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GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

GEOLOGY, HYDROLOGY, AND GEOCHEMISTRY OF THE BLACK CREEK WATERSHED NEAR MOCANAQUA, LUZERNE COUNTY, PENNSYLVANIA

By

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ABSTRACT

The Black Creek watershed is in the southwestern end of the Northern Anthracite field in Luzerne County, northeastern Pennsylvania. The study of the watershed described in this report is designated as Project No. 2 in the Joint Federal-State Acid Mine Drainage Pollution Control Demonstration Program. The area studied encompasses the West End mine of the Blue Coal Company.

Bedrock in the watershed, from oldest to youngest, consists of the Mauch Chunk Formation of Mississippian and, in part, of Pennsylvanian age; the Pottsville Formation of Pennsylvanian age; and the Llewellyn Formation of Pennsylvanian age. The anthracite beds are in the Llewellyn Formation.

, that "canoe-shaped" has been deleted on p. 26. TMD

See p. 28, line 9 (simple structural depression TMD)

The watershed is a small part of a long, narrow, complexly deformed synclinorium that embraces the Northern Anthracite field. The West End mine is divided into three sub-basins. The West basin is a relatively shallow, ~~dish-shaped~~, slightly elongated syncline. The East basin is a northeastward-striking, southward-dipping homocline whose south limb has been overturned by thrust faulting. The Priscilla Lee basin is an eastward-plunging, closely folded syncline; locally its southern limb is overturned. These three structural depressions are separated by anticlinal folds or faults.

Surficial materials have been classified as glaciofluvial deposits, mine waste, strip-mine waste, and artificial fill. These materials have been mapped along with areas of bedrock and outlines of pits.

A test-drilling program was completed with ~~twelve~~ 12 churn drill holes and two core holes. Lithologic logs of the holes were made as well as electric and gamma-ray logs.

It was determined that there were four pools of mine water. One pool in the west basin, draining into the Susquehanna River; one pool in the east basin, draining eastward through the barrier pillar; and two pools in the Priscilla Lee basin, which drains eastward through the barrier pillar, although some acid water drains northwest into Stump Lake and then into the west basin pool.

A detailed study was made as to the formation of the acid water. This is discussed in the quality distribution section of the report. The chemistry of the water in the various geologic formations is discussed as well as the water passing through the piles of mine waste. The acid load in the water from the mine drainage tunnel was computed and explained.

INTRODUCTION

Acid Mine Water Problem in Pennsylvania

The acid water entering the streams in Pennsylvania is being formed where water and oxygen come in contact with sulfurous material, chiefly iron pyrite, associated with coal deposits. The pyrite reacts with air and water to form sulfuric acid and ferric sulfate. Part of the iron is precipitated in various insoluble compounds, leaving behind a solution that contains the remaining iron and dilute sulfuric acid.

In Pennsylvania about 2,900 miles of streams are reported to be seriously affected by acid mine pollution. This acid water causes damage to bridges, dams, and other structures, and also causes an increase in the cost of treating the water for industrial and municipal use. Many more miles of stream are affected less seriously by the acid waters. Occasionally, a slug of acid water will travel far downstream from a mining area and cause an extensive fish-kill. These slugs of acid water last for only short periods of time before they are diluted and/(or) neutralized, and then the stream returns to normal, and fish and plant life is re-established.

Purpose of This Study

The Black Creek watershed was the target of a special study conducted in 1965-67 through a joint program of the Federal Water Pollution Control Administration, U.S. Bureau of Mines, U.S. Bureau of Sport Fisheries and Wildlife, U.S. Geological Survey, and the Pennsylvania Department of Mines and Mineral Industries. The purpose of the program was to evaluate, in a mining area, some effective and economic methods of preventing and controlling water pollution caused by acid-mine drainage.

In following the general plan for the joint investigations, the Geological Survey initiated geologic, hydrologic, and geochemical studies to describe the environmental framework of the area. After adequate documentation, the Federal Water Pollution Control Administration and the U.S. Bureau of Mines were to experiment with prevention and control techniques. However, internal administrative changes in the research program of the Federal Water Pollution Control Administration led to the termination of the Black Creek watershed study by the federal government before the scientific background investigations were completed. The Geological Survey then decided to preserve in this report the incomplete but significant data and interpretations it had gathered on the geology and hydrology of the area.

The study described in this report was designated Project No. 2 in the Joint Federal-State Acid Mine Drainage Pollution Control Demonstration Program. The following conditions favored this area as a site for evaluating abatement techniques for acid mine water: (1) Relatively small size, (2) lack of inhabitants, (3) lack of current mining activities, (4) easy accessibility, (5) lack of surface drainage, (6) a restricted hydrologic system, (7) modern topographic map coverage, and (8) availability of coal company maps and records of surface and underground mines.

Description of the Area

The Black Creek watershed is near the southwestern end of the Northern Anthracite field in Luzerne County, northeastern Pennsylvania. The area studied is bounded on the north and west by the Susquehanna River, on the south by Turtle Creek, and on the east by the barrier pillar between the West End mine and the Glen Lyon mine (fig. 1). The area is included on the U.S. Geological Survey's Shickshinny and Nanticoke $7\frac{1}{2}$-minute topographic quadrangle maps of Pennsylvania. Altitude ranges from 500 feet above sea level along the Susquehanna River at the western edge of the area to 1,275 feet above sea level on the ridge just south of the Susquehanna River along the northern edge; other ridges reach altitudes of 1,150 feet above sea level. Maximum relief is 775 feet; local relief is as much as 740 feet on the ridge south of the Susquehanna River but is less than 500 feet in other parts of the area.

Figure 1.--(Caption on next page) belongs near here.

Figure 1.--~~Map showing~~ area of the Black Creek watershed,/ ~~Pennsylvania~~.

The only inhabitants of the area live in the village of Mocanaqua (in the southwestern corner) and in the small settlement of Lee (in the southeastern corner). The area is accessible from U.S. Highway 11, which follows the west and north banks of the Susquehanna River; from Pennsylvania State Route 239, which follows the east bank of the river south of Mocanaqua; and from a local route that traverses the valley of Turtle Creek between Mocanaqua and Lee and then turns north and east through the town of Glen Lyon to Nanticoke.

The study area includes the West End Mine of the Blue Coal Company (formerly the Glen Alden Coal Company) where anthracite has been mined by both underground and strip methods. The coal company has delineated three coal-producing areas within the mine: the West basin, East basin, and Priscilla Lee basin (fig. 1). The East basin is also known as the Dupont basin.

Prior to strip mining, Black Creek flowed west to the Susquehanna River at Mocanaqua and drained the area, except for a small part of the East basin that was drained by an eastward-flowing tributary of Newport Creek. Strip mining has destroyed the original surface drainage system, and underground mining has disrupted the original ground-water flow patterns. As a result, all surface runoff is now diverted into underground mine workings through the numerous fractures in the bedrock and through strip pits that intersect the workings and cut the stream channels. Most drainage courses are clogged by mine dumps and overburden cast piles so that their water is diverted to stripped and fractured areas.

The underground mines have been abandoned and flooded for many years. Each basin contains a mine-water pool in the underground workings. Mine water did flow through an underground connecting tunnel ~~from~~ the East basin pool to the West basin pool. This tunnel was blocked by caving ground or mine timbers and water ~~no longer~~ is no longer able to flow from the East basin into the West basin. Mine water in the Priscilla Lee basin pool leaks through the barrier pillar into the Glen Lyon mine to the east; ~~and~~ also, mine water is discharged from the West basin pool to the Susquehanna River through a water-level drainage tunnel just north of Mocanaqua (fig. 1).

History of Coal Mining in the Black Creek Basin

The first reported coal mining along Black Creek was done in the winter of 1836-37. The coal was mined by several different people until 1865. In 1865 the property was leased for 99 years to the E.I. du Pont de Nemours & Company and operated for them until 1872 when a miners strike stopped operations. After the strike was settled, the mine, then called the "West End Property", was worked by several small companies for du Pont. The Delaware, Lackawanna, and Western Railroad operated the mine from 1901 until 1921. It was operated by the Glen Alden Corp. until 1938, when the underground mines were closed. Strip mining started before 1938 and continued infrequently until 1955, when all mining was stopped. The property is now owned by the Blue Coal Company. Approximately 22 million tons of coal, including both underground and strip mine tonnage, were mined from the area.

Methods of This Investigation

The U.S. Geological Survey work was administered as a special project by the Water Resources Division, which also conducted the hydrologic study. The Geologic Division conducted the geologic investigations as an extension of current mapping programs in the Northern Anthracite field.

Geologic field work was done from October to December 1965. The observations were plotted on aerial photographs at a scale of 1:24,000 and then transferred to base maps at a scale of 1:4,800. Subsurface structural data were compiled from company maps of the underground coal mines and modified from data obtained from wells drilled in the area.

Core and rock cuttings were collected and described as the wells were drilled between October 1966 and June 1967. The cored material and the churn-drill cuttings were collected so that chemical analysis could be made to determine zones of pyrite concentration. Two core holes were drilled in the barrier pillars, one in the East basin and the other in the Priscilla Lee basin. Twelve churn-drill holes were ~~drilled~~ placed to gain access to the mine pools and to determine the water levels between the different pools. ~~Some~~ electrical and gamma-ray logs were made in several holes. Water samples were collected at each void space or coal seam to determine the changes in the chemical character of the water with depth. FNO

Two precipitation gages were put in operation, one ~~at an elevation~~ near the mine drain and the other at the top of the hill over the barrier pillar. These precipitation gages were to help determine rate and amount of infiltration into the mine pools.

A standard gagehouse and stilling well were constructed in 1965 about 100 feet below the end of the mine drainage tunnel. The gagehouse was equipped with a continuous recorder having a 10 to 20 scale. A Trenton-type control with a sensitive "V" notch in the center was constructed to create a pool so that 0.001-foot change in stage could be read. All piping in this installation was plastic (PVC). The ends of the intake pipes were equipped with static tubes. Standard current-meter measurements were made at regular intervals. Special measurements were made when the discharge rate was high.

Acknowledgments

The authors wish to thank officials of the Blue Coal Company, and the West End Coal Pockets who permitted access to their properties during field investigations. Blue Coal Company also permitted use of their maps of underground mines and other data that greatly aided in interpreting the geologic structure, the stratigraphic sequence, and the correlation of coal beds. Personnel of the U.S. Bureau of Mines, Pittsburgh, Pa., supplied copies of aerial photographs and base maps, and administered contracts for the services of L. Robert Kimball Consulting Engineers and Pennsylvania Drilling Company. Norman Melvin was the field project representative of the Federal Water Pollution Control Administration. Information about the various mining activities was obtained from many local miners and we wish to thank all of them for their cooperation.

Much of the unpublished data on the regional geology was obtained by M. J. Bergin and co-workers during previous geologic investigations concerning flood-control problems in the Northern Anthracite field.

GEOLOGY

Regional Features

The Black Creek watershed includes only a few square miles in the southwestern part of the Northern Anthracite field (fig. 1, inset map), which occupies the core of a long, narrow, arcuate, synclinorium in northeastern Pennsylvania. The coal field is about 60 miles long and has a maximum width of 9 miles in the vicinity of Wilkes-Barre and Kingston. Anthracite beds are assigned to the Llewellyn Formation (Wood and others, 1962) of Pennsylvanian age that underlies the eroded lowland core of the synclinorium. Although the upper beds of the Llewellyn have been removed by erosion, as much as 2,200 feet of strata containing as many as 26 anthracite beds are preserved in the deepest part of the synclinorium. Rocks between the coal beds are those typical of the coal measures; namely, quartz-granule and pebble conglomerate, fine- to coarse-grained and conglomeratic sandstone, siltstone, claystone, shale, carbonaceous shale, and, locally, minor amounts of limestone. Coal beds range from 1 inch to 27 feet in thickness and are the most persistent units; strata between the coal beds are variably thick and are typified by extreme lateral changes in thickness and lithology.

The successively older formations, Pottsville (Pennsylvanian), Mauch Chunk (Mississippian and, in part, Pennsylvanian), Pocono (Mississippian), and Catskill (Mississippian and Devonian) underlie the high ridges and intervening valleys that rim the coal field (see Geologic Map of Pennsylvania, 1960). The Pottsville Formation ranges from 90 to 300 feet in thickness and is composed predominantly of white quartz-pebble conglomerate with lesser amounts of fine- to coarse-grained sandstone, siltstone, shale, and carbonaceous shale. The Pottsville forms a resistant, light-gray-weathering, continuous strike ridge surrounding the coal field. The Mauch Chunk Formation is absent at the northeast end of the coal field but is as much as 1,300 feet thick at the southwestern end. The Mauch Chunk consists of light-greenish-gray and dark-grayish-red to reddish-brown shale, siltstone, and fine- to medium-grained sandstone and light-gray to dark-grayish-brown, medium- to coarse-grained sandstone, conglomeratic sandstone, and pebble conglomerate. Commonly, the upper part of the formation underlies a ridge capped by the more resistant Pottsville Formation, whereas the lower part generally has been eroded into a strike valley developed on dip slopes of the underlying Pocono Formation. The Pocono is about 250 feet thick at the southwestern end of the coal field, about 400 feet thick south of Wilkes-Barre near the middle of the length of the coal field, and may be absent at the northeastern end of the coal field. Light-yellowish-gray and light-olive-gray sandstone, conglomeratic sandstone, and conglomerate comprise most of the Pocono Formation; however, some medium-gray to light-greenish-gray siltstone and shale are interbedded with the coarser grained rocks. The basal part of the formation is a white quartz-pebble conglomerate, ~~usually~~ generally less than 75 feet thick, which White (1881) included as the upper part of the Griswold Gap Conglomerate in this area. The rocks of the Pocono Formation are hard and erosional~~ly~~ resistant and generally crop out in dip slopes of the second strike ridge that encloses the coal field. The upper part of the Catskill Formation, about 1,800 feet thick, is exposed on the flanks of the Northern Anthracite field synclinorium; the formation is estimated to be about 6,000 feet thick in this part of Pennsylvania. The Catskill is composed of dark-grayish-red to reddish-brown shale, claystone, and siltstone; greenish-gray and dark-grayish-red, fine- to medium-grained sandstone; and yellowish- to

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greenish-gray, medium- to coarse-grained sandstone and conglomerate. Lesser amounts of grayish-brown calcareous conglomerate and greenish-gray conglomeratic mudstone are present locally. In general, coarse-grained, erosionally resistant rocks dominate the upper part of the formation and finer grained, less resistant rocks dominate the lower part. At most places, the upper part of the Catskill underlies the crest and steeper slopes of a ridge and the lower part is eroded into broad valley and lowlands. ?

Reconnaissance inspection indicates that the Northern Anthracite field synclinorium is a long, narrow, simple, structural depression whose limbs are characterized by gently curving strikes and moderate to steep homoclinal dips toward a central core. The strike of the axis of the synclinorium is arcuate ranging from N. 70° E. at the southwestern end through N. 50° E. in the central part to N. 10° E. at the northeastern end. Dips on the limbs of the synclinorium range from less than 20° [degrees] in the northern part to [as much as] vertical, and even slightly overturned, on the south limb near the southwestern end. Detailed mapping and mining has shown that the rocks of the anthracite-bearing Llewellyn Formation are complexly folded and faulted and characterized by unusual structural features. A single synclinoral axis cannot be traced in the Llewellyn Formation; instead, the formation contains a multitude of anticlines, synclines, and related faults, none of which are continuous throughout the length of the synclinorium, but which die out within a few miles as others develop to take their place. Faults are abundant; most are longitudinal, trending parallel to or diverging slightly from [diagonal to] the fold axes; cross faults are scarce and have ~~little~~ small displacements. FN The various types of faults include high-angle reverse, low-angle thrust, folded thrust, and rotational. Stratigraphic throw across these faults generally is less than 300 feet, although a reverse fault with 500 feet of throw and a folded thrust fault of undetermined transport have been mapped. Most fold axes and longitudinal faults in the Northern Anthracite field strike N. 70°-75° E., paralleling the trend of the synclinorium in the Black Creek watershed but cutting diagonally across the arcuate trend of the synclinorium to the northeast.

Northeastern Pennsylvania was glaciated during Pleistocene time. The pre-glacial course of the Susquehanna River valley in the Northern Anthracite field, which apparently was similar to the modern course, was overdeepened by erosive action of the glacier and associated streams. When the glacier receded, the deeply eroded valley was filled with an accumulation of clay, silt, sand, gravel, cobbles, and boulders. The glaciofluvial deposits associated with this ancient valley, known as the Buried Valley of the Susquehanna River, extend northeastward from the West basin in the Black Creek watershed to the Luzerne-Lackawanna County line near Pittston, Pennsylvania. Coal-mining companies, because of the danger of mine disasters, were forced to accurately locate the buried bedrock surface and the intersections between anthracite beds and the unconsolidated valley-fill deposits. A comprehensive study on the Buried Valley of the Susquehanna River has been published by the U.S. Bureau of Mines (Ash, 1950). At its most deeply eroded point near Plymouth, Pennsylvania, the bedrock floor of the ancient valley is about 320 feet below the present land surface. From this point the bedrock floor of the valley rises along its length both to the southwest and northeast. However, the bottom of the ancient valley is not a smooth surface with an even gradient, but rather an irregular surface composed of depressions, mounds, and ridges that have various shapes and sizes. In the Black Creek watershed, remnants of the buried valley deposits are preserved in each of the three basins. At many places the buried valley deposits, other related glaciofluvial surficial deposits, and waste piles from underground and strip mines effectively cover bedrock in the Northern Anthracite field, thereby making mapping difficult and interpretation questionable. Bedrock is relatively well exposed on resistant ridges, where the glaciofluvial deposits have been largely removed by erosion, and in artificial cuts for roads and strip mines.

GEOLOGY OF the PROJECT AREA ← Caps and lower case

The geology in a nearly rectangular area of approximately 5 square miles was studied for this report (fig. 1). Bedrock consists of, from oldest to youngest, the Mauch Chunk Formation, the Pottsville Formation, and the Llewellyn Formation; all economically important anthracite beds are in the Llewellyn Formation. A generalized stratigraphic section for the rocks in the Black Creek watershed is shown in Figure 2. Areal distribution of the bedrock and structural features is shown on the geologic map (figs. 3A & 3B); subsurface distribution is shown by geologic cross sections (figs. 4A, 4B, & 4C). Surficial material in the area has been categorized as glaciofluvial deposits undifferentiated, mine waste, strip-mine waste, and artificial fill; their distribution, along with the location of strip-mine pits and areas of bedrock, is shown on the surficial geologic map (figs. 5A & 5B).

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Stratigraphy

Mauch Chunk Formation.--As much as 800 feet of the upper part of the Mauch Chunk Formation is fairly well exposed in a steep, north-facing bluff south of the Susquehanna River (figs. 3A & 3B). In the valley of Turtle Creek, where dips are almost vertical, as much as 1,400 feet of the formation is present; however, this is ~~a~~ greater than normal thickness

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because of duplication by near-bedding-plane thrust faults (figs. 3A, 3B, 4A, 4B, & 4C). About 1,200 feet seems to be a reasonable estimate for the original thickness of the Mauch Chunk Formation in the Black Creek watershed. The Mauch Chunk consists of light-greenish-gray and dark-grayish-red to reddish-brown shale, siltstone, and very fine- to medium-grained sandstone and light-gray to dark-grayish-brown, medium- to coarse-grained sandstone, conglomeratic sandstone, and small-pebble conglomerate. Dark-grayish-red and reddish-brown rocks predominate over lighter colored rocks.

How the faults

Pottsville Formation.--The Pottsville Formation ranges from 90 to 130 feet in thickness; the rocks are correlated with the Sharp Mountain Member (Wood and others, 1956). The strata are fairly well exposed between the coal basins, and are very well exposed on the high ridge north of the East basin and on the ridge along the south edge of the Priscilla Lee basin (figs. 3A & 3B). The Pottsville Formation in this area consists predominantly of conglomerate and coarse-grained sandstone and a few beds of fine-grained sandstone, siltstone, and shale (fig. 2). The conglomerate is made up of rounded to subrounded, white quartz pebbles that range from $\frac{1}{4}$ inch to 2 inches in diameter and are siliceously cemented in a groundmass of fine- to coarse-grained, subrounded quartz sand. Weathered exposures of conglomerate are characteristically light gray to almost white, but in fresh exposure the conglomerate has a dark-gray, somewhat carbonaceous groundmass. The conglomerate is very dense, hard, and quartzitic, and forms resistant ledges. The coarse-grained sandstone is composed predominantly of silica-cemented, subrounded quartz grains and ranges from sparsely to very conglomeratic. Fresh exposures show a medium-dark-gray carbonaceous texture, whereas weathered exposures are medium light gray to light yellowish gray. The coarse sandstone is tightly cemented, dense, and hard and forms resistant ledges

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similar to the conglomerate. Units composed of interbedded fine-grained, shaly sandstone, siltstone, and shale are generally less than ~~five~~ 5 feet thick. Where fresh, they are dark-gray and carbonaceous; however, they weather medium-dark-gray and mainly underlie covered slopes between resistant ledges of conglomerate and coarse sandstone. These softer units are less tightly cemented and apparently are porous and permeable, as evidenced by wet weather springs located along their outcrops.

The lowermost 15 to 25 feet of the Pottsville Formation is conglomerate locally containing several thin sandstone beds. This conglomerate unit generally weathers into a continuous resistant ledge whose contact with the underlying Mauch Chunk Formation is definite and sharp. Rocks in the Pottsville overlying this lowest conglomerate unit are interbedded conglomerate, coarse sandstone, and softer, finer grained sandstone, shale, and siltstone. About five feet of interbedded dark-gray, fine-grained sandstone, siltstone, and shale is fairly persistent about 40 to 50 feet below the top of the Pottsville Formation. The top of the Pottsville is at the base of the carbonaceous shale and siltstone below the lowest anthracite bed in the Llewellyn Formation.

Llewellyn Formation.--As much as 450 feet of the lower part of the Llewellyn Formation is preserved as erosional remnants in the three basins of the watershed. The Llewellyn is made up of interbedded, variably thick, and laterally changing beds of quartz-granule and pebble conglomerate, fine- to coarse-grained and finely conglomeratic sandstone, siltstone, claystone, shale, carbonaceous shale, and anthracite (fig. 2). The coal beds are the most persistent units and their positions are known from underground and strip-mine data; therefore, they are used as mappable key beds within the formation. However, exposures of coal beds are rare because abandoned underground mine entries are caved and the deeper parts of strip pits are covered either by back-fill or slumped highwall. The five anthracite beds that have been mined in the Black Creek watershed are, in ascending order: the Lower Red Ash, the Upper Red Ash, the Lower Ross, the Upper Ross, and the Baltimore (figs. 2, 3A, 3B, 4A, 4B, & 4C). For the purposes of this report the Llewellyn Formation in this area has been informally subdivided using the coal beds as stratigraphic boundaries (see fig. 3A, explanation).

The Lower Red Ash coal bed attains a maximum thickness of 14 feet in the West End mine. The bed commonly contains several shale and impure coal partings that may total as much as ~~two~~ 2 feet in thickness. This persistent bed was mined extensively throughout the mine. The Lower Red Ash coal bed commonly rests on a few feet of dark-gray, carbonaceous, silty shale and siltstone that directly overlies sandstone or conglomerate of the Pottsville Formation.

The stratigraphic thickness from the Lower Red Ash coal bed to the Upper Red Ash coal bed ranges from 70 to 90 feet. This stratigraphic interval is composed predominantly of coarse-grained sandstone and conglomerate; black shale and dark-gray siltstone are present in the upper and lower parts (fig. 2). As much as 12 feet of thin alternating beds of black, carbonaceous shale, dark-gray, thin-bedded, carbonaceous siltstone, and dark-gray, fine-grained sandstone overlie the Lower Red Ash coal bed. This unit is overlain by a bed of coarse-grained sandstone and conglomerate that grades upward into a 5- to 20-foot unit consisting in ascending order of fine-grained sandstone, dark-gray siltstone, and balck carbonaceous shale. This latter unit is overlain by the Upper Red Ash coal bed.

The Upper Red Ash coal bed is of variable thickness and composition. It ranges from less than 1 ~~one~~ to as much as 12 feet in thickness and contains carbonaceous shale and bone coal partings that may total as much as 4 feet thick. ross The total thickness of partings is not necessarily proportional to the total thickness of the bed; that is, at places where the bed is thick it actually contains little coal. The Upper Red Ash bed has been mined in each basin where of sufficient thickness; mine maps indicate that the bed was too thin to mine in most of the western part of the Priscilla Lee basin. In local areas, especially in the East basin, two thin coal beds separated by about 15 feet of strata are present in this stratigraphic position. In these areas the lower bed is known as the Upper Red Ash coal and the upper is known as the Top Split of the Upper Red Ash coal.

Strata between the Upper Red Ash coal and the next overlying coal bed, the Lower Ross, range in thickness from 65 to 90 feet; sandstone generally predominates in the lower half of the stratigraphic interval and black shale and dark-gray siltstone in the upper half (fig. 2). The Upper Red Ash bed (or, where present, the Top Split of the Upper Red Ash bed) is commonly overlain by black, laminated, carbonaceous shale ranging from 1 to 10 feet in thickness. This shale is overlain by medium-gray coarse-grained to pebbly, thick-bedded to massive sandstone that ranges from 20 to 35 feet in thickness. The sandstone is overlain by black, thinly laminated shale that grades successively upward into silty shale, dark-gray laminated siltstone, and dark-gray silty shale and carbonaceous shale. This upper unit of shale, silty shale, and siltstone ranges from 30 to 45 feet in thickness and is overlain by the Lower Ross coal bed.

The Lower Ross coal bed ranges from 3½ to 16 feet in thickness in the West Ed mine; coal comprises from 2 to 11 feet of these respective measurements and carbonaceous shale and impure coal partings 1½ to 5 feet. A proportional relationship between thicknesses of coal and partings seems to exist in the Lower Ross bed; that is, the thicker the bed, the more numerous and thicker the partings. The Lower Ross coal bed is persistent and has been mined extensively throughout the East, West, and Priscilla Lee basins.

The Lower Ross and Baltimore coal beds are separated by 100-150 feet of strata consisting of conglomerate, sandstone, siltstone, shale, and coal. In general, thinly laminated black shale and dark-gray siltstone and coal predominate in the lower half of this stratigraphic interval; sandstone predominates in the upper half (fig. 2). A unit of thinly interlaminated black, carbonaceous shale and dark-gray siltstone ranging from 10 to 25 feet in thickness rests on the Lower Ross coal bed. This unit is overlain by a coal bed that has been mined as the Upper Ross in the East and Priscilla Lee basins. The coal bed is mined with the Lower Ross bed where the shale and siltstone unit is thin or by itself where the intervening unit is thick. In the adjacent Glen Lyon mine the two beds are mined as the Twin coal bed. The Upper Ross coal bed of the East and Priscilla Lee basins is commonly thin, rarely exceeding ~~four~~ 4 feet thick; data indicate that this coal bed was too thin to be mined in the West basin. A unit of thinly interlaminated black carbonaceous shale and dark-gray siltstone separates the Upper Ross coal bed of the East and Priscilla Lee basins from the next stratigraphically higher coal bed, some 20-30 feet above, ~~that~~ which has been mined as the Upper Ross in the West basin (fig. 2). Thicknesses are not recorded for this higher bed on maps of the West End mine, but the coal is sufficiently thick to have been mined extensively throughout the West basin. A thinly laminated, black carbonaceous shale unit ranging from 1 to 10 feet in thickness overlies the Upper Ross coal bed of the West basin and is overlain by a medium-gray, coarse-grained, pebbly to conglomeratic, thick-bedded to massive sandstone unit that ranges from 60 to 80 feet in thickness. Locally, this sandstone unit contains several beds of siltstone and shale that cause the unit to weather to a series of ledges, but in most of the area this sandstone unit weathers into a single resistant cliff. The sandstone unit is overlain by a 15-20 f~~oo~~eet thick unit composed of dark-gray siltstone, silty shale, and black shale ~~that~~ which is, in turn, overlain by the Baltimore coal bed.

The Baltimore coal bed occupies small areas in the East, West, and Priscilla Lee basins (figs. 3A & 3B). Where mined the coal bed ranges from 4 to 13 feet in thickness and generally contains numerous partings of shale and impure coal; at some localities as much as half the bed is refuse material.

The Baltimore bed is overlain by as much as 100 feet of rocks of the Llewellyn Formation. These rocks are predominantly coarse-grained sandstone (fig. 2). A bed of coal, less than ~~one~~ 1 foot thick, occurs about 10-15 feet above the Baltimore bed at most localities. Strata between the two coal beds are dark-gray siltstone with interlaminated black shale and thin beds of medium-dark-gray, fine-grained sandstone. Light-yellowish-gray, coarse-grained to pebbly, thick-bedded to massive sandstone as much as 90 feet thick overlies the upper coal bed and constitutes the stratigraphically youngest rock of the Llewellyn Formation in the area. Several lenses of siltstone and silty shale as much as 8 feet thick are variably distributed through the sandstone.

Structure

The Black Creek watershed is near the southwestern end of the Northern Anthracite field synclinorium. Strata in the area have been complexly folded and faulted. The principal structural elements are three downwarped coal-bearing areas, known as West basin, East basin, and Priscilla Lee basin, and several unnamed intervening anticlines (figs. 3A, 3B, 4A, 4B, & 4C). These structural elements have been greatly modified by numerous subsidiary anticlines and synclines and by faults. Two episodes of faulting affected the area; one occuring prior tointense folding and the other occuring in response to, and as an extension of, compressional forces that developed the folds.

West basin.--Of the three coal basins in the watershed, the West most nearly represents a structural basin. It is a slightly elongate syncline; the area underlain by coal-bearing strata is about 1.3 miles long and, on the average, about 0.4 mile wide (fig. 3A). The syncline is relatively shallow and dish-shaped in cross section (fig. 4A). Generally, the lowest coal bed, the Lower Red Ash, crops out between altitudes 700 and 800 feet above sea level on the limbs of the syncline, but locally on the south limb it rises in a flat-iron erosional remnant to an altitude of 1,000 feet above sea level (figs. 3A & 4A, sec. B-B'). In the subsurface the Lower Red Ash bed folds across the axis of the syncline at altitude 200 feet above sea level; maximum relief on this coal bed in the West basin is, therefore, about 800 feet and local relief is about 600 feet (fig. 4A). As can be seen on the cross sections, the simple synclinal structure has been modified by numerous subsidiary folds and a complex of high- and low-angle faults (fig. 4A). A sharp anticlinal fold, from which the coal-bearing strata have been eroded, separates the West basin from the Priscilla Lee basin to the south. A similar anticline in the plate of a thrust separates the West and East basins at the surface (figs. 3A & 4A, sect. E-E').

East basin.--The area underlain by coal in the East basin part of the West End mine is about 1.5 miles long from southwest to northeast and ranges from ½ mile wide at the western end of the basin to 1 mile wide at the barrier pillar between the West End and Glen Lyon mines. The East basin is in reality a thrust-faulted northeast-striking homocline in which the coal-bearing strata generally dip 15°-25° southeast from the outcrop to a fold axis where they are overturned to the north and cut-off (figs. 3A, 3B, 4A, 4B, & 4C). The homocline probably was termed a basin by mining personnel because the southeast-dipping coal beds were dragged northward and overturned by a thrust fault. The East basin homocline is modified by several flexures and faults, most of which have been sharply defined by the underground mine-map control. The Lower Red Ash coal bed crops out at an altitude of 1,160 feet above sea level on the north edge of the homocline and is at an altitude of 30 feet above sea level in the subsurface at the barrier pillar; therefore, relief on the Lower Red Ash bed is about 1,130 feet in the East basin homocline (figs. 4B & 4C). The East basin homocline is separated from the Priscilla Lee and West basins by anticlinal folds in the upper plate of a thrust. Strata in the upper plate near the fault plane are cut by numerous faults and contorted in associated drag folds (figs. 4B & 4C). The Lower Red Ash coal bed and its overlying shales and sandstone are preserved in erosional remnants on an anticline in the eastern part of the area (figs. 3B, 4B, & 4C).

Priscilla Lee basin.--The Priscilla Lee basin is a narrow, eastward-plunging syncline whose limbs dip steeply into a deep, tightly folded trough (figs. 3A, 3B, 4A, 4B, & 4C). Locally, the south limb is overturned. The syncline is modified complexly by faulting. A transcurrent structural high in the vicinity of cross section E-E' (figs. 3A & 4A) separates the trough into two subtroughs. Within the West End mine coal-bearing strata in the Priscilla Lee basin occupy an area about 2.5 miles long and as much as $\frac{1}{4}$ mile wide. The area underlain by coal in the syncline extends eastward into the Glen Lyon mine. The western two-thirds of the Priscilla Lee basin in the West End mine underlies a high topographic ridge; whereas, in the eastern third, only the south limb underlies the ridge and the axial area and the north limb have been eroded into a valley. The Lower Red Ash coal bed crops out at altitudes between 840 and 1,140 feet above sea level on the limbs of the syncline; in the subsurface and at the axis the Lower Red Ash bed crosses the trough line at altitudes between 360 and 880 feet above sea level. Maximum relief on this coal bed in the Priscilla Lee basin of the West End mine is 780 feet; local relief ranges from 180 to 640 feet.

Faults.--Rocks in the Black Creek watershed are highly fractured and are characterized by an abundance of faults. The faults are longitudinal, most being either thrust or reverse faults. The faults that cut the coal beds in the Llewellyn Formation are well documented on maps of the underground mines. The more prominent and easily recognized faults are those which displaced the coal beds as a result of compression during and after folding; for example, the thrust along the southern edge of the East basin and the many high-angle reverse faults throughout the area (figs. 4A, 4B, & 4C). Less easily recognized are those faults that cut the bedding at very low angles and are folded as complexly as the transected strata. These folded thrust faults are apparent on cross sections where underground mine data and surface mapping data have been carefully plotted. Northwestward movement on these thrust faults occurred prior to folding of the strata and must have been related to glide thrusting or gravity sliding along a zone of detachment or a décollement. Regional variations in thickness and local conflicting rock attitudes suggest that the Mauch Chunk Formation was the site of a detachment zone or décollement.

zone or décollement.

The folds and faults in the Black Creek watershed were formed in a compressional environment subsequent to the consolidation of rocks of Pennsylvanian age. A structural history is as follows: 1) regional warping of horizontal strata into broad, low-amplitude anticlines and synclines, 2) near-bedding-plane glide thrusting along décollement and associated imbricate low-angle thrust faulting, 3) intense folding and associated faulting in which décollement and imbricate low-angle thrust faults were deformed along with enclosing rocks to form subsidiary folds of the synclinorium, and 4) thrust and high-angle reverse faulting to release pressures of the continuing compressional forces. Such a history would include the first three of five progressive stages of the Late Paleozoic orogeny in eastern Pennsylvania described by Arndt and Wood (1960).

Surficial geology

Surficial geology in the Black Creek watershed is shown on figures 5A and 5B as 1) bedrock, 2) glaciofluvial deposits undifferentiated, 3) mine waste, 4) mine waste removed, 5) strip mine waste, 6) artificial fill, or 7) pit. Bedrock is at the surface over most of the area; however, in some areas shown as bedrock there are localities covered by glaciofluvial deposits, mine waste, or strip mine waste that are too small to show at the scale of the maps. Bedrock is also exposed in most of the pits shown on figures 5A and 5B, but for the purpose of this report, showing existence of a pit rather than a bedrock exposure seemed more appropriate.

Most of the glaciofluvial deposits are preserved in depressions or valleys that were probably eroded by the combined actions of plucking by ice and abrasion by debris-loaded streams. These deposits consist predominantly of fine- to very coarse grained sand with lesser amounts of intermixed clay, silt, gravel, and cobbles; small boulders are present locally. Most glaciofluvial deposits are unstratified and unconsolidated. In test well 4 in the West basin, 78 feet of glaciofluvial material was drilled below a surficial veneer of mine waste (figs. 4A & 5A). The anciently eroded valley in this basin appears to coincide with the modern channel of Black Creek. Glaciofluvial deposits as much as 25 feet thick are exposed in strip pits in the Priscilla Lee basin in the vicinity of the barrier pillar at the eastern edge of the area. As in the West basin, the anciently eroded depression in Priscilla Lee basin appears to be followed by the channel of Black Creek. In test well 12 (fig. 5B) at the barrier pillar in the East basin, 48.5 feet of glaciofluvial material was Penetrated drilled; in well 10 (fig. 5B) in the western part of the East basin 20 feet was Penetrated drilled. According to mine-map data, as much as 120 feet of glaciofluvial material is present in the East basin where locally the ancient channel was eroded through the Lower Ross coal bed (see section K-K', fig. 4C). The glaciofluvial deposits preserved in the East basin probably were continuous with those described by Ash (1960) in the Buried Valley of the Susquehanna River; however, his report does not include this area as a part of that buried valley. Areas of exposed bedrock intervene between the glaciofluvial deposits in the East basin and those in the Priscilla Lee and West basins. All may have been continuous prior to modern erosion. Some investigators might interpret the unconsolidated sediments shown as glaciofluvial deposits along the Susquehanna River and Turtle Creek as alluvium and terrace deposits, but these sediments are similar lithologically to known glaciofluvial deposits and show little evidence of reworking except on the flood plain of the river. Drill hole records suggest that these are glaciofluvial sediments that are being eroded to expose underlying glacially carved valleys. In test wells 1 and 2 (fig. 5A) near Mocanaqua, 12 and 30 feet, respectively, of glaciofluvial deposits were drilled and in test well 9 (fig. 5A) along Turtle Creek 16 feet were drilled.

Mine waste includes piles of rock refuse derived from underground mines; dump piles of rocks, culm, and cinders at coal cleaning and preparation plants; and clay, silt, and sand in settling basins. Mine-waste material is predominantly black shale, siltstone, and impure coal that was mined with the coal; lesser amounts of sandstone and the finer sizes of coal are intermixed. Mine waste is concentrated near the Lee shaft in the Priscilla Lee basin (fig. 5B) and in the central and western parts of the West basin (fig. 5A) because these were sites of coal cleaning and preparation plants. Just west of Lee shaft (fig. 5B) ridges of mine waste are as thick as 70 feet; the finger-shaped ridges in the central part of the West basin (fig. 5A) are mine waste as much as 120 feet thick. At the western end of the West basin (fig. 5A) mine waste was dumped over the cliff of the Pottsville Formation; the 100-foot high conical hill where Black Creek crosses the cliff is composed of mine waste.

An area at the western end of the West basin (fig. 5A) is shown as mine waste removed. Local residents report that during World War II mine waste that covered this area was rerun through the coal processing plant to recover the fine-sized coal. The surface where the mine waste was removed is partially covered by a thin veneer of mine waste and a yellowish-orange-brown precipitate from sulfur and iron-enriched water that had leached the overlying mine waste.

Strip-mine waste includes piles of overburden excavated from pits where coal was extracted. The piles are composed of a mixture of the bedrock and unconsolidated sediments encountered in the removal of overburden, such as: conglomerate, sandstone, siltstone, and shale from the Llewellyn Formation; clay, sand, gravel, cobbles, and boulders from the glaciofluvial deposits; and, locally, mine waste.

Railroad beds in the area have been mapped as artificial fill. The tracks of the Pennsylvania Railroad parallel the Susquehanna River along its south and east bank. This fill consists of locally derived material from rock cuts along the route of the tracks supplemented by mine waste and capped by crushed limestone gravel for ballast between ties. The artificial fill along the abandoned railroad tracks in the southeast corner of the area consists of mine waste capped by ballast of cinders. To the west this railroad grade has been largely destroyed by strip pits and by dumps of mine waste and strip-mine waste.

Most pits shown on the surficial geologic maps (figs. 5A & 5B) are abandoned strip mines; a few are former entries to underground coal mines or are areas of subsidence where overlying strata collapsed into underground workings. Along the south limb of the Priscilla Lee basin many pits appear to be localities where the surface collapsed into underground workings of nearly vertical coal beds. Some of these pits are as much as 100 feet deep.

Throughout the area the walls of pits dug into bedrock are generally deep and steep sided, especially where dips are steep; in contrast, pits dug in glaciofluvial deposits or mine waste commonly are shallow and partly filled by unconsolidated material that has slumped into the pits to form gentle slopes. Many pits intersect underground mine workings and where the dips of coal beds are steep appear to be bottomless. The pits at former entries to underground workings developed by caving of overlying bedrock or glaciofluvial deposits after roof supports were removed during salvage operations.

TEST DRILLING

Fourteen test holes were drilled in the study area to provide geologic and hydrologic information and for the collection of water samples for chemical analysis. Two of the holes were cored in the barrier pillar by a diamond drill to obtain samples for study of the complete stratigraphic section. The other 12 holes were drilled by churn drill, and drill cuttings were taken each time the holes were bailed. Test holes drilled into the coal mines were cased with a plastic casing, which was perforated at mine workings so that water samples could be collected.

Water samples were collected from all churn-drill holes at the point where water was first encountered at each of the flooded mine tunnels and at the bottom of the holes. Prior to sampling, pumps were installed in the holes and each hole was pumped until successive water samples had the same conductance. The chemical quality of the borehole water was checked frequently to determine if acid water was entering the well. After the test hole reached the water table, the conductance of a water sample taken with a bailer from the bottom of the hole was measured every morning. Additional water samples were collected from all the test holes after they were completed by using a thief-type sampler, which was lowered to the depth of the desired sampling point. The sampler was closed by dropping a messenger, and was then raised to the surface and emptied into plastic sample bottles.

Recorders were placed on seven churn-drill holes and on the Lee mine shaft to collect data on water-level fluctuations.

Lithologic Logs

The drill cuttings were dried and examined megascopically. Lithologic logs of the drill cuttings were prepared and are listed in table 1. The rock-color terms used in these logs are from the Rock-Color Chart (Goddard and others, 1948). Because of early termination of the project, plans to determine zones of high pyrite content (chemical analysis of drill cuttings and thin sections of core samples) were not carried out.

Fluid Resistivity and Gamma Ray Logs

A fluid-resistivity log was run on the Lee shaft and formation-resistivity logs were made on two of the uncased test holes. Copies of these logs are presented in figures 6,7, and 8. In addition, gamma-ray logs were run on seven test holes and are shown in figures 9 through 15.

Figures 6 through 15.--(Captions on next page) belong near here.

Temperature Logs

A temperature log of the Lee mine shaft was made to try to determine which coal seam had the most rapid circulation of water. Results of this one temperature log were not conclusive so the log is omitted from this report. In future studies, temperature logs could be made after each period of recharge to determine the ground-water circulation pattern.

Figure 6.--Fluid resistivity log of test hole 1-BC

Figure 7.--Fluid resistivity log of test hole 2-BC.

Figure 8.--Fluid resistivity log of Lee mine shaft.

Figure 9.--Gamma-ray log of test hole 1-BC.

Figure 10.--Gamma-ray log of test hole 2-BC.

Figure 11.--Gamma-ray log of test hole 4-BC.

Figure 12.--Gamma-ray log of test hole 8-BC.

Figure 13.--Gamma-ray log of test hole 10-BC.

Figure 14.--Gamma-ray log of test hole 17-BC.

Figure 15.--Gamma-ray log of test hole 19-BC.

HYDROLOGY

Climate

The climate of the Black Creek basin is mild. Temperatures above 100° F are infrequent. Temperatures below freezing are common. Killing frosts occur from October to May. At the U.S. Weather Bureau station at Wilkes-Barre, the extreme maximum and minimum daily temperature for the 21 years of record from 1945 to 1966 was 101° F and -15° F, respectively.

FWO

Two recording precipitation gages were installed in the basin; one gage, was ~~located~~ at Mocanaqua, at an altitude of 525 feet, and the other at Lee, at an altitude of 980 feet. Precipitation was below average in 1966 and about average in 1967. The precipitation at two recording gages located in the area for the ~~two~~ [illegible] years of the study is listed in tables 2, 3, 4, and 5.

930

No measurements of evaporation were made ~~on~~ in the project area, but data provided by the U.S. Weather Bureau indicates a rate of about 30 inches per year at an altitude of 500 feet. The evaporation rate decreases approximately 1 inch per year for each 200 feet increase in altitude.

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Drainage

Two perennial streams form the boundaries of the project area. The Susquehanna River forms the northern and western boundaries and Turtle Creek the southern boundary. A third stream, Black Creek, is ephemeral and crosses the central part of the project area from east to west. The northern edge of the area drains directly into the Susquehanna River. Most of the water comes from a drainage tunnel 800 feet north of the bridge across the Susquehanna River on Route 239. Black Creek, which formerly drained the central part of the project area, now loses water into the underground mines through fractures in the bedrock. The channel of Black Creek is interrupted by strip mines and piles of waste rock, and water in the creek is diverted by the piles of waste rock into strip pits. At some places the floors of the strip pits are broken and fractured, and water in the strippings travels directly into the underground mines. There is some surface drainage down the old stream channel into Stump Lake. The discharge from Stump Lake travels only 500 to 600 feet on the surface to a highly fractured zone and disappears into the ground. Some water is probably lost from Stump Lake through fractures in the bedrock under the lake. These fractures are partially plugged by vegetation, iron oxide, and silt. Runoff to the south is directly into Turtle Creek, but is very small because strip pits intercept much of this water. The water enters the flooded part of the Priscilla Lee mine and then drains either toward Black Creek, or, more likely, through the barrier pillar into the Glen Lyon mine. The large flooded strip pit (at station PL-1P on figure 16) east of the Priscilla Lee shaft is reported to have a direct connection with the mined-out coal beds in the Priscilla Lee basin.

Permeability

Primary permeability in the undisturbed rocks is quite low. The rocks are well cemented; so, movement of water through the rocks is restricted to secondary openings, such as fractures, bedding planes, and fault zones. The Mauch Chunk and Pottsville Formations are largely undisturbed and yield water chiefly from secondary openings. The Llewellyn Formation in the project area is highly fractured owing to the use of explosives and the caving connected with mining operations. As described earlier, much of the surface runoff is diverted to the underground mines through fractures. There are four large fractures that reach the surface in the East basin. These fractures are more than 200 feet long and 1 to 1½ feet wide. The depth of the fractures could not be determined, because trees, rocks, and leaves have bridged them at a depth of about 50 feet, but they are believed to reach the underground mine workings in the basin.

The glaciofluvial materials are highly permeable. Water enters the underground mines readily where these materials are in contact with coal beds or fractured bedrock along the walls of buried valleys.

The large piles of mine waste rock from both the underground mines and from stripping operations allow rapid downward movement of infiltrate and may contribute acid to this water.

Circulation Pattern

Artesian Water

Two of the test holes, numbers 7 and 9 (fig. 16), flowed at the surface. Test hole 7, on the north side of the area, about 100 feet below the top of the ridge, was drilled to a depth of 235 feet. The hole was started in the Pottsville Formation and entered the Mauch Chunk Formation at 154 feet. The first water was encountered in this hole at about 55 feet below land surface. This water was perched on top of a thin shale bed, and the yield was less than 1 gpm (gallon per minute). At a depth of about 160 feet the hole started to yield about 2 gpm. This last increase in the volume of water was coming from the top of the Mauch Chunk Formation. Twelve hours after drilling was completed water was flowing at the surface. Several days after the well was completed the flow was measured at 2 gpm.

Figure 16.--(Caption on next page) belongs near here.

The south face of this ridge is a dip slope of the Pottsville Formation, and the surface is fractured. The precipitation falling on this dip slope enters these fractures, moves downward to either the shale bed or to the top of the Mauch Chunk Formation, then follows the dipping beds under the coal basins. Twice during the summer the water level declined below the top of the pipe.

Figure 16.--Map of the Black Creek watershed showing the parts of the underground mines that are flooded, location of test holes, and sampling points.

Test hole number 9, drilled along the southern boundary of the project area to a depth of 80 feet, started to flow while being drilled and has flowed continuously since the hole was completed. The head could not be measured because of leakage around the surface casing. The water enters the hole from the unconsolidated sand and gravel deposits and the highly fractured upper few feet of the Mauch Chunk Formation. The most likely source of the water is Turtle Creek because the chemical quality of the waters are similar.

The site labeled PL-OP on the map is discharge of an artesian well that was drilled many years ago on the south side of Turtle Creek. A pipe was laid from this well to the vicinity of Priscilla Lee shaft. Data on the depth of this well are scanty because no log was kept. Reports from local people give different depths, ranging from 700 to 2,200 feet. This well is now discharging into Turtle Creek.

Stagnant Water

The water at the bottom of the mine workings is believed to be stagnant for a number of reasons. The circulation is probably limited to places where fractures in the underlying formations allow water under artesian pressure to enter the mine workings. The barrier pillars are thickest at the lower levels in the mines, which reduces circulation from one mine to another. The deeper waters have higher concentrations of dissolved mineral matter, indicating that these waters have had much longer contact time with the rocks.

Gradients and Divides

The hydraulic gradients are steep in the undisturbed areas, because the geologic formations are poorly permeable and a high hydraulic head is necessary to force the water through the few small fractures in these rocks. In the areas where coal was mined the hydraulic gradients are flat. The circulation pattern for each mine pool is discussed below.

The West basin pool is recharged by the infiltration of precipitation and runoff in the drainage area of the pool. Some runoff is diverted to the pool by spoil piles along the eastern side of the basin. The pool drains through a tunnel at the western end to a surface channel and then to the Susquehanna River. Some recharge enters the West basin from the area east of Stump Lake. Part of the drainage into Stump Lake could come from the west pool of the Priscilla Lee basin because it is at a higher elevation. However, there is no surface evidence of such drainage.

As described earlier, the tunnel between the East and West basins must be blocked because water stands about 80 feet higher in the East basin pool than in the West basin pool. The test holes drilled in the East basin pool demonstrate that the water table maintains the same elevation across the pool. In 1967, the pool elevation in the Glen Lyon mine (the adjoining mine east of the barrier pillar) was approximately the same as the pool elevation in the East basin. Water undoubtedly moves from the East basin through openings or fractures in the barrier pillar into the Glen Lyon mine.

Circulation of water in the East basin is from the recharge areas over the underground workings into the mines and through the barrier pillar to the east. The northern limits of the recharge areas extend to the top of the mountain along the Susquehanna River. The southern limit of the recharge area for the East basin is difficult to define but is near the southern limit of the strip pits that surround this basin.

The circulation of water in the Priscilla Lee basin is from the recharge area into the mines. The limit of the recharge area is the outer limit of the strip mining in this basin. The information now available indicates that the water in the western pool in the Priscilla Lee basin is controlled by the low saddle in the coal beds just east of test hole 20. The pool drains through the mine workings and flows over this saddle into the eastern pool. The eastern pool in this basin is controlled by the barrier pillar at the Glen Lyon mine property. Two tunnels may affect the water levels in the eastern pool. One tunnel is blocked by caving ground and only a small volume of acid water is discharged. This discharge is at point PL-1S on figure 16. The second tunnel is at an elevation of 868 feet, and this is higher than the water level in the western pool of the Priscilla Lee basin. This second tunnel should have little effect on the present water levels.

Ground-Water Storage

The amount of water in storage fluctuates continually in response to changes in recharge and discharge. A declining water table indicates that water is being discharged faster than it is being replenished (a net loss of ground water in storage). A rising water table indicates that water is being replenished faster than it is being discharged (a net gain in storage). Ground-water levels in undisturbed rocks exhibit a seasonal pattern. Levels rise in the spring, in response to recharge from snowmelt and rainfall, and then decline for the rest of the year. Some potential recharge is captured by growing vegetation in summer, some is temporarily stored as snow and ice in winter. Water levels are usually lowest in late winter or early spring, just before the spring thaw.

The amount of water stored in the bedrock is thought to be very small compared to that stored in areas where coal was mined. Only small amounts of water were encountered in some of the test holes drilled outside the area of the coal seams as compared to that in the areas where the coal was mined. Test hole 8 produced less than 1 gpm from a depth of 55 feet. When this hole was completed at a depth of 185 feet it produced less than 3 gpm.

The volume of ground water stored in the mines and fractured rocks associated with them was estimated by measuring the flooded area and assuming 45 percent of the void space to be flooded. The water is stored in four separate bodies, as shown in figure 16. Each is discussed below.

The flooded part of the West basin is controlled by the drainage tunnel to the Susquehanna River. The west end of this tunnel is partly blocked and the pool elevation is 525 feet, as indicated by the water level in test hole number 4 and the elevation of the overflow. The West basin is estimated to contain about 32 million cubic feet of water.

The East coal basin is connected to the West basin by a tunnel at an altitude of 537 feet. This tunnel is probably plugged because the water table of the East basin pool, in test holes 10 and 17, has an altitude of 604 feet. The East basin is estimated to contain about 48 million cubic feet of water.

In the Priscilla Lee coal basin there are two bodies of water separated by a saddle in the coal-bearing beds. The altitude of the water table is 920 feet in the westernmost pool and in test holes 5 and 20. This pool contains 11 million cubic feet of water. The water level in the eastern pool of the Priscilla Lee basin is at an altitude of 840 feet, as shown by water levels in the Priscilla Lee mine shaft and test hole 16. This eastern pool contains 48 million cubic feet of water. The total volume of water in the West End mine property is estimated to be about 140 million cubic feet, which is a minimum estimate based on the lowest water levels measured in the basin.

Recharge and Discharge

Precipitation

The precipitation records collected from two recording gages are in tables ~~1~~ 2 to ~~4~~ 5. Figures 17 and 18 contain the hydrograph of the Priscilla Lee mine shaft and a graph of precipitation data, showing the effects

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Figures 17 and 18.--(Captions on next page) belong near here.

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of recharge and discharge at one of the flooded mine pools.

Evapotranspiration

Evapotranspiration from the ground-water reservoir is dependent upon climatic factors, the depth of the water table, and the nature of the vegetation and its root system. It varies areally and seasonally. In areas of high relief it may occur chiefly in valleys and low lying areas. In the Black Creek watershed, ~~project area~~ evapotranspiration occurs mostly during the growing season. The depth to the water-table over the coal beds is generally too deep to supply moisture to plants. The soil cover that has developed on the undisturbed rocks retains moisture for plant growth. A few of the older waste rock piles have developed a tree cover; however, most of the waste rock piles have little or no plant cover; probably because of the acid soil conditions and lack of moisture in the coarsely broken rock.

Figure 17.--Hydrograph of P~~riscill~~a Lee shaft showing precipitation at Lee, Pa. 1966.

Figure 18.--Hydrograph of P~~riscill~~a Lee shaft showing precipitation at Lee, Pa. 1967.

Mine Effluent

The hydrographs of the mine drain (BC-1) are shown in figures 19 and 20. These hydrographs show the rapid response of the mine-drain

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Figures 19 and 20.--(Captions on next page) belong near here.

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discharge to recharge of the West basin mine workings. There is very little direct runoff into the mine drain and the changes in the mine-drain discharge are related to the recharge and discharge regimen of the pool in the West basin mine workings. ~~Chemical analysis made at various discharge rates shows how the dissolved solids vary with discharge.~~ The highest instantaneous discharge recorded was 17.1 cfs (cubic feet per second) on March 17, 1967, and the lowest instantaneous discharge, which occurred several times during the period of record, was 1.8 cfs.

Figure 19.--Daily mean discharge for water year ending September 30, 1966, at mine drain near Mocanaqua, Pa.

Figure 20.--Daily mean discharge for water year ending September 30, 1967, at mine drain near Mocanaqua, Pa.

There are three more places in the project area where small amounts of water are discharged from the ground. These places are shown on figure 16 as BC-1A, DT-2, and P1-OP, and each is discussed briefly below. The discharge at BC-1A is acid water, which appears to be draining from a large spoil pile. Some of this water might be surface runoff from the dip slope of the Pottsville Formation east and south of the spoil pile. Additional data are needed to determine the pattern of circulation of the water under this spoil pile. Site DT-2 is a mine entrance in the largest outlier near the eastern end of the project area. The coal seams dip generally to the south and the water moves through the mine working to the mine entrance in this outlier. Recharge to the mine workings is derived from precipitation on outliers and in the strip pits around them. The water draining at site DT-2 soaks into the spoil banks, and its direction of movement is thought to be toward Stump Lake. P1-OP is the discharge point of a flowing well. This well lies outside of the project area. It was drilled to supply water for the Priscilla Lee mine shaft and now flows into Turtle Creek.

CHEMICAL QUALITY OF WATER

Interest in the pollution of steams, particularly mine drainage from coal mining areas in Pennsylvania, has grown in recent years. This interest has been stimulated by various groups who may have different or even contradictory ideas of the optimum approach for reclamation or the optimum quality of water desired after treatment. Various control and preventive measures such as "sealing" of mines and neutralization techniques ~~like~~ such as Operation Yellow Boy attest to this. Industry, in general, requires water having very low concentrations of iron, manganese, and other constituents, although the brewing industry prefers very hard, sulfate water.

The ferric iron and sulfuric acid in acid mine discharge attack metallic iron in steel emplacements or in boilers. The reaction is as follows:

$$Fe^{\circ} + 2Fe^{+3} \rightarrow Fe^{+2} + 2Fe^{+2}$$

$$Fe^{\circ} + 2H^{+} \rightarrow Fe^{+2} + H_2\uparrow + 2e^{-}$$

When fresh, well-oxygenated waters enter the system the ferrous iron is oxidized, permitting the cycle to be repeated and the metal is destroyed rapidly.

Mine waters can be neutralized by adding sufficient soda ash or lime to neutralize the sulfuric acid and to react with the ferric sulfate. Corrosion is stopped, but a small amount of loose scale is precipitated.

Factors That Influence Quality of Recharge Water

Rain falling on the watershed area contains small amounts of dissolved solids and gases. The water infiltrates downward through the soil and the organic zones, and picks up carbonic acid and minor amounts of metallic ions. As the water moves through the bedrock, including the coal measures, the carbonic acid-charged waters dissolve additional metals and products of pyrite decomposition. The amount of materials dissolved from the surrounding rocks depends chiefly on the character and concentration of ions in the circulating water, the amount of circulating water, and the rate and distance of movement of the water.

Chemical Weathering Processes

The presence of some solutes in ground water is due to the solution of atmospheric gases and other substances as described above, but the greater part is due to the solution of by-products of chemical weathering released by active mining and the subsequent disturbed areas.

Part of the decomposition products of minerals remains in solution. Some of these products precipitate and others recombine to form insoluble minerals. The types of insoluble products that are formed are a function of many variables. Weathering of rocks proceeds more slowly and contributes less solutes to ground water in the anthracite region than in the bituminous region because there is more orthoquartzite and a paucity of shale-carbonate facies.

The principal chemical processes that decompose the rocks outside the mine area are hydration and carbonation. The cations removed from the rocks are hydrated to bases, and the bases are converted to carbonates. The carbonate ion reacts with water and carbon dioxide, abundant in the organic fraction, to form bicarbonate. Products formed by this reaction are dissociated into their ionic components, and exchange phenomena with sulfate ion become important.

The production of acid in mine water is mostly a normal chemical weathering process of oxidation. The process is accelerated by extensive mining that disturbs the geologic formations and intercepts the groundwater table, allowing moisture transfer through the metal sulfide strata in the deepened zone of aeration. The process of oxidation within the flooded part of the mine is catalyzed by bacteria and by the metals having higher oxidation potentials that are abundant in the mine waters and in the coal measures.

The chemical decomposition of the silicate minerals is catalyzed by acid waters. The sedimentary rocks in this region are composed of detrital components of sandstone, siltstone, and shale, and ion exchange reactions between cations in solution and loosely adsorbed cations in the clay-mineral lattice become important. Non-detrital calcite and gypsum are present in minor amounts and are extremely soluble.

Gypsum, which was formed by the oxidation of pyrites at the surface and by the decomposition of the silicate lattice at depth, is not the most soluble mineral in the area. Selenite crystals were taken from well cuttings and probably are found in nodules and in cleats and joints in the coals. Some of the gypsum may be diagenetic, forming during or immediately after deposition of the organic series. The most soluble minerals in the area are sulfate salts of iron and aluminum.

Evapotranspiration

Little is known about the effect of evapotranspiration upon the quality of ground water in this area. Some concentration of mineralization may occur during summer months when white and yellow salt residues appear on exposed surfaces of spoil and on coal in the mines. These water — soluble, hydrated minerals have been identified by Lorenz (1962, p. 7), and most commonly include both ferrous and ferric sulfates: melanterite, $FeSO_4 \cdot 7H_2O$, a monoclinic, greenish white, fibrous, bivalent iron salt and coquimbite, $Fe_2(SO_4)_3 \cdot 9H_2O$, a rhombohedral, white to yellow brown, granular, oxidized mineral. Also of singular importance are members of the alum group containing variable amounts of magnesuim and manganese, 953 which substitute in part for the bivalent iron. Such a mineral is halotrichite, $FeSO_4 \cdot Al_2(SO_4)_3 \cdot 22H_2O$, a monoclinic, yellowish, silky or fibrous variety, commonly found in highly acid spoils. Other salts on exposed surfaces include alunogenite, $Al_2(SO_4)_3 \cdot 16H_2O$, usually a white, fibrous mineral in either the monoclinic or triclinic crystal system, depending on the water content, and copiapite, $Fe_4(OH)_2(SO_4)_5 \cdot 18H_2O$, the only basic ferric sulfate of importance. The latter is orthorhombic, yellow and has a scaly or granular appearance.

Classification of Waters in the Area

Water is classified by the relative proportion of mineral constituents, expressed in equivalent weights. If a cation or anion exceeds 50 percent of the total cations or total anions, in equivalents, only this cation or this anion will be used to denote the type of water. If the cation or anion does not exceed 50 percent of its total equivalent a hyphenated combination of names of the major constituents is used; the most abundant ~~are~~ is listed first. The ion must exceed 10 percent to be listed. Only two anion combinations are present in the Black Creek basin (see symbols used, p.76 and table 6, p. ~~76a~~ 164).

Example:

1. (Ca) (HCO_3)--calcium comprises more than 50 percent of the total cations, in equivalents; bicarbonate comprises more than 50 percent of the total anions in equivalents.
2. (Ca-Mg) (SO_4)--the sum of Ca + Mg ions, in equivalents, is more than 50 percent of the total cations; calcium is more abundant than magnesium, and each of the remaining cations comprises less than 10 percent; sulfate comprises more than 50 percent of the total anions in equivalents.
3. (Mg - Al - Fe) (SO_4)--the sum of Mg + Al + Fe ions, in equivalents, is greater than 50 percent of the total cations: Mg>Al>Fe, ~~and~~ each remaining cation makes up less than 10 percent of the total equivalents; sulfate comprises more than 50 percent of the total anions in equivalents.

Below is a simplified outline of the possible anion groups in the Black Creek basin, which includes natural, polluted, and mixed waters. The waters are grouped first by the dominant anion and the concentrations. The dominant anion is indicated by the following symbols:

A - acid sulfate $>$ neutral sulfate (acidity $>$ 50 percent)

S - neutral sulfate $>$ acid sulfate
(acidity $<$ 50 percent)
neutral sulfate $>$ bicarbonate

C - bicarbonate $>$ sulfate

The cations are listed according to their relative abundance; the most common cation is listed first.

Some ion combinations of waters existing in the Black Creek basin are listed in table 6, in order of decreasing percent acidity. For purposes of identification in this report, the term "acid sulfate" (symbol A) is used to define those waters whose total hydrogen (or sulfuric acid) ion equivalents exceed half of the total equivalents of sulfate ions. "Neutral sulfate" refers to the sulfate equivalents in excess of acid sulfate.

Table 7 provides an estimate of the relationship of combined ions to dissolved-solids concentration (D.S.).

The table shows that

¶ The dominant anions and cations change as the ~~with increasing~~ concentration of dissolved solids increases and provides a very general and approximate idea of the character of variations with increased ~~in the~~ mineralization of these waters in the Black Creek basin. Most of these variations in water quality are the result of movement within the aquifer, retention time, mixing of waters, and contact with surrounding rocks. Some of these combinations probably would hold for short distances, even after dilution. Hydrochemical facies maps, (figs ~~ure~~ 21A and 21B) of the mine pools show the ranges of acidities in the area. The dominant anions and cations have been plotted on the hydrochemical map, (figs ~~ures~~ 21C and 21D) using the anion symbols and are shown by Stiff diagrams.

Figure 21A to 21D.--(Captions on next page) belongs near here

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Figure 21A.--Hydrochemical facies map of the Black Creek basin, western half.

Figure 21B.--Hydrochemical facies map of Black Creek basin, eastern half.

Figure 21C.--Hydrochemical map of the Black Creek watershed, western half.

Figure 21D.--Hydrochemical map of the Black Creek watershed, eastern half.

Chemistry of water in aquifers and coal seams

Ground water, in areas outside of those influenced by mining and in formations older than the coal measures, is of the calcium bicarbonate and calcium bicarbonate-sulfate type. Surface water in this same area is of the calcium bicarbonate type. Ground water in the mines and below the coal measures, and surface water inside the coal-mining area, are influenced markedly by coal mine pollution and vary considerably in cationic combinations. (See page ~~76a~~ 164, table 6.)

The chemical character of water in rocks older than those of Upper Mississippian age are excluded in this section because their potential for yielding water to the mined-out areas is small and does not affect the quality in the Black Creek basin.

Mauch Chunk Formation

The water in the Mauch Chunk Formation is generally of the calcium bicarbonate, calcium bicarbonate-sulfate and calcium sulfate types, except where infiltrated by acid water from the overlying coal measures.

Pottsville Formation

The Pottsville Formation is not a major source of large ground-water supplies except in fracture zones, and the water is mostly of good quality except where contaminated by ~~infiltration of~~ mine waters. ~~are present.~~ Wells drilled into the Pottsville Formation show a seasonal variation in artesian head. This phenomenon and chemical quality variation seem to be dependent upon nearness to area of recharge. The water in test holes 2BC, 7BC, 8BC, and 19BC is alkaline where it is moving across the contact with the Mauch Chunk; otherwise the water becomes acid where surface flow or mine water is introduced. Ground-water supplies from the Pottsville are principally calcium sulfate and calcium-magnesium sulfate types.

Llewellyn Formation

Much of the water in observation holes that penetrated the Llewellyn Formation contains hydrogen sulfide, which was probably generated by the reaction of acid water and/or ferric sulfate with metal sulfides, or by the reduction of sulfates by anaerobic bacteria.

Regional differences in the quality of the water are great and correlation of water withi individual coal seams is difficult. Few data are reported ~~on~~ for water from the Llewellyn Formation outside of the coal seams. Where analyses are available, they show the water to be high in sulfate content which was derived principally from pyrite~~s~~. Types of water ranged from magnesium-calcium sulfate to iron sulfate. The iron sulfate type was found under extreme reducing conditions.

The amount of water available from Quaternary deposits is small but of good quality. The alluvium and glaciofluvial deposits contribute a good quality water to the underlying Llewellyn Formation or, where the Llewellyn Formation is missing, to older formations. However, since ground-water yields are low, most of the inflow to bedrock formations probably is derived from recharge water of good quality that moves down the dip slopes into Black Creek basin. Solutes in the ground water from unconsolidated formations consist chiefly of calcium bicarbonate, unless contaminated with acid and solutes from the Llewellyn Formation.

Chemistry of water in mine waste material

Samples from culm piles were leached with distilled water in the laboratory and were found to yield free sulfuric acid, and aluminum, ferrous, and ferric sulfate. Upon standing, the solution reached equilibrium in several days, as hydrogen ions replaced the metal ions. During this period of ion exchange only a moderate increase in specific conductance occurred.

Mine wastes and waste rock in the area differ in character from place to place, so that different types of water occur within relatively short distances of each other, the acidity and salinity of the water ranging widely. Seventy-five percent of the mine waste is believed to yield water having a pH less than 4.5. The major cations in water leached from the moderately acid spoil piles were calcium and magnesium; only minor amounts of iron, aluminum, and manganese were leached. Extremely acid mine wastes, having a pH of 3 or less, were highest in aluminum, iron, and magnesium. The spring at BC-1A has a high concentration of dissolved constituents. (See fig. 16.) The effluent is at the base of a large spoil pile, and may be derived from rainwater that has leached and flushed the pile. The water is of the aluminum-iron-magnesium, sulfuric-acid type and has a unique coagulating property that may be due to the very high aluminum sulfate content. This water contains a large excess of free sulfuric acid.

Variations in Chemical Character of Ground Water and Surface Water

Figures 22 through 26 are water analysis diagrams showing the general chemical character of ground water and surface water. The analytical values are tabulated on each figure in milligrams per liter and are plotted on the diagram in milliequivalents per liter. Each point on the diagram represents a sample of water from a well, spring, or surface-water body. With the exception of alkaline waters, the shift in percentage concentrations is from alkaline-earth sulfates to metallic-acid sulfates.

Figures 22 through 26.--(Captions on next page) belong near here.

Figure 22.--Water analysis diagram of the chemical quality of ground water influenced by mine waters.

Figure 23.--Water analysis diagram of the chemical quality of ground water restricted to the coal measures.

Figure 24.--Water analysis diagram of the chemical quality of ground water from the Lee Shaft.

Figure 25.--Water analysis diagram of the chemical quality of surface waters influenced by mine waters.

Figure 26.--Water analysis diagram of the chemical quality of ground water and surface water with alkalinity.

Constituents of mine waters and their geochemistry.

Analytical methods and special techniques.

The parameters determined on the mine waters from the Black Creek basin on a routine basis were ferrous and ferric iron, aluminum, manganese, calcium, magnesium, sulfate, pH, and total acidity. Total acidity, calculated as sulfuric acid, was determined potentiometrically in the laboratory by titrating with standard 0.0248N NaOH to pH 7. Mine-water samples first were oxidized with hydrogen peroxide, boiled, and cooled rapidly to room temperature. Determinations of pH and acidity (or alkalinity) were also made occasionally in the field.

Residues on evaporation (ROE) were determined occasionally as a check on the calculated sum of dissolved constituents.

Aliquots for ROE were oxidized with hydrogen peroxide to remove the formic acid "fix" (used to prevent precipitation), evaporated to dryness, and dried at 180° C for 1 hour.

Water temperatures were measured on all samples. At least one complete chemical analysis was performed on a sample from each collection site. When several analyses were made, the analyses were spaced to show the effects of seasonal fluctuations. The complete analyses also included determinations of sodium, potassium, chloride, nitrate (including total non-protein nitrogen), fluoride, silica, and trace metals such as zinc, copper, nickel, and strontium.

Spectrographic analyses of trace metals were made on the major mine effluent (BC-1) during high- and low-flow periods. (See table 8.) Trace metals were determined also on the major underground pools and surface-water bodies. (See tables 9 through 13.)

Calcium, magnesium, and manganese were determined routinely by the atomic adsorption spectrophotometer. Aluminum was determined by the spectrophotometric ferron-orthophenanthroline method, and iron field and laboratory analyses was determined by the bipyridine method. Sulfates were determined by titration with barium chloride and thorin indicator.

Dissolved oxygen was determined in the field by the revised micro-Winkler method.

Values for redox potentials probably are higher than the true Eh, ~~since~~ as they were imperfectly attained. Water samples were collected in a 1-liter Foerst Sampler, and the Eh was measured in a nitrogen, gas-purged atmosphere.

The presence of phosphorus was not detected by the analytical methods used, possibly because the element is metabolized rapidly by organisms such as bacteria in the mines.

Bicarbonate (HCO^-_3)

The bicarbonate ion in ground water is directly dependent upon the partial pressure of free CO_2 in the environment and upon the pH. The presence of free CO_2 in mine waters is influenced to a marked degree also by temperature, barometric pressure, permeability of the adjacent aquifer rocks, velocity of the ground water, and by biological activity. For these reasons, and because of a variable hydrogen ion concentration, bicarbonate in mine water is subject to a wide range of fluctuations.

Bicarbonate becomes important in alkaline mine waters because of its association with the ferrous ion. At pH 6 and below, carbonic acid, together with other weak acids, increases the oxidation potential required to oxidize the heavy metals and thus retards the process of oxidation. Below pH 4, as in the water of the major mine drain (BC-1), practically all of the carbonate exists as carbonic acid, and the dissociated form may be released from solution as CO_2 gas. Insignificant amounts of CO_2 are released at the mine opening, and some CO_2 is lost in the summer owing to increased external temperatures. Analyses reveal that from 15 to 25 percent of acidity is lost from field (immediate acidity) determination to laboratory (free and potential acidity) determination. The major loss can be explained by the removal of carbonic acid in the laboratory analyses.

The mine waters within the Lee Shaft (PL-MS on fig. 21D) are relatively alkaline and reducing at depth. These semi-stagnant waters have a range of pH values from 5.7 to 6.6, and redox measurements (Eh) range from + 435 mv (millivolts) at the water table to + 3 mv near the bottom of the shaft (table 14). Volatile carbons were determined on a few samples (table 14), because the potentiometric measurement for bicarbonate on these waters was not reliable. Dissolved CO_2 may increase sevenfold between a pH of 6.59 and a pH of 5.77. If bottom waters are near saturation for CO_2, this would explain the effervescence at the 330-foot level at Lee shaft.

Sulfate (SO_4)

The preponderance of sulfate ion in this ground-water system is an indication of the degree of oxidation from metal sulfide to ionic sulfate. Most of the mine-drainage effluent in Black Creek basin (BC-1) contains high concentrations of ferrous and aluminum sulfates as well as of calcium and magnesium sulfates. On exposure to air, the ionic solution of Fe^{+2}, SO_4^{-2} yields the hydrated oxide of iron and basic sulfate. The relatively insoluble iron compounds precipitate and impart a yellow color to stream channels.

The reduction of sulfate in the presence of organic matter produces H_2S and CO_2. The mine shaft samples (PL-MS) exhibit a gradual increase in the odor of sulfide compounds starting at the 290-foot level and reaching a maximum sulfide odor at the 320-foot level. Intervals sampled below this have no trace of H_2S, but contain a gas having a petroleum odor. This gas was not analyzed except for total carbon (table 14), and it probably includes abundant carbon dioxide. The odor of sulfide also was found in mine pools intercepted by boreholes. Borehole No. 17 contained a very strong odor of sulfide at the 810-foot and 888-foot levels, where pressures were between 14 and 16 atmospheres.

The high concentration of hydrogen sulfide between the 310 to 320-foot level at Lee Shaft may be explained by the dissociation of carbonic acid to carbon dioxide at the high pH value (pH 6.6) near the 330-foot level in the mine pool (see remarks, table 14.) The effervescent CO_2 gas displaces H_2S at the lower level and transports it to the higher level in the mine pool where the much more soluble H_2S is concentrated.

Pyrite and marcasite are polymorphs of ferrous iron and sulfur (FeS_2). They are commonly disseminated in the coal and are often crystallized out secondarily from solution along bedding planes and along intraformational diastems. The frequently cited oxidation reaction of pyrite with water does not occur at depth in mine pools.

$$FeS_2 + 7O + H_2O = Fe^{+2} + 2SO_4^{-2} + 2H^+$$

Barnes, and others (1964, p. B1) have provided the following anaerobic reaction:

$$FeS_2 + 8H_2O = Fe^{+2} + 2SO_4^{-2} + 2H^+ + 7H_2$$

From carbon analyses previously mentioned and from the relationship of the gas to pH change, it is postulated that carbon dioxide is indeed being produced under confining pressures and may be another source of oxygen. Gas composition was not determined because of difficulties involved in sample collection. If hydrogen gas is evolved, an interesting and theoretically possible reaction may explain its behavior in deep mines.

$CO_{2(g)}$	+	$4H_{2(g)}$	=	$CH_{4(g)}$	+	$2H_2O_{(1)}$
$\Delta F°$		$\Delta F°$		$\Delta F°$		$\Delta F°$
-94,260 cal.		0 calories		-12,140 cal.		2(-54,630) cal.

Product of reaction: $\Delta F° = -27,140$ calories.

Because the free energy value is negative, the reaction proceeds spontaneously to the right and indicates that it is possible to synthesize methane from CO_2 and H_2 at standard conditions. The reaction rate, and hence the practicality of the reaction, is not known.

Redox potentials plot above the zone of water reduction on the stability field diagram for water in the Lee shaft (Hem, 1960, p. 61 fig. 6). Therefore, the oxygen must be supplied from ~~another~~ a source other than water. Assuming saturation of solutions with pyrite, the following possibility is submitted and may account for the abrupt presence of the "petroleum" odor (formation of hydrocarbons, equations 3 and 5) and complete loss of sulfide odor at greater depths. FNO

$$2Fe^{+3}_{(aq)} + FeS_{2(c)} = 3Fe^{+2}_{(aq)} + 2S^{\circ}_{(c)} \qquad (1)$$

Free sulfur is unstable in this environment and may be reduced to hydrogen sulfide or oxidized to sulfate. From Hem (1960, p. 60) we obtain the following at pH< 7.

$$S^{\circ}_{(c)} + 2H^{+} = H_2S_{(aq)} - 2e \qquad (2)$$

This would occur at the 320 foot level in the Lee shaft at a pH< 6. The 330 foot level, where the pH> 6, the bicarbonate ion predominates over carbonic acid, and the following reactions may take place:

$$S^{\circ}_{(c)} + 2H^{+} + 2HCO_3 = SO_4^{-2} + \underset{\overset{\uparrow\;\downarrow}{2CH_2O}}{\left[CO_2 + CH_4\right]} -2e \qquad (3)$$

The free energy value is such that the reaction will proceed to the right; however, the formaldehyde is less stable at standard conditions.

Sulfide oxidation may proceed through the following two hydrolysis reactions:

$$Fe^{+2} + 2H_2O = Fe\ (OH)_2 + 2H^+$$

$$2(OH^-) + H_2S + CO_2 = SO_4{}^{-2} + CH_4$$

Sulfate reduction may be responsible for considerable loss of sulfate in solution and may be used to explain the difficulty in correlating sulfate concentrations between mines, between aquifers, and between these and surface waters.

Iron (Fe^{+2}, Fe^{+3})

Ferrous and ferric ions possess a high degree of solubility, but their solubility is pH dependent. Oxidation, reduction, and hydrolysis are also important processes of iron solution. High iron concentration can only be found in waters of low pH or in water under reducing conditions. Little correlation appears to exist between total acidity, dissolved solids, and oxidation state (fig. 27), although underground mine waters may show a tendency toward increased Fe^{+2}/Fe^{+3} ratios with lower percentages of free acidity. Very often iron is found as a colloid, where the ratio of bi- to tri-valent iron (Fe^{+2}/Fe^{+3}) is low, indicating an increase in oxidation. Iron generally is more abundant in the more saline acid waters, making up 6 to 26 percent by weight of dissolved constituents.

Figure 27.--(Caption on next page) belongs near here.

The concentration of ferric ions in water with a pH 5 or greater is small because of hydrolysis and the formation of the insoluble ferric hydroxide. Ferrous ions hydrolyze and pass into the insoluble hydroxide at pH 7 or greater. Large quantitites of iron in mine ~~drain~~ water bears testimony to the solution of pyrites ~~which~~ that occurs during intensive oxidation, under either aerobic or anaerobic conditions. The ferrous ion is readily oxidized to the ferric ion by atmospheric oxygen. Other oxidizing agents also convert it easily to the ferric state, and for this reason ferric ions are practically al~~p~~ways present in small amounts in a solution containing ferrous ions.

Figure 27.--Relation of acidity to ferrous-ferric iron ratio.

Figure 28 shows the stoichiometric relationship of total iron to

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Figure 28.--(Caption on next page) belongs near here.

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ferrous sulfate. Equivalent ratios of less than 0.5 indicate the presence of a sulfate combined with some other cation than iron, such as hydrogen (sulfuric acid) or calcium (gypsum). Ratios of more than 0.5 are probably due chiefly to the presence of iron as ferrous bicarbonate or as a hydrated oxide of iron. Theoretically, all plots along the pyrite ratio line 1:2, or an equivalent ratio of 0.5, would indicate that all of the iron and sulfur species are derived from pyrite. Figure 28 also relates the sulfate, as "free" and potential sulfuric acid, to the total iron present in the water. Large concentrations of "free" acidity ($pH<4.5$) suggest a pickup of sulfuric acid from the spoil and plot to the left of the 0.5 equivalent pyrite-ratio line.

Samples from the Lee mine shaft below the 190 foot-level indicate that most of the sulfur probably is derived from pyrite ($Fe\ S_2$), although another source for the iron also may be present. The iron to sulfuric acid ratio for the deep mines, especially Lee shaft, plot far to the right of the 0.5 ratio line, indicating little, if any, free acidity.

Figure 28.--Relation of total iron to iron-sulfate ratio.

The formation of high concentrations of iron in near-surface mine waters~~,~~ that occur when oxidizing waters circulate in areas of pyrite~~,~~ are comparatively well known because the reactions can be easily studied. Not so well known is the action of deep circulating reducing waters in strata containing pyrites. Reducing waters in contact with iron oxides or hydrous oxides of iron will theoretically dissolve high concentrations of iron, butthese reactions are not known to take place in mine waters, in the study area, where reducing environments are the rule. The reaction of hydrous oxides and sulfates of iron and aluminum with pyrite may be the mechanism by which the pyrites are oxidized (Lorenz, 1962, p. 7):

$$FeS_2 + 14Fe^{+3} + 8H_2O = 15Fe^{+2} + 2SO_4^{-2} + 16H^{+1}$$

Since hydrogen sulfide is often detected in mine waters, especially in stagnant pools, ferric ions may be reduced before coming in contact with pyrite (Hem, 1960, p. 60):

$$2Fe^{+3} + H_2S = 2Fe^{+2} + 2H^{+} + S°_{(c)}$$

The ferrous ion forms a stable insoluble sulfide precipitate (hydrotroilite) in solutions having a pH greater than 6, and most of the underground pools are very nearly neutral and have no free acidity. Presumably, these iron sulfide precipitates are being formed in many underground pools but are absent from highly acidic, oxidized mines.

As explained under the section on "Bicarbonate", the increased solubility of ferrous sulfate and carbon dioxide in mine water at depth is apparent; and waters easily become supersaturated with CO_2 and ferrous iron as the pressure is reduced. This retards the oxidation of the iron until CO_2 is released at the mine discharge.

Aluminum

The trivalent ion of aluminum hydrolyzes readily to the hydroxide. In mining areas the double salt forms with ferric iron, and solutions of these salts have a variable composition partly because of isomorphous substitution.

The mine waters in Black Creek basin reveal a variable aluminum concentration. Aluminum is low to absent in deeper parts of the mine pools, because at the prevailing pH the aluminum ions form a white gelatinous hydroxide which precipitates. The ion begins to hydrolyze at about pH 3 and precipitation of the colloid begins above pH 4. The mobility of this ion is not affected by the redox potential, but the kinetic behavior of the hydrous oxide is similar to that of iron. Some sulfate is coprecipitated with aluminum and iron. In the low-pH mine waters of Black Creek basin the aluminum ion may exceed 70 mg/l (milligrams per liter) or 6 percent of the dissolved solids by weight. Such concentrations serve to emphasize the intensity of aluminosilicate rock decomposition. High aluminum concentrations more frequently are associated in solutions with abundant free hydrogen ions or low pH (fig. 29).

Figure 29.--(Caption on next page) belongs near here.

Figure 29.--Triangular percentage distribution graph of metalic ions in Black Creek basin waters

Manganese (Mn^{+2})

The most favorable environment for the presence of manganese in water is one that has reducing conditions and one in which the pH of the water is low. One hundred or more milligrams per liter of manganese (1.4 percent by weight of dissolved solids) may be present in water under reducing conditions in the Black Creek area. Surface waters under oxidizing conditions and having a low hydrogen ion concentration generally have less than 5 mg/l. The Mn^{+2} ion is difficult to oxidize (Day, 1963, p. 321). The oxidation potential in acid solution is high (+ 1.51 volts at pH 4), and the ions remain mobile after Fe^{+2} oxidizes and precipitates (+ 0.77 volts at pH 2.5).

Manganese is similar to iron, being derived from many of the same sources and occurring in the same reduced valence. The migration of manganese in ground-water circulation has not been evaluated sufficiently to determine interrelations between aquifers and surface waters.

Manganese percentages are greatest in the less highly mineralized alkaline waters (fig. 29). At the major mine discharge (BC-1), concentrations of manganese are directly related to iron concentrations (tables 15 and 16.).

Calcium (Ca^{+2})

Calcium in the ground water in the Black Creek area ranges from 2 to 30 percent by weight of the dissolved solids and generally increases as the acidity and dissolved solids increase.

Solutions containing more than about 2,000 mg/l of calcium sulfate ($CaSO_4$) at 10°C are saturated with respect to this molecule and precipitates of gypsum may form above this concentration. Saturation is important in some mine waters where sulfate is sufficiently abundant and constitutes the dominant anion. The solubility of calcium sulfate increases as concentrations of chlorides of magnesium or alkali metals increase (Morozova, 1956, p. 160); however, more importantly in these mine waters, the solubility of calcium sulfate decreases by the common-ion effect as concentrations of either sulfate or calcium ions increase. Sulfates of iron possess a relatively high degree of solubility but are more dependent upon low pH or Eh values than is calcium sulfate. The triangular diagram (fig. 30) shows the percentage decrease in calcium concentration along with increased acidity and increased metal ions.

Figure 30.--(Caption on next page) belongs near here.

Figure 30.--Triangular percentage distribution graph of alkaline-earth metals and heavy metals in Black Creek basin waters.

Magnesium (Mg^{+2})

Magnesium in the non-polluted ground water of Black Creek basin ranges from 0.2 to 9 percent of the dissolved constituents by weight, or from 1 to 5 mg/l. In polluted mine waters the magnesium content ranges from 3 to 11 percent, or from 4 to 440 mg/l.

The increased magnesium content in the acid mine waters may be due to the ion exchange between the abundant hydrogen ions in the water and the magnesium adsorbed on the shales. In the highly mineralized mine waters of the Black Creek basin, where the dominant anion is sulfate, a decrease in the Ca/Mg ratio may result from the reduced solubility of calcium sulfate. Saturation for $Ca\ SO_4$ is about 2,000 mg/l at 10°C, but it decreases markedly with addition of magnesium sulfate (solubility of $Mg\ SO_4$ is about 300,000 mg/l at 10°C). The Ca/Mg ratio appears to be independent of dissolved-solids concentration, but analyses suggest that the Ca/Mg imbalance is maintained, notwithstanding subsequent dilution of these highly mineralized waters. (See table 17 and fig. 31.) A very distinct correlation can be made between the acidity of Black Creek basin waters and the calcium-magnesium ratio. (See fig. 32.)

Figure 31.--(Caption on next page) belongs near here.

Figure 32.--(Caption on next page) belongs near here.

Figure 31.--Relation of dissolved solids and calcium magnesium ratio.

Figure 32.--Relation of acidity to calcium magnesium ratio.

Potassium (K^+) and Sodium (Na^+)

The ratio of Na/K is highest in the Black Creek basin in water having low pH (table 17). It ranges from 1.6 to 2.1 in surface waters. The lowest ratios are found in highly mineralized, nearly neutral water in the flooded mine areas, where concentrations of aluminum are generally low. Potassium concentrations of about 20 mg/l are found in the waters of the lower part of the Llewellyn and Mauch Chunk Formations (table 14), probably because of abundant sericite or other potassium-bearing minerals.

The sodium ion is not abundant (less than 10 mg/l) in the Black Creek basin but does increase downdip to the northeast. Sodium is very soluble but is subject to ion-exchange reactions.

The presence of free acidity (pH below 4.5) facilitates the release of potassium into solution by promoting a dissociation of clay minerals. Most of the potassium probably is derived from desorption of clay and micaceous minerals rather than from decomposition of an undiscernible potash feldspar. The discharge of potassium by desorption maintains the low Na/K ratio even when mine waters are diluted and/or neutralized at the surface. The relation of potassium to acidity or dissolved solids is quite variable. (See fig. 33.)

Figure 33.--(Caption on next page) belongs near here.

Figure 33.--Relation of dissolved solids and sodium potassium ratio.

Silica (SiO_2)

Silica hydrolyzes readily to silicic acid, which occurs in mine waters primarily in colloidal form and secondarily in the ionic state. The intensive oxidation of mine waters and release of free hydrogen ions during hydrolysis causes decomposition of the aluminosilicate rocks. These waters become enriched with silicic acid, which acts together with other weak acids to raise the oxidation potential required to oxidize the heavy metals found in the mine water and to inhibit their precipitation. The pH is particularly important in the transportation and deposition of alumina (Al_2O_3) and silica (SiO_2) from solution. Aluminum is soluble at very low pH values, and silica is soluble at very high pH values. Aluminum and silica concentrations trend to be highest in waters having pH's below 4, but the normal pH range of mine waters (pH 4 to 6) favors low silica concentrations.

Silica concentrations appear to be low in fresh, bicarbonate type waters (table 17) and in underground mine pools having high pH values. The fresh waters, seemingly unaffected by mine drainage, range from 5 to 24 mg/l silica or up to 10 percent of the dissolved constituents, but in mine water the silica concentrations range from 0 to 34 mg/l or up to 3 percent by weight of the dissolved constituents.

Trace Constituents

The study of trace-constituents in mine waters helps to determine the interrelations of individual aquifers and surface waters. The trace elements appear to be bound in the carbon-rich (coal and shale) fractions, in the sulfides (pyrites, etc.), on the clay minerals (adsorbed), and in the silicate lattice.

The number of ions present in trace amounts in mine-water discharges is moderately large. Some elements may be negligible in amount because of a scarcity in the rocks, or because they form compounds of low solubility in the underground mine pools under the existing physical and chemical conditions. Most of the inorganic constituents probably remain in the coal long after deposition, except for some volatiles removed from anthracites and those that are readily soluble.

Nitrogen is stable in underground mine waters and occurs most frequently in the reduced valence state. It is rarely abundant because of its scarcity in the rocks. Nitrate in the mine wastes is extremely low (less than 1 mg/l), but ammonia in these waters is high in comparison, containing as much as 11 mg/l nitrogen as NH_4^+ (PL-MS, 385 feet, table 14). The ammonium salt results from the reducing conditions in which organic matter is present. The nitrogenous organic material could be of recent origin because organic nitrogen is decomposed easily before or after deposition. Francis (1954, p. 484) describes the loss of nitrogen and sulfur from peat by solution as ammonia and hydrogen sulfide.

The chloride ion ranges from 0 to 14 mg/l in the Black Creek basin, and increases downdip at the Glen Lyon pump to 24 mg/l. Glen Lyon is 1 mile to the northeast, across the coal barrier. The chloride ion is extremely stable.

Fluoride concentration is generally low in mine waters (less than 1 mg/l) because of the low solubility of alkaline earth and heavy metal fluorides. The element probably occurs as fluorapatite in coals (Francis, 1954, p. 498).

Spectro-chemical analyses were made for aluminum, barium, beryllium, bismuth, boron, cadmium, chromium, cobalt, copper, iron, lead, lithium, manganese, molybdenum, nickel, rubidium, silver, strontium, tin, titanium, vanadium, zinc, and zirconium on 14 water samples. These samples were taken from four levels in the Lee shaft, from two boreholes penetrating drifts in the lower coals, from the surface and bottom waters of the largest strip-pit lake in the project area, from two surface-water sites along Black Creek, from the main mine drainage at high and low flow, and from wells penetrating the Pottsville Sandstone that lies below the coal measures (one of which is contaminated by water from the coal). The analyses are shown in tables 8 through 13. 9 5 B

Analyses indicate that most of the elements in the mine waters are mo~~re~~st concentrated at depth. Most differences in minor element concentrations can be ascribed to pH, Eh, and coprecipitation. Only iron, tin, and possibly zinc, appear to be in greater concentrations than that normally found in coals within this area. (See Table 10). Therefore, these elements may have been derived from rocks other than the coal fraction. Only minor differences in trace metal concentrations seem to be related to stratigraphic position, differences in source rocks, and minor elements found in pyritic zones.

Trace metals that are particularly abundant in this area are zinc, nickel, cobalt, and strontium. Cooper, lead, zirconium, lithium, and boron rarely occur in high concentrations. The cations of zinc, cooper, and lead may be coprecipitated with aluminum and ferric hydroxide. Sulfides of manganese, nickel, zinc, cobalt, and iron are soluble in acid media.

Ions that precipitate as the sulfide in acid solution are not likely to be found in abundance under conditions existing in acid-mine-drainage studies. These ions are silver, lead, bismuth, cooper, cadmium, and the amphoteric sulfides of arsenic, antimony, and tin. They exhibit increased concentration with increase in discharge (table 8), because of a possible decrease in sulfide activity. The following divisions of the trace metals attempt to relate them to their abundance, solubilities, source rock, and associations.

Extremely water-soluble trace elements

Lithium is a product of aluminosilicate decomposition. It is quite rare, is exceedingly mobile, and migrates farther than potassium and rubidium. In the acid waters of the Black Creek basin the lithium concentration ranges from 0.02 to 0.20 mg/l. Rubidium may occur in the lattices of aluminosilicates (Vinogradov, 1959, p. 81) and is released by decomposition. Concentrations up to 0.04 mg/l were found in the area. Boron is soluble but is not especially abundant in the non-marine sediments of the area. Boron ranges from 0.005 to 0.55 mg/l in analyses of mine waters from Black Creek basin.

Alkaline earth metals in trace amounts

Barium concentrations are generally less than 0.07 mg/l in the Black Creek basin. The solubility of barium sulfate is extremely low. Strontium sulfate saturation in acid mine waters is low also, although the solubility is over 50 times greater than barium sulfate. Both barium and strontium are found in association with calcium and potassium minerals. Strontium is particularly abundant (up to 4.4 mg/l) in water from the lower coal measures where selenite (calcium sulfate) crystals and minor carbonate minerals were identified. Strontium bicarbonate solubility exceeds that of calcium bicarbonate, but strontium is readily precipitated as the sulfate.

Minor oxide and silicate elements

Titanium is not a rare element. The average concentration in Appalachian coals is 407 parts per million. (See table 10.) It is widely prevalent in the soil and may rise in concentration with a simultaneous leaching of iron minerals. In very acid media ($pH<3$), a high content of iron and aluminum is generally associated with a high concentration of titanium. In highly reducing media, the Ti^{+4} can be reduced to Ti^{+3} (Vinogradov, 1959, p. 101) and possibly to Ti^{+2}. Titanium in these mine waters is less than 0.17 mg/l.

Beryllium and zirconium, like titanium, precipitate as the result of hydrolysis. Their presence in mine waters probably results from the far-reaching decomposition of aluminosilicate rocks. Both are strongly adsorbed on residual clays, although zirconium accumulates also in sandstone. Mine waters within the Black Creek basin have less than 0.06 mg/l beryllium and less than 0.55 mg/l zirconium.

Chromium, vanadium and molybdenum are generally present in mine waters in amounts less than 0.01 mg/l. The three metals are amphoteric and form complex ions. Heteropolyacids (complex acids derived from two or more metals oxides) may be important in raising the oxidation potential of heavy metals and retarding the process of oxidation. Chromium is present in only very acid waters and is not retained in the sulfide minerals. Vanadium is more mobile in alkaline waters having a high redox potential, and it is more abundant in marine sediments. Molybdenum is associated mostly with silicate rocks, but it also occurs as the sulfide.

Minor sulfide elements largely soluble in acid media

Cobalt and nickel are relatively abundant in Black Creek basin mine waters and concentrations range from 0.07 to 0.93 mg/l for cobalt, and from 0.09 to 1.2 mg/l for nickel. In addition to their occurrence as the sulfide in coals, they may be dispersed in the aluminosilicate lattice. The Co/Ni ratio is 0.24 in Appalachian coals (table 10) and 0.46 in natural ground water in the area (DT-1, table 11). In the deep mine waters the Co/Ni ratio is 0.80 to 1.0 and is probably due to the increased mobility of the cobaltous ion under reducing conditions. In acid media the potential needed to overcome the higher oxidation state of cobalt is very high ($Co^{+2} = Co^{+3} + e^{-}$; Eo = 1.84 volts), much higher than that for iron, and this explains the near absence of cobaltic ions. The nickel ion is more stable and is not oxidized, as are cobalt and iron.

The greater concentrations of cobalt and nickel in mine water from the Lee shaft are found at the greater depths. However, water at the 310-foot level contains more cobalt and nickel than at the 330-foot level. Water at the 330-foot level is less reducing than at the 310-foot level and has a lower Fe^{+2}/Fe^{+3} ratio.

Zinc compounds are easily dissolved in acid solutions and in bicarbonate solutions. An excess of CO_2, which is found in the lower coal voids, increases the amount of zinc in solution by converting the carbonate to the bicarbonate. A slight increase in hydrogen ion activity at the bottom of the large strip pit lake (PL-1P), results in a 5-fold increase in zinc, a 70-fold increase in copper, and more than a 10-fold increase in lead. (See table 12.) Zinc values listed in table 14 for the two borehole samples should be considered excessive and suspect, as sampling was made through galvanized pipe. The analyses of water from borehole 17 show a rapid decline in zinc values as the well was pumped. The concentration of 7 mg/l collected after four hours of pumping represents a realistic value when compared with the bailed sample.

Zinc concentrations at the mine drain (BC-1) for the 1966 and 1967 water years averaged 0.83 and 0.79 mg/l, respectively. (See tables 15 and 16.) The zinc concentration in the bailed sample from borehole 17, from the upper Red Ash coal seam (table 14), showed a 10-fold increase over the average for the main mine discharge at BC-1. More than 4 mg/l were present in a sample from the Glen Lyon pump, and more than 2 mg/l were present at the bottom of the large strip-pit lake, PL-1P (table 12). Zinc concentrations appear to increase in mine waters in direct relation to increase in depth of collection.

Minor sulfide elements largely insoluble in acid media

The copper content of Appalachian coals is very low (table 10), being only slightly higher than that which is found in the average soil. The paucity of copper minerals may be attributed to the weak acids, formed during the formation of coals, which were inimical to copper retention. The copper ion varies from less than 0.01 mg/l to a maximum of 0.88 mg/l at the bottom of the large strip-pit lake (PL-1P, table 12). Copper from the major mine drain (BC-1) does not exceed 0.07 mg/l.

Silver is a comparatively rare element and probably occurs as the sulfide. The unpolluted ground water of the Llewellyn Formation (DT-1, table 11) contains 0.02 micrograms of silver per liter. The largest concentration found in the underground workings was slightly less than 0.03 mg/l, or more than 1,000 times greater than the concentration in water from the Llewellyn Formation.

The content of tin in Appalachian coals (table 10) may be only a fraction of that in the mine pools. Lead appears to be relatively abundant in coals and forms a large number of insoluble compounds. Both elements can exist in the bivalent and trivalent state and form complexes with an affinity for humic materials. The highest concentrations were found at the lower levels of the Lee shaft and were less than 0.55 mg/l and 0.28 mg/l for tin and lead, respectively. The main mine drain (BC-1) contained 0.01 to 0.09 mg/l tin and 0.03 to 0.05 mg/l lead during low and high flow periods and showed an increase in concentration as the discharge increased.

Relation between the major mine discharge, the total loads, and the ground-water level in the West basin

The acid water flows directly from the main mine drain (BC-1) into the North Branch of the Susquehanna River, where it becomes diluted and neutralized by the alkaline river water. The river stage is important because sufficient river water is needed during peak discharges from numerous mine drains to neutralize and oxygenate the mine water. The critical period, when most fish kills can occur, is during low flow in the river and during first high flow from the mine drains.

Ground-Water Discharge

A rating curve (fig. 34) shows the relation ~~was prepared~~ between the ground water

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Figure 34.--(Caption on next page)belongs near here.

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stage at borehole #4 and the major mine discharge (BC-1) from the basin. The mine-drainage hydrographs (figs . 19 & 20) are based entirely on ground-water discharge and assume no surface water enters the mine discharge above the gage. The gage is approximately 100 feet below the mine discharge point, and base flow (ground-water discharge) must be assumed for the rating curve to be meaningful.

Figure 34.--Rating curve for discharge at mine drain BC-1 for 1967.

Figures 35 through 41 show the hydrographs of test holes.

Figures 35 through 41.--(Captions on next page) belong near here.

Maximum fluctuations in ground- and mine-water stages occur in the upper reaches of Black Creek watershed and in adjoining basins, and only minor fluctuations occur in the West basin at borehole No. 4. For the most of the year the rating curve (fig. 34), for ground-water discharge, is a direct linear function of mine discharge (BC-1) and water-level stage in the flooded part of the West basin (BH-4), so that regular gaging stations may not be needed to monitor the entire ground-water discharge. A normal lag in the increase of ground-water discharge as the ground-water stage rises produces a parabolic rating curve for most observation wells. This phenomenon was not observed for the flooded mine, indicating an extremely rapid response to recharge conditions. The response of mine discharge to first spring runoff is direct and rapid, through fractures and mine openings, and only a small part is absorbed into the frozen soil and rocks. For this period of about 2 weeks (5 percent of the time), the rise in ground-water stage lags behind the increased rate of ground-water discharge, and values for the 2 weeks plot well below the rating curve (fig. 34). Finally, when ground-water storage is at equilibrium throughout the basin the rating curve becomes valid.

Figure 35.--Water level in test hole No. 1 penetrating the Pottsville Formation near the Susquehanna River.

Figure 36.--Water level in test hole No. 2 penetrating the Pottsville Formation and Mauch Chunk Formation.

Figure 37.--Water level in test hole No. 4 penetrating the West basin.

Figure 38.--Water level in test hole No. 5 penetrating the western pool Priscilla Lee basin.

Figure 39.--Water level in test hole No. 10 penetrating the East basin pool.

Figure 40.--Water level in test hole No. 15 which penetrates the Mauch Chunk Formation.

Figure 41.--Water level in test hole No. 17 penetrating the East basin pool.

Mine-Drainage Hydrograph

The dissolved-solids load increases as ground-water discharge increases, except for the 2-week period during the first spring rain. The 1966 hydrograph (fig. 42) records more than a 5-fold increase in discharge in the middle of February and a corresponding increase for dissolved-solids load. The 1967 hydrograph (fig. 43) shows a 7-fold increase for both discharge and load in the middle of March. Subsequent peak ground-water discharge for both water years shows a considerably reduced ratio of dissolved-solids load to discharge.

Figure 42.--(Caption on next page) belongs near here.

Figure 43.--(Caption on next page) belongs near here.

The relationship of cation concentrations to changes in discharge at BC-1 are shown on the precipitation-discharge hydrograph. (See figs. 44 and 45.) The concentration of iron is greater than any other cation at BC-1 during low-flow, but the iron concentration decreases and is exceeded by concentrations of calcium and magnesium during high flow.

Figures 44 and 45.--(Caption on next page) belong near here.

Figure 42.--Fluctuations in loads of dissolved constituents at mine drain BC-1 for the 1966 water year.

Figure 43.--Fluctuations in loads of dissolved constituents at mine drain BC-1 for the 1967 water year.

Figure 44.--Fluctuations in concentrations of dissolved constituents at mine drain BC-1 for the 1966 water year.

Figure 45.--Fluctuations in concentrations of dissolved constituents at mine drain BC-1 for the 1967 water year.

Frequency Distribution

Chemical tables 18 and 19, for the 1966 and 1967 water years, are based on time- and discharge-weighted composites. Only samples of like composition, as determined by specific conductance, and waters with similar discharge rates (±0.05 cfs) were composited. The sampling program was designed to measure both lateral and vertical changes in the ground-water reservoir as a function of time, and required continuous surveillance. Tons per day of iron, sulfuric acid, sulfate, and dissolved solids were calculated for each composite period. The weighted averages were computed for each water year and included the tons per day of each major constituent. Tables 15 and 16 provide the extremes and averages of the major constituents and loads for the two water years. Over 420 tons of iron and over 5,200 tons of dissolved solids were transported from the West End basin during the 1966 water year. During the 1967 water year, the tonnages increased to over 500 tons and 6,200 tons, respectively, primarily because of increased precipitation.

These composited data were used to prepare frequency curves for the West End mine drain (BC-1) that show the percentage of time that discharge, concentration, and load equaled or exceeded any given value. The curves for iron loads for both water years show the point of extreme departure from the most frequently observed range to be only about 5 percent of the time. The steep slopes for 1966 and 1967 (fig. 46) represent the first high-flow high-concentration water in the mine pool to be discharged in response to the first spring recharge. The low slopes represent both low-flow high-concentration water for dry, late summer and fall months and high-flow low-concentration water that follows in the wake of the first spring flushing of the mine pool. The discharge and load relationships are corroborated by the mine-drainage hydrograph and by the points of departure shown on the rating curve for ground-water discharge (fig. 47).

Figure 46.--(Caption on next page) belongs near here.

Figure 47.--(Caption on next page) belongs near here.

Figure 46.--Frequency distribution curve for total loads of iron at mine drain BC-1.

Figure 47.--Frequency distribution curve for discharge at mine drain BC-1 during 1966 and 1967 water years.

The composited time-load frequency curve for iron for the 1966 and 1967 water years (solid line, fig. 46) shows that a closer relationship exists between chemical loads of iron and the discharge-distribution curve (fig. 47) than exists between the frequency curve for the concentration of iron (fig. 48) and the discharge-distribution curve. A close relationship also exists between sulfate load and discharge.

For 5 percent of the time, the total load of iron exceeded 1.60 tons per day in the 1966 water year and 2.20 tons per day in the 1967 water year; thus, showing approximately a 30 percent increase in load in 1967. (See fig. 46.)

The concentration of iron, as shown in the frequency-distribution curve, exceeded 145 mg/l 50 percent of the time. (See fig. 48.) The dissolved-solids frequency-distribution curve for the 2 water years (1966-67) shows that the concentration was 1,700 mg/l or more 50 percent of the time. (See fig. 49.)

Figure 48.--Frequency distribution curve for total iron concentrations at mine drain BC-1 during 1966 and 1967 water years.

Figure 49.--Frequency distribution curve for total dissolved-solids concentration at mine drain BC-1 during 1966 and 1967 water years.

SUMMARY

The anthracite beds in the project area occur in three elongated, synclinorial basins. Complex folding and faulting within the area are responsible for the discontinuity of surface and underground mining activities and have influenced the derangement of surface- and groundwater flow patterns. Surface runoff, which drained originally into Black Creek and small eastward-flowing tributaries, has been diverted into underground mine workings. In addition, the surface drainage pattern has been redirected through numerous strip pits, around cast piles, and into fractures and subsidence cracks.

The underground mines have been abandoned and flooded for many years, and in most places the Bottom Red Ash, Top Red Ash, and Ross veins are completely submerged and are 100 percent robbed and badly caved. Four separate mine-water levels in the deep mines occur in the study area, and the hydrologic connections and movement of these large acid water bodies have been discussed in detail. The outfall from the West basin pool is into the Susquehanna River and results from direct gravity overflow through a tunnel into the West basin. Moreover, a seepage investigation along the Susquehanna River and adjacent areas shows that no acid ground water seeps out beyond the confines of the West basin, except the BC-1 outfall. The majority of the water in the East basin pool drains to the east, across the barrier pillar and through deep alluvial channels into the Glen Lyon mines (Susquehanna Company property), while minor amounts of mine water in the East basin possibly seeps through an obstructed underground tunnel and flows over the surface into the pool in the West basin. The two pools in the Pricilla Lee basin drain principally eastward into pools across the barrier; however, some acid waters seep out through an underground mine drainage tunnel and flow over the surface out of breached zones, into Stump Lake (West basin drainage) on the north and into Turtle Creek on the southern perimeter. Additional seepage occurs through spoil material and can be seen as perennial flow into Mocanaqua at BC-1A, which eventually reaches the Susquehanna River.

At present, the movement of waters in the East basin (approximate water level of pool: 605 feet) and the eastern pool of the Pricilla Lee basin (water level: 840 feet) are considered to be eastward through the barrier pillar into Susquehanna Company property (water level of pool: 602 feet). One possibility that should not be dismissed lightly is the discontinuing of pumping at Glen Lyon and the subsequent rise of water above the level in the East basin. In this eventuality, the hydraulic movement of acid mine water would be reversed.and would drain westward into the East basin pool. Although the water level in the Pricilla Lee pool would not be affected, the water level in the Glen Lyon pool can rise to 770 feet before overflowing the barrier pillar into the Wanamie Mines to the east, providing the barrier is not breached.

A rise of 100 feet or more of the strongly acidic Glen Lyon water would cause the water to overflow into the East basin pool and be relieved only through surface eruptions from the Lower Red Ash outcrop near the West End basin, and through increased flow through the gravity overflow tunnel connecting the two basins. In either event, this acid mine-water seepage would add measurably to the mine-water discharge at the Mocanaqua gravity outfall (BC-1). The ultimate effect of this occurrence would be to increase the discharge and concentrations of sulfuric acid and metals, and the loads in tons per day could be increased by a factor of three. In areas where acid mine water is recycled as surface water and then seeps into the deep mine workings through cracks and fissures, the acid pollution is particularly severe. The probable explanation lies with the increased hydrogen ion concentration available after oxidation and hydrolysis at the surface.

The continuous production of acidic, highly mineralized waters from abandoned mines requires that efforts be made to find methods to abate pollution of this kind. The relationships of mine-water levels and volumes to pH, acidity, sulfate, aluminum, manganese, total iron and iron in both oxidation states have been investigated in this report. The concentration of most common mineral constituents in mine waters increases during periods of low flow, and total loads are directly related to discharge. (See fig. 50.) Exceptions occur within the trace metals found in the gravity outfall (BC-1). Trace metals that increase with above average discharge are those that are inversely related to the concentration of sulfate and hydrogen ion, or are directly related to the dissolved oxygen-carbon dioxide concentration. Metals that would increase as discharge increases (table 8) are the alkaline earths, sulfide elements that are practically insoluble in acid solution, and those elements that become more soluble through the addition of oxygen and bicarbonate-enriched recharge waters.

The total dissolved-solids loads ranged from 9.06 to 62.7 tons per day during the 2 water years of this study and averaged 15.7 tons per day. The iron load for the same period ranged from 0.64 to 5.16 tons per day and averaged 1.27 tons per day.

Many methods are available for abatement of acid mine waters, and new methods are on the threshold of discovery. Probably the most easily adapted method for this area would be the construction of conveyance channels from the deep mines, strip pits and associated culm banks. This may be all that is required to restrict runoff from entering the deep mines and markedly reduce the amount of acid and metal loads discharging from the West basin gravity outfall (BC-1). The remaining mine-water discharge could be stabilized by treatment facilities.

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Table 1.--Lithologic logs of test holes.

Log of Test Hole 1

Black Creek Basin, Luzerne County, Pa.

Elevation of land surface 540.32 feet

Material	Thickness (in feet)	Depth (in feet)
ocene Series		
Spoil pile material, sandstone, shale, some coal	5	5
Spoil pile material, sandstone, shale, some coal	5	10
Spoil pile material, sandstone, shale, silt	13	23
Spoil pile material, sandstone, silt, some quartz conglomerate	3	26
nsylvanian System		
Pottsville Formation		
Conglomerate, quartz, white to medium gray, N5	5	31
Conglomerate, quartz, white to light gray, N7	5	36
Gravel, sand, silt	5	41
Conglomerate, quartz, white to medium light gray N6	5	46
Conglomerate, quartz, white to grayish black, N2	5	51
Conglomerate, quartz, white to grayish black, N2	5	56
Conglomerate, quartz, white to medium gray N5	5	61
Conglomerate, quartz, light gray N7	5	66
Conglomerate, quartz, light gray, N7	5	71
Conglomerate, quartz, very light gray N8	5	76
Conglomerate, quartz, very light gray, N8	5	81
Conglomerate, quartz, very light gray N8	9	90

Log of Test Hole 2

Black Creek Basin, Luzerne County, Pa.

Elevation of land surface 602.61 feet

Material	Thickness (in feet)	Depth (in feet)
Holocene Series		
Spoil pile, shale, sandstone, some coal	30	30
Pennsylvanian System		
Pottsville Formation		
Sandstone, very fine grained, light olive gray 5Y6/1	5	35
Sandstone, very fine grained, greenish gray 5GY6/1	5	40
Sandstone, very fine grained, greenish gray, 5GY6/1, some black shale	4	44
Sandstone, very fine grained, greenish gray 5GY6/1, some iron staining	1.5	45.5
Sandstone, very fine grained, greenish gray 5GY6/1	4	49.5
Sandstone, very fine grained, dark greenish gray 5GY4/1	2.5	52
Sandstone, very fine grained, light olive gray 5Y6/1	3	55
Sandstone, very fine grained, dark greenish gray 5GY4/1	5	60
Conglomerate, quartz, white, some sandstone, very fine grained	5	65
Conglomerate, quartz, white to medium gray N6, some iron staining	5	70

Log of Test Hole 2--Continued

Material	Thickness (in feet)	Depth (in feet)
Conglomerate, quartz, white to medium gray N6, some sandstone	10	80
Conglomerate, quartz, white to medium gray N6, some iron staining	4	84
Sandstone, very fine to coarse grained, white to medium light gray N7, some conglomerate	8	92
Sandstone, medium to coarse grained, white to medium light gray N7, some iron staining	6	98
Conglomerate, quartz, white, some iron staining	7	105
Sandstone, white, some iron staining	2	107
Conglomerate, quartz, some iron staining	15	122
Mississippian System		
Mauch Chunk Formation		
Sandstone, very fine grained, silty, dark greenish gray 5GY4/1	31	153
Shale, sandy, medium gray N5	4	157
Shale, sandy, dark gray N3	11	168
Shale, sandy, medium gray N5	2	170

Log of Test Hole 4

Black Creek Basin, Luzerne County, Pa.

Elevation 705.41

Material	Thickness (in feet)	Depth (in feet)
olocene Series		
Soil, moderate brown 5YR4/4	9	9
Soil, dark yellowish brown 10YR4/2	11	20
uaternary System		
Alluvium, subrounded pebbles, shale, siltstone and coal	10	30
Alluvium, sandy with coal	5	35
Alluvium, subrounded pebbles of shale, siltstone, and coal	15	50
Sand and gravel, fine to coarse, much coal	10	60
Sand and gravel, fine to coarse, some coal	10	70
Sand and gravel, fine to coarse	8.5	78.5
ennsylvanian System		
Llewellyn Formation		
Sandstone, very fine to medium grained, medium light gray N6	10.5	89
Shale, medium gray N5	10	99
Sandstone, coarse, light gray N7	36	135
No samples, Upper Red Ash bed	35	170
Sandstone, very fine to coarse grained, medium light gray	5	175
Shale, coal, grayish black N2	17	192
Coal, bone coal, shale, black N1, Upper Red Ash bed	18	210
Sandstone, very fine to medium grained, medium gray N5	13	223

Log of Test Hole 4--Continued

Material	Thickness (in feet)	Depth (in feet)
Coal lenses and shale, grayish black N2, Upper Red Ash bed	12	235
Sandstone, medium grained, medium light gray N6	5	240
Sandstone, fine to medium grained, some coal medium light gray N6	5	245
Sandstone, fine to medium grained, light gray N7	5	250
Sandstone, medium grained, light gray N7	10	260
Sandstone, fine grained, some coal, medium gray N5	5	265
Sandstone, medium to coarse grained, medium light gray N6, some shale, medium gray N5	5	270
Siltstone, medium dark gray N4	75	345
Sandstone, very fine to medium grained, medium light gray N6	10	355
Siltstone, dark gray N3	10	365
Sandstone, very fine to coarse grained, medium gray N5, and coal	5	370
No sample	11	381
Coal, black, Upper Red Ash bed	4	385
Sandstone, fine to medium grained, medium gray N5	5	390

Log of Test Hole 4--Continued

Material	Thickness (in feet)	Depth (in feet)
Sandstone, very fine to medium grained, light olive gray 5Y6/1	5	395
Sandstone, very fine to fine grained, silty, light gray N7	40	435
Sandstone, very coarse grained, medium dark gray N4, shale, black N1	4	439
No sample, Lower Red Ash bed	6	445
Sandstone, very fine to coarse grained, medium gray N5	10	455
Sandstone, very fine to coarse grained, medium gray N5, some coal	5	460
Sandstone, fine to very coarse light gray N7	24	484
Siltstone, medium gray N5	3	487
Sandstone, conglomerate, very fine to coarse, light gray N7	13	500

Log of Test Hole 5

Black Creek Basin, Luzerne County, Pa.

Elevation of land surface 1076.78 feet

Material	Thickness (in feet)	Depth (in feet)
Holocene Series		
Soil, dark yellowish brown 10YR4/2	4	4
Pennsylvanian System		
Llewellyn Formation		
Sandstone, coarse grained, medium gray N5, with iron-stained shale fragments	11	15
Sandstone, fine to coarse grained, light gray N7	5	20
Sandstone, fine to very coarse grained, light brownish gray 5YR6/1	5	25
Sandstone, very fine to coarse grained, medium light gray N6	5	30
Sandstone, fine to coarse grained, medium light gray N6	20	50
Sandstone, very fine to very coarse grained, medium gray N5, some shale and coal, Upper Red Ash bed	10	60
Sandstone, medium to very coarse grained, medium gray N5	10	70
Sandstone, fine to coarse grained, light gray N7	20	90
Shale, dark gray N3	5	95
Shale, medium dark gray	30	125
Sandstone, fine to medium grained, medium gray N5	25	150
Shale, silty, dark gray N3	10	160
Pottsville Formation		
Conglomerate of siltstone pebbles, medium gray N5	25	185

Log of Test Hole 5--Continued

Material	Thickness (in feet)	Depth (in feet)
Llewellyn Formation		
Sandstone, fine to medium grained, micaceous, medium light gray N6	35	220
Sandstone, fine to medium grained, medium gray	40	260
Sandstone, fine to medium grained, medium dark gray	40	300
Bone coal and pyrite	5	305
Coal, black N1, Lower Red Ash bed	10	315

Log of Test Hole 7

Black Creek Basin, Luzerne County, Pa.

Elevation 1,072.45 feet

Material	Thickness (in feet)	Depth (in feet)
locene Series		
Top soil and weathered bedrock, gravel, sand, silt, and clay, grayish yellow 5Y8/4	5	5
aternary System		
Gravel, sand, silt, and clay, pale yellowish brown 10YR6/2	5	10
nnsylvanian System		
Pottsville Formation		
Conglomerate, quartz, greenish gray 5GY6/1	53	63
Shale, light gray N7	2	65
Conglomerate, quartz, very light gray N8	5	70
Conglomerate, quartz, pinkish gray 5YR8/1	5	75
Conglomerate, quartz, yellowish gray 5Y8/1	5	80
Conglomerate, quartz, yellowish gray 5Y8/1 some coal and black shale	5	85
Conglomerate, quartz, very light gray N8	5	90
Conglomerate, quartz, very light gray N8, some shale, medium gray N5	5	95
Conglomerate, quartz, medium light gray N6	10	105
Conglomerate, quartz, yellowish gray 5Y8/1	30	135
Conglomerate, quartz, light gray N7	19	154
ssissippian System		
Mauch Chunk Formation		
Sandstone, very fine grain, medium gray N5	6	160
Shale, silty, sandy medium gray N5	5	165

Log of Test Hole 7--Continued

Material	Thickness (in feet)	Depth (in feet)
Shale, sandy, medium gray N5	5	170
Shale, sandy, light gray N7	15	185
Sandstone, very fine grained, silty, light olive gray 5Y6/1	10	195
Sandstone, very fine grained, light gray N7	5	200
Sandstone, very fine grained, light gray N7, some shale, grayish red 5R4/2	5	205
Shale, grayish red 5R4/2	10	215
Sandstone, very fine grained, medium gray N5	20	235

Log of Test Hole 8

Black Creek Basin, Luzerne County, Pa.
Elevation 745.25 feet

Material	Thickness (in feet)	Depth (in feet)
Holocene Series		
Spoil pile, shale, sandstone	4	4
Soil, grayish orange 10YR7/4	2	6
Sandstone, very fine to coarse grained, micaceous, medium light gray	9	15
Siltstone, sandy, brownish gray 5YR4/1 and shale, dark gray N3	5	20
Sandstone, very fine to coarse grained, silty, light brownish gray 5YR6/1	5	25
Sandstone, very fine to coarse grained, silty, medium gray N5	10	35
Sandstone, very fine to very coarse grained, micaceous, medium gray N5, and siltstone, dark gray N3	15	50
Sandstone, very fine to very coarse grained, medium gray N5	20	70
Sandstone, very fine to very coarse grained, light gray N7	10	80
Sandstone, very fine to coarse grained, medium dark gray	10	90
Sandstone, very fine to very coarse grained, light gray N7	30	120

Log of Test Hole 8--Continued

Material	Thickness (in feet)	Depth (in feet)
Sandstone, very fine to medium grained, medium gray N5	5	125
Sandstone, medium grained, medium dark gray, N4, some coal	5	130
Mississippian System		
Mauch Chunk Formation		
Sandstone, very fine to medium grained, silty medium gray N5	55	185

Log of Test Hole 9

Luzerne County, Pennsylvania

Elevation of land surface 813.19 feet

Material	Thickness (in feet)	Depth (in feet)
Holocene Series		
Gravel, sand, silt and clay, dark yellowish orange 10YR6/6	8	8
Gravel, sand, silt, and clay, dark yellowish brown 10YR4/2	4	12
Gravel, composed of sandstone pebbles and shale	6	18
Pennsylvanian System		
Pottsville Formation		
Sandstone, silty, greenish gray 5G6/1	5	23
Shale, silty, greenish gray 5G6/1	5	28
Shale, silty, greenish gray 5G6/1	4½	32½
Shale, silty, greenish gray 5G6/1	2½	35
Shale, silty, greenish gray 5G6/1	3	38
Shale, sandy, silty, greenish gray 5G6/1	5	43
Shale, sandy, silty, greenish gray 5G6/1	6	49
Shale, sandy, greenish gray 5G6/1 some grayish red 10R4/2	5	54
Shale, sandy, silty greenish gray 5G6/1 some grayish red 10R4/2	6	60
Sandstone, silty, greenish gray 5G6/1	5	65
Sandstone, silty, shaly, greenish gray 5G6/1	5	70
Shale, sandy, greenish gray 5G6/1 some grayish red 10R4/2	5	75
Shale, grayish red 10R4/2	5	80

Log of Test Hole 10

Black Creek Basin, Luzerne County, Pa.

Elevation of land surface 936.73

Material	Thickness (in feet)	Depth (in feet)
Holocene Series		
Soil, moderate yellowish brown 10YR5/4	5	5
Sand, silt, gravel, pale yellowish brown 10YR6/2	5	10
Gravel, sand, silt, pale, yellowish brown 10YR6/2	5	15
Silt, sandy, yellowish gray, 5Y8/1	5	20
Pennsylvanian System		
Llewellyn Formation		
Sandstone, fine to coarse grained, medium gray, N5	15	35
Sandstone fine to coarse grained, medium dark gray, N4, some shale at base	5	40
Coal, black, Upper Red Ash bed	5	45
Siltstone, sandy, medium gray, N5	15	60
Coal, black, shale lenses, Upper Red Ash bed	25	85
Shale, silty, dark gray, N3	10	95
Siltstone, sandy, medium dark gray N4	25	120
Sandstone, very fine to coarse grained, medium light gray N6	25	145
Siltstone, sandy, light gray, N7	5	150
Sandstone, very fine to coarse grained, medium dark gray, N4	5	155
Sandstone, silty, very fine grained medium light gray, N6	5	160
No sample	5	165
Sandstone, fine to coarse grained, medium light gray N6	20	185

Log of Test Hole 10--Continued

Material	Thickness (in feet)	Depth (in feet)
Siltstone, sandy, medium dark gray N4	5	190
Sandstone, fine to coarse grained, medium gray N5	10	200
Siltstone, dark gray, N3	15	215
Sandstone, silty, dark gray, N3	5	220
Siltstone, some shale, medium gray, N5	5	225
Sandstone, fine to coarse grained, medium dark gray, N4	10	235
Sandstone, silty, medium dark gray, N4	10	245
Sandstone, fine to coarse grained, medium gray, N5	20	265
Siltstone, medium dark gray, N4	10	275
Sandstone, fine to coarse grained, medium dark gray, N4	25	300
Siltstone, medium dark gray, N4	5	305
Sandstone, fine to coarse grained, medium dark gray, N4	5	310
Siltstone, medium dark gray, N4	10	320
Sandstone, fine to coarse grained, dark gray, N3	5	325
No sample	5	330
Sandstone, fine grained, medium gray, N5	5	335
No sample (lost in fractures)	70	405
Sandstone, very fine to coarse grained, dark gray, N3	5	410
Sandstone, fine to coarse grained, medium dark gray, N4 (wood fibers at bottom from mine prop.), Lower Red Ash bed.	3	413

Log of Test Hole 12

Black Creek Basin, Luzerne County, Pa.

Core Hole AX size

Elevation of land surface 933.70 feet

Material	Thickness (in feet)	Depth (in feet)
ternary System		
Gravel and sand	48.5	48.5
nsylvanian System		
Llewellyn Formation		
Sandstone, medium to coarse grained, micaceous, medium light gray, N6	1.5	50
Sandstone, medium to coarse grained, micaceous, medium light gray, N6, some coal and shale laminae	7	57
Sandstone, medium to coarse grained, micaceous, light gray, N7, few coal and shale laminae	20	77
Sandstone, medium to very coarse grained, medium light gray, N6, few quartz pebbles to 1/4 in., few coal and shale laminae	20	97
Shale and siltstone, black, thinly laminated	1	98
Shale, medium dark gray, N4, thinly laminated some very fine grained sandstone	6	104
Sandstone, very fine to medium grained, very micaceous medium gray, N5	10	114
Sandstone, fine to coarse grained, micaceous, medium light gray, N6, some shale and coal laminae	3	117
Sandstone, fine to very coarse grained, medium dark gray, N4, some coal and shale laminae	6.5	123.5
Coal, black	.2	123.7
Shale, black, silty	.3	124

Log of Test Hole 12--Continued

Material	Thickness (in feet)	Depth (in feet)
Siltstone, sandy, medium dark gray N4	5.0	129
Shale, silty, black	.6	129.6
Sandstone, silty, medium light gray, N6	2.4	133.
Sandstone, fine to medium grained, medium gray N5	3.7	136.7
Siltstone, medium gray N5	1.3	138.
Shale, silty, black, some pyrite near base	2.1	140.1
Coal, black	.2	140.3
Shale, black, abundant pyrite stringes	.35	140.65
Coal, black	.35	141.
Shale, black	.2	141.2
Coal, black	.25	141.45
Shale, black	.05	141.50
Coal, black	1.50	143.00
No sample	.9	143.9
Coal, black, Baltimore bed	4.0	147.9
Boney coal, black	2.0	149.9
Boney coal, black	2.0	151.9
Boney coal, black	2.0	153.9
Shale, black, some coal	1.0	154.9
Shale, black, some coal	2.0	156.9
Shale, black, some coal	2.0	158.9

Log of Test Hole 12--Continued

Material	Thickness (in feet)	Depth (in feet)
Sandstone, fine to medium grained, medium gray, N5 some shale laminae	2.0	160.9
Shale, silty, black	1.8	162.7
Sandstone, very fine to fine grained, medium gray, N5	1.4	164.1
Siltstone, sandy, medium gray, N5	1.9	166.0
Siltstone, sandy, medium dark gray, N4	2.4	168.4
Sandstone, fine to medium grained medium dark gray, N4	3.6	172
Core reduced to BX size at 172 feet		
Sandstone, fine to very coarse grained, medium gray, N5	9	181
Sandstone, silty, some thin coal veinlets	9	190
Sandstone, fine to very coarse grained to conglomerate layers, medium light gray, N6, some coal slicks	13	203
Sandstone, fine to medium grained, medium gray, N5	1.1	204.1
Sandstone, conglomeratic, medium gray, N5	2.7	206.8
Sandstone, fine to very coarse grained, medium light gray, N6	5.2	212
Sandstone, fine to very coarse grained to conglomerate, medium light gray, N4	16	228
Sandstone, fine to very coarse grained, medium gray, N5 many coal and shale lenses, some conglomerate pebbles near base	6	234
Sandstone, fine to very coarse grained, conglomeratic with quartz pebbles, medium light gray N6	8.2	242.2
Shale, silty, some very fine sandstone laminae, dark gray, N3	11.8	254

Log of Test Hole 12--Continued

Material	Thickness (in feet)	Depth (in feet)
Shale, siltstone, laminae, some coal, black	8	262
Shale, silty, black	16.6	278.6
Coal, black	1.5	280.1
Shale, silty, dark gray, N3	1.9	282
Shale, black, grades to siltstone at bottom	7.0	289
Shale, black	1.5	290.5
Coal, boney	.2	290.7
Shale, black	1.2	291.9
Coal, black	.3	292.2
Shale, black	.3	292.5
Coal, black, highly fractured	4.7	297.2
Shale, black, some coal	.5	297.7
Coal, black	1.4	299.1
Shale, black, some coal	2.6	301.7
Shale, black, silty	10.0	311.7
Shale, black, siltstone, dark gray, N3	10	321.7
Shale, black, grades to sandstone at base	18	339.7
Sandstone, fine to medium grained, medium light gray, N6, very micaceous	13	352.7
Sandstone, medium to very coarse grained to conglomeratic medium gray, N5	6	358.7
Shale, grayish black, N2	6	364.7
Coal, black, broken up at base, some shale	5	369.7
Coal and shale	6.5	376.2

Log of Test Hole 12--Continued

Material	Thickness (in feet)	Depth (in feet)
No sample	3.8	380
Shale, dark gray, N3, silty	1.0	381
Shale, medium dark gray, N4	2.1	383.1
Siltstone, medium gray N5, shaly	2.6	385.7
Shale, silty, medium dark gray, N4	2.8	388.5
No sample	3.9	392.4
Siltstone, medium gray, N5	.8	393.2
Sandstone, very fine to fine grained, medium gray, N5, micaceous	7.8	401.0
Sandstone, medium to very coarse grained, medium gray, N5, micaceous	9.0	410.0
Conglomerate, sandy, medium light gray, N6, micaceous	4.0	414.0
Sandstone, medium to very coarse grained, medium gray, N5, very micaceous, conglomeratic at base	15	429.0
Sandstone, fine to very coarse grained, and conglomeratic, medium gray, N5	2.4	431.4
Shale, black, some coal veinlets, soft	2.6	434.0
Shale, grayish black, N2, soft	6.0	440.0
Boney coal, shale, black	5.7	445.7
Coal, black	3.3	449.0
Coal, black	1.2	450.2
Coal, honey	.3	450.5
ennsylvanian System		
Pottsville Formation		
Siltstone, sandy, micaceous	2.5	453.0
Sandstone, medium to coarse grained, medium gray, N5	4.5	457.5
Conglomerate, quartz, some sandstone, dark gray, N3	2.5	460.0

Log of Test Hole 15

Black Creek Basin, Luzerne County, Pa.

Elevation of land surface 945.07 feet

Material	Thickness (in feet)	Depth (in feet)
ssissippian System		
Mauch Chunk Formation		
Shale, grayish red 5R4/2	0	5
Shale, grayish red 5R4/2	3.5	8.5
Shale, grayish red 5R4/2	1.5	10
Shale, grayish red, 5R4/2 some greenish gray 5GY6/1	3.5	13.5
Shale, grayish red 5R4/2	4	17.5
Shale, grayish red 5R4/2	2.5	20.0
Shale, moderate red	10	30
Shale, moderate red 5R5/4 some greenish gray 5GY6/1	5	35
Shale, grayish red 5R4/2	2.5	37.5
Shale, greenish gray 5GY6/1	2.5	40.0
Shale, greenish gray 5GY6/1 some grayish red 5R4/2	5	45
Shale, light gray	5	50
Siltstone, sandy, medium light gray N6	25	75

Log of Test Hole 16

Core Hole AX size

Black Creek Basin, Luzerne County, Pa.

Elevation of land surface 875.00 feet

Material	Thickness (in feet)	Depth (in feet)
ennsylvanian System		
Llewellyn Formation		
Siltstone, medium gray, N5	15	15
Sandstone, fine to medium grained, medium gray, N5	5	20
Siltstone, medium gray, N5	8	28
Sandstone, fine to coarse grained, dark gray N3	20	48
Coal, black	4	52
Sandstone, fine grained, dark gray, N3	14.5	66.5
Shale, silty, grayish black, N2	1.5	68.0
Sandstone, fine to very coarse grained to conglomeratic, medium dark gray, N4	20.2	88.2
Shale, black	7.8	96.0
Sandstone, fine grained, medium gray, N5	.8	96.8
Shale, black	1.7	98.5
Sandstone, fine grained, medium gray, N5	1.5	100.0
Sandstone, fine to coarse grained, medium dark gray, N4	4.5	104.5
Sandstone, fine to very coarse to conglomeratic medium dark gray, N4	2.5	107
Sandstone, fine to coarse grained medium gray, N5	31.0	138
Siltstone, shaly, black	1.0	139

Log of Test Hole 16--Continued

Material	Thickness (in feet)	Depth (in feet)
Sandstone, fine to very coarse grained to conglomeratic, medium dark gray, N4	40	179
Conglomerate, medium gray, N5	38	217
Sandstone, fine to coarse grained, medium gray, N5	24	241
Sandstone, fine grained, medium gray	1	242
Shale, black	25	267
Shale and coal	1.5	268.5
Shale, black	.5	269.0
No sample	1	270
Shale, black, some coal	3	273
Sandstone, fine to medium grained, medium dark gray, N4	58	331
Shale, silty, black	12.5	344.5
Coal with pyrite	2.5	347.0
Sandstone, fine grained, medium gray N5	1.0	348
andstone, fine to coarse grained, medium dark gray, N4	16.5	364.5
andstone, fine grained, medium gray, N5	11	375.5
andstone, fine to medium grained, medium dark gray, N4	8.5	384.0
ndstone, fine grained, medium dark gray, N4	6.0	390
ndstone, fine to coarse grained, medium gray N5	1	391
glomerate, medium gray, N5	5.5	396.5
dstone, very fine to fine grained, medium gray, N5	1.5	398.0

Log of Test Hole 16--Continued

Material	Thickness (in feet)	Depth (in feet)
Sandstone, fine grained, some silt, dark gray N3	5	403
Sandstone, fine to medium grained, some siltstone layers, medium dark gray, N4	3.5	406.5
Sandstone, fine grained, medium gray, N5	1.0	407.5
Void	.5	408.0
Sandstone, fine grained, medium gray, N5	2.0	410
Void	.5	410.5
Shale, black	.5	411
Void	.5	411.5
Sandstone, fine grained, medium gray, N5	1.0	412.5
Void	1.5	414
Shale, black, some 1" to 2" void spaces	4.0	418
Void	1.5	419.5
Coal, black, Upper Red Ash bed	5.1	424.6
Shale, black, some 1" to 2" void spaces	1.4	426.0
Coal with shales lenses	5.5	431.5
Shale, black, sandstone at bottom	4.0	435.5
Reduce size of hole to BX		
Sandstone, fine grained, medium gray, N5	7.5	443.0
Shale, sandy, dark gray, N3	2.0	445
Sandstone, shaly, medium gray, N5	1.5	446.5
Sandstone, fine to coarse grained, medium gray, N5, pyrite	7.5	454.0

Log of Test Hole 16--Continued

Material	Thickness (in feet)	Depth (in feet)
Sandstone, fine to medium grained, medium gray N5	9.5	463.5
Shale, dark gray, N3	1.5	465
Coal, black	.3	465.3
Shale, dark gray, N3	3.7	469.0
Sandstone, fine to very coarse to conglomeratic, medium gray, N5	5.0	474.0
Conglomerate, with coarse sandstone layers, medium gray, N5	8.5	482.5
Sandstone, very fine to medium grained, medium gray N5	11.5	494.0
Sandstone, fine to medium grained, medium gray, N5, some pyrite	.5	494.5
Coal, black, some shale lenses black, Lower Red Ash bed	5.5	500.0
Coal, black, some shale lenses black	9.0	509.0
Pottsville Formation		
Sandstone, fine to very coarse to conglomeratic at bottom, medium gray	5.0	514.0

Log of Test Hole 17

Black Creek Basin, Luzerne County, Pa.

Elevation of land surface 942.77 feet

Material	Thickness (in feet)	Depth (in feet)
locene Series		
Soil, sandy, light gray, N7	1.0	1.0
ennsylvanian System		
Pottsville Formation		
Conglomerate, quartz, some sandstone, light gray, N7	12.5	13.5
Shale, black, some coal	4.5	18.0
Shale, black, silty, soft	5.0	23.0
Sandstone, fine to medium grained to conglomeratic light gray, N7	8.0	31.0
Shale, black, silty, soft	.5	31.5
Sandstone, fine to coarse grained to conglomeratic very hard, light gray, N7	3.5	35.0
Coal, black, some shale, Lower Red Ash bed	4.0	39.0
Pottsville Formation		
Sandstone, fine to very coarse to conglomeratic light gray, N7	18	57.0
Sandstone, fine to medium grained, dark gray, N3 micaceous	8	65.0
Conglomerate, some sandstone, white N9, very hard	53	118.0
ssissippian System		
Mauch Chunk Formation		
Shale, silty, greenish gray 5GY6/1	60	178.0
Sandstone, fine to medium grained, greenish gray 5GY6/1	33	211.0
Sandstone, fine to medium grained, greenish gray, 5GY6/1, hard	12	223

Log of Test Hole 17--Continued

Material	Thickness (in feet)	Depth (in feet)
Siltstone, shaly, light greenish gray 5GY8/1	22	245.0
Sandstone, very fine to fine grained, light greenish gray 5GY8/1	27	272.0
Shale, silty, light greenish gray 5GY8/1	15	278.0
Sandstone, very fine grained, silty, greenish gray 5GY6/1	33	320.0
Shale and siltstone interbedded, greenish gray 5GY6/1 to grayish red	12	332.0
Shale, some siltstone, grayish red SK 4/2	103	435.0
Shale, some siltstone, light greenish gray 5GY8/1	40	475.0
Sandstone, very fine to fine grained, shaly, light greenish gray 5GY8/1	41	516.0
Sandstone, fine grained, greenish gray 5GY6/1	9	525.0
Sandstone, very fine grained, silty, light greenish gray 5GY8/1	35	560.0
Shale, very light gray, N8, soft	1	561.0
Siltstone, shaly, light greenish gray 5GY8/1 soft	40	601.0
nnsylvanian System		
lewellyn Formation		
Shale, siltstone, sandstone, conglomerate, and coal chips, soft, probably fault gauge zone	19	620.0
Shale and siltstone, dark gray, N3, soft	21	641.0
Shale and coal, black, soft	5	646.0
Coal, black, some shale in lower part, Lower Ross bed	20	666.0

Log of Test Hole 17--Continued

Material	Thickness (in feet)	Depth (in feet)
Sandstone, fine to coarse grained to conglomeratic medium dark gray, N4	33	699.0
Shale, black, some siltstone and coal	53	752.0
Shale, black, some coal	5	757
Sandstone, fine to medium grained, little sample recovery--probably working into fractures in rock over mine workings	54	811.0
Void space, underground mine tunnel in Upper Red Ash coal bed	8	819.0
Sandstone, fine to very coarse to conglomeratic, medium gray, N5, hard	69	888.0
Coal, black, soft, caving, Lower Red Ash bed	13	901.0

Log of Test Hole 19

Black Creek Basin, Luzerne County, Pa.

Elevation of land surface 814.69 feet

Material	Thickness (in feet)	Depth (in feet)
locene Series		
Soil, clay, silt, sand	4.5	4.5
nnsylvanian System		
Pottsville Formation		
Conglomerate, light gray N7	26.5	31.0
Conglomerate, some sandstone, light gray, N7	16	47
Shale, some coal, black	9	56
Conglomerate, light gray, N7, some iron staining	5	71
Conglomerate, medium dark gray, N4	8	79
Shale, black, sandstone, black	4	83
Conglomerate, light gray, N7	13	96
Conglomerate, sandy, medium dark gray, N4	7	103
ssissippian System		
Mauch Chunk Formation		
Shale, silty, medium light gray, N6	13	116
Shale, sandy, greenish gray 5GY6/1	10	126
Sandstone, shale, clay, light gray N7	4	130

Log to Test Hole 20

Black Creek Basin, Luzerne County, Pa.

Elevation of land surface 1,072.45 feet

Material	Thickness (in feet)	Depth (in feet)
olocene Series		
Soil, light olive gray 5Y6/1	5	5
ennsylvanian System		
LLewellyn Formation		
Sandstone, very fine to fine grained weathered yellowish gray 5Y7/2	5	10
Sandstone, very fine to medium grained, yellowish gray 5Y7/2	5	15
Sandstone, very fine to medium grained, light gray N7	10	25
Sandstone, very fine to medium grained, grayish orange 10YR7/4	10	35
Sandstone, very fine to coarse grained, medium gray N5	5	40
No sample	4	44
Sandstone, very fine to coarse grained, medium light gray N6	11	55
Sandstone, very fine to coarse grained, medium gray N5	10	65
Sandstone, very fine to medium grained, silty medium light gray N6	10	75
Sandstone, very fine to coarse grained, medium dark gray N4	15	90
Coal, black, N1, Lower Red Ash bed	10	100
Coal, bony, siltstone, dark gray N3	5	105

Table 2.--Precipitation at Mocanaqua, Pennsylvania during 1966

(In inches)

DAY	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1		.15	.04	.04	.04		.02			1.00		
2		.09		.05				.03			.22	
3		.03		.18					.11		.28	
4			.15	.03					.70		.02	
5			.37	.02			.17					.02
6					.13		.31				.07	.02
7				.15		.02	.91					.08
8					.27		.02				.19	
9					.45						.04	
10		.31			.01	.62				.12	.57	.47
11		.02	.01	.01				.09			.03	.01
12			.30		.64							
13		1.07	.03	.05	.07						.01	.33
14						.05		1.31	1.17			.06
15		.04				.01	.10	.05	.17			
16		.12			.02			.87		.15	.01	
17					.01			.02			.10	
18					.06					.17		
19	Start		.02	.04	.18		.01		.01	.63		
20	.03								.36	.02		.28
21	.02		.01	.10	.39	.02			.58	.02	.01	.02
22	.03		.06	.02	.14	.01	.01	.35	.35			
23	.55		.01	.58	.03			.16	.05			
24		.42	.88	.25	.02							.29
25		.58		.01					.06		.13	.02
26	.01		.03	.01	.01				.02		.06	
27	.02			.61			.07	.03				
28		.25		.30	2.28	.37	.74		.04	...	1.25	.06
29	.07				.09	.01	.03		.17		.02	.42
30	.38		.03	.52		.01			.11			
31			.02		.02							
TOTAL	---	3.08	1.96	2.97	4.86	1.12	2.39	2.91	3.90	2.11	3.01	2.08

Table 3.--Precipitation at Mocanaqua, Pennsylvania during 1967

(In inches)

DAY	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1	.03			.01			.01	.91				
2	.01	.25	.01		.57						1.77	.98
3		.06	.02		.58		.84	3.35				.03
4		.03	.01				.06	.56		.01	.30	
5		.07	.80	.09			.01					
6		.11	.93	.26	.41	.02	.02					
7	.20	.27	.79	.12	.88							.04
8	.04				.02							.12
9		.01					.74	.75	.26	.17		
10				.09			.03		.70	.54		.21
11					.84	.03	.06				.02	.17
12						.01					.10	.27
13												
14		.02		.13	.10					.13	.07	
15			1.63		.61	.01	.20				.03	
16		.05	.03			.01						
17		.01	.18	.48		.01					.32	
18		.07		.15		.26	.09			.62	.05	.03
19					.55	.08						
20		.02		.01	.07			.16		.20		
21		.17	.18	.03			.14	.09	.91	.21		
22	.01		.05	.12						.20	.13	.18
23	.01	.03	.03		.03	.15	.19				.22	
24		.02		.38			.74	.02	.03			
25						.13	.28	1.21		1.16	.19	
26			.02	.19				1.47				
27	.76	.01		.74	.03			.74				
28	.03		.14			.01	.48		1.12			.63
29	.03		.11		.87		.04		.34		.07	.04
30						.04					.18	
31	.15		.02									.34
OTAL	1.27	1.20	4.95	2.80	5.56	.76	3.93	9.26	3.36	3.24	3.45	3.04

Table 4.--Precipitation at Lee, Pennsylvania during 1966

(In inches)

DAY	JAN	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1		.12	.02	.05	.08					1.15		
2		.14	.03	.07								
3		.03		.18							.42	
4		.01	.18									
5			.35									
6					.05						.07	.02
7				.11			.55					.08
8					.30						.15	
9					.57						.02	
10		.33				.36				.10	.58	.52
11	Start										.07	.03
12			.12		.55							
13	.05	1.12	.11		.05							.32
14	.01	.02			.02			1.34				.08
15	.02						.06					
16	.01	.05			.06			.85		.10		
17											.02	
18					.03					.15	.10	
19	.02				.19					.70		
20												.35
21	.01			.08	.42			.25				.04
22	.10			.03	.11			.25				
23	.75			.38								
24		.38	.72	.37								.44
25		.61	.12	.02					.05			.02
26	.09		.04								.18	
27	.02			.54					.05			
28		.27		.38	2.29		1.35				1.50	.07
29	.12				.07				.20			.46
30	.63		.10	.45					.07			
31	.02											
TOTAL	---	3.08	1.69	2.66	4.79	.36	1.96	2.69	.37	2.20	3.11	2.43

Table 5.--Precipitation at Lee, Pennsylvania during 1967

(In inches)

DAY	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1								.41				
2		.35			.36		.52				1.67	
3							.17	3.32				.71
4		.01					.04	.97			.31	
5			.75	.05				.06				
6		.21	.90	.23	.39							
7	.22	.11	.53	.10	.81							.01
8		.28										.12
9							1.09	.74	.02	.07		
10				.06			.05		.93	.49		.17
11					.79		.77					.02
12	.02										.09	.37
13											.12	
14					.09					.13	.08	
15			1.73		.70		.19				.01	
16			.07									
17		.05	.29	.35						.02	.38	
18		.02		.10			.31			.69	.06	
19		.10			.37	.16				.12		
20		.10					.13	.38				
21		.06	.15				.06	.06	1.36			
22			.10	.12					.03		.11	.13
23			.06			.14	.17				.24	
24							.65	.01	.02			
25						.09	.49	1.15		1.20	.19	.14
26				.07				1.49				.05
27	.71			.79				.63				
28			.04				.47		.37			.78
29	.04		.21		.89		.03		.09			.06
30						.02					.29	
31	.03							.01				.37
L	1.02	1.29	4.83	1.87	4.40	.72	4.83	9.23	2.82	2.72	3.55	2.93

Table 6.--Correlation of waters in Black Creek Basin

Cations	Percent acidity as $H_2SO_4$1/	Map numbers	Water bearing formation2/
$Al\text{-}Fe^{+3}\text{-}Mg$	77	BC-1A	Qmw
$Mg\text{-}Al\text{-}Fe^{+2}\text{-}Fe^{+3}$	58	5	URA
$Mg\text{-}Al\text{-}Fe^{+2}$	53	20	LRA
Mg-Al-Ca	52	BC-2	(mixed)
$Fe^{+2}\text{-}Mg\text{-}Ca\text{-}Fe^{+3}$	51	PL-MS (190 feet)	UR
Fe^{+2}	50	PL-MS (310 feet)	URA
Fe^{+2}	46	PL-MS (390 feet)	LRA
$Fe^{+2}\text{-}Mg\text{-}Ca$	43	PL-MS (350 feet)	URA
Mg-Al-Ca	43-47	DT-2, PL-2P	URA
$Mg\text{-}Fe^{+2}\text{-}Fe^{+3}\text{-}Al\text{-}Ca$	42	Glen Lyon pump	Forge
$Mg\text{-}Fe^{+2}\text{-}Ca$	40	PL-MS (175 feet)	B
Mg-Ca-Al	24-41	PL-1P (27 feet), PL-1S, 4	B-LRA
$Mg\text{-}Ca\text{-}Fe^{+2}$	24-28	BC-1, 10, 17, (888 feet)	LRA
Mg-Ca	24-26	8, PL-MS (39 feet), PL-1P(top)	Pp-Pl
$Ca\text{-}Mg\text{-}Fe^{+2}$	22	1	Pp
Ca-Mg	15-16	PL-6P, 9	Qgf-Mm
Ca	(-22)—19	2, DT-1, 19	Pp-Mm
Ca	(-46)	17(462 feet), 30	Mm
Ca	(-90)—(-57)	15, 7, 17 (305 feet) Turtle Creek	Mm

tive value, in parenthesis, refers to percent alkalinity.

figure 3A for explanation of geologic symbols.

Table 7.--Dominant ion relationship to dissolved solids

<table>
<tr><td>issolved solids (mg/1)</td><td colspan="2">250</td><td colspan="5">250-500</td><td colspan="3">500-1,000</td><td colspan="5">1,000-3,000</td><td colspan="3">3,000</td></tr>
<tr><td>inant Anion</td><td>HCO_3</td><td colspan="6">Neutral SO_4</td><td colspan="6">Acid SO_4</td><td colspan="5">Netural SO_4</td></tr>
<tr><td>ndary Anion</td><td>SO_4</td><td colspan="3">HCO_3</td><td colspan="3">Acid SO_4</td><td colspan="6">Neutral SO_4</td><td colspan="5">Acid SO_4</td></tr>
<tr><td>inant Cation</td><td colspan="4">Ca</td><td colspan="4">Mg</td><td colspan="3">Fe^{+3}</td><td colspan="2">Al</td><td colspan="3">Mg</td><td colspan="2">Fe^{+2}</td></tr>
<tr><td>ndary Cation</td><td colspan="3">Mg</td><td colspan="2">Al</td><td>Ca</td><td colspan="3">Fe^{+2}</td><td>Mg</td><td colspan="2">Ca</td><td colspan="2">Fe^{+3}</td><td>Al</td><td colspan="2">Ca</td><td>Mg</td></tr>
</table>

Table 8.--Trace metal analyses of the major mine drain (BC-1) for low and high discharge rates 1/

Constituent	Concentration in mg per liter 1.7 cfs discharge (low flow)2/	Concentration in mg per liter 10.0 cfs discharge (high flow)	Change with increased discharge3/
Aluminum (Al)	16	13	-
Barium (Ba)	.012	.020	+
Beryllium (Be)	.023	.018	-
Boron (B)	.029	< .090	+
Chromium (Cr)	< .017	< .045	+
Cobalt (Co)	.66	.45	-
Copper (Cu)	.014	.070	+
Iron (Fe)	> 150	> 90	-
Lead (Pb)	.029	< .050	+
Lithium (Li)	.10	.080	-
Manganese (Mn)	32	22	-
Molybdenum (Mo)	.004	< .020	+
Nickel (Ni)	1.2	.83	-
Rubidium (Rb)	.007	.005	-
Silver (Ag)	< .002	.005	+
Strontium (Sr)	.88	.72	-
Tin (Sn)	< .015	< .090	+
Titanium (Ti)	< .015	< .027	+
Vanadium (V)	- < .015	< .045	+
Zinc (Zn)	< .7~~2~~ 3	< 2.30	+
Zirconium (Zr)	< .025	< .090	+
Dissolved solids (residue on evaporation at 180°C)	2,340	1,800	-

---

1/ Analyses determined by the Spectrographic Laboratory, Denver, Colorado.

2/ Low flow measurement made at time of sample collection October 4, 1965.

3/ (+) refers to increased concentration with increase in discharge;

(-) refers to decreased concentration with increase in discharge.

Table 9.--Trace metal analyses of waters in two test holes penetrating Lower Red Ash coal seams mined in the East basin [1]

Constituent	Concentration in milligrams per liter	
	No. 10, sampled 405 feet Lat 41°09'44N76°06'36"	No. 17, sampled 888 feet Lat 41°09'50"N76°05'46"
Aluminum (Al)	3.8	9.0
Barium (Ba)	.02	.03
Beryllium (Be)	.015	.035
Boron (B)	.02	<.03
Chromium (Cr)	<.01	<.02
Cobalt (Co)	.93	.15
Copper (Cu)	.007	<.006
Iron (Fe)	>200	>380
Lead (Pb)	<.02	<.04
Lithium (Li)	.20	.15
Manganese (Mn)	53	90
Molybdenum (Mo)	<.008	<.012
Nickel (Ni)	1.2	.30
Rubidium (Rb)	.013	<.025
Silver (Ag)	<.002	<.004
Strontium (Sr)	1.7	4.4
Tin (Sn)	<.02	<.04
Titanium (Ti)	<.02	<.04
Vanadium (V)	<.002	<.04
Zinc (Zn)	3.0	4.0
Zirconium (Zr)	<.10	<.10
Bismuth (Bi)	Not detected	Not detected
Cadmium (Cd)	do.	do.
Gallium (Ga)	do.	do.
Germanium (Ge)	do.	do.
Dissolved solids (residue on evaporation at 180°C)	4,180	7,550
pH value	--	--
Temperature (°C)	15.0	11.9

---

[1] Analyses determined by the Spectrographic Laboratory, Denver, Colo.

Table 10.--Trace metal analyses of water from various depths in the

lat 41°09'14", long 76°05'56"

Constituent	in ppm	Concentration in mg per liter			
	Average in Appalachia coals[b]	285 feet below land surface datum	310 feet below land surface datum	330 feet below land surface datum	390 feet below land surface datum
luminum (Al)	--	0.07	0.08	0.20	0.60
arium (Ba)	--	.02	.02	.03	<.06
eryllium (Be)	2.4	.01	<.03	.06	<.06
ismuth (Bi)	[c]1.0	.01	.01	.01	--
oron (B)	55	.02	<.06	<.13	<.55
admium (Cd)	[c].2	.02	.02	.02	--
hromium (Cr)	15	.01	.01	.01	<.28
obalt (Co)	4.7	.13	.24	<.13	.72
opper (Cu)	15	.01	.01	<.04	.10
ron (Fe)	--	>57	>140	>320	>550
ead (Pb)	[c]30	.01	.01	.02	<.28
ithium (Li)	[c]15	.05	.08	.15	.16
anganese (Mn)	--	14	35	75	160
olybdenum (Mo)	3.8	.01	.01	.01	<.11
ickel (Ni)	20	.24	.33	.13	.88
ubidium (Rb)	--	.00	<.01	<.02	<.04
Silver (Ag)	--	.00	<.01	<.02	<.03
Strontium (Sr)	--	.19	.63	1.2	.99
Tin (Sn)	.1	<.04	<.09	<.20	<.55
Titanium (Ti)	407	.02	<.06	<.13	<.17
Vanadium (V)	21	.01	.01	.01	<.28
Zinc (Zn)	12	.30	.44	.68	<14
Zirconium (Zr)	[c]150	.04	.09	.17	<.55
Dissolved solids (residue on evaporation at 180°C)		1,150	2,880	6,520	11,000
pH value		5.91	5.77	6.59	6.08
Temperature (°C)		10.4	10.7	11.2	11.8

---

[a] Analyses determined by the Spectrographic Laboratory, Denver, Colo.
[b] From "Coal Science" - Zubovic, 1966; Zubovic, et al., 1966, G.S. Bul. 1117-C
[c] From "Coal, its formation and composition" - Francis, 1954, p.498

Table 12.--Trace metal analyses of water from surface and bottom of the

Table 1..--Trace metal analyses of water from two springs in the Pottsvill

Formation 1/

Constituent	Concentration in milligrams per liter West End basin rock tunnel DT-1	 Priscilla Lee basin discharge PL-1S 2/	 Multiple increase
Aluminum (Al)	0.24	0.38	< 2
Barium (Ba)	.070	.034	.5
Beryllium (Be)	.0005	.0006	1+
Boron (B)	.006	.015	2+
Chromium (Cr)	<.0002	.004	20
Cobalt (Co)	.006	.07	10+
Copper (Cu)	.001	.033	33
Iron (Fe)	.14	.46	3
Lead (Pb)	.004	.012	3
Lithium (Li)	.001	.016	16
Manganese (Mn)	.21	1.6	8
Molybdenum (Mo)	<.00007	<.002	30
Nickel (Ni)	.013	.088	7
Rubidium (Rb)	.0004	.002	5
Silver (Ag)	<.00002	.0004	20
Strontium (Sr)	.10	.05	.5
Tin (Sn)	< .0004	<.008	20
Titanium (Ti)	.0004	.003	7+
Vanadium (V)	< .0002	< .004	20
Zinc (Zn)	.11	.34	3
Zirconium (Zr)	.0004	.008	20
Dissolved solids (residue) on evaporation at 180°C)	41	160	4
pH value	5.63	3.70	(H^+)100
Temperature (°C)	8.4	8.9	1+

1/ Analyses determined by the Spectorgraphic laboratory, Denver, Colo.

2/ Contaminated with water from the Llewellyn Formation.

Table 12.--Trace metal analyses of water from surface and bottom of the largest strip pit (PL-1P)[1]

Lat 41°09'15", long 76°05'38"

Constituent	Concentration in milligrams per liter		
	Lake surface	Lake bottom 27 feet	Multiple increase
Aluminum (Al)	4.2	5.4	1+
Barium (Ba)	.016	.032	2
Beryllium (Be)	.004	.003	<1
Boron (B)	.005	<.03	6
Chromium (Cr)	<.002	<.02	10
Cobalt (Co)	.15	.16	1+
Copper (Cu)	.012	.88	73
Iron (Fe)	2.2	18	9
Lead (Pb)	.013	.170	13
Lithium (Li)	.022	.027	1+
Manganese (Mn)	6.7	8.6	1.3
Molybdenum (Mo)	<.0006	<.006	10
Nickel (Ni)	.24	.32	1.3
Rubidium (Rb)	.002	.003	1+
Silver (Ag)	<.0002	<.002	10
Strontium (Sr)	.09	.10	1+
Tin (Sn)	<.004	<.03	7+
Titanium (Ti)	.003	<.01	3+
Vanadium (V)	<.002	<.02	10
Zinc (Zn)	.46	2.2	5
Zirconium (Zr)	<.004	<.03	7+
Residue on evaporation	353	531	1.5
pH value	3.15	3.07	(H^+) 1.2
Temperature (°C)	7.1	1.2	.2

---

[1] Analyses determined by the Spectrographic Lab, Denver, Colo.

Table 13.--Trace metal analyses of water from two sites on Black Creek November 9, 1965 [1]

Constituent	Concentration in milligrams per liter	
	Strip pit above Stump Lake - PL-2P	Black Creek below Stump Lake - BC-2
Aluminum (Al)	6.4	1.1
Barium (Ba)	.04	.01
Beryllium (Be)	.007	.010
Boron (B)	.017	.013
Chromium (Cr)	<.002	<.002
Cobalt (Co)	.16	.24
Copper (Cu)	.04	.17
Iron (Fe)	1.7	.34
Lead (Pb)	.010	.006
Lithium (Li)	.018	.015
Manganese (Mn)	3.1	3.4
Molybdenum (Mo)	<.0004	.0005
Nickel (Ni)	.20	.29
Rubidium (Rb)	.0008	.001
Silver (Ag)	.0002	<.0002
Strontium (Sr)	.07	.08
Tin (Sn)	<.003	<.003
Titanium (Ti)	<.001	<.001
Vanadium (V)	<.002	<.002
Zinc (Zn)	.62	.92
Zirconium (Zr)	<.003	<.003
Dissolved solids (residue on evaporation at 180°C)	230	263
pH value	3.27	3.17
Temperature (°C)	7.3	9.0

---

[1] Analyses determined by the Spectrographic Laboratory, Denver, Colo.

Table 15.--Chemical analysis of BC-1 mine-drainage water at Mocanaqua, Pa. for extremes, average concentrations, and loads, for 1966 water year

Constituent	Concentration in mg per liter		
	Maximum	Minimum	Average
Silica (SiO_2)	28	23	--
Aluminum (Al)	20	8.5	16
Iron (Fe) (Fe^{+3})	217 (--)	59 (--)	143 (5.0)
Zinc (Zn)	1.2	.70	.83
Manganese (Mn)	30	16	23
Calcium (Ca)	190	111	153
Magnesium (Mg)	144	88	117
Sodium (Na)	4.1	2.6	--
Potassium (K)	2.6	2.1	--
Acidity (H_2SO_4)	468	261	356
Sulfate (SO_4)	1,490	847	1,210
Chloride (Cl)	3.0	1.0	--
Fluoride (F)	.6	.0	--
Total Nitrogen (as NO_3)	1.4	..1	--
Total Hardness (T.H.)	1,080	639	869
Dissolved solids (D.S.)	2,200	1,190	1,700
pH value	3.68	3.21	--
Specific conductance (micromhos at 25°C)	2,160	1,520	1,860
Temperature (°C)	12.4	10.7	11.8
Discharge (cfs)	14.6	1.7	3.4
	Loads, in tons per day		
Iron (Fe)	4.04	0.74	1.16
Acidity (H_2SO_4)	11.5	1.83	3.08
Sulfate (SO_4)	34.5	6.84	10.3
Dissolved solids	48.3	9.81	14.4

Table 16.--Chemical analyses of BC-1 mine-drainage water at Mocanaqua, Pa. for extremes, average concentrations, and loads, for 1967 water year.

Constituent	Concentration, in mg per liter		
	Maximum	Minimum	Average
Silica (SiO_2)	--	--	a/24
Aluminum (Al)	19	10	15
Iron (Fe) (Fe^{+3})	265 (--)	55 (--)	153 (5.7)
Zinc (Zn)	1.1	.67	.79
Manganese (Mn)	33	14	22
Calcium (Ca)	230	99	160
Magnesium (Mg)	165	80	120
Sodium (Na)	--	--	a/2.8
Potassium (K)	--	--	a/2.5
Acidity (H_2SO_4)	485	224	341
Sulfate (SO_4)	1,760	757	1,240
Chloride (Cl)	--	--	--
Fluoride (F)	--	--	--
Total nitrogen (as NO_3)	--	--	--
Total hardness (T.H.)	1,240	576	896
Dissolved solids (D.S.)	2,500	1,050	1,740
pH value	3.63	3.47	--
Specific conductance (micromhos at 25°C)	2,410	1,370	1,880
Temperature (°C)	12.2	11.3	11.7
Discharge (cfs)	16.6	1.8	4.1
	Loads, in tons per day		
Iron (Fe)	5.16	.64	1.38
Acidity (H_2SO_4)	b/--	1.85	3.44
Sulfate (SO_4)	44.4	6.48	12.2
Dissolved solids	62.7	9.06	17.0

a/ Based on a single analysis.

b/ Acidity not analyzed during peak flow in March 1967.