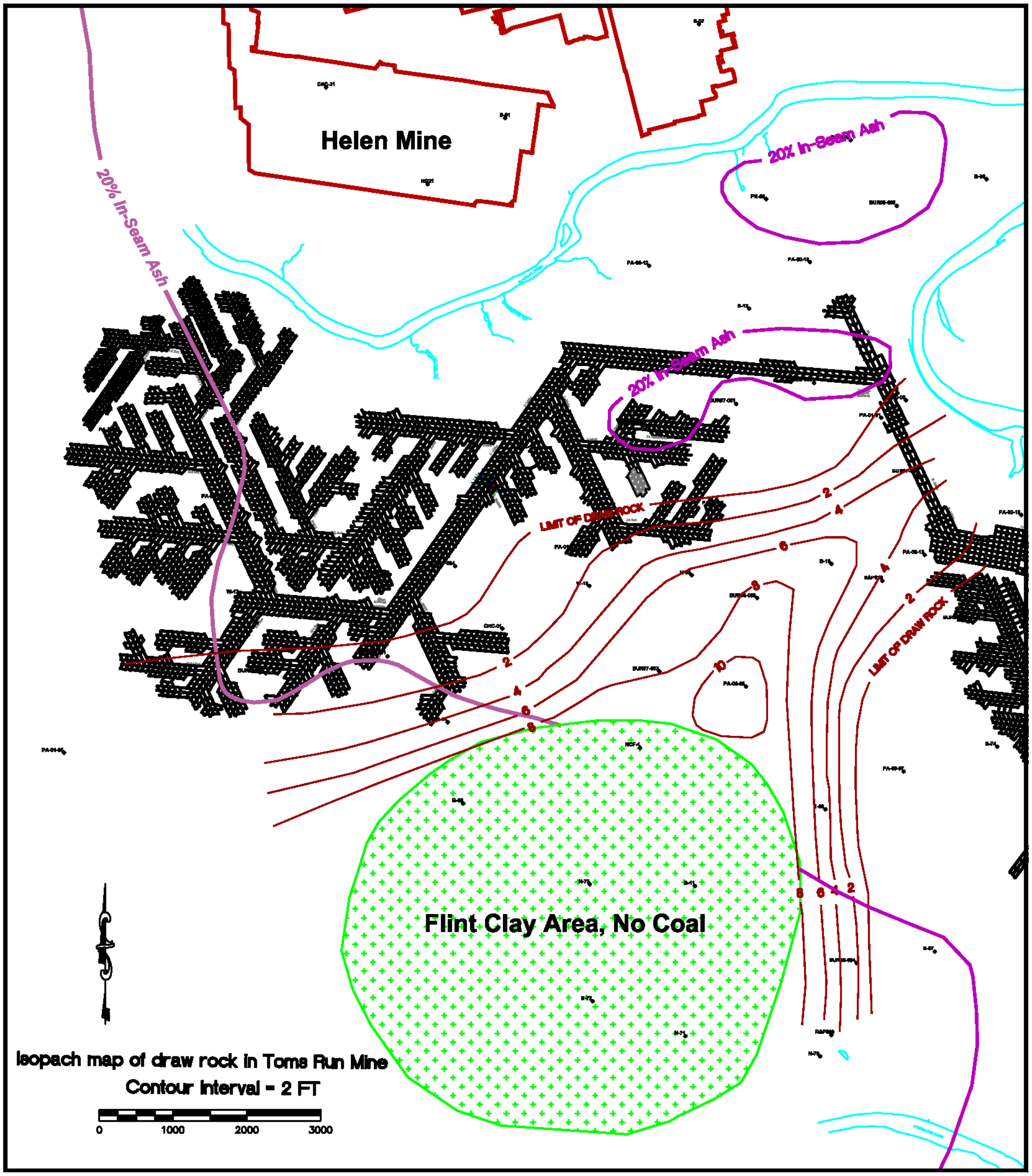

Figure 2. Isopach map of the draw rock overlying the Upper Freeport coal in the Toms Run reserve area. Thicknesses are in feet. Also shown are the no coal (flint clay) area and areas of high (greater than 20%) in-seam ash.

Lithology

Figure 4 shows the general texture of the draw rock in the Tom's Rum mine. In this image the draw rock is approximately 18 inches thick and can easily be distinguished from the underlying coal seam and the overlying roof shale. The striking difference between the roof shale and the draw rock is the bedding. While there is some semblance of bedding in the upper half of the draw rock, the lower half has a churned, non-bedded appearance. This stands in sharp contrast to the thin parallel laminae of the roof shale.

Figure 3. Image of the intake air heading in E Mains of the Toms Run Mine where over 5 feet of draw rock was mined. Rock dust obscures the deposit but the top of the coal is discernable just under half way up on the rib. The heading is approximately 18 feet wide and 10 feet high.

Figure 4. Image of draw rock showing vitrain streaks and numerous small slickensides. Compare the more chaotic texture of the draw rock with the laminae in the overlying Uffington shale. The distance between the blue and white tape on the hammer is 6 inches.

While not directly observable in Figure 4, the grain size of the draw rock is predominately silt but commonly intermixed with clay. The choppy appearance of the draw rock is in part due to slickensides indicative of the presence of clay. In Figure 5 the draw rock has a similar non-bedded appearance with obvious slickensides. Also, note the presence of dark fragments of plant material within the draw rock in both Figures 4 and 5.

Figures 6 and 7 show another relevant aspect the draw rock. There is a crude color banding, most commonly restricted to the top half of the unit. Again, as in Figure 4 there is a distinct difference between the bedding in the draw rock and the finely laminated strata of the overlying roof shale visible at the very top of the image.

Figure 5. Image of draw rock showing numerous slickensides and a chaotic texture. Note the difference in the texture of the draw rock with the laminae in the overlying Uffington shale. The distance between the blue and white tape on the hammer is 6 inches.

Figure 6. Image of draw rock showing vitrain streaks and a crude layering or color banding compared with the distinct laminations in the overlying roof shale. Note that the more defined layering in the draw rock is near the top of the deposit and is interpreted as an interference ripple effect of an initial strong wave pulse. The distance between the blue and white tape on the hammer is 6 inches.

Figure 7. Image of draw rock showing vitrain streaks, slickensides and a crude color layering as compared with the overlying roof shale at the top of the image. As in Figure 6, the more defined layering is in the upper half of the draw rock deposit, indicative of interference ripples after an initial strong wave pulse. The distance between the blue and white tape on the hammer is 6 inches.

Organic Content

Vitrified plant fragments, mostly parallel to sub-parallel with the bedding, may be seen in Figures 4 through 7. In many areas of the mine the vitrain fragments are not only more plentiful, but much larger than those in the above images. Figure 8 was taken in an area of the mine that is some distance from the working face where the rock has had time to 'weather.' Chemical weathering of the draw slate has produced yellow sulfur oxides that define vitrain fragments within the deposit, the obvious source of the sulfur. The vitrain fragments are interpreted to be tree branches and logs. In Figure 8 the organic fragments are sub-horizontal and generally follow bedding planes that are themselves sub-horizontal, but as shown in Figure 9, the plant material can occur at high angles to bedding.

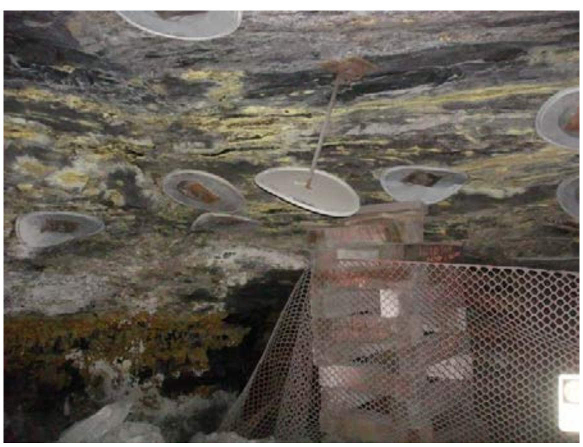

Figure 8. Exposure of draw rock in an outby heading of the Toms Run Mine where yellow sulfur oxides define vitrain within the deposit. The vitrain is interpreted to be flattened logs and/or branches. The circular roof bolt plates are 18 inches in diameter.

Figure 9. Exposure of draw rock showing a log deposited at a high angle to horizontal. As in Figures 6 and 7, note the crude color layering confined to the upper half of the draw rock deposit. The distance between the blue and white tape on the hammer is 6 inches.

In the center of Figure 10 there is an area of darker sediment that is completely surrounded by a layer of vitrain. This is interpreted as a compacted log that was partially filled with sediment and deposited within the draw rock. Several of these were noted in Toms Run mine and they demonstrate that plant material of considerable size exists within the draw rock.

Additionally, plant material of considerable size exists in the immediate roof of the Toms Run Mine, *but only in areas directly under or immediately adjacent to the draw rock*. Figures 11 through 14 illustrate not only the immense size of these logs, but their multi-directional distribution within the immediate roof.

Figure 10. Exposure of draw rock showing a dark area near the center of the image surrounded by vitrain. This is interpreted as a partially flattened log in cross section. Note that the sediment inside the log is darker than the surrounding sediment, indicating that it was partially filled with sediment and then transported. Also note the rock fragment near the top of the image. The distance between the blue and white tape on the hammer is 6 inches.

Figure 11. A large Sigillaria tree traverses the entire intake air entry in the Toms Run Mine. The entry is approximately 20 feet wide. Large tree fossils only occur directly over or near the peripheral edges of the draw rock. They are not present where the Uffington shale lies directly on the coal. The roof bolt plate is 6 inches square.

Figure 12. Flattened and randomly oriented fossil logs in the roof of Toms Run Mine. These logs occur only directly over or near the peripheral edges of the draw rock. They are not present where the Uffington shale lies directly on the coal. The roof bolt plate is 6 inches square.

Arguments for a Single-Event Deposit

Paleontological

A single event deposit with respect to the draw rock refers to the subaqueous deposition of a stratigraphic unit involving a high-energy flow regime triggered by a catastrophic event. The time of deposition would, in all probability, be measured in hours. The cause of such an event is unknown, but breaching of a natural dam, a storm or a tsunami are considered possibilities.

Figure 13. Flattened and randomly oriented fossil logs in the roof of Toms Run Mine. These logs occur only directly over or near the peripheral edges of the draw rock. They are not present where the Uffington shale lies directly on the coal. The roof bolt plate is 6 inches square.

The cross-sectional view of an entire compressed tree trunk in Figure 10 is arguably the most revealing testament to a single event deposit. Note that the sediment inside the compressed tree is darker than the surrounding sediment, indicating that the sediment inside the log existed prior to its deposition. The weight of a large tree partially filled with sediment would require a substantial amount of energy to transport. This is in stark contrast to the large trees shown in Figures 11 through 14 in the roof of the mine above the draw rock. With the possible exception of the large lycopsid in Figure 11, all of the logs in the roof images are, in taphonomic terms, transported compression assemblages, which contain a very minimal amount of sediment within the logs themselves. Furthermore, these logs have random orientations with respect to each other. There are two possible explanations for this. The trees could simply have died at different times and fallen over in different directions or they could have been washed in *en masse* and deposited as a logjam. The latter explanation is preferred since these trees only occur directly over or near the peripheral edges of the draw rock. It is

In genetic terms the thickness distribution, lithologic characteristics and organic content of the draw rock are all interpreted as indicative of a single event deposit. The nature of the organic content is the most striking manifestation of this explanation. As shown in Figure 8 a majority of the organic matter is fragments of vitrain ranging in size from six inches to two feet. These are interpreted as remnants of branches and/or tree trunk material and their abundance and size is indicative of a higher energy flow regime. Furthermore, while most of this plant material has been deposited sub horizontally, Figure 9 illustrates that a small percentage exists at high angles to bedding. Assuming compactional effects would reduce the angle of primary deposition, it may be argued that the original deposit contained plant material rather chaotically amassed.

Figure 14. Large flattened Sigillaria tree in the roof of Toms Run Mine. Large tree fossils only occur directly over or near the peripheral edges of the draw rock. They are not present where the Uffington shale lies directly on the coal. The round roof bolt plate is 18 inches in diameter.

suggested that sediment-laden logs were heavier and deposited within the draw rock while others simply floated and were deposited on top of the draw rock sediment only after floodwaters receded.

Sedimentological

The lithologic components described above are also suggestive of a single event deposit. Figures 4 and 5 illustrate the more jumbled, chaotic texture often seen in the draw rock, commonly highlighted by numerous small-scale slickensides. The distinction between the finely laminated roof shale and the more diffuse color banding of the draw rock has been noted (See Figures 5, 6 and 7). Note that the banding in Figures 6 and 7 is restricted to the upper half of the draw rock, which is typical of the deposit in general. Whereas, the genesis of the draw rock is being interpreted herein as a “single-event” deposit, a “single” onrush of sediment-laden water will produce “multiple” refraction waves within the area of deposition. The crude color banding observed in many exposures within the Tom’s Run Mine, mostly restricted to, or at least more pronounced, in the upper portion of the deposit, is therefore interpreted as deposition from multiple refraction waves. Notice that within a single color-banded layer the color is darkest on the bottom and lightens up, which is also an indication of fining upward, as would be expected.

Finally, the areal distribution of the draw rock strongly suggests rapid deposition. Figure 2 defines the geometry of the draw rock over the Tom’s Run reserve area. Several aspects of the distribution are noteworthy. First, the deposit is aerially restricted. Additionally, there is a thickness variation from zero to 10 feet and back to zero over a relatively short distance and the deposit exhibits a lineal geometry.

Note that the thickest draw rock is adjacent to the no coal area that is composed of flint clay. This requires a brief discussion of the genetic relationship between coal and flint clay. Upper Allegheny coals commonly grade into brecciated flint clays. Bragonier (1989) suggests that flint clays in close proximity to a coal seam form as a result of the swamp deepening into a shallow lake. The chemistry of the waters within lakes associated with Upper Allegheny coal seams would likely have a pH of neutral to alkaline since fresh water limestones commonly occur immediately beneath the underclays of these coal seams (and laterally adjacent lithologies). However, the pH near the peripheral margins of these lakes would likely be altered due to the presence of acidic swamp waters. The effect of organic acids on the flocculation of clay particles is well documented. [Hopkins (1898), Stout et. al., (1923), Hodson (1927), Schofield and Sampson (1954), Falla (1967), Keller (1968), Chukhrov (1970), Staub and Cohen (1978), and Keller (1981).] Consequently, as peat accumulates, flocculated flint clay correspondingly amasses along the lake margins and roughly approximates the thickness of the peat. However, the compaction ratio of peat is much greater than that of clay and numerous drill holes have demonstrated a much thicker flint clay section in close proximity to mineable upper Allegheny coals. (Bragonier, 1989).

Returning to the discussion of the draw rock distribution, it is quite conceivable that the Upper Freeport peat was either partially compacted prior to deposition of the draw rock (i.e., under its own weight) or was, in fact, compacted by the draw rock. This would result in the relatively uncompacted flint clay creating a topographic high that would act as a barrier to an onrushing torrent of sediment and logs, thus explaining the exceptional draw rock thickness juxtaposed to the flint clay.

Further evidence of high regime flow may be observed in an outby area of the Toms Run Mine. Figure 15 is an image of a current crescent located in sandstone roof at point CC on Figure 1. Current crescents are horseshoe shaped features formed as a current passes around a standing obstacle and causes sediment accumulations (in this case, sand) on the up-current side of the obstacle and on the both sides of the obstacle appearing as two wings formed by the stream flow deflected around the obstacle (Pye and Tsoar, 1990). As such, they are important current direction indicators. Although there are no apparent remains of the obstacle, vegetation is a likely candidate. (Rygel et. al., 2004). What is significant about the current crescent shown in Figure 15 is its immense size. Most current crescents are on the order of one or two feet. The mine post pictured in Figure 15 is over four feet in height (note hammer in lower right corner of image for scale). The long axis of the current crescent is approximately eleven feet. It is interpreted herein that the deposition of such a large feature must require an exceptionally strong current flow. The direction of the current flow is southwest at approximately the same angle as the main headings of the Toms Run Mine southwest of point CC (Note arrow direction on Figure 2). The southwesterly direction roughly aligns with the depositional strike of the draw rock shown in Figure 2, a feature not considered coincidental.

Figure 15. Exposure of a large horseshoe-shaped sandstone deposit in the roof of the Toms Run Mine. The sandstone is thickest near the apex of the bend and thins to nothing on both sides of the horseshoe. The deposit is interpreted to be a large current crescent created as sand was deposited around a stationary object such as a large tree. The current moved from right to left in the image. What is significant about the deposit is its size. The mine post is over 4 feet in height. Note hammer for scale. The size of the current crescent is interpreted as an indication of high-regime flow.

Regional Setting

Figure 16 illustrates some of the regional features associated with the Upper Freeport coal in central western Pennsylvania. Of particular interest is the northwest trending split seam area outlined in blue that traverses an area from northern Westmoreland County, through Indiana and Armstrong Counties and into eastern Butler County. The blue lines roughly define the 20% in-seam ash isopleth of the Upper Freeport coal. Within this area the coal obtains multiple "splits" or shale partings. In fact, some drill holes near the center of this area contain mostly shale with coal streaks and very little coal. This high ash zone is modified from Clark (1979).

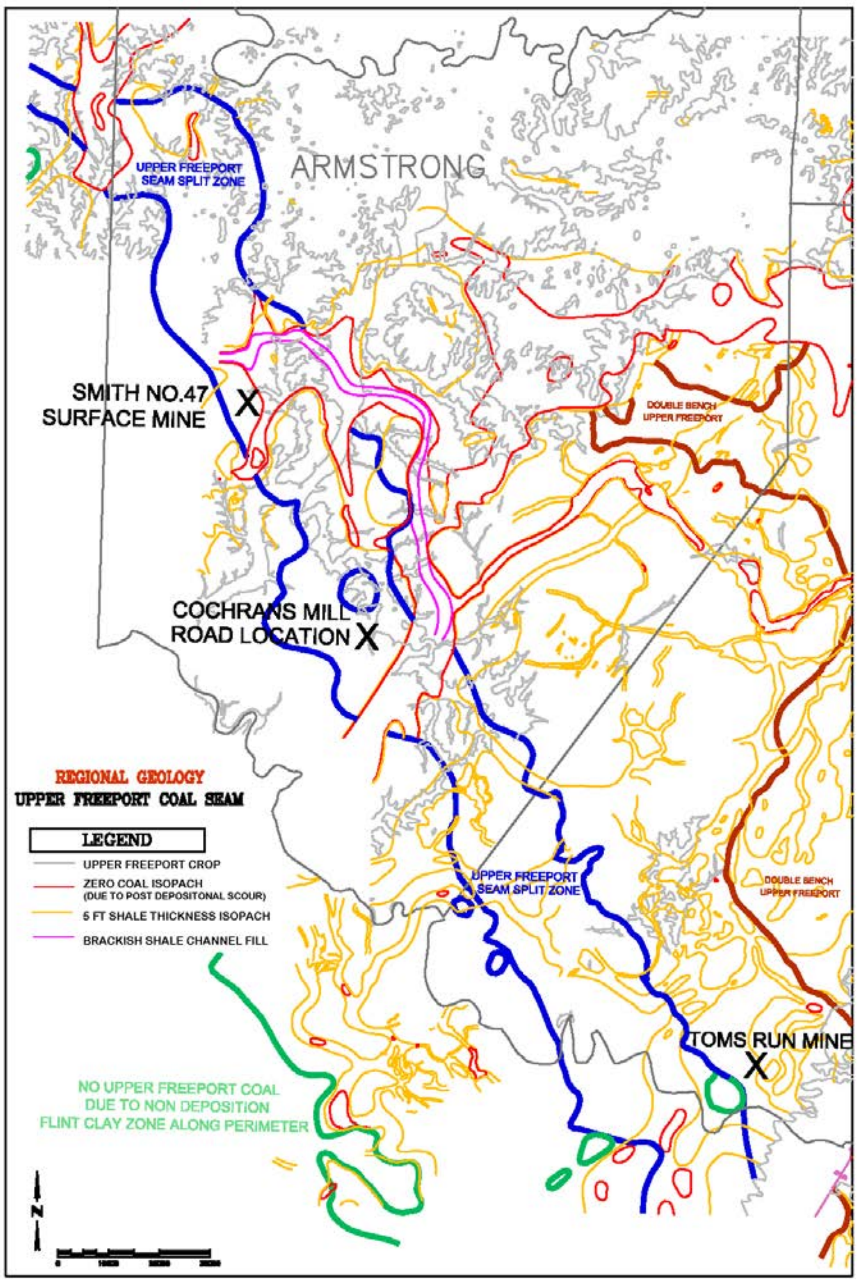

Figure 16. Map illustrating the paleogeography of the Upper Freeport seam split zone in a portion of central western Pennsylvania. The blue lines, which are modified from Clark (1979), roughly correspond to the 20% in-seam ash isopleth.

Between the lines the Upper Freeport coal contains numerous shale partings.

Also shown are the locations of the Toms Run Mine, the Cochrans Mill Road Upper Freeport exposure and the Smith No. 47 Surface Mine.

Figure 17 shows an exposure of the Upper Freeport high wall in the Smith No. 47 surface mine. As may be seen on Figure 16, the Smith No. 47 mine lies within the northwest striking in-seam split zone. The Upper Freeport in this area is near the perimeter of the high ash split zone, but numerous in-seam shale partings are visible in Figure 17. Also note in Figure 17 approximately one foot of soft clayey draw rock immediately above the coal. This lithology is strikingly similar to the draw rock in the Toms Run Mine. These two mines are roughly 30 miles from each other and the presence of draw rock in both prompted speculation that the single event deposit in Toms Run may be a more regional event somehow associated with the Upper Freeport split seam zone.

Figure 17. Exposure of the Upper Freeport coal at the Smith No. 47 surface mine in western Armstrong County approximately 30 miles northwest of the Toms Run Mine. The upper Freeport coal is within the in-seam split zone shown in Figure 16 and numerous shale partings are visible within the seam. Overlying the Upper Freeport coal is approximately 1 foot of a soft clayey draw rock that appears very similar to the draw rock in the Toms Run Mine.

This speculation was further encouraged by the presence of 47 inches of black and dark gray shale with plant fossils overlying the Upper Freeport coal at a natural exposure and road cut near the Cochrans Mill /Polka Hollow Road area in south central Armstrong County (location shown on Figure 16). Note that the latter location is more centrally located within the split seam zone.

There are numerous drill holes located within and adjacent to the Upper Freeport split zone and an attempt was made to develop an isopach map of the draw rock along the strike of the split zone. For various reasons the attempt was problematic. Many of the drill hole logs did not record the presence of coal streaks or plant fossils above the Upper Freeport seam even though they may have existed. Holes where a definite draw rock thickness could be determined were too few to develop a consistent trend. In the central split seam zone many drill holes recorded sporadic thin coals rendering a clear definition of seam limits impossible. Post-depositional scouring of part or all of the seam added a further complication.

The attempt to develop an isopach map of the draw rock within and adjacent to the Upper Freeport seam split zone did yield several important generalizations including the following:

- There are numerous data points within the seam split zone that contain a lithology similar to draw rock overlying the split Upper Freeport seam.
- The thickness of the draw rock within the split zone increases toward the center.
- There is very little or no draw rock above the Upper Freeport coal adjacent to the split zone.
- The thickness of the draw rock decreases from southeast to northwest along the strike of the split zone.
- The width of the split zone thins substantially into Butler County (i.e. to the northwest).

The above observations suggest the Toms Run Mine draw rock has a more regional extent that is related to the northwest-striking seam split zone. However, based on the available data, which includes drill holes, deep mine observations and surface exposures, conclusions regarding depositional trends are difficult, if not contradictory. The large current crescent in Toms Run Mine and the thickest draw rock occurrence adjacent to and northeast of the no-coal flint clay area strongly suggest a flow direction from northeast to southwest. However the decreasing thickness of the draw rock in the Upper Freeport seam split zone from southeast to northwest suggests a southeastern source.

The exposures at the Cochrans Mill/Polka Hollow Road area in south central Armstrong County are also conflicting. Here a substantial thickness of draw rock (47 inches) overlies a split coal seam. In the streambed of an unnamed tributary of Crooked Creek that parallels Polka Hollow Road, hundreds of haphazardly oriented fossilized tree trunks are exposed that strongly resemble those in Figures 13 and 14. Genetically, there are two taphonomic mechanisms that will produce this configuration. One is the autochthonous model of water stressed conditions (including drowned, sub-aerially exposed, salinity variations and/or sediment influx); the "clastic swamp" of Gastaldo (1986, 1987). The other, the allochthonous model, assumes catastrophic deposition (i.e., a log jam). An argument for the latter has been made with respect to the Toms Run Mine draw rock and would seem, by extension, to apply to the draw rock at the Cochrans Mill/Polka Hollow site. However, there is a problem. The fossil rich partings within the split Upper Freeport seam are no different in appearance than the draw rock above the seam, yet they are intercalated with bands of apparently in-situ coal. The band thicknesses vary but generally increase toward the bottom of the seam. Within the split Upper Freeport seam, then, it may either be assumed there were multiple allochthonous events that interrupted a stable peat forming environment or a peat-forming swamp was intermittently subjected to water stressed conditions, resulting in multiple "clastic swamp" conditions. This amounts to a conundrum. Multiple layers of banded coal suggests the latter option seems more reasonable, that is, there were not multiple catastrophic events. However, the similarity of the draw rock in the Toms Run Mine, the Cochrans Mill/Polka Hollow exposure and the Smith 47 surface mine cannot be summarily dismissed. In an established drainage channel, raging torrents are intermittently possible.

Conclusions

Evidence has been presented to demonstrate that the draw rock overlying part of the Toms Run Mine reserve area was deposited as the result of a single catastrophic event. Both sedimentological and paleontological features of the deposit suggest rapid deposition.

Site specific paleontological evidence includes:

- Abundant remnants of branches and/or tree trunk material scattered throughout the deposit (Figure 8). While most of this plant material is oriented sub horizontally, a small percentage exists at high angles to bedding.
- The cross-sectional view of an entire compressed tree trunk partially filled with dark sediment surrounded by lighter colored draw rock (Figure 10) indicating the log had to be transported.
- The existence of large, randomly oriented tree trunks in the roof rock overlying the draw rock deposit interpreted as a floating log jam that constituted the final depositional facet of the catastrophic event. These logs are restricted to areas in the mine roof either directly over or near the peripheral edges of the draw rock.

Site specific sedimentological evidence includes:

- The deposit is aerially restricted. There is a thickness variation from zero to ten feet and back to zero over a relatively short distance and the deposit exhibits a lineal geometry.
- A churned, chaotic texture of the draw rock highlighted by numerous small scale slickensides
- Color banding largely restricted to the upper half of the deposit interpreted as a result of diffraction waves created by an initial catastrophic deluge.
- The existence of a large-scale current crescent (indicative of high-regime flow) in an outby section of the Toms Run Mine, the current direction of which matches the lineal geometry of the draw rock deposit.

The presence of draw rock above the Upper Freeport coal seam in a surface mine approximately 30 miles northwest of the Toms Run Mine prompted the investigation of the possibility of a more regional extent of a single event deposit. From drill hole records within and adjacent to a previously identified northwest trending split seam zone in the Upper Freeport coal, it was determined that draw rock was, indeed, associated with the split seam zone. However, a definitive isopach map of the draw rock within the seam split zone was not possible to generate. Furthermore, conclusions regarding draw rock depositional trends were contradictory. A surface outcrop of the Upper Freeport coal within the split seam zone in south central Armstrong County revealed further contradictions. The draw rock exhibits all of the features of a transported compression assemblage, but similar exposed lithologies within the split Upper Freeport coal are intercalated with apparently in-situ layers of coal. Consequently, the distinction between allochthonous and autochthonous compression assemblages becomes problematic.

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STRATIGRAPHY OF FLINT CLAYS OF THE ALLEGHENY AND POTTSVILLE GROUPS, WESTERN PENNSYLVANIA

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Introduction

Keller (1968, p. 113) defined flint clay as a dominantly kaolinitic underclay that breaks with a conchoidal fracture and resists slaking in water. Flint clays occur between, or are associated with, most coal horizons of the Allegheny and Pottsville Groups of western Pennsylvania. An understanding of the coal-flint clay relationship is important to the prediction of clay occurrence, and also to coal stratigraphy.

Flint clays are physically, mineralogically, and chemically intermediate between plastic clays and high alumina nodule clays. They are commonly of local extent, brecciated, multicolored, hard and contain an abundance of well-crystallized kaolinite. Considerable attention has been devoted to an understanding of the origin of flint clays and the subject has not been without controversy. Late nineteenth and early twentieth century investigators into the origin of various types of Carboniferous clays rapidly found themselves polarized over the question of a residual versus a transported origin. The evolutionary outcome of this controversy, with respect to flint clay, involves the role of differential colloidal flocculation versus the processes of <u>in</u> <u>situ</u> residual leaching. Pottsville and Allegheny flint clays exhibit evidence of both petrogenetic mechanisms.

The purpose here is to describe the physical characteristics, stratigraphic relationships and origin of flint clays in the Allegheny and Pottsville groups of western Pennsylvania. A discussion of the relationship between flint clays and other lower Pennsylvanian clay types is necessarily included.

Physical Properties

The definitive megascopic properties necessary for flint clays are conchoidal fracture and a resistance to slaking. Another common characteristic is hardness (3 to 5 on Mohs hardness scale) the degree of which is broadly attributed to the amount of kaolinitic recrystallization (Patterson and Hosterman, 1960).

Flint clays occur in a great variety of colors including medium to dark gray (rarely black), light greenish gray to olive to green, tan to dark brown to red. Individual deposits are usually varicolored, although one color often predominates. Lower Allegheny and Pottsville clays are neutral to dark gray or brownish gray whereas Upper Allegheny clays are typically, tan, olive, greenish-gray and, rarely, red.

Ferm and Smith (1981) after examination of several hundred core samples, have subdivided flint clays into four categories based on physical appearance: massive, layered, brecciated and mosaic (see discussion, Figure 1). Oolitic flint clays occur in some Allegheny and Pottsville core samples. Patterson and Hosterman (1960, p. 186) note that “oolites are very abundant in some flint clay but they are not present at all in others." Similarly, some flint clays are root penetrated and contain broken plant fragments whereas others are devoid of fossils. Slickensides are extremely rare in flint clay.

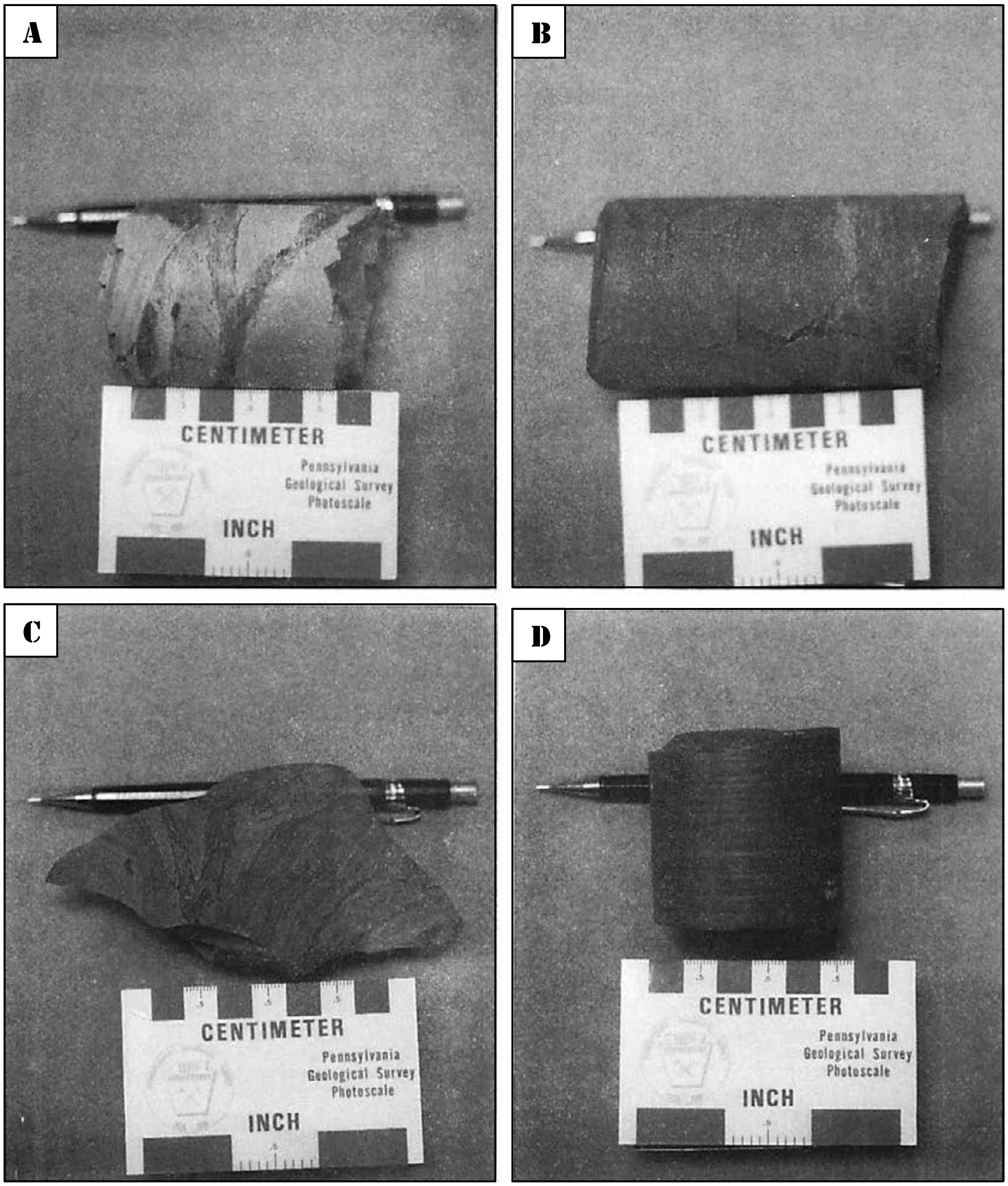

Figure 1. Photographs of various flint clays. (A) Brecciated semi-flint clay (Upper Freeport, Westmoreland Co.) composed of angular clay fragments in a sandy or silty matrix; volumetrically, this type of clay is disproportionately abundant. (B) Mosaic flint clay (Upper Freeport, Indiana Co.). "Mosaic" refers to a type of brecciation where the individual clay fragments may be seen to fit together if the matrix were removed. (C) Layered flint clay (Lower Mercer, Centre Co.) Less common; usually occurs as color laminations in brecciated fragments. Fracture is independent of layering. (D) Massive flint clay (Lower Mercer, Clearfield Co.). Also occurs as brecciated fragments, but may be represented as continuous lengths of core.

Definitions and Nomenclature

Flint clays are middle members of a physical, mineralogical, and chemical continuum ranging from illitic-rich plastic clays to aluminum-rich (boehmite, diaspore) nodule clays. Table 1 contains a summary of three generally recognized groups of clays.

Table 1. Properties of the Flint Clay Facies (from Smyth, 1980)
Data compiled from Patterson and Hosterman (1960, p. F52-F58), Keller (1968, p. 113-115), Keller (1976, p. 262), Keller (1978a, p. 15, 19), Keller (1978b, p. 239, 241), and Keller (1982, p. 150-151).

CHARACTERISTICS	CLAY TYPE		
	FLINT	SEMI-FLINT	PLASTIC
FRACTURE	Conchoidal	Rough, irregular approaching conchoidal	Rough, irregular
HARDNESS	3	2-3	Softer than semi-flint
GENERAL CLAY MINERALOGY	85% kaolinite 15% illite+ mixed layer clays	60-85% kaolinite	60% kaolinite 40% illite+ mixed layer clays
NATURAL PLASTICITY	Almost no plasticity unless very finely ground with water	Little plasticity unless finely ground with water	Considerable plasticity when wet
SLAKING CHARACTERISTICS	Resistant to slaking	Intermediate between flint and plastic clays	Breaks down rapidly into small particles in water
SLICKENSIDES	Very few	Abundant Diversely oriented	Abundant Becoming sealed upon weathering and clay becomes homogeneous in appearance
S.E.M. CHARACTERISTICS	Kaolinite plates or flakes can be seen to be well-developed, interlocking, inter-grown, dense and randomly oriented	Shows some swirl pattern composed of overlapping curved kaolinite flakes. Flakes are less curved than in plastic clays	Shows platy, anhedral bent, and twisted flakes with a swirl pattern

Plastic clays are characterized by a soft, plastic or shaly texture, are often internally slickensided, may be silty or sandy, and break down when mixed with water. Much of the nomenclature for plastic clays has evolved through common usage. To clarify the inherent ambiguity Table 2 (definitions) is included.

Table 2. Definitions of plastic and related clay types

CLAY TYPE	DEFINITION
Underclay	A layer of fine-grained detrital material, usually clay, lying immediately beneath a coal bed or forming the floor of a coal seam. It represents the old soil in which the plants (from which the coal was formed) were rooted and it commonly contains fossils of roots (esp. of the genus *Stigmaria*) (AGI Glossary, p. 676).
Seat Rock or Seat Earth	A British term for a bed of rock underlying a coal seam representing an old soil that supported the vegetation from which the coal was formed (AGI Glossary, p. 564).
Fireclay	1) A siliceous clay rich in hydrous aluminum silicates capable of withstanding high temperatures without deforming (either disintegrating or becoming soft and pasty), and useful to the manufacture of refractory ceramic products (such as crucibles or firebrick for lining furnaces). It is deficient in iron, calcium and alkalis, and approaches kaolin in composition, the better grades containing at least 35% alumina when fired (AGI Glossary, p. 230). 2) A clay that resists fusion or heat deformation below the arbitrarily defined pyrometric cone equivalent* 28 – customarily written PCE 28 (about 1615° C under specified conditions of heating). (Keller, 1975, p. 65-66). 3) A term formerly, but inaccurately, used for underclay. Although many fireclays commonly occur as underclays, not all fireclays carry a roof of coal and not all underclays are refractory (AGI Glossary, p. 230).
Ganister	In England, a highly siliceous seat earth (AGI Glossary, p. 252).
Tonstein	Originally meant an argillaceous rock, but has come to imply a number of additional characteristics including: association with coal seams, homogeneous mineral composition, usually kaolinite-rich, relatively thin (usually 2-3 inches), laterally persistent, and often considered a stratigraphic marker bed for correlation purposes (Moore, 1968, p. 108-109). Tonsteins are often of volcanic origin.

Underclays and seat earths commonly coarsen and lighten in color downward in the stratigraphic section. They are typically rooted, but despite the above definitions, it is often speculative as to whether the roots were from the plants that formed the overlying coal seam or from plants that pre-dated the coa1 seam.

Mineralogically, illite predominates in plastic clays, but subordinate amounts of kaolinite, mixed layer clay minerals and chlorite are common. Non-clay minerals, which can be abundant, are quartz, feldspar, mica, siderite, and calcite. Chemically, $Si0_2$ predominates (60 to 80 percent by weight) and $Al_2 0_3$ comprises between 10 and 20 percent by weight. Minor oxides include $K_2 0$, MgO, $Fe_2 0_3$, Ti02 and CaO (Williams and others, 1968).

Semi-flint clays are a broad category of clays that contain properties intermediate between plastic and flint clays. Ideally, they are intermediate physically, mineralogically, and chemically. They are softer than flint clay (2 to 3 on Mohs hardness scale), possess a sub-conchoidal fracture, and are frequently slickensided. They may be strongly to weakly slaking or even non-slaking. The kaolinite range for semi-flint clay is between 60 and 85 percent (Smyth, 1980) with illite and mixed layer clay minerals comprising the bulk of the remainder. Chemically, semi-flint clays contain 35 to 37 percent $Al_2 0_3$ (Weitz, 1954). $Si0_2$ and the minor oxides present in plastic clays constitute the complementary chemical components.

The distinction between flint clay and higher grades of semi-flint clays can be problematic. The definition of flint clay incorporates both microscopic (percent kaolinite) and megascopic (conchoidal fracture and slaking) properties. Yet many clay types will satisfy only two of the three criteria for the definition of flint clay (and the term "sub-conchoidal" is ambiguous).

Table 3 shows chemical analyses and X-ray diffraction data of clays from the Allegheny and Pottsville Groups. All of these clays possess some degree of conchoidal fracture, and some are non-slaking, yet chemically they contain less $A1_2 0_3$ than Weitz's (1954) definition of semi-flint clay. Furthermore, Figure 39 illustrates X-ray diffraction data for four of twelve X-rayed samples of conchoidally fracturing clay from the Allegheny and Pottsville Groups. Note that the quartz (siderite in IND-D-3055) peaks are commonly more significant than the kaolinite peaks. Although these data are not directly quantitative, the implication is that there is a substantial quantity of quartz in rocks that are megascopically termed flint clays. Stricter definitions and/or nomenclatural expansion of the plastic/semi-flint/flint clay continuum appear to be warranted.

Hard clays are broadly subdivided into two categories; flint clays and nodule clays. Flint clays contain greater than 85 percent kaolinite and less than 15 percent illite and mixed layer clays (Smyth, 1980). Halloysite and chlorite may exist in minor amounts. Quartz, siderite, and feldspar are the most common non-clay minerals, although heavy minerals (tourmaline, rutile, and zircon) may occur in the form of sand size grains (Bragonier, 1970). $Al_2 0_3$ should be in the 38 to 40 percent-by-weight range (Weitz, 1954). The minor oxides occurring in plastic and semi-flint clays are also present in flint clay. Commercial quality flint clay must have a pyrometric cone equivalent (PCE) (see Table 2) of 32 (1700 °C in standard heating environment) or higher and a bulk density above 2, preferably 2.2 (Baumann and Keller, 1975).

Nodule clays are hard clays that contain rounded nodules of the aluminum hydroxide minerals boehmite ($HA10_2$) and diaspore (AlO OH). Nodule clays may contain only a few nodules in a kaolinite groundmass or be comprised almost entirely of aluminum hydroxide nodules. Gibbsite may be present in minor amounts. Nodule clays may be quite hard (greater than 5 on Mohs hardness scale) and contain up to 75 percent $AL_2 0_3$ by weight. In western Pennsylvania nodule clays are stratigraphically restr1cted to the Mercer horizon and geographically restricted to Clearfield, Centre, and Clinton Counties.

Table 3. Chemical analyses and x-ray diffraction results of flint and semi-flint clay samples from the Allegheny and Pottsville Groups of western Pennsylvania.

SAMPLE	CHEMICAL ANALYSES				X-RAY DIFFRACTION RESULTS		
	SiO_2	$Al2O_3$	FeO_2	PCE*	MAJOR MINERALS	CHARACTERISTIC PEAK	PEAK HEIGHT
Upper Freeport Westmoreland County	63.82	17.33	5.52	15-16			
Upper Freeport Westmoreland County	42.66	24.78	11.62	5			
Upper Freeport Westmoreland County	59.74	15.80	9.85	15			
Lower Freeport Westmoreland County	56.36	23.20	6.10	19	Quartz Kaolinite	4.26 Å 7.17 Å	65 24
Lower Freeport Westmoreland County	64.82	23.87	1.53	30			
Brookville Jefferson County	60.70	24.60	5.30	20-23			
Brookville Jefferson County	67.67	22.82	2.17	31.5-32	Quartz Kaolinite	4.26 Å 7.17 Å	45 50
Brookville Jefferson County	62.73	27.81	1.78	30-31			
Mercer Clearfield County	42.90	40.45	1.45	33			

*Pyrometric cone equivalent - a measure of the firing or melting temperature of the clay.

Lithologic names and descriptions used in the mining industry (Table 4) have been summarized by Foose (1944) and modified slightly by Weitz (1954). The descriptive terminology in Foose's classification is advantageous, but it is based on physical properties and has no petrographic significance. Weitz and Bolger (1951) advanced an alternative classification of fireclay types (Table 5). They used Foose's descriptions as their framework, but subdivided the high-alumina clay types on the basis of mineralogical composition. Erickson (1963) combined aspects of both previous classifications to produce a more systematic and moderately descriptive arrangement of fireclay types (Table 5).

The above classifications serve as workable instruments for the hard clay industry but all emphasize the more exotic but less common, nodule clay types. Furthermore, Weitz and Bolger (1951) and Erickson (1963) incorporate the problem of creating a field classification that is ultimately based on microscopic properties.

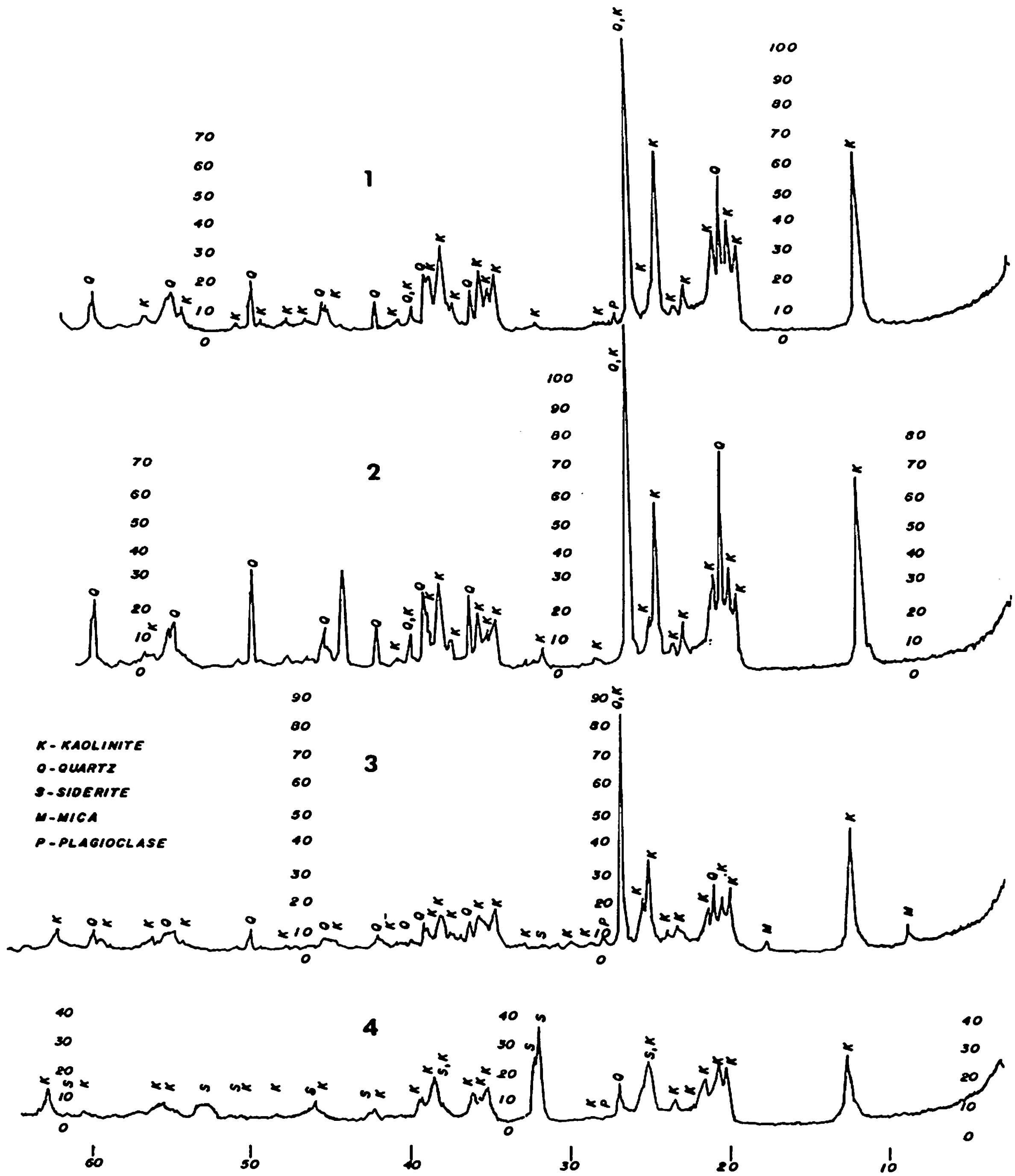

Figure 2. X-ray diffraction patterns of flint and semi-flint clays from the Allegheny and Pottsville groups of western Pennsylvania. (1) Lower Mercer, Centre Co. Hard, higher-grade flint clay. Note sharp, symmetrical and well-resolved nature of reflections. (2) Flint clay from Widman St. Exit, Johnstown, below Upper Kittanning coal. Well-resolved peaks indicate fairly high-grade flint clay, but quartz peaks more distinct than in (1). (3) Semi-flint clay from Lower Freeport horizon, drill hole in Conemaugh Twp., Indiana Co. Lower amounts of both kaolinite and quartz are present; peak heights and resolution not as well defined as in (1) and (2). Also note existence of mica, siderite, and plagioclase. (4) Siderite-rich semi-flint clay from above Upper Freeport coal, West Wheatfield Twp., Indiana Co. Note poor resolution.

Table 4. Nomenclature of fireclays as used in the mining industry
(from Weitz, 1954, modified from Foose, 1944)

CLAY TYPE	DESCRIPTION	APPROXIMATE % OF Al_2O_3
"Burnt" nodule clay	Gray to brown, porous, cindery appearance; usually nearly all diaspore; very rough fracture	65 – 75
Fine-grained (or blue) nodule clay	Homogeneous appearance; smaller nodules and harder than green nodule clay	60 – 65
Green nodule clay	Coarsely nodular; rough fracture; usually greenish cast	50 – 60
Nodule block clay	Gradational between green nodule and block clay; scattered nodules comprise less than half of the mass; rough, blocky fracture	40 – 50
Nodule flint clay	Gradational between green nodule and flint clay; scattered nodules comprise less than half of the mass; rough, conchoidal fracture	40 – 50
Flint clay	Very hard; smooth, conchoidal fracture with sharp edges and points; weathers into smaller jagged fragments; usually clear light or dark gray, but may contain dark spots or widely scattered nodules	38 – 40
Block clay	Hard; blocky fracture; weathers to rounder granules than flint clay; usually clear, light or dark gray, but may contain dark spots and widely scattered nodules	38 – 40
Semi-Flint clay	Gradational from flint clay to soft plastic clay; rough, irregular fracture, approaching conchoidal Associated nonrefractory clays include:	35 – 37
Slabby soft clay	Fracture slabby and irregular; slickensides common	
Soft (plastic) clay	Soft; irregular fractures; plastic when wet	
Shaly clay	Bedding evident; shaly fracture	

Table 5. Classification of high-alumina rock types
(modified from Erickson, 1963)

Composition	Weitz and Bolger's Classification	Equivalent Miner's Term	Erickson's Classification
Over 90% aluminum hydroxides	Diasporite	"Burnt" Nodule	Diasporite
Over 50% aluminum hydroxides	Argillaceous Diasporite	Fine-grained Nodule	Argillaceous (over 50% nodules)
		Green Nodule	Diasporite
Over 50% kaolinite	Diaspore Claystone	Nodule Flint Clay	Nodule Claystone (25-50% nodules)
		Nodule Block Clay	Nodule Block Claystone
			Flinty Nodule (5-25% nodules)
			Claystone
			Nodular Flinty (5% nodules)
			Claystone
Apparently all kaolinite	Flinty Claystone	Flint Clay	Flinty Claystone
	Blocky Claystone	Block Clay	Blocky Claystone
	Shaly Claystone	Shaly Clay	Shaly Claystone
	Soft (plastic) Clay	Soft (plastic) Clay	Soft (plastic) Clay

Stratigraphic Relationships

Flint clays occur at nearly all stratigraphic horizons in the (post-Connoquenessing) Pottsville and Allegheny Groups of western Pennsylvania. Smith and O'Brien (1965) have also reported flint clays as young as late Pennsylvanian, indicating that they formed throughout much of the Pennsylvanian. Nevertheless, they are much less common above the lowermost Conemaugh. Williams and others (1968) have demonstrated that there is an overall up-section increase in the illite: kaolinite ratios of underclays from the Mercer to Upper Freeport (consistent with data presented in Table 2. Keller (1975) also confirms that higher quality refractory clays are stratigraphically confined to the lower part of the Pennsylvanian system in the eastern United States. The Mt. Savage clay of western Maryland, the Olive Hill clay of Kentucky, the Cheltenham clay of Missouri and the Mercer of central Pennsylvania are examples of high quality refractory clays that temporally represent the Lower and Middle Pennsylvanian. Keller suggests that they characterized “a particular geologic environment that was widely prevalent in the eastern United States during early Pennsylvanian time” Keller, 1975, p. 65). The Cheltenham and Mercer are the only clay deposits in the United States that contain the high alumina Diaspore/Boehmite facies and both are believed to rest unconformably on Mississippian sediments (Keller, 1975).

Non-plastic clays of the middle and upper Allegheny range from semi-flint to flint clay. Although many possess characteristic conchoidal fracture and brecciation, they are slightly to strongly slaking and marginally kaolinitic. Nevertheless, some Upper Allegheny flint clays are of refractory quality (e.g., the Bolivar flint clay of southwestern Indiana County).

Flint clays in the Allegheny Group usually occur in association with other “chemical'' rocks, specifically limestone and coal. Thin layers of flint clay have been found interbedded with the freshwater limestones beneath the Upper and Lower Freeport and Upper Kittanning coals, but are more characteristically found immediately beneath these limestones (Buswell, 1980). Williams and others (1968) demonstrated that flint clays are laterally equivalent to the Vanport Limestone in portions of Clarion County, Pennsylvania.

Figure 3 illustrates that flint clay is commonly the lateral equivalent of both coal and limestone. Coal equivalent with flint clay has been documented by Sturgeon (1958) for the Pittsburgh seam, by T. Miller (personal communication) for the Mahoning seam, by Smith and O'Brien (1965), Pedlow (1977), Clark (1979), and Hohos (1979) for the Upper Freeport, by Buswell (1980) for the Upper Kittanning, by Merrill (1952) for the Middle Kittanning and by Williams and others (1968) for the Scrubgrass (Clarion No. 3).

Genesis

Introduction

Despite numerous geochemical and petrologic investigations of flint clays, controversy still exists concerning their origin. Smyth (1980) has summarized the existing published theories of the origin of flint clays and related clay types. Her overall subdivision of theories into allogenic, authigenic, and combined recognizes a fundamental problem of flint clay origin -were they formed in-situ or transported?

Williams and others (1968) have demonstrated that although the illite/kaolinite ratios of underclays within the Pottsville and Allegheny Groups increase stratigraphically upward, the same is not true for shales immediately overlying the respective coal seams. Their conclusion is that “the composition of the sediments received from unknown source areas did not change in the stratigraphic interval examined” (Williams and others, 1968, p. 75). Their conclusion necessarily implies clay mineral alteration within the environment of deposition. This evidence stands in opposition to the theories proposed by Lovejoy (1925) Grim and Allen (1938) Greaves-Walker (1939), Schultz (1958) and Wilson (1965), all of whom invoke an external source area.

Formation of flint clays within the environment of deposition may be accomplished either by differential colloidal flocculation controlled by the chemistry of the depositional environment (Bolger and Weitz, 1952; Falla, 1967; and Williams and others, 1968) or by in situ leaching (Halm, 1952; Keller, 1952; Slatkine and Heller, 1960; Patterson and Hosterman, 1960; Smith and O'Brien, 1965; Goldberry, 1979; and Keller, 1981).

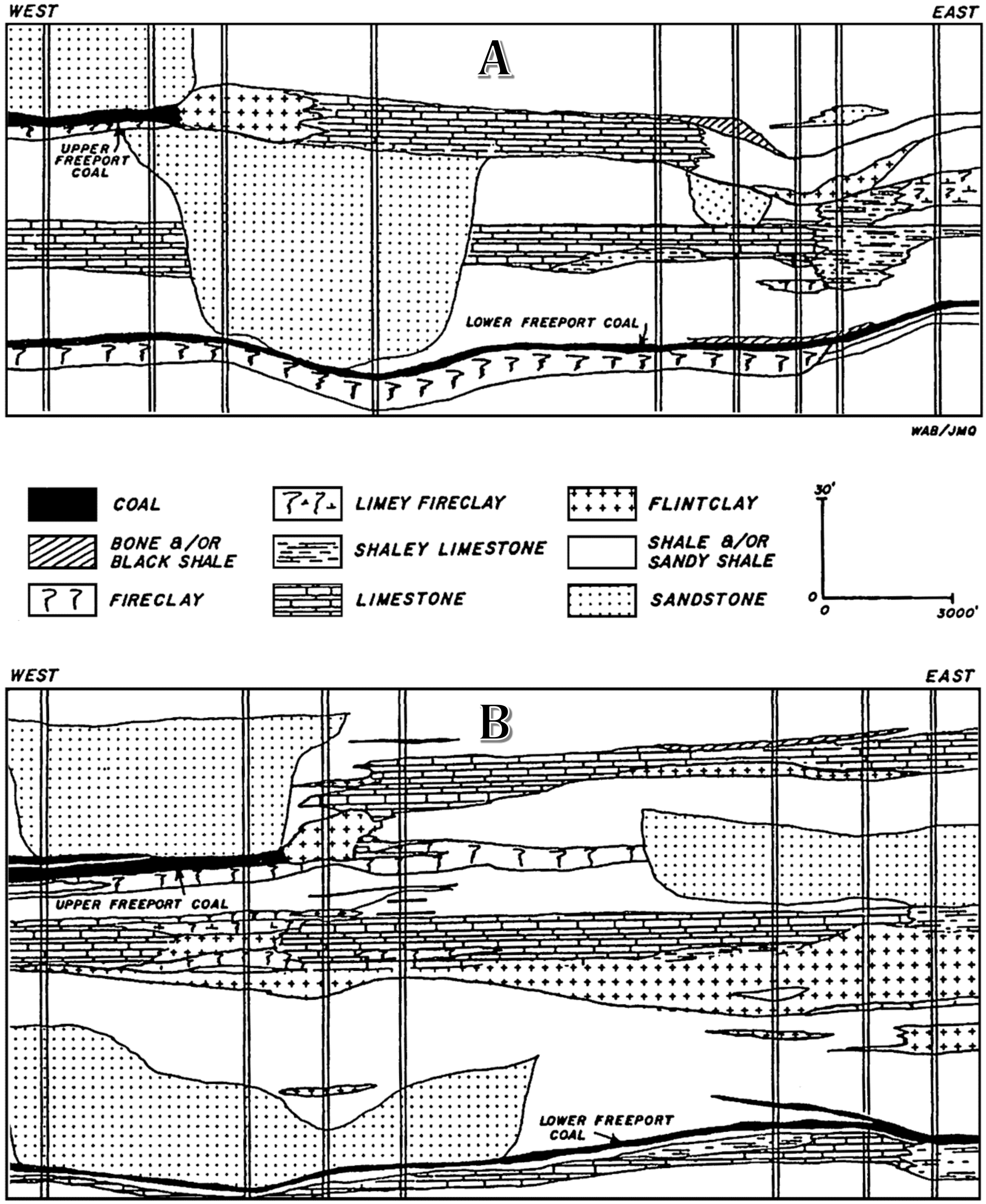

Figure 3. Cross-sections A (top) and B (bottom), showing lateral facies changes from coal to flint clay to fresh water limestone in the Upper Freeport horizon near Brush Valley, Indiana County. The datum is the top of the Upper Freeport limestone.

In-Situ Leaching

Keller (1981) provides one of the most complete accounts of in situ flint clay genesis. He interprets flint clay as a product of very early d1agenetic alteration of a parent alumina-silicate material. During a period of crustal stability in non-marine paludal/fluviatile environments, colloidal to fine-grained sediments accumulated in quieter, commonly plant-fringed, swamps. Removal of silica, iron, and alkaline and alkali earths presumably were the result of dialysis, hydrolysis, and the action of organic complexing compounds, organic acids, and silica accumulating plants. Keller (1968) suggests that acid swamp waters are the source of H^+ ions, which replace K^+ ions in illite, producing H-rich illite and kaolinite by structural rearrangement of the remaining silica and alumina. These processes could have been initiated in the fringing soil to produce colloidal kaolin. This, in turn, led to the formation of "a colloidal-chemical phase, possibly gel-like, having a composition essentially that of kaolin, from which the mineral kaolinite crystallized or crystallized into packets of inter-grown kaolinite crystals…" (Keller, 1981, p. 239). Other theories of in situ flint clay origin commonly incorporated the processes which Keller details, emphasizing various aspects for specific clay deposits.

Evidence which suggests in situ leaching is an important mechanism in flint clay genesis include the following:

Mineralogical: Vertical kaolinite enrichment within individual clay beds (both upward and downward kaolinite enrichment has been reported respectively by Smyth, 1980 and Keller, 1981).

Etching and complete dissolution of quartz grains (Patterson and Hosterman, 1960; Bragonier, 1970; Smyth, 1980).

Lack of feldspar (Patterson and Hosterman, 1960).

A change in kaolinite mineralogy from the outside of clay breccia fragments, where poorly crystalline kaolinite occurs in the cores of the breccia fragments surrounded by a well-crystallized kaolinite rim (Smith and O'Brien, 1965).

Kaolinite enrichment on paleotopographic highs (Holbrook and Williams, 1973).

Geochemical: Vertical alumina enrichment (Smyth, 1980; Keller, 1981).

Enrichment in titanium dioxide (Jaron, 1967; Williams and others, 1968).

Lack of Fe203 in the upper portions of some clays (Williams and others, 1968).

Iron and calcium concentrated in concretions or cracks in the lower portions of clays (Huddle and Patterson, 1961).

Upward loss of K20 (Holbrook and Williams, 1973).

General: Soil-like features in some clay deposits including cutans, clay-filled pores, ooliths, aggregates, spherulitic siderite, and mottled zones, roots, and soil profiles (Smyth, 1980).

The Effects of Organics

Keller's (1981) mention of organic complexing compounds, organic acids and silica-accumulating plants is important. Keller (1968, p. 122) notes:

> "The vegetation contributed to flint clay formation in several ways. Mechanically, it may have served as a filter that lined marshes and held out coarser clastics but allowed colloidal clay suspensions to pass. Plants growing in the clay extracted alkali and alkaline earth metals from the clay for growth and metabolism. These metal ions are easily leached out of leaves and stems after they fall from plants, thus mobilizing the flux ions for removal by solution. Silica likewise will be mobilized, thereby enriching the clay residue in alumina. Silica accumulating plants, such as reeds and bulrushes, live in this type of environment. If Equisetum was present, the aqueous solubility of silica could have been more than doubled relative to its value in freshwater as observed by Lovering (1959). Chelation by organic compounds and complexing by $C0_2$ from decaying organic matter could enhance the removal of fluxes and silica from the clay colloids and mud in the swamps. H^+ ions from organic acids would react with the silicates present to accelerate kaolinization."

The chemical effect of plants on the genesis of flint clays has been discussed by numerous authors including Hopkins (1898), Stout and others (1923), Hodson (1927), Chukhrov (1970), and Staub and Cohen (1978).

Furthermore, some tonsteins (see Table 2) associated with coal seams are believed to be volcanic ash deposits that owe their alteration to kaolinite almost entirely from the interaction with organic compounds and acids (Stach, 1950; Chalard, 1951; Bouroz and others, 1958; Bohor and Triplehorn, 1981). The influence of organic compounds on the recrystallization of kaolinite and the formation of diaspore and boehmite is also believed to be substantial (Bragonier, 1970; Keller, 1975).

Differential Colloidal Flocculation

Williams and others (1968) provide the most comprehensive argument for flint clay genesis via differential colloidal flocculation. They note that the Lower Kittanning flint clay in Clarion County is confined to an area laterally equivalent to the Vanport Limestone and an unnamed coal they also interpret as a lateral equivalent. They note that the distribution of illite/kaolinite ratios in the insoluble residue of the Vanport Limestone roughly correspond to the thickness distribution of the Vanport. They interpret this to suggest that the clay ratios parallel the Vanport shoreline. This reasoning is further supported by an overall agreement between the distribution of the illite/kaolinite ratios and the $Si0_2$:clay ratios and Fe_20_3 distribution within the Vanport insoluble residue.

Noting that Millot (1942) has shown colloidal flocculation is strongly affected by pH and electrolyte concentration, Williams and others conclude that flint clays are most likely to occur in areas where pH changes range from acid to basic, such as paludal-lacustrine environments that fringe a shallow sea. In such environments, if cation concentrations are low, colloidal alumina would be more readily flocculated while silica would remain in solution to be flocculated in near-shore marine areas.

Williams and others (1968) propose a four-phase paragenesis for the flint clay as follows:

1) Flocculation of a colloidal gel in electrolytic solution forming interlocking kaolinite grains.
2) Recrystallization and shrinkage with water loss producing a brecciated appearance.
3) Resuspension of clay and quartz under more acid, swamp water conditions resulting in reprecipitation of the fine-grained groundmass, kaolinite books and quartz crystals.
4) Compaction and lithification.

Flint and semi-flint clays of the Allegheny Group illustrated in Figures 2 to 5 are believed to have originated from differential colloidal flocculation. Several stratigraphic relationships suggest this. Flint clay is commonly most abundant immediately adjacent to a coal seam, and appears to fringe the coal swamp. In the non-coal (basinward) direction flint clay is often laterally equivalent to freshwater limestone (a similar relationship observed by Williams and others, 1968 between the Vanport limestone and Kittanning flint clay). Near Trees Mills, in northern Westmoreland County, a black shale containing fresh water fossils (conchostracans and ostracods) appears to be the lateral equivalent of the Upper Freeport flint clay (Figure 4).

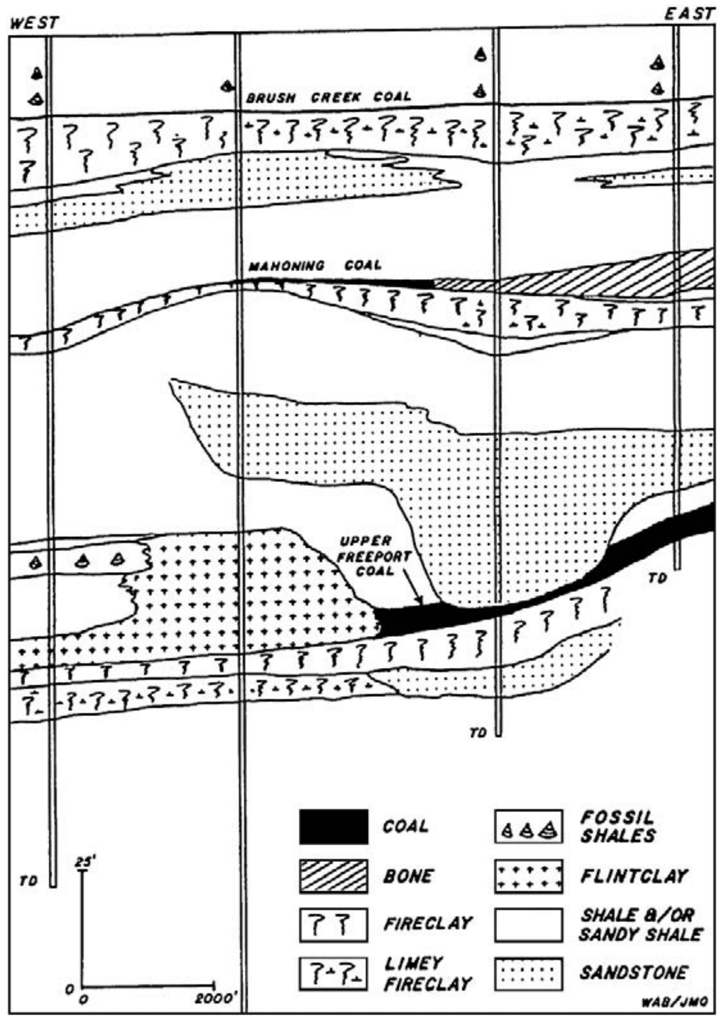

Figure 4. Cross-section showing lateral facies changes from coal to flint clay to black shale with fresh water fossils in the Upper Freeport horizon near Trees Mills, Westmoreland County. The datum is the overlying Brush Creek coal. Note position of coal relative to base of flint clay.

The genetic implication is that Upper Allegheny coal swamps were commonly adjacent to freshwater lakes. As peat accumulated, colloidal clays coming into contact with the acid swamp waters were flocculated. Staub and Cohen (1979) have documented the rapid flocculation of clay particles entering an acid environment in the modern Snuggedy Swamp of South Carolina. Schofield and Sampson (1954) note that acidity and a low cation concentration will cause edge-to-face (non-layered) flocculation of clay particles. The overall acidity of the lake would determine whether clay flocculation would be continuous across the lake or confined to the more acidic near-shore environments. Acidity, in turn, is strongly influenced by the size and shape of the lake, which controls internal circulation.

A further argument for a lacustrine flint clay origin-deposition in a paleotopographic low may be directly observed in the roadcut at the Widman Street exit (see description of Stop #10). Figure 5 illustrates a similar circumstance with a thicker coal and flint clay sequence (Upper Freeport). When the underlying Upper Freeport limestone is used as a datum, the Upper Freeport coal corresponds to a position near, but not at, the base of the adjacent flint clay. If the peat and clay accumulated at roughly the same rate, but the peat compacted four to five times more than the clay, this is the relationship to be expected.

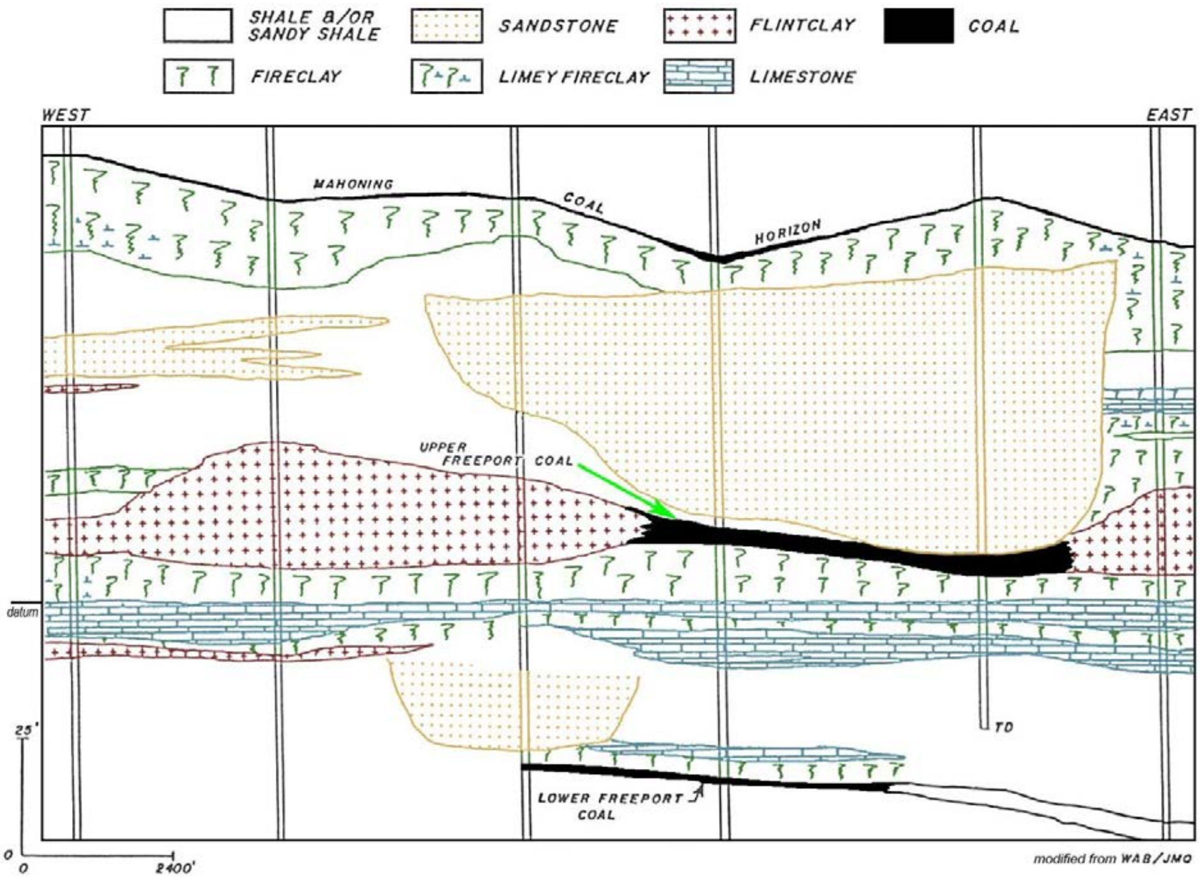

Figure 5. Cross-section of Upper Freeport coal and associated flint clay near Five Points, Westmoreland County. The datum is the top of the Upper Freeport limestone. Note vertical position of coal relative to the base of the flint clay.

The very fine laminae observed in many flint clays (Figure 1C) are also suggestive of sedimentation in a low energy environment. Such laminae have been observed in flint clay deposits believed to be of authigenic origin and may represent sedimentation of previously formed clay particles in localized depressions. Nevertheless, the presence of delicate, thin laminae, indicative of quiet water sedimentation, certainly does not preclude a lacustrine origin, especially for semi-flint clays.

Brecciation

The brecciation associated with many flint clays (Figure 1A) may, in fact, be related more to loading rather than shrinkage and drying as suggested by Williams and others (1968). The matrix for many of the brecciated flint and semi-flint clays is commonly not clay, but much coarser grained sand- and silt-sized material, often similar to the immediately overlying lithology. At

Cambridge, Ohio, a roadcut exposes brecciated semi-flint clay that is laterally equivalent to the Upper Freeport coal. Here, the material between the brecciated clay fragments is the same composition, color, and texture as the overlying lithology. Several large-scale slump blocks are also present, indicating that when the clay was loaded, it was structurally incompetent. The overlying material appears to have been oozed and slumped into the flint clay causing it to acquire a brecciated, fragmental appearance. The brecciation, of course, may be aided by the release of entrapped water. These conclusions are supported by evidence for early diagenetic slumping of flint clay at the Widman Street exit of Route 56 at Johnstown (see description of Stop #10). Figure 6 illustrates the hypothetical genetic model for deposition of the Upper Freeport flint clay and laterally equivalent facies prior to (6A) and after (6B) sediment loading.

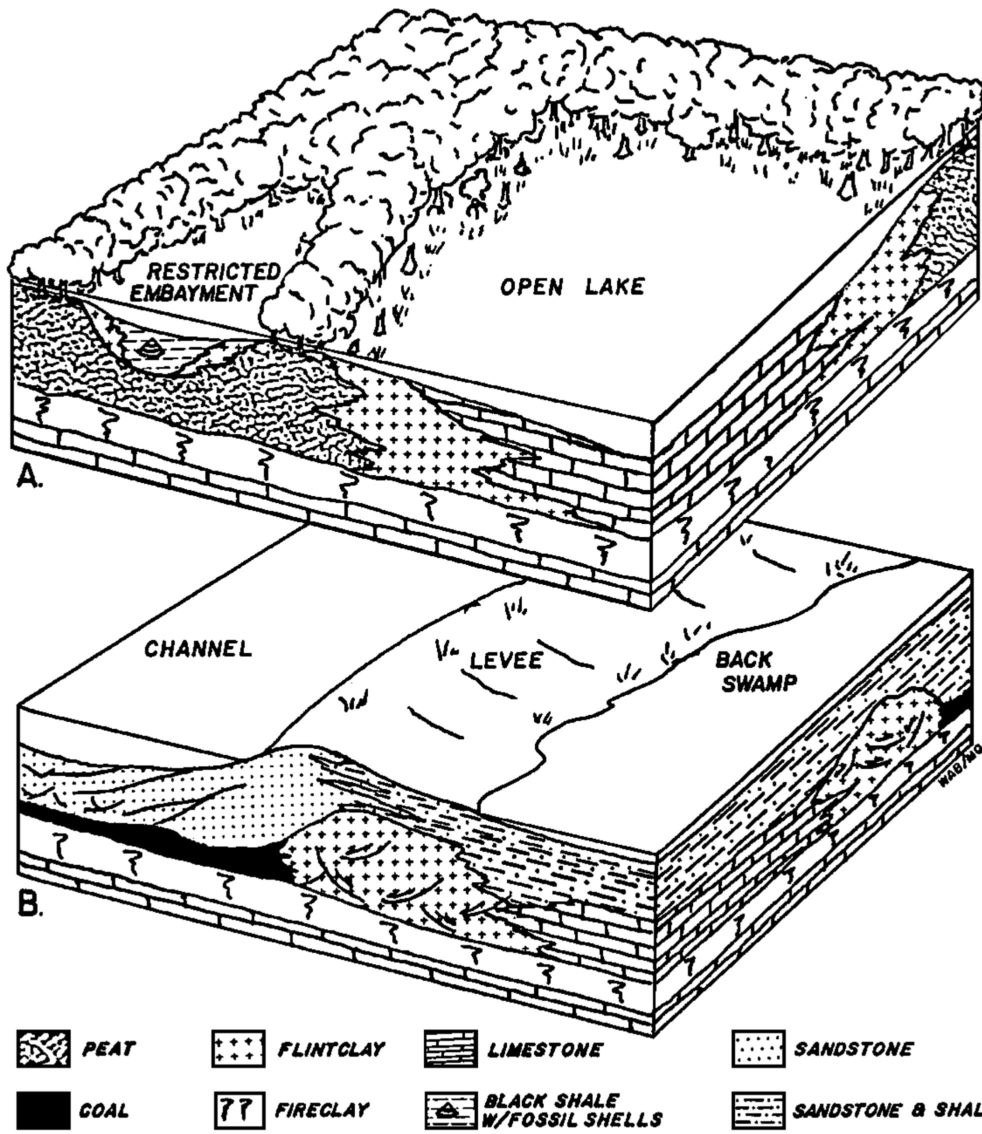

Figure 6. Depositional model and resultant compactional effects in the Upper Freeport sequence. (A) Depositional model for the Upper Freeport flint clay during deposition of the coal-flint clay-limestone sequence. (B) Resultant compactional effects of the Upper Freeport sequence after 10 to 20 ft. (3.1 to 6.2m) of loading by overlying sediments. Channel sandstones are commonly attracted to thick peat sequences (see Figures 3 to 5). Restricted embayment facies not shown in (B); presumed eroded by channel sandstone.

Conclusions

Geologic literature on the genesis of flint clay provides evidence that flint clays and related clay types may originate via three genetic mechanisms.

1) Leaching of an existing alumino-silicate deposit causing an alumina enrichment and the formation of kaolinite and/or aluminum hydroxide clay minerals.
2) Differential colloidal flocculation of kaolinite in shallow, low-energy, lacustrine or paludal environments.
3) The interaction of certain alumino-silicate deposits with organic compounds and acids. This mechanism is often supplementary but has been invoked exclusively to explain the genesis of tonstein deposits in coal seams.

In the Pottsville and Allegheny Groups, with few exceptions, higher grade flint clay {and nodule clay) occurs in the Pottsville and Lower Allegheny whereas less kaolinitic flint and semi-flint clay occurs in the Middle-to-Upper Allegheny {and Lowermost Conemaugh). Genetically, evidence such as dissolved and pitted quartz grains and boehmite enrichment on topographic highs strongly suggests that the Lower Mercer {Pottsville) flint and nodule clay was formed from intensive leaching over a long period of time, with the supplementary aid of organic compounds and acids. Other Lower Allegheny flint clays may have had a similar origin.

Upper Allegheny flint and semi-flint clays are thought to originate from differential colloidal flocculation in shallow paludal/lacustrine environments. This conclusion is supported by the following observations:

1) The association of flint clay with the perimeter of several coal seams.
2) The apparent distal equivalence of flint clay with limestone and/or other freshwater lacustrine rocks.
3) The paleotopographically lower position of flint clays relative to adjacent coal seams.
4) The occurrence of flint clay at the base of a coarsening upward sequence, laterally equivalent to black shale with coal streaks.
5) Very fine laminae observed in many fragments of brecciated flint clays.

The brecciation observed in many flint clays and formerly attributed to shrinkage and drying is believed to be caused at least partially by loading of the flint clay prior to complete lithification and possibly aided by the release of entrapped water. Incorporation of the immediately overlying lithology as the matrix material between brecciated flint clay fragments has been observed in drill holes and surface exposures. In the surface exposures it may be seen that the overlying material has been squeezed and slumped into the flint clay. It may also be demonstrated from surface exposures that sedimentary slumping occurred early after 12 to 15 ft. (3.7 to 4.6 m) of material had accumulated on top of the clay and that the flint clay was not sufficiently lithified at the time of slumping to incorporate underlying units in the slump.

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THE ROGUE KIMBERLITE DIKES IN INDIANA COUNTY, PENNSYLVANIA PART 1. UNUSUAL INTRUSIVE HABIT OF KIMBERLITE DIKES IN COAL SEAMS

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Abstract

Group II micaceous kimberlites have been recovered from underground workings in three coal mines in northern Indiana County, Pennsylvania. They occur as thin, relatively long dikes that exhibit a flow fabric, porphyritic texture with large phlogopite, chrome diopside and magnesian ilmenite phenocrysts/megacrysts, and exotic pyrope garnet xenocrysts. The apparent confinement of these intrusions to coal seams may be significant. The collinearity of the locations suggests the intrusions are part of an east-west trending dike system, but their continuity cannot be verified from surface exposures. They are mapped as long and narrow dikes with relatively few breaks along strike, and rarely split into multiple segments. Aberrations include minor bulbous sills, thin stringers and wedge-shaped apophyses, with both horizontal and steeply inclined terminations in the host coal seam. The former are described as oblate cylindrical sills, and the latter as bladed dikes. Clearly, the coal seam has influenced or controlled these bizarre intrusive habits. Samples examined are typical hypabyssal-facies, carbonate-rich kimberlite, with a poly-textured (agglomeratic) fabric. A passive expansion into the coal is apparent without the aggressive stockwork configuration of many intrusive contacts. Thermal metamorphism is restricted to 4-8 inches of coke in the coal, and is minimal in the underclay and overlying siltstone and shale. A high content of volatiles (±8 % H2O and 17.5 % CO2 in quenched whole rock) dissolved in the magma would promote crystallization and out-gassing at depth. We speculate that highly porous coal seams may have acted as a catalyst triggering crystallization, as well as a sink for outgassing phases, and is a likely scenario for hydraulic fracturing the favorable thicker coal seams. Unresolved questions include (a) whether their apparent confinement to coal seams is real, or is simply a sampling artifact linked to anthrogenic activity, (b) is there a tectonic significance to their off-craton setting in the Appalachian foreland basin, and (c) what is their potential to carry diamonds?

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Introduction

Kimberlites are rare, exotic ultramafic rocks whose name unfortunately conjures an unwarranted, but popular association with diamonds. Less than 10% of the 6974 localities known worldwide (De Wit, 2014) carry diamonds. Of these only 1% are economically viable (Coopersmith, 2014). To appreciate the rarity of diamonds one needs to consider that commercial operations express grades of diamonds in carats per 100 loads, where a load is approximately 16 cubic feet of broken rock, equivalent to ± 0.9 ton. Productive mine grades of 7 to 28 carats per 100 loads equate to 25 to 100 parts per billion (Gold, 1968).

Their tectonic association with old, cold cratons, similarities in texture, mineralogy and geochemistry between diverse types, and different ages "suggest kimberlite magmas are generated by a systematic and reproducible process" (Harris and Middlemost, 1969). They are the mavericks of volcanic rocks, with distinctive habits and various facies that reflect emplacement depth. They occur almost exclusively in steeply dipping fissures and narrow dikes (hypabyssal facies) that may expand into funnel-shaped pipes and vents (diatreme and crater facies) near the surface. Sills are extremely rare and none of the crater facies sites have demonstrable lava flows. These small intrusions (1 cm to meters scale for dikes; pipes rarely exceeding 1 km across) underscore their volumetric rarity in the crust, but overreach their petrological significance as the source of fist-sized samples of xenocrysts and up to boulder-sized xenoliths of the mantle. A signature mineralogy consisting of xenocrysts/phenocrysts of pyrope garnets, magnesian ilmenites and chrome diopsides is used as an exploration tool to locate eroded kimberlites from the heavy minerals in the stream sediment. Of the 10 groups of garnets found in kimberlites (Dawson and Stephens, 1975) only the G-9 and G-10 types correlate with diamonds.

Kimberlites are veritable windows to the upper mantle, where accumulations of fluid-rich magma migrate upward, cool and exsolve dissolved volatile phases, to generate a fluidized gas streaming system capable of rapidly moving kimberlite melt through small orifices over great distances. Their emplacement is envisaged as penetrative, rapid, and sufficiently cool to preserve the metastable phases of the upper mantle and lower crust. As such, kimberlites are composite assemblages of minerals and rocks from both the source and transit localities entrained during emplacement. A porphyritic texture implies an intermediate magma chamber, with growth time between eruptions, and disequilibrium between the phenocrysts and their kindred species in the matrix. We will not debate the subtle distinction between phenocryst and xenocryst here. We prefer to use non-generic terms based on crystal size of megacryst (>> matrix) to microcrysts that blend in with matrix). Fortunately, the polymineralic lithic inclusions (xenoliths) represent the equilibrium assemblages favored for petrogenetic studies.

We are fortunate in having three sites (Figure 1) in Indiana County, albeit all underground, linked by a common trend over a distance of approximately 9 miles. All were exposed by mining operations in at least two different coal seams (Lower Freeport and Lower Kittanning) (see Figure 2) and we are attempting to integrate their discovery into a coherent story. There is no known surface crop, nor has any magnetic anomaly, common to kimberlites, been detected in traverses over the projected surface locations. So far, a reconnaissance search for heavy minerals in the streams draining the potential crop sites failed to detect kimberlite signature (sputnik) minerals. They appear to represent an en echelon set of dikes with an approximately eastnortheasterly strike, and bulbous sills and wedged-shaped apophyses in the coal. A key question is whether there is a unique spatial relationship with the coal seams? Other issues include the source of excess argon in the phlogopites, the presence of an early melt phase in diopside and garnet megacrysts, the significance of G-9 garnets, and the emplacement temperatures inferred from the degree of coking in the coal.

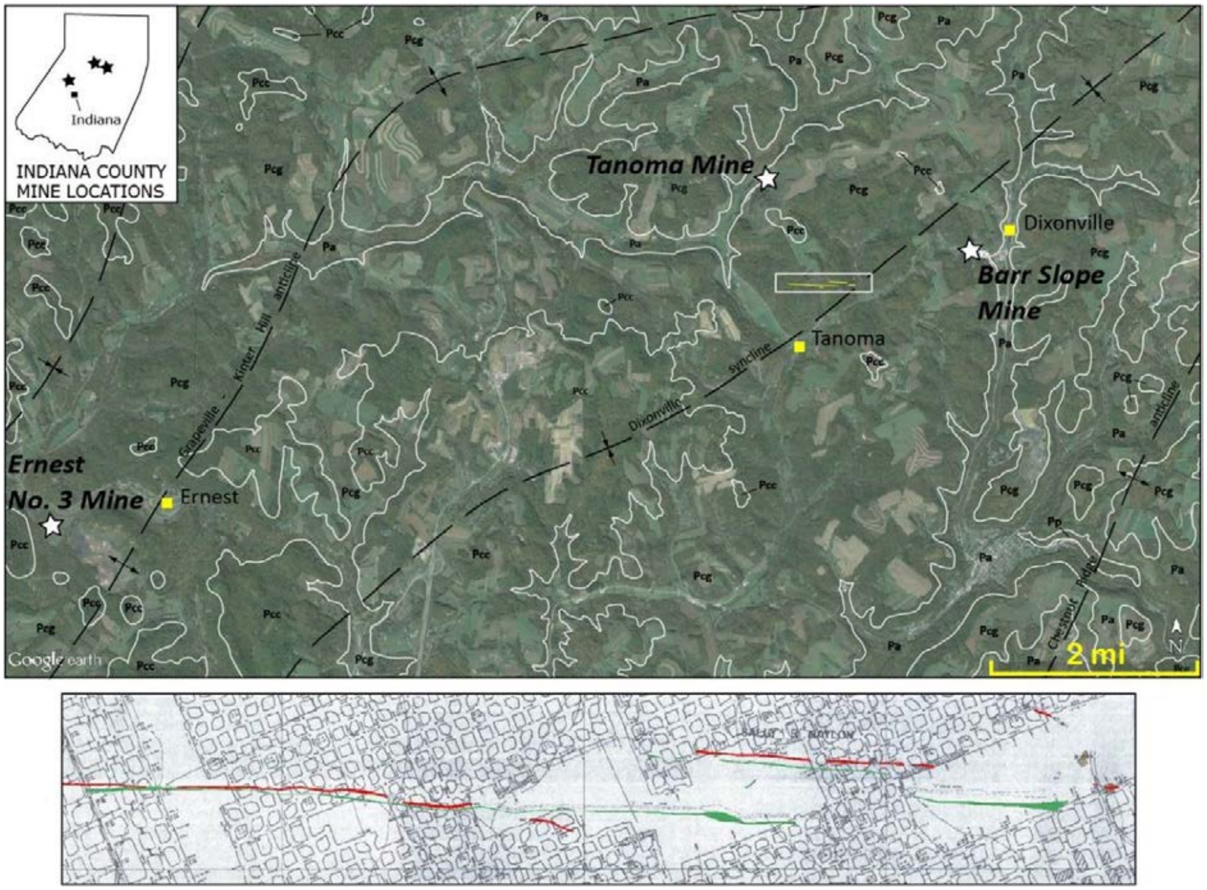

Figure 1. Map for part of Indiana County showing locations of the Ernest, Tanoma, and Barr Slope mines with white stars (Google Earth base image dated 10/11/2015, map scale in lower right corner). The Tanoma/Dixonville kimberlite dikes location is indicated with yellow lines in a white box, which corresponds to the detailed map below. Regional geology from Glover (1976a,b,c). Pennsylvanian age sedimentary units: Pp = Pottsville Group, Pa = Allegheny Group, Pcg = Glenshaw Group, and Pcc = Casselman Formation. Inset mine map provided by Michael Moore, PA DCNR, showing details of kimberlite dikes. Red lines portray the dikes exposed in the Lower Kittanning Coal of the Tanoma Mine and green lines show dike exposures in the Lower Freeport Coal in the Barr Slope Mine. The strike length of the red dikes is approximately 7200 feet.

It is gratifying that the geologic sleuthing skills of the discoverers (Honess and Graeber, Joseph and Jeanne Dague, Robert Smith, Viktoras Skema, and Joseph Tedeski) have led to follow-up studies and/or collections by Peter Deines, D. Dobransky, Peter Wyllie, David Gold, Charles Shultz, Robert Smith, John Barnes, Michael Moore, E. Law, Ryan Mathur, Andrew Sicree, Gareth Mitchell, Alan Davis, William Bragonier and Arnold Doden, as well as student theses by Max Borella (1997), Patrick Cassidy (2015), Chuma Mbalu-Keswa (1995), Susan Radomski (1995), and Pedro Faria (ongoing) and a number of abstracts and reports.

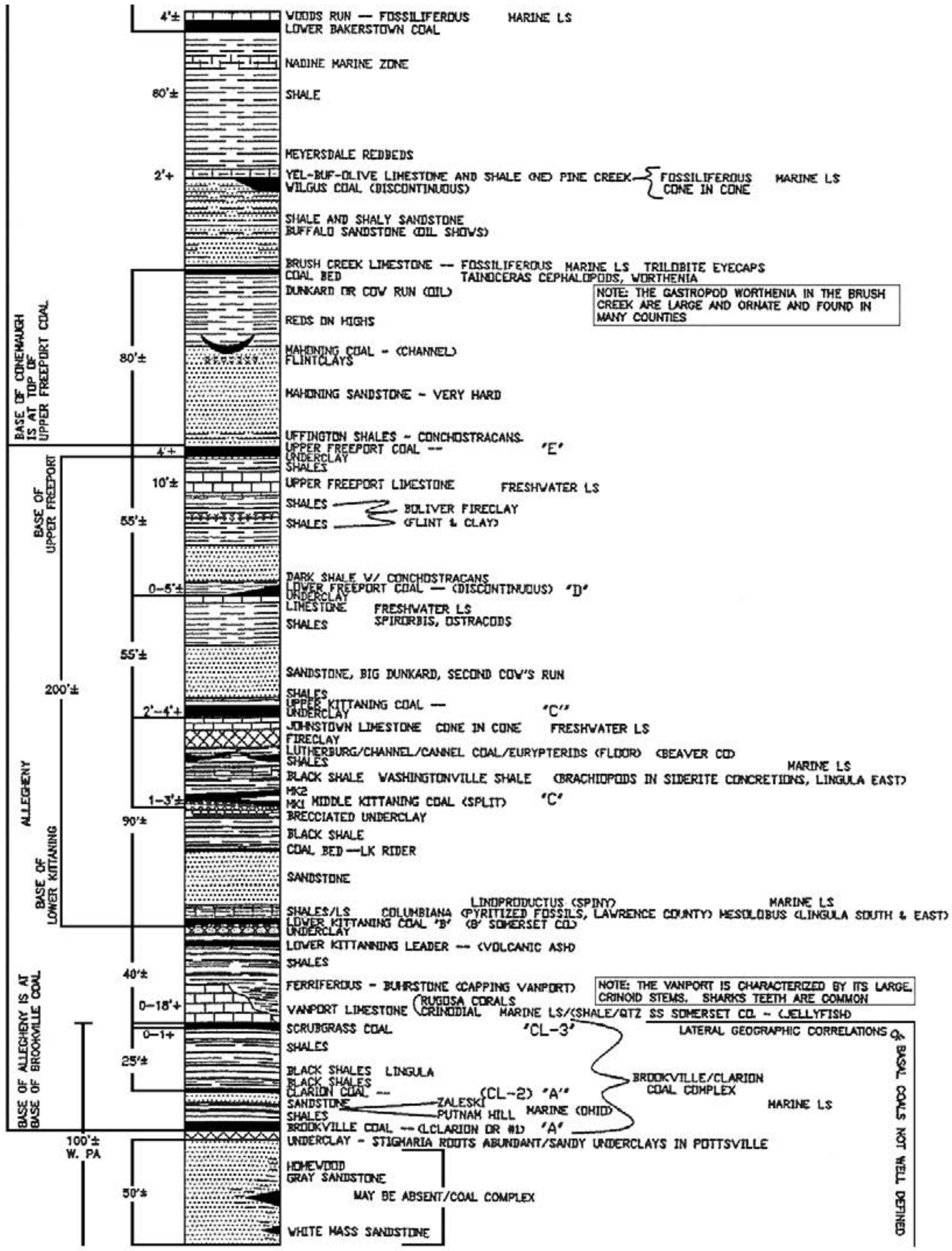

Figure 2. Generalized Stratigraphic Column for part of the Allegheny Section in western Pennsylvania. Not to scale. from W.J. Marks, 1999.

History and Previous Studies

There is a temptation to link Barr Slope, Tanoma and Ernest Mines with the surface trace of a line approximately 9 miles long, trending 255°. The link is more likely *en echelon* dikes striking 080° in Barr Slope Mine at a depth of approximately 200 feet in the Lower Freeport Coal, and the western end of the Tanoma Mine, where Tedeski (2002) recorded an attitude of 264°/84°, complemented by 273° (1982) and 268° (1984) in Smith *et al*., (Pers. Comm., 2016) in the Lower Kittanning Coal. Neither the attitude nor location of the dike in the Ernest Mine is known, but it is suspected to intrude the Upper Freeport Coal in the crown pillar at No. 3 Portal.

The Barr Slope/Dixonville Mine Kimberlite

It is likely that miners were aware of the nature of the dikes in the area long before scientific recording of the mica peridotite dike at Dixonville in 1924 (Honess and Graeber, 1924). The Dixonville dike was encountered in at least four places along a strike of 080° (Honess and Graeber, 1926) in the underground workings of the Barr Slope Mine of the Clearfield Bituminous Coal Company, and correctly identified as a mica peridotite. They record a thickness of less than 2 feet near its ends to 45 feet in the middle. This greatly underscores the real extent, revealed during a search of archival mine maps by Michael Moore (Figure 3).

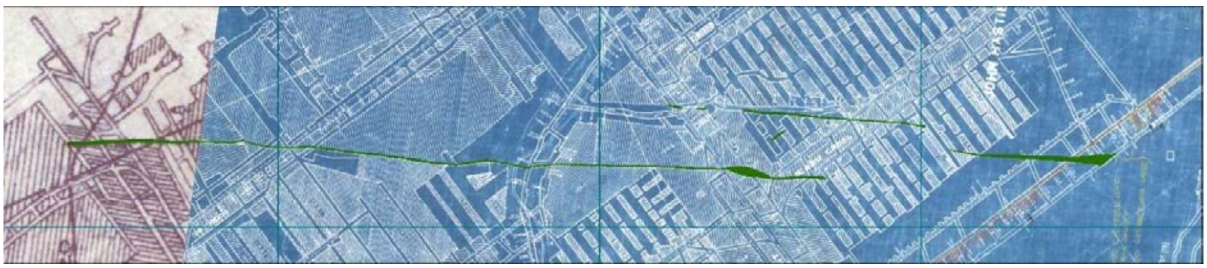

Figure 3. Barr Slope Mine map showing exposure of Dixonville Dike in the Lower Freeport workings. Map courtesy of Michael Moore (2016).

Unfortunately, samples archived at "The Pennsylvania State College", consist mainly of coke from the 8-inch thick metamorphic aureole. Stimulated by petrological investigations at Penn State on carbonatites and mantle carbonates during the late 1950's and early 1960's (Wyllie and Tuttle, 1960), Peter Wyllie acquired additional samples of the Dixonville dike from the Barr Slope Mine to study carbonate nodules. Part of this sampling (PJW 2 to 4), collected by graduate student Gil Franz, were given to Peter Deines, a graduate student in the Department of Geochemistry and Mineralogy (Pers. Comm., P.J. Wyllie, 2016) to examine the distribution of carbon and oxygen isotopes in carbonate inclusions (Deines, 1968). Unfortunately, there is no record of where these samples were collected. A systematic attempt to alert mine operators was initiated during 1964 and coordinated through Dave Snell, the Earth and Mineral Sciences Museum Director. Correspondence with R.C. Beerbower, Jr., of the U.S. Steel Corporation yielded an underground map of the Gates-Adah dike near Masontown. An August, 1964 letter to W.J. Shields of the Rochester and Pittsburgh Coal Company alludes to a kimberlite in the Ernest No. 3 Mine. Correspondence from the same period with J. L. Marshall of Imperial Keystone Mine, focused on the Dixonville dike in the Barr Slope Mine. During the mid- to late- 1960's, Penn State faculty (McKenzie Keith, David Gold, Peter Wyllie and Dave Snell) distributed kimberlite samples to mine operators in the region, along with a request to report similar findings in any of their operations.

The Tanoma Mine Kimberlite

Barnes and Tucker Coal Company opened the Tanoma Mine in 1982 to supply coal, for the South Korean market, from the 180-400 feet deep Lower Kittanning coal. "The slope and shaft for the Tanoma Mine were constructed in the pit of a Lower Freeport surface mine" (Moore, Pers.

Comm., 2016). The Tanoma Mine was developed 130 to 150 feet below the Barr Slope workings. The mapped exposures of the Tanoma kimberlite are shown in the mine map (Figure 4). A superposition of Figures 3 and 4 is shown in Figure 1. The traces of the dikes are an almost exact match if adjusted for the 84° dip separation. Hence, the Dixonville Dike and the Tanoma Kimberlite Dike are the same intrusion.

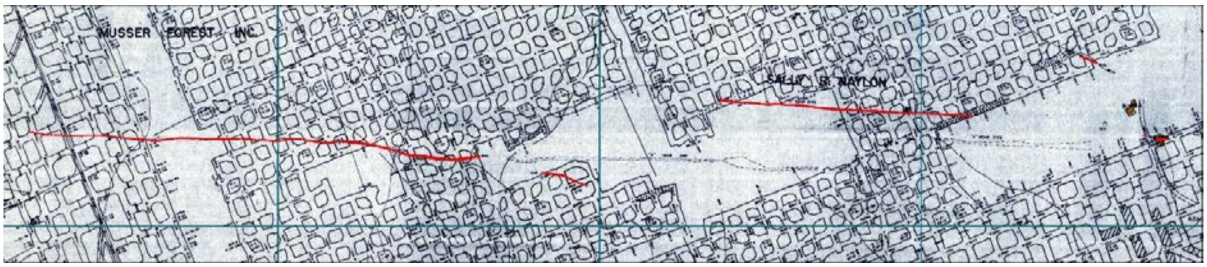

Figure 4. Tanoma Mine map showing exposure of Dixonville Dike in the Lower Freeport workings. Map courtesy of Michael Moore (2016).

DCNR geologists Robert Smith and Viktoras Skema visited the mine on October 13, 1984 and recorded a 16-22 cm thick kimberlite dike, striking N87°W, with a 7-cm coke margin exposed over a strike length of 20 m. Analyses of samples of coal/coke are included in the National Coal Resource Data System (N.C.R.D.S.). A second visit by them (3/1/88) was to the Main D, L2 Entry 30+000 where the dike, 7.5 to 8 cm thick, was seen to trend S88°W. A study of garnets revealed that 42 of 56 analyzed were classified as G9 group (Smith and Barnes, 2006). Projections of the dike 0.9 miles north of Tanoma Village, and a cluster of six E-W dikes, said to project to the surface approximately 0.25 miles south of the Village of Barr Slope, have not been verified (Smith, Skema and Dague, Pers. Comm., 2016).

Joseph Tedeski, a geology student at IUP, working part time in the Tanoma Coal Mine as an Assistant Mine Foreman/Fireboss, started mapping the dikes, communicating with interested professionals, and distributing samples for scientific study. We are indebted to the manager of the Tanoma Mine (Scott Britton, 1991) not only for encouraging Tedeski to map the dike in the underground workings (Figure 3), but also for facilitating excursions underground for interested parties from the University of Pittsburgh (Michael Bikerman, Henry Pellwitz), Penn State University (Duff Gold, Peter Deines, Gary Mitchell, Andy Sicree, Barry Scheetz and David Eggler, and Temple University (Gene Ulmer and Natalie Flynn). A Mini-Conference on the Pennsylvania kimberlites was convened at Penn State on May 11, 1994. Most subsequent studies on the Tanoma kimberlite dikes stem from samples collected during these excursions, the private collection of Joseph Tedeski and samples acquired by James G. Tilton, of the Equitable Gas Company. After joining the Pennsylvania Geological Survey in Pittsburgh in 1992, Tedeski worked his notes and photographs into a CD (Tedeski, 2002). In these, he chronicles underground exposures, thickness and orientation changes, and the unusual habit of the intrusion in the coal seam over a strike length of 7200 feet. These notes highlight locations of the megacrysts of garnet (up to 3.8 cm), phlogopite (12 x 18 cm), and Cr-diopside (10 to 12 cm long). Coke from the metamorphic aureole was taken from Section D5 track entry, between the airlock doors for reflectance studies in the Coal Characterization Laboratory of Penn State University. The petrography of the Tilton samples is included in the summary chapter on Jurassic Kimberlite Dikes in the Geology of Pennsylvania (1999) by Charles H. Shultz, of Slippery Rock University.

A tapered brick size sample collected by Bill Bragonier while with Rochester and Pittsburgh Coal Company, shows a thin bioclastic limestone bed 4-5 cm thick separating 1-cm thick beds of khaki-colored siltstone in the hanging wall of the coal (Figure 5). A cursory examination of the fossils (Roger Cuffey, Pers. Comm., 2016) suggest they are shrimp clam shells (*Estheriids* and *Conchonstrids*). They occur as delicate curved shells in cross section, and some of these are preserved in a granular textured coquina.

Figure 5. Dark gray bioclastic limestone in khaki colored, calcareous siltstone, with fossil shrimp clams exposed on top surface. W. Bragonier collection. (Photograph by C. Miller)

The Ernest Mine Kimberlite

The Ernest Mine in White and Rayne Townships produced Upper Freeport (Upper E) coal in 1903 and left a "refuse pile of some 9.0 million tons of abandoned coal waste over an area of 94 acres" (Stant *et al*., 2007). There is no record of dikes in the archived maps examined. Initially a Rochester and Pittsburgh Company operation, it closed under Consolidation Coal Company. A reclamation permit was issued to Cambria Reclamation Company November 1995. Although the Ernest Mine is mentioned in the 1960's Penn State kimberlite correspondence, it was not until 2007 that Brent Means, a PA-DEP Mine Inspector, found the first recorded specimen (identified by Robert Smith at DCNR). Subsequent searches focused on the Ernest No. 3 Mine portal area, specifically in an excavation as part of the Americkohl Reclamation program (Figure 6). Reclamation included refuse re-mining and dumping (1998 to 2004) of 1,437,282 tons of FBC fly ash from the Cambria co-generation plant (Stant *et al*., 2007).

Figure 6. Ernest No. 3 Mine showing location of kimberlite specimen and part of the Americkohl Reclamation program. Image courtesy of R.C. Smith, 2016.

In August, 2009, Jeanne Dague "found an excellent, 2- to 3-kg specimen (Figure 7a) with ≥2.5 cm of coked coal attached to both contacts of a 9 ±0.5 cm-thick dike section" (Smith et al., 2016). Note the "rounded" megacryst of fresh phlogopite (Figure 7b) embedded in the kimberlite matrix. Thin sections were cut (D.P. Gold) in June, 2016 and examined by Arnold Doden. A 2-mm red garnet with a 0.6 mm kelyphitic alteration rim was extracted, cleaned and fragments were analyzed by SEM/EDS in the DCNR laboratory by Smith and Barnes (Pers. Comm., 9/1/2016). The preliminary results (refer to Table 1, Mineralogy and Petrology section in this document) are interpreted as a high calcium G-9 pyrope rather than a subcalcic G-10 garnet.

Figure 7a. Jeanne Dague sample collected on waste dump at Ernest No 3 Mine, (Photograph by J. Dague)

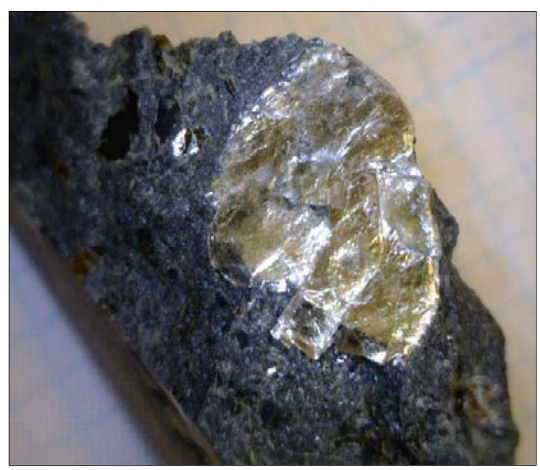

Figure 7b. Phlogopite megacryst in Jeanne Dague sample. Background grid is 1/10 inch.

Location of the Jeanne Dague sample is recorded as 40° 40' 21" N, -79° 11' 00" W, not far from the entrance to the No. 3 portal (Figure 6) at approximately: 40° 40' 25"N, 79° 10' 50"W (Smith e*t al.,* Pers. Comm., 2016).

A geological reconstruction by Viktoras Skema placed the dike in the Upper Freeport coal that remained intact in support pillars around the mine entrance, until the 2009 reclamation. Smith, Skema, and Dague, (Pers. Comm., 2016) conclude "that the kimberlite came from the relatively small re-mined area on the north and northeast edge of the site (near the creek) and not from the dark deep mine spoils on the south end". Neither the attitude nor location of the dike in the Ernest Mine is known, but it is suspected to be in the support pillar at No. 3 portal.

The Sandy Ridge Kimberlite

Doden and Gold (2000) recorded another outlier in Sandy Ridge Quarry, 4.5 miles south-southeast east of Philipsburg, in Clearfield County Pennsylvania (see Figure 30, later this text). Here Butler sandstones between Lower and Upper Freeport coals, and the overlying Lower Mahoning sandstone, up to the Mahoning coal seam, are mined and crushed on site for aggregate. This kimberlite is an enigma because the only samples came from an aggregate stockpile. Despite days of searching by at least 6 different geologists, no dikes or sills have been identified in the sandstones and siltstones exposed in the highwalls, or floor, nor have any magnetic anomalies been found on the property. This kimberlite could be restricted to intrusions in one of the Freeport coals?

Spatial and Thermal Nature of the Intrusions

Habit, Temperature, and Intrusive Mode

Similarity in traces of Dixonville/Tanoma dikes demonstrates their vertical continuity (Figures 1, 3 and 4), as thin dikes, rarely more than a few feet thick. Their apparent absence in surface crop is an enigma. The most striking attribute of the Dixonville, and Gates-Adah dike is the very large length-to-thickness ratio and rarity of satellite intrusions despite a well-jointed host. These are not swarms but rather segments of dikes along the same strike trend. Other unusual habits exposed in the Tanoma Mine are the wedge-shaped dikes and sills terminating in the coal, and bulbous dikes (or cylindrical sills).

Late carbonated veins, some with fibrous calcite, point to a shear component adjacent to and within the intrusion. Except for a coked aureole up to 8 inches thick in the coal, no hornfels is noted adjacent to shale or around shaley inclusions. Law *et al*., (2004) note flow fabric (aligned phenocrysts and xenocrysts), and subparallel fracture alignment through xenocrysts and matrix, as petrographic evidence for an "instant freeze". Implications are that there was little or no volumetric transport of magma through the fissures. They note the consistent orientation of shear and tensional fractures penetrating minerals and matrix, and conclude solidification during a phreatomagmatic (presumably outgassing?) event. Agglomeratic textures and flow fabric apparent in some samples suggest a local fluidized condition for the magma, where the only vesicles noted are in coke inclusion (see Figure 22, later this text).

The dike intruded a well-developed east-west joint set (Figure 8) locally parallel to calcite veins and a strike-slip fault. The relationships are shown in more detail in Figure 9a.

Figure 8. Dike (left), joints and fault (top right corner) in roof (Tedeski, 2002)

Late shear zones, some with transverse fiber calcite veins near the contact and in the chilled contact (Figures 9b & c) suggest both a shear and tensional component post emplacement.

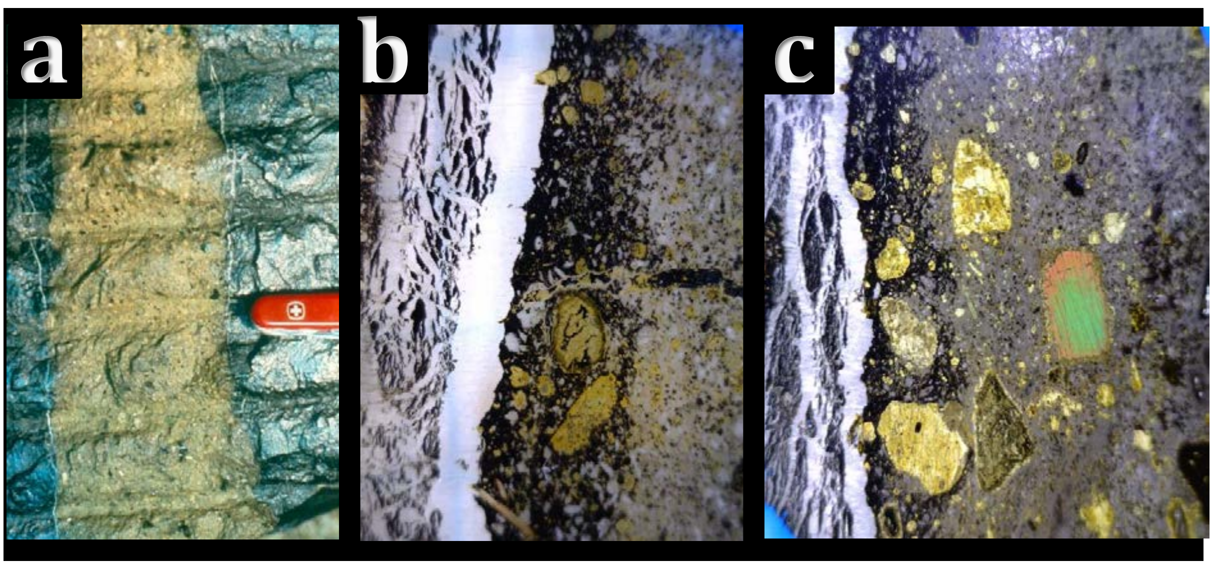

Figure 9a. Dike and calcite veins in roof (Gold, 1994)

Figure 9b. Shear with cross fiber calcite (thick vein) in "chilled margin." Sample PC1-1A.

Figure 9c. Sigmoidal calcite stringers in thick vein and cross-fiber calcite veins along dike contact. Sample TK-3.

Narrowness of the conduits and paucity of thermal metamorphism of shale and sandstone adjacent to, or as inclusions within the Tanoma dikes, indicates a highly fluid medium and relatively low emplacement temperature.

Incompatibility of high-temperature minerals and low thermal metamorphism is a paradox for kimberlite emplacement that has intrigued geologists for more than a century. However, estimating emplacement temperature is no trivial exercise. Thermal metamorphic effects are strongly dependent on the duration heat flowed from the dike into the country rock (Jaeger, 1961), and the latent heat of crystallization (heat capacity) of the magma (Szekely and Reitan, 1971). Szekely and Reitan (1971) modelled the distance a melt can travel in tabular conduits before freezing and conclude that the heat loss from a 1 meter-thick dike of "normal" silicate magma under hypabyssal conditions would freeze less than 10 km from its source. A 10-m thick dike could be as long 28 km. Intrinsic and positional properties of magmas are density, viscosity, magma pressure, heat capacity, latent heat of fusion, heat loss and thermal diffusivity between the magma and adjacent country rock, liquidus and solidus temperatures, and depth. Other critical factors include flow rate (velocity), time to solidify (freeze), and tectonic setting. A dike or fissure emplacement mode is favored in terranes under tectonic tension (high vertical stress) and sills in compressional regimes, where $\sigma 1$ is essentially horizontal.

Emplacement temperature are greater than those indicated by metamorphic changes in wall rock, and this discrepancy decreases with longer residence time and slow rate of magma cooling (Jaeger, 1961). The best estimates of emplacement temperature are likely to come from metamorphism of wall rock inclusions in the kimberlite. An innovative approach for estimating emplacement temperature uses Color Alteration Indices (CAI) for conodonts (Pell *et al*., 2015). Paleozoic carbonate xenoliths from the Chidliak kimberlite field on Baffin Island, Canada suggest heating temperatures of 460^{o}C to 735^{o}C, with some outliers 700^{o}C to 935^{o}C. A distillation study on tar, hydrogen, oxygen and nitrogen on unaltered coal and coke adjacent to the Masontown (aka Gates-Adah) dike in southwestern Pennsylvania, led Sosman (1938) to deduce (sans burial-depth corrections) that the maximum temperature reached by the coke was between 440°C and 520°C, and an emplacement temperature not exceeding 600°C. Based on carbonate content he speculated on a state of "hot plastic stiff mud" for the magma. An attempt to apply metamorphic grade on Tanoma Mine samples (Dobransky, 1986) found changes in fixed carbon, ash and volatiles correlate with a logarithmic rise in vitrinite reflectance from 1.0% to 4.5%, but Dobransky was able only to constrain the temperature to >325°C for the transformation of kaolinite/illite in shales, 60 cm from the dike, to kaolinite/smectite closer to the contact. Preliminary studies by Mitchell and Davis (1996) and (Mitchell *et al*., 2015) using reflectance data suggest an emplacement temperature of approximately 500°C for coke from Main A Entry l-3. A refinement of their data is presented in Part II.

Geology of the Dixonville Dike

Honess and Graeber (1926) describe the dike as a porphyry with phenocrysts of olivine, phlogopite, light-green pyroxene (diallage), jet-like crystals of "glassy" ilmenite, "massive to rounded or subangular crystals of dolomite", and serpentine-rich patches in a carbonate/serpentine matrix. Accessory minerals include rutile, perovskite, titaniferous magnetite, pyrrhotite, rare spinel and red garnets (up to 4 mm). At least three stages of carbonate mineralization are noted, and the authors suggest hydrothermal alteration for the high CO_2 and water content (the quench values in Table 1 are a lower limit). Although they call attention to the lack of metamorphosed shale inclusions, and only an 8-inch thick coke aureole, they do not address an emplacement temperature.

A resurgence of interest in igneous carbonates during the 1960's led Peter Deines to examine the carbon and oxygen isotopic composition of calcite and dolomites in freshly collected samples. Deines (1968) found (a) an extreme variability of the C^{13} concentration over short distances, (b) the heaviest terrestrial carbon (12 to 24.8%o) in any geologic environment, (c) a striking correlation between the carbon and oxygen isotopic composition, except for the lighter carbon values, and (d) a systematic gradient from light carbon at the margin to heavy in the middle of the dike.

Geology of the Tanoma Dike

The kimberlite intrusions in the Tanoma Mine are exposed in the gently dipping seam of the lower Kittanning Coal (Figure 2) in the Allegheny Group, at a depth of 180 to 400 feet below the surface. Tedeski (2002) provides detailed observations on the dike. Most exposures reveal a steeply dipping single dike oriented 264°/84°. Local offsets impart an overall pattern of *en echelon* sheets (vertical to horizontal) from 1 to 18 inches thick that extend through the mine working for some 7200 feet. In most places the dike is apparent both in the roof and floor, with segments of the intrusion transecting as well as terminating (up, down and sideways) in coal and overlying shale. Flow textures indicate upward, lateral, and downward movement. The dikes appear to intrude along mode 1 fractures (joints) rather than adjacent strike-slip faults with the same attitude.

Figure 10. Dikes from floor and roof terminating in 48-inch coal seam. Main Drive L-1 west (Tedeski, 2002)

Tedeski (2002) mapped the westernmost exposure as a dike 6 inches thick in the Main A, R1 entry, near Station 1352, with an attitude of 264°/84°. At station 1348, the dike changes to a sill (wedge) 37 inches long, tapering to the southeast, pinching out after 6 feet in the roof, and reappears 3 feet to the north as an 8-inch thick dike that is continuous along strike over the next three entries. Near Main Drive L-1 *en echelon* dikes from the roof and floor terminate in the coal (Figure 10).

At the L-3 Entry, the dike is 12 -13 inches thick in the roof, tapers towards the floor and forms a sill, 15 inches thick and 52 inches long in the coal, (Figure 11). The floor to roof height is 48 inches, and the coked aureole is at least 4 - 8 inches thick. This was selected as the main sampling site for coke and coal because of the limited volume of kimberlite dike to have flowed through this terminal sill. Coal and coke samples from this setting, sampled by Mbalu-Keswa and Gold in 1994, are identified as I-94 1 to 1-94.15 in the sketch (Figure 12). Note the small steeply dipping appendage at the distal end of the sill. Some coal balls were recovered from 3 to 6 inches beneath the sill. The coal balls occur in mesophase coke 3-6 inches from the contact. Five textural zones, extending for 7.5 inches from an 18-inch thick dike, are apparent in the metamorphic

Figure 11. Dike from roof, to a sill in the coal, and wedging out in the floor. The white coating (top left) is rock grout (Gold, 1994)

aureole in the coal exposed in the D-6 track entry. These grade from 2.5 inches of hard coke and calcite, to “baked” coke (2 inches), then into mesophase, “coal ball” zone 2 inches thick, and into shiny, weakly cleated coal (±1-inch), and back to normal coal with cleats preserved. Maceral changes are likely to be more refined.

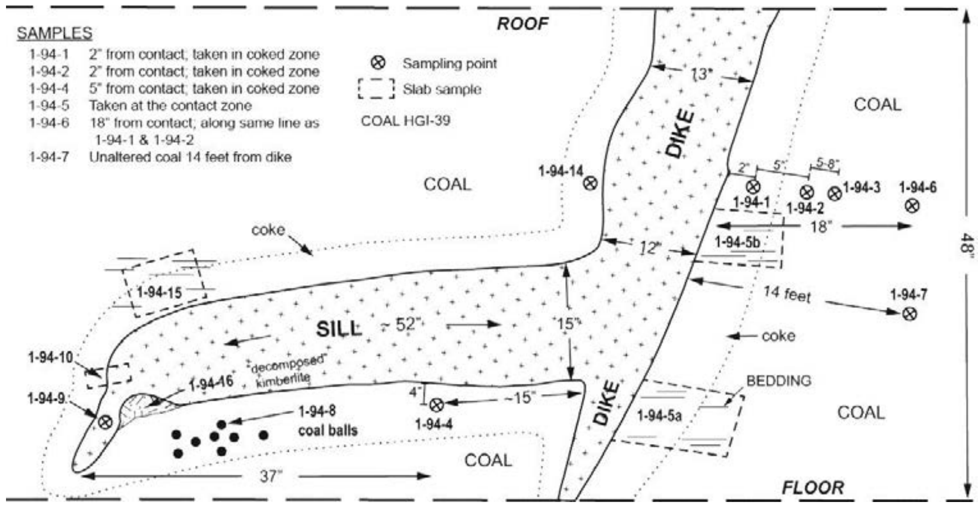

Figure 12. Sketch of wall at MD L-3 entry, the main sampling site for coke and coal (Mbalu-Keswa and Gold, 1994)

A 16-inch thick dike through the floor, coal, and roof is exposed for 410 feet again in Section D2 near Station 4822, disappears in a blind cut of 20 feet and reappears without change for another 350 feet. The strike of the changing dike is N84°W with a lateral shift 4 feet to the north. However, there is a change east of the pillar to N76° E and a bifurcation into a 12-inch northern and 5-inch southern fork, 5 feet apart. The next pillar exposes the dike trending N83°W split into a 10-inch thick northern and 2-3 inches thick southern segment. Both segments enter a barrier block of coal approximately 40 feet apart, where a garnet megacryst (1.5 inches across) was recovered from weathered kimberlite. At the next entry the dike is exposed for 4.5 feet above the coal seam in the “intake air belt overcast”, where it splits and jogs through the hanging wall sandstone sub-parallel to a strike-slip fault at Main D R 2-3 (Figure 13)

Figure 13. Dike in coal and fractures adjacent to strike-slip fault in H/W shales and siltstones. Main Drive R 2-3 (Tedeski, 2002)

Along Main D are single and *en echelon* dike segments as well as dikes from the floor and roof that terminate in the coal. Single and multiple dikes, ranging from thin selvages to 8 inches, were exposed in a highly weathered state along several Main D entries. In the L1 entry, near section D5, a polished garnet 1.5 inches across (Figure 14) was recovered. Coal balls (Figure 15) and elongate forms of mesophase coke in the metamorphosed aureole were collected at the D5 track entry. At Section D6 airlocks the dike is 19 inches thick in the roof and floor, 36 inches in the coal, with phenocrysts of phlogopite 5 by 7 inches, chrome diopside up to 5 inches long, and dolomite nodules 3 by 4 inches. Garnets are abundant.

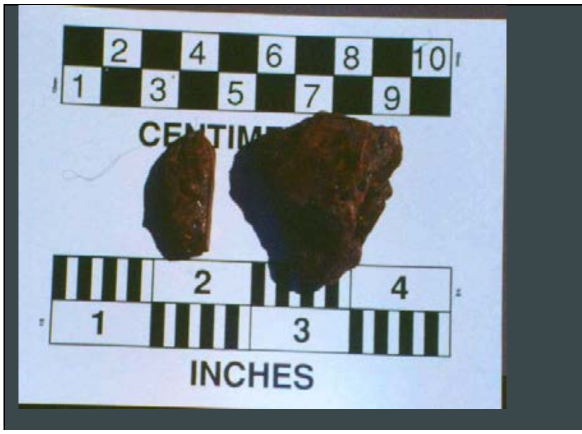

Figure 14. Megacrysts of garnet from weathered (decomposed) kimberlite. L-1 Entry, near D-5. (Tedeski, 2002)

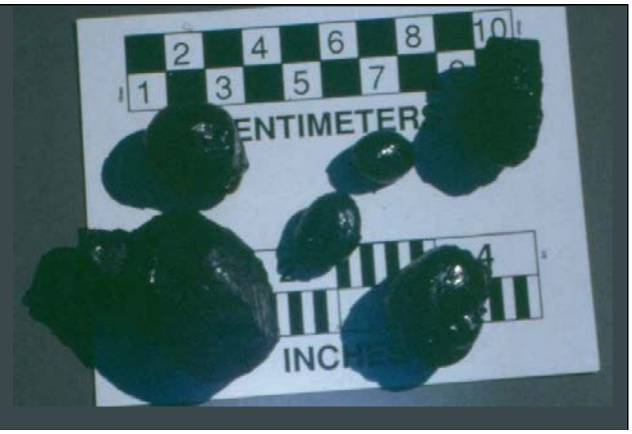

Figure 15. Meso-state balls (apples) of coke 6-8 inches from contact. D-5 track entry. (Tedeski, 2002)

Dike segments are exposed in Main D, between D6 and D5. At the left rib of the belt entry “fingers” in the coke (mesophase thermoplastic deformation?) are exposed in decomposed (weathered?) kimberlite. The “fingers” point slightly upward to N85°W (Figure 16) and appear to have been incorporated in a kimberlite melt flowing eastward.

Figure 16. Finger of coke pointing upward to west in decomposed kimberlite. Left rib of belt entry, Main Drive. (Tedeski, 2002)

At the Entry to D5 airlock door, two dikes 9 inches and 7 inches thick are exposed in the roof, separated by 5.5 feet of coke and coal in the coal seam, and by 5.5 feet of shale in the roof. Along Main D belt a pod of breccia is exposed adjacent to the dike (top left and bottom right in Figure 17). The "breccia" consists of angular fragments of coke and coal shot through by carbonate veins, many of which are lens–shaped.

Figure 17. Breccia consisting of coal and coke fragments in a matrix of carbonate veins, along contact with dike (top left and bottom right). Main D belt. FOV 3 feet. (Tedeski, 2002)

These dikes thicken (bulge) to 29 and 26 inches respectively in the coal. In the next Entry D5B, on MD R-2, the dike, 18 inches thick in the floor and 17.5 inches in the roof, bulges smoothly into an oval-shaped cylinder approximately 104 inches wide in the center (Figure 18; looking east).

Figure 18. Bulbous sill in coal, looking east. Note only a single dike in floor and roof. Axis of sill is 104 inches. MD R-2. The overlapping circular pattern are scour marks from the continuous miner. (Tedeski, 2002)

A quasi conformable relationship of an incipient kimberlite "sill" overriding thin (1-3 cm) layers of coke on well-bedded underclay is apparent (Figure 19). The feeder dike is exposed in the lower right corner. Apart from an increase in the number of calcite veins and stringers, the dike to sill transition in the coal is a remarkably simple, perhaps even passive event.

Figure 19. "Sill" of kimberlite, quasi-conformable to the underlying underclay bed, marked with the pencil. Note the coke wedge on the left side between the carbonate veined kimberlite and the underclay, and the dike phase in the lower right corner (Tedeski, 2002)

This "bulbous sill" can be traced for at least 50 feet along strike. The view to the west (Figure 20) shows a single dike in the floor, "ballooning" in the coal to 109 inches, and two dikes, respectively 11 inches (north) and 9.5 inches (south) in the roof.

Figure 20. Bulbous sill in coal seam, looking west. Note the two dikes on the left and the thin apophysis offset by a bedding fault on the right. For scale the hammer is 13 inches long: the long axis of the "sill" is 109 inches. (Tedeski, 2002)

In addition there is an intrusive stringer (top right) of kimberlite that is offset along a bedding fault in the hanging wall of the coal seam (Figure 21). We deduce that the displacement occurred during the expansive phase of sill development.

Figure 21. Apophysis of kimberlite off "bulbous sill", truncated on bedding fault in roof. The displacement is in the direction of sill propagation. (Tedeski, 2002)

The last exposures (3 segments of dike) are at the end of the rooms to the left of D5, the limit of the mining.

Mineralogy and Petrology

Samples from all Indiana County dikes are porphyritic micaceous kimberlites hosting olivine, phlogopite and chrome-diopside, and picro-ilmenite and garnet (including G9 varieties) as phenocrysts, megacrysts and microcrysts. The term megacryst is preferred because many of the phenocrysts are broken fragments. Other accessory minerals typical of kimberlites are titaniferous magnetite and perovskite. Despite the variation in texture, distribution, concentration and type of phenocrysts/megacrysts apparent in mapping, as well as in hand specimens, there is a commonality of a distinctive mineralogy. These are summarized in **Table 1**.

Olivine (mostly pseudomorphed by serpentine and calcite) dominates the megacryst assemblage. The matrix minerals include euhedral olivine, phlogopite, perovskite, spinel, diopside, monticellite, apatite, zircon, calcite, and late-stage serpentine (Mbalu-Keswa, 1995). The most common xenoliths are local country rocks and coke, some as rounded vesicular clasts with carbonate infill (Figure 22), and rare dolomitic nodules (Figure23). The contact (upper left corner in Figure 23) shows cleated coal adjacent to agglomeratic kimberlite (Figure 24). A coarse-grained dolomite(?) nodule occurs less than 50 cm from the contact (Figures 23 and 24).

Kimberlites are composite assemblages of minerals and rocks from both the source and transit localities entrained during emplacement. Their brecciated nature and porphyritic texture inhibits the development of equilibrium assemblages and complicates radiometric age-dating measurements. A porphyritic texture signifies an interrupted emplacement history with significant residence time for some crystallization of phenocrysts in an intermediate magma chamber(s). Compositional differences between phenocrysts and their kindred species in the matrix are likely.

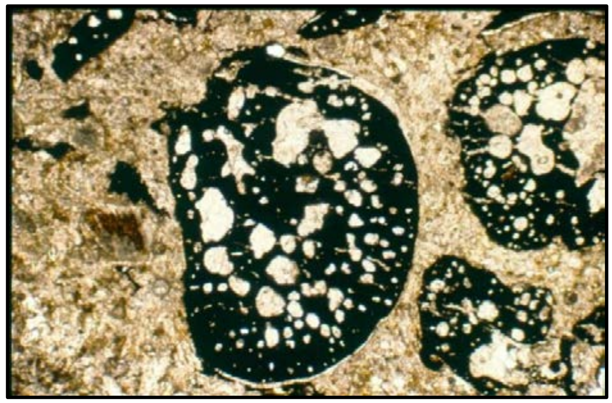

Figure 22. Vesicular coke pellets in kimberlite. FOV 1.5 cm. (Mbalu-Keswa, 1995)

Polymineralic lithic inclusions (xenoliths) represent the equilibrium assemblages amenable for petrogenetic analysis, but no suitable specimens were found at Tanoma. However, a proxy for these may be the assemblages in the "bleb" inclusions in the pyroxene and garnet megacrysts.

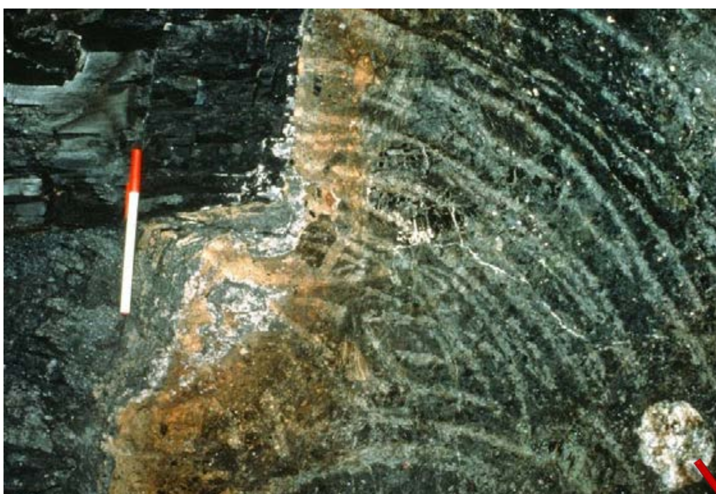

Figure 24. Cleated coal (top left) in contact with kimberlite. Details on texture surrounding dolomite nodule (lower right) are shown in Figure 24 below. D-6 track (Tedeski, 2002)

Figure 23. Dolomitic xenolith (white) in kimberlite agglomerate (Tedeski, 2002)

TABLE 1. Chemical Analyses and Mineral Components of Pennsylvania Kimberlites

Whole Rock							Mineral
Major	I		II	III	IV	V	VI
	Dixon-		Tanoma	Tanoma	Sandy	Mason-	Ernest
(wt %)	ville		D5	D6	Ridge	town	garnet
SiO2	14.48		23.28	27.15	24.09	28.83	44.60
TiO2	1.56		1.82	2.32	1.58	5.67	0.48
Al2O3	5.44		1.78	1.69	3.52	2.94	20.54
Fe2O3	7.23		9.24	9.96	7.62	9.30	
FeO	3.13						4.40
MnO	0.27		0.17	0.18	0.19		0.28
MgO	22.53		26.40	24.69	15.26	24.31	21.40
CaO	18.21		12.43	12.26	21.39	11.24	4.84
Na2O	0.53		0.21	0.22	0.15	0.75	
K2O	0.45		0.59	0.54	1.35	1.31	
P2O5	0.39		1.22	0.87	0.64	0.77	
H2O+	8.46				4.41	3.96	
H2O-	0.38	LOI	23.04	19.64	2.48	0.83	
CO2	17.51				15.5	11.34	
S	0.28						
Total	100.86		100.18	99.52	98.44	100.98	99.99
Cr2O3							3.35
NiO							0.1
Trace Elements in ppm							
	Ba		856	695	1663		
	Cr		1187	1420	1150	185	
	Nb				166		
	Ni		493	588	564	700	
	La				144	142.5	
	Ce				368	270	
	Nd				114	85	
	Sm				15.7	13.35	
	Eu				4.23	3.25	
	Gd				9.75		
	Dy		493	588	5.11	3.4	
	Rb		18	19	45		
	Sr		382	321	1372		
	V		155	163	181		
	Y		7	8			
	Zr		122	93	269	13.75	
	Th				23.4	17	

Tanoma Samples (after Mbalu-Keswa, 1995)		
MINERALS IDENTIFIED (Relative Abundance)		
Mineral	***Common***	***Rare***
XENOCRYST:		
Dolomite?		*
MEGACRYST:		
Olivine	XX	
Ilmenite	XX	
Garnet	X	
Diopside	X	
Phlogopite	XX	
Spinel		*
GROUNDMASS		
Olivine	X	
Phlogopite	XX	
Spinel	X	
Carbonate	XX	
Serpentine	XX	
Perovskite	X	
Apatite		*
zircon		*
Monticellite		*
Pyroxene		*
BLEBS (inclusions in pyroxenes and garnets)		
Phlogopite	X	
Ilmenite	X	
Calcite	X	
Olivine	X	
Perovskite		*
Apatite		*
Spinel		*

I = Dixonville Dike,Barr Slpe Mine (Wet chemical analysis from Honess and Graeber, 1926)
II = Tanoma D5 (XRF analysis from Mbalu-Keswa, 1995)
III = Tanoma D6 (XRF analysis from Mbalu-Keswa, 1995)
IV = Sandy Ridge ACT-Labs, Ontario, Canada (from Gold and Doden)
V = Masontown. Majors from Kemp and Ross (1907). Trace elements from Shervais et al., (1987). Minerals include: pyrrhotite, pentlandite, chalcopyrite, and Pt-iron alloy in olivine megacrysts (Stone and Fleet, 1990)
VI = An average of 6 red garnets from Ernest sample: normalized to 100% (Smith and Barnes, 9/01/2016)

An interesting feature in the Tanoma dikes are "blebs" of polymineralic assemblages within megacrysts of pyroxene and garnet (Figure 25). The "blebs" range from a few microns to 1 mm in diameter, are circular, semi-polygonal to irregular in shape and do not appear to mimic the host's shape. Most of the "blebs" are spherical and are completely enclosed by the host, but a few irregular "blebs" occur as embayments on the margin. The blebs are interpreted as entrapped magma during the growth of the host (Mbalu-Keswa *et al.,* 1994). A phlogopite inclusion was noted in an olivine megacryst.

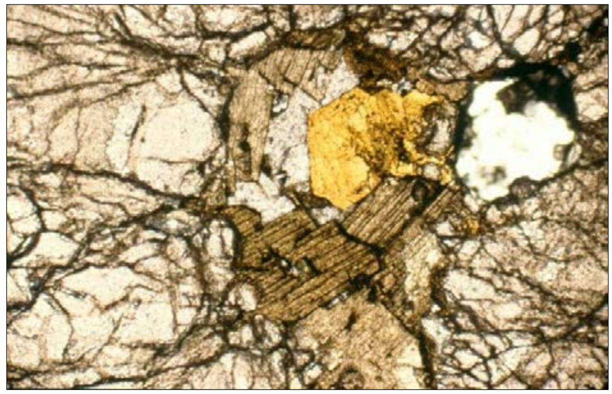

Figure 25. Polymineralic inclusion in garnet megacryst. Plain light. FOV 2.5 mm. (Mbalu-Keswa, 1995)

The following description on selected minerals in the Tanoma kimberlite are taken from the thesis by Chuma Mbalu-Keswa (1995).

Olivine

Olivines and its pseudomorphs are the most obvious mineral in the Tanoma kimberlite. They occur as megacrysts, microcrysts in the matrix, and in polymineralic "blebs" in pyroxene megacrysts.

Megacrysts ranging from 1-8 cm long, as well as fragments with rounded margins. Many exhibit marginal reaction rims and some show compositional zoning (Fe enrichment) on backscatter electron (BSE) images.

Euhedral and subhedral microcrysts in the matrix, range from 100 to 500 microns across. Most are altered to serpentine.

Olivines in the polymineralic "blebs" in pyroxene are 100-350 microns long and are distinctly enriched in MgO (Fo_{88} to Fo_{91}).

Pyroxene

Two distinct varieties of clinopyroxenes are apparent:

An emerald green, well-cleaved euhedral Cr-rich pyroxene (chrome diopside) up to 6 cm across (Figure 26).

A lighter greenish-gray, Cr-poor variety as large as 10 cm across. The latter contain polymineralic inclusion or "blebs" consisting mainly of phlogopite, ilmenite, and titanomagnetite in a carbonate matrix. Despite their physical difference their chemistry is similar.

Figure 26. Polymineralic inclusion in garnet megacryst. Plain light. FOV 2.5 mm. (Mbalu-Keswa, 1995)

Other clinopyroxenes occur within the “blebs”, and these differ from those in the host kimberlite matrix in their greater TiO_2 content.

Orthopyroxenes are suspected amongst the altered and serpentinized megacrysts and microcrysts, particularly those with euhedral and subhedral outlines. They may have been more abundant than the 0.4% noted by Shultz (1999) in Tanoma samples.

Ilmenite

Tanoma ilmenites are glassy magnesium-rich ilmenites (picro-ilmenites of a bygone generation), with relatively constant MgO values ranging from 9.4 to 11.46%. Four paragenetic types have been recognized (Mbalu-Keswa, 1995).

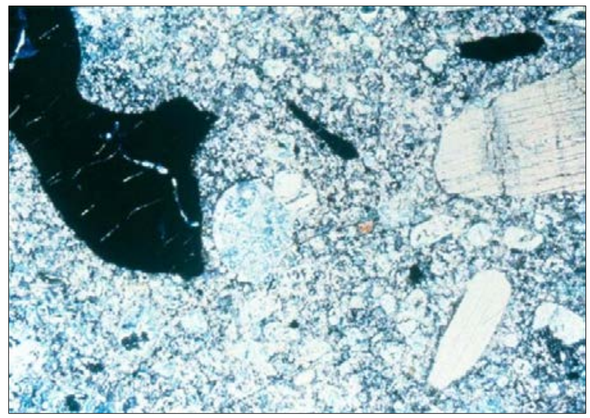

Figure 27. Ilmenite, olivine and phlogopite megacrysts in globular textured matrix. Plane Light. FOV 2 cm (Mbalu-Keswa, 1995)

1. Large (up to 5cm across) rounded to irregular-shaped single crystals with carbonate veinlets and fractures containing small phlogopite crystals similar to those in the matrix (Figure 27). These are interpreted to be xenocrysts rounded by abrasion during transportation.
2. Large subhedral crystals up to 3 cm across.
3. Small (50 to 100 μm) euhedral to anhedral crystals dispersed in the groundmass. No chemical data are available.
4. (a) Small rounded grains, 50-100 μm across, occur in the multiphase “blebs” in pyroxenes, and more rarely in garnet megacrysts, where they occur as one of the most abundant phases. The trend in the ilmenites within the “blebs” is low MgO with increasing Cr_2O_3, in contrast to larger crystals in the matrix with higher MgO and a decrease in Cr_2O_3 with an increase in MgO. A possible chemical discriminator is “low chrome, low magnesium”.

   (b) Small euhedral (rectangular) grains in a similar setting and association as 4a, are Cr-poor relative to their round neighbors.

Chemically there is a separation between Cr- rich and Cr-poor ilmenites megacrysts at approximately 2.5 % Cr_2O_3. In the latter Fe is enriched at the expense of Mg. The cores of the subhedral megacrysts analyzed show remarkably uniform Ti, Fe and Mg content. However the reaction rinds preserved on some of the more regular faces show a marked enrichment in iron, and in some also alumina (Cassidy, 2015).

The reaction rims, ranging from 5-30 μm thick (Figure 28), are enriched in Al, Mg and Fe and depleted in Ti and Cr: and contain discrete spinel phases of titanomagnetite and magnetite (Borella, 1997). A non-uniformity of reaction rim development around all or part of the megacrysts is interpreted as local fragmentation of a late iron-enrichment oxidation trend of relatively short duration (Borella, 1997). Pre- and syn- reaction rim developments in micro-veins are consistent with fragmentation events prior to and during emplacement. Elemental components in the EDEX spectrum of the veins (and their likely mineral phases) include: Fe (magnetite); Mg + Si (olivine); Ca + Mg +C (calcite/dolomite), Ba + S (barite). The late veins are composed primarily of carbonates and are clearly post-emplacement phenomena.

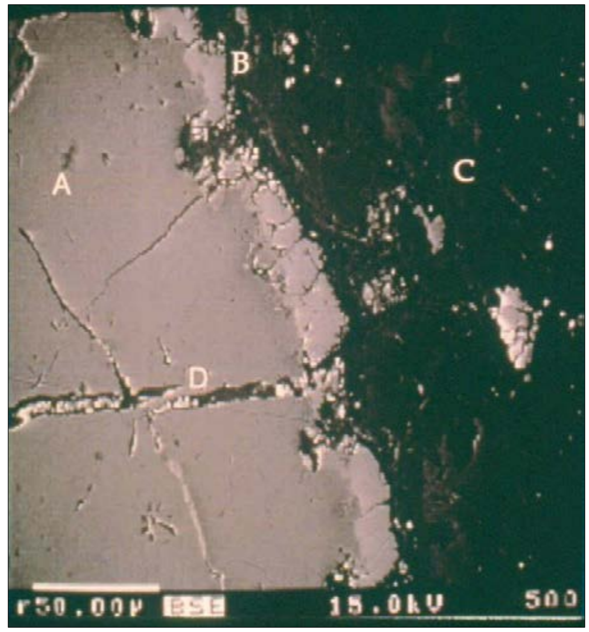

Figure 28. Back-scatter image of ilmenite, spinel in rim and matrix. FOV 5500 µm. (Borella 1997)

Phlogopite

The most distinctive mineral characterizing the Tanoma kimberlite is phlogopite. It occurs as megacrysts and microcrysts in the groundmass, and the polymineralic "blebs" in garnets and pyroxenes, and modally are second only to olivine. All are titanium rich (TiO_2 values from 1.74 to 2.70%), with SiO_2 steady in the range of 38.59 to 41.97%. There is no obvious chemical discriminant between matrix and "bleb" phlogopites except for a slightly greater chrome content (> 0.5% Cr_2O_3) in the latter. The megacrysts crystals have yet to be analyzed.

Dark brown to bronze-colored phlogopites are ubiquitous as megacrysts, as well as microcrysts in the matrix. They occur as large euhedral crystals typically less than 8 cm across (Mbalu-Keswa, 1995), but Tedeski (2002) records some from 12 -18 cm across. The booklets typically are intergrown with carbonate along the cleavage planes. Many of the larger crystals are distorted and kinked (Figure 29), and generally have corroded margins.

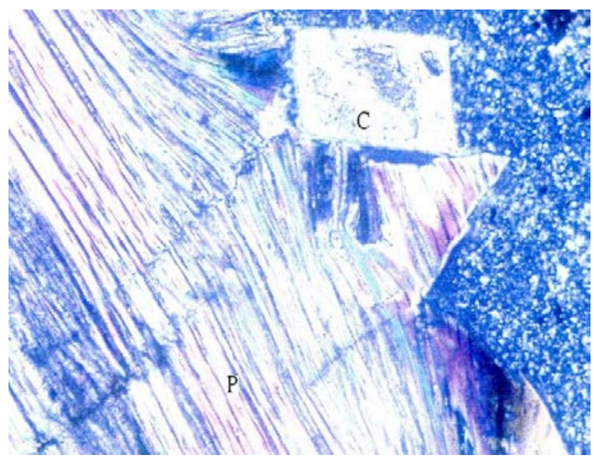

Figure 29. Phlogopite megacryst, with calcite laminae on cleavage. Crossed Nicols. FOV 2 mm. (Mbalu-Keswa, 1995)

The groundmass phlogopites occur as small laths that only locally show a flow-alignment fabric.

Phlogopites also populate the polymineralic "blebs" in clinopyroxenes and garnet, and may occur as single crystals in olivine. The former occur as laths up to 5 mm long and are well-preserved with sharp outlines. In some pyroxene hosted "blebs" the laths are distorted and exhibit reaction margins. Others are intergrown with an unidentified, Mg-rich silicate phase (37.3 % MgO; 34.5% SiO_2; depleted in Al_2O_3 (0.3%) and CaO (0.18%)).

Garnets

Most of the garnets are reddish brown and range in size from 0.1 mm to 5 cm. They typically occur as rounded isolated crystals or as irregularly-shaped fragments. Less than 25% of the analyzed samples have a corona of kelyphite (see Appendix 1 image 8). They are mainly titan pyropes, or G1 garnets in the Dawson and Stevens (1975) classification. Borella (1997) examined the reaction rinds, typically 5 to 20 μm thick, around G-1, Cr-poor pyrope. These showed a decrease in silica and alumina and a marked increase in K_2O and H_2O in the rims.

Polymineralic inclusions in garnet consist mainly of phlogopite and calcite with accessory amounts of pyrite (?), apatite, sphalerite, ilmenite and zircon. From a limited number of analyses, garnets with inclusions appear to be slightly enriched in Cr_2O_3 and depleted in TiO_2.

Unusual pyrope garnets exhibiting color changes from daylight to fluorescent lighting conditions (alexanderite effect) were collected from the Gates-Adah kimberlite (Smith and Barnes, 2006). Embedded in a supplement to this report are SEM analyses of 58 pyrope garnets from Tanoma (collected on the Smith and Skema excursions in 1982 and 1984). This population contained six G1, six G3, and forty four G9's (16 were judged normal, 4 as low Ca and 9 as low Fe, 14 with both low Ca and Fe, and 2 with low Ti. There were two anomalous garnets with high Mg. These compositions are not favorable for the preservation of diamonds (Doden *et al.,* 1998).

Spinels

The spinels, mostly titanomagnetites occur as:

(1) Relatively rare rounded megacrysts up to 1 cm in diameter.
(2) Very small (< 1 μm) crystals in the matrix. No analyses are available, but reddish outlines on some grains suggest incipient oxidation.
(3) Clusters of small (100-500 μm) magnetite crystals along the margin of serpentinized olivines.
(4) Micron-size crystals of magnesian-rich titanomagnetites(?) occur in polymineralic inclusions in pyroxenes. They exhibit some unusual chemistries. High MgO in the 5-6% range, TiO_2 (11.25 to 16.21%), FeO (33.74 to 37.79%), Fe2O_3 (37.13 to 44.42%), and less than 0.3% Al_2O_3. Cr_2O_3, typically in the 1.18 to 1.98% range, reaches a value of 10.38% in one analysis.

Micro-veins

Several stages of micro-veins are apparent in many of the megacrysts of garnet, pyroxene and ilmenite. Early veins in the garnets occur wholly within the megacryst, a second set that pierces or occurs between the reaction rim and the host, and later veins that extend through the megacrysts in to the matrix.

Barite was detected in some early stage internal veins; carbonate (calcite and dolomite) in the late through-going veins. The former may represent deformation during, and the latter post emplacement (Borella, 1997).

Emplacement Depth and FO_2 Considerations

The coal resources in the Appalachian foreland basin have stimulated many studies on the coal rank and the thermal regimes. White's (1925) regional carbonization map (fixed carbon, dry, ash-free) shows the 65-75 isocarbs for Indiana County. The burial depth at the time of kimberlite emplacement (assumed 160 to 180 Ma) is variously estimated as 2.1 to 2.9 km from fission track annealing data on apatites (Blackmer, 1992), and 3.4 km from vitrinite reflectance of coal (Zhang, 1992). Paxton (1983) concluded that coal rank and reflectance were produced before folding and thus supported a burial depth of approximately 3-4 km over the High Plateau. Bulk density/porosity/compaction measurements on Lower Allegheny sandstones (Chou, 1985) showed a steep gradient over the High Plateau, consistent with the isocarb data, and Paxton's estimate. A variable heat flow is inferred for blocks within the basin (Blackmer, 1992) who notes an elevated thermal anomaly in the vicinity of the Gates-Adah kimberlite. From fission track annealing dates in apatites, and vitrinite reflectance temperatures, Blackmer (1992) and Blackmer *et al.,* (1994) were able to reconstruct the following unroofing history of the Appalachian foreland basin. From the end of the Alleghenian Orogeny into the Jurassic unroofing was rapid and greater in the east than the west. This was followed by a quiet period of relatively little erosion into the Miocene, and then rapid unroofing to the present (Blackmer, 1992). The unroofing history is important because vitrinite reflectance data record maximum temperature and not the temperature adjusted for the amount of erosion at the time of kimberlite emplacement. The probable burial depth of 2.3 to 2.9 km for a mid-Jurassic age for intrusion coincides with a tensional regime of drift and subsidence of the North American passive margin.

Temperature and log f_{O2} data were attained from Fe-Ti geothermometry and geobarometry calculations using the Andersen and Lindsley (1988) model for ilmenite-spinel pairs in pyroxene-hosted "inclusions". These range from 788°C to 882°C and from -12.5 to -14.5 atmospheres respectively (Mbalu-Keswa, 1995). With inferred emplacement conditions more oxidizing than either the FMQ and MW buffers, the preservation of any carbon polymorphs is negligible.

Tectonic Setting and Age of Emplacement

A Jurassic event is favored for the emplacement of these Pennsylvania kimberlites, based on stratigraphy and radiometric age dates (Shultz, 1999). Despite mineral equilibration difficulties a 167 ±3 Ma date from U-Pb in perovskites, in the Masontown dike, is considered tight (Smith, Pers. Comm., 2016), and in good agreement with the K/Ar dates of 176±10 and 188 ± 10 Ma, by Pimental *et al.*, (1975). In a later study (Bikerman *et al.,* 1994) found the fine-grained, matrix phase phlogopite to be younger (147±1.5 Ma) than the phenocrystic phlogopite (353.2±2.2 Ma). The Dixonville/Tanoma dikes intrude Alleghenian Group strata and are clearly post-Pennsylvanian in age.

Current attempts to determine $^{40}Ar/^{39}Ar$ crystallization ages on phlogopite megacrysts, as well as microcrysts in the matrix, from the Tanoma intrusion, are described below. Samples were hand-picked and 0.1 gm aliquots were measured by Chris Hall at the Argon Geochronology Laboratory at the University of Michigan, following the protocol of Hall and Farrell (1995). The Tanoma phlogopites yielded total gas ages of 551.2 ± 1.4 Ma for the megacrysts and 516.2 ± 1.4 Ma for the microcrysts. Their plateaus are relatively flat and yield similar (within the reported error) ages to the total gas ages. The MSWD (mean square weighted deviation) for the age calculations are less than 1.5. Interpretation for these ages is complicated by their complex petrogenesis and because they pre-date the host strata. Other studies of phlogopite in kimberlite occurrences have yielded similar geologically older than host rock ages. Phillips and Onstott (1988) demonstrated that phlogopites from kimberlites have zoned age determinations within crystals and attribute the disequilibrium to acquisition, by diffusion, of excess argon during and after crystallization. This excess argon anomaly in the Tanoma samples has yet to be resolved. Most likely the reported ages here possess the same isotopic disequilibrium.

The alignment of isolated kimberlites in a northeast trending belt from Tennessee through New State coincide with the axis of the Appalachian foreland basin (Figure 30).

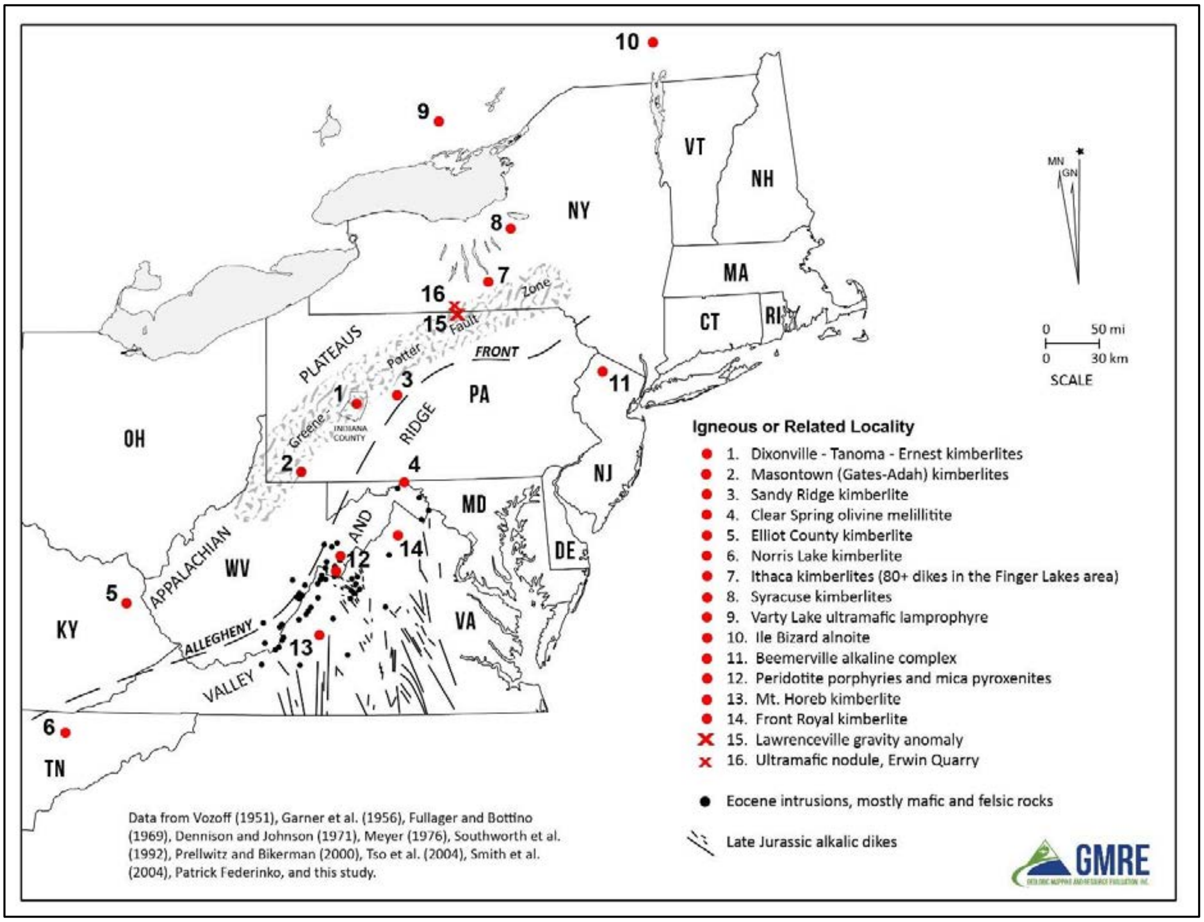

Figure 30. Regional map showing locations of kimberlites and other ultramafic/alkaline rocks in Pennsylvania and nearby states. Greene-Potter fault zone adapted from Root (1978) and Parrish and Lavin (1982). Also illustrated is the Allegheny structural front that marks the boundary between the Appalachian Plateaus and Valley and Ridge Provinces.

Sub-surface structures include the Rome Trough graben and the Greene-Potter fault zone (Root, 1978), which overlie Grenville Basement. The basin-axis trend from Mannheim, Syracuse and Ithaca, New York to Dixonville and Masontown, Pennsylvania is reinforced if one infers that a 15-milligals anomaly approximately 12 miles in diameter, that is centered on Lawrenceville, Tioga County, Pennsylvania (Vozoff,1951) represents a local, high density intrusion. No surface exposures have been reported, but a garnet lherozolite nodule approximately 30 cm across was recovered by Pat Federenko from the nearby G.O. Hawbaker, Inc., sand and gravel quarry at Erwin, New York. An emplacement age of 139 Ma (Basu *et al.,* 1984) for kimberlites near Syracuse in New York, and Ile Bizard in Quebec (spatially associated with the Oka Carbonatite Complex, dated as 117 Ma) may define a northward younging trend.

A more diverse variety of relatively small intrusive centers is exposed east of the Allegheny Front (see Figure 30). These include clusters of Eocene alkali plugs in Virginia and West Virginia and swarms of Jurassic dikes, as well as some older ultramafic bodies such as kimberlite at Mount Horeb, Virginia, olivine melilitite flows and tuffs at Clear Springs, Maryland (433± 3 Ma and 436±4 Ma) (Smith, 2004), and a 435±20Ma age for an alkali complex at Beemersville, New Jersey (Zartman *et al.*, 1967). However, all occur in significantly different allochthonous hosts.

G-9 garnets have been recovered (Smith and Barnes, Pers. Comm., 2016) from a number of these sites (Ile Bizard, Portland Point, N.Y., Tanoma, Gates-Adah, Mount Horeb, and the Clear Spring diatreme tuff) on both sides of the Allegheny Front. It is noteworthy that high Cr pyropes in the Gates-Adah dike are inferred to come from a peridotitic environment (ibid).

Cross-strike, essentially vertical discontinuities in the crystalline basement terrane are apparent in the regional gravity and magnetic maps (Alexander *et al.,* 2005). Parrish and Lavin (1982) suggest that deep-seated, cross-strike basement fractures were reactivated during the Jurassic reopening of the Atlantic Ocean. There are convincing correlations for Ile Bizard, as part of the Monteregian Hills intrusive trend along the Ottawa-Bonchere Graben (Krumapelli, 1970), and the Lawrenceville gravity anomaly on the Attica-Lawrenceville lineament (Parrish and Lavin, 1982). The Gates-Adah dike parallels but does not coincide with the basement, Highlandtown fault zone on the Pittsburgh-Washington lineament, but Roen (1968) concluded the dike intruded a preexisting strike-slip fault of minimal left-lateral movement. He called attention to "northwest-trending transcurrent structural lineaments, -…- considered to be reflections of differential movement along the margin of a subsurface decollement". The Dixonville/Tanoma Dike overlies the 140° trending Home-Gallitzen basement lineament (Alexander *et al.,* 2005). However, the 086° strike of the Dixonville/Tanoma dike is not consistent with basement fractures trajectories, nor is it apparent in the overlapping sets of physiographic lineaments (110° and 140°) mapped from LANDSAT imagery (Gold, 1999). The kimberlite "intrusion" at Sandy Ridge (# 12) is included despite its "phantom" nature, because it is close to the Tyrone–Mt Union lineament. Intuitively, this model for the Appalachian Foreland Basin does not apply to the Clear Springs olivine melilitite and the Beemersville alkali complex in allochthonous tectonic settings.

The kimberlite has been emplaced through Proterozoic basement (Grenville crust of ± 1 billion year age) and Phanerozoic cover after at least the deposition of the Allegheny Group during the Pennsylvanian. In a recent study of the Gates- Adah dike Schultze and Hearn (2015) call attention to the presence of SiO_2-enriched spinels and speculate a buried UHP (ultra-high pressure) terrane beneath the Grenville. A diamond potential is indicated from the G9 garnets, and the equilibrium condition of the clinopyroxenes with respect to a steady-state subcratonic geothermal gradient to a surface heat flow of 40 mW/m^2 in the diamond stability field, despite its off-cratonic tectonic setting in the Appalachian foreland basin (Schultze and Hearn, 2015).

The fact that minerals in many kimberlites yield a crystallization age that predates emplacement and a porphyritic texture suggests a residence time below the Ar-blocking temperatures in a secondary magma chamber, or preservation of mantle argon. A gas-fluidization system is envisaged in which a reduction in temperature during upward migration triggers exsolution and outgassing of volatile components and promotes a large pressure build up, sufficient to develop cracks and erode fissures through the crust, particularly in regions of tectonic tension (Gold, 1972).

Summary and Conclusions

- The rogue intrusions in Indiana County are carbonatized hypabyssal kimberlites.
- The Dixonville dike and the Tanoma dike are the same intrusion, and extend almost continuously from the lower Kittanning coal to the Lower Freeport coal through a vertical distance of approximately 180 feet.
- With a demonstrated vertical extent of several hundred feet in the underground workings, there should be surface crops. Their apparent absence is an enigma.
- The singularity of the Dixonville dike and the Masontown (Gates-Adah) dike is remarkable. They are essentially single-fissure, small volume events.
- The kimberlite dikes in Indiana County provide an opportunity to address problems of kimberlite emplacement relative to emplacement temperatures and habit of intrusion. Novel terms such as "bulbous sills" and "blades dikes" represent well-documented underground exposures, in which nearly flat-lying coal seams have played an important role. Relatively cold intrusion and long reach are part of this genre.
- The off-craton setting in the Appalachian foreland basin coincides with an extensional tectonic regime during the Jurassic and the opening of the Atlantic Ocean.
- Dike and sill habits suggest that magma pressure may have been in balance with lithostatic load; a condition that would have promoted a lateral (quasi- horizontal) component to crack development with only limited upward migration towards the surface. We propose that the coal seams provided a convenient escape sink for the outgassing volatile phases from the magma, stifling their upward migration.
- A volatile-rich kimberlite melt is inferred from the high H_2O and CO_2 content of emplaced kimberlite. We conclude that a fluid-rich melt, with a low heat capacity, was necessary for the emplacement of these thin dikes (cm scale) a long distance from their source.
- We propose that intrusion-induced hydraulic fracturing augments the emplacement of kimberlites in the thicker foreland basins coal seams.
- Heavy isotope work by Shank (1992) indicated a Sr^{87}/Sr^{86} ratio of 0.750 (quoted from Mbalu-Keswa, 1995), which is well within the Bristow et al., (1987) field for micaceous Group II kimberlites.
- The potential for diamonds is low.

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THE ROGUE KIMBERLITE DIKES IN INDIANA COUNTY, PENNSYLVANIA PART 2. COKED COAL MARGINAL TO KIMBERLITE INTRUSION IN THE TANOMA MINE

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Introduction

The Tanoma Mine is located approximately 5 km west of Dixonville, in Indiana County Pennsylvania, where a kimberlite dike was exposed while mining in the Lower Freeport or "D" coal (Honess and Graeber, 1926) in the Barr Slope Mine (Figure 1). *En echelon* dikes striking E-W were exposed for over 2 km in the Tanoma Mine tending towards Dixonville, and there is little doubt these represent the same dike swarm, albeit in a different seam, the Lower Kittanning or "B" coal, approximately 50 meters stratigraphically below. The Tanoma kimberlite was formally noted in a Pennsylvania Department of Environmental Resource internal report (Smith II, R.C, 1984). However, no detailed petrologic or mineralogic studies were undertaken for comparison with the Dixonville intrusion until now. Besides characterization of an igneous intrusion in workings of the Tanoma coal mine, Indiana County, Pennsylvania, an investigation of the contact metamorphism with the coal was initiated in an attempt to use maximum reflectance measurements to estimate the temperature of intrusion. (Figure 1).

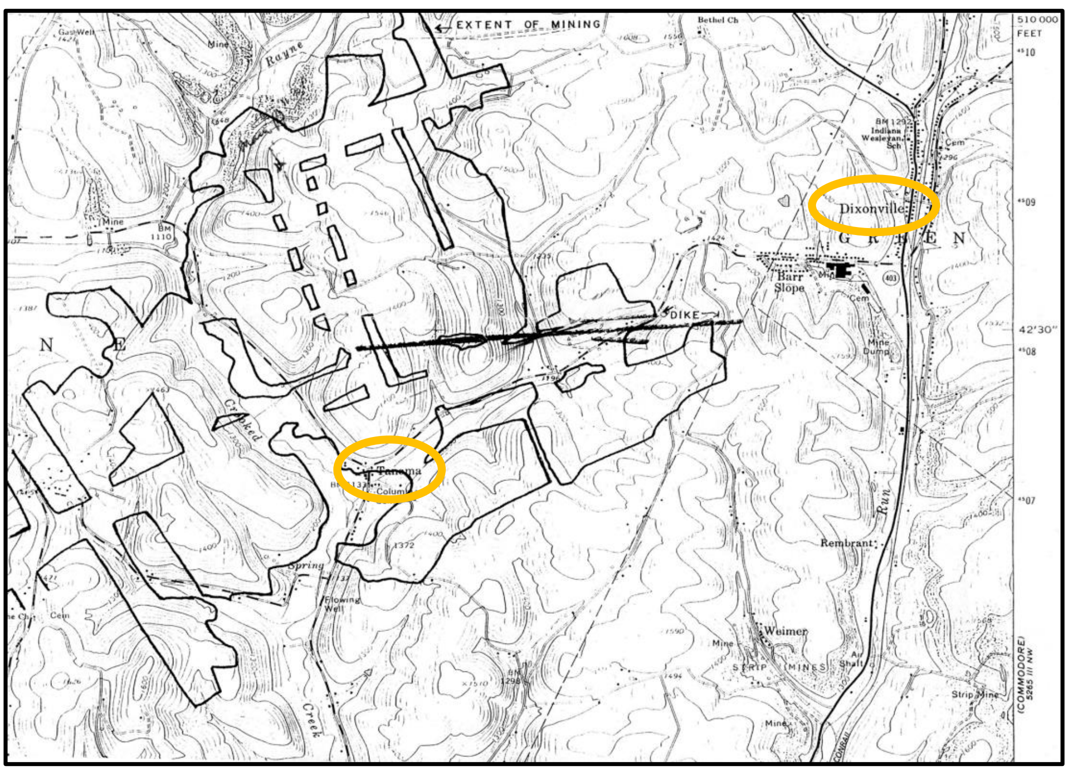


Figure 1. Location of the Tanoma Mine Workings and the East-West Trending Intrusion West of Dixonville, Bar Slope Mine on the Clymer, 7.5' quadrangle.

Evaluation of Thermal History

Figure 2 portrays a 24-30 cm thick dike intruding the full height of the Lower Kittanning coal seam and that was composed mostly of serpentine, but containing large megacrysts (phlogopite shown), remnants of olivine as well as unaltered kimberlite. A chill zone beside the contact with the natural coke was observed along with the characteristic shrinkage fractures in the coke that form parallel with the thermal gradient and are generated from thermoplastic deformation and devolatilization of the coal. These coke structures strongly suggest that the coal had reached bituminous rank at the time of intrusion and likely had reached its current medium volatile rank (i.e. 1.11% mean max. vitrinite reflectance, ASTM D388). However, the question being asked at the time this work was conducted (1994), "can the temperature of the intrusion be determined by optical microscopic techniques, specifically using coke reflectance?" Textural and reflectance evaluations of metallurgical coke suggest useful information could be derived using these techniques, although application to the thermal metamorphism of coal would be more complicated in accounting for a long list of unknown influences of geological setting and variable reaction conditions.

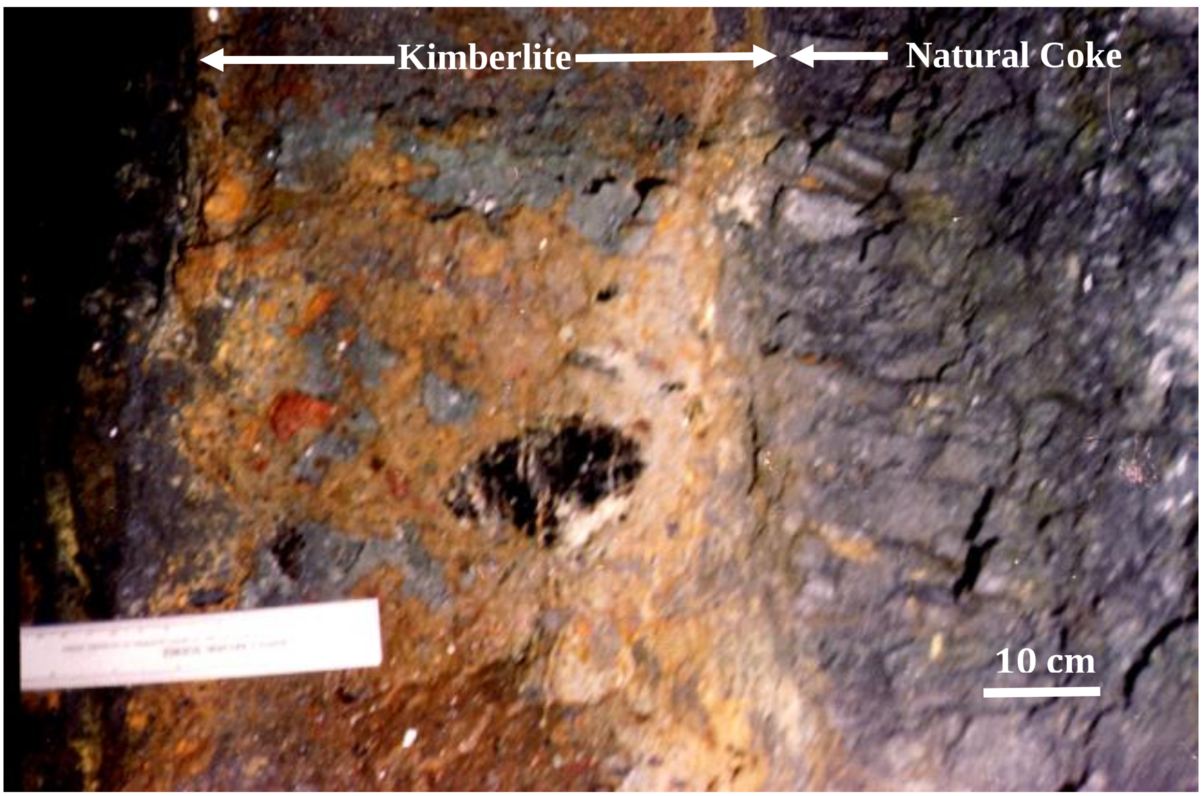


Figure 2. Photograph of contact between kimberlite dike (left) and natural coke (right). Note the phlogopite megacryst (center) and shrinkage cracks perpendicular to the intrusion.

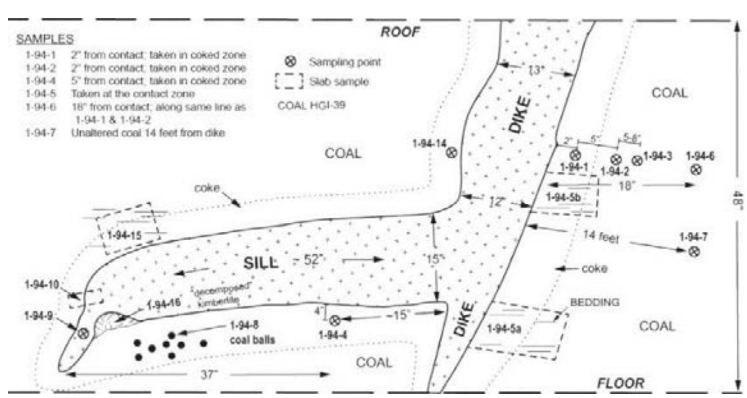
Thin dikes of a highly fluid magma like those encountered at the Tanoma Mine would probably result in fairly rapid heating for a limited time period and may be influenced by the latent heat of crystallization of the magma, groundwater circulation and expulsion of volatile matter, as well as thermal conductivity and diffusivity of rocks, etc., (Delaney 1987). Bostick and Pawlewicz, 1984; Stewart et al., 2005 used kinetic solutions (Carslaw and Jaeger, 1959) to estimate temperature across intrusions and wall rock as well as laboratory carbonization in an attempt to determine maximum dike temperature. Spear (1993) suggests that thin dikes of <1 meter may cool in a matter of days, making the maximum temperature achieved during intrusion a dominant factor in defining morphological changes such as the size and shape of optical textures and measured reflectance values (Cooper et al., 2007; Baker et al., 1998; Price, 1983). Using fluid inclusions, vitrinite reflectance, apatite fission track analyses of Gippsland Basin dikes, Barker et al., (1998) found that cooling next to relatively thin dikes may interfere with development of an incipient conversion systems. The cooling causes estimates of maximum temperature determined by reflectance techniques to be lower than those estimated by fluid inclusions.

A more direct approach is taken in our investigation based on the assumption that the maximum temperature attained by the coal at the contact is determined by subjecting the contact coke to progressively high temperatures in the laboratory to determine the temperature below which thermal treatment fails to induce a change in the measured reflectance. Using one of the contact samples to generate a reflectance profile from contact to unaffected coal establishes (a) whether the coal had been heated though it's thermoplastic phase, and (b) whether it developed a coalesced mesophase and a solid anisotropic carbon, thereby producing a partially condensed and crosslinked aromatic carbon. This means that exposing the natural coke to further increases in temperature will only result in additional condensation of the pseudo-lattice by the shedding of small aromatic and aliphatic compounds. In support of this approach, not only will a reflectance profile of the natural coke be necessary, but laboratory carbonization of the coal at progressively high temperatures will be needed to provide template of how the coal would react to thermal input in a manner similar to Bostick and Pawlewicz, (1984).

Samples *(see Part 1, Figure 12)*

Two block samples (~ 8x10x14cm) of the natural coke were obtained for general characterization and to determine contact temperature using quantitative reflectance techniques. Each block contained a thin layer of kimberlite and the complete aureole along with some unaltered coal. One block sampled from the top surface of a sill (I-94-15), and the other block used to extract contact coke for direct carbonization was collected from a ~30 cm thick dike (I-94-5b). Finally, a sample of unaltered coal 4.3 m from the dike was employed to obtain background reflectance values as well as coal for laboratory carbonization measurements at progressively higher temperatures.

(Figure 12 from Part I, which is a map showing the sample locations, is reproduced here for your convenient reference):



Polished specimens were prepared from block sample (I-94-15) containing natural coke after an initial vacuum impregnation with a cold-setting epoxy resin. A cross-sectional surface measuring approximately 8 by 14 cm sized from the original block was cut into six smaller subsamples of 2 by 7 cm (Figure 3). These were re-impregnated in epoxy for added stability, and then ground using 400 and 600 grit silicon carbide papers and polished, using 0.3 µm and 0.05 µm alumina slurries, for reflected-light optical microscopy. The other, smaller block sample (I-94-5b) containing kimberlite material sampled from a vertical dike was used in laboratory coking experiments. In addition, a representative sample of the coal was crushed and prepared into briquettes for petrographic analysis. This control sample yielded background reflectance values as well as powdered coal (minus 0.25 mm, or 60 mesh) for micro-carbonization tests.

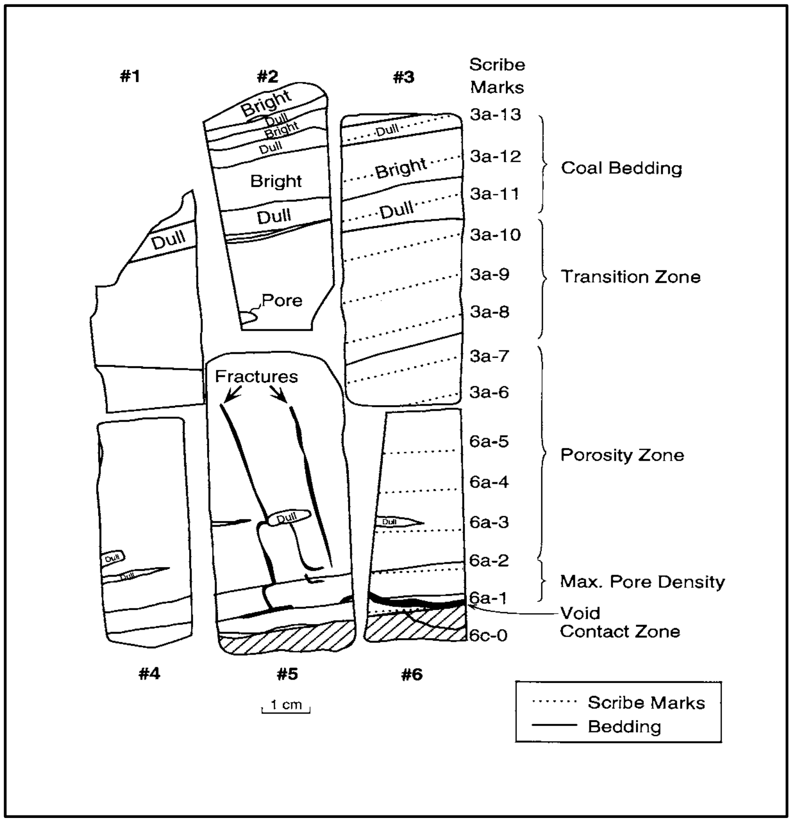


Figure 3. Sample preparation of larger large block (I-94-15) containing contact zone (bottom), natural coke and marginally reacted coal (top). Orientation of bedding planes suggest this sample was collected from the top surface of a connecting sill 1.3 m from the dike.

Analytical Protocol

Reflectance analyses were performed using a Leitz MPV 2 research microscope with white-light illumination and a 50 X oil-immersion objective for a total system magnification of 625 X. The incident light was polarized at 45°. Light from the polished surface was passed through a 1.9 µm diameter limiting aperture and then through an interference filter centered around 546 ±5 nm. For measurement of reflectance the photomultiplier system was standardized using optical glasses of 1.009% and 1.662% reflectance. Calibrated neutral density filters were used to reduce light intensity of the natural coke into the reflectance range of the glasses, the optimal stability range of the photomultiplier, then reflectance values were calculated based on the transmittance of the filter at 550 nm.

Mean maximum (R_{max}) and mean minimum (R_{min}) reflectance values were collected on all samples by rotating the specimens through 360° and recording the highest and lowest values measured by the photomultiplier, respectively for 100 individual readings. Typically, random reflectance is employed for temperature profiling of igneous/coal contacts. This is understandable when measuring reflectance values on fine size or immature dispersed organic matter in sedimentary rocks, but not from coal that developed a mesophase and solidified into fairly large isochromatic textures.

To establish a reflectance/temperature profile for this Lower Kittanning coal carbonized under atmospheric pressure, small aliquots of coal were heated using a micro-carbonization technique. The procedure involved loading ≈1.0 g of <0.25 mm coal into a quartz tube stopped with quartz wool, and placed into a small stainless steel reaction tube. Samples were set into a programmable laboratory furnace and carbonized under a slight over-pressure of nitrogen at a heating rate of about 5°C/min to the desired maximum temperature and allowed to soak at that temperature for 2 hours. Carbonization temperatures between 200° and 900°C were employed at 100°C increments with runs at 350° and 450°C added later to complete the thermal/reflectance profile. This procedure was not used to simulate coking conditions occurring at depth during intrusion. Rather it provides a correlation between temperature and reflectance for this coal under uniform coking conditions.

Carbonization runs using the same procedures were performed on material retrieved from the contact zone from the second block sample (I-94-5b) containing natural coke. A particulate sample of natural coke was obtained by removing the contact zone containing kimberlite material and then cutting a 5 mm thick slab from the end of the specimen. The recovered material was crushed to minus 0.25 mm and carbonized as describe before. Four carbonization tests were made at 100°C increments from 400° to 700°C. Samples of the contact coke and those from micro-carbonization were prepared for reflectance microscopy.

Results and Discussion

Under the polarizing microscope using oil immersion, the contact zone (6c-0, Fig. 3) was seen to be composed of serpentine with significant rounded porosity and small amounts of irregularly shaped coke fragments commonly possessing a 2-12 μm mosaic texture. The first competent coke layer (6c-1, Fig. 3) also possessed rounded porosity and was composed predominantly of irregularly shaped mosaic carbon of 2-10 μm with minor 1-3 μm circular mosaic carbon. Rounded porosity within the contact zone suggests the presence of a fluid phase being trapped in a more viscous melt, gas or liquid. For the next 3 cm beyond the contact zone, slightly lenticular mosaic carbon of 8-40 and 8-25 μm was observed. Farther away from the contact zone, mosaic size diminished and approximately 7 cm from the contact 1-5 μm mosaic textures (more characteristic of the current coal rank), were found along with a fairly high concentration of partially coalesced spherical mesophase in an isotropic pitch (3a-7, Fig. 3) similar to that observed by Brooks and Taylor (1961 & 1968). In contrast to the pitch matrix, the size and concentration of mesophase spheres decreased until the first vitrinite containing bands of liptinite and inertinite macerals was observed, at 10.75 cm from the contact (3a-10, Fig. 3).

Beyond this point, normal coal features with bedding structures were observed oriented parallel to the contact, which would be consistent with a sill. The vitrinite reflectance values in aureole remained higher (1.22% ±0.02) than the mean reflectance of the background coal specimen (1.11% ±0.02). Based upon these results the reflectance profile for the upper contact of a thin sill showed a gradual decrease equal to one half of the width of the intrusion from the contact. Similar results have been reported by Cooper et al., (2007) for stills and dikes of lamprophyric composition intruding 1.0% reflectance coal in the Raton Basin.

Mean reflectance values relative to distance from the intrusion are plotted in Figure 4 which shows that the greatest maximum reflectance was measured for anisotropic material intimately associated with the kimberlite within the contact zone. As distance from the contact increased, maximum reflectance decreased, whereas minimum reflectance remained about the same. At 6.75 cm from the datum, measurements became possible on the pitch phase, initially found in low concentration and trapped within an anisotropic carbon matrix. The pitch had reflectance values that were similar to, but slightly higher than, the present-day unaltered coal (1.11% Ro). Reflectance values measured on vitrinite from the region 10.75 cm from the datum also were only slightly higher than that measured for the unaltered coal.

Coals of medium volatile bituminous rank produce lenticular isochromatic mosaic units of ≈1-4 μm and with maximum reflectance values between 7.0-10.0% when carbonized to 1000°C (Gray,1976: Gray & DeVanney, 1986, ASTM D5061, 2015). The mosaic units observed in the thermally metamorphosed coal were much larger and the maximum reflectance lower compared to metallurgical cokes. These differences probably result from the influences of factors such as time, low thermal conductivity, maximum temperature, cooling rate, influence of a liquid phase, possible incorporation of higher molecular weight aromatic volatiles and the confining pressure that existed during the magmatic intrusion.

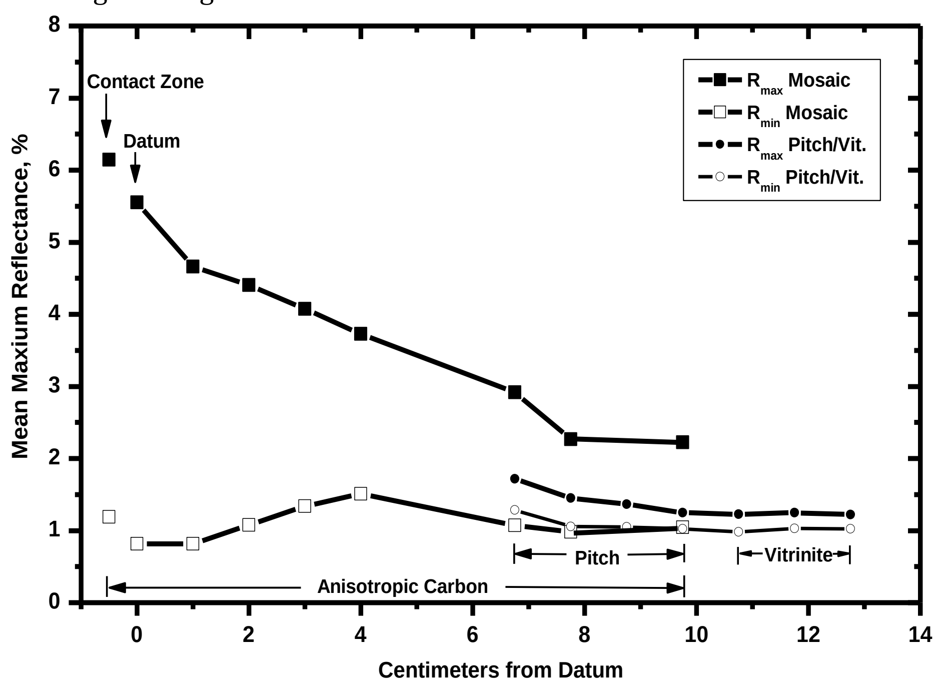


Figure 4. Mean Apparent Maximum and Minimum Reflectance of Natural Coke from the Lower Kittanning Coal, Tanoma Mine, Indiana Co., PA (I-94-15)

Laboratory Carbonization Experiments

Reflectance results of the carbonization experiments from 200° to 900°C are plotted in Figure 5. Maximum and minimum reflectance was measured on the anisotropic mosaic, pitch-like material and recognizable vitrinite. During these tests, a significant weight-loss rate was recorded between 400° and 500°C, which corresponding to the coal fluid temperature range. Laboratory carbonization of the coal at 900°C resulted in a maximum reflectance and a bireflectance (B_i, difference between maximum and minimum reflectance) nearly double that measured from the contact zone with the intrusive (Figure 4). Also, the mosaic units observed from the 900°C test were considerably smaller (1-4 μm) and more uniform than those derived from thermal metamorphism with little change in all carbonization runs between 450° - 900°C. At 400°C a pitch-like material was observed in which there was evidence of thermoplasticity and devolatilization. For lower temperature runs (350° - 200°C) no sign of plasticity was observed. Therefore, measurements were taken on vitrinite. Plotting of the reflectance distribution measured from the Tanoma aureole (Figure 4) on the laboratory temperature distribution in Figure 5, revealed temperature distributions in the range of 585° to 408º C. Taking into consideration the pressure effects described by Chandra (1965), the mosaic sizes and the level of bireflectance measured on these laboratory cokes suggest the coal had attained its present-day rank at time of intrusion. Also, coke material in direct contact with the kimberlite had progressed through the development of coalesced mesophase and had become a partially condensed, solid anisotropic carbon.

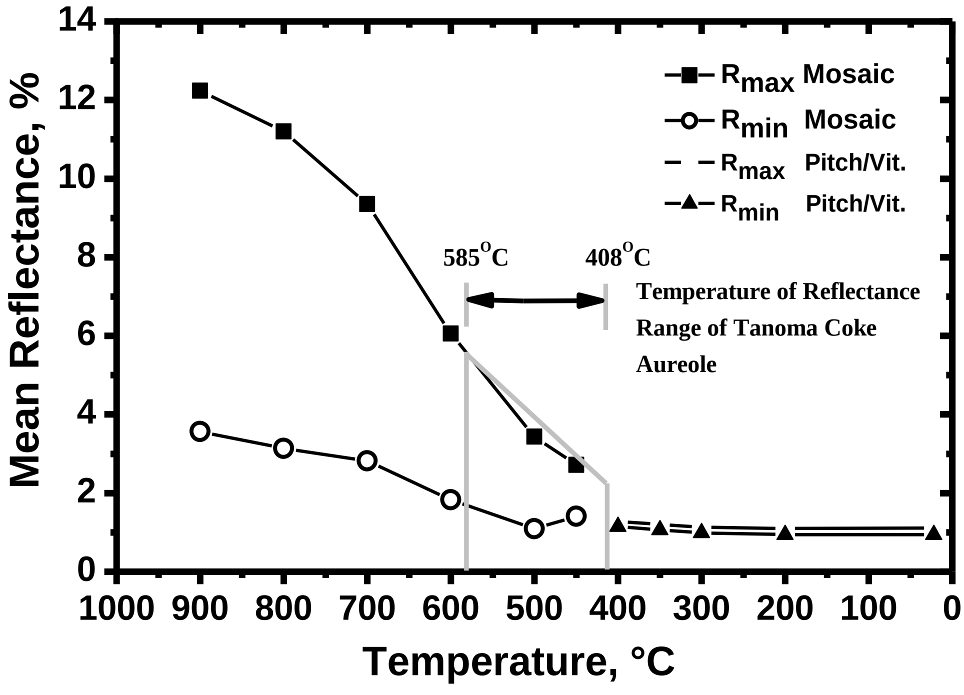


Figure 5. Reflectance results from laboratory semi-cokes using the Tanoma coal showing the temperature range of the aureole based upon reflectance of the natural coke

To complete direct temperature evaluation at the intrusive/coal contact, a sample of the thermally metamorphosed coke was removed from the datum region of dike sample I-94-5b.

Laboratory carbonization of this material was performed at 100°C increments in the 400° - 700°C range to define the temperature at which thermal treatment no longer changes reflectance of the material. Reflectance values measured on the material removed from block I-94-5b compare well with those values measured from the datum region of the sill sample, i.e., 5.64% vs 5.55%, respectively. R_{max} and B_i values for the 700°C product were similar to those values measured from the laboratory carbonization of the coal at 900°C (11.04 & 8.78 vs 12.24 & 8.67, respectively). However, a rapid linear decrease in R_{max} was observed for the natural coke carbonization products as the temperature dropped to 500°C. At 400°C, there was no significant difference between the reflectance of the starting material and the carbonization product. Using the reflectance values obtained from the 500° - 700°C products as a basis for linear regression, the temperature at which the regression line intersected the reflectance of the starting material was determined. As shown in Figure 6, coal adjacent to the intrusion at the datum was estimated to have reached a maximum temperature of at most 494 ±5°C. Using the maximum reflectance value measured for the carbonaceous material included within kimberlite a temperature of 514 ±9°C was estimated for the contact zone. These estimates closely correspond to the upper level of the fluid temperature range and maximum devolatilization measured for the coal under ambient conditions.

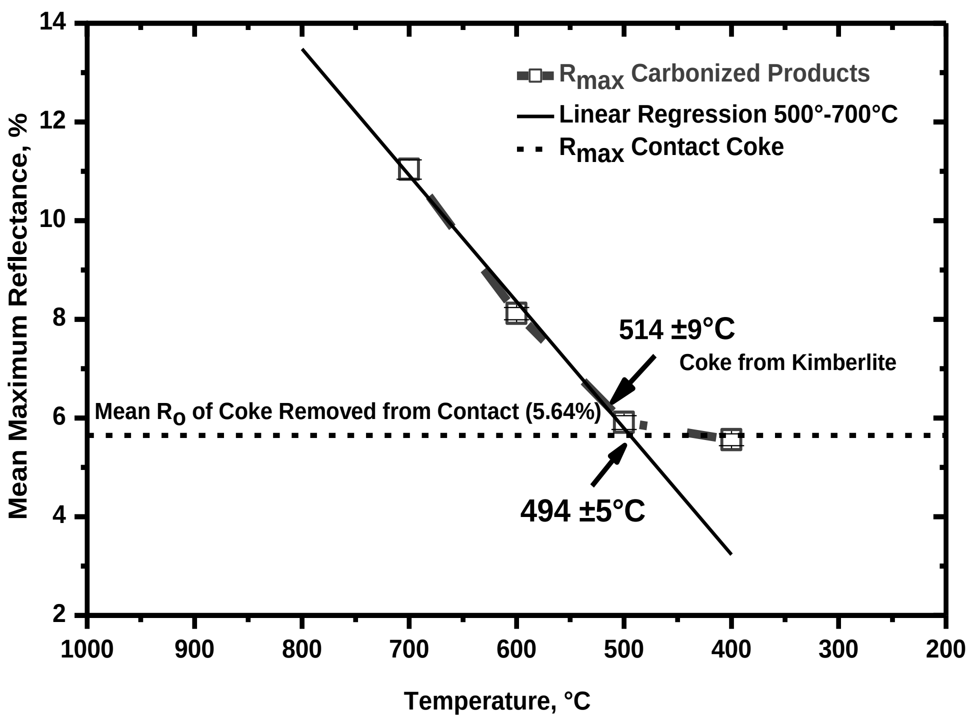


Figure 6. Mean max. reflectance distribution of heat treated contact coke from I-94-5b

Conclusions

Using reflected-light optical microscopic and laboratory carbonization techniques, natural and laboratory coke samples were evaluated to reveal that:

- The Lower Kittanning coal of the Tanoma Mine had attained its current rank of medium volatile bituminous by the time of intrusion.
- The contact coke had been exposed to sufficient temperature to cause resolidification of a coalesced mesophase.
- Progressive laboratory carbonization of the current Tanoma coal suggested that contact temperature could have reached 508ºC, but
- Laboratory carbonization of coke removed from the contact zone provided a temperature of 514 ±9°C for the material intimately mixed with the kimberlite and a temperature of 494 ±5°C for material adjacent to the contact.

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