CHAPTER 2. GEOLOGY OF THE PENNSYLVANIA COAL REGIONS

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The geology of the Anthracite and Bituminous Coal Regions of Pennsylvania is fundamental to most of the contents of this book. Since most of the coal ash placement sites described in this book are in the anthracite coal fields, the geology of the Anthracite Region is emphasized. However, the significant differences and similarities between the anthracite and bituminous regions, in their regional-scale physiography and local-scale topography, geologic structure, stratigraphy and hydrogeology will be briefly discussed in this chapter.

2.1 PHYSIOGRAPHY AND TOPOGRAPHY

Pennsylvania's Anthracite Region is located in the Valley and Ridge Province of the Appalachian Mountains as shown on Figure 2.1. The Valley and Ridge Province and other provinces and sections of the Appalachian Highlands were described in Fenneman (1938) and delineated on a U.S. Geological Survey Map by Fenneman and Johnson (1946). The province extends for a distance of 1200 miles from the St. Lawrence Lowland to Alabama, according to Thornbury (1965) who calls it the Ridge and Valley Province. This province is generally divided into three sections: a northern section also known as the Hudson-Champlain section; a middle section reaching from the Delaware River to the New River in southern Virginia; and a southern section from southern Virginia to the end of the highlands in Alabama. The width of the Valley and Ridge Province ranges from about 20 miles in New York near the Hudson River to about 80 miles wide in central Pennsylvania between Williamsport and Harrisburg, according to Hunt (1974) and Thornbury (1965).

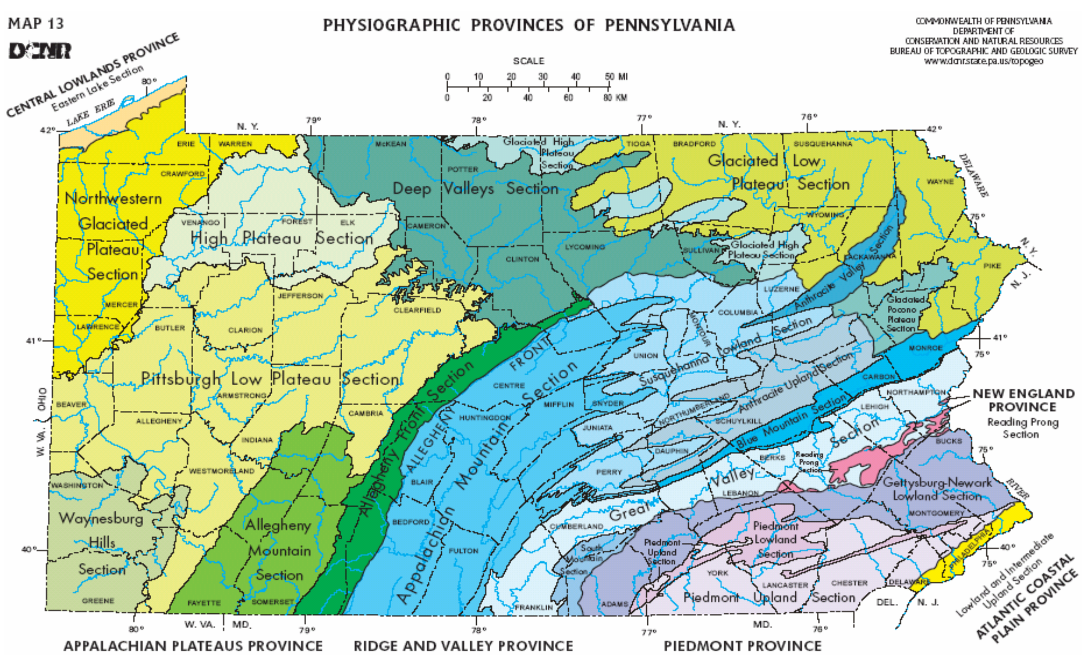

Figure 2.1. Map of Physiographic Provinces of PA.

In a classic work on the evolution of North America, King (1977) divides the Appalachian Mountains into two parts, referred to as the “sedimentary Appalachians” including the Valley and Ridge Province and the “crystalline Appalachians” in the New England Upland and Piedurant Plateau. King (1977, p. 45) states: “In the humid climate of the eastern states, the limestones and dolomites are more susceptible to erosion than are the sandstones and shales; wherever deformation has raised them to view they are worn down to low ground, whereas the adjacent sandstones and shales project in ridges. Characteristic topography of the sedimentary Appalachians is thus a succession of parallel valleys and ridges which form the Valley and Ridge province”. This pattern of alternating ridges and valleys, with many cross-cutting water gaps and wind gaps in the ridges is very distinctive on the USGS digital shaded relief map of land forms of the conterminous United States by Thelin and Pike (1991). Additional description of the Appalachian Mountain Section of the Ridge and Valley Province, including the topographic features of the Anthracite Regions is included in Way (1999).

The Anthracite Region consists of 4 major coal fields: the Northern, Eastern Middle, Western Middle, and Southern Anthracite Fields as shown on Figure 1.1. The anthracite coal fields contain approximately 95% of the remaining identified anthracite and semianthracite resources in the United States (Averitt, 1975). The anthracite fields are of Pennsylvanian age and are time equivalent to the bituminous fields of western Pennsylvania. The time equivalence and other stratigraphic relationships between the Anthracite and Bituminous Coal Regions of Pennsylvania will be discussed in the stratigraphy section of this chapter. The principal difference between the anthracite and bituminous regions is the geologic structure, with the anthracite coals located within the extensively folded and faulted terrain of the Valley and Ridge Province and the bituminous coals located on the adjacent Allegheny Plateau Province shown on Figure 2.1 which was considerably less affected tectonically.

The four anthracite fields are preserved in synclinal basins that are essentially surrounded and “defended” by sandstone ridges. These ridges are more resistant to erosion than the shales and coals of the Pottsville and Llewellyn Formations. The slope forms of the ridges are typically mature (i.e., convexo-concave), but some free faces occur, such as the Harveys Creek water gap in the Northern Field. Descriptions of Appalachian slope form development are contained in Hack (1960, 1979). Additional information on weathering in the Ridge and Valley is found in Thornbury (1965, 1969), Clark and Ciolkosz (1988), and Sevon (1989, 2000a).

The bituminous coal fields of Western Pennsylvania lay within the Appalachian Plateau Physiographic Province, which in Pennsylvania extends from the western state border to the Allegheny Front, the prominent southeast-facing escarpment of approximately 1000 feet of topographic relief that clearly defines the boundary of plateau with the adjacent Valley and Ridge Province.

The major and most typical section of the plateau in Western Pennsylvania is termed the Unglaciated Allegheny Plateau by Fenneman (1938). It has a smooth, undulating surface with narrow, relatively shallow valleys. Highest hilltops are typically about 1600 feet throughout the section. Relief is usually several hundred feet and as much as 400 to 500 feet along the larger streams. This area is designated as the Waynesburg Hills Section and Pittsburgh Low Plateau Section by Sevon (2000b) on Figure 2.1. Between this section and the Valley and Ridge

Province of the Appalachian Mountains to the east lies a strip of the plateau known as the Allegheny Mountains Section, which is much higher in elevation, attaining 3,213 feet of elevation atop Mount Davis, the highest point in Pennsylvania and whose topography, though distinctly plateau-like, is much affected by open folds (Fenneman, 1938 p. 283). Northward, starting at approximately 41° latitude, the land surface of Fenneman's Unglaciated Allegheny Plateau exhibits a steady increase in altitude all the way up to the New York border where the elevation is greater than 2100 feet (640 meters). This area comprises the High Plateau Section and part of the Deep Valleys Section on Figure 2.1 (Sevon, 2000b). It has broad, rounded to flat uplands separated by distinctively deep, angular valleys.

According to Thornbury (1965 p. 130): "The Appalachian Plateaus have not been subjected to the intense deformation that affected the other Appalachian provinces. A few mild folds exist, particularly adjacent to the Ridge and Valley Province, but they are broad open folds and not strongly compressed or faulted like those in the Ridge and Valley Province." Briggs (1999) provides additional description of the sections of the Appalachian Plateaus Province in Pennsylvania, including maps of generalized topography and topographic relief classes.

2.2 GEOLOGIC STRUCTURE

The structural geology of the four anthracite coal fields within the folded and faulted Valley and Ridge Province is much more complex than the relatively flat-laying strata of most of the bituminous coal fields within the Allegheny Plateau of western Pennsylvania, shown on Figures. 1.1 and 2.1.

Intense orogenic activity in the Ridge and Valley Province occurring during the Permian Period resulted in: (a) substantial increase in rank of the anthracite coals due to metamorphism as compared to time-equivalent coal beds in the Appalachian Plateau Province of the bituminous region, and (b) the preservation of the anthracite coal fields within synclinal basins which are essentially surrounded by sandstone/conglomerate ridges that are more resistant to erosion than the coal and associated finer-grained sedimentary rocks. Though there were three major orogenies responsible for the formation of the Appalachian Mountains, only the final one, the Alleghenian Orogeny, had any effect on the rocks of the Ridge and Valley Province in Pennsylvania. According to Rodgers (1970, Chapter 11) who summarized the tectonics of the Appalachian Mountains, there were three major orogenic movements which resulted in the development of the Valley and Ridge Province of the Appalachian Mountains in Pennsylvania, including the Anthracite Region; the Taconic Orogeny occurring from approximately 450 through 500 million years ago, the Acadian Orogeny occurring during the Devonian Period from approximately 360 through 400 million years ago, and the Allegheny Orogeny occurring from approximately 230 through 260 million years ago.

The Allegheny Orogeny was the most significant mountain-building development in the present geologic structure of the Valley and Ridge Province of central and eastern Pennsylvania (including the anthracite coal region). The anthracite coal beds were deposited during the Pennsylvanian Period approximately 275 million years ago. At the type section of the Pottsville Group strata located on Sharp Mountain at Pottsville, Pennsylvania, the Mammoth coal seam and associated strata have been uplifted from a horizontal, to a nearly vertical structural orientation.

Orogenic deformation preceding Pennsylvanian sedimentation did not structurally affect Pennsylvanian rocks. As the Allegheny Orogeny postdated the deposition of these coal seams, it is responsible for most of the structural deformation.

A comprehensive description of the geologic history of the north-central Appalachians, is contained in Faill (1997a, 1997b, 1998a 1998b). The most recent orogenic episode, the Alleghenian, commenced in the Early Permian (Faill, 1997b). Faill (1997a, p. 552) states that "(l)ate in the Allegheny orogeny, rock thrust northward over the Carboniferous rocks in the Anthracite Region of northeastern Pennsylvania and caused anthracitization of the underlying coals."

Following these significant orogenic episodes during Paleozoic times, the Appalachian Mountains continue to mature. Concerning the post-Paleozoic history, Rodgers (1970, p. 218) states: "Our next glimpse of the Appalachians is in the Late Triassic; they were now a chain of mountains, though not necessarily lofty ones, and the core areas were already deeply eroded.… Only in the Cretaceous or the Late Jurassic did the sea once more enter the region, and then only to wash the southeastern and southern margins of the Appalachian chain, which repeated arch-like uplifts kept high and subject to erosion .… During this period the mountains approached the forms we see today.".

For the past approximately 65 through 100 million years Sharp Mountain in Schuylkill County, Pennsylvania and other Appalachian ridges have been undergoing further weathering and erosion to produce the mature slope forms seen today. During these millions of years of weathering the rough edges of the tops of these mountains were worn down and colluvium developed as a veneer over the bedrock on the middle to lower slopes of the ridges.

A concise description of the structural geology of the Ridge and Valley Province in Pennsylvania is provided by Faill and Nickelsen (1999), including a tectonic map of the province, a cross-section of the Minersville Synclinorium, and other relevant information about the Anthracite Region. Much of the Southern and Western Middle Fields has been geologically mapped by Wood and associates (e.g., the Minersville Quadrangle, Wood, et al., 1968). The maps depict the synclinoria and other complex geologic structures. The geologic structure and stratigraphy of the Southern Anthracite Field are described in Wood et al. (1969) and the depositional and structural history of the entire Anthracite Region are presented in Wood et al. (1986). The complexity of the geologic structure, particularly the nearly vertical beds of rocks in many areas of the anthracite fields, has impeded the acquisition of stratigraphic data from routine exploration drilling.

According to Wood et al. (1986): "Each coal field of the Anthracite Region is a complexly folded and faulted synclinorium, with structural trends between N55°E and N85°E.… The Southern field is the most highly deformed, with several highly faulted, closely spaced synclinal basins. Deformation is most complex toward the southeast, where it is characterized by hundreds of thrust, reverse, tear and bedding plane faults and tightly compressed, commonly overturned folds." (p. 45).

The principal structural features of these four anthracite coal fields are shown on Figure 2.2, from Wood et al. (1986, p. 44) and Wood and Bergin (1970, p. 150). The tremendous structural complexity of the Southern Field is described in greater detail in Wood et al. (1969), including descriptions of the largest structural features, the Minersville Synclinorium, the New Bloomfield Anticlinorium and the Broad Mountain Anticlinorium, plus detailed descriptions of individual anticlines, synclines and fault complexes within these three major structural features. Of the many hundreds of anticlines, associated synclines and significant faults present in the area, (Wood et al., 1969, p. 87) examples include: the Donaldson Syncline, with an amplitude of 4,000 to 7,800 feet in the Tower City, Donaldson and Tremont area (p. 91), and the Mine Hill fault complex (in the area of the Lytle, Oak Hill and Wadesville Collieries) which has, in places, a klippe composed of beds of the Schuylkill Member overlying the Upper Mine Hill fault and upright beds of the Llewellyn Formation (p. 102).

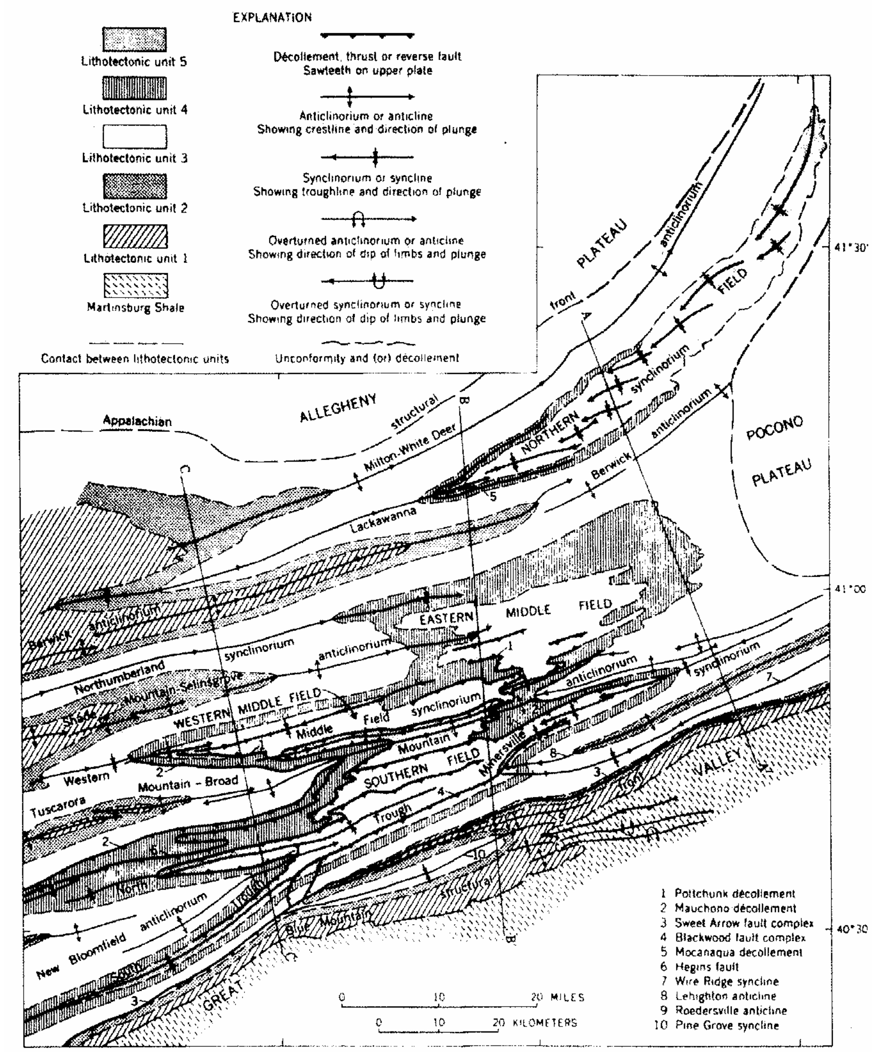

Figure 2.2. Principal structural features of the Anthracite Coal Fields (from Wood et al**.,** 1986).

The distinct contrast between the geologic structure of the Allegheny Plateau and the Valley and Ridge Plateau is depicted in the series of Appalachian cross-sections constructed by King (1977) as shown in Figures. 2.3a, and 2.3b. The entire area east of the Findley Arch in Ohio on Figure 2.3a, labeled the Allegheny Synclinorium, is termed a foreland basin by King (1977, p. 44), who describes this basin extending southward from Pennsylvania into Kentucky, and states: "Surface rocks of the plateau and synclinorium are largely Pennsylvanian continental and coal-bearing strata…. The Pennsylvanian and associated rocks have been warped into a series of anticlines and synclines by the Appalachian movements, but most of the deformation is so light that over wide areas the strata appear to lie nearly flat." (p. 45).

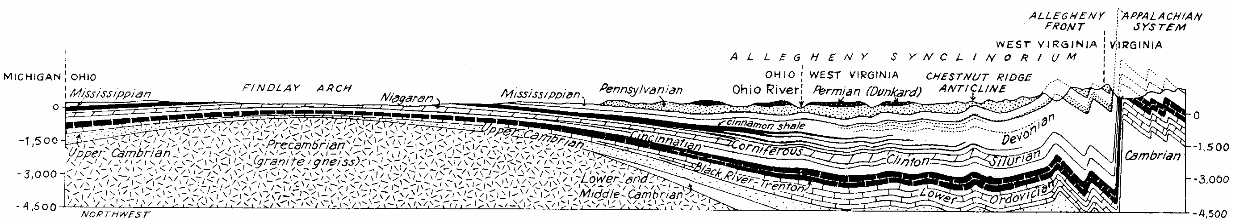

Figure 2.3(a). Cross-section of the geologic structure of the Allegheny Plateau (from King 1977).

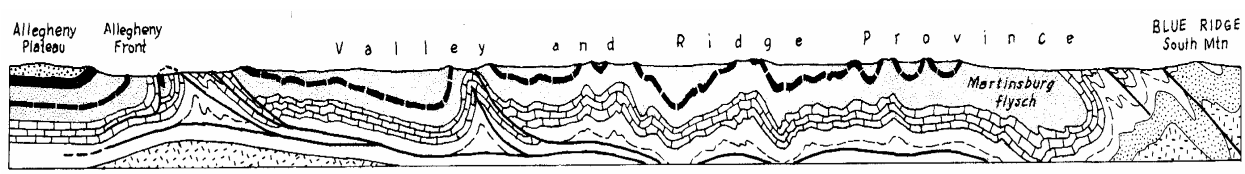

Figure 2.3(b). Cross-section of the geologic structure of the Ridge and Valley Province.

The entire Allegheny Plateau in western Pennsylvania is part of a major structural basin referred to as the Appalachian Coal Basin (Rodgers, 1970) or Allegheny Synclinorium (Kay, 1942) or as the Pittsburgh-Huntingdon Basin (Richardson, 1928). According to Gwinn (1964, p. 866): "Viewed on a regional basis the surface structure of the Plateau is a broad asymmetrical synclinorium, steeper on the southeast …. the surface axis of the synclinorium plunges southwestward in a smooth arc from Binghamton, New York, through Pittsburgh, Pennsylvania, and south-southwestward toward Parkersburg and Huntington, West Virginia."

Although the axis of the structural basin is known to curve in plan view and plunge toward the southwestern corner of the state, the basin may be three-dimensionally visualized as a broad spoon-shaped structure, in which the youngest strata are at the center of the spoon and successively older strata become exposed toward the outer edge of the spoon (Richardson, 1928; Ashley, 1928; Piper, 1933). Consequently a bed such as the Upper Freeport Coal of the Allegheny Group, which is present at the land surface at elevations of approximately 2,000 feet above sea level at the northern and eastern margins of the bituminous coal field in western Pennsylvania, is present in the southwestern corner of Pennsylvania at an elevation several hundred feet below sea level and beneath hundreds of feet of younger rocks, including the Pittsburgh Coal, which may be mined at the land surface.

The asymmetry of the basin is evident in the contrast between the northwestern and southeastern sides in terms of the intensity and manner of production of folds and other geologic structures. The folds and smaller scale irregularities manifested in the surficial configuration of the basin have been described by Gwinn (1964), Rodgers (1970), Fettke (1954) and others. Rodgers (1970) divides the basin into a northwest flank and a southeast flank which are both about 60 to 80 miles (37 to 50 kilometers) wide. The north-west flank generally has a gentle and persistent regional dip toward the basin center. At a more detailed scale, irregular minor structural features become evident on the northwest flank which have been described by Rodgers (1970, p. 15) as "scattered and apparently planless irregularities – folds of erratic trend, domes, noses, etc. – whose structural relief is rarely more than a few tens of meters (a hundred feet)." A belt of transition (i.e. the bottom of the basin) separates the northwestern flank from the markedly different structure of the southeastern flank which Rodgers (1970, p. 16) describes as "a succession of roughly parallel anticlines and synclines, mostly many times longer than broad…. As these folds are superposed on the southward regional dip they show a consistent asymmetry, the southeast flanks of the anticlines being the steeper."

According to Gwinn (1964) structural relief decreases north-westward in a step-like fashion from the well-defined folds of the southeastern side of the plateau where anticlines rise 800 to 2500 feet (244 to 1067 meters) above adjacent synclines. Gwinn (1964) provided the decollement interpretation of the mechanics of formation of the high folds and other structural features of the Appalachian Plateau in western Pennsylvania, which involved movement associated with major thrust faults along bedding planes in the sedimentary rock sequence. Rodgers (1970) provides additional description of the manner of production of structures of the plateau, confirming Gwinn's interpretation as applicable to the southeastern flank of the plateau in Pennsylvania, while relating the irregular structures of the northwestern flank to a contrasting interpretation involving tectonics of the basement rocks.

The axes of anticlines and classes of structural relief associated with the anticlines and synclines of the Appalachian Plateau in western Pennsylvania have been described by Gwinn (1964), Berg et al. (1980) and Beardsley et al. (1999). Figure 2.4 from Beardsley et al. (1999) shows the major Chestnut Ridge, Laurel Hill anticlines and the Smethport-Sharon anticline labeled CR, LH and SS respectively. The importance of linear structural features of various scales in western Pennsylvania has been discussed by Nickelsen and Williams (1955), Hough (1959), Poth (1963), Nickelsen and Hough (1967), Gold et al. (1974), Kowalik (1975) and others. Nickelsen and Hough (1967) illustrate regional joint patterns in Pennsylvanian aged coals and shales of western Pennsylvania. The systematic joint pattern defined by Nickelsen and Hough (1967) was found to be generally east-west trending, perpendicular to major fold axes, and somewhat arcuate in north-central Pennsylvania, presumably in response to a Paleozoic doming episode in that area.

The structural and topographic transition between the Allegheny Plateau and the Valley and Ridge Province to the east is the Allegheny Front, which is shown on the eastern side of Figure 2.3a and the western side of Figure 2.3b, and is described by King (1977) as follows: "On the southeast the Allegheny Plateau breaks off along the Allegheny Front (Fig. 2.3b), an imposing escarpment that overlooks the more varied, linear ridges and valleys of the true Appalachians. The front marks an abrupt change in style of deformation; the strata now turn up abruptly, and beyond they are heavily folded and faulted; we pass here from the foreland into the main deformed belt." (p. 45).

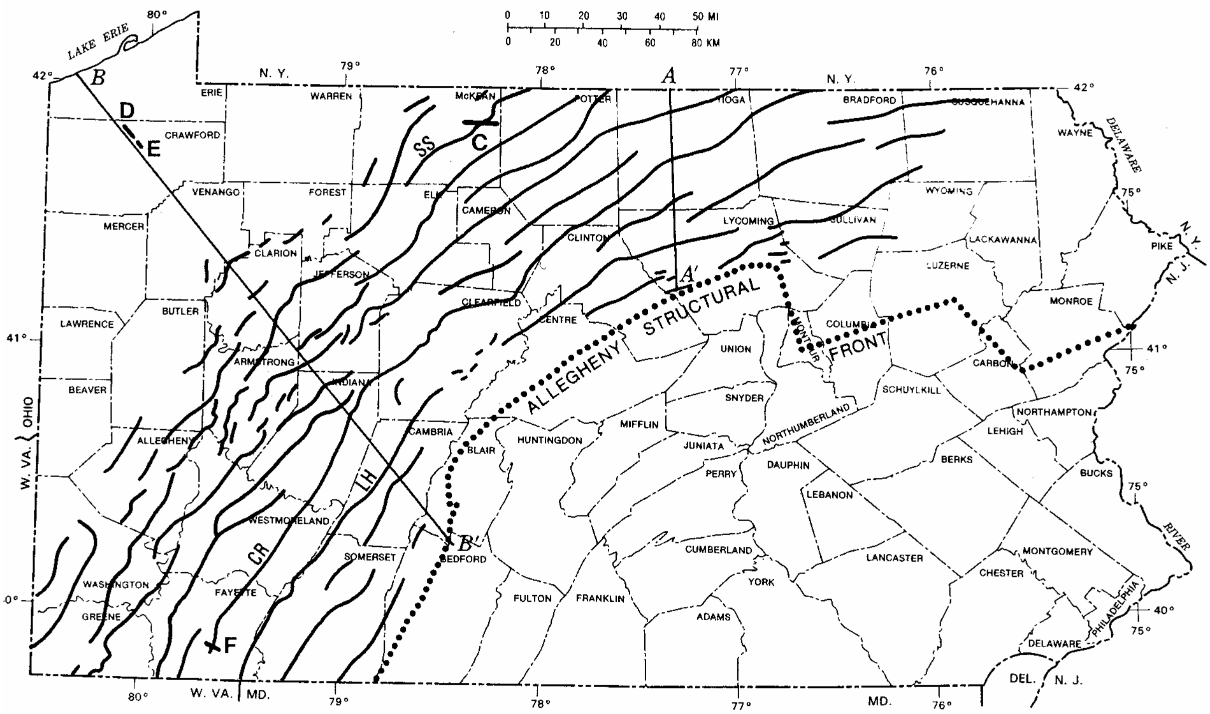

Figure 2.4. Generalized location of surface anticlines in the Appalacian Plateau's Province. (from Beardsley et al., 1999).

2.3 STRATIGRAPHY

Far more is known about the stratigraphy of the Bituminous Coal Region of western Pennsylvania than the Anthracite Coal Region for several reasons, including the abundance of drill hole data, the availability of paleontological information, and the fact that it is less difficult to correlate strata between drill holes and other exposures in the relatively flat-lying strata of the Allegheny Plateau than in the structurally complex anthracite coal region. The stratigraphy of the Anthracite Region of eastern Pennsylvania has not been studied as extensively as that of Pennsylvania's bituminous coal region. Geologic and mining engineering work done in the Anthracite Region over the past 150 years documents some significant stratigraphic differences between the Anthracite and Bituminous Coal Regions. The complexity of the geologic structure, resulting in nearly vertical beds of coal and other rocks in some areas of the anthracite fields, has impeded the acquisition of stratigraphic data from routine exploration drilling. Detailed mine maps of the abandoned underground mines and cross-sections through vertical shafts and nearly horizontal tunnels have added to the understanding of the structure and stratigraphy of the anthracite coal fields, however most stratigraphic efforts have been directed toward coal seam delineation.

The coal-bearing rocks in Pennsylvania are from the Pennsylvanian and Permian Periods of geologic time. The rocks of the Bituminous Coal Field of western Pennsylvania are divided, from oldest to youngest, into the Pottsville, Allegheny, Conemaugh, Monongahela, and Dunkard

Groups. The majority of mineable coal occurs in the Allegheny and Monongahela Groups. The strata in the Anthracite Region are divided, from oldest to youngest, into the Pottsville and Llewellyn Formations.

Generalized stratigraphic sections of the Allegheny Formation and the Conemaugh Group of western Pennsylvania are depicted on Figure 2.5 from Edmunds et al. (1999). The graphic drill logs and overburden analysis data for the entire Pennsylvania coal bearing sequence are included in a series of figures in Brady et al. (1998), examples of which are shown in Figures 2.6a and 2.6b. These figures were constructed from overburden analysis drill holes with percent sulfur and neutralization potential (NP) that were obtained from the permit files of the Department of Environmental Protection's District Mining Offices.

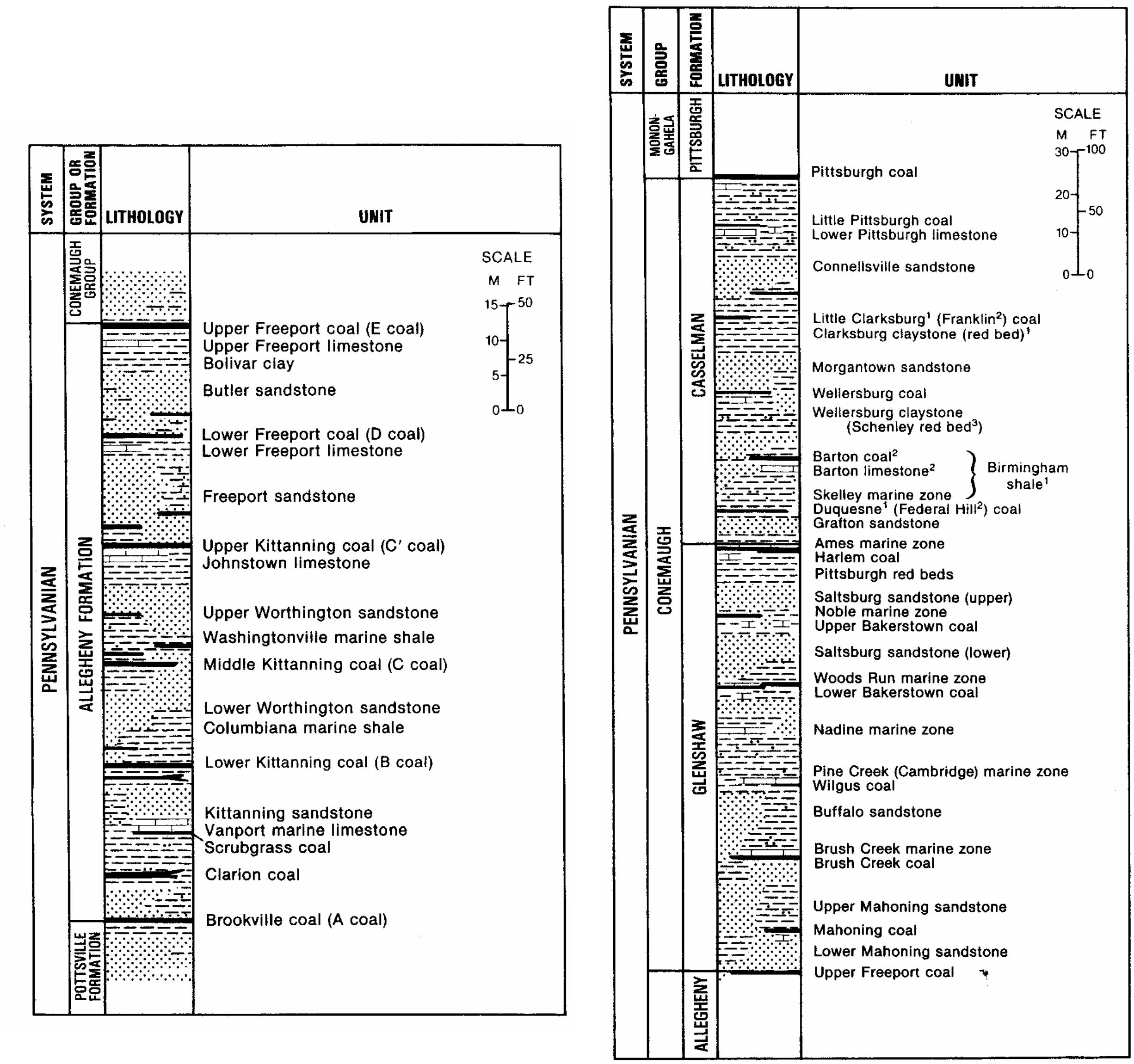

Figure 2.5. Generalized stratigraphic sections of the Allegheny and Conemaugh Group (from Edmunds et al., 1999).

2.3.1 Pottsville Group – Bituminous

The Pottsville Group is variable in thickness. For the most part, it is dominated by sandstone, and the coals are discontinuous. Because of the discontinuous nature of these coals, and the fact that they are often thin and split with numerous partings, mining is not common in the Pottsville Group. The principal coal that is mined is the Mercer. Edmunds et al. (1999) discuss the Pottsville of western Pennsylvania in terms of strata below the Mercer Coal and above the Mercer Coal: "In practice, the western Pottsville is usually divided into an upper sequence consisting of the Mercer coals and associated and overlying rocks, and a lower sequence dominated by sandstone." They also report that "The Pottsville Formation in western Pennsylvania ranges from 20 ft (6 m) to at least 250 ft. (75 m) in thickness. Its basal contact is apparently everywhere disconformable and from south to north overlies increasingly older Mississippian and possibly uppermost Devonian rocks…." (p. 150-151).

2.3.2 Allegheny Group – Bituminous

The Allegheny Group is one of two groups within the Pennsylvanian that contains the majority of economically mineable coals. For the purpose of discussion, the Allegheny has been divided into the upper and the lower Allegheny. The lower Allegheny extends from the base of the Brookville coal to the base of the JohnstownLlimestone (or Upper Kittanning Coal where the limestone is absent). The upper Allegheny extends from the base of the JohnstownLlimestone to the top of the Upper Freeport Coal. This division is made because "marine units occur only below the upper Kittanning underclay…. and, with minor exceptions, nonmarine limestones occur only at or above that unit" (Edmunds, et al., 1999, p. 154). This distinction of "marine" and "nonmarine" is to a large extent based on the work of Williams (1960). Williams defined four faunal groups, inferred as "fresh-water", "restricted marine or near-shore marine", and two marine groups, one having a more diverse fauna than the other. Williams also relied on the geochemical investigations of Degens et al. (1957, 1958) in defining his depositional environments.

According to Edmunds et al. (1999) the Allegheny Group: "was specifically defined to include all of the economically significant coals present in that part of the Pennsylvanian sequence. The thickness of the formation is between 270 (82 m) and 330 feet (100 m) in Pennsylvania, and there is no obvious regional trend. The Allegheny Formation is a complex, repeating succession of coal, limestone, and clastics, ranging from claystone or underclay to coarse sandstone.... No individual bed or lithosome is universally persistent, but some coals, marine shales, and limestones seem to be fairly continuous over thousands of square miles (thousands of square kilometers). The group is fairly uniform in its lithologic diversity.… The Allegheny Formation contains six major coal zones. The coal in each zone may exist as a single, more-or-less continuous sheet, as a group of closely related individual lenses, or as a multiple-bed complex in which the various beds can be separated by tens of feet or merge into a single thick coal" (pp. 153-154).

The major coal zones in the Allegheny Group, from oldest to youngest are the Clarion, Lower Kittanning, Middle Kittanning, Upper Kittanning, Lower Freeport and Upper Freeport. Geochemical data for overburden strata of Allegheny Group coals are shown in Figures 2.6a and

2.6b. The numbers on the left side of each drill hole represent the total sulfur (%) content of the stratigraphic unit, and numbers on the right side of the drill holes represent the Neutralization Potential (parts per thousand). A comparison of the overburden strata in Figures 2.6a and 2.6b shows that the brackish strata of the lower Allegheny are characterized by high total sulfur contents and relatively low NP values, while the nonmarine (freshwater or continental) overburden strata of the upper Allegheny are characterized by relatively low total sulfur content and relatively high NP (calcareous) overburden strata.

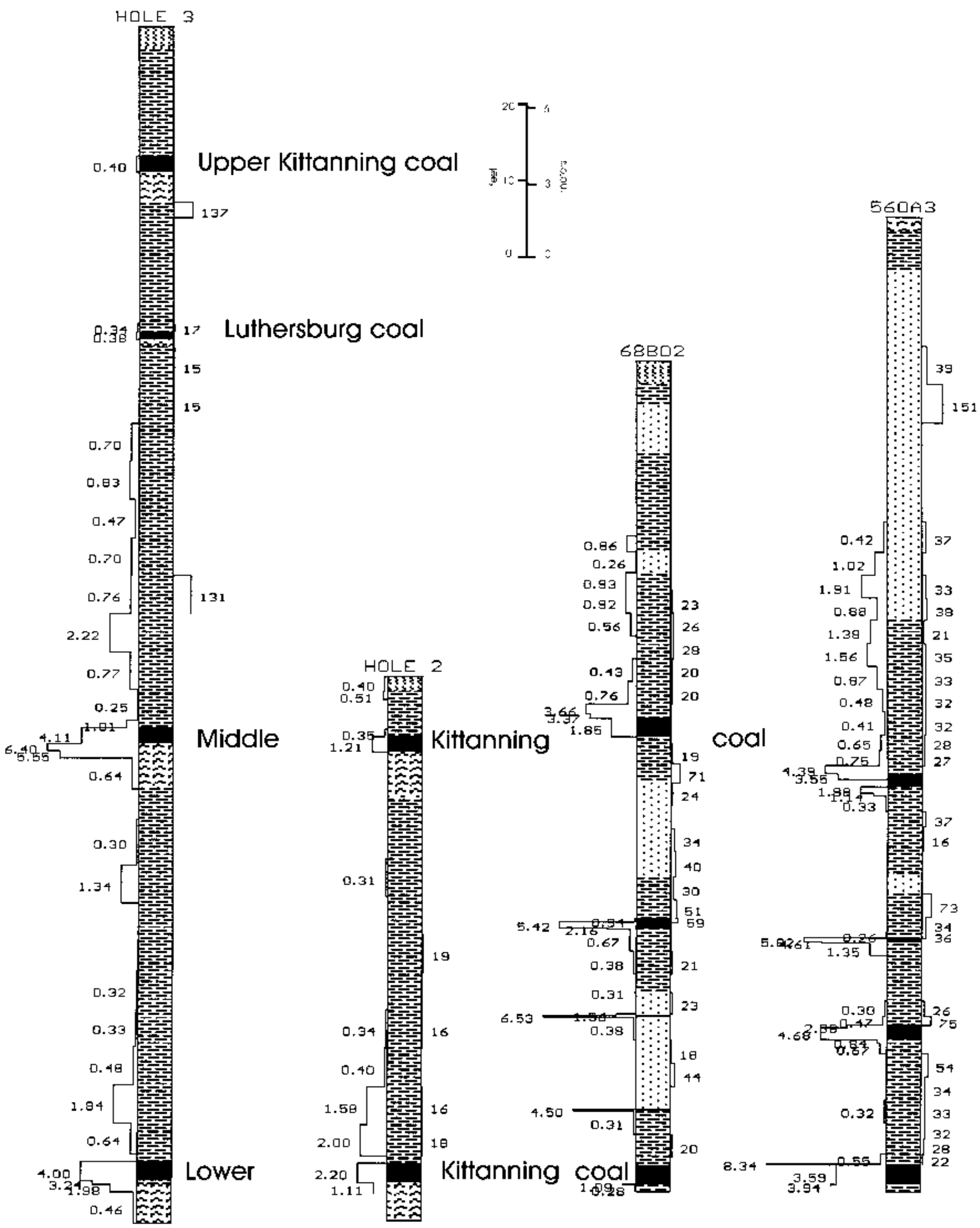

Figure 2.6(a). Lower Kittanning and Middle Kittanning Coals and brackish overburden strata from Clearfield County, PA. (from Brady et al., 1998).

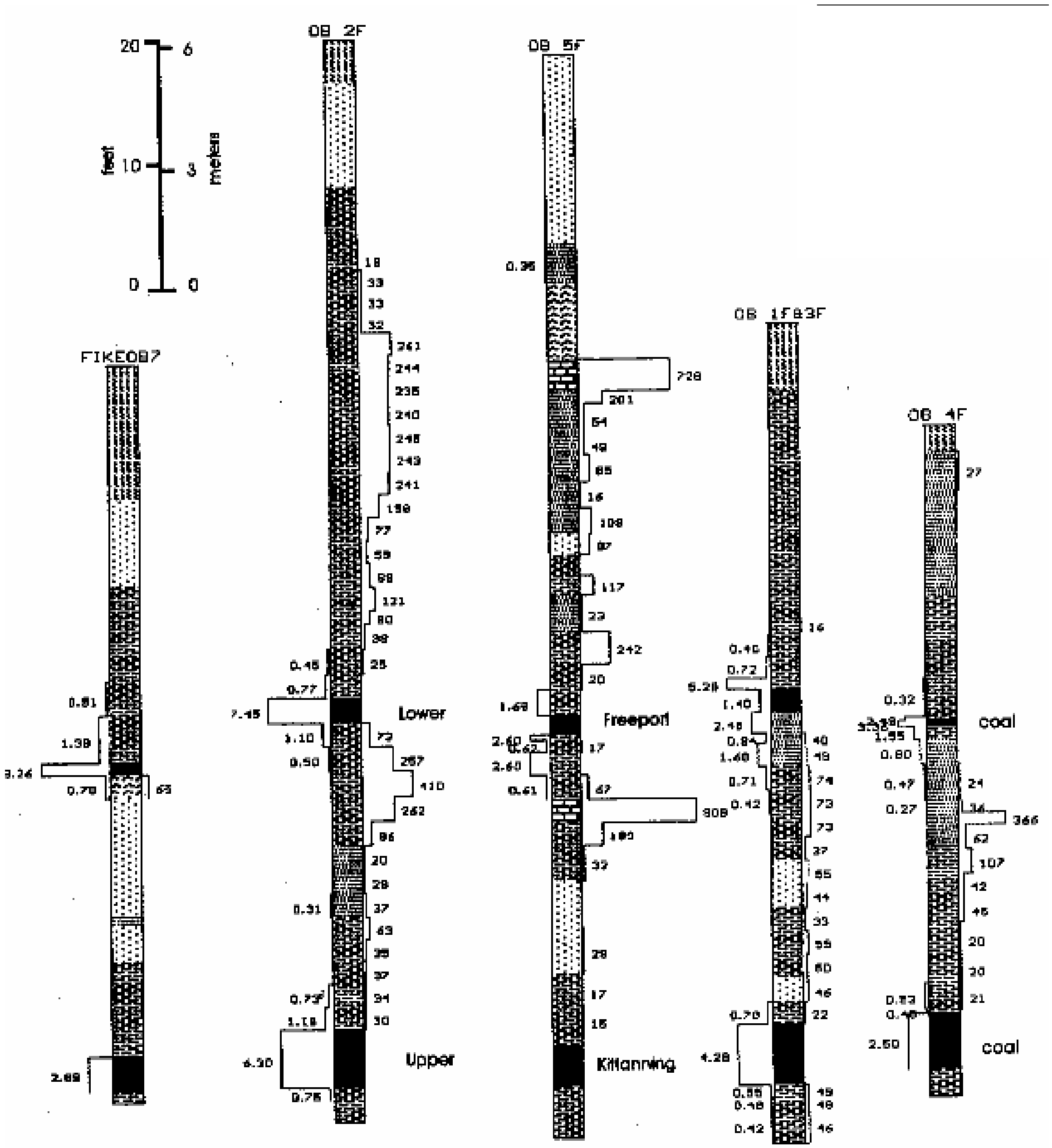

Figure 2.6(b). Upper Kittanning and Lower Freeport Coals and nonmarine overburden strata from Fayette County, PA.

2.3.3 Conemaugh Group – Bituminous

The Conemaugh Group contains two formations, the older Glenshaw Formation and the overlying Casselman Formation.

2.3.3.1 Glenshaw formation

The Glenshaw contains several widespread marine zones, the most prominent of which include the Brush Creek, Pine Creek, Woods Run, and Ames. There are also several less prominent and obscure marine zones , bringing the total of possible marine zones within the Glenshaw to as many as seven (Edmunds et al., 1999). The Glenshaw is thickest in Somerset and southern Cambria Counties, where it reaches 400 to 420 ft (122 to 128 m). It is thinnest near the Ohio border where it is about 280 ft (85 m) thick (Edmunds et al., 1999). The mineable coals of the Glenshaw Formation, from oldest to youngest, typically are the Mahoning, Brush Creek, Lower and Upper Bakerstown.

2.3.3.2 Casselman formation

According to Edmunds et al., (1999) “The thickness of the Casselman Formation ranges from 230 feet (70 m) in the extreme western part of the Appalachian Plateaus province to 485 feet (148 m) in southern Somerset County” (p. 156). With the exception of the marine shales above the Ames limestone, and the Skelly horizon, which occurs about 30 to 60 ft (9 to 18 m) above the Ames marine zone, the Casselman is made up of exclusively fresh water rocks. Redbeds, which are regionally discontinuous, are scattered throughout the Casselman in the western portion of Pennsylvania. “Eastward they become thinner and fewer in number. This trend continues into eastern Somerset and Cambria Counties, where large areas are completely devoid of red beds in the Casselman Formation . Conversely, coals are nearly absent or very thin in the west but increase in quantity eastward. In Somerset County, a few coals are thick enough to mine” (Edmunds, et al., 1999, p. 156). The coals of the Casselman Formation, typically include from oldest to youngest, the Duquesne (or Federal Hill), the Barton (or Elk Lick), Wellersburg, Little Clarksburg (or Franklin), and the Little Pittsburgh. Except for the Federal Hill, the Barton, the Wellersburg, and the Little Pittsburgh Coals in portions of Somerset County (Shaulis, personal communication, 2004), these coals are generally not mineable.

2.3.4 Monongahela Group – Bituminous

The Monongahela Group extends from the base of the Pittsburgh Coal to the base of the Waynesburg Coal. It is divided into the Pittsburgh and Uniontown Formations at the base of the Uniontown Coal. According to Edmunds et al. (1999): “The group is about 270 to 400 feet (82 to 122 m) thick in Pennsylvania, increasing in thickness irregularly from the western edge of the state to western Fayette County.... It is entirely nonmarine and dominated by limestones and dolomitic limestones, calcareous mudstones, shales, and thin-bedded siltstones and laminites.... The only sandstone of significant thickness within the formation lies directly above the Pittsburgh coal complex. A major fluvial channel system flowing north to northwest through what is now Greene and Washington Counties, deposited an elongate sandstone body up to 80 feet (24 m) thick and several miles (kms) wide” (Edmunds et al., 1999, pp. 156-157).

The Pittsburgh Coal is unusually continuous, covering thousands of square miles (km^2) and is unusually thick (4 to 10 ft.; 1.5 to 3 m, Edmunds et al., 1999) for a coal of western Pennsylvania. The other major coals are the Redstone and Sewickley. In Somerset County an additional coal, the Blue Lick, occurs between the Pittsburgh and Redstone Coals. Shaulis (1993) believes the Blue Lick Coal is a split of the Pittsburgh Coal.

2.3.5 Dunkard Group – Bituminous

The Dunkard Group is found only in the most southwestern corner of Pennsylvania in Greene and Washington Counties. It is made up of Waynesburg, Washington and Greene Formations (Berryhill et al., 1971). The Dunkard reaches a maximum thickness of about 1120 ft (340 m) in Greene County and the upper surface is the modern day erosional surface. The lower boundary of the Dunkard Group is defined as the base of the Waynesburg coal, which is the only coal routinely mined in the Dunkard.

The Dunkard is generally composed of fine-grained clastics which are frequently calcareous. Thick lacustrine limestones are especially prevalent in the Washington Formation. The only significant interval with sandstone is above the Waynesburg coal. This sandstone is often, but not always, calcareous.

2.3.6 Pottsville Group – Anthracite

Pennsylvanian age rocks contain all the coal seams of the Anthracite Region of Pennsylvania, and have been divided into two major formations, the Pottsville and the Llewellyn. Generalized columnar sections of the Pottsville and Llewellyn Formations are shown on Figure 2.7.

The Pottsville Formation ranges in thickness from a maximum of approximately 1600 ft (490 m) in the Southern Field to less than 100 ft (30 m) in the Northern Field. The Pottsville Formation is subdivided into three members, from oldest to youngest, they are the Tumbling Run Member, the Schuylkill Member and the Sharp Mountain Member. The Tumbling Run and Schuylkill Members of the Formation are not present in the Northern Anthracite Field (Wood et al., 1969, 1986; Meckel, 1967, 1970; and Edmunds et al. 1979, 1999).

The Pottsville Formation contains up to 14 coal beds in some areas, but most are relatively discontinuous and only a few persist outside of the Southern Field (Edmunds et al. 1999). Figure 2.7 shows the mineable coals of the Pottsville Formation. The Lykens Valley Coal Numbers 4 through 7 are within the Tumbling Run Member; the Lykens Valley Coal Numbers 1 through 3 are within the Schuylkill Member; and the Scotty Steel and Little Buck Mountain Coals are within the Sharp Mountain Member of the Pottsville Formation (Fig. 2.7). The base of the Buck Mountain Coal is considered the top of the Pottsville Formation in the anthracite fields of eastern Pennsylvania. The Buck Mountain Coal is tentatively correlated with the lower Kittanning Coal within the lower Allegheny Group in western Pennsylvania, and since the upper boundary of the Pottsville Formation in western Pennsylvania is defined as the base of the Brookville Coal, positioned below the Lower Kittanning Coal, the Pottsville of eastern Pennsylvania and the Pottsville of the western Pennsylvania main bituminous field are not precisely equivalent (see Edmunds et al., 1999). The type section of the Pottsville Formation (located near Pottsville) is described by C.D. White (1900) and more recently by Wood et al. (1956) and Levine and Slingerland (1987).

The Pottsville Formation in eastern Pennsylvania is entirely of a nonmarine depositional environment (Edmunds et al., 1999). As in western Pennsylvania, the dominant lithology of the Pottsville Group is sandstone and conglomerate; but the Pottsville Formation of the Anthracite

Region contains significantly more pebble conglomerates derived from an orogenic source area relatively close to the southeast (Meckel, 1967, 1970; Edmunds et al. 1999; and Faill, 1997a,b). The Tumbling Run Member is composed of approximately 55% conglomerate and conglomeratic sandstone, about 30% fine- to coarse-grained sandstone, and about 15% shale and siltstone. Conglomerate and conglomeratic sandstone comprise about 50% of the Schuylkill Member, and the sandstone in the member ranges from very fine to very coarse, constituting approximately 30% of the member. The Sharp Mountain Member in most of the Southern Anthracite Field is composed of about 45% conglomerate, 25% conglomeratic sandstone, 15% sandstone, 5% siltstone, 9.5% shale, and 0.5% anthracite (Wood et al. 1969, 1986). The carbonate content of the rocks has not been determined, except for a few localities.

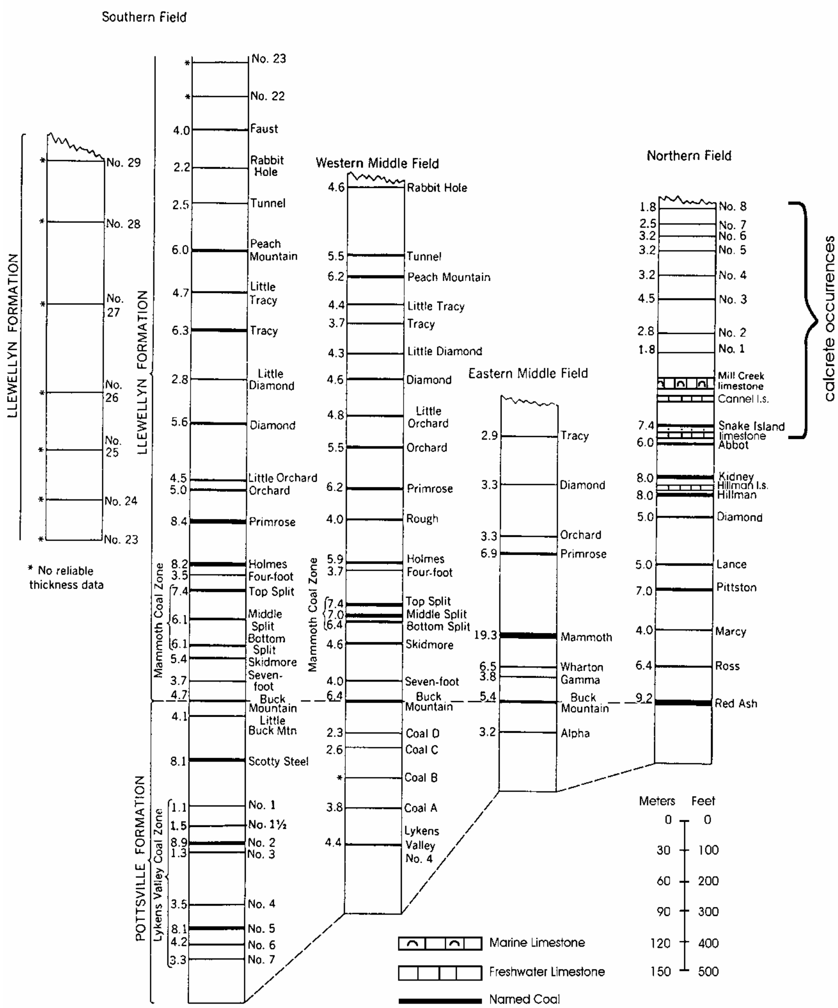

Figure 2.7. Generalized columnar sections showing names, average thickness of coals (in ft), and intervals between coal beds in the Pennsylvania Anthracite fields. Figure is primarily from Wood et al. (1986). Information on calcareous zones in the Northern Field has been supplemented by data from Edmunds et al. (1999) and Inners and Fabiny (1997).

2.3.7 Llewellyn Formation- Anthracite

The Llewellyn Formation is as much as 3500 feet thick. The maximum known thickness of the Pennsylvanian in Pennsylvania is approximately 4400 ft near the town of Llewellyn in Schuylkill County (Edmunds et al., 1999). The Llewellyn Formation contains up to 40 mineable coals (Edmunds et al., 1999), most of which are shown on Figure 2.7. The thickest and most persistent coals occur in the lower part of the Llewellyn Formation, particularly the Mammoth Coal zone. The Mammoth Coal zone typically contains 20 ft of coal, and thicknesses of 40 ft to 60 ft. are not unusual. A local thickness of greater than 125 ft has been reported in the Western Middle Field. This was attributed to structural thickening in the trough of the syncline. The nomenclature and stratigraphy of the coal bearing rocks of the Llewellyn Formation in the Northern Anthracite Field are different than in the Southern and Middle Fields (Fig. 2.7).

The dominant lithology of the Llewellyn Formation is sandstone, including conglomerate units, as in the Pottsville Formation. According to Edmunds et al. (1999, p. 159): "Lithologically, the Llewellyn is a complex, heterogeneous sequence of subgraywacke clastics, ranging from conglomerate to clay shale and containing numerous coal beds. Conglomerates and sandstones dominate". The Llewellyn Formation in the Southern and Middle Fields is believed to be entirely terrestrial in depositional environment (i.e., lacking any marine beds). The Llewellyn Formation in the Northern Field, however, contains one known marine bed, the Mill Creek Limestone (Fig. 2.7). I.C. White (1903) suggested that the Mill Creek was correlative with the Ames Limestone in the Conemaugh Group of western Pennsylvania. This belief is generally held to the present. The Mill Creek Limestone is a one- to three-ft, richly fossiliferous marine limestone (Chow, 1951). The Llewellyn Formation contains several nonmarine limestones in the Northern Field in a 330 ft thick zone directly below the Mill Creek Limestone, including the Cannal and Hillman Limestones (Chow, 1951, and Edmunds et al., 1999). Additionally, Inners and Fabiny (1997) have identified calcareous paleosols ("calcrete") in the uppermost Llewellyn Formation in the Northern Field. They have tentatively correlated this portion of the stratigraphy with the Conemaugh of western Pennsylvania. These two zones combined potentially provide an appreciable amount of calcareous material in the top approximately 850 feet of the Llewellyn Formation of the Northern Anthracite Field.

Deep drill holes of the stratigraphic sequence of the Pottsville and Llewellyn Formations in the AnthraciteRegion are rarely included in the permit files for anthracite coal mine permits. However, DEP cooperated with the Pennsylvania Geologic Survey, Reading Anthracite Company and Mr. Louis DeNaples (a landowner in the Northern Anthracite Coal Field) to obtain two significant cores and several deep air-rotary drillholes in the Southern Field (at Reading's Wadesville mine) and in the Northern Field (on Mr. DeNaples' land). A graphic drill log for 500 feet of the Llewellyn Formation above the Mammoth Coal is shown in Figure 2.8, for one of the air-rotary drill holes at Wadesville.

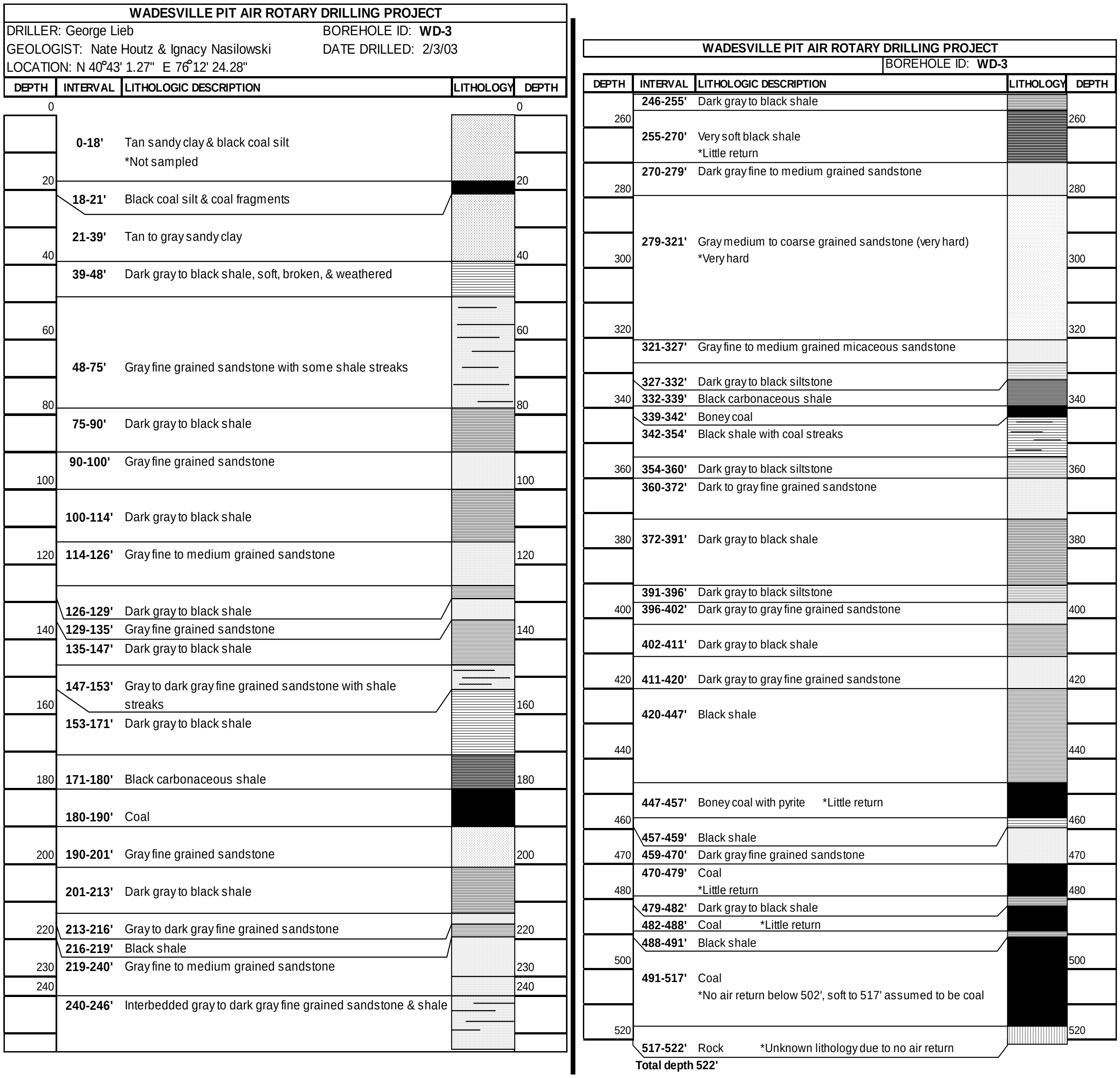

Figure 2.8. Stratigraphic interval from the Mammoth Coal zone up to the Primrose Coal bed at the Wadesville site.

2.3.8 Stratigraphic Observations and Inferences in the Anthracite Coal Fields

Bedrock formations exposed near the Eastern Middle Field are the products of weathering to the southeast. A poorly understood tectonic event in the early Carboniferous produced uplift to the southeast that was the primary source of clastic material to the basin. It is speculated that the cause of this possible orogeny may have resulted from strike slip movement generated by the approaching African plate (Faill, 1997a,b). While these highlands were eroding, the Mauch Chunk Formation and the overlying Pottsville Formation were deposited. The Mauch Chunk consists of predominantly fining upward alluvial cycles of interbedded sandstones, siltstones, mudstones, and conglomerates (Inners, 1988), and can be recognized in the field by its characteristic red color. The contact between the Mauch Chunk Formation and the Pottsville represents a transition from the warm, seasonally dry climate present at the time of Mauch Chunk red bed deposition to the much wetter climate in which the Pottsville coal forming peat swamps flourished (Edmunds et al., 1999). Sedimentary structures, thickness patterns, and a southeastward increase in grain size indicate that the Pottsville Formation was also derived from a southeastern source (Wood et al., 1986).

Figure 2.9 shows a schematic of the Spring Mountain cut along I-81, approximately 4 miles south of Hazleton. The outcrop exposes the contact between the Mauch Chunk and the Pottsville Formation as part of a large syncline (Bolles and Geyer, 1976). Superimposed on the syncline in Figure 2.9 is a large fault, which occurred during the rock's burial during the Permian. The resistant Pottsville Formation forms many of the high ridges around each field, and the overlying less resistant Llewellyn Formation occupies the valley floors within each field (Eggleston et al., 1999).

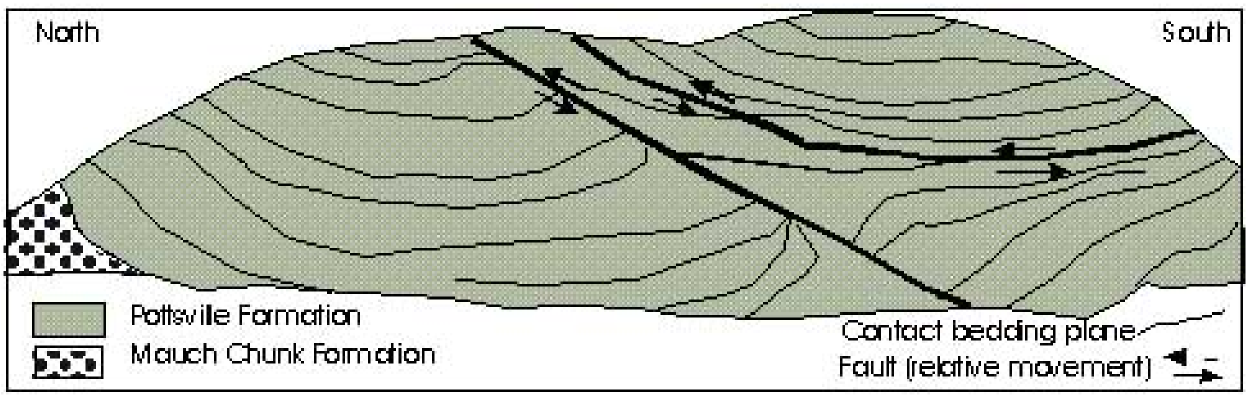

Figure 2.9. A schematic of the outcrop at mile marker 138 along Interstate 81, near McAdoo, PA, showing the contact between the Mauch Chunk and Pottsville Formations (modified from Bolles and Geyer, 1976).

The identification and mapping of limestone and other calcareous rocks in the Southern and Middle Fields have not been reported in the literature; however, some large mine pool discharges such as the Wadesville Colliery (Table 2.1), have alkalinity of several hundred milligrams per liter, which must be attributed to some carbonate minerals in the overburden. Discharges in the Eastern Middle Field have little if any alkalinity (Table 2.1). This strongly suggests a lack of calcareous rock in this coal field. Kochanov (1997) has found calcareous sandstones in the lower part of the Llewellyn in the Northern Field. Further study of carbonate minerals and identification of calcareous lithologic units in the Southern and Middle Fields is needed.

2.4 HYDROGEOLOGY

The hydrogeology of the Anthracite and Bituminous Coal Regions of Pennsylvania is the product of the topography, geologic structure and stratigraphy of these regions. Whereas the Bituminous Region has a more conventional integration of these geologic factors, the hydrogeology of the Anthracite Region is largely controlled by the hydrology of the mine pools related to large abandoned underground mine complexes, or collieries as they are called in the region.

2.4.1 Regional Hydrogeology of the Bituminous Coal Region

Regional and local patterns of groundwater flow on the Allegheny Plateau of western Pennsylvania are established in response to topographic, structural and stratigraphic controls, some of which were discussed separately in preceding sections on the regional geology, but which are briefly integrated below at various scales to comprise the hydrogeologic setting. In addition to the stratigraphic controls on the general configuration of the flow system, lithologic variations within the Pottsville and Allegheny Groups can be related to factors that influence the quantity and quality of ground and surface water supplies available on the Allegheny Plateau in western Pennsylvania.

Groundwater flow of the Appalachian Plateau of Pennsylvania is described in detail in Callaghan et al. (1998), including several mining case studies. A similar comprehensive chapter on the hydrogeology of the Appalachian Bituminous Coal Basin is in Callaghan et al. (2000). Hawkins (1998) provides additional valuable information on the hydrogeologic characteristics of mine spoil within the Appalachian Coal Basin.

In the regional geomorphic setting of the Allegheny Plateau, variations in relief and the configuration of the topographic surface are closely related to the drainage pattern. The regional topographic highs are the major groundwater recharge areas while the elevation and configuration of regional groundwater discharge areas are controlled by the depth of incision of the major streams and rivers such as the Allegheny and Monongahela Rivers. Within this regional flow system, local and intermediate scale flow systems exist, wherein local and intermediate scale topographic lows are usually groundwater discharge areas, while corresponding topographic highs are usually groundwater recharge sites, (Fig. 2.10).

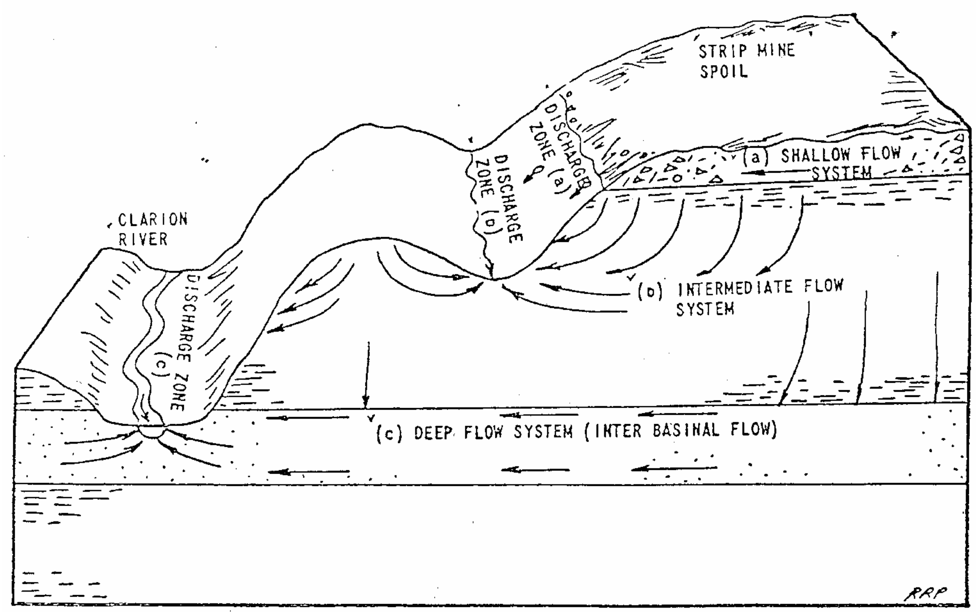

Figure 2.10. Block diagram showing shallow, intermediate, and regional (deep) groundwater flow systems in the Bituminous Coal Region of western PA, (from Parizek 1979).

Groundwater flow systems of various scales and configurations for various geologic settings have been discussed by Hubbert (1940), Toth (1962), Meyboom (1966), Brown and Parizek (1971), Freeze and Cherry (1979) and others. Parizek (1979) provides a review of the flow systems cited above and discusses a high-relief, coal-field, flow-system model as shown on Figure 2.10. That model of groundwater flow is most appropriate for most of the Allegheny Plateau and the bituminous case study sites described in Chapter 5.

As the bedrock structure is often closely related to the present topography, the structural configuration may be related to the groundwater flow system as with topography above. For example, the crests of anticlines or other structural highs may be groundwater recharge areas, with the discharge areas located in the synclinal lows coincident with the topographic lows. However, numerous interacting geologic and hydrologic factors produce flow-system behavior which deviates considerably from the ideal case where the groundwater is flowing through isotropic, homogeneous media. In a typical geologic setting for Pottsville and Allegheny Groups strata in western Pennsylvania where a cyclical sequence of varying rock types outcrops in a gently dipping or folded configuration, a three-dimensional representation of the groundwater flow system may reveal structurally-induced flow pattern controls. The uplands may still be the principal recharge areas with the lowlands as the principal discharge areas, but groundwater flow may follow preferred avenues, such as along bedding planes and selected lithologic units of contrasting permeability, to down-dip discharge sites.

Strong control on the patterns of groundwater flow also may be exerted by the orientations and the frequency of joints, zones of fracture concentration (revealed by fracture traces), and other linear structural features which introduce a secondary porosity and permeability to the bedrock. The dramatic influence of these linear features on groundwater flow has been shown by Lattman and Parizek (1964), Parizek (1971, 1976), Brown and Parizek (1971), Parizek, et al. (1971), Lovell and Gunnett (1974), Cline (1968) and others. The relationship of fracture-trace intersections and/or lineament intersections to high productivity of water supply wells has been documented by Siddiqui and Parizek (1971a, 1971b) and others.

The general stratigraphy of the Pottsville and Allegheny Groups in western Pennsylvania and the lithologic characteristics of specific stratigraphic intervals therein are interrelated with the topographic and structural controls on regional and local groundwater flow systems. The most resistant lithologic units generally form the topographic highs while the most easily weathered units form the topographic lows. The fundamental or primary properties of the sedimentary rocks, such as the mineralogical composition of the rock and the size, shape, orientation and packing of the mineral grains, (Griffiths, 1967), not only determine the relative resistance to weathering, but also greatly influence other derived or secondary lithologic properties such as the intergranular porosity and permeability. Hence, the variations in lithology of the Pottsville and Allegheny Groups (as discussed in the preceding section on stratigraphy), are highly related to variations in the potential to store and transmit groundwater. For example, the large sandstone units may be the best aquifers regionally, while the shales and underclays tend to be confining beds. The coal seams, which often occur in a highly-jointed condition between the underclays and thick sequences of overlying shale, may readily transmit groundwater accumulated by vertical leakage from the overlying beds. The prevalence of springs and seeps at the outcrop line of coal seams in some topographic settings reflects the role of these beds in the transmission and discharge of infiltrating groundwater as part of shallow and intermediate flow systems.

The relationship between the stratigraphy and permeability of rocks of the Pottsville and Allegheny Groups has been discussed by Caruccio and Parizek (1967), Brown and Parizek (1971) and Schubert (1978) who found horizontal permeability greatly exceeds vertical permeability and thus causes a predominantly lateral groundwater movement. A multiaquifer hydrogeologic setting on the Allegheny Plateau, in which the shallow flow system is significant, has been investigated by Poth (1963), and Brown and Parizek (1971) Emrich and Merritt (1969).

In a detailed study of the geology and hydrology of the Pottsville and Allegheny Groups in a portion of Mercer, Lawrence, and Butler counties, Pennsylvania, Poth (1963, p. 88) describes the relationship between patterns of groundwater flow and the major stratigraphic units as follows: "The mature dissection of the bedrock divided the Mercer quadrangle into a number of "hydrologic islands", each with its own pattern of groundwater circulation. Precipitation enters the upper part of the "islands" and is discharged through the outcrop areas of the aquifers along the perimeter of the "islands."

According to Poth, the "hydrologic islands" are a few square miles in area, and are composed of rocks younger than the lower member of the Connoquenessing Formation which is generally the highest hydrologically-continuous stratigraphic unit throughout the area. As shown on Figure 2.11 (from Poth, 1963, p. 58), infiltrating groundwater is discharged into glacial deposits in valleys around the margin of the "islands", or is carried downward into the deep circulation system of Connoquenessing Sandstone and lower aquifers through the aid of fracture zones.

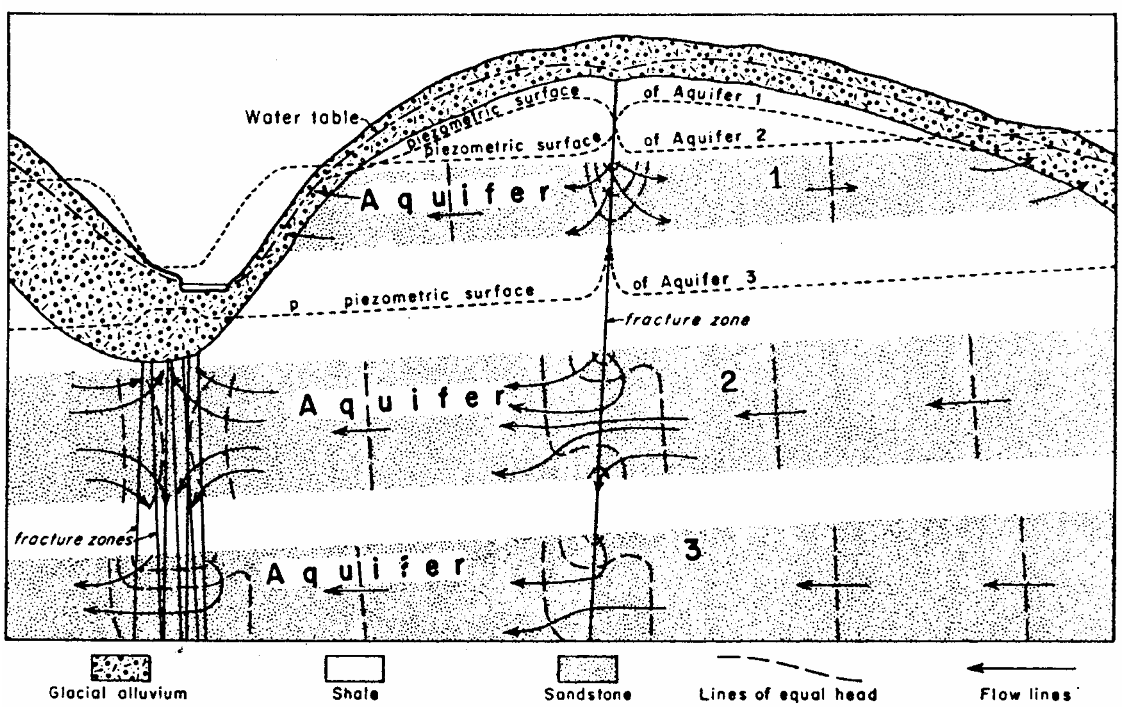

Figure 2.11. Idealized pattern of groundwater flow in the Mercer Quadrangle, PA**.**

Several studies have been completed within the Allegheny Plateau of western Pennsylvania, which relate the above hydrogeologic principles and associated topographic, structural and stratigraphic factors to the mining of coals from the Pottsville and Allegheny Groups as well as to coal mining in other areas. Parizek and Tarr (1972) provide a survey of existing and proposed techniques of mine drainage pollution prevention and abatement, employing naturally occurring hydrogeological and geochemical systems which are prevalent in western Pennsylvania and elsewhere.

The relationship between stratigraphy and mine drainage quality in the bituminous and anthracite mining regions of Pennsylvania are described in Brady et al. (1988). A bimodal frequency distribution of the pH of coal mine drainage was first reported by Brady et al. (1997). Figures 2.12a and 2.12b from Brady et al. (1998) shows the bimodal distribution of pH for bituminous and anthracite mine discharges. Table 2.1 shows the relationships between mine drainage quality and stratigraphic intervals for water samples representing the coal-bearing Pennsylvania and Permian stratigraphic sequence in western and eastern Pennsylvania. Table 2.1 in this chapter is an abridged version of mine drainage quality data compiled in Table 8.2 and 8.14 in Brady et al. (1998).

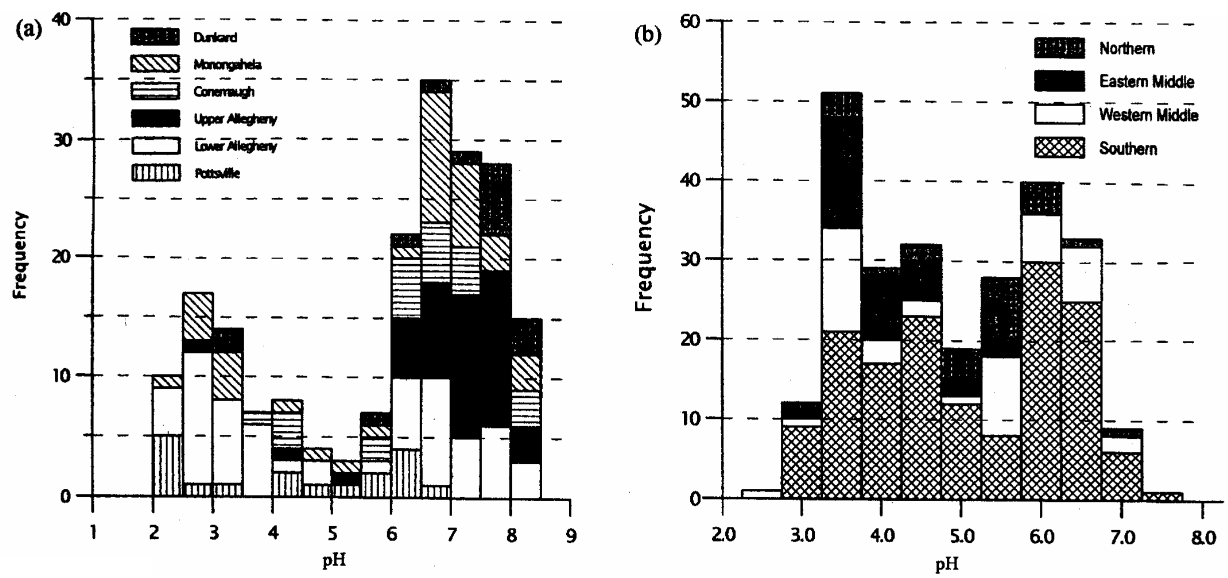

Figure 2.12. Bimodal distribution of pH for (a) bituminous mines and (b) anthracite mine discharges in PA. (Bituminous data are from Table 8.2 in Brady et al. (1998) and anthracite data are from Growitz et al., (1985). Bituminous data are displayed by stratigraphic group and anthracite data by coal field.)

2.4.2 Regional Hydrogeology of the Anthracite Coal Region

The hydrogeology of the Anthracite Coal Region of eastern Pennsylvania is similarly the product of the topography, geologic structure and stratigraphy of the region, as described for the bituminous region. However, in considering the integration of these geologic factors, the hydrogeology of the Anthracite Region is much simpler in some respects, while being more complex than the bituminous regions hydrogeology in other respects. Part of the simplicity is that a large portion of the groundwater in the four anthracite coal fields is accounted for by about 100 large mine pool discharges, in comparison to the many thousands of mine drainage discharges and AMD seeps in the bituminous coal fields of Pennsylvania. Also, much is known about the areal extent, depth and other aspects of the geometry and hydrology of the anthracite mine pools along with their interconnections from the detailed mine maps that are available for most of the abandoned deep underground mines.

The complexity of the Anthracite Region hydrogeology is largely a result of the complexity of the geologic structure and how that complex structure is translated into an elaborate system of mine development patterns, including numerous overlapping gangways, chutes or breasts, and slopes, that are interconnected by nearly horizontal rock tunnels and vertical shafts. The configuration of anticlinal and synclinal folds and the presence of significant faults can often be interpreted from the mine development patterns on the colliery maps. The gangways are frequently significant components of groundwater flow patterns, analogous to the conduit and sinkhole systems in karst hydrology, because the gangways are long voids developed parallel to the strike of the beds, that are often connected vertically to the land surface by cropfalls (mine subsidence features), which resemble sinkholes and promote infiltration of surface water into the groundwater flow system.

Adding to the complexity of the Anthracite Region hydrogeology in some areas is the presence of local-scale shallow groundwater flow systems, that may be somewhat independent of, or interconnected with, the more regional-scale underlying mine pool flow systems (similar to Figure 2.10). Examples of these shallow groundwater flow systems are found along ridges in the Southern Anthracite Field near Tamaqua, where abandoned, relatively small pits on the flanks of the ridges, and the sandstone ridge tops themselves, serve as groundwater recharge areas, and the discharge areas are through the collovium or underlying bedrock into the underlying mine pool system in the valley bottom.

The configuration of the mine pools and associated barrier pillars for most of the Anthracite Region were documented in a series of reports by S.H. Ash and associates at the U.S. Bureau of Mines (Ash and Eaton., 1947; Ash et al., 1949; Ash et al., 1950a,b; and Ash, 1954). These reports contain delineations of the shorelines of the mine pools, locations of documented breeches in the barrier pillars, and estimations of the volume of water impounded in specific mine pools. Two USGS reports contain data for most of the large anthracite mine pool discharges from 1975 (Growitz et al., 1985) and (Wood, 1996) that allow comparison of water quality changes through time.

The work of J.R. Hollowell of the Susquehanna River Basin Commission (SRBC) and associates provided significant hydrogeological information on the Northern and Eastern Middle Coal Fields. Hollowell (1971) described the mine-water hydrology for the Wyoming Basin of the Northern Field, and Hollowell and Koester (1975) contains a similar description of the mine-water hydrology of the Lackawanna Basin of the Northern Field. Figure 2.13 from Hollowell (1971) is a map of the collieries of the Wyoming Basin, and Figure 2.14 from the same publication is a companion schematic plumbing diagram of mine water flow through these abandoned underground mines of the Wyoming Basin. Hollowell and Koester (1975) contains a large water-table contour map (Plate 2 of that publication) showing the collieries of the Lackawanna Basin and the associated mine pool shoreline, plus the mine pool elevations in key shafts and the associated potentiometric surface contours.

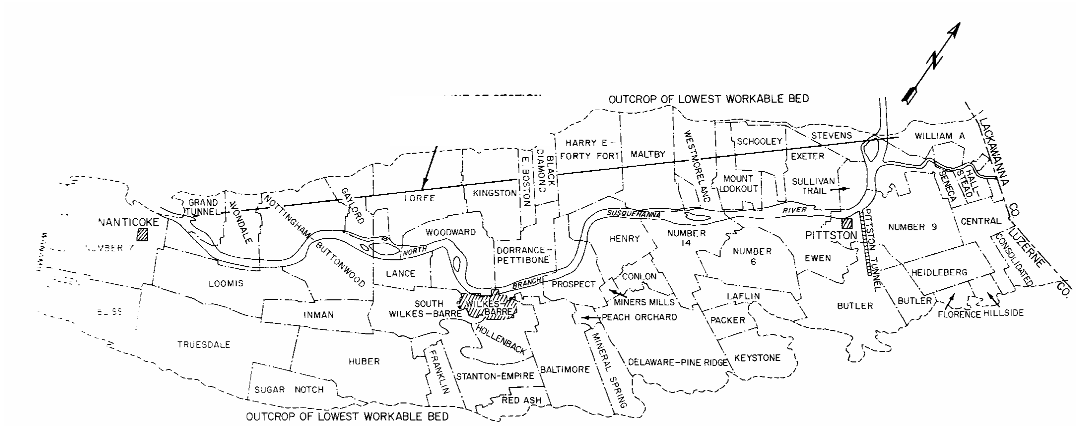

Figure 2.13. Map of collieries in Wyoming Basin of the Northern Field (from Hollowell,1971).

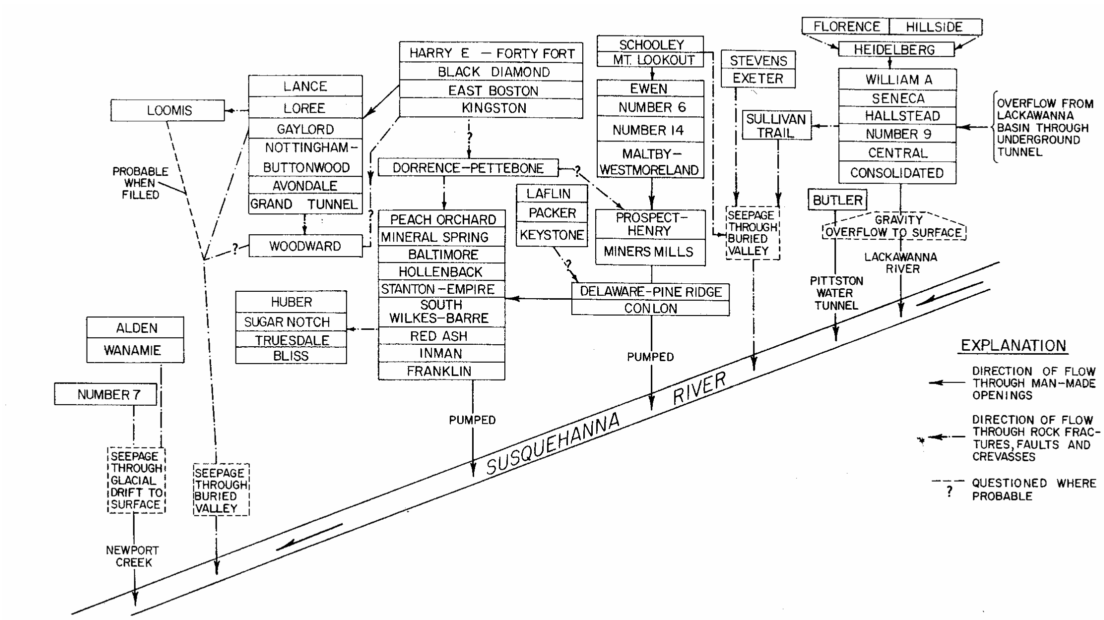

Figure 2.14. Schematic diagram of water flow through the mines (eg. Barrier pillar breaches) in the Wyoming Basin, (from Hollowell 1971).

Hollowell (1999) describes the mine drainage outfalls of the Eastern Middle Field, and delineates the individual coal basins, the locations of the outfalls and the extent of the Jeddo drainage tunnel system, as shown on Figure 2.15. According to Hollowell (1999, p. 1), there are 13 functional mine drainage tunnels in the Eastern Middle Field that were specifically driven to dewater the mine workings. This drainage system was most successful in the Eastern Middle Field because of the comparable elevation of the drainage tunnel discharge to the receiving streams. The Jeddo Tunnel is by far the most extensive of these. The other discharges each yield a comparatively minor amount of water.

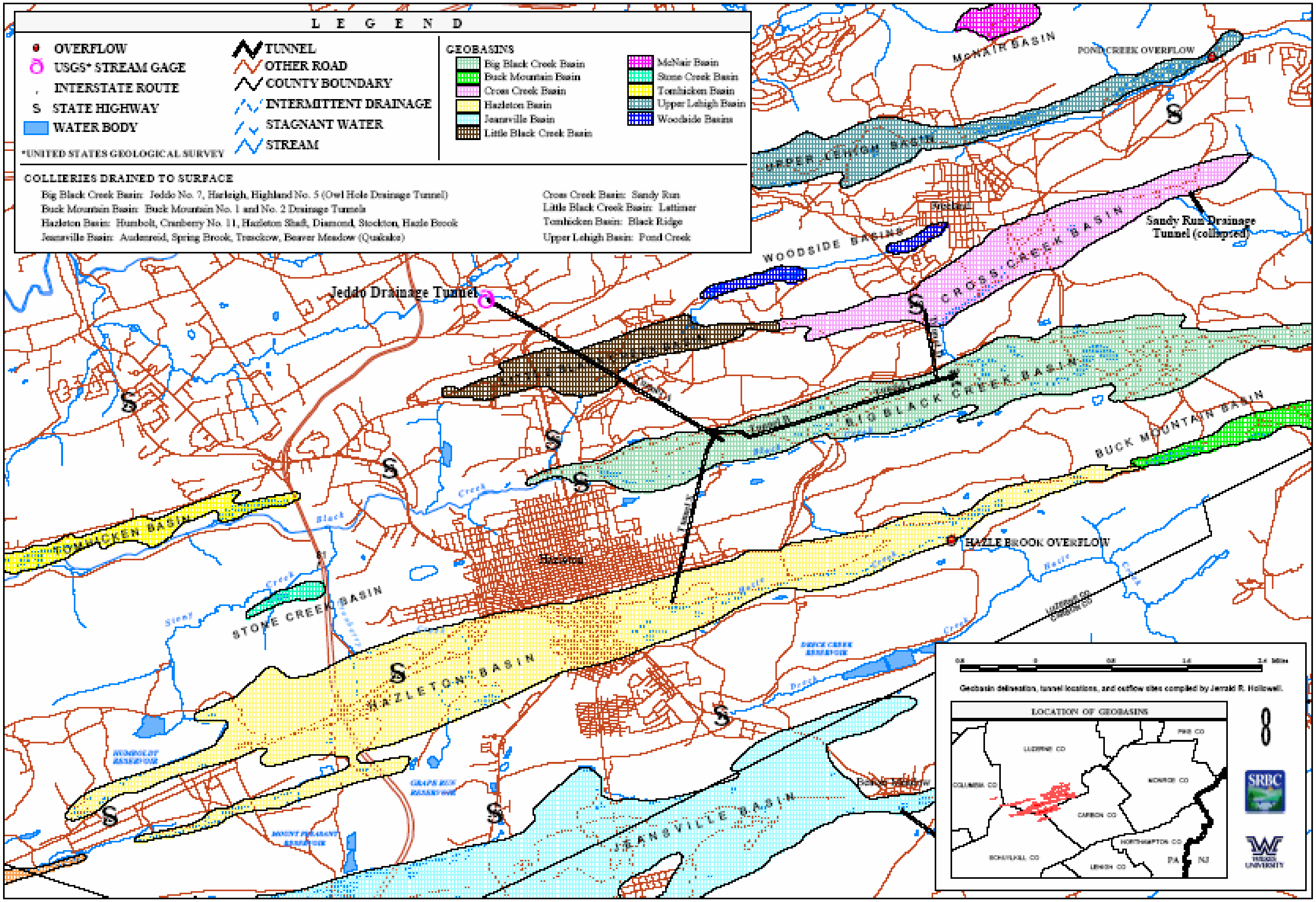

Figure 2.15. Jeddo Tunnel drainage system (from Hollowell 1999).

The report by Hollowell (1999) includes plots of the flow and pollution load (i.e. acidity, sulfate, iron, manganese, aluminum, magnesium, zinc) of the 16 major mine drainages of the Eastern Middle Field for 3 water years. In a companion report by the SRBC, Ballaron (1999) describes a hydrologic budget for the Jeddo Tunnel Basin that was done in cooperation with USGS, DEP and the Little Nescopeck Watershed Association.

Few detailed hydrogeologic studies have been completed for the Southern Field and the Western Middle Field, except for some unpublished hydrogeologic reports in DEP files, and some thesis publications including the groundwater modeling study by Bair (1980) of an area near Tamaqua in the Southern Field. However, a number of significant geochemical and hydrologic studies have been completed by C.A. Cravotta and associates at USGS for the Swatara Creek Watershed and other selected watersheds in the Southern Field and Western Middle Fields including Cravotta (2000), Cravotta and Watzlaf (2002), Cravotta (2003) and Cravotta et al. (2004).

2.4.3 Jeddo Tunnel Discharge

Much has been written about the Jeddo Tunnel, in terms of an extraordinary engineering feat, the eventual success of dewatering the coal basins (Ash et al., 1950b) and more recently, its environmental impact. The Jeddo Tunnel mine discharge near Hazleton, Pennsylvania is the largest abandoned underground mine discharge in the Eastern Middle Field of the Anthracite Region, and is among the largest mine drainage discharges in Pennsylvania. The Jeddo Tunnel has a total drainage areas of 32.24 square miles, and its underground drainage system collects and discharges more than half of the precipitation received in the drainage area (Ballaron et al., 1999).

The flow of this discharge was monitored with a continuous recorder from December 1973 through September 1979 by the USGS in cooperation with Pennsylvania Department of Environmental Resources. The results of that monitoring for the water year from October 1, 1974 through September 30, 1975 are shown in Figure 2.16 (Growitz et al., 1985). During that year, the discharge ranged from 36 to 230 cfs (16,157 to 103,224 gpm).

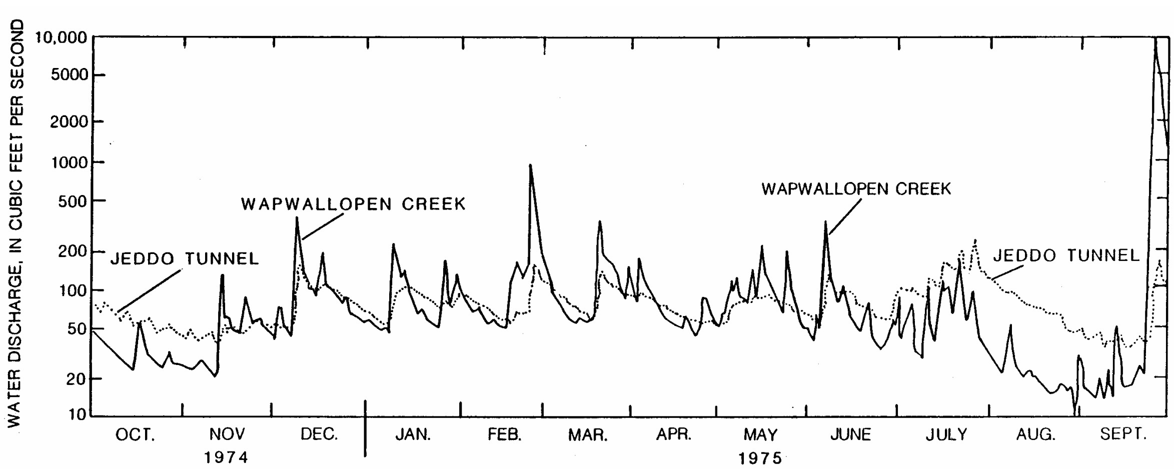

Figure 2.16. Water discharge from the Jeddo Tunnel in Hazleton, and Wapwallopen Creek near Wapwallopen, PA, October 1, 1974 to September 30, 1975 (from Growitz et al. 1985).

The Wapwallopen Creek, ten miles north of the Jeddo Tunnel drains an area of 43.8 square miles and has a measured mean discharge of 78 cfs (35,008 gpm) (Growitz et al., 1985). The Jeddo Tunnel discharge flows are compared to the stream-flow of Wapwallopen Creek (approximately 10 miles north of the Jeddo Tunnel) on Figure 2.16. Growitz et al. found that the response of the Jeddo Tunnel discharge to precipitation events is considerably less than that of the Wapwallopen Creek, and that during large storm events, the Jeddo Tunnel data peaked later than the stream discharge.

The continuous flow recording station at the mouth of the Jeddo Tunnel was reconstructed and operated by USGS from October 1995 through September 1998 in cooperation with PA DEP, the Susquehanna River Basin Commission, US EPA and other project cooperators. Figure 2.17a (from Ballaron et al., 1999) shows variations in the flow of this discharge during this period. The average annual discharge flow was 79.4 cfs (35,635 gpm) and the range of recorded flow measurements was between 20 cfs (8,976 gpm) in October 1995 and 482 cfs (216,322 gpm) in November 1996, following 3.89 inches of rainfall (Ballaron, 1999). In comparison, Figure 2.17b shows a graph of precipitation data from Hazelton Pennsylvania for the period from October 1995 through September 1998. This graph was plotted from data contained in Ballaron (1999). Additional information on the Jeddo Tunnel discharge is contained in Fox et al. (2001).

2.4.4 Anthracite Region Water Quality

Regional variations in mine drainage quality of the Anthracite Region are shown in Table 2.1. The relationships between the post-mining water quality and specific stratigraphic intervals of the Anthracite Region are much less well known than those of the Bituminous Region for at least two reasons: 1) the complexity of the geologic structure has impeded the acquisition of stratigraphic data from routine exploration drilling and made correlations of units and associated mine drainage difficult; and 2) a large portion of the mining hydrology of the four anthracite fields is controlled by large-volume, mine pool discharges. The mine drainage from gangways developed in multiple coal beds is commingled in rock tunnels (that crosscut the geologic structure and strata), which interconnect the mine workings. Thus discharges are often a composite representing water from multiple coal seams throughout a large mine complex. Despite this, some significant regional variations in mine drainage quality are evident for the anthracite fields (Figure 2.18). These are probably related to mineralogic differences between the fields.

Some Northern Anthracite Field mine waters have significant alkalinity (e.g., Plains Borehole, Table 2.1). This may be attributable to the presence of marine and freshwater limestones and other calcareous rocks in the Northern Field. A few post-mining discharges of the Northern Field have low pH and high acidity (Loomis Bank discharge), although high acidity discharges are relatively rare in the anthracite fields. Many large volume discharges of the Northern Field have circumneutral pH with nearly equal concentrations of acidity and alkalinity. However, some of these discharges have relatively high concentrations of iron, manganese or aluminum, and because of large flows they have high pollution loads.

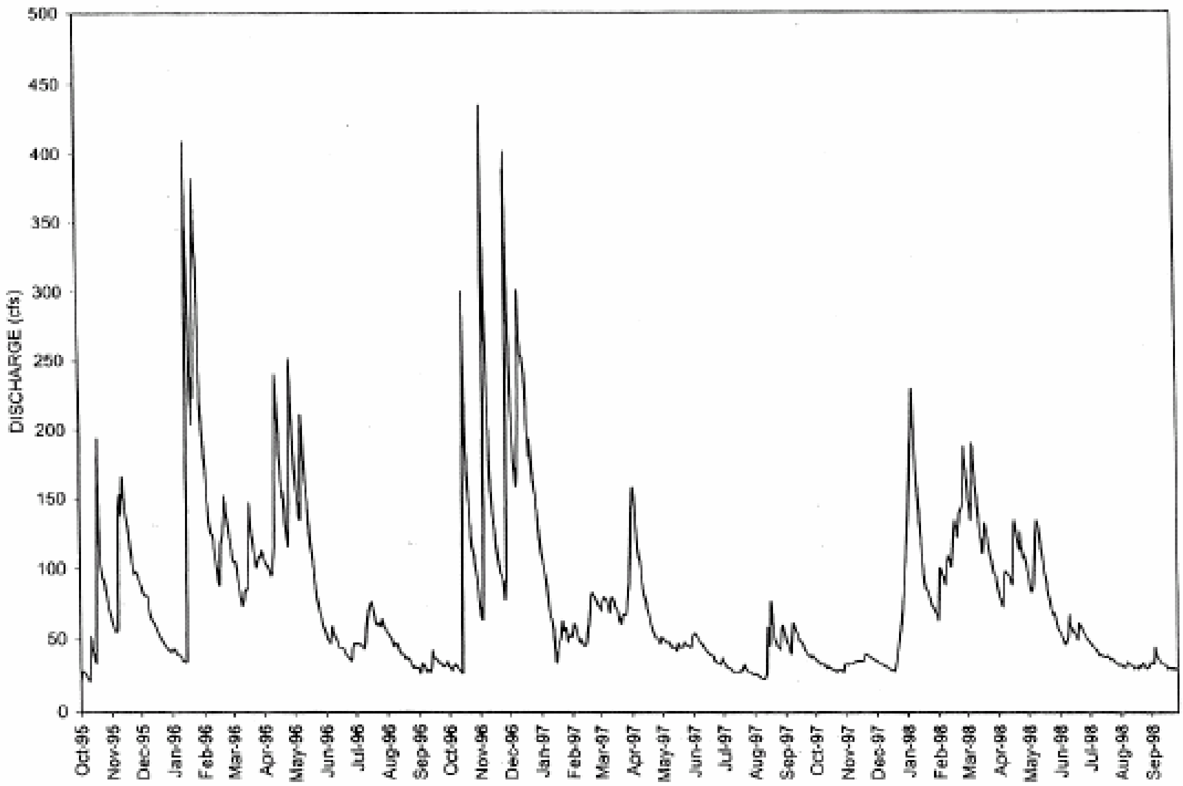

Figure 2.17(a). Discharge from the Jeddo Tunnel - water years 1996-1998 (from Ballaron 1999).

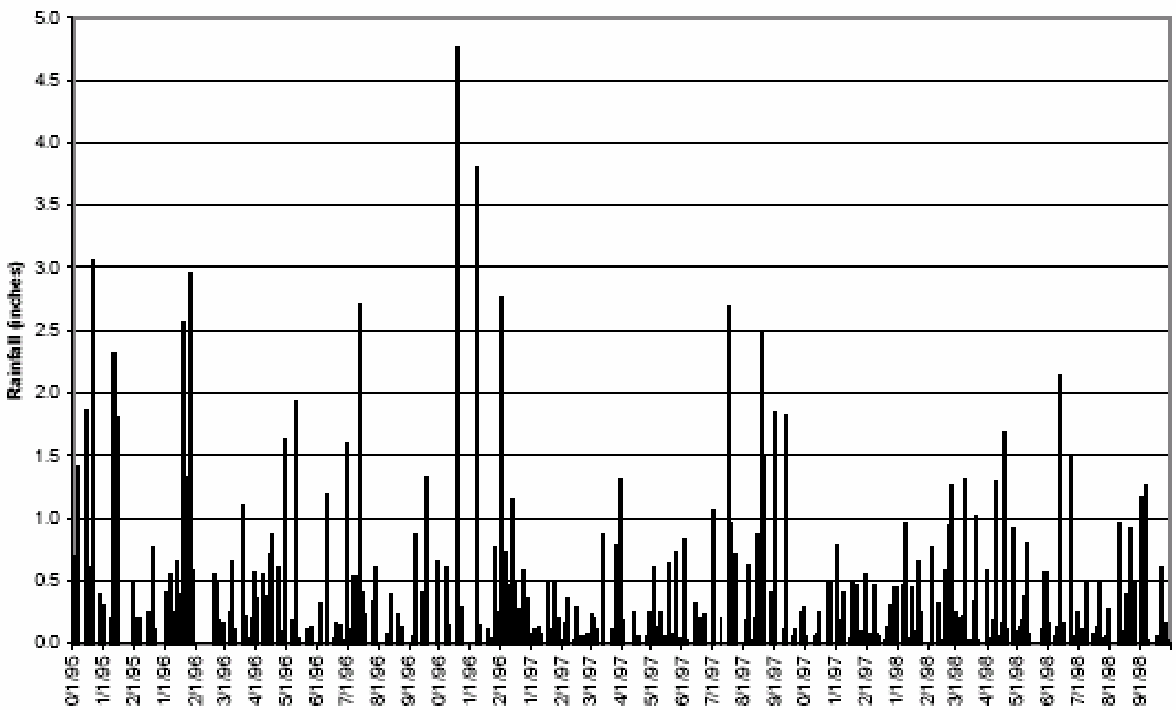

Figure 2.17(b). Precipitation data from Hazleton, PA 1996-1998 (from Fox et al., 2001).

Table 2.1. Mine drainage quality of the Bituminous and Anthracite Coal Regions of PA
(Bituminous mine sites are identified by major coal seams mined: WY= Waynesburg, RS = Redstone, PT = Pittsburgh, UB= Upper Bakerstown, BC = Brush Creek, UF = Upper Freeport, LF = Lower Freeport, UK = Upper Kittanning, LK = Lower Kittanning, CL = Clarion, MR = Mercer. Anthracite mines are identified by coal field: N = Northern Field, EM = Eastern Middle Field, WM = Western Middle Field, S = Southern Field.

Site Name	County	Coal ID	Sample Date	pH	Alkalinity mg/L	Acidity mg/L	Iron mg/L	Mn mg/L	Al mg/L	SO_4 mg/L	TSS mg/L	Flow (gpm)
Susan Ann	Greene	WY	10/24/91	7.9	286	0	2.61	17.60	<0.50	1392	15	<1
Smith	Westmoreland	RS	7/16/92	7.7	246	0	1.47	0.27	1.22	122	57	0
Brown	Fayette	RS	8/17/93	7.4	626	0	1.65	1.05	<0.50	1440	12	
Trees Mills	Westmoreland	PT	10/6/88	2.4	0	2,086	371.00	20.04	159.90	2409	26	8
State Line	Somerset	UB	4/29/96	8.1	210	0	<0.30	1.37	<0.5	416	<3	
Hager	Fayette	BC	7/12/95	6.9	189		0.21	0.40	0.07	68	1	4
Laurel Hill #1	Cambria	UF	1/6/97	8.1	484	0	0.97	1.98	1.04	590	34	0
Chanin	Fayette	LF	1/4/89	4.3	7	186	0.30	28.40	24.60	1152	8	
Morrison	Fayette	UK	6/22/89	7.0	308	0	0.63	3.49	<0.50	327	5	<1
Swisscambria	Cambria	LK	10/25/90	4.2	5	88	0.09	24.20	10.00	1070	36	
Albert #1	Clearfield	LK	1/30/89	3.1	0	1,335	186.00	111.00		3288	0	55
Snyder #1	Armstrong	LK	7/24/90	6.9	114	0	1.10	3.14		264	127	0
Lawrence	Fayette	LK	1/18/82	2.2	0	5,938	2,060	73.00	146.00	3600		0
Phillipsburg	Centre	CL	2/5/96	3.0	0	1,063	153.70	20.92		1796		900
Old 40	Clarion	CL	11/12/85	2.2	0	10,000	3,200	260.00	550.00	1400		well
Horseshoe	Cambria	MR	4/3/84	2.3	0	1,835	194.00	27.00	88.00	2510	0.2	700
Duryea Ditch	Lackawanna	N	11/1/85	5.9	90	2	35.20			464		11,670
Alden Strip #2	Luzerne	N	7/28/92	7.1	168	7	0.90	0.30	<0.50	628	22	
Jeddo Tunnel	Luzerne	EM	10/24/96	4.3	6	104	7.20	4.50	11.10	346	22	50,150
Oneida #3	Schuylkill	EM	12/30/96	4.7	9	26	0.10	0.30	1.10	22	<2	7,415
Packer V	Schuylkill	WM	7/29/97	6.4	160	0	20.90	7.80	0.10	597	30	1,200
Richards	Northumberland	WM	8/19/97	3.7	0	70	7.50	2.50	4.80	82	2	1,672
Scott Overflow	Columbia	WM	8/19/97	5.9	54	68	28.30	4.10	0.30	254	2	4,386
Goodspring #1	Schuylkill	S	9/27/95	6.2	66	0	15.20	2.50	<0.50	112	6	127
Goodspring #3	Schuylkill	S	9/27/95	6.0	54	32	22.20	3.40	<0.50	323	26	516
Markson	Schuylkill	S	9/27/95	3.4	0	82	18.30	5.60	1.60	491	4	844
Wadesville	Schuylkill	S	5/19/86	7.1	330	0	1.90	2.60	<0.50	1164	14	

There are 16 major discharges in the Eastern Middle Field. Mine drainage from two of these are shown in Table 2.1. There is no significant alkalinity in any of the discharges. As far as is known, there are no limestones or other calcareous strata in this region. No severe AMD (pH < 3.0, acidity > 1000 mg/L) is known in the Eastern Middle Field. The Eastern Middle Field appears to lack both calcareous rocks and high-sulfur rocks. The Jeddo Tunnel discharge, in the Eastern Middle Field, (Table 2.1), generally has an acidity concentration > 100 mg/L and a flow > 40,000 gpm. Though the acidity concentration is not "high", the acid load is large because of the high flow.

The water quality of the post-mining discharges of the Western Middle and Southern Anthracite Fields is somewhat more mysterious than that of the Northern and Eastern Middle Fields. Some discharges have significant alkalinity, but no carbonate stratigraphic units have been reported in these fields. The Packer V discharge in the Western Middle Field has alkalinity of 160 mg/L and iron of 20.9 mg/L (Table 2.1). The Richards discharge near Mt. Carmel has a pH of 3.7 and an acidity of 70 mg/L. Because some of these discharges drain large interconnected underground mines spanning square miles, various anthropogenic sources may also contribute to water quality. However the North Franklin and the Doutyville Tunnel discharges are located in a mostly rural area, and questions remain.

Several mine discharges of the Southern Anthracite Field have significant alkalinity concentrations, including the Wadesville, Eagle Hill, and Kaska discharges. For example, the water pumped from the Wadesville shaft has an alkalinity of 330 mg/L, in Table 2.1. This is one of the most alkaline mine waters found in Pennsylvania. It is almost certain that a detailed study of stratigraphy in this area would reveal calcareous strata or calcareous secondary mineralization. Several Southern Field discharges have significant acidity concentrations (Bell, Newkirk, Porter Tunnel and Markson discharge). Promisingly, a study by C.R. Wood (1996) shows that many abandoned underground mine discharges in the anthracite fields have improved in water quality between 1975 and 1991.

A final factor that may affect the relationships between post-mining water quality and stratigraphy in the Anthracite Region is the stratification of mine pool water. The mine pools consist of water accumulated in void spaces within abandoned underground mines, and deep pools or lakes in abandoned surface mines that are hydrologically connected to abandoned underground mines. These mine pools typically become chemically stratified into "top water" and "bottom water". The stratification of anthracite mine pools is discussed in Barnes et al. (1964), Erickson et al. (1982) and Ladwig et al. (1984). Additional discussions on the areal extent and volume of impounded water in the mine pools are contained in a series of studies by Ash et al. (1949) and Ash (1954).

The top water discharges are typically of circumneutral pH, although some samples in Table 2.1 may have elevated iron, manganese or aluminum. Top water is believed to reflect shallow groundwater systems, with relatively short residence times, where most of the flow is confined to the upper part of the mine pool. The bottom water typically has higher concentrations of acidity, metals, and sulfate than the top water of the same mine pool. Bottom waters are indicative of longer residence times, less circulation (and less oxygen). For example, the Markson and Good Spring No. 1 mine pool discharge samples shown in Table 2.1 are from adjacent collieries within the Donaldson Syncline in the Southern Anthracite Field. The mine maps of these two collieries indicate that the coal seams mined, mining engineering factors, and geologic conditions of the collieries are essentially the same; yet the Good Spring No. 1 discharge has a pH of 6.2 (and sulfates of 112 mg/L) and the Markson discharge has a pH of 3.4 (and sulfates of 491 mg/L) (Table 2.1). The Good Spring No. 1 and Good Spring No. 3 discharges are top water and the Markson discharge is bottom water with a distinct hydrogen sulfide aroma. The samples of the Markson, and Good Spring No. 1 and Good Spring No. 3 mine pool discharges were collected on the same date in relatively low flow conditions and are within a few mg/L of the average sulfate values from five years of monthly samples.

Figure 2.18a depicts variations in the pH of mine discharges for the four anthracite fields. The Eastern Middle Field has the lowest median pH and the least variability in pH, consistent with an absence of carbonate strata. Figure 2.18b shows that the Eastern Middle Field discharges also have the lowest sulfate concentrations and the least variability in concentration. The other fields show a wider range in pH and sulfate, although the Southern Field typically has lower sulfate than the Northern and Western Middle Fields.

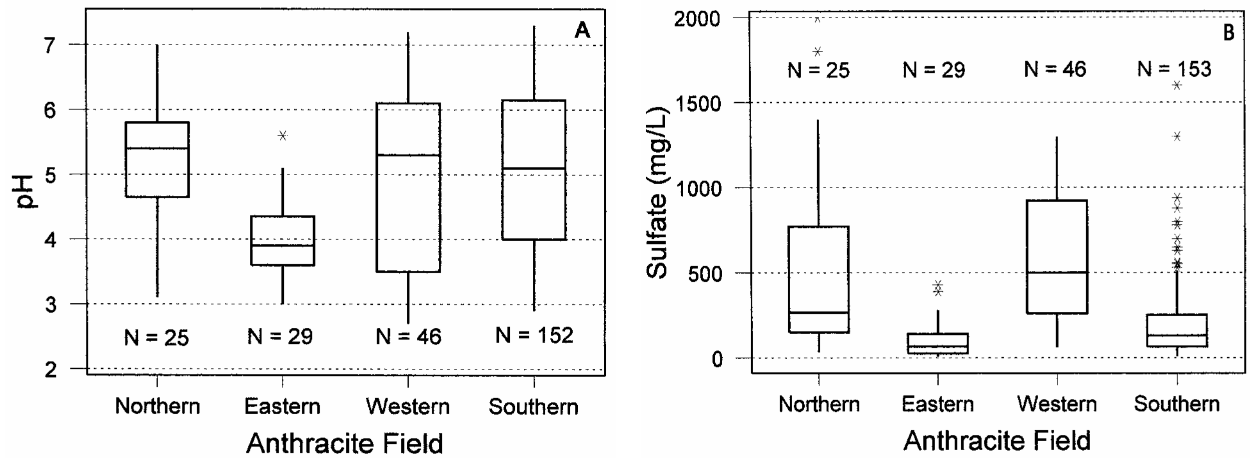

Figure 2.18 (a) and (b). Boxplots showing differences in pH and sulfates from the four anthracite fields in eastern PA (from Brady et al., 1998).

2.5 ANTHRACITE MINING

The Anthracite Region has been mined commercially from the late 1700s until the present. Anthracite mining peaked in 1917 (Fig. 2.19), and has declined significantly since then due to: 1) competition from cheaper and cleaner fuels; 2) labor disputes that disrupted supplies at critical times; 3) labor intensive mining methods; 4) depletion of more accessible coal beds; and 5) liability for water treatment and environmental concerns.

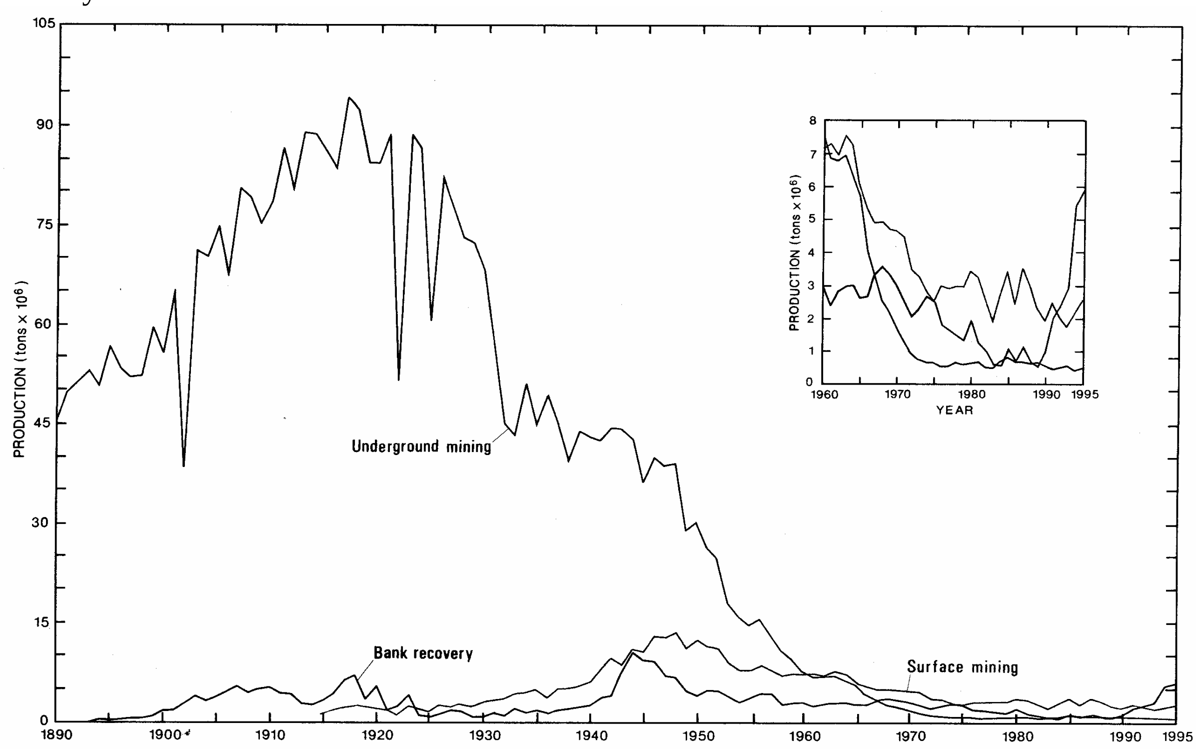

Figure 2.19. Anthracite production, 1890-1995 (from Eggleston, et al., 1999).

Anthracite production in 2001 was reported as 2,979,287 tons. Of this total amount, underground mining, once the dominant method for extraction, accounted for 154,111 tons, only 5 percent of Pennsylvania's total anthracite production, and surface mines produced 725,452 tons (Dodge and Edmunds, 2003). Eggleston et al. (1999) describe the process of underground mining anthracite coal in the following steps: 1) miners enter by a tunnel, slope, or shaft, 2) two horizontal headings are driven parallel to the strike of the coal bed from the shaft, 3) the upper heading, called the monkey, provides access to drill and blast upwards in the coal bed dip for distances of 200 to 300 feet (breast development), 4) coal then falls by gravity into coal cars in the lower heading, called the gangway, and 5) coal is hauled out through the gangway (Figure 2.20). The breast-and-pillar method just described is very labor intensive.

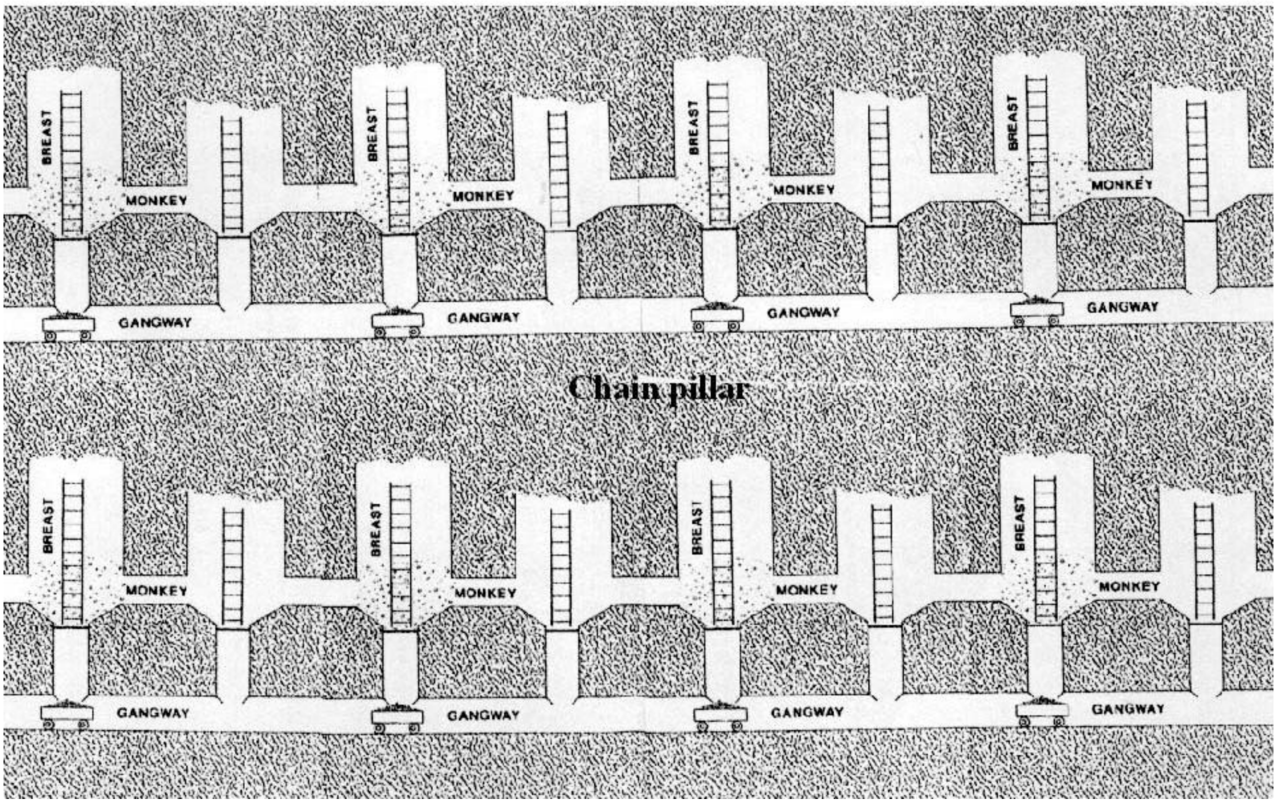

Figure 2.20. Typical anthracite underground mining practices (modified from Eggleston et al., 1999).

Neither surface mining nor bank recovery has surpassed the quantity of coal historically extracted by underground mining in the Anthracite Region of Pennsylvania. Surface mining dominated anthracite production in Pennsylvania between 1961 and 1991 (Eggleston et al., 1999). Bank recovery of coal silt and waste anthracite (culm) currently accounts for the largest percentage of anthracite production, 10,661,043 tons of coal extracted in 2001 (Dodge and Edmunds, 2003). Small (18 to 108 MW) co-generation plants have been constructed throughout the Anthracite Region in order to make use of this formerly discarded material (Inners et al., 1996). The culm-burning plants have provided a number of benefits to the region, including: 1) a reduction in AMD production from the culm, 2) reclamation of land, 3) a regional increase in jobs, and 4) an increase in the attractiveness of the landscape. Because many of these waste piles were created prior to SMCRA (1977), little money has been available to remove them.

2.6 SUMMARY

The geologic setting of the Anthracite and Bituminous Coal Fields of Pennsylvania provides a foundation for much of the subject matter in this book. Pennsylvania was blessed with abundant coal reserves. Along with this blessing, Pennsylvania was also bestowed with a curse of abundant abandoned mine land problems----including greater than 189,000 acres of abandoned, unreclaimed surface mines, more than 3,100 miles of stream polluted by acid mine drainage, and thousands of mine subsidence features, mine fires and other mine hazards. The physiography, geologic structure, stratigraphy and hydrogeology of the Anthracite and Bituminous Coal Regions are significantly different, but there are substantial similarities in the beneficial use of coal ash in these regions to reclaim abandoned mine lands and remediate acid mine drainage problems. The Anthracite Coal Fields have the most significant abandoned mine land reclamation problems due to the complexity of the geologic structure, the thickness of these coals, and the hydrology of the minepool systems. The Bituminous Coal Fields have the greatest number of acid mine drainage discharge problems and the most severe concentrations of acidity, iron and other parameters of the acidic drainage, due to the stratigraphy and depositional environments (i.e. greater sulfur contents) of these coals and overburden strata.

An attempt was made in the preceeding sections of this chapter to include sufficient information from the current scientific literature and older relevant references in order to provide an understanding of the geologic setting of the coal ash sites described in Chapters 4 through 9. The section on anthracite mining was included because most of the sites featured in these chapters are from the Anthracite Region, and an understanding of the underground mining methods is useful in relating the geology to the abandoned mine land reclamation problems. Additional information on the geology of the Anthracite and Bituminous Coal Regions of Pennsylvania is contained in two recent comprehensive publications: *The Geology of Pennsylvania* published by the Pennsylvania Geological Survey and the Pittsburgh Geological Society in 1999, and *Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania* published in 1998 by Pennsylvania Department of Environmental Protection.