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Stratification in Water Quality in Inundated Anthracite Mines, Eastern Pennsylvania

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	m^3/s	cubic meter per second
cm	centimeter	mL	milliliter
°F	degree Fahrenheit	µm	micrometer
ft	foot	µmho	micromho per centimeter
gal	gallon	mV	millivolt
gal/min	gallon per minute	mV/m	millivolt per meter
in	inch	ohm-ft	ohm-foot
km	kilometer	ohm-m	ohm-meter
m	meter	pct	percent
mi	mile	ton	metric ton
mi^2	square mile	yr	year

STRATIFICATION IN WATER QUALITY IN INUNDATED ANTHRACITE MINES, EASTERN PENNSYLVANIA

By K. J. Ladwig,[1] P. M. Erickson,[2] R. L. P. Kleinmann,[3] and E. T. Posluszny[4]

ABSTRACT

The Bureau of Mines conducted a field investigation of the water quality in inundated underground coal mines in the Northern Anthracite Field, eastern Pennsylvania. Water samples were collected at multiple depths from nine abandoned mine shafts in the Wyoming Basin, ranging from 68 to 650 m (223 to 2,132 ft) in depth and intersecting as many as seven mined seams in a single shaft. The shafts were also monitored for fluid resistivity, fluid temperature, Eh, and pH using downhole instrumentation. The monitoring program showed that the formerly highly acidic mine water is now slightly alkaline. Sulfate concentrations decreased as much as 74 pct in the flooded workings and 54 pct at a mine water discharge from values reported in 1964 and 1968, respectively. These data are consistent with the inhibition of pyrite oxidation and gradual flushing of oxidation products in flooded mine environments.

The monitoring program also revealed significant vertical stratification in water quality in five of the nine shafts, each characterized by two easily recognizable zones. The transitions between zones were sharp, marked by rapid changes in Eh, pH, and ionic composition, the upper zones being less contaminated than the lower zones. The development of stratification appears to be a function of shallow localized flow conditions, arising primarily from the relative positions of mine openings and structural features of the coalbeds.

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INTRODUCTION

Eastern Pennsylvania originally contained approximately 20 billion tons[5] of anthracite, 95 pct of the minable anthracite in the United States (2, 15).[6] Between 1807 and 1967, more than 5 billion tons were mined from four coalfields in the Susquehanna and Delaware River Basins (fig. 1). The extensive underground and surface mining operations have created a number of serious environmental problems, including severe surface and ground water quality degradation as a result of acid mine drainage (AMD) formation (6, 8, 17-18, 20, 23, 31).

AMD is often associated with the extraction of coal (9, 26). During and after mining operations, pyrite (iron disulfide) occurring in the coal and adjacent strata reacts under oxidizing conditions to yield soluble iron, sulfate, and acid. These products are

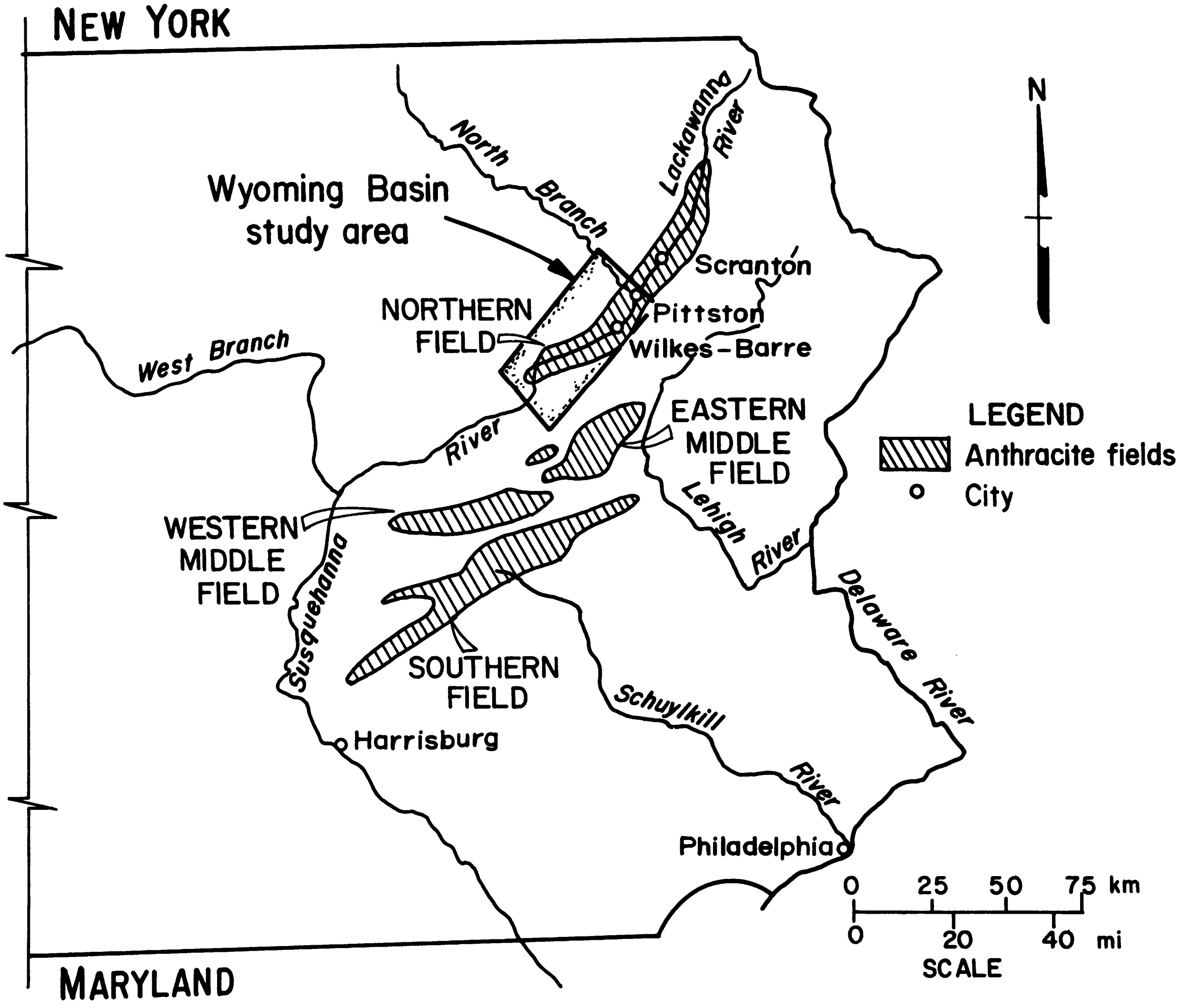

FIGURE 1. - Location of Wyoming Basin study area, Northern Anthracite Field, eastern Pennsylvania.

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[5] In this report, "ton" refers to metric ton unless otherwise indicated.

[6] Underlined numbers in parentheses refer to items in the list of references preceding the appendix at the end of the report.

flushed into the hydrologic system by the circulation of ground and surface water over weathered surfaces. The production of AMD also accelerates the dissolution of other minerals, adding trace metals to the water.

In the Northern Anthracite Field, 18 workable coal seams were mined to depths of several hundred meters below sea level (5). Massive dewatering was required to keep the deep mines operational. As the mines were abandoned, water levels rose and a vast reservoir of AMD-contaminated mine water developed. The contaminated water flows through a complex array of mine openings and natural fractures, eventually discharging to the surface by way of seepage outlets and specially constructed drainage tunnels and boreholes.

Monitoring of mine water discharge points (outfalls) in the Northern Field has indicated a steady improvement in water quality over the last 10 years (13). However, contaminant levels in the discharged water still exceed maximum acceptable concentrations for drinking water and recreational use. Two fundamental questions regarding the desired total abatement of AMD in the anthracite region are (1) will the surface discharge quality continue to improve and, if so, at what rate and to what end point; and (2) does the surface discharge quality reflect the quality of the entire subsurface reservoir? The latter question has many implications with respect to the potential utilization of the subsurface water for consumptive, industrial, or other uses.

The Bureau of Mines initiated a field investigation of the mine water system in the Wyoming Basin of the Northern Anthracite Field to study the physical and chemical processes occurring within an inundated mine complex. Specific project goals include identification of sites where pyrite oxidation may still be occurring and mapping patterns of contaminant flow.

Background of the AMD problem in the Wyoming Basin and results of the first phase of the study are given in this report. Nine abandoned mine shafts were monitored for vertical and seasonal variations in the chemical composition of the mine water system. Monitoring included the collection of shaft water samples, downhole Eh and pH measurements, and fluid resistivity and temperature logging. These results are correlated to general flow patterns and outfall water quality. Future work will include flow gaging and water quality monitoring at the outfalls, estimation of the contribution of surface contaminants to the mine drainage problem, and more detailed hydrologic and geochemical modeling.

ACKNOWLEDGMENTS

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BACKGROUND

GEOLOGY

The Northern Anthracite Field is located in an elongated, crescent-shaped basin in the Valley and Ridge physiographic province in Pennsylvania. The field is 100 km (62 mi) long, averages between 5 km (3.1 mi) and 10 km (6.2 mi) in width, and has a surface area of 456 km^2 (176 mi^2) in Luzerne and Lackawanna Counties (5). The valley is relatively flat bottomed with steeply dipping flanks.

Structurally, the Northern Field lies in a synclinal trough striking at N 50° E (fig. 2). The axis of the syncline approximates the axis of the valley, with the ends tapering to form a large enclosed basin. Superimposed on the primary simple synclinal structure are many subordinate folds, flexures, and faults (10-11, 14). Most of the subordinate features are discontinuous and also strike to the northeast. A major exception is a large anticlinal saddle striking at 90° to the valley axis and dividing the field into two subbasins: the Lackawanna Basin in the northeast and the Wyoming Basin in the southwest (figs. 2 and 3). The saddle is located approximately along the boundary between Luzerne and Lackawanna Counties.

Most of the minable anthracite reserves are in the Pennsylvanian age Llewellyn Formation, which outcrops on the synclinal axis and is more than 610 m (2,000 ft) thick in the deepest part of the Wyoming Basin (14). The unit consists of conglomerates, sandstones, and shales interbedded with as many as 18 workable coal seams, the lowest of which is the Red Ash[7] bed. The general structure of the Wyoming Basin is shown on the contour map drawn on the base of the Red Ash bed (fig. 4). The deepest part of the Wyoming Basin is near Askam, where the coal measures extend to an elevation[8] of -466 m (-1,530 ft). The Red Ash bed rises in all directions from Askam, reaching an elevation of +152 m (+500 ft) at the anticlinal saddle near Old Forge. Northeast of Old Forge, the Red Ash bed again plunges to near sea level, forming the Lackawanna Basin (fig. 3). The Red Ash bed outcrops as high as +336 m (+1,200 ft) and +549 (+1,800 ft) on the valley flanks in the Wyoming and Lackawanna Basins, respectively (5, 14).

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[7] Names of coal seams vary among collieries; only the general names are used here.

[8] Minus sign (-) indicates elevation below mean sea level; plus sign (+) indicates elevation above mean sea level.

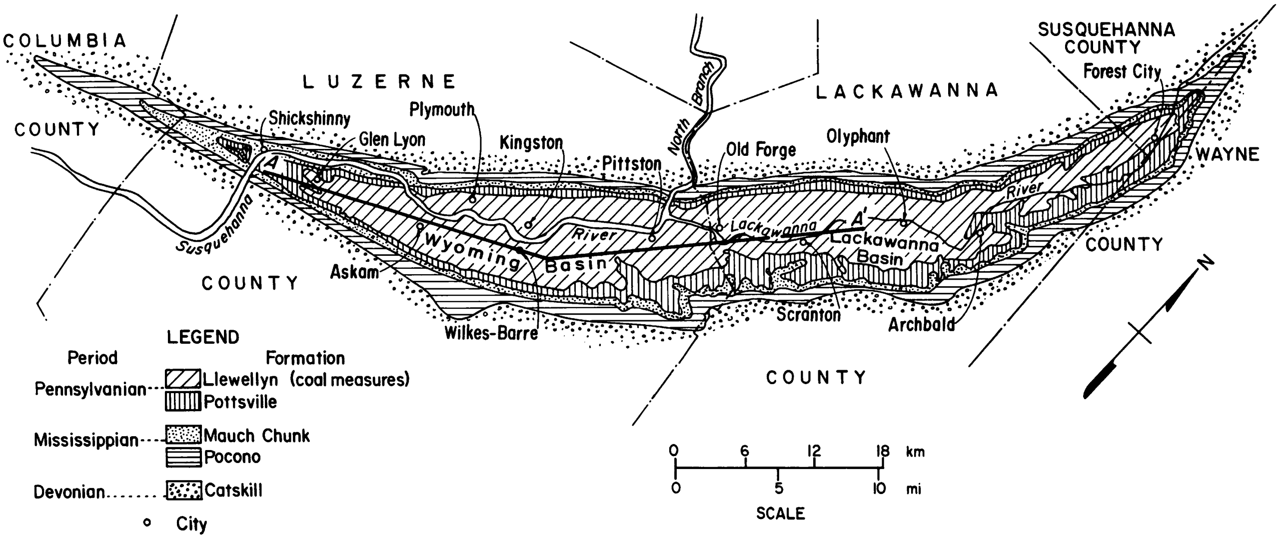

FIGURE 2. - Geologic map of Northern Anthracite Field. Pleistocene glacial deposits not shown; A-A' refers to longitudinal section in figure 3 (after Ash (3)).

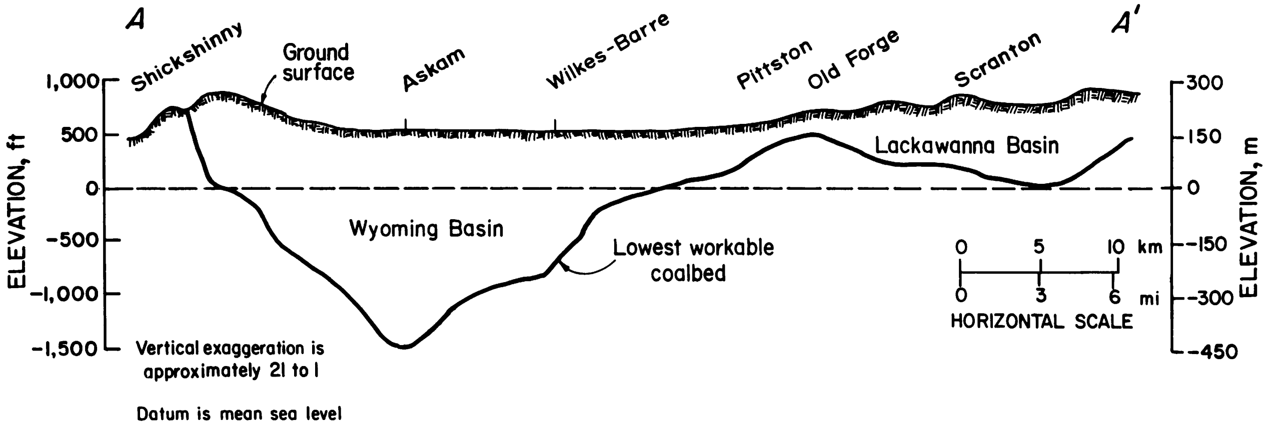

FIGURE 3. - Longitudinal section showing general structure of the coal measures along the synclinal axis in the Northern Anthracite Field. Location of section is given on figure 2 (after Ash (5)).

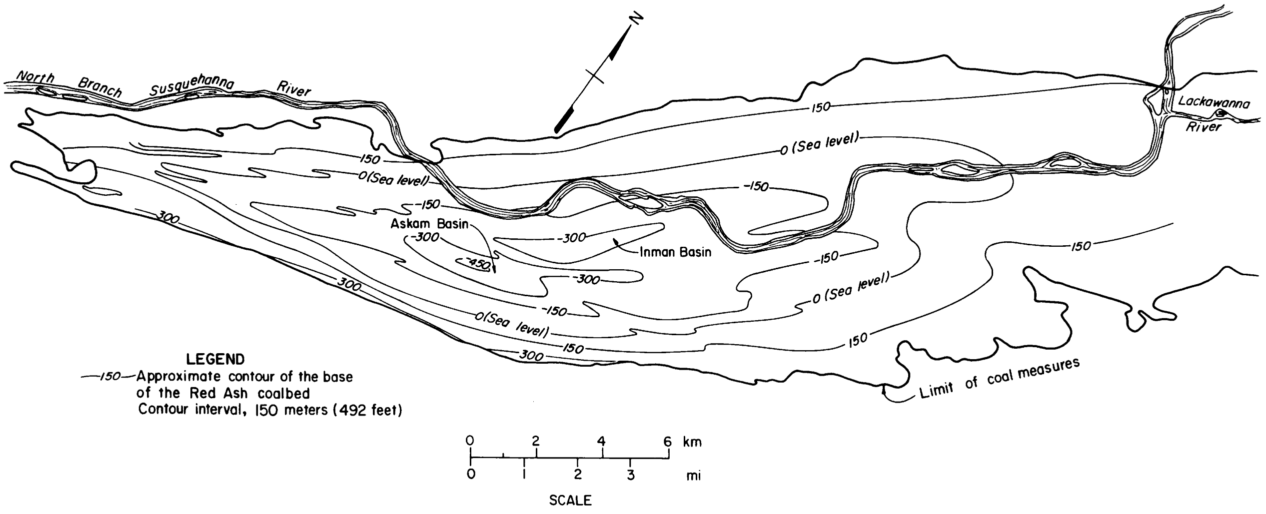

FIGURE 4. - Structure map of Red Ash bed in the Wyoming Basin. The Red Ash bed is the lowest workable seam in the Wyoming Basin (after Darton (13)).

Underlying the Llewellyn Formation, from youngest to oldest, are the Pennsylvanian Pottsville Formation, the Mississippian Mauch Chunk and Pocono Formations, and the Devonian Catskill Formation (10-11, 24, 28). The hard sandstones and conglomerates in the Pottsville and Pocono Formations form a twin-ridge system rimming the basin. The Llewellyn Formation is partially overlain by unconsolidated Pleistocene glacial sediments, ranging up to 91 m (300 ft) thick and covering 96 km^2 (37 mi^2) on the valley floor near the Susquehanna River (3, 22, 25). In the Wyoming Basin, maximum reliefs from the flood plain to the inner and outer ridges are approximately 335 m (1,100 ft) and 503 m (1,650 ft), respectively (22).

REGIONAL HYDROLOGY

The Northern Anthracite Field is in the North Branch Susquehanna River drainage basin. The area is characterized by warm summers and mild winters, with a mean annual temperature of 10° C (50° F) (22). Average annual precipitation is about 100 cm (39 in) at Wilkes-Barre and slightly higher in the uplands (28).

The Susquehanna River enters the Wyoming Basin through a breach in the north valley rim north of Pittston and flows southwest along the axis of the valley in the soft Llewellyn Formation and Pleistocene deposits for a total of 26.5 km (16.5 mi) (fig. 2). The average discharge of the Susquehanna River at Wilkes-Barre for the period from 1900 to 1980 was 397 m^3/s (6.29×10^6 gal/min) (32). Most of the 59 tributary streams in the Wyoming Basin originate outside the coal measures in the upland ridge area.

The Lackawanna Basin is drained by the Lackawanna River, the largest tributary to the Susquehanna River in the Northern Field (fig. 2). The average discharge of the Lackawanna River at Old Forge for 43 yr of record was 14.0 m^3/s (2.22×10^5 gal/min) (32).

Ground water in the Wyoming Basin flows downdip from the outcrop recharge areas toward the central valley and the Susquehanna River. Most of the ground water movement in the Pottsville and underlying rocks is controlled by secondary permeability features, such as bedding planes, joints, and faults. Artesian wells are common (28). Complex flow patterns develop in the Llewellyn Formation as subsurface water moves laterally and vertically through mine openings as well as natural and induced fractures toward discharge points near the Susquehanna River. Ground water flow in the unconsolidated alluvium and Pleistocene deposits is principally intergranular. In nonflood stages, the water table in the glacial deposits slopes gently toward the river, creating a smaller local flow system. Newport (28) and Hollowell and Koester (24) described the hydrogeology of Luzerne and Lackawanna Counties, respectively, and Hollowell (22) described the hydrogeology of the Pleistocene deposits.

MINE DRAINAGE

Mining and Pumping History

At the start of commercial mining of anthracite in 1807, the Northern Field contained over 5 billion tons of coal reserves, 3.6 billion tons of which were in the Wyoming Basin (5). Originally, production was confined to shallow outcrop mines, limited in depth by the natural water table. As the demand for coal increased and mine dewatering techniques improved, mining extended hundreds of meters below the surface. The massive dewatering efforts required for such deep mines eventually created a large ground water trough across the basin. The hydraulic gradient in the glacial sediments reversed, and the Susquehanna River became a source of ground water recharge rather than discharge. Ash and Whaite estimated that as much as 49 pct of the mine water pumped in the Wyoming Basin was seepage from the Susquehanna River (7). Tributary flow crossing into the coal measures was largely diverted into the underlying mines along subsided, fractured and broken strata (7, 15).

As collieries were abandoned and pumping stopped, flooding occurred naturally and isolated pools of water formed. In 1948, an estimated 6.0×10^7 m^3 (1.6×10^{10} gal) of water were impounded in 39 inactive mines (5). The mine pools formed reservoirs for continuous infiltration to active mines through interconnections and breached barrier pillars, further compounding the dewatering problem. Despite efforts to revive the industry, by 1960 mining below the natural water level in the Lackawanna Basin had stopped completely and only a few high-cost deep mines were operating in the Wyoming Basin (15). In 1967, all mines except the Wanamie colliery on the far west end of the basin were shut down due to high pumping and water treatment costs (23). The Wanamie colliery continued operation until the mid-1970's.

Water Level Recovery

With the end of mining, the hydrologic system began to revert to nonpumping equilibrium conditions. As collieries were abandoned, water levels within the mines began to rise to natural drainage levels, and isolated mine pools coalesced to create the present complex ground water system. The rate of recovery in any one colliery was dependent on the availability of recharge and the influence of pumping in surrounding collieries. Borehole and shaft monitoring records from 1960 through 1980 indicate that water level recovery in all but the active Wanamie colliery was more than 95 pct complete by the end of 1972 (13).

As water levels neared the ground surface, seepage outlets developed and discharged large quantities of AMD (23). To regulate mine water levels and uncontrolled seepage, the Pennsylvania Department of Environmental Resources (PA DER) constructed four gravity outfalls in the Wyoming Basin between 1968 and 1974: the Buttonwood tunnel, the South Wilkes-Barre boreholes, the Askam borehole, and the Plains borehole (fig. 5).[9] As a further control measure, the Delaware-Pine Ridge colliery pumps were restarted in 1968 and operated until Tropical Storm Agnes prompted widespread flooding in June 1972, inundating the entire mine complex.

Based on barrier pillar data compiled by Ash (4) and mine water levels, the inundated collieries have been grouped into three major hydrologic divisions (fig. 5): the northwest (NW) complex, the southeast (SE) upper complex, and the SE lower complex (23). The original boundary of the SE lower complex has been modified slightly to include the Inman and Loomis collieries. The collieries on the ends of the basin are not included in the above three divisions and have been arbitrarily grouped into the west end and east end complexes.

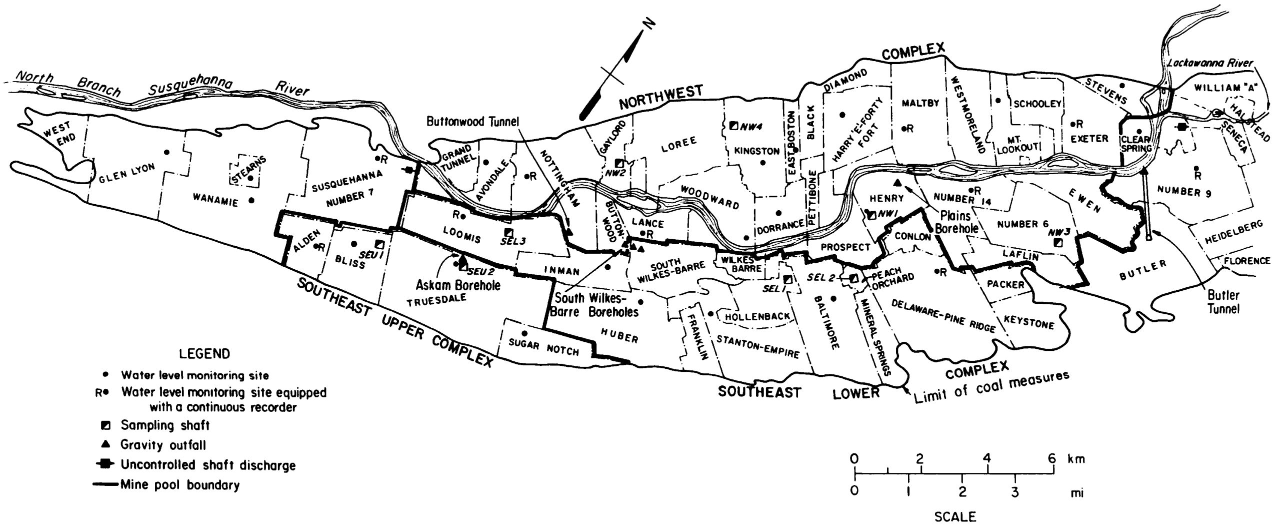

FIGURE 5. - Wyoming Basin, showing colliery names and boundaries, mine complex boundaries, sampled shafts, outfalls, and water-level-monitoring stations.

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[9] The Askam borehole extends to the No. 4 seam, elevation approximately +155 m (+510 ft). The Buttonwood tunnel taps the Buttonwood air shaft and is believed to terminate in the Bottom Ross seam, elevation approximately -153 m (-503 ft). Construction details for the other outfalls are not available (13).

Flow Patterns

The coal measures represent an extreme case of a hydraulically stratified medium. Worked seams and mine interconnections are thin, high-permeability layers in which flow is primarily parallel to the plane of the bed. Thick sandstones, siltstones, and shales are low-permeability, confining strata. Unmined coal and intact barrier pillars are low-permeability baffles further complicating flow paths.

The primary sources of recharge to the mine flow system are direct surface seepage, streambed losses, and ground water interflow from adjacent formations. Surface seepage and streambed losses occur along numerous avenues for infiltration resulting from subsidence fracturing and strip mining operations. Infiltrating water is at least partially contaminated at the surface by contact with, and percolation through, exposed coal waste material. Many tributary streams lose most or all of their flow shortly after entering the coal measures (17-18). The net results of the increased infiltration are reduced streamflow and routing of contaminated water through the subsurface flow system.

The mine water system may also be recharged by ground water inflow from underlying formations. This assumption is supported by water budget analyses (19) and by the existence of artesian wells in the Pottsville and Mauch Chunk Formations (24, 28), but the degree of hydraulic communication between the formations has not been established and no quantitative predictions of the significance of this source of inflow can be made.

Subsurface flow in the coal measures is through mine openings toward the outfalls, seepage outlets, and the Susquehanna River. The extent of mine cavity continuity is complicated by barrier pillar robbing, shafts, tunnels, collapse features, highly contorted structure of coalbeds, and numerous fault offsets. Although defining the intricacies of the subsurface flow system is beyond the scope of this paper, general flow patterns are shown on the equipotential diagram in figure 6. The flow patterns were derived from mine water levels observed in partially and fully penetrating boreholes and shafts located in the various collieries. The hydraulic gradient is assumed to be relatively small within a single colliery, and therefore,

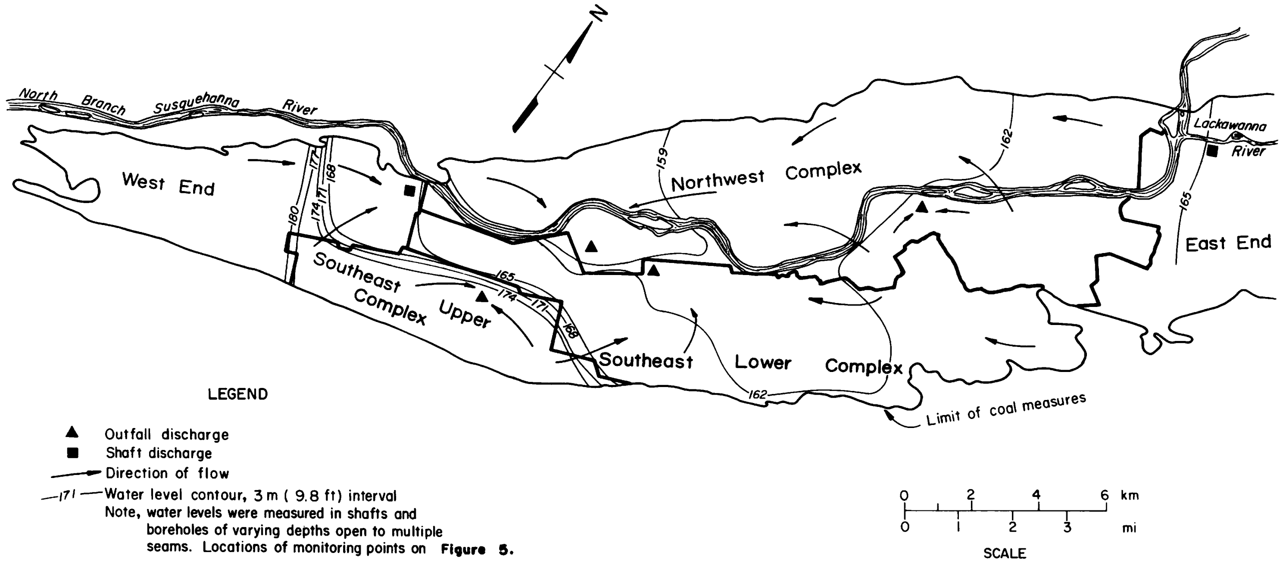

FIGURE 6. - Flow diagram showing generalized direction of mine water flow in the Wyoming Basin. Water-level-monitoring stations are shown on figure 5. Water levels are given as meters above mean sea level in December 1975.

the equipotential lines have been concentrated along the colliery boundaries.

Flow in the NW complex and SE lower complex is essentially downdip from the structurally high areas to the Buttonwood and South Wilkes-Barre outfalls in the deeper part of the basin. The two outfalls discharge AMD year round at rates as high as 1.3 m^3/s (21,000 gal/ min) and 1.8 m^3/s (29,000 gal/min), respectively (17-18). The Plains outfall serves as a relief well for the NW complex, but apparently has only a limited radius of influence (19).

In the early 1970's, high water levels resulted in the formation of several uncontrolled mine discharges from the SE upper complex near Askam. The Askam outfall, constructed in 1972, now serves as a high-water relief well for the upper complex, damping extreme water level fluctuations and intermittently discharging mine drainage at flow rates as high as 0.76 m^3/s (12,000 gal/min) (17). Discharge from the west end collieries issues from uncontrolled seeps near the Susquehanna River.

The ultimate recipient of the deep mine drainage is the Susquehanna River, by way of streamflow and upward seepage through the Pleistocene deposits. The magnitude of seepage discharge has not been explored in detail, but the potential for seepage has been verified in studies near Kingston (19) and Plymouth (17). It is reasonable to assume that significant seepage may occur along the length of the river course west of Pittston.

WATER QUALITY

Although mine pool development began before 1900, no water quality records are available for the early mining period. The Bureau of Mines began surveying pumped and artesian mine discharges in the 1940's to assess the mine drainage problem. Only 15 of 70 discharges sampled in a 1941 survey (16) were above the now legally acceptable minimum pH of 6.0; the most acidic source was at pH 2.7. A followup survey in 1946 found that mine drainage tunnels in the Wyoming Basin alone discharged approximately 2.7 × 10^4 m^3 (7.2 × 10^6 gal) per day, containing a daily acid load equivalent to approximately 8 tons of sulfuric acid (16).

Most of the small surface discharges in the Wyoming Basin were eliminated by construction of the four gravity outfalls mentioned previously. The PA DER established a program to monitor quantity and quality of the mine drainage discharges (13). Additional recent data are available from the PA DER-sponsored Operation Scarlift (SL), including outfall monitoring during two hydrologic years in the period 1973-76 (17-18).

Table 1 gives the mean flow and sulfate concentration in outfall discharges for 1973-74 from SL and PA DER data. Sulfate content of mine drainage is less susceptible to change by chemical or biological processes than are the other pyrite oxidation products.

TABLE 1. - Comparison of discharge quantity and quality at mine pool outfalls, September 1973-March 1974

Outfall	Mean flow		Mean sulfate concentration, mg/L	References
	m^3/s	gal/min		
Askam.............	0.279	4,420	2,029	17-18
	.425	6,740	2,270	12[1]
Buttonwood.........	.592	9,380	1,425	17-18
	.848	13,440	1,560	12
South Wilkes-Barre.	.776	12,300	2,150	17-18
	1.074	17,030	2,417	12

[1] Mean computed from only 2 data points for this period.

Agreement between the two data sources was poor, even when sampling dates coincided exactly. Since the outfalls are somewhat inaccessible and drain into surface streams, slight differences in the sampling location may be responsible for the disagreement in results. Both data sets show that mean discharge and sulfate load (mass per unit time) decreased in the order South Wilkes-Barre (SWB), Buttonwood (BWD), Askam (ASK). Contaminant concentrations were comparable at South Wilkes-Barre and Askam, and significantly lower at Buttonwood.

Long-term monitoring at the outfalls by PA DER has shown a trend toward improved quality in the mine discharge, as illustrated by the change in sulfate concentrations at the Buttonwood outfall over a 13-yr period (fig. 7). From 1968 to 1979, mean sulfate concentrations decreased 49 pct (2,090 to 1,070 mg/L) and acidity decreased 74 pct (from 380 to 97 mg/L). The pH range observed was 3.3 to 5.6 in 1968, compared with 5.8 to 6.2 in 1979.

The U.S. Geological Survey (USGS) undertook direct investigation of mine pool water quality in the 1960's (31). Measurements of pH on samples from 11 flooded shafts generally indicated a much less acidic environment than in the pumped discharges when the mines were operational. Several shafts also exhibited stratification of pH, usually becoming more acidic with depth. A later study included chemical analyses of samples from several depths in a shaft in the Wyoming Basin (8). Zones of differing water quality were found in the water column, marked by sharp changes in chemical composition, Eh, and pH. Analysis of the data showed most of the water to be in equilibrium with pyrite and/or amorphous ferric hydroxide.

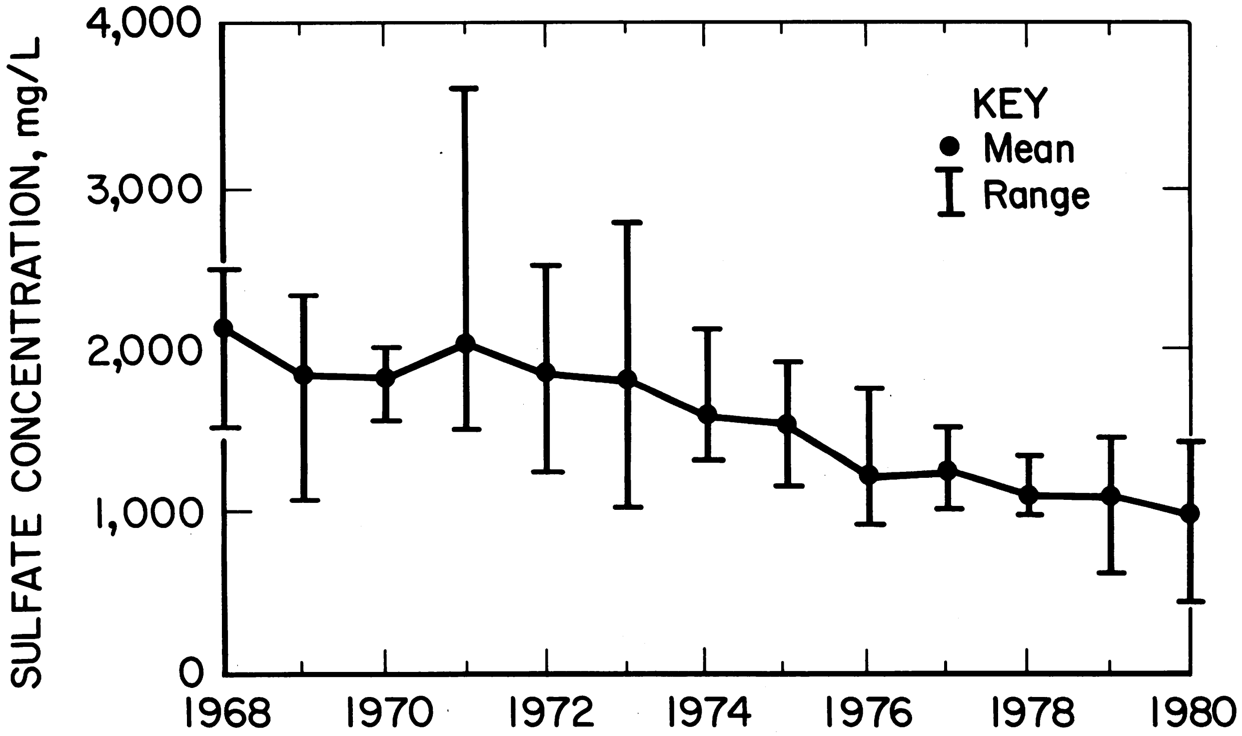

FIGURE 7. - Mean and range of sulfate concentrations for Buttonwood tunnel discharge for 13 years of record (13).

METHODS

GENERAL APPROACH

Many previous studies of underground mine drainage have relied solely on measurements made at surface discharge points. The approach taken here is to examine the subsurface characteristics of the mine drainage system. Correlation of water chemistry and hydrologic variables provides the basis for understanding the processes occurring within the system.

Nine abandoned mine shafts in the Wyoming Basin offer accessibility to the subsurface system: four in the NW complex, three in the SE lower complex, and two in the SE upper complex (fig. 5). Water samples were obtained from multiple depths in the shafts, and downhole instruments were used to measure Eh, pH, resistivity, and temperature. Water analysis results are given in the appendix. Noteworthy features are summarized and discussed in the following sections.

Discussion of the results of the shaft monitoring is necessarily limited to gross features of the mine drainage system and their implications for basinwide water quality. More detailed work will be done on isolated subbasins in future phases of the study.

INSTRUMENTATION

Downhole pH and Eh

Great Lakes Instruments[10] meters and submersible probes were used for downhole pH and Eh measurements in the shafts. Downhole pH and Eh measurements were used because of the inherent instability of pH and Eh to changes in environment (27), particularly exposure to atmospheric gases. Water with the high ferrous iron content associated with mine drainage is highly sensitive to aeration. Both instruments are equipped for automatic temperature compensation. Temperature compensation was confirmed by observation of constant Eh values in ZoBell's solution (33) over a range of 4° to 25° C (39° to 77.0° F). The pH meter was calibrated with two buffers prior to each logging run, and single-point scale calibration was used for the Eh meter. Measurements were made at discrete depths within the shaft, at intervals of 6 m (20 ft) or less. The Eh meter is sensitive to flow, responding with a fluctuating signal if the probe is moved rapidly.

Downhole, surface, and laboratory pH values were obtained when possible (see appendix); the three sources of data show significant variations. Changes occurring between field and laboratory measurements are well documented and not unexpected (30). Differences between downhole and field measurements are similarly accountable: Dissolved gases are lost as pressure decreases in withdrawing the sample, and vigorous mixing with atmospheric gases occurs in transferring the water from the sampler to the sample bottle.

Geophysical Logging

Continuous logs of fluid resistivity and fluid temperature were run in each shaft using a Johnson-Keck model SR-3000 borehole logger. The resistivity and temperature sensors are mounted in separate probes. Recordings were made on consecutive downhole runs, resistivity being run first. Field operational difficulties have hampered the progress of the geophysical logging, and only a limited number of usable logs have been collected to date.

Water Sampling and Analysis

A 500-mL Bacon bomb sampler was used for all shaft water sampling. Steel aircraft cable marked at 1.52-m (5-ft) intervals was used for raising and lowering the sampler. Monofilament nylon line attached to the plunger valve was used to mechanically open and close the sampler at the desired depth. Sampling depths

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[10] Reference to specific products does not imply endorsement by the Bureau of Mines.

were determined in the field after review of the resistivity, temperature, Eh, and pH logs. Although the sampled shafts range in depth to 650 m (2,133 ft) below the surface, the mechanically activated sampler was useful to a depth of only 170 m (558 ft).

Samples were transferred directly from the sampler to 500-mL plastic bottles. Conductivity and pH were measured in the field using a Horizon model 1484-10 meter and a Fisher model 150 meter, respectively. A portion of each sample was then passed through a 0.45-µm membrane filter and acidified. Samples initially were analyzed for ferrous iron, sulfate, pH, and acidity or alkalinity; total dissolved aluminum, iron, and manganese; and fecal and total coliform. Aluminum, manganese, and total coliform analyses were eliminated after the first series of shaft samples was completed; calcium and magnesium analyses were added. All analyses were done according to standard methods (1) by personnel of Wilkes College in Wilkes-Barre, PA.

RESULTS AND DISCUSSION

GENERAL OBSERVATIONS

Water quality in the mine complex has shown significant improvement over that reported for drainage from active mines in 1946 (16) and from flooded collieries in 1964 (8). In fact, most of the mine water sampled is no longer acidic; 93 pct of the shaft water samples contained net alkalinity. Downhole pH's as high as 7.80 were recorded, and no sample had a pH less than 5.05. The high pH and alkalinity appear to be a result of reduced acid production, flushing of residual acid products from the mine water system, and dissolution of carbonate minerals as a buffer source.

Evidence for carbonate mineral buffering is the parallel increase in calcium and magnesium with increasing sulfate concentrations (fig. 8). Calcium and magnesium carbonate minerals dissolve readily in an acidic environment (21), adding both cations as well as alkalinity in the form of bicarbonate to the solution. Given sufficient reaction time for equilibration, a more acidic environment causes greater carbonate mineral dissolution. Assuming the present sulfate concentrations reflect antecedent acidity, the concomitant rise of calcium and magnesium with sulfate would be expected. Although no major limestone or dolomite beds are known to occur in the coal measures, it is assumed carbonate minerals in the shales and cementing agents in the sandstones are sufficient to explain the observed concentrations.

Raw sewage dumping into the abandoned mines has been known to occur in the study area. Fecal coliform counts were made to determine if the alkalinity observed in the mine drainage was affected by the introduction of sewage. Although fecal coliform populations were present in all but two of the shafts, no significant correlation with alkalinity was observed.

The only samples containing net acidity were taken from shafts NW3 and NW4. Both shafts are in ground water recharge areas near the coal measure boundaries (fig. 5), and the net acidity may indicate rapid flow-through and the introduction of recently produced contaminants. The effect of circulation and flushing on water quality will be discussed with respect to the individual shafts in a later section.

Like calcium and magnesium, iron concentrations parallel sulfate concentrations (fig. 8). The increase in iron with an increase in sulfate is a logical result of pyrite oxidation; further reactions and precipitation of ferric hydroxide account for the nonstoichiometric relationship. Dissolved iron occurred primarily in the ferrous state, the ferrous to ferric ratio generally increasing with depth. Eh also generally decreased with depth.

Downhole Eh and pH data from seven shafts are plotted in figure 9. Discussion in this report is limited to

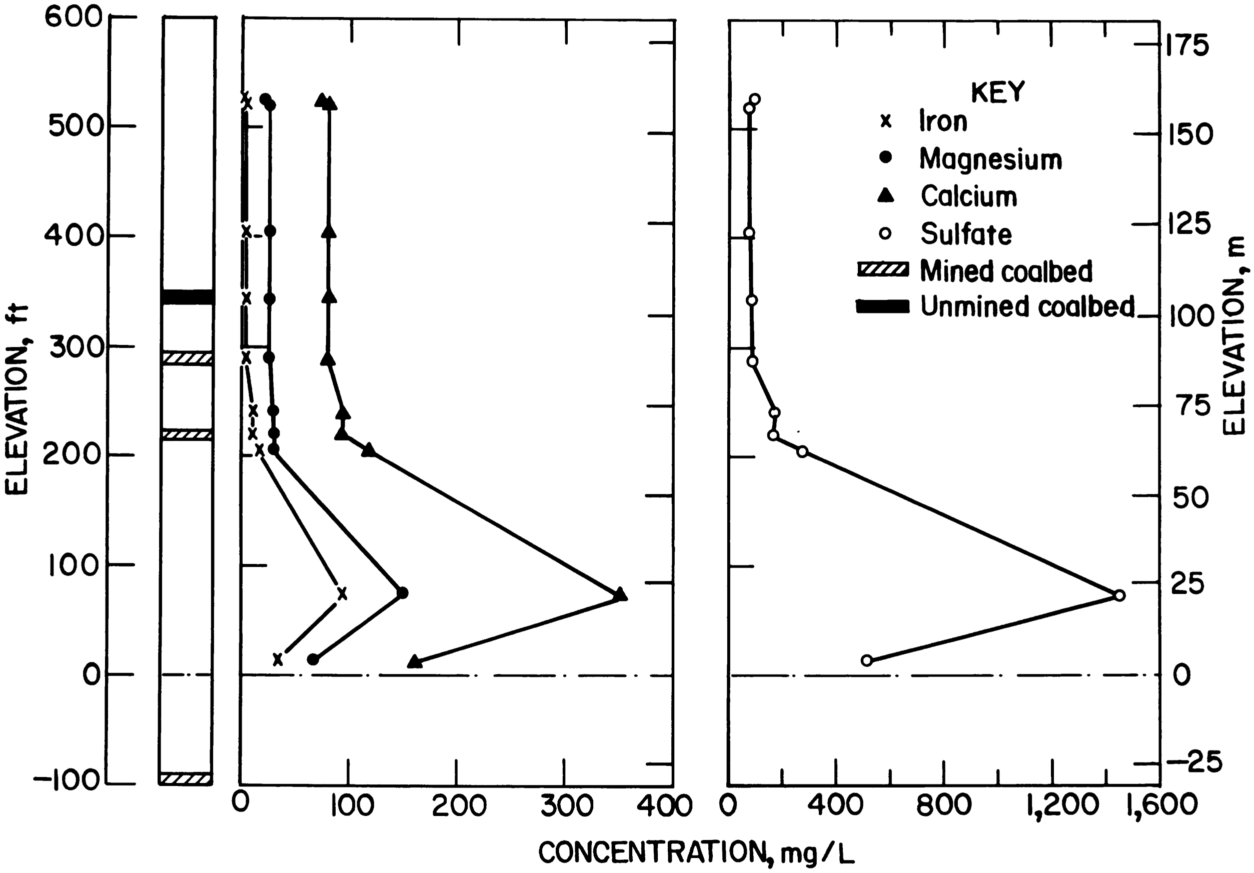

FIGURE 8. - Vertical profiles of selected chemical constituents in the Henry colliery, shaft NW1, showing similar trends in calcium, magnesium, iron, and sulfate concentrations versus depth.

qualitative observations; results of computer modeling with WATEQF (29) will be reported later.

Most of the data clustered in a region bounded by pH of 5 and 7 and by Eh of 10 and 310 mV. These values are well above the FeS_2-Fe^{2+} boundary, indicating that pyrite in contact with the shaft water would be thermodynamically unstable. Pyrite oxidation, however, appears to be slower in flooded mines than it was in active operations. Significant improvement in outfall water quality over time (fig. 7) indicates that ameliorative processes, such as buffering and flushing, are occurring faster than acid production. Oxygen depletion at depth, and the near-neutral pH range could account for unfavorable oxidation kinetics. These findings support the basic concept underlying mine sealing.

The most oxidizing conditions were found in the upper zones of shafts SEU2 and SEU1, with Eh values greater than 400 mV. Eh values above 200 mV were also found in shafts NW3 and NW4. Water samples from the latter shafts contained suspended ferric hydroxide. NW3 and NW4 and the upper zones of SEU1 and SEU2 are located in perimeter areas where recharge conditions may lead to a relatively rapid turnover of mine water. (See figure 6 and discussions of the NW and SE upper complexes.)

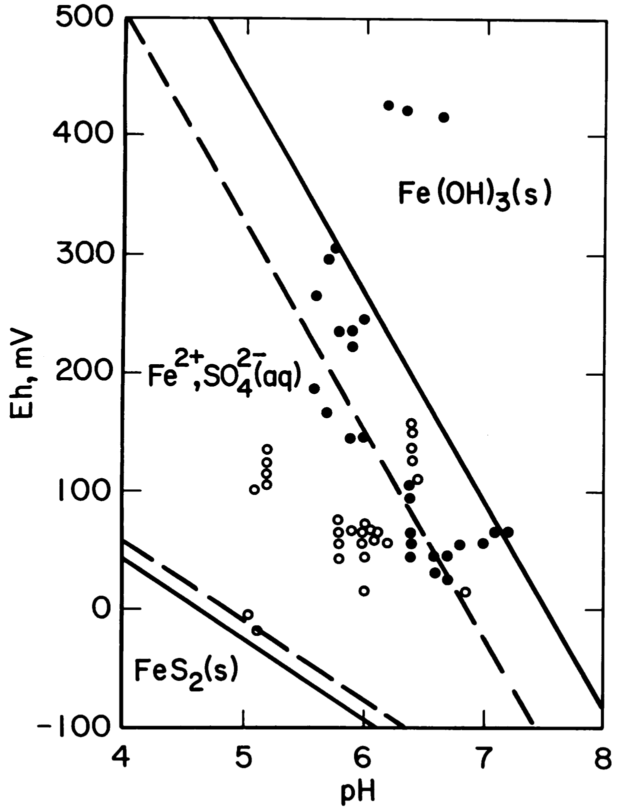

FIGURE 9. - Selected Eh and pH data from seven shafts, showing data from near-surface zones (●) and deeper water (○). Stability boundaries are shown for pyrite and amorphous ferric hydroxide, with aqueous ferrous iron activities of 1 (—) and 100 (---) mg/L, respectively, and sulfate activities of 100 (—) and 1,000 (---) mg/L, respectively.

The bulk of the data from the lower zones lies in the aqueous ferrous iron and sulfate field, apparently not controlled by equilibrium with ferric hydroxide or pyrite. Iron occurred predominantly in the ferrous state (see appendix). In general, the ferrous-to-ferric ratio increased and Eh decreased with depth. Many water samples developed a yellow-orange precipitate within minutes of contact with the atmosphere. It appears, therefore, that the shaft water is unable to reach equilibrium with ferric hydroxide owing to lack of a ferrous iron oxidant at depth.

Relatively reducing environments were found in narrow zones within two of the shafts. Water composition, Eh, and pH data from one of the shafts appear to be consistent with pyrite equilibrium.

NORTHWEST COMPLEX

Shaft NW1, Henry Colliery

Shaft NW1 is open from +172 m (+564 ft) to the Red Ash bed at -31 m (-102 ft) and contains a 190-m (623-ft) column of water. Three seams were mined from the shaft.

Water quality was distinctly stratified within the shaft (fig. 10). The upper 90 m (295 ft) comprise a uniform zone of relatively good quality water. Sulfate concentrations in this zone were less than 100 mg/L, lowest in the Wyoming Basin. Just above the Skidmore bed, sulfate concentrations began to increase, reaching a maximum of 1,460 mg/L midway between the Skidmore and Red Ash beds before again decreasing to less than 500 mg/L.

Eh and pH data similarly have a break in continuity associated with the Skidmore bed (fig. 10). After a sharp decrease near the surface, Eh decreased gradually in the upper zone at a rate of about 0.4 mV/m, while pH varied between 6.0 and 7.0. Just above the Skidmore bed, the Eh suddenly increased by about 40 mV over a 6-m (20-ft) interval. At the same elevation, pH decreased to 6.0 and varied by only 0.2 unit in the remainder of the shaft.

Shaft NW2, Gaylord Colliery

Shaft NW2 is open from +183 m (+601 ft) to +7 m (+23 ft), just below the Ross bed. Four of the six seams above the present floor were mined from the shaft.

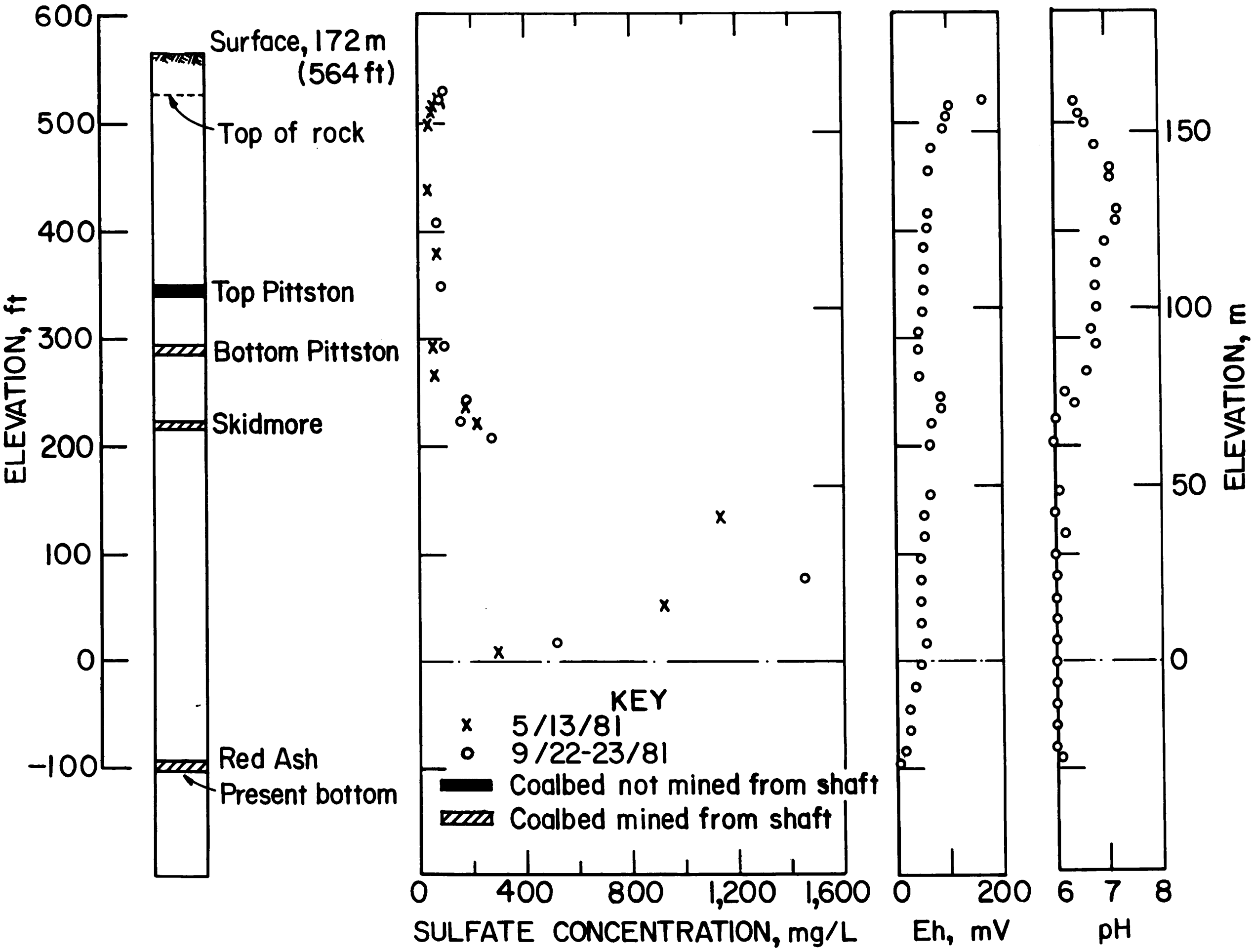

FIGURE 10. - Data profiles for shaft NW1, Henry colliery.

Water quality in NW2 was among the poorest in the basin and exhibited marked stratification at elevation +68 m (+223 ft) between the Top and Bottom Pittston beds (fig. 11). In the upper 90 m (295 ft), sulfate concentrations were between 950 and 1,100 mg/L. At the Bottom Pittston bed, concentrations increased sharply to a maximum of 1,530 mg/L. This transition zone is also evident in the pH, which decreased by nearly one unit just above the Top Pittston bed. The pH was constant at 6 in the upper zone and 5 in the lower zone. No Eh data are available.

Shaft NW3, No. 6 Colliery

Shaft NW3 is open from +256 m (+840 ft) to just above the Red Ash bed at +144 m (+472 ft). The shaft contained only an 18-m (59-ft) column of water, and all of the seams mined from the shaft are either above the present water table or below the present floor.

Water quality in the shaft was uniform vertically, containing no significant stratification (fig. 12). Sulfate concentration fluctuated between 300 and 400 mg/L. Eh and pH were also uniform with

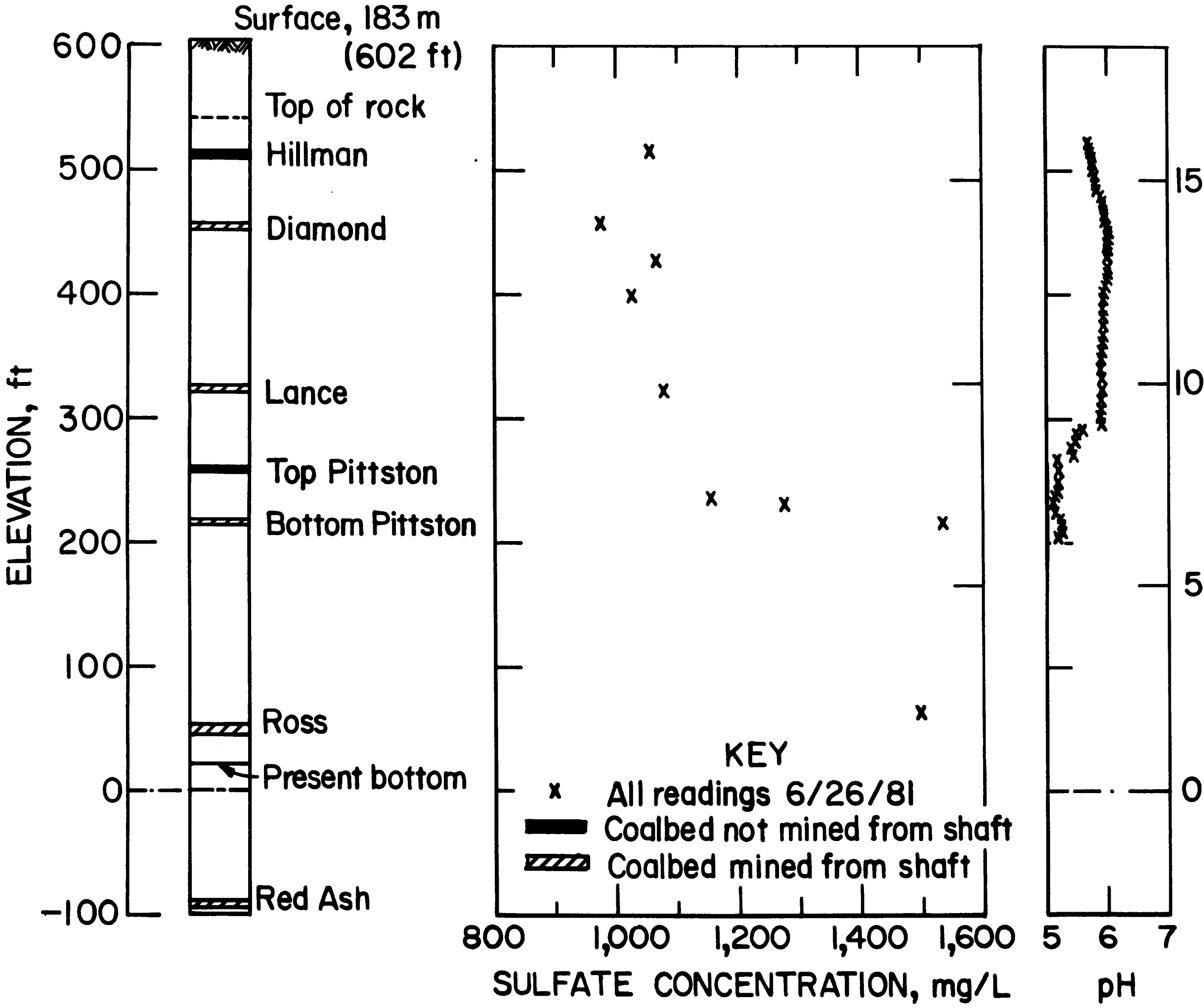

FIGURE 11. - Data profiles for shaft NW2, Gaylord colliery.

depth, at approximately 235 mV and 5.8 to 6.0, respectively. All parameters varied slightly between sampling periods.

Shaft NW4, Kingston Colliery

Shaft NW4 is open from +221 m (+725 ft) to the present floor at +154 m (+505 ft). The shaft contained only 11 m (36 ft) of water, and again the coal seams are either above the water table or below the floor.

Aside from the very-near-surface layering observed in most of the shafts, no vertical stratification was observed (fig. 13). Water quality did, however, vary significantly during the study period. Sulfate concentrations increased from 200 mg/L in June 1981 to 600 mg/L in November 1981. The pH decreased by approximately 1.5 to 2.0 units during the same time period, from just above 7 to just above 5.5.

Discussion

The NW complex is areally the largest of the subcomplexes in the Wyoming Basin. The four shafts monitored are widely spaced across the complex (fig. 5) and cover a broad range of water quality. The variability is apparently due to the relative positions of the shafts in the flow system and local controls on circulation. The shafts contain water of both

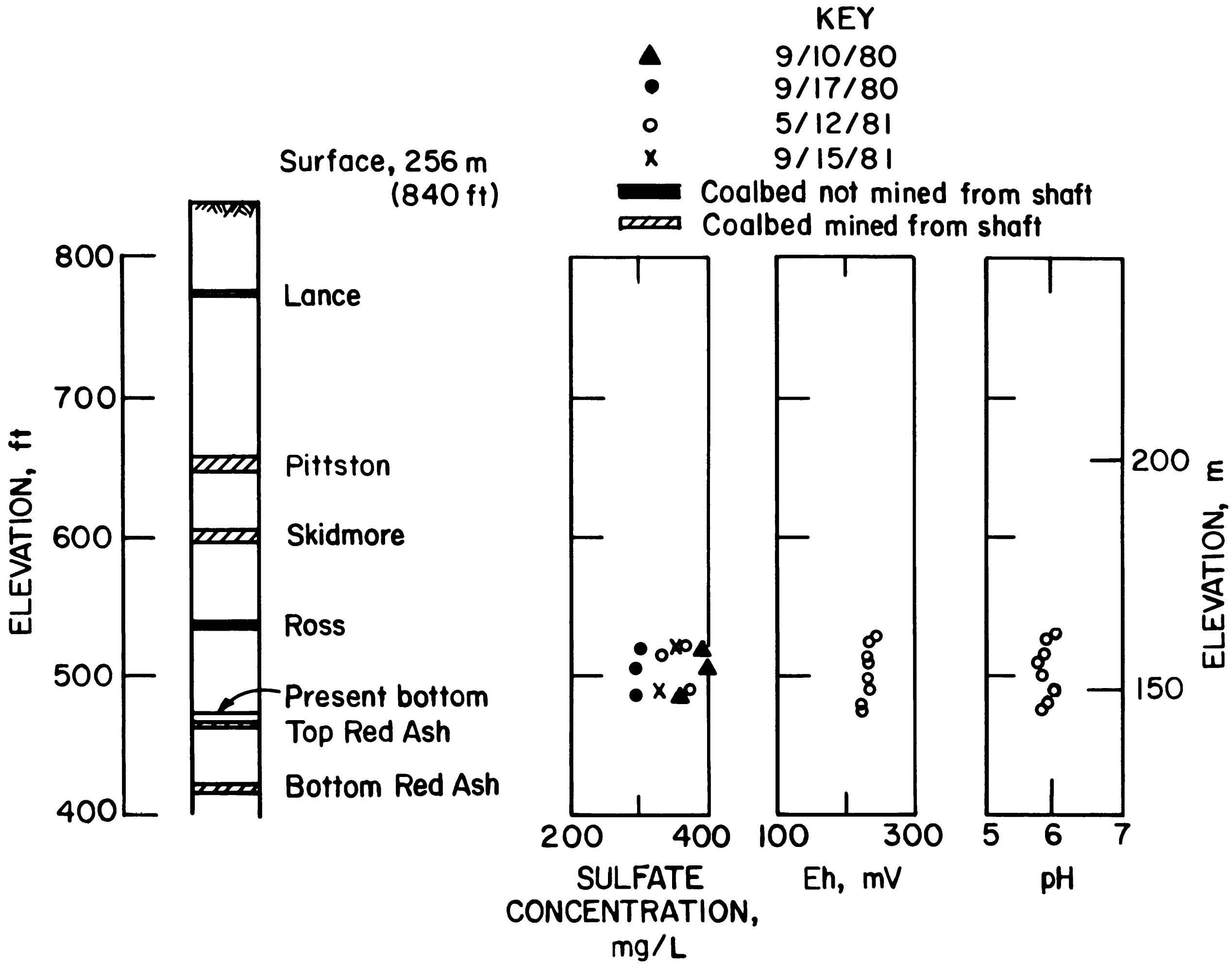

FIGURE 12. - Data profiles for shaft NW3, No. 6 colliery.

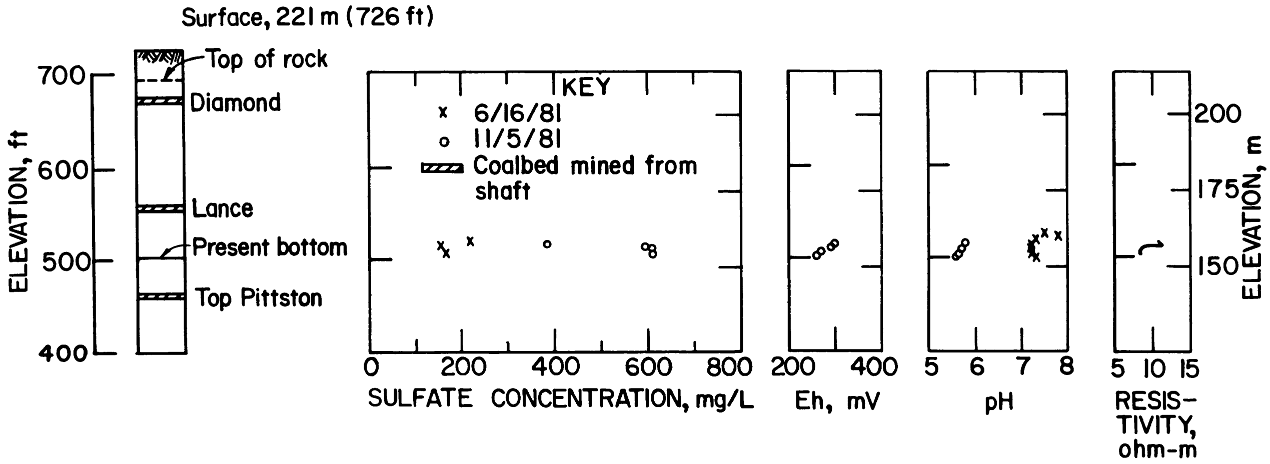

FIGURE 13. - Data profiles for shaft NW4, Kingston colliery.

TABLE 2. - Water quality in the NW complex, milligrams per liter

Sampling site	Date	Iron, total	Sulfate
Shafts:			
NW3	9/10/80	27.4 -27.9	360- 400
	9/17/80	27.7 -32.6	295- 305
	5/12/81	30.0 -30.8	330- 354
	9/15/81	36.8 -37.3	333- 374
	6/16/81	.05	157- 215
NW4	11/ 5/81	7.6 -31.9	383- 610
	5/13/81	1.7 -70.0	33-1,130
NW1	9/23/81	.16-94.5	8-1,460
	6/26/81	21.5 -86.1	974-1,530
NW2	6/19/81	88.0	1,050
Outfall: Buttonwood	6/24/81	85.9	1,150

better and worse quality than the discharge at the NW complex outfall, the Buttonwood tunnel (table 2).

Shafts NW2 and NW1 are the deepest shafts in the complex, and both have developed conspicuous stratification into two zones of water quality. In both, the upper zone is less contaminated than the lower zone, and the transition between zones occurs at the elevation of the lowest seam containing mined barrier pillars.

NW2 is located near the boundary of the Gaylord colliery with the Lance colliery (fig. 5). The barrier pillars between the two collieries have been mined in the Hillman, Diamond, Lance, Top Pittston, and Bottom Pittston seams, and are intact in the Ross and Red Ash seams (4). The sharp stratification in water quality occurs at the Pittston seams (fig. 11). The development of stratification in NW2 may reflect higher flow rates through the upper seams with mined barrier pillars, or may be an artifact of the initial flooding of the colliery. Concerning the latter possibility, workers in Europe (12) have suggested that water quality stratification in mine workings occurs at elevations at which the water level has been held constant, as by pumping. Based on barrier pillar analysis, Ash (4) determined that cessation of pumping in the Gaylord colliery would cause water to rise to the elevation +75 m (+246 ft) and then discharge to the Lance colliery through the Bottom Pittston (Baltimore) seam. Water level rise in the Gaylord colliery would therefore be temporarily slowed or halted at the Bottom Pittston seam until the Lance colliery was allowed to flood. The static or near-static water level conditions may be responsible for the observed development of water quality stratification.

NW2 is the only shaft in the basin for which comparable water quality data exist. Observation of stratification at the Bottom Pittston seam is consistent with data from the Loree No. 2 shaft published by the USGS in 1964 (8). The Loree and Gaylord mines are adjacent and well interconnected by mined barriers in all seams below the Diamond (4). The USGS investigation found a zone of water quality bounded by the Stanton (Diamond) and Bennett (Pittston) seam elevations characterized by sulfate and iron concentrations on the order of 3,400 and 480 mg/L, respectively. Eh and pH data were consistent with ferric hydroxide saturation. A lower zone of water quality was identified in samples from the Ross and Red Ash beds, characterized by sulfate and iron concentrations on the order of 6,300 and 1,260 mg/L, respectively. This environment was sufficiently reducing for pyrite to be stable.

Comparison of water quality from the Loree and Gaylord shafts indicates significant changes have occurred in the last 16 years. Sulfate concentrations in each zone have decreased by about 70 to 75 pct. Eh has decreased and pH has increased in the upper zone. The lower zone appears to have become a much more oxidizing environment, although downhole measurements reached only the upper few meters of this zone.

NW2 is nearer to the Buttonwood outfall than the other shafts in the complex, and water quality in the upper zone most closely reflects the quality at the outfall (table 2). The water quality in both zones in NW2, although improving, is relatively poor and may indicate either a slow rate of flushing in this area or progressive degradation with distance from the recharge areas.

In shaft NW1 (Henry colliery), the water quality is stratified into two major zones partitioned at the Skidmore seam. The barrier pillars in the Skidmore and all higher elevation seams were continuously mined across the boundary between the Henry and Prospect collieries, while the barrier pillars in all lower seams were unmined, making the Skidmore seam the lowest flow-through junction between the two collieries (4). The occurrence of stratification at the Skidmore seam again suggests either a higher flow rate through the upper seams with mined pillars or discharge through the Skidmore seam at the time of flooding.

The upper zone in NW1, with less than 100 mg/L sulfate, contains the least contaminated water in the basin. Although no data exist for comparison, this zone apparently has been flushed of residual oxidation products. The lower zone, high in sulfates but maintaining a nearly constant pH over a wide range in water quality, is consistent with slow, nonturbulent flow in the bottom beds. Owing to the intact barrier pillars in the lower seams, water movement is controlled by horizontal seepage and by upward mixing and discharge through the Skidmore seam. The stability of the pH in this zone, as sulfate ranged from 175 to 1,460 mg/L, is indicative of chemical buffering. High calcium and magnesium associated with the high sulfates suggests carbonate minerals are the buffer source (fig. 8).

The improved water quality in the deepest part of the shaft may result from either flow of less contaminated water through the deep Red Ash bed or flushing by the upward circulation of deep ground water from the underlying Pottsville Formation. Flow of less contaminated water in the Red Ash bed is not supported by other water quality data or by barrier pillar analyses. The upward circulation of deep ground water is supported by the regional ground water flow patterns and artesian conditions reported for the Pottsville Formation (24, 28).

Shafts NW3 and NW4 are much shallower than the other two shafts in the complex. Both NW3 and NW4 occupy positions near the coal measure boundary and are consequently in ground water recharge zones. The lack of stratification in either shaft can be attributed to the absence of coal seams intersecting the shallow water columns above the present shaft floors. The relatively low sulfate concentrations observed in the shafts suggest that circulation has been sufficient to remove most of the residual oxidation products. The present water quality may be indicative of ongoing oxidation processes in the recharge areas, both at the surface and in unflooded portions of the mine. Temporal extremes observed in NW4 support this contention: Sulfate concentrations varied by an order of 3 between sampling periods, the greatest variation found in any shaft in the basin.

SOUTHEAST UPPER COMPLEX

Shaft SEU1, Truesdale-Bliss Colliery

Shaft SEU1 is open from +221 m (+725 ft) to the Kidney seam at -51 m (-167 ft). Of the 10 beds originally mined from the shaft, 3 are above the present floor.

The profile of sulfate concentration in SEU1 is essentially featureless from the water surface to the depth limit of the sampler, ranging from 630 to 688 mg/L (fig. 14). Eh and pH are also relatively constant in this zone. After increasing slightly in the upper 30 m of the shaft,

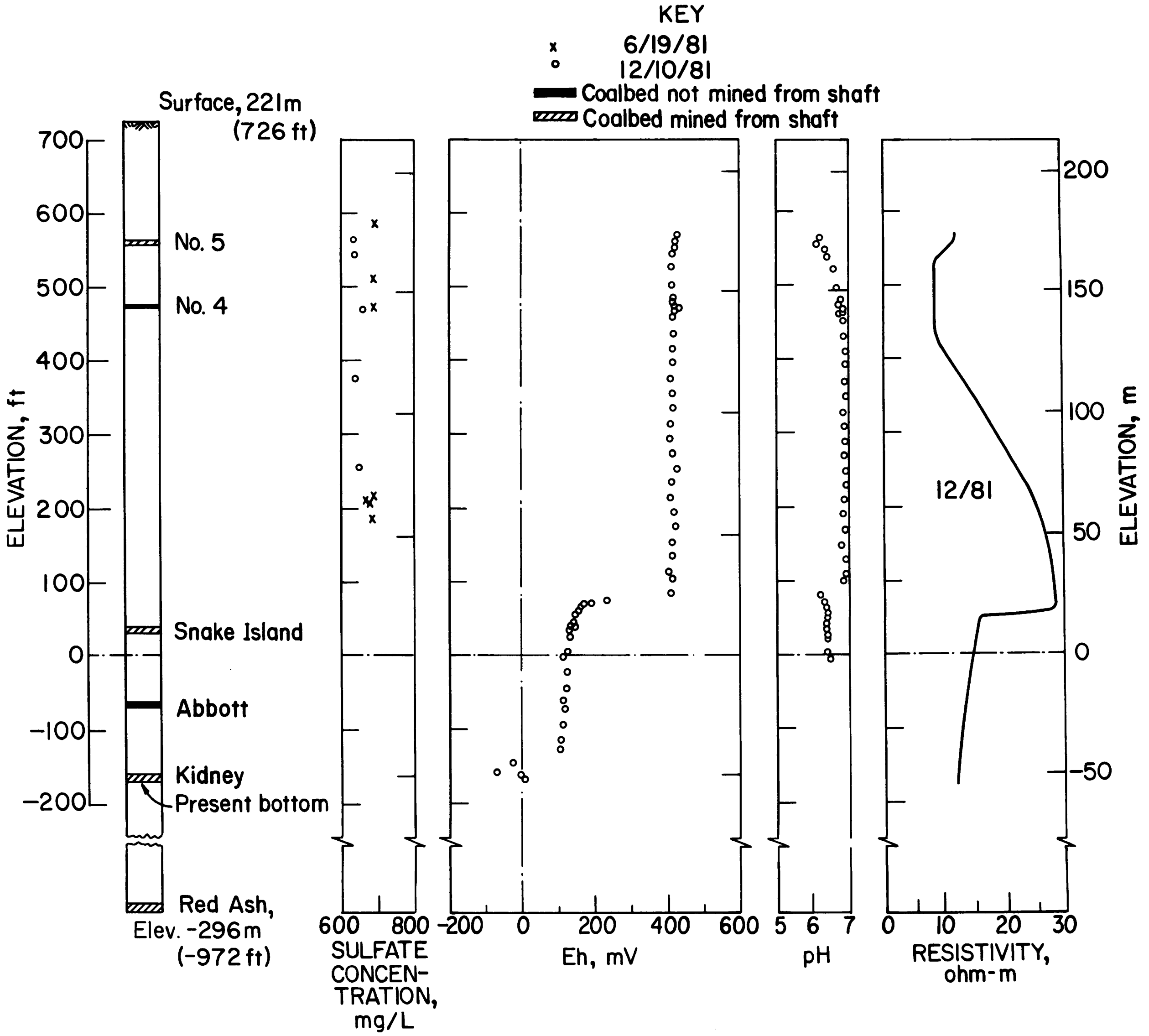

FIGURE 14. - Data profiles for shaft SEU1, Truesdale-Bliss colliery.

pH stabilizes at 6.9. The S-shaped resistivity profile in the upper zone is not consistent with water quality analyses.

A sharp transition occurs between elevations of +15 m (+49 ft) and +30 m (+98 ft), just below the range of the water sampler. Over a 5-m (16-ft) inverval, Eh decreased by 240 mV, pH decreased by more than 0.5 units, and resistivity decreased by 10 ohm-m. Below the transition, resistivity and Eh continued to slowly decrease and pH remained essentially constant at 6.4. Eh again decreased sharply near the bottom of the shaft.

Shaft SEU2, Truesdale-Bliss Colliery

Shaft SEU2, the deepest shaft monitored, is open from +195 m (+641 ft) to the Red Ash bed at -455 m (-1,492 ft). Only two seams, the No. 3 and Kidney, were mined from this shaft.

Owing to physical restrictions on the site, no water samples could be obtained.

However, downhole Eh, pH, and resistivity measurements were made and clearly indicate stratification into two zones (fig. 15). The upper 150 m (492 ft) is characterized by nearly constant resistivity and, following some near-surface variability, constant Eh at 310 mV and pH at 7.2.

A sharp transition occurred at elevation +23 m (+75 ft), just above the No. 3 seam. Over a 10-m (33-ft) interval, Eh decreased 270 mV, pH decreased 1 unit, and resistivity decreased 9.5 ohm-m (31 ohm-ft). The elevation of this transition zone is just a few meters lower than the transition in SEU1. Below the transition zone Eh and pH stabilize. Resistivity increases slightly near the bottom of the profile, possibly indicating less contaminated water at depth.

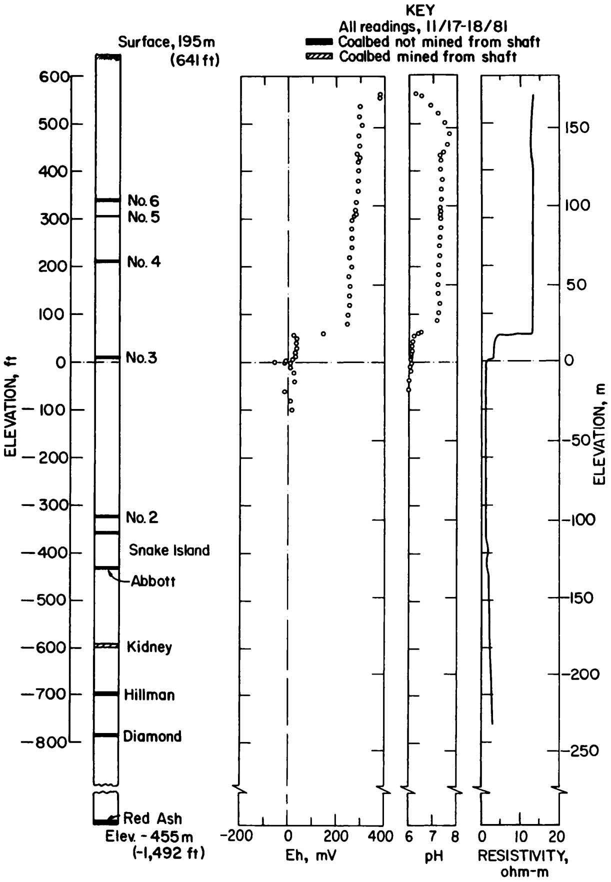

FIGURE 15. - Data profiles for shaft SEU2, Truesdale-Bliss colliery.

Discussion

The SE upper complex is an example of the controls that local structural features and outfall position exert on water quality distribution. The complex occurs in the deepest part of the Wyoming Basin (fig. 3) and contains many subordinate structural features. Of greatest interest in this study is a small synclinal trough in the upper beds, the axis of which parallels the main valley axis (fig. 16). The Askam outfall taps into the No. 4 seam on the northwestern limb of this syncline (<u>24</u>), creating a small local flow system. The flow system is recharged at the southern outcrop of the beds in the synclinal trough and discharges at the northern end by way of the Askam outfall. Considerable downward seepage also occurs.

The SE upper complex is in a regional recharge zone (<u>18</u>). Recharge raises the water level in the synclinal trough above the elevation of the Askam outfall, stimulating discharge. When the water level drops below the elevation of the outfall, only downward seepage occurs. The deeper zone reflects the poor water quality in a larger, more stagnant subsystem that flows into the SE lower complex and will be discussed in the later section on shaft SEL3 in the Loomis colliery.

SOUTHEAST LOWER COMPLEX

Shaft SEL1, Hollenback Colliery

Shaft SEL1 is open from +171 m (+561 ft) to the present floor at +53 m (174 ft). Only the Hillman seam was mined above the present floor. Originally, the shaft was open to a tunnel connecting to the Diamond seam at elevation +39 m (+128 ft).

AMD contamination was moderate in SEL1 (fig. 17). Sulfate concentrations did not exceed 300 mg/L. The water in the shaft was stratified into two zones partitioned at the Hillman seam. The upper zone contained less than 125 mg/L sulfate and had variable Eh and pH. Below the Hillman seam, sulfate increased to over

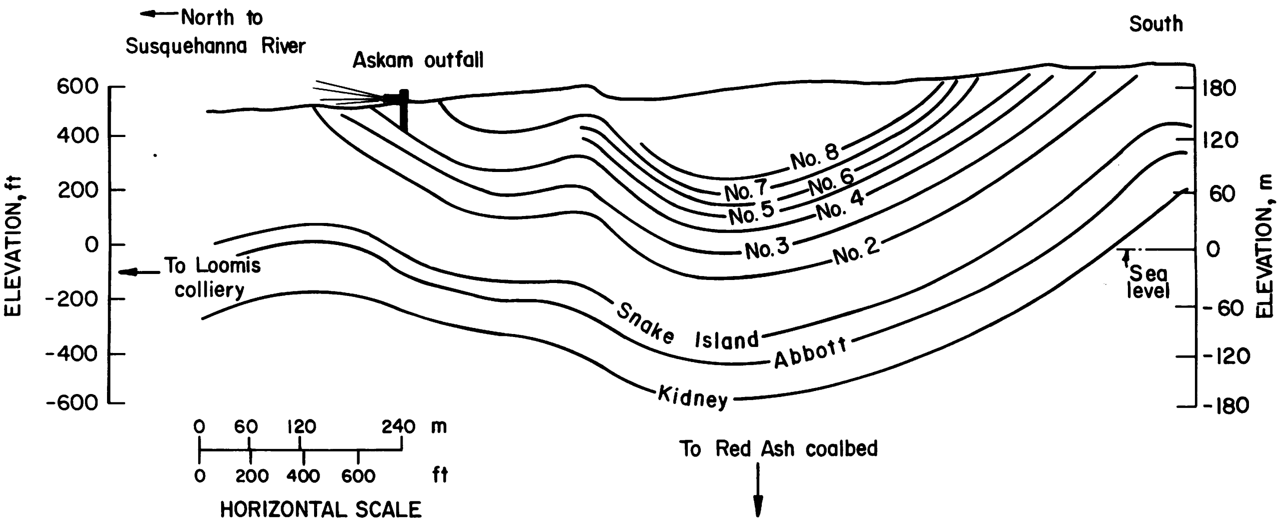

FIGURE 16. - Synclinal structure tapped by the Askam outfall.

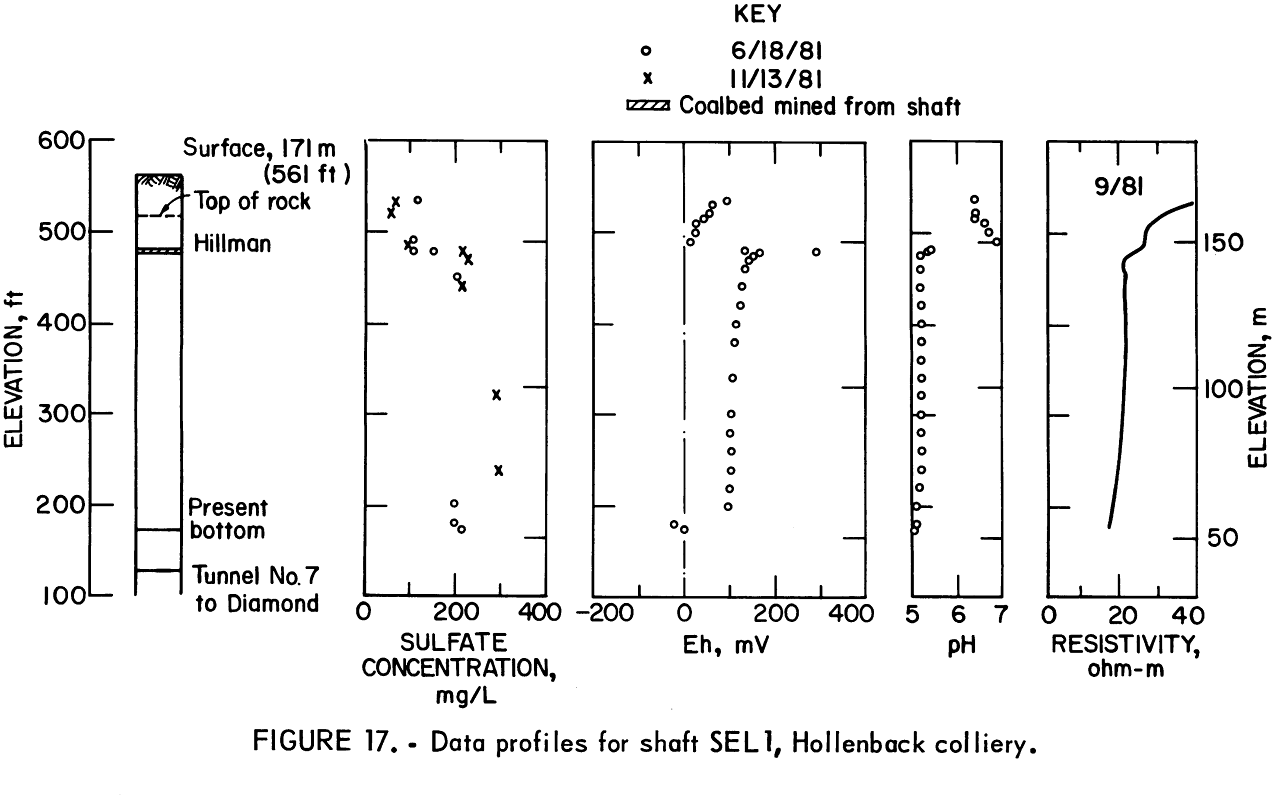

FIGURE 17. - Data profiles for shaft SEL1, Hollenback colliery.

200 mg/L, Eh increased by more than 100 mV, and pH decreased by over 1.5 units. Eh and pH were nearly constant in the lower zone. A third zone just above the present shaft floor is marked by a sharp decrease in Eh.

Shaft SEL2, Peach Orchard Colliery

Shaft SEL2 is open from +178 m (+584 ft) to the Red Ash bed at −155 m (−509 ft). Ten beds were mined from the shaft.

Water quality in the upper 125 m (410 ft), accessible with the water sampler, had slight variations between sampling periods but no distinct stratification (fig. 18). Sulfate concentrations were between 350 and 550 mg/L. Apart from near-surface fluctuations, Eh, pH, and resistivity were constant to elevation -29 m (-95 ft), near the Top Pittston seam. At this point, Eh became too unstable to read, pH increased by 0.6 units, and resistivity decreased slightly.

Shaft SEL3, Loomis Colliery

Shaft SEL3 is open from +161 m (+528 ft) to the present collapsed floor just above the Hillman seam at +3 m (+10 ft). Three of the four seams mined from the shaft are above the present floor.

Overall water quality in SEL3 was the worst in the basin (fig. 19). Sulfate concentrations were between 1,240 and 1,560 mg/L. Water quality, Eh, and pH

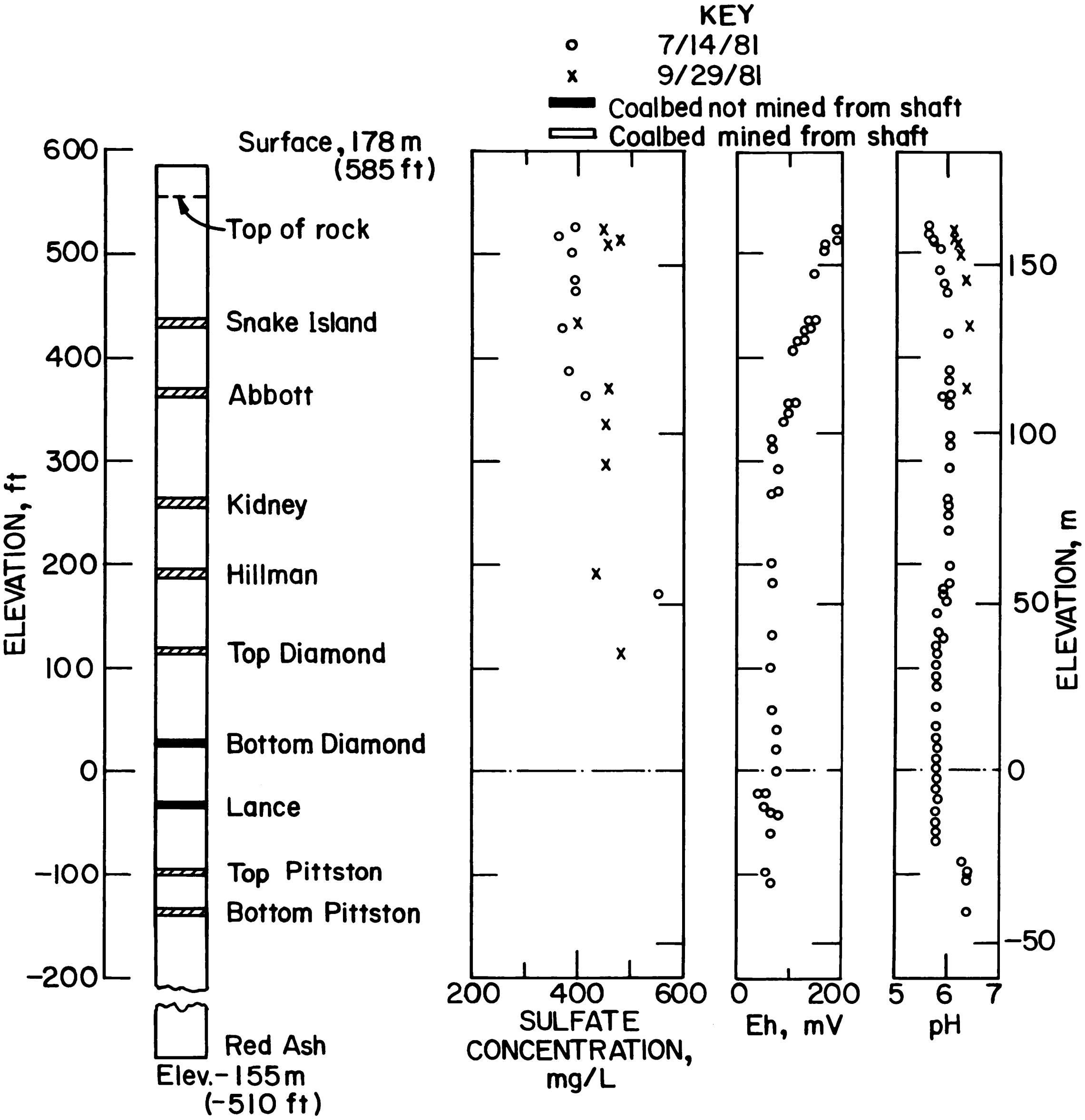

FIGURE 18. - Data profiles for shaft SEL2, Peach Orchard colliery.

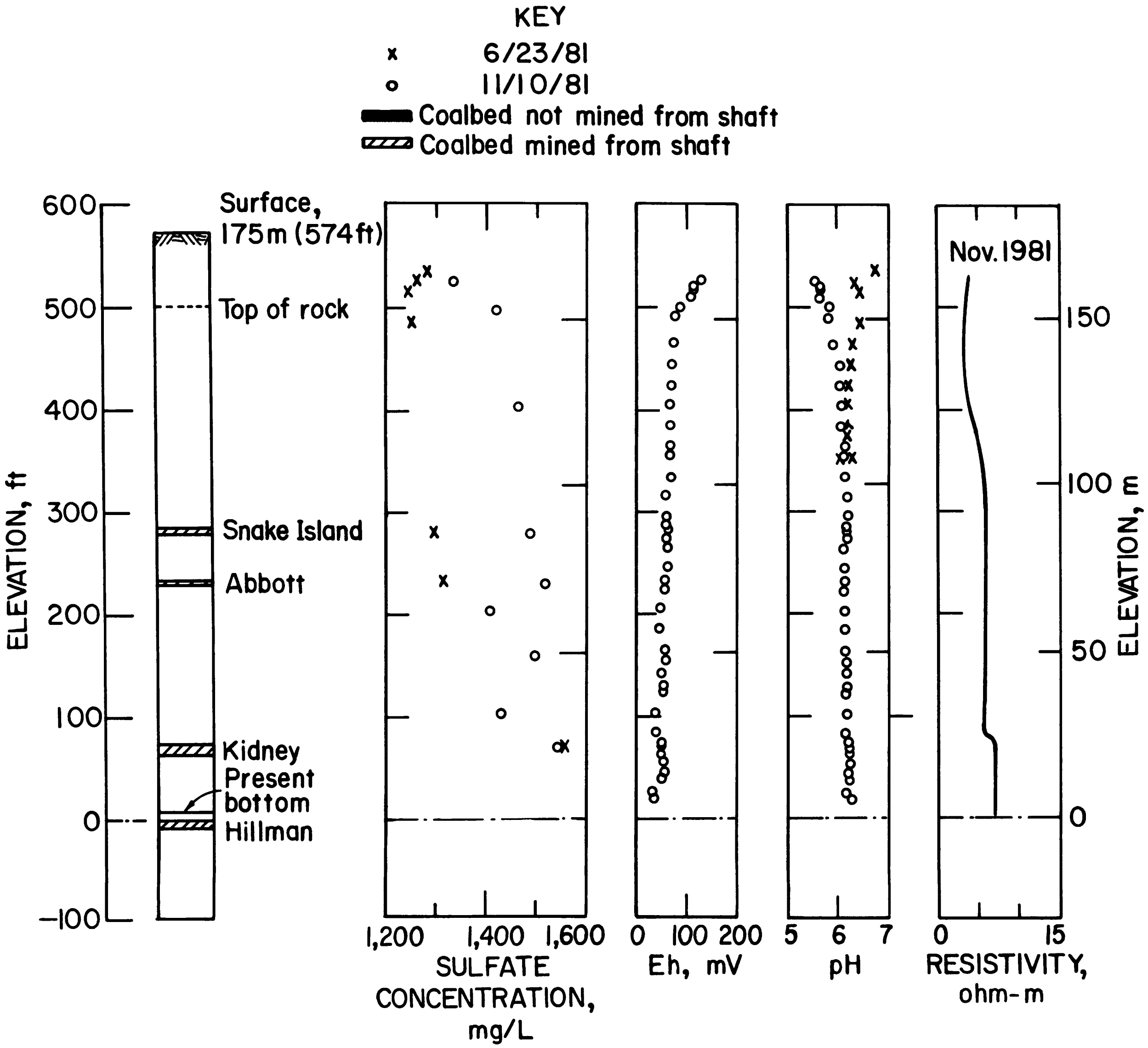

FIGURE 19. - Data profiles for shaft SEL3, Loomis colliery.

did not indicate significant stratification with depth. Resistivity registered a small but sharp increase at +24 m (+79 ft), the elevation of the Kidney seam.

Discussion

SEL1 was the only one of the three shafts in the SE lower complex to exhibit significant vertical stratification. The stratification is apparently due to flow through the mined Hillman seam. Although the quality of water in the Hillman seam is slightly poorer than that of near-surface water, overall quality is the best in the complex, indicating good circulation and flushing (table 3). Barrier pillars in the Hillman seam have been mined between the Hollenback and Stanton-Empire collieries, and between the Stanton-Empire and South Wilkes-Barre collieries, promoting rapid flow from Hollenback to the South Wilkes-Barre outfall (fig. 5).

TABLE 3. - Water quality in the SE complex, milligrams per liter

Sampling site	Date	Iron, mg/L	Sulfate, mg/L
UPPER COMPLEX			
Shaft: SEU1	9/23/80	0.5 - 11.6	698- 788
	6/19/81	.06- .09	662- 688
	12/10/81	.16- .64	630- 656
Outfall: Askam	6/18/81	93.0	1,150
	6/24/81	88.7	1,250
LOWER COMPLEX			
Shafts:			
SEL1	6/18/81	9.5 - 27.2	57- 297
	11/ 3/81	12.5 - 22.4	105- 213
SEL2	5/14/81	20.3 - 26.0	396- 560
	9/29/81	17.3 - 31.8	362- 560
SEL3	6/23/81	65.9 - 74.1	1,250-1,550
	11/10/81	57.8 - 63.2	1,340-1,540
Outfall: South Wilkes-Barre	6/24/81	131	1,350

The Peach Orchard and Loomis collieries are more isolated from the primary flow paths in the SE lower complex. The Peach Orchard colliery is surrounded by unmined barrier pillars, although some encroachment has occurred in the pillars of the adjacent Baltimore colliery (4). Water quality is slightly poorer than in Hollenback, reflecting decreased water movement and slower flushing. A minor transition zone at the Top Pittston bed in SEL2 is marked by an increase in pH. Fluctuation in Eh meter response suggests flow through the seam.

The Loomis colliery is located in a regional ground water discharge zone for the basin, but has no major discharge point to stimulate rapid flow. The poor-quality water in the Loomis shaft is the northern extension of the large lower flow cell described for the SE upper complex (fig. 16). Because the barrier pillars are essentially unmined between the Truesdale-Bliss and Loomis collieries (4), water movement and flushing are slow. Given the slower rate of movement, the great depth of the coal measures in the area, and the upward flow of deep contaminated water, the Loomis colliery may require a longer flushing period than other parts of the basin.

SUMMARY

Water quality in the Wyoming Basin has exhibited marked improvement since inundation of the mine complex, as measured at the outfalls and within the flooded mines. Sulfate concentrations have decreased by 49 pct at the Buttonwood outfall and by over 70 pct within the one area of the mine complex where two comparable data sets are available. The pH has increased to the neutral range, and the acidity has been replaced by net alkalinity. Concomitant decreases in iron, aluminum, manganese, calcium, and magnesium were also observed.

The improvement in water quality can probably be attributed to inhibition of pyrite oxidation due to flooding, dissolution of carbonate minerals to buffer residual acidity, and flushing of residual contaminants from the system. In light of the high calcium and magnesium concentrations reported in earlier studies (8), the buffering mechanism may have been more important in the initial, highly acidic environment.

The shaft monitoring documented an aspect of deep mine drainage not often considered, i.e., the development of stratification of water of different quality within a flooded mine system. In five of the nine shafts studied, water was layered into two major zones separated by sharp changes in Eh, pH, and water quality parameters. The stratification appears to be related to discharge elevations at the time of inundation, as well as present flow conditions. Relative positions of mined barrier pillars, outfall installations, and natural structural features combine to create an environment more favorable to flushing in the shallower parts of the mine system. As a result, the least contaminated water was found in the upper zones of the system, while the poorest water quality was observed in flow-restricted, deeper zones.

The rate of flushing and minimum contamination levels attainable are difficult to quantitatively assess at this time. Pyrite oxidation is occurring at the surface in refuse piles and strip pits, as well as in oxygenated portions of the deep mines. These oxidation products are progressively washed into the subsurface flow system and are a continuous supply of contamination. The recharging pollutants will probably be confined to small, near-surface flow systems and may tend to dominate the discharge quality at the outfalls.

The upward mixing of the deep, poorer quality water will also continue to supply some residual oxidation products to the upper zones and outfall discharges. Stimulation of flow from the deep zones by the addition of fully penetrating discharge structures may increase the rate of flushing, but would aggravate the pollutant load on the surface streams if the discharge is left untreated. The construction of additional outfalls also may be self-defeating; lowered water levels would increase the unflooded volume of the mine and possibly renew pyrite oxidation in these areas.

The results of this study raise the possibility that the relatively good quality water within some of the upper zones may eventually become a usable resource. For example, additional discharge structures taking advantage of those areas in the basin receiving uncontaminated recharge could potentially serve as a commercial water source as well as reduce total discharge at the existing outfalls. Before any resource development is considered, however, careful thought must be given to the effects of ground water withdrawal on the present geochemical environment and water quality zonation, and the possibilities of induced recharge, subsurface flow diversion, and subsidence.

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APPENDIX.--RESULTS OF THE SHAFT-MONITORING PROGRAM

TABLE A-1. - Water quality in shaft NW1, Henry colliery

5/13/81; sample depth...........m..	14	15	17	21	39	57	84	91	104	105	132	157	170
pH:													
Field............................	6.65	7.10	7.10	7.15	7.15	7.10	7.05	7.10	6.90	6.90	6.55	6.70	6.85
Downhole.........................	6.70	6.85	6.95	7.05	7.10	7.20	NA	NA	NA	NA	NA	NA	NA
Laboratory.......................	6.9	6.6	6.8	6.9	7.3	7.0	6.8	7.1	7.0	7.0	6.7	6.6	6.9
Temperature, field.............°C..	13.0	13.5	13.0	13.0	13.0	13.5	14.0	13.5	13.5	14.0	14.0	14.0	14.0
Conductivity, field.......µmho/cm..	465	450	460	480	450	470	490	480	570	595	1,160	1,030	650
Alkalinity[1]............mg $CaCO_3$/L..	170	170	180	170	180	170	180	170	170	170	170	170	160
Iron,[2] mg/L:													
Ferrous..........................	0.7	1.1	1.1	1.2	1.2	1.1	1.4	1.3	8.6	10	57	52	16
Total............................	1.7	1.7	1.8	1.7	1.7	1.7	1.7	1.8	8.9	9.7	70	57	16
Sulfate....................mg/L..	69	50	50	33	33	67	45	57	175	213	1,130	920	296
Manganese[1].................mg/L..	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.7	1.7	5.9	5.2	2.4
Fecal coliform...cells per 100 ml..	0	0	0	0	0	0	0	0	0	0	0	0	0
9/23/81; sample depth...........m..	12	13	49	67	84	99	105	109	149	168			
pH:													
Field............................	6.8	6.8	6.8	6.9	6.9	6.8	6.7	6.7	6.4	6.6			
Downhole.........................	7	6.6	7.2	6.8	6.8	6.3	6	6	6	6			
Laboratory.......................	7.1	7.2	7.2	7.1	7.2	6.2	7.0	6.8	6.4	6.8			
Temperature, field.............°C..	13	14	13	13	13	13	13	13	13	13			
Conductivity, field.......µmho/cm..	710	760	740	800	820	870	950	1,090	2,200	1,430			
Acidity,[3] net..........mg $CaCO_3$/L..	-120	-180	-180	-180	-180	-150	-170	-170	-130	-150			
Iron,[2] mg/L:													
Ferrous..........................	0.05	2.3	2.4	2.7	2.9	9.5	9.9	15	86	30			
Total............................	0.16	3.4	3.4	3.7	3.5	11	12	17	95	35			
Sulfate....................mg/L..	90.7	78.3	70.9	83.3	90.7	175	165	272	1,460	516			
Calcium....................mg/L..	74	80	80	80	80	94	93	120	350	160			
Magnesium..................mg/L..	23	25	25	25	25	28	28	30	150	67			
Fecal coliform...cells per 100 mL..	274	10	14	68	6	286	28	8	0	NA			

NA Not available.

[1] Values reported as alkalinity were measured by direct titration with acid; acidity was not determined on these samples.

[2] In filtered, acidified sample.

[3] As determined by the American Public Health Association (_1_) back-titration procedure; minus sign indicates net alkalinity.

TABLE A-2. - Water quality in shaft NW2, Gaylord colliery

6/26/81; sample depth.................m..	26	44	53	62	63	113	114	118	165
pH:									
Field..................................	6.45	6.45	6.5	6.5	6.5	6.45	6.3	6.3	6.35
Downhole...............................	5.72	5.98	6.0	5.92	NA	5.1	5.12	NA	NA
Laboratory.............................	6.4	6.4	6.4	6.4	6.4	6.3	6.4	6.2	6.4
Temperature, field...................°C..	16	16	15.5	16	16	16.5	16.5	17	17
Conductivity, field..............µmho/cm..	1,080	1,080	1,070	1,070	1,010	1,040	1,130	1,230	1,270
Alkalinity[1]...................mg $CaCO_3$/L..	150	150	140	140	140	110	140	100	130
Iron,[2] mg/L:									
Ferrous................................	17	18	18	19	19	34	48	79	58
Total..................................	22	22	22	22	22	38	53	86	62
Sulfate..........................mg/L..	1,070	974	1,060	1,020	1,080	1,160	1,280	1,530	1,500
Manganese........................mg/L..	9.3	9.0	9.0	9.1	9.2	10	11	12	9.8
Fecal coliform...........cells per 100 mL..	38	12	28	26	16	0	2	0	0

NA Not available.

[1] Values reported as alkalinity were measured by direct titration with acid; acidity was not determined on these samples.

[2] In filtered, acidified sample.

TABLE A-3. - Water quality in shaft NW3, No. 6 colliery

9/10/80; sample depth … m	98	102	108
pH, laboratory	6.3	6.3	6.3
Alkalinity[1] … mg $CaCO_3$/L	46	38	43
Iron, total … mg/L	28	28	28
Sulfate … mg/L	395	400	360
Manganese … mg/L	2.9	2.9	2.9
Fecal coliform … cells per 100 mL	0	0	2
9/17/80; sample depth … m	98	102	107
pH, laboratory	6.2	6.2	6.1
Alkalinity[1] … mg $CaCO_3$/L	40	45	46
Iron, total … mg/L	33	30	28
Sulfate … mg/L	305	295	299
Manganese … mg/L	3.0	2.9	2.8
Fecal coliform … cells per 10 mL	15	27	22
5/12/81; sample depth … m	97	107	
pH:			
Field	6.20	6.05	
Downhole	6.10	6.03	
Laboratory	6	6	
Temperature, field … °C	13	13	
Conductivity, field … µmho/cm	600	610	
Alkalinity[1] … mg $CaCO_3$/L	31	31	
Iron,[2] mg/L:			
Ferrous	31	31	
Total	31	30	
Sulfate … mg/L	354	330	
Manganese … mg/L	3.0	2.9	
Fecal coliform … cells per 100 mL	0	0	
9/15/81; sample depth … m	97	99	107
pH:			
Field	6.1	6.3	6.3
Downhole	5.88	5.85	6
Laboratory	6.4	5.7	5.7
Temperature, field … °C	18	17	17
Conductivity, field … µmho/cm	850	760	790
Acidity,[3] net … mg $CaCO_3$/L	-24	+13	+6
Iron,[2] mg/L:			
Ferrous	33	34	34
Total	37	37	37
Sulfate … mg/L	369	333	374
Calcium … mg/L	88	69	69
Magnesium … mg/L	30	29	29
Fecal coliform … cells per 100 mL	2	0	0

[1] Values reported as alkalinity were measured by direct titration with acid; acidity was not determined on these samples.

[2] In filtered, acidified sample.

[3] As determined by the American Public Health Association (1) back-titration procedure; minus sign indicates net alkalinity.

TABLE A-4. - Water quality in shaft NW4, Kingston colliery

6/16/81; sample depth..........m..	63	65	68	
pH:				
Field	6.8	6.7	6.8	
Downhole	7.3	7.2	NA	
Temperature, field..........°C..	20	20	19	
Conductivity, field..........μmho/cm..	100	410	400	
Alkalinity[1]..........mg $CaCO_3$/L..	92	100	110	
Iron,[2] mg/L:				
Ferrous	0.01	0.01	0.01	
Total	0.05	0.05	0.05	
Sulfate..........mg/L..	215	157	165	
Manganese..........mg/L..	0.02	0.01	0.02	
Fecal coliform..........cells per 100 mL..	0	0	0	
11/5/81; sample depth..........m..	64	65	66	68
pH:				
Field	6.75	6	6	5.9
Downhole	5.75	5.7	5.7	5.6
Laboratory	6.6	5.6	5.6	5.3
Temperature, field..........°C..	14	14	14	14
Conductivity, field..........μmho/cm..	870	1,145	1,160	1,180
Acidity,[3] net..........mg $CaCO_3$/L..	-47	+23	-4.9	+6.3
Iron,[2] mg/L:				
Ferrous	5.3	24	27	31
Total	7.6	31	32	32
Sulfate..........mg/L..	383	596	607	610
Calcium..........mg/L..	81	120	110	120
Magnesium..........mg/L..	63	80	81	81
Fecal coliform..........cells per 100 mL..	0	0	0	0

NA Not available.

[1] Values reported as alkalinity were measured by direct titration with acid; acidity was not determined on these samples.

[2] In filtered, acidified sample.

[3] As determined by the American Public Health Association (1) back-titration procedure; minus sign indicates net alkalinity.

TABLE A-5. - Water quality in shaft SEU1, Truesdale-Bliss colliery

9/23/80; sample depth, m	52	131	183				
pH, laboratory	6.6	6.6	6.6				
Alkalinity[1], mg $CaCO_3$/L	160	160	160				
Iron,[2] total, mg/L	0.5	0.7	11.6				
Sulfate, mg/L	788	698	698				
Manganese[1], mg/L	0.1	0.2	2.6				
Fecal coliform, cells per 100 mL	0	0	0				
6/19/81; sample depth, m	52	66	77	155	157	158	165
pH:							
Field	6.5	6.5	6.5	6.6	6.5	6.7	6.7
Downhole	6.9	6.85	6.85	NA	NA	NA	NA
Laboratory	6.9	7.2	6.9	6.8	7.2	7.2	7.1
Temperature, field, °C	15	15	15	14	16	14	14
Conductivity, field, µmho/cm	775	875	900	925	800	900	925
Alkalinity[1], mg $CaCO_3$/L	160	170	160	160	160	160	160
Iron,[2] mg/L:							
Ferrous	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total	0.08	0.07	0.06	0.07	0.09	0.08	0.08
Sulfate, mg/L	687	684	688	686	662	676	680
Manganese[1], mg/L	0.13	0.11	0.11	0.11	0.12	0.11	0.11
Fecal coliform, cells per 100 mL	3	1	0	0	0	0	0
12/10/81; sample depth, m	49	55	78	107	143		
pH:							
Field	6.9	8.2	8.0	7.2	7.6		
Downhole	6.1	6.4	6.8	6.9	6.9		
Laboratory	6.8	7.2	7.3	7.2	7.3		
Temperature, field, °C	9	10	10	11	10		
Conductivity, field, µmho/cm	1,150	1,300	1,510	1,300	1,410		
Acidity,[2] net, mg $CaCO_3$/L	-190	-180	-180	-180	-180		
Iron,[2] mg/L:							
Ferrous	0.07	0.03	0.03	0.04	0.07		
Total	0.16	0.14	0.20	0.39	0.64		
Sulfate, mg/L	630	636	656	640	648		
Calcium, mg/L	190	200	190	190	200		
Magnesium, mg/L	92	91	89	92	93		
Fecal coliform, cells per 100 mL	0	0	0	0	0		

NA Not available.

[1] Values reported as alkalinity were measured by direct titration with acid; acidity was not determined on these samples.

[2] In filtered, acidified sample.

[3] As determined by the American Public Health Association (1) back-titration procedure; minus sign indicates net alkalinity.

TABLE A-6. - Water quality in shaft SEL1, Hollenback colliery

6/18/81; sample depth...............m..	9	12	23	25	27	37	73	99
pH:								
Field................................	6.5	6.3	6.2	6.0	6.0	5.9	5.8	5.8
Downhole.............................	7.1	6.55	6.85	5.9	5.55	5.6	NA	NA
Temperature, field.................°C..	15	18	18	17	17	17	17	16
Conductivity, field...........µmho/cm..	210	220	260	340	340	360	400	360
Alkalinity[1]................mg $CaCO_3$/L..	73	78	100	66	66	62	52	52
Iron,[2] mg/L:								
Ferrous..............................	8.4	8.2	15	21	21	22	24	24
Total................................	9.5	9.6	17	23	23	24	26	27
Sulfate..........................mg/L..	68	57	94	219	224	216	294	297
Manganese........................mg/L..	1.3	1.4	1.8	2.9	3.0	3.1	3.6	3.5
Fecal coliform.......cells per 100 mL..	500	18	0	0	0	0	0	0
11/3/81; sample depth...............m..	8	21	24	25	34	110	116	118
pH:								
Field................................	6.2	6.4	6.55	5.95	6.1	6.35	6.2	6.2
Downhole.............................	6.4	6.85	5.35	5.35	5.2	5.1	5.1	5.05
Laboratory...........................	6.9	7.0	6.8	6.6	6.3	6.3	6.2	6.5
Temperature, field.................°C..	16	16	15	14	14	14	16	15
Conductivity, field...........µmho/cm..	825	825	900	660	745	750	780	760
Acidity,[3] net..............mg $CaCO_3$/L..	-88	-100	-160	-74	-47	-54	-43	-40
Iron,[2] mg/L:								
Ferrous..............................	5.2	3.9	7.3	3.7	17.2	15.5	7.6	8.4
Total................................	13	13	15	18	22	21	22	22
Sulfate..........................mg/L..	120	105	107	151	205	197	200	213
Calcium..........................mg/L..	41	41	44	48	54	55	58	59
Magnesium........................mg/L..	21	22	23	24	29	29	30	30
Fecal coliform.......cells per 100 mL..	4	360	4	4	0	8	0	0

NA Not available.

[1] Values reported as alkalinity were measured by direct titration with acid; acidity was not determined on these samples.

[2] In filtered, acidified sample.

[3] As determined by the American Public Health Association (<u>1</u>) back-titration procedure; minus sign indicates net alkalinity.

TABLE A-7. - Water quality in shaft SEL2, Peach Orchard colliery

5/14/81; sample depth......m..	18	21	23	46	65	76	88	120	143
pH:									
Field......................	5.86	6.05	6.15	6.2	6.2	6.15	6.10	6.10	6.10
Downhole....................	6.05	6.08	6.12	6.35	6.30	NA	NA	NA	NA
Laboratory..................	6.6	6.5	6.5	6.5	6.6	5.9	0	6.5	6.4
Temperature, field........°C..	14	15	22	21	19	19	19	16	0
Conductivity, field..µmho/cm..	710	725	775	750	770	700	750	650	720
Alkalinity[1]......mg $CaCO_3$/L..	120	110	120	120	120	120	110	120	130
Iron,[2] mg/L:									
Ferrous.....................	26	26	25	25	26	27	26	24	27
Total.......................	25	25	24	20	25	26	25	24	25
Sulfate.................mg/L..	441	474	452	396	452	450	452	434	496
Manganese...............mg/L..	3.3	3.4	3.4	3.4	3.4	3.5	3.4	3.4	3.4
Fecal coliform cells per 100 mL..	0	0	0	0	0	0	0	0	0
9/29/81; sample depth.....m..	**18**	**20**	**24**	**34**	**37**	**47**	**60**	**67**	**126**
pH:									
Field......................	6.2	6.2	6.3	6.3	6.3	6.3	6.4	6.3	6.2
Downhole....................	5.6	5.6	5.8	5.9	6.0	6.0	6.0	6.0	5.9
Laboratory..................	6.4	6.5	6.5	6.5	6.4	6.5	6.5	6.5	6.3
Temperature, field........°C..	15	15	14	15	14	14	14	14	14
Conductivity, field..µmho/cm..	1,100	1,190	1,200	1,140	1,170	1,150	1,220	1,230	1,360
Acidity,[3] net......g $CaCO_3$/L..	-140	-140	-140	-140	-140	-140	-140	-140	-120
Iron,[2] mg/L:									
Ferrous.....................	13	14	12	13	16	15	16	13	18
Total.......................	21	20	17	21	21	21	21	22	32
Sulfate.................mg/L..	389	362	386	389	391	369	381	411	560
Calcium.................mg/L..	100	100	110	100	110	100	110	100	110
Magnesium...............mg/L..	56	57	57	56	56	54	57	56	66
Fecal coliform cells per 100 mL..	0	0	0	0	0	0	0	0	0

NA Not available.

[1] Values reported as alkalinity were measured by direct titration with acid; acidity was not determined on these samples.

[2] In filtered, acidified sample.

[3] As determined by the American Public Health Association (1) back-titration procedure; minus sign indicates net alkalinity.

TABLE A-8. - Water quality in shaft SEL3, Loomis colliery

6/23/81; sample depth......m..	12	15	18	27	89	104	154		
pH:									
Field......................	6.7	6.45	6.42	6.42	6.45	6.42	6.45		
Downhole...................	6.7	6.3	6.4	6.4	NA	NA	NA		
Laboratory.................	6.7	6.6	6.6	6.7	6.7	6.7	6.7		
Temperature, field........°C..	18.5	18	19	19	18	18	18		
Conductivity, field..µmho/cm..	1,680	1,700	1,700	1,750	1,700	1,750	1,700		
Alkalinity[1].......mg CaCO$_3$/L..	244	254	252	250	248	256	254		
Iron,[2] mg/L:									
Ferrous....................	49	64	66	64	65	67	66		
Total......................	66	73	73	73	73	74	71		
Sulfate................mg/L..	1,280	1,260	1,250	1,250	1,300	1,310	1,550		
Manganese..............mg/L..	5.4	5.6	5.8	5.6	5.7	5.7	5.7		
Fecal coliform cells per 100 mL..	700	0	0	0	0	0	0		
11/10/81; sample depth.....m..	15	23	52	91	105	113	125	143	154
pH:									
Downhole...................	5.5	5.8	6.05	6.15	6.1	6.1	6.15	6.15	6.2
Laboratory.................	7.7	8.0	7.9	7.7	7.7	7.8	7.6	7.6	7.7
Conductivity, field..µmho/cm..	2,250	2,450	2,500	2,450	2,450	2,250	2,450	2,455	2,455
Acidity,[3] net......g CaCO$_3$/L..	-240	-240	-240	-240	-240	-240	-240	-240	-240
Iron,[2] mg/L:									
Ferrous....................	51	40	33	56	56	56	55	42	55
Total......................	60	58	63	61	61	62	61	59	61
Sulfate................mg/L..	1,330	1,420	1,460	1,480	1,520	1,410	1,500	1,430	1,540
Calcium................mg/L..	150	160	140	180	170	180	170	170	170
Magnesium..............mg/L..	67	70	71	66	67	67	67	65	66
Fecal coliform cells per 100 mL..	0	NA	0	0	NA	0	0	0	0

NA Not available.

[1] Values reported as alkalinity were measured by direct titration with acid; acidity was not determined on these samples.

[2] In filtered, acidified sample.

[3] As determined by the American Public Health Association (1) back-titration procedure; minus sign indicates net alkalinity.

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