Geologic and Hydrologic Studies in the Birmingham Red-Iron-Ore District Alabama

GEOLOGICAL SURVEY PROFESSIONAL PAPER 473-C

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By THOMAS A. SIMPSON

MINING HYDROLOGY

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The geology and related ground-water problems in the mines of the Birmingham red-iron-ore district, with practical applications of ground-water hydraulics

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1965

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

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By Thomas A. Simpson

ABSTRACT

The Birmingham red-iron-ore district in north-central Alabama is underlain by consolidated Paleozoic rocks that have been extensively folded and faulted. Mine-water problems started in 1909, when the Sloss mine was completely flooded. Since then, four other mines have been flooded by large inflows under high hydrostatic pressure heads. These inflows caused serious damage, and the flooded ore areas were abandoned temporarily.

The iron-ore seams are overlain by the Fort Payne Chert of Mississippian age and by a limestone unit of Warsaw age. The Fort Payne is cavernous in places and about 140 feet thick. The limestone unit contains an extensive solution-cavity system and is about 150 feet thick. These formations are water bearing and are the source of most of the ground water in the mines in Red Mountain.

Hydrostatic pressures of 950 pounds per square inch were recorded underground in diamond-drill holes in the Shannon mine underlying Shades Valley. Pressures of 550 pounds per square inch were recorded in similar drill holes in the Pyne mine in the shear zone of the Shannon fault. In both mines, large flows were backed by hydrostatic pressure.

The largest amounts of recharge to the ground-water reservoir are derived from rainfall, and smaller amounts are derived from surface streams and underflow from deep-surface sources. Discharge measurements in Shades Creek indicate seepage losses where the creek flows over outcrop areas of the Fort Payne Chert, the limestone unit of Warsaw age, and the Recent alluvium. Ground water is discharged by pumping and flows from domestic and municipal wells, springs, outflows from deep-subsurface sources, streams, and mine pumpage. The total recharge is estimated to be about 13,000 gallons per minute and the discharge about 11,000 gallons per minute.

Ground-water flow in the district can be classified according to three zones: (1) an upper or water-table zone, (2) an intermediate artesian zone, and (3) a deeper water-table and artesian zone. Accordingly, the movement in each zone ranges from a slow rate on flat gradients to a rapid rate on steeply inclined and nearly vertical gradients.

Ground water occurs: (1) in the slope mines, where it seeps into the mine openings through broken and caved ground, and in (2) water-bearing fractures under high hydrostratic pressures near highly faulted and folded rocks.

The hydrologic characteristics of the rock formations were determined from eight pumping tests. The coefficients of transmissibility ranged from 50 to 6,240 gallons per day per foot. A pressure-flow test in Pyne mine determined coefficients of transmissibility and storage that ranged from 3,840 to 4,330 gallons per day per foot and from 0.000079 to 0.000122, respectively. These data were applied to three methods for dewatering the Shannon fault zone.

INTRODUCTION

The red-iron-ore mines in Birmingham, Ala., have been supplying ore to this nation's iron and steel industry since the early 1840's (Armes, 1910, p. 46). Substantial deposits of coal, limestone, and iron ore, all the raw materials essential for the manufacture of iron and steel products, lie within a radius of 30 to 40 miles of Birmingham. The importance of the iron and steel industry of Birmingham to the national economy is evident by the world-wide distribution of products from its blast furnaces and steel mills.

The Birmingham red-iron-ore district, with an annual production of over 7 million gross tons, ranks as the third largest producer of hematite iron ore in the United States. Estimated reserves indicate a probable mining life of 50 years at this rate of extraction (Clemmons and others, 1953, p. 18).

Mine floodings occurred as early as 1909, and the water problem has become more critical as mining has progressed downdip under Red Mountain. The need for a thorough investigation of the occurrence and movement of ground water became apparent when flooding seriously damaged one mine and shut down another.

The problem of mine drainage is not restricted to the Birmingham district; it is common to mining regions throughout the world. The influx of ground water into underground mines and surface-mining pits has become serious. Excessive amounts of water are hazardous to mining operations and increase the cost of mining owing to the necessity of handling wet ores and the construction of elaborate drainage structures. Oftentimes the rise in costs is so great that further development is prohibitive; operations cease and many tons of ore are left unmined.

The U.S. Geological Survey undertook the investigation of ground-water problems in the Birmingham mining district in November 1952. Some hydrologic data, such as records of wells and springs and chemical analyses of ground water, which were obtained as a part of the investigation, are not included in this report.

LOCATION AND EXTENT OF AREA

The Birmingham red-iron-ore district is in the southern part of Jefferson County in north-central Alabama (fig. 1). The area is rectangular and includes about 113 square miles in parts of nine townships. The industrial cities of Birmingham and Bessemer lie north and west, respectively, of the area of investigation. The red-ore mining area is about 75 miles long. The more productive mines lie within the area covered by this study, and it is within this area that mine-water problems have become prevalent.

TOPOGRAPHY AND DRAINAGE

The Birmingham red-iron-ore district lies within the Valley and Ridge physiographic province (Fenneman, 1938, p. 195). The altitude of the area ranges from about 450 feet in the deeply eroded valleys to about 1,150 feet on the crest of Shades Mountain.

The distinctively parallel and arcuate forms of the ridges and valleys reflect the geologic structure of the area (fig. 1). The ridges are resistant sandstone and chert and have steep escarpments that face northwest and dip gently southeast. The flat to gently rolling valley floors are underlain by beds of nonresistant limestone and shale. The most prominent topographic features of the area are Red Mountain and Shades Mountain, which rise to altitudes of 950 and 1,150 feet.

The drainage system of the area has become adjusted to the structure, and the resulting trellis-type drainage pattern is typical of an area of eroded parallel folds. The major streams are perennial, but most of the tributary streams flow only during the winter and spring months.

MINING METHODS

The ore in the Birmingham district is red hematite and occurs as beds or seams which strike generally northeast and dip southeast. There are three seams, the Ida or "hickory nut," the Big Seam, and the Irondale. The Ida and Irondale seams are not being mined at present (1965). The middle or Big Seam (fig. 2), whose thickness ranges from 3 to 30 feet, is the most economically important. The seam is divided, for mining, into an upper and lower bench; the marker bed that forms the division ranges from a thin parting to a shale bed about 2 feet thick. In general, northeast of Woodward Red Ore mine the upper and lower benches are worked, whereas southwest of this mine only the upper bench is worked.

Most of these mines, which are driven from the outcrop of the Big Seam on Red Mountain, follow along the seam down the dip and thus are termed "slope mines." There are two shaft mines in the area, the Shannon and Pyne. The Shannon mine shaft is inclined 52° SE. and penetrates the Big Seam at a depth of 2,100 feet beneath the surface. Pyne mine has a vertical shaft and penetrates the Big Seam about 1,200 feet below the shaft collar.

The direction and control of development is dependent on the continuity of the ore bed, the occurrence of structural features, and the character of the roof in each local area. Pillars of ore are left for support of the roof in such a manner as to prevent "squeeze" and crushing. In areas where roof conditions are bad, roof bolting is widely used. Wooden cribs and stulls are used occasionally as supplementary roof support.

Normal development work is termed "first mining," and generally 40 to 60 percent of the ore is left in place to support the roof. The extraction of ore from remaining pillars is the last stage of mining and is termed "second mining" or "robbing." Pillar extraction is started at a point farthest from the main haulageways and slopes and retreats toward the shaft. After this second mining, about 70 to 80 percent of the original ore has been removed.

Water entering the mines near the working areas is collected in small sumps and relayed by pumping to the main sumps, where it is discharged to the surface for disposal. The main sumps are generally mined-out stopes in low areas. Centrifugal pumps, with capacities of 800 to 2,000 gpm (gallons per minute) operating against heads of 800 to 1,000 feet, are used to move the water. It is often necessary that the water be transferred from auxiliary stations and secondary sumps by relay pumps several times before being discharged into the main sumps.

PREVIOUS INVESTIGATIONS

Water was reported in a fault at Woodward (Red Ore) No. 2 mine by Burchard and others (1910, p. 69), who referred to "water channels passing along fractured beds." In the same report, flows of water were reported to be larger in Muscoda No. 4 than at any other mine in Red Mountain. Crane (1925a, 1927), in a series of reports, mentioned water-bearing formations overlying the ore beds. The problem of driving an underground opening across a water-bearing fault in the Shannon mine was discussed in detail by Crawhall (1929). Ball and Beck (1937) reported flows of 530

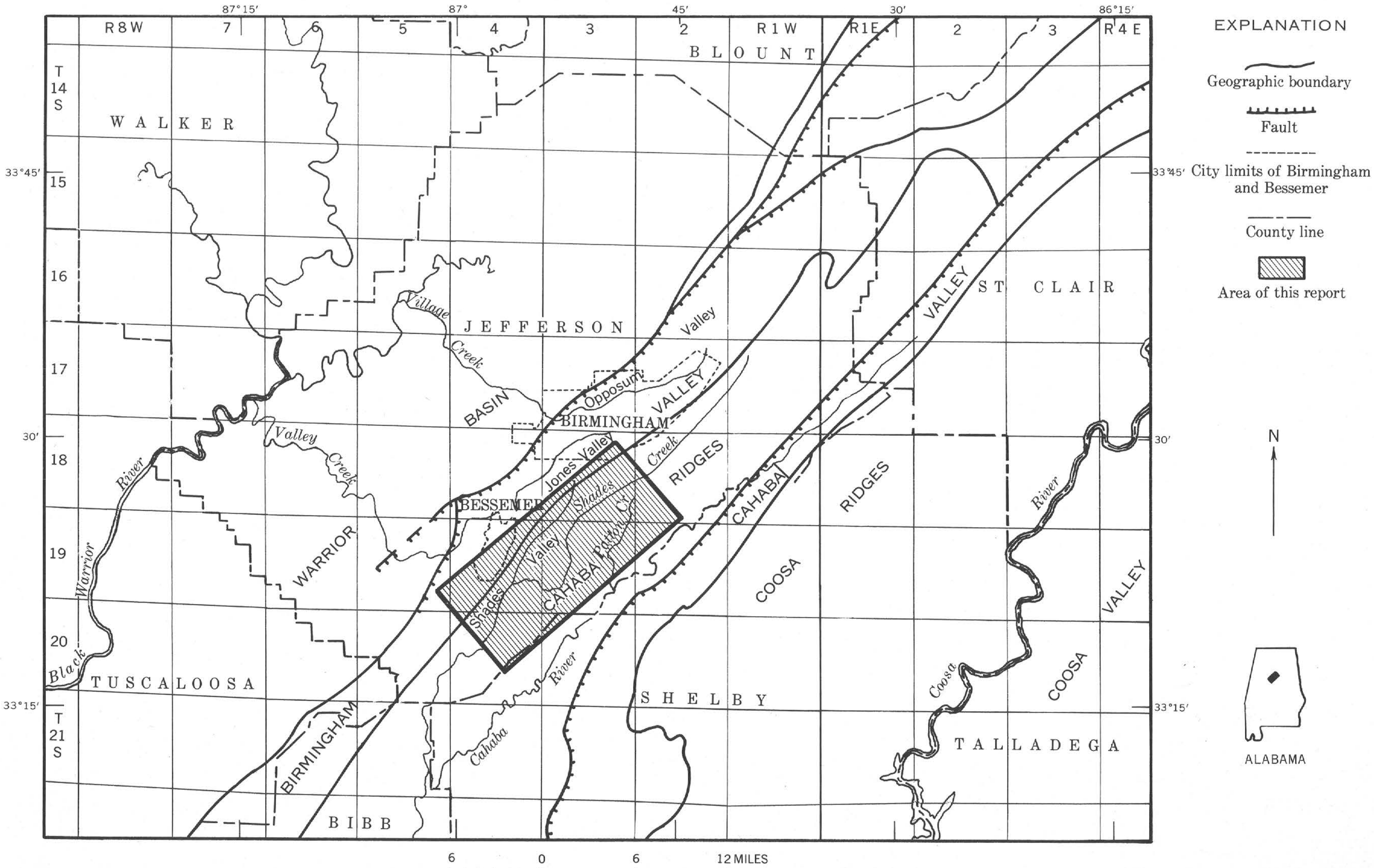


FIGURE 1.—Alabama, showing the Birmingham area and generalized physiographic and structural features.

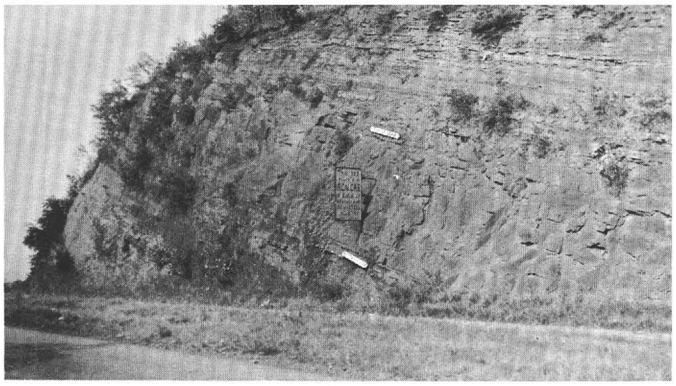


FIGURE 2.—Exposure of Red Mountain Formation in roadcut in SE¼NW¼ sec. 14, T. 18 S., R. 3 W., on Green Springs Highway, Alabama Highway 149. Sign in center reads "This Red Mountain iron ore is basis of Birmingham's iron-steel industry"; white signs mark top and bottom of the Big Seam.

and 250 gpm in developing a mine in the limestone unit of Warsaw age. They also stated that the weathered parts of the limestone unit of Warsaw age and the Fort Payne Chert are "heavily water-bearing as indicated by inflows of 3,000 gpm for considerable periods."

HISTORY OF WATER PROBLEMS

The ownership of the red-ore mines and mineral rights are divided among four companies, the Tennessee Coal and Iron Division of United States Steel Corp., the Republic Steel Corp., the United States Pipe and Foundry Co., and the Woodward Iron Co. The mine properties and areas having water problems are shown in figure 3.

A brief history of some of the major mine-water occurrences are described below.

SLOSS MINE

The first serious water problem in the district occurred in Sloss No. 1 on November 19, 1909, when a rockfall at mine heading 17-right was accompanied by a flow of water that flooded the workings. The mine was pumped out, and operations were resumed a year later.

Another rockfall in the same mine occurred at mine heading 42-left on May 4, 1932. This fall was accompanied by an initial inflow of about 4,500 gpm, which decreased in 1 year to about 700 gpm.

SHANNON MINE

In 1924, while sinking an inclined shaft for the Shannon mine, a fault was penetrated which yielded small amounts of water. Development work continued normally until March 1925, when continued seepage from the roof in one of the headings indicated the presence of a nearby water source. Through a hole drilled into the working face, water flowed at about 40 gpm. Further test drilling in other faces disclosed a water-bearing fault in which hydrostatic pressures were as high as 950 psi (pounds per square inch). Flows containing pyritiferous mud, pebbles, and hydrogen sulfide gas issued from the boreholes. A special tunnel-driving crew contracted to cross the fault zone. This fault, the Shannon fault, was successfully crossed by the use of a special grouting technique (Crawhall, 1929).

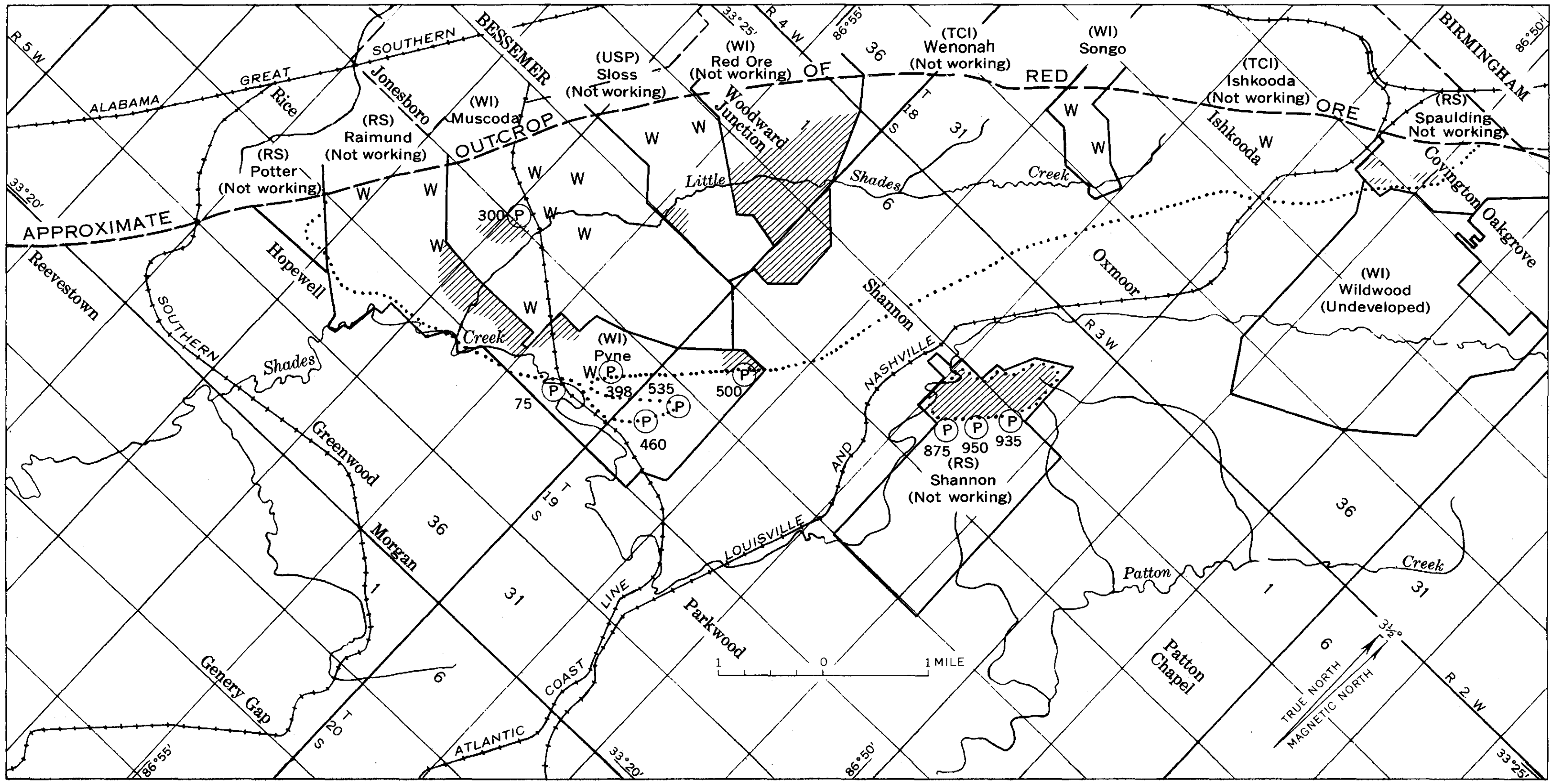
About 90 feet beyond the main fault, diamond drilling penetrated another water-bearing fracture, which also registered a static pressure of 950 psi and had a flow of about 600 gpm. Work was stopped at this point, and a dam was constructed at the face to prevent flooding. The dam held effectively, but the mine was shut down because of economic conditions.

PYNE MINE

The Woodward Iron Co. opened the Pyne mine in Shades Valley in the early 1920's. During the sinking of the shaft, waterflows totaling about 13 gpm occurred at depths between 30 and 60 feet below the collar. The sinking work was stopped in 1934 and water filled the shaft. The mine was reopened in 1941 and the shaft was completed. However, waterflows in the shaft were not stopped until 1945, when the periphery of the shaft was grouted.

Several years later, as the mining advanced into the northwestern part of the property, a haulage tunnel was driven through the Shannon fault, which crosses the property diagonally. Large quantities of water were pumped because the tunnel penetrated the main fault zone. In the shear zone the water flowed from open fractures which were as much as 30 inches in width. The fault zone was crossed by drilling a pattern of diamond-drill holes around the periphery of the tunnel and injecting grout under high pressure. A concrete bulkhead and steel door were installed to prevent the spreading of floodwater should the grout curtain fail.

In June 1953 a diamond-drill hole in the east workings penetrated a water-bearing fracture that flowed about 250 gpm at a static pressure of 300 psi. Water flowed from the fracture at the rate of about 50 gpm for 1 month. Further development toward the northeast indicated that the fracture was a sympathetic fault related to the Shannon fault and was hydraulically connected with it. Pressures measured in holes drilled into the faulted area ranged from 300 to 500 psi. The mine-development headings had to be reoriented to the northwest perpendicular to the main fault in order to leave a barrier pillar to contain the water.



EXPLANATION

Flooded area

Ⓟ75
Hydrostatic pressure, in pounds per square inch

(WI)
Woodward Iron Co.

(USP)
U.S. Pipe & Foundry Co.

W
Water source <100 gpm

Approximate limit of underground development

(RS)
Republic Steel Corp.

(TCI)
Tennessee Coal & Iron Division U.S. Steel Corp.

FIGURE 3.—Mine properties and areas of ground-water problems.

769-652 O—65——2

MUSCODA NO. 4 MINE

In 1950 a rockfall from the roof in the Muscoda No. 4 mine resulted in an inflow of about 3,000 gpm, which increased within a month to about 4,000 gpm and later decreased to a uniform flow of about 1,800 gpm. An emergency emplacement of pumps saved the mine from complete inundation.

SONGO MINE

In April 1952 two rockfalls from the roof in the Songo mine caused an inflow of water of about 900 gpm. Throughout the remainder of 1952 additional rockfalls increased the inflow of water until September, when a severe rockfall caused an inflow of about 2,000 gpm. The mine filled with water to mine heading 26 and had to be abandoned. Dewatering was begun in October 1952 and continued until February 1953. During this period a total of 2.5 billion gallons of water was pumped from the mine.

RED ORE MINE

In February 1953 a rockfall in the Red Ore mine permitted an inrush of water estimated at 12,000–13,000 gpm. The water was pumped at an initial rate of 3,500 gpm and decreased to 2,700 gpm several months later.

ACKNOWLEDGMENTS

The writer is especially grateful for the cooperation of the mining companies, who permitted underground examination of their properties and contributed information freely concerning diamond-drill holes, geologic data, water-level data, and pumpage records.

The writer extends thanks to those individuals of the engineering and geological staffs of the Republic Steel Corp., United States Pipe and Foundry Co., Tennessee Coal and Iron Division of United States Steel Corp., and Woodward Iron Co. who devoted their time to furnish the data and discuss various aspects of the mine drainage problem.

The project was greatly assisted by the interest and encouragement of Walter B. Jones and his staff, of the Geological Survey of Alabama.

Arthur J. Blair and Grover Miller, consulting geologists, discussed the geology of the area with the author and gave helpful comments during the fieldwork of the report.

The project was started in November 1952 with J. B. Ivey as project chief and the writer was made project chief in March 1953. The writer was assisted in the field from March to August 1953 by Glenn A. Davis and from February 1956 to January 1957 by David D. Heald. Davis obtained data on wells in the area and supervised a survey crew in running elevations to some of the wells and springs. Heald maintained the observation-well network and assisted in geologic mapping. Seepage measurements on Little Shades, Shades, and Patton Creeks were made by personnel from the Surface Water Branch of the U.S. Geological Survey. The work was done under the technical supervision of W. T. Stuart, hydraulic engineer in charge of mining hydrology; and under the direct supervision of P. E. LaMoreaux, former district geologist in charge of ground-water investigations in Alabama. Later phases of the preparation of the report were under the supervision of W. J. Powell, district geologist.

GENERAL GEOLOGY

The rocks cropping out in the area consist of about 15,000 feet of consolidated Paleozoic sediments and range in age from Cambrian to Pennsylvanian (pl. 1). The oldest rocks are carbonates deposited as stable shelf-type sediments, and the youngest are clastic sediments of terrestrial origin that have been folded and faulted into typical Appalachian-type structures.

A more detailed discussion on the geology and stratigraphy of the area is available in Adams and others (1926), Butts (1927), and Burchard and others (1910).

FORMATIONS AND THEIR WATER-BEARING PROPERTIES

The outcrop patterns shown on the geologic map (pl. 1) appear on the surface as parallel and subparallel bands of rocks that strike northeast and dip generally southeast. The stratigraphic relationships and structural features are shown by a fence diagram (pl. 2). The data necessary to construct the fence diagram were taken from the geologic map and logs of 40 diamond-drill holes.

The thickness, lithology, and water-bearing properties of the formation were based on field observation, an inventory of 1,000 domestic, municipal, and industrial water wells, and analysis of logs of 150 exploratory diamond-drill holes. A summary of the description, thickness, and water-bearing properties of the rock formations is given in table 1.

STRUCTURE

The structural features of the area are typical of the Appalachian system. At the close of the Paleozoic Era, initially flat-lying or gently dipping sedimentary strata were extensively folded and faulted. Erosion has bevelled the folds into a series of parallel valleys and ridges in which the formations strike generally northeast and dip southeast (pl. 1).

The major structure in the Birmingham area is the Birmingham anticline. This feature is an eroded asymmetrical anticline slightly overturned to the northwest

TABLE 1.—*Thickness, lithology, and water-bearing properties of formations in the study area*

Era	System	Formation	Thickness (feet)	Lithology	Water-bearing properties
Paleozoic	Pennsylvanian	Pottsville Formation	750–5,500	Sandstone, shale, conglomerate, and coal beds, thin- to thick-bedded.	Generally yields small amounts (½–10 gpm) of water to wells; locally under artesian pressure; yields as much as 170 gpm to one well on local synclinal basin; in or near coal seams, yields highly mineralized (133–200 ppm total dissolved solids) water.
	Mississippian	Parkwood Formation	900–1,300	Shale, massive; interbedded with hard sandstone layers.	Generally yields small amounts (½–10 gpm) of water to wells; locally under artesian pressure; water generally high (8–261 ppm) in bicarbonate.
		Floyd Shale	750–1,200	Shale, black and gray, soft, fissile; interbedded sandstone and limestone beds.	Generally yields different amounts (1–40 gpm) of water to wells; quality of water varies (0–6.8 ppm of iron; 0–23 ppm carbonate).
		Bangor Limestone	0–300	Limestone, bluish-gray, coarsely crystalline, thick-bedded	Yields 200 gpm of water to one well; 89–139 ppm of carbonate hardness.
		Hartselle Sandstone	0–120	Sandstone, white to tan, medium-grained, quartzose, locally friable.	Generally yields moderate amounts (30 ± gpm) of water to wells; one analysis high (261 ppm) in bicarbonate.
		Girkin Formation	0–125	Shale and sandstone, dark-gray, thin-bedded.	No wells developed in formation, but usually penetrated by wells drilled through to and deveolped in the Bangor Limestone and Hartselle Sandstone; probably would yield small amounts (½–5 gpm) of water to wells.
		Limestone unit of Warsaw age	80–150	Limestone, bluish-gray to gray, coarsely crystalline, fossiliferous, cavernous.	Yields large amounts (500 ±gpm) of water to wells developed in solution cavities; water has high (321 ppm) carbonate content and (131–201 ppm) hardness.
		Fort Payne Chert	90–140	Chert, bedded, brittle; iron- and and manganese-stained bands; cavernous in weathered zone.	Generally yields moderately large amounts (200±gpm) of water to wells; accommodates water from overlying Limestone Unit of Warsaw Age; yield is high (1.8–2.7 ppm) in iron.
		Maury Formation	1–3	Shale, green and red, glauconitic; contains phosphate nodules.	Nearly impermeable and too thin to be of importance as an aquifer.
	Devonian	Frog Mountain Sandstone	6–22	Sandstone, yellow to gray, fine- to medium-grained, ferruginous, quartzitic.	Not known to be an aquifer; too thin and impermeable.
	Silurian	Red Mountain Formation	300–500	Shale, sandstone, limestone, thin- to thick-bedded, generally red to dark-brown; contains red-iron-ore (hematite) seams.	Yields small amounts (½–10 gpm) of water from joints and fractures in underground mine opening.
	Ordovician	Chickamauga Limestone	110–340	Upper part: light-gray to dark-gray, fine-grained to coarsely crystalline, extremely fossiliferous limestone. Attalla Chert Conglomerate Member; nodular, angular well-cemented chert and quartz.	Possibly yields (50–150) gpm water to wells developed in solution cavities; solution cavity system not as extensively developed as are other limestones in area; springs discharge along base of formation near faulted areas.
	Cambrian	Copper Ridge Dolomite	800–2,000	Dolomite and chert, fine-grained, massive, tough, compact.	Yields moderately large amounts (200 gpm) of water to wells; yields hard (132 ppm carbonate) water.
		Ketona Dolomite	150–900	Dolomite, white to tan, crystalline, massive.	Generally yields large amounts (500 gpm) of water to wells; yields hard (132–136 ppm of carbonate) water.
		Conasauga Formation	2,000+	Limestone, dark-gray thick-bedded, locally shaly.	Generally yields moderately large amounts (300 gpm) of water from joints and beddings to wells; yields hard (130–239 ppm of carbonate) water.

and marked by a line of low-angle thrusts that dip southeast. Smaller folds superimposed on the flanks of the major structure have their axes alined in a general northeast direction.

FOLDS

DOLLY RIDGE ANTICLINE

The Dolly Ridge anticline, or Aldrich dome, is an asymmetrical structure in the eastern margin of the area. The anticline strikes northeast and plunges steeply to the southwest. It extends about 3½ miles farther to the northeast beyond the area of investigation. The Patton fault, a high-angle reverse fault, shears the rocks along the northwestern flank and runs parallel to the strike of the anticlinal axis. In the early 1900's the anticline was drilled for gas and three of the wells yielded 75,000 to 100,000 cubic feet per day (Semmes, 1929, p. 115).

DICKEY SPRINGS ANTICLINE

In the Greenwood-Morgan area a prominent anticline is indicated by the conspicuous oval-shaped outcrop pattern of Fort Payne Chert. An erosional fault scarp, striking generally northeast, truncates the structure along its southeastern flank. A subsurface-structure map with a 50-foot contour interval (pl. 1), based on the Fort Payne Chert, clearly shows the anticlinal nature of the structure.

MINOR FOLDS

In the extreme western part of the area the Conasauga Formation, Ketona Dolomite, and the Copper

Ridge Dolomite of Cambrian age crop out in parallel ridges indicating parallel folds. The large anticline that underlies Jones Valley is part of the larger composite structure—the Birmingham anticline.

A small subsidiary overturned fold forms an anticline in which parts of the Wenonah, Red Ore, Sloss, and Muscoda slope mines have been developed. Another small, tightly folded overturned anticline is visible in a railroad cut along the Louisville and Nashville Railroad, about half a mile south of Graces Gap. Many other small folds occur throughout the area.

JOINTS

Joints are very common in the competent beds in nearly all parts of the area. The joints occur as strike and dip types, part of a conjugate system of two or more sets. Occasionally as many as four sets occur, two of which are much weaker in expression than the others. The joint system is composed of conjugate sets that strike about N. 18° E.–E. and N. 2° E.–N. 68° W.

Most of the joint surfaces are straight and well defined; rarely, the weaker set displays a curved surface. Generally the joints are perpendicular, or nearly so, to the bedding planes and do not continue vertically from one bed to another. Most of the joints occur in, and apparently are restricted to, the beds of the more competent rocks such as limestone and sandstone. Shale beds, unless they are very sandy and thick, are not jointed to a recognizable extent. Thick-bedded sandy shale of the Pottsville Formation shows well-defined joints and planes of axial shear (fig. 4).

FAULTS

The Birmingham area is characterized by typical Appalachian thrust and normal faulting. The mapping of the faults along the slopes of Red Mountain was greatly facilitated because of extensive underground mine workings.

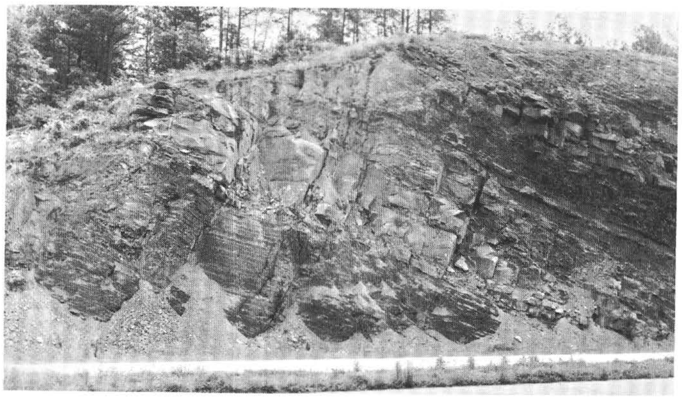


FIGURE 4.—Joints and axial shear in sandy shale beds of the Pottsville Formation in roadcut on U.S. Highway 31, in the NW¼NE¼ sec. 13, T. 19 S., R. 3 W.

ISHKOODA-POTTER FAULT SYSTEM

The Ishkooda-Potter fault system strikes N. 40°–50° E. and consists mainly of two high-angle faults, which were penetrated by the Ishkooda mine slopes on the northeastern flank of Red Mountain and by the Potter mine slopes on the southwestern flank of Red Mountain. The extent of this fault system is well known because of the extensive mine workings developed in it.

Faults of this system show dip-slip and strike-slip components that cut obliquely across the northeastern part of Red Mountain and form an arcuate pattern concave to the southeast, then cut obliquely back across the southwestern end of Red Mountain. The faults are parallel and have different amounts of throw.

Most of the faults intersected by the Ishkooda-Potter mine slopes are high angle and many of the mine slopes penetrate the same fault, although the exposures show different dips of the fault plane and different throws.

The faults in the Ishkooda-Potter system are tight and are filled with calcite. In some places the fault surfaces exhibit slickensides, breccia zones, and some calcite and gouge material.

A tear or wrench fault visible at Readers Gap is the result of a left-lateral movement. The strike is N. 63° W., and the beds on each side are displaced about 50 feet.

SHANNON FAULT SYSTEM

The Shannon fault system lies in the central part of the area and is composed of one large displacement and several smaller ones. The main displacement, the Shannon fault, strikes generally N. 50° E. This fault was intersected and crossed by headings in the Pyne and Shannon mines. Diamond-drill holes that penetrated the shear zones contiguous to the fault indicated that large amounts of water under high hydrostatic pressures were in the system. The angle of dip of the fault surfaces exposed in the mines averages about 60° SE. (fig. 5). The throw ranges from 100 feet in the Pyne mine to about 400 feet 3 miles northeast in Shannon mine. Figure 6 shows the shear planes and illustrates the zone of active shear contiguous to the fault in the Pyne mine. On the upthrown side, shear planes were observed as far as 50 feet from it. Many faults that strike parallel or subparallel to the main one and have throws of 20 to 30 feet were observed in Pyne mine.

DICKEY SPRINGS–PATTON FAULT SYSTEM

The Dickey Springs–Patton fault system occurs in the southwestern part of the area and consists of sev-

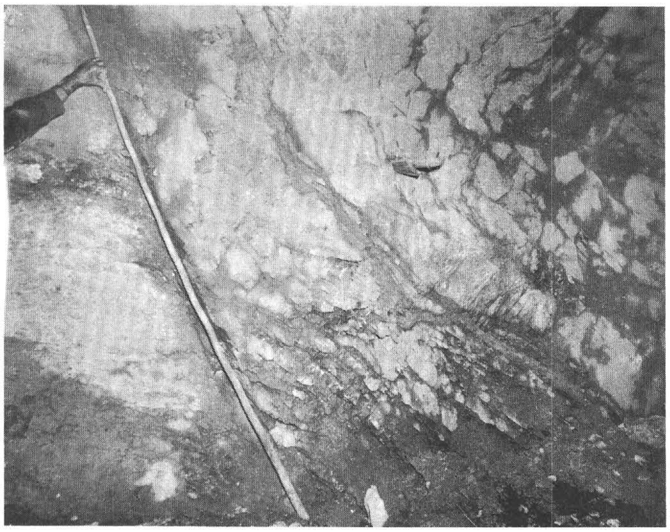


FIGURE 5.—Fault plane and drag of the Shannon fault in Pyne mine; loading pole marks trace of major fault plane. Photograph courtesy of Woodward Iron Co.

eral normal faults and a large reverse fault and associated fractures.

The name of the system originates from the reverse fault known as the Patton fault, which is exposed in a roadcut on the old Columbiana–Green Springs Highway in the NE¼NW¼ sec. 1, T. 19 S., R. 3 W., and from the high-angle normal fault in the vicinity of Morgan and Greenwood identified as the Dickey Springs fault by Butts (1927).

The Dickey Springs fault, in the vicinity of Morgan and Greenwood, is an extension of this system toward the southwest. It is easily identified by the erosional faultline scarp of chert upthrown in contact with shale on the southeastern side. The faultline is sinuous; it strikes generally N. 53° E. and has a dip of about 85° SE. and a maximum throw of about 225 feet.

The Patton fault is a high-angle reverse fault or underthrust which generally has a strike of N. 50° E. and a dip of 58° NW. (fig. 7). This fault can be

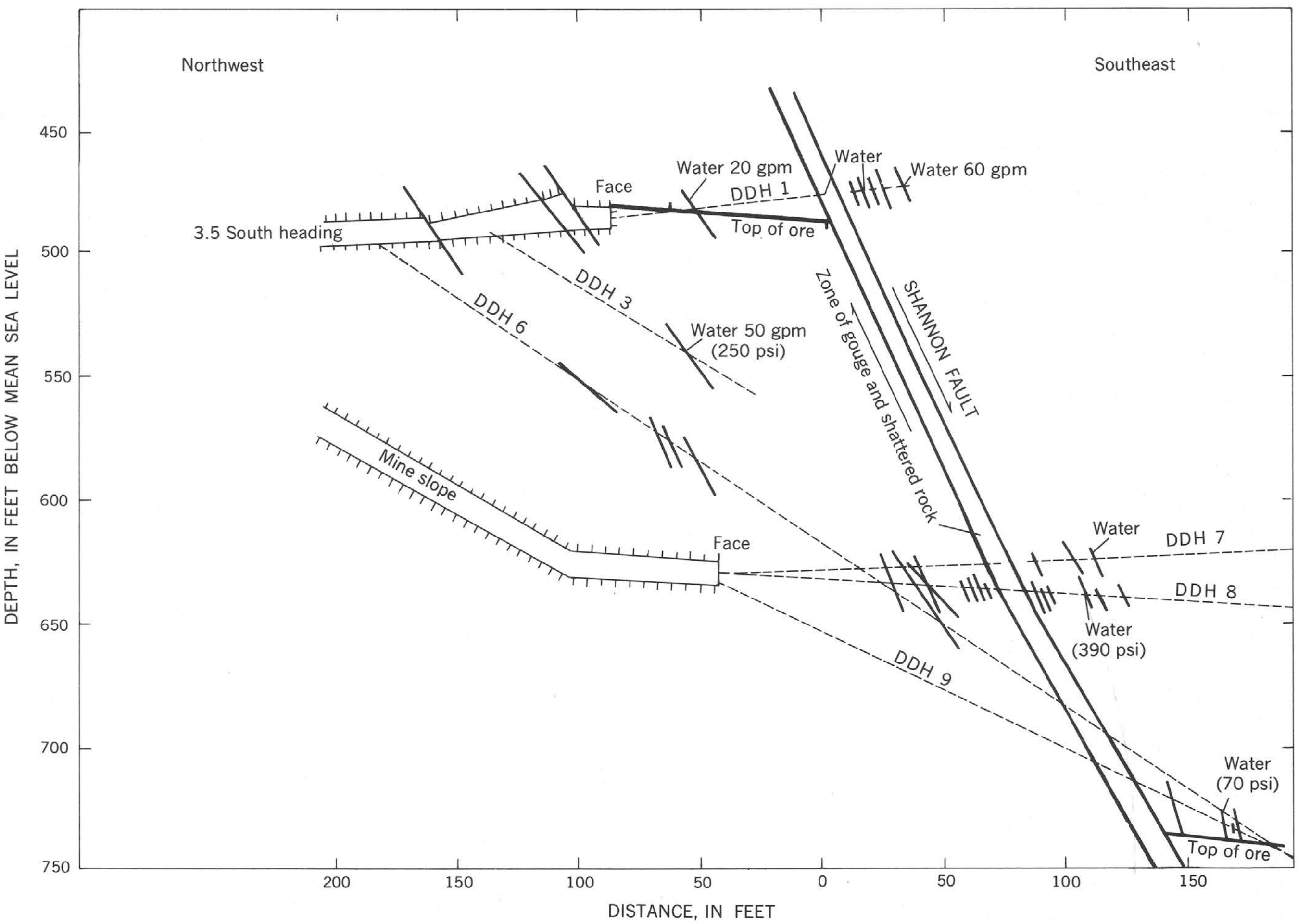


FIGURE 6.—Cross section in Pyne mine showing the Shannon fault. D.D.H., diamond drill hole.

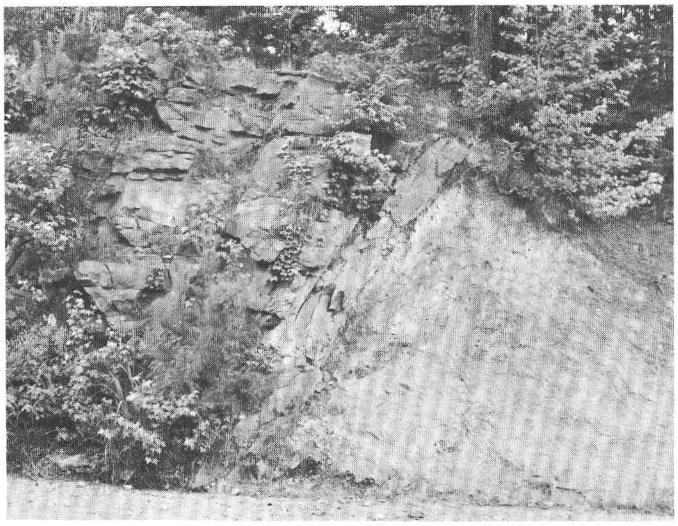


FIGURE 7.—Patton fault in roadcut on the old Columbiana–Green Springs Highway in the NE¼NW¼ sec. 1, T. 19 S., R. 3 W.

traced southwest to the NE¼NW¼ sec. 21, T. 19 S., R. 3 W., where it becomes indistinct. In the NW¼ sec. 1, T. 19 S., R. 3 W., it has a throw of about 425 feet. Diamond-drill hole T–71 (SE¼NW¼ sec. 11, T. 19 S., R. 3 W.) penetrated it at a depth of 352 feet. About 100 feet northwest of T–71 the Shades Sandstone Member has been highly fractured, and two main planes of shear are easily identified (fig. 8). The acute angle between the two planes of shear is about 50° and, at this point, the dip of the fault plane is about 60° NW.

Two smaller faults are visible in sec. 16, T. 19 S., R. 3 W., where they cut across the crest of Shades Mountain and cause displacement of the Shades Sandstone Member. The downthrown sides are toward the north, and about 30 to 40 feet of vertical displacement is indicated.

Evidence of other faults belonging to this system can be found along the roadcut of Alabama Highway 150 through Little Shades Mountain, in the vicinity of Parkwood, where strong departures from the normal dip of 14° SE. indicate high-angle faults. A fault visible at the south edge of Parkwood dips about 70° NW. and has a throw of 70 feet. About 50 yards south, another fault of the same type is apparent from the abnormally steep dip of the formation.

CHEMICAL QUALITY OF GROUND WATER

The chemical quality of ground water in the Birmingham red-iron-ore district was determined from the analyses of 48 water samples. Of the samples, 20 were from drilled wells, 22 from ore mines, 3 from shallow dug wells, 2 from Shades Creek, and 1 from a diamond-drill hole. The points of collection are shown in figure 9, and the analyses are shown in table 2.

FIGURE 8.—Fractures in the Shades Sandstone Member of the Pottsville Formation contiguous to the Patton fault in the SW¼NW¼ sec. 11, T. 19 S., R. 3 W.

CLASSIFICATION OF WATER

Most of the ground water in the area is the calcium bicarbonate ($Ca(HCO_3)_2$) type (fig. 10). No distinctive pattern of water types can be correlated to sample sources, nor can any correlation be made with regard to rock formations in the vicinity of the source areas. Sample 12 from the Wenonah mine (table 2) is an example of highly mineralized water, it plots as a sodium chloride (NaCl) type, and it may be a sample of connate water. The quality of water in relation to use was discussed by Hem (1959).

The occurrence of hydrogen sulfide (H_2S) gas in the water and the presence of calcite ($CaCO_3$) deposits in the cavities and fracture surfaces of the rocks in Pyne mine offer some clues in determining the chemical reac-

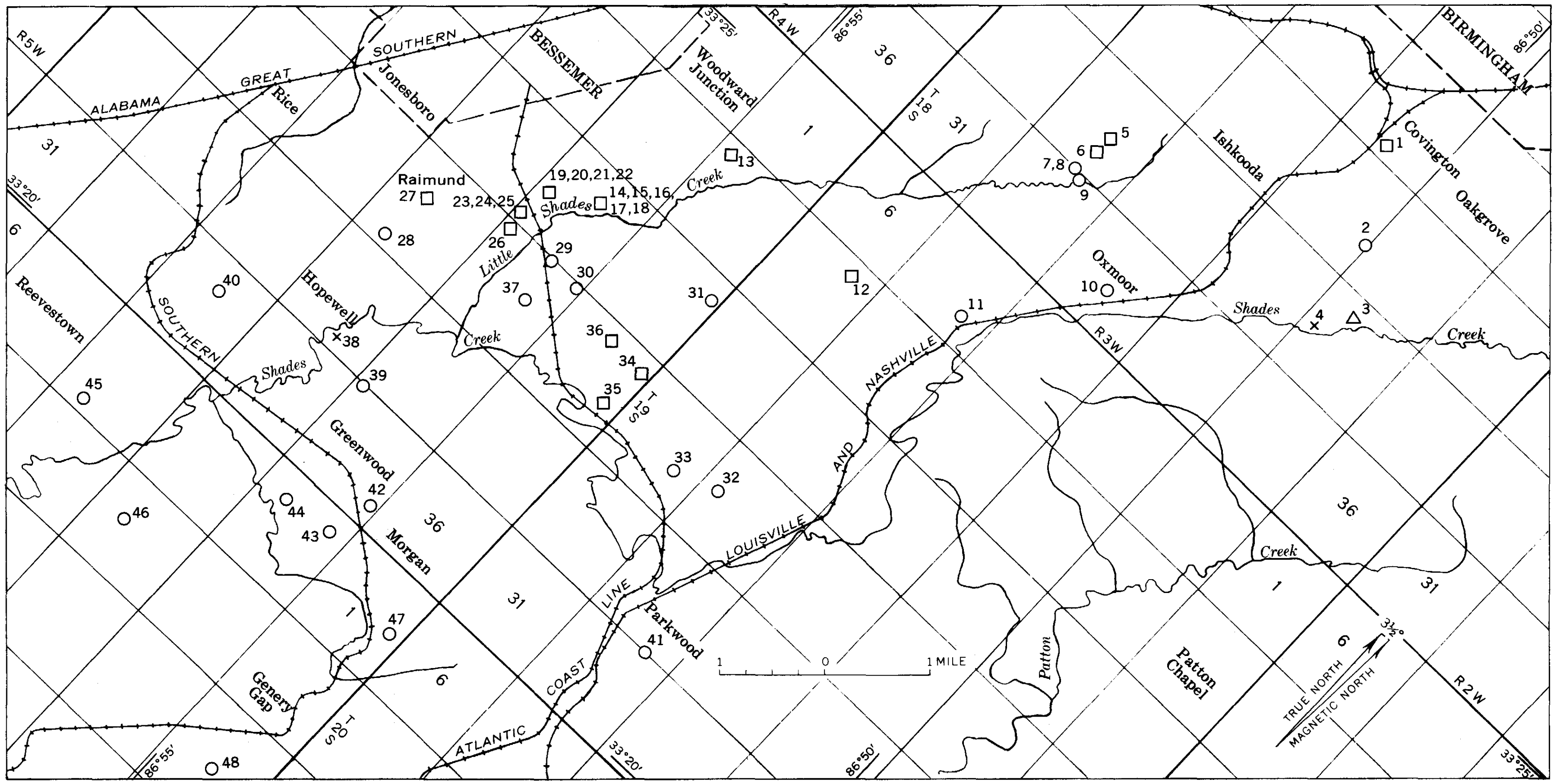


FIGURE 9.—Location of water-sampling points. ○, well; △, diamond-drill hole; □, mine; ×, stream.

TABLE 2.—*Chemical analyses of water samples from wells, mines, and streams in the study area*

[Chemical constituents, in parts per million. Samples from sources owned by Tennessee Coal and Iron Division of United States Steel Corp. were analyzed by owner. Others were analyzed by U.S. Geol. Survey]

Water-bearing formation: Srm, Red Mountain Formation; Mfp, Fort Payne Chert; Mw, limestone unit of Warsaw age; Mb, Bangor Limestone; Mf, Floyd Shale; Mp, Parkwood Formation; Pp, Pottsville Formation.

Owner: RISC, Republic Iron and Steel Corp.; TCI, Tennessee Coal and Iron Division of U.S. Steel Corp.; USGS, U.S. Geological Survey; USPF, U.S. Pipe and Foundry Co.; WIC, Woodward Iron Co.

Sample	Source	Owner	Date of collection	Water-bearing formation	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Carbonate (CO_3)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (from residue on evaporation at 180°C)	Hardness as $CaCO_3$: Calcium magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25°C)	pH	Temperature (°F)
1	Spaulding mine.	RISC	10-14-54	Srm	11	0.0	0.20	45	8.7	14.3	0	164	34	4.8	0.4	1.4	206	148	14	331	7.9	62
2	Drilled well	R. E. Riley	4-9-54	Mf	19	.2	2.4	28	11	50	0	258	6.5	6.8	.2	1	245	115	0	426	7.6	62
3	Diamond-drill hole.	WIC	4-9-54	Mp Mf	23	.1	.45	14	3.4	101	0	261	12	29	.4	0	311	49	0	510	8.1	63
4	Shades Creek	---	6-11-56	---	---	---	.00	32	7.1	16	0	96	50	5.8	.1	1.7	---	109	30	274	7.6	74
5	Songo Mine	WIC	6-12-56	Srm	---	---	.00	49	4.0	12	0	160	23	2.8	.2	.1	---	139	8	298	8	65
6	do	WIC	3-17-54	Srm	8.8	.0	.90	40	2.0	19	0	155	16	2.8	.1	.8	169	108	0	284	7.9	63
7	Drilled well	USGS	8-10-54	Mb	9.9	.0	4.8	52	2.2	3.3	0	152	16	5.8	0	1.4	167	139	14	288	7.6	63
8	Drilled well	USGS	4-12-55	Mb	1.3	0	8.1	29	4.1	11	0	72	41	2.8	.1	5.8	130	89	30	208	7.3	63
9	do	USGS	4-15-54	Mf	1.9	0	4.4	33	10	27	0	174	29	7.8	.2	.1	200	123	0	359	7.8	---
10	do	Cammick	4-22-54	Mp	31	---	.89	25	4.8	9.3	0	118	4.2	2.0	.1	.2	133	82	---	204	7.3	63
11	Dug well	C. Harris	4-22-54	Mf	5.4	.1	.47	2.9	2.4	23	0	10	14	24	.1	10	94	17	9	158	5.9	62
12	Wenonah mine.	TCI	---	Srm	11	---	---	6.4	2.3	1,040	---	[1] 1,370	194	678	---	---	2,650	---	---	---	9.1	---
13	Sloss mine	USPF	8-19-54	Srm	8.8	0	.21	18	5.1	201	0	536	44	17	2.0	.1	566	66	0	925	8	66
14	Muscoda No. 5 mine.	TCI	5-6-52	Srm	7.2	---	---	37	4.1	35	---	[1] 118	14	9.0	---	---	193	---	---	---	8.2	---
15	do	TCI	6-6-53	Srm	9.5	---	---	40	4.3	40	---	[1] 210	27	4.0	---	---	255	---	---	---	8	71
16	do	TCI	8-17-53	Srm	7	---	---	44.3	4.6	29.3	---	[1] 192	19	11	---	---	203	---	---	---	7.9	70
17	Muscoda No. 5 mine.	TCI	9-2-53	Srm	8.2	---	---	43	5.3	37	---	[1] 210	21	11	---	---	232	---	---	---	8.1	70
18	do	TCI	10-28-53	Srm	8	---	---	43	6.1	21	---	[1] 201	248	9.0	---	---	286	---	---	---	8.4	70
19	Muscoda No. 4 mine (domestic use).	TCI	6-17-49	Srm	7.2	---	---	64	6.9	12	---	[1] 208	31	9.0	---	---	276	---	---	---	8.1	---
20	do	TCI	10-10-50	Srm	7.4	---	---	65	12.1	24	---	[1] 230	32	28	---	---	284	---	---	---	8.1	---
21	do	TCI	9-2-53	Srm	7.6	---	---	66	10.3	11	---	[1] 228	29	11	---	---	265	---	---	---	8.5	67
22	do	TCI	9-15-53	Srm	10	---	---	66	14.5	5.4	---	[1] 233	31	8.0	---	---	255	---	---	---	8.3	67
23	Muscoda No. 4 mine.	TCI	5-6-52	Srm	7.8	---	---	40	5.6	36	---	[1] 118	23	7.0	---	---	213	---	---	---	8.4	70
24	do	TCI	9-15-52	Srm	7.4	---	---	44	6	30	---	[1] 203	29	9.0	---	---	241	---	---	---	8.3	---
25	do	TCI	10-28-53	Srm	10	---	---	47	6.6	15	---	[1] 200	26	9.0	---	---	236	---	---	---	8.4	71
26	Muscoda No. 4 and No. 2 mines.	TCI	---	Srm	6.6	---	---	47	4.1	15	---	[1] 172	17	6.0	---	---	191	---	---	---	8.2	---
27	Raimund mine.	RISC	10-13-54	Srm	9.8	.0	.19	59	5.8	50	0	236	60	14	.0	.2	324	171	0	512	8.2	67
28	Drilled well	T. Sadler	4-21-54	Mf	6.8	---	1.9	43	12	6.9	0	174	8.2	17	.1	.1	196	157	14	347	7.3	63
29	do	TCI	---	Mf	5.6	---	---	13	7.1	7.2	---	[1] 63	17	6.0	---	---	94	---	---	---	7.2	---
30	Dug well	J. Smith	4-9-54	Mf	11	.1	.22	3.2	1	88	0	197	30	5.2	.2	1.7	239	12	0	384	7.5	63
31	Drilled well	M. Grubbs	4-9-54	Mf	17	---	2.9	71	55	62	0	189	295	51	.2	.8	675	403	248	1,010	6.8	63
32	do	Maxwell	4-9-54	Mp	13	.1	.23	1.7	1.2	3.8	0	14	2.5	3.0	.1	1.1	38	9	0	42	6	63
33	Dug well	J. C. Miller	4-9-54	Mf	14	.6	2.5	12	9.3	17	0	112	7.2	4.8	.1	.5	119	68	0	197	7.2	62
34	Pyne mine	WIC	3-22-54	Srm	11	.2	1.8	24	11	67	0	257	22	11	1.0	.1	276	105	0	472	7.6	78
35	do	WIC	6-14-56	Srm	---	---	.03	20	10	92	0	276	24	20	2.4	.2	---	91	0	528	8.1	75
36	do	WIC	3-22-54	Srm	11	.0	2.7	21	10	74	0	263	22	14	1.0	.1	277	94	0	488	7.8	76
37	Drilled well	A. Pharr	4-9-54	Mf	7.5	.1	.23	2.1	1.2	5.6	0	6	5	5.2	.1	12	48	10	5	66	5.7	62
38	Shades Creek	---	6-11-56	---	---	---	.02	35	7.7	33	0	132	57	10	.2	9.7	---	119	11	361	7.5	70
39	Drilled well	---	3-24-54	Mf	19	.4	3.1	22	14	33	0	152	44	12	.2	2.5	219	112	0	370	7	68
40	do	Boswell	3-24-54	Mf	19	.3	6.8	31	24	42	0	225	50	34	.2	.0	292	176	0	581	7.1	66
41	Drilled well	O. G. Smith	4-9-54	Mp	25	.0	1.2	16	6.1	18	0	112	7.2	4.0	.2	.2	127	65	0	204	7.2	62
42	do	Mahan	3-24-54	Mw	8.8	---	5.5	99	18	8.5	0	42	272	12	.2	2.1	488	321	286	672	6.1	63
43	do	E. Gober	4-21-54	Mf	11	.1	6.9	9.2	5.8	32	0	57	12	46	.1	.3	139	47	0	269	6.6	61
44	do	Greenwood Water Assoc.	3-24-54	Mw, Mfp	.9	5.1	2.4	25	3.1	5.8	0	44	36	11	.1	.8	119	75	39	196	7.1	64
45	do	C. E. Dunkling.	6-12-56	Mf	---	---	.00	.6	1	1.8	0	6	2.5	1.2	.0	2.8	---	6	0	20	6.6	63
46	do	U. S. Sim	6-13-56	Mf	---	---	.00	35	10	10	0	154	6	5.5	.2	.1	---	128	2	257	7.9	64
47	do	B. W. Bush	6-12-56	Mp	---	---	.00	10	7.8	14	0	83	5.2	6.0	.3	.5	---	57	0	154	7.5	64
48	do	J. Rich	6-12-56	Pp	---	---	.00	8.4	13	15	0	101	2.8	2.0	.4	.1	---	74	0	159	7.7	63

[1] Includes carbonate (CO_3).

tion taking place in the water in Pyne mine. Bacteria counts of 6 and 300 per cubic centimeter in two samples of water from Pyne mine may be the result of daily sewage discharge into Shades Creek in the NE¼SE¼ sec. 27, T. 18 S., R. 3 W. The water in Pyne mine also has a strong hydrogen sulfide odor and a sulfurous taste. The ionic equation

$$SO_4^{-2} + CH_4 \xrightarrow{\text{(bacteria)}} \text{yields } HS^{-1} + H_2O + HCO_3^{-1}$$

represents the bacterial reduction of sulfate (SO_4); however, the reaction probably is more complex than the equation indicates (Hem, 1959, p. 223). Hem (p. 224) stated, "waters which have been subjected to sulfate reduction can be expected to contain some hydrogen sulfide unless conditions have existed which allowed the gas to escape or react with metals to form metallic sulfides. Many of these waters have a high content of

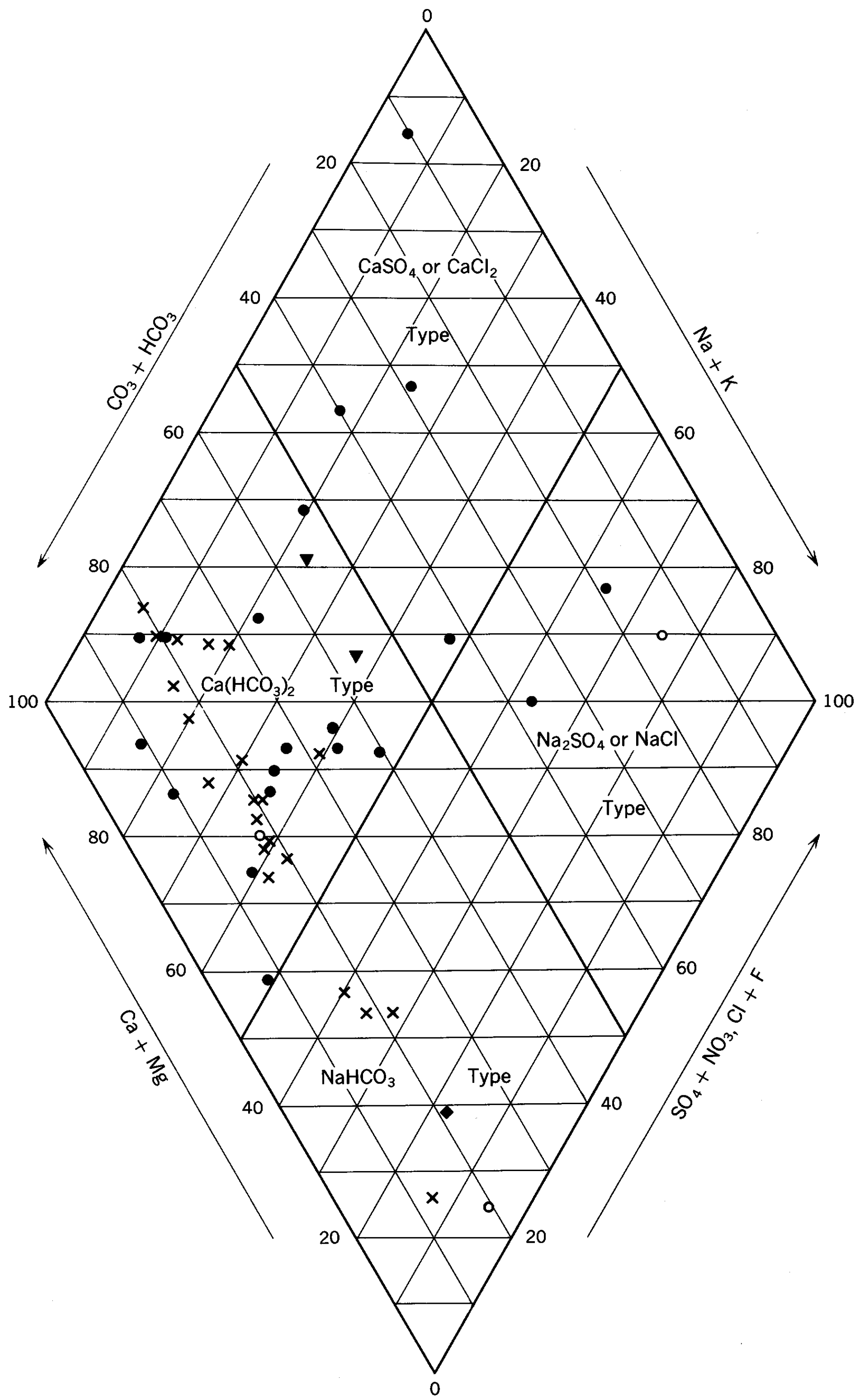


FIGURE 10.—Chemical classification of ground water in the area of study. ×, mine water; ●, drilled well; ○, dug well; ▼, Shades Creek; ◆, diamond-drill hole.

bicarbonate and often of carbon dioxide which can be gained at the expense of sulfate." Comparison of water sample 38 with water samples 34, 35, and 36 indicates a loss of sulfate (SO_4) and a gain of bicarbonate (HCO_3) ions.

In many areas, the mineralization of ground water tends to increase below a certain depth, possibly because of decreased permeabilities, which in turn cause slower rates of ground-water movement. However, this explanation does not seem to apply to this area. Some

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of the well water contains higher amounts of dissolved constituents than does water from the mines that are deeper. This relation probably is indicative of water circulating freely through a system of interconnected large open fractures. Undoubtedly there are places where the movement is restricted and the water is impounded, as shown by the sample from Wenonah mine (sample 12).

TEMPERATURE STUDIES

The approximate geothermal gradient for the area is 1°F for every 100 feet of depth (fig. 11). Anomalous departures from the curve in figure 11 are indicative of recharge from sources closer to the land surface through a network of connected fractures.

The depth-temperature curve is ideally a straight line or a slight curve that gradually increases with depth. The minimum ground-water temperature recorded was 58°F at a depth of 19 feet, and the maximum was 78°F at a depth of 1,490 feet. Temperatures of shallow ground water correspond very closely to the mean annual air temperature at the land surface (63.5° F).

DYE STUDIES

Uranin dye, a sodium salt of fluorescein, was used successfully to determine the existence of a hydraulic connection between a deep drilled well and water-yielding rocks in the Songo mine. The well is 540 feet deep, 12 inches in diameter, and drilled in rock that overlies Songo mine in the NW¼SE¼ sec. 29, T. 18 S., R. 3 W. The water level in the well was 406 feet below the land surface on June 25, 1954, when the dye was introduced. At 3:30 p.m., 1 kilogram of uranin mixed with 1 gallon of water was poured into the well. About 11:30 p.m. on June 28, 1954, 57 hours later, the dye was detected in a sample of water collected from the sump in mine heading 67-left of Songo mine.

Another attempt to use dye for determining hydraulic connections gave a negative result. An exploratory diamond-drill hole, 1,820 feet deep, in the SE¼SE¼ sec. 18, T. 18 S., R. 3 W., overlying Pyne mine, penetrated broken and factured rock at 650 and 1,707 feet below the land surface. One kilogram of uranin mixed with about 50 gallons of water was allowed to drain slowly into the diamond-drill hole for a period of 4 hours. Water samples were collected from a drill hole in Pyne mine at 4-hour intervals for a period of 6 days, and the dye was not detected.

Negative results from the use of dye do not necessarily prove that a system of fractures is not interconnected. It is possible that the dye was adsorbed by clay particles in the underlying shale formation, or that time of travel was more than 6 days, or that the point of injection was downgradient from the point of discharge in the mine.

GROUND WATER

This investigation is primarily concerned with that part of the hydrologic cycle which involves the occurrence and movement of water beneath the land surface, particularly the water penetrated by underground mining operations in the Birmingham district. Fundamental concepts and definitions of the occurrence and movement of ground water are given in Meinzer (1923a, b), Tolman (1937), and Todd (1960).

SOURCE AND MOVEMENT OF GROUND WATER

Normal annual precipitation of 53 inches falls mostly as rainfall and occasional light snow and is the source of all ground water in the Birmingham district. When the precipitation reaches the land surface, part of it runs off directly and contributes to the streams, part is evaporated, and part enters the soil. Some of the water that percolates into the soil zone is transpired and evaporated back into the atmosphere, and some is retained in capillary and subcapillary openings in the soil by molecular attraction in the zone of aeration. The rest of the water moves downward, in response to gravity, into the zone of saturation and becomes ground water.

The permeability and porosity of the rock formations have been increased by the structural development. The steeply dipping formations exposed on Red Mountain—namely the Fort Payne Chert, limestone unit of Warsaw age, Hartselle Sandstone, and Bangor Limestone—have been exposed to intensive weathering by extensive fractures and joints. Rock weathering has subsequently increased the permeability and activity of ground-water movement. A drilling program by the mining companies to determine the extent of weathering revealed a zone of weathering in the Fort Payne Chert and limestone unit of Warsaw age that extended downdip about 1,000 to 1,500 feet from the portals of the mine slopes to mean sea level.

WATER LEVELS AND ARTESIAN CONDITIONS

A water-table map for the mining area was not constructed because of the sporadic distribution of wells and the complex geologic and hydrologic conditions in the area. The depth-to-water measurements in the wells in the area indicate a shallow water table or the composite effect of several confined pressure surfaces.

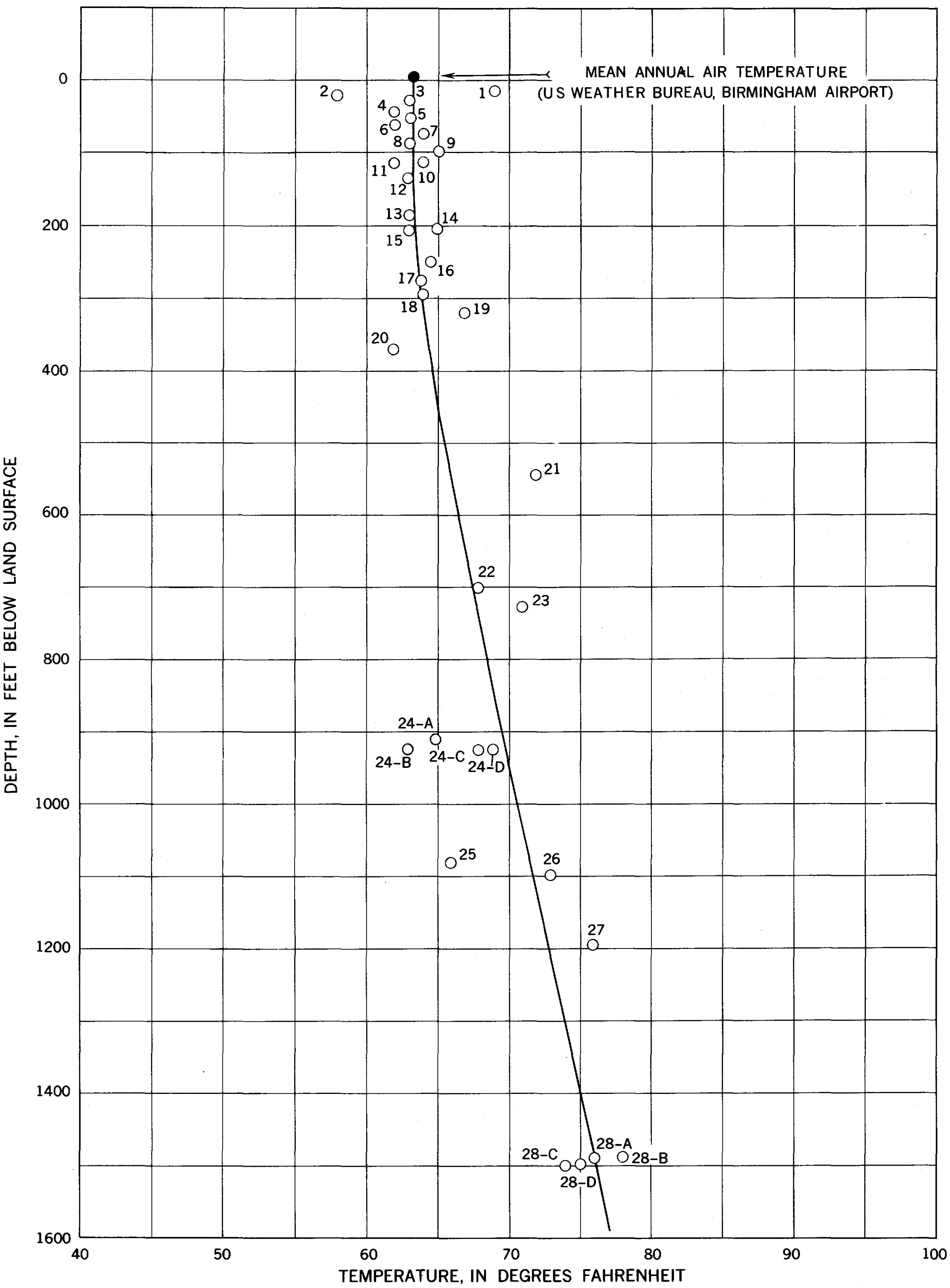

FIGURE 11.—Geothermal graph.

Penetration of a pressure surface or surfaces during the drilling of a well can be detected when a rise or fall in the water level is noted. The water level in a well is assumed to be the result of one or several water tables whose existence is indicated by underlying geologic conditions.

Clayey beds in the Floyd Shale form gouge along most of the faults, which reduces the permeability along the fault. In Hopewell, domestic wells have to be drilled to a depth of 200 to 300 feet before an adequate supply can be developed. The area is cut by several faults which have formed isolated blocks having a very restricted amount of recharge and ground-water flow. Figures 12 and 13 are diagrammatic cross sections typical of geologic and hydrologic conditions in the district. Wells drilled to different depths would have different water levels; thus a contour map constructed from random data would not represent natural conditions.

Mining activity underlying the southeastern slope of Red Mountain, particularly in those areas northeast of Readers Gap, has resulted in cave-ins, subsidence, and surface cracking, which have greatly increased the porosity and permeability of the formations that overlie the ore seams. In recent years drainage of ground water into the mines through caving stopes and roof falls has no doubt greatly modified the shape and slope of the water table in these areas.

Hydrographs from a number of observation wells are shown in figures 14 and 15. Figure 16 shows the location of the wells in the area and table 3 gives the records of the wells.

Hydrographs of wells that penetrate shale and limestone aquifers are shown in figure 14. Well 6 shows a fluctuation of about 9 feet from June to December 1, 1954. Wells 4, 7, 8, and 10 follow the same pattern and show fluctuations which reflect seasonal trends from rainfall. These changes of water level are cyclic and are temporary changes related to the amount of rainfall each year.

Wells 2 and 11 in figure 15 penetrate solution cavities in limestone aquifers. Well 11 had a water-level change of about 110 feet from February 1 to December 1, 1954. Well 2 had a water-level change of about 35 feet from the end of April 1955 to the 1st of February 1956. Both wells reflect seasonal trends related to the amount of rainfall and are therefore only temporary changes in the water level.

Well 1 (fig. 15) is developed in chert and limestone; it had a sudden drop of water level of about 185 feet on the 1st of June 1953 and continued to decline until the 1st of December 1953 for a total of 270 feet. However, heavy rainfall in December 1953 caused the water level to rise about 35 feet, and decreased rainfall in January 1954 caused the level to fall rapidly until the end of January when the level rose slowly until June. The sharp decline from June to December 1953 was the result of drainage into the mine underlying the well and was a permanent change of water level. After December 1 the water level in the well followed normal seasonal fluctuations related to the rainfall.

Table 4 is a compilation of 23 diamond-drill holes from which ground-water flows were obtained. Of the 23 holes, only 7 were flowing in 1957 and, according to reports, these wells were flowing at a much decreased rate. Hydrogen sulfide gas bubbled from most of the wells.

Figure 17 is an idealized geologic cross section in the northeastern part of the area of investigation. The faults along the Ishkooda-Potter system allow water to move under pressure from the intake areas on Red Mountain down against the fault on the southeast where it becomes impounded and then moves back up through the shear zone of the fault to the surface. Where two permeable formations are so displaced that they are moved in a position opposite one another, a transfer of water across the fault zone occurs, provided the fault plane has not been sealed with gouge or impermeable material from an overlying or underlying formation. The diagram also shows the beds that confine under pressure the water penetrated by diamond-drill hole W–34, southeast of Little Shades Mountain. Between the fault on the southeastern side of Red Mountain and Little Shades Mountain is the area of recharge for the displaced formation which would give rise to water under pressure at depth if the rocks were fractured and the water could move downgradient to the southeast.

The fluctuations of artesian pressure for a well in this area from May 1954 to March 1957 are shown in figure 18. The hydrograph shows a rising trend from 1953 to 1957, owing to an increasing average annual precipitation. The sharp rises and declines probably were caused by the changes in precipitation.

SOLUTION CAVITY DEVELOPMENT

The outcrops of the limestone unit of Warsaw age and the Bangor Limestone are marked by funnellike sinkholes and other surface depressions caused by the collapse of underground openings (fig. 19). Solution cavities in the Fort Payne Chert are much less common because of the high percentage of chert in the formation.

Exploratory drilling in Shades Valley and in areas southeast of Shades Valley penetrated a number of water-bearing fractures and crevices in the limestone unit of Warsaw age and the Fort Payne Chert, but no solution openings were penetrated. The fractures and

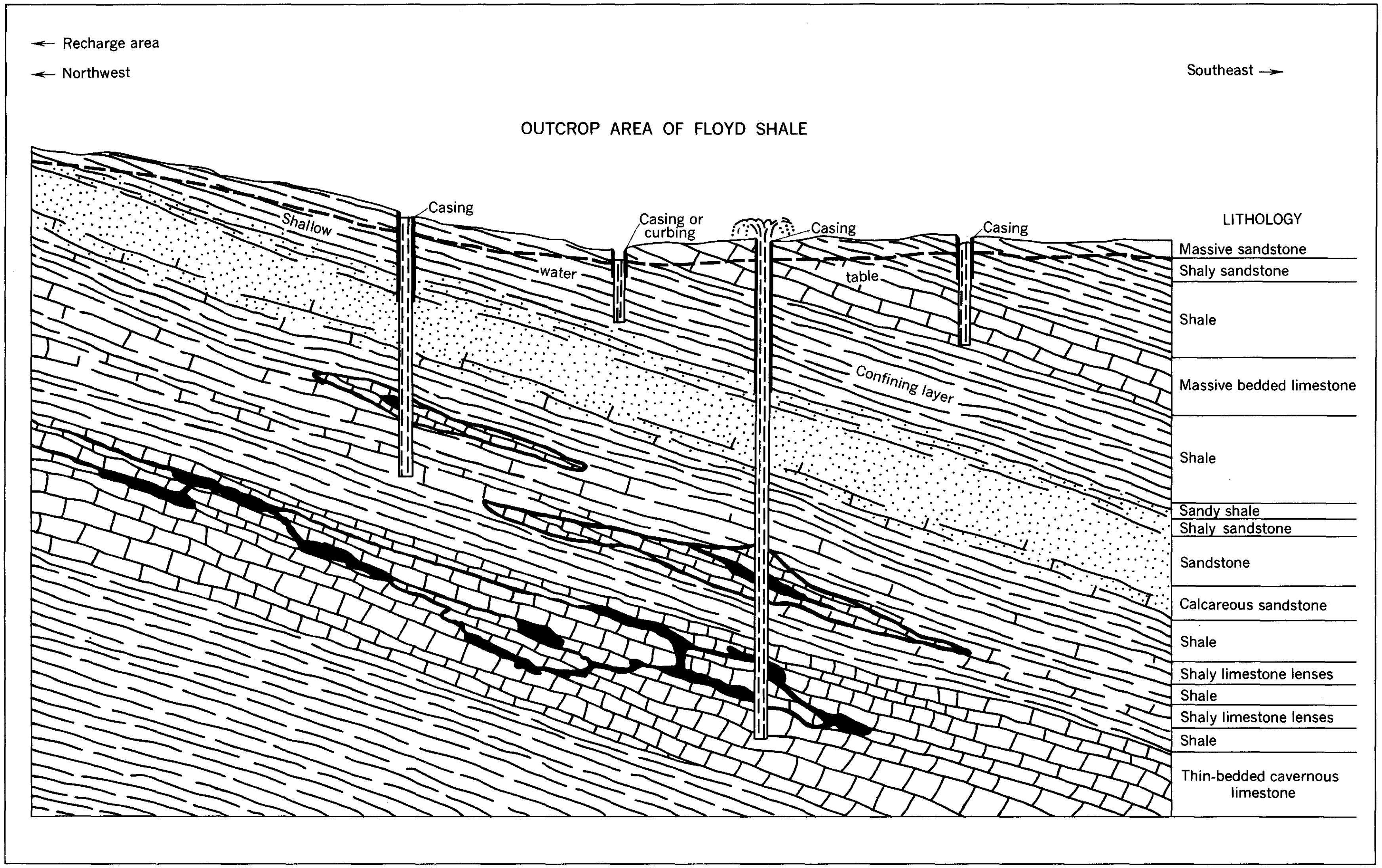

FIGURE 12.—Geologic section showing typical occurrences of ground water in the Floyd Shale and the composite effects of confined water in one or more aquifers.

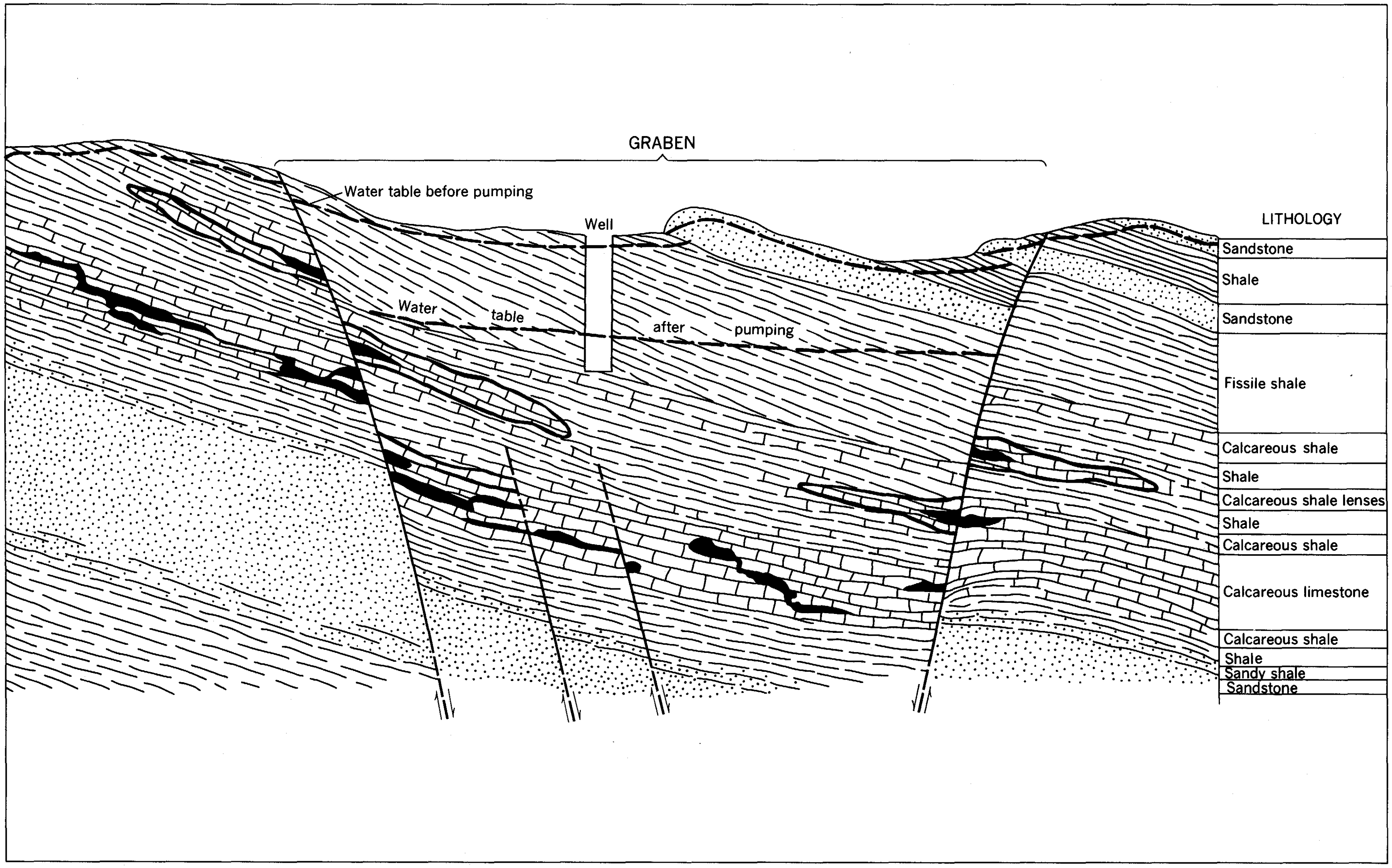

Figure 13.—Geologic section showing the effects of faulting and the lower water level in the downthrown fault block as a result of limited recharge from impermeable fault zones in the Floyd Shale.

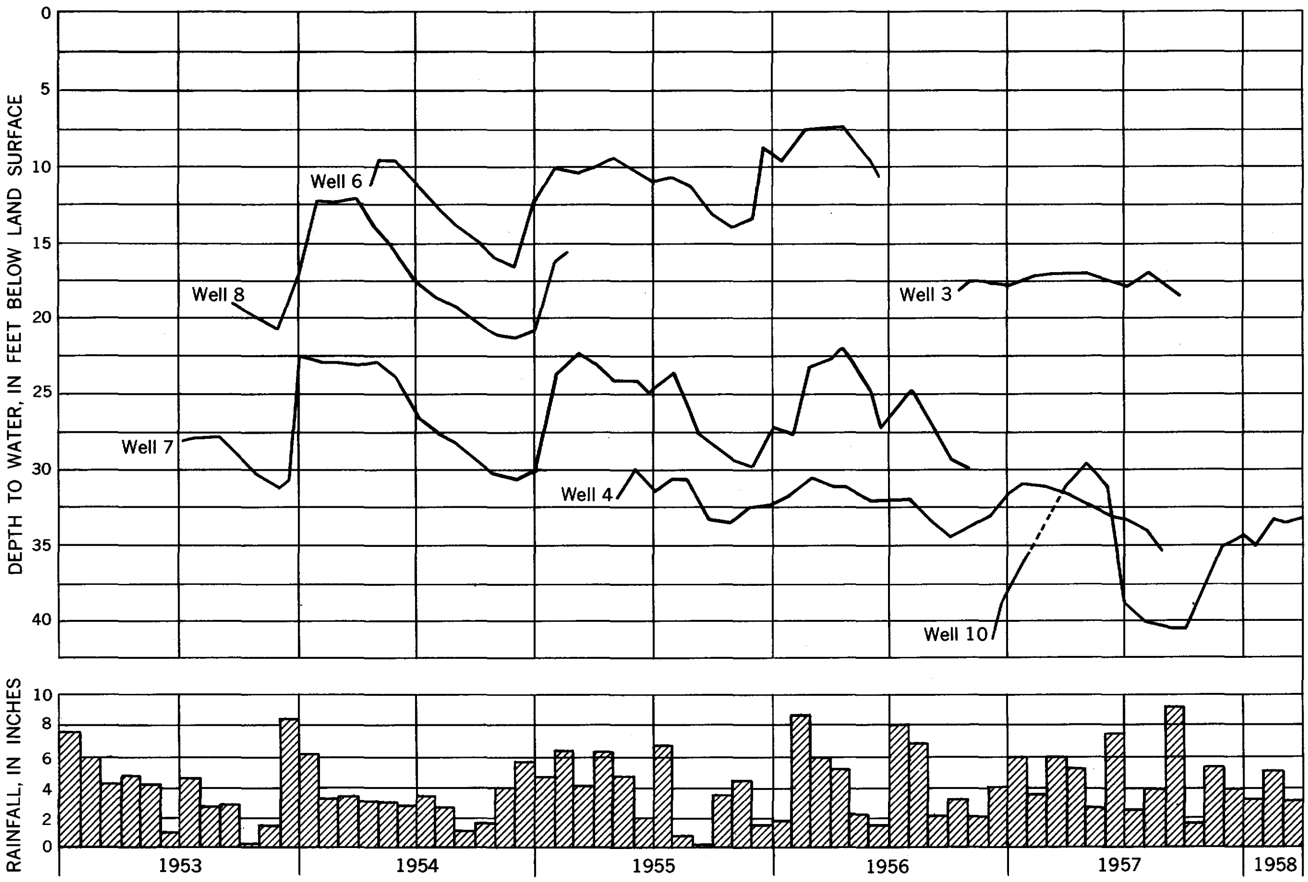

FIGURE 14.—Precipitation and fluctuation of water levels in six observation wells.

crevices were most prevalent near faults and strong folds. Holes not drilled near zones of faulting or tight folding generally penetrated solid chert and limestone, void of any cracks or cavities.

Several large tubular-shaped solution channels lined with thin deposits of calcite and pyrite were penetrated in the Muscoda No. 5 limestone mine. The channels occur between an altitude of 600 feet and mean sea level. Several smaller channels leading off the main openings were plugged with debris. The channels were formed along the joints in the limestone and consequently are oriented in a northeasterly and southeasterly direction. Some of the openings are as wide as 3 feet and one was reported to be about 15 feet high and 20 feet wide (Grover Miller, oral commun., 1957). The channels or caves extend an undetermined distance into the overlying rock.

No evidence of filled channels or sinkholes has been discovered that could be considered relics of youthful karst topography formed on an old land surface and subsequently buried beneath the overlying shale beds.

Generally the drainage in an interconnected solution system seeks a base level that corresponds very closely to that of the surface drainage system. The solution openings in the limestone unit of Warsaw age and the Bangor Limestone apparently are related to a base level superposed on a water table which was slowly declining during structural development. The presence of swamps downdip and downslope from the intake areas along Red Mountain indicates ground-water discharge.

STRUCTURAL CONTROL OF THE MOVEMENT OF GROUND WATER

Geologic structure is the major influence on the movement of ground water in the Birmingham red-iron-ore district. The deformative forces responsible for the structure of the area also modified the water-bearing characteristics of the rock formations. The porosities and permeabilities of the formations generally were increased owing to extensive faulting and fracturing.

The general southeasterly dip of the formations has confined the water in an artesian condition that persists throughout most of the area. Anticlines and synclines as well as simplified monoclines and minor flexures are common. Folding has deformed the southeast flank of the Birmingham anticline to such an extent that ground-water flows are directed from the northeast to

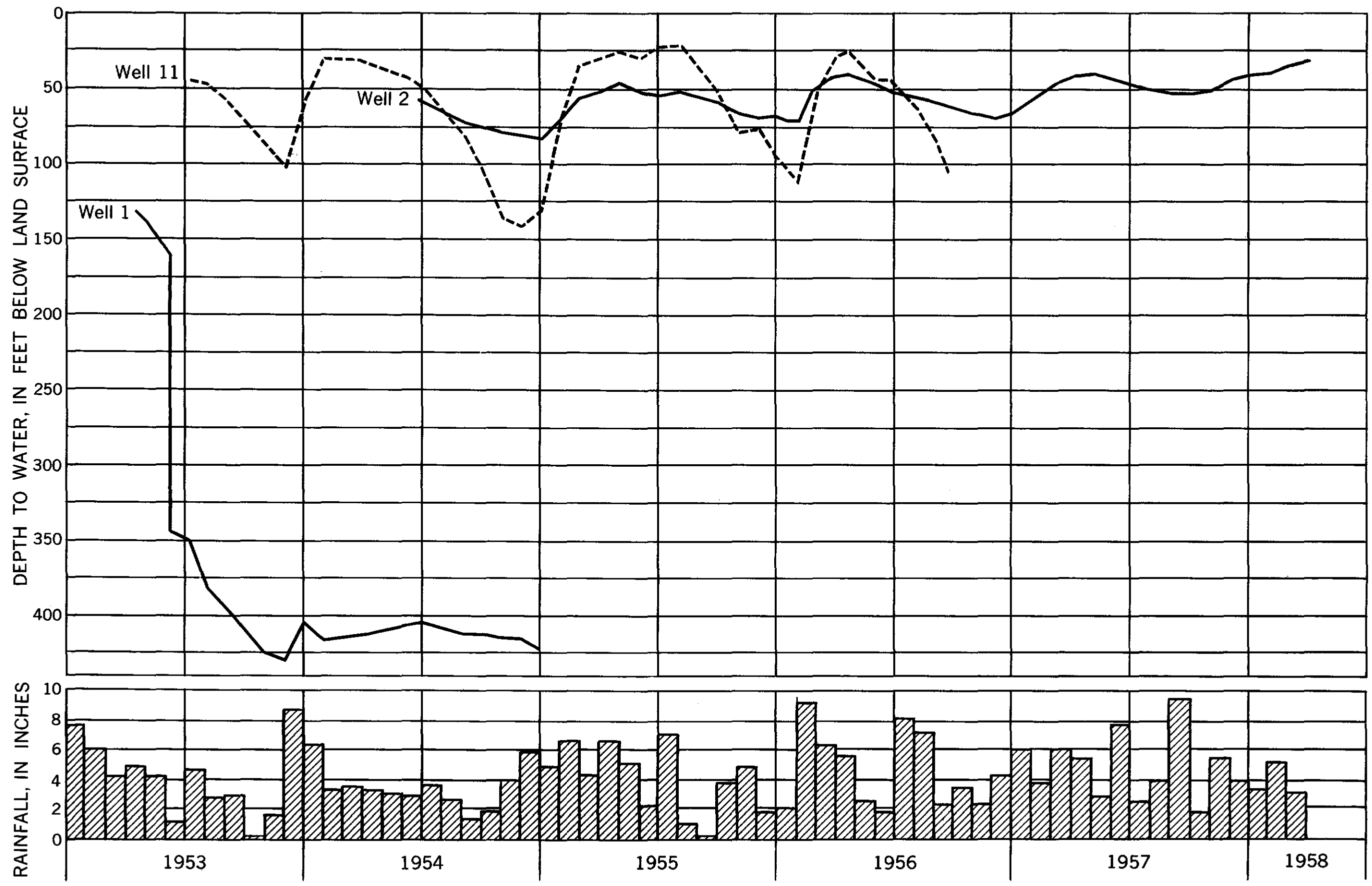

FIGURE 15.—Precipitation and fluctuation of water levels in wells developed in chert and limestone.

the central part of the structure; from the southwestern part, the flow is diverted northeast toward a central basinlike area (pl. 1).

Where faults have placed permeable beds in juxtaposition with impermeable beds, the water is trapped and either fills the bed or overflows along the fault zone to a discharge point at lower elevation.

All the rock formations exhibit well-defined joint systems and the ground-water flow is controlled in part by the joint orientation. Open-joint systems contiguous to water-bearing fault zones are common in the area and present water problems in all of the mines in which this condition exists.

The most effective structural control on the flow of ground water in the Birmingham area is the extensive system of faults that parallels the axis of the major folds, particularly those that have large vertical displacement. Some of the initial displacement in the district is the result of tension rather than shear; therefore, an increase in volume is introduced because of the opening created between the fault surfaces. An extensive system of open fractures along and contiguous to the main fault acts as conduits for the flow of ground water. Irregular contact surfaces along the fracture planes also serve as conduits for the flow of water.

A distinctive graben between the major faults of the Ishkooda-Potter system, together with the fracturing in the downthrown block that accompanied the growth of the graben, has formed a broad zone of relatively high permeability. Large quantities of ground water circulating in the graben have been particularly troublesome in the slope mines. In contrast, the water problems in the shaft mines have been solely the result of fault-zone and open-joint penetrations.

High hydrostatic pressures and large ground-water flows are present in the Pyne and Shannon mines where they intersect the Shannon fault. Water-bearing fractures in the Pyne mine range in width from a few inches to 30 inches. Diamond drilling about a thousand feet beyond the Shannon fault penetrated subsidiary fractures of several inches in width which contained water under pressures as high as 550 ps. The high hydrostatic pressures are the result of recharge and interconnections along the plunging structure of the Dickey Springs anticline. Figure 20 is a geologic section showing the piezometric surface for part of the structure. This section shows the Fort Payne Chert and the limestone unit of Warsaw age exposed in the Greenwood-Morgan

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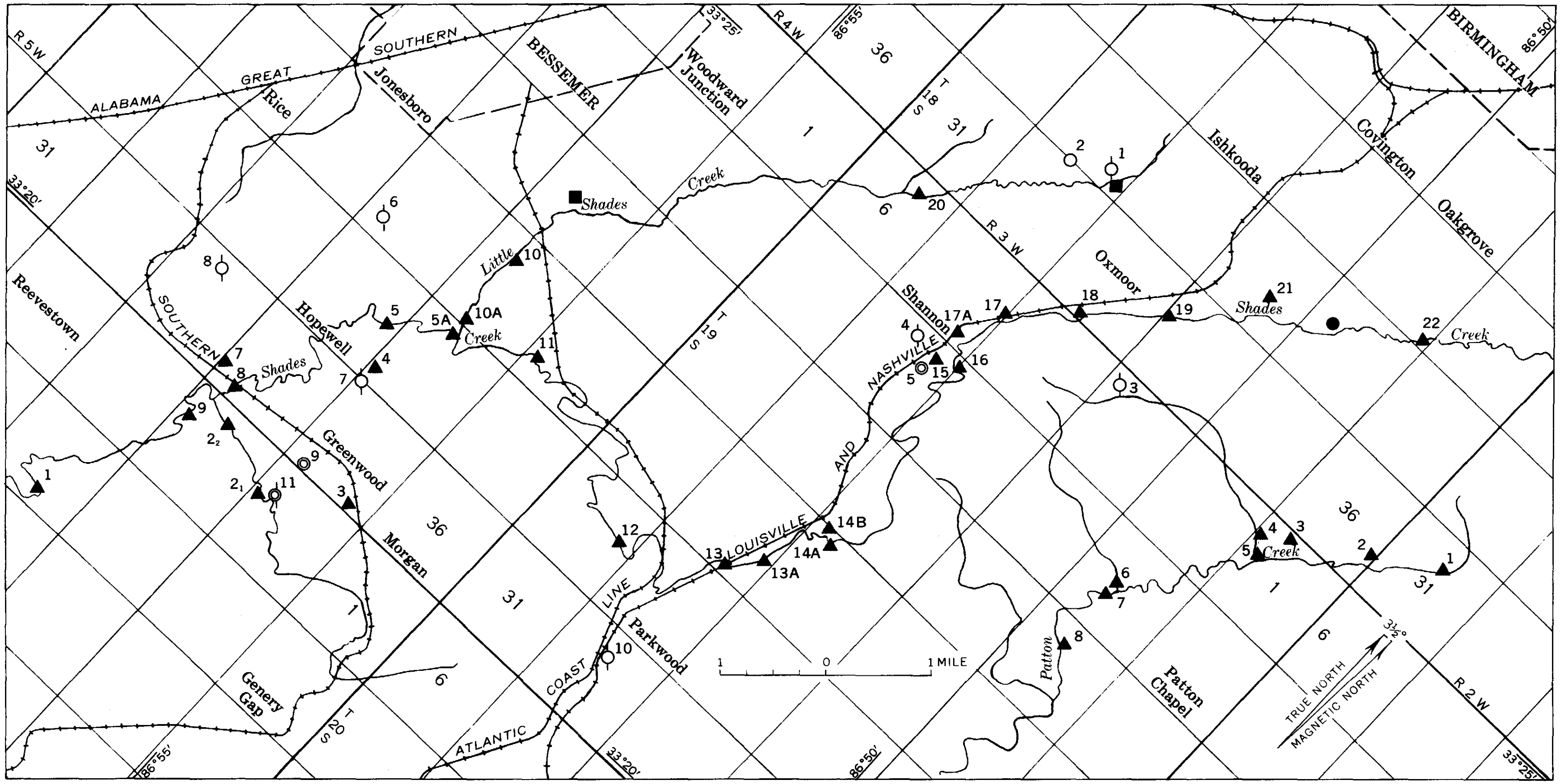


EXPLANATION

○2 Well (observation)

◎5 Well (public supply)

▲18 Open-channel site

● Sewage effluent

Abandoned well (observation) (10)

Abandoned well (public supply) (11)

■ Mine discharge

FIGURE 16.—Location of wells used in the collection of hydrologic data and location of stream-measure sites on Shades and Patton Creeks.

TABLE 3.—*Records of wells used in this report*

Well: All wells drilled.
Depth of well: Depths shown as integers are reported; those expressed to the first decimal are measured.
Altitude: Those shown as integers are taken from USGS Bessemer Iron District quadrangle map; those expressed to the first decimal are from level circuits.
Method of lift: N, none; S, submergible; T, turbine.
Use: O, observation; P, public supply.
Water-bearing formation: Pp, Pottsville Formation; Mp, Parkwood Formation; Mf, Floyd Shale; Mb, Bangor Limestone; Mw, limestone unit of Warsaw age; Mfp, Fort Payne Chert.

Well (fig. 16)	Owner	Driller	Depth of well (feet)	Diameter of well (inches)	Water-bearing formation	Altitude of land surface (feet)	Method of lift	Use of water	USGS field chemical analysis (ppm)		Remarks
									Chloride (Cl)	Hardness as $CaCO_3$	
1	Woodward Iron Co.	H. W. Peerson	546.0	10	Mw, Mfp	651.8	N	O	0	122	See hydrograph (fig. 15).
2	U.S. Geol. Survey	do	138.7	6	Mb	641.9	N	O	0	210	Do.
3	W. W. Randel		114.7	6	Pp	998	N	O	18	80	See hydrograph (fig. 14).
4	Tenn. Coal & Iron Div., U.S. Steel Corp.	H. W. Peerson	302.0	8	Mp, Mf	659.8	N	O			Do.
5	Shannon Waterworks		+200	8	Mp, Mf	610	S	P			
6	T. H. Sadler		67.8	6	Mf	540.7	N	O			Do.
7	J. A. Stevens	McMichens	65.9	6	Mf	524.7	N	O	0	128	Do.
8	W. Boswell	John McCarty	80.0	6	Mf	523.0	N	O	22	210	Do.
9	Greenwood Water Assoc.	H. W. Peerson	150	10	Mw, Mfp	510.8	T	P			
10	Louisville & Nashville Railroad.		62.0	6	Mp	583.7	N	O			Do.
11	Greenwood Water Assoc.	H. W. Peerson	276.0	10	Mw, Mfp	514.2	N	O			See hydrograph (fig. 15).

TABLE 4.—*Diamond-drill holes from which water flowed at the land surface*

Diamond-drill hole	Owner	Location	Year drilled	Flowing (1957)	Gallons per minute	Remarks
R-G-2	Republic Steel Corp.	SW¼NW¼ Sec. 9, T. 19 S., R. 3 W.	1919	No		Reported flowing when drilled.
T-40	Tenn. Coal & Iron Div., U.S. Steel Crop.	NE¼SW¼ Sec. 5, T. 19 S., R. 3 W.	1927	Yes	2	
T-43	do	SE¼NE¼ Sec. 5, T. 19 S., R. 3 W.	1928	Yes	1	
T-44	do	NW¼NE¼ Sec. 5, T. 19 S., R. 3 W.	1929	No		Do.
T-52	do	SE¼NW¼ Sec. 8, T. 19 S., R. 3 W.	1930	Yes	1	Do.
T-53	do	SW¼SE¼ Sec. 33, T. 18 S., R. 3 W.	1931	No		Do.
T-54	do	SW¼NE¼ Sec. 17, T. 19 S., R. 3 W.	1931	Yes	10	
T-55	do	SW¼SW¼ Sec. 35, T. 18 S., R. 3 W.	1931	No		Do.
T-56	do	NE¼SE¼ Sec. 18, T. 19 S., R. 3 W.	1931	Yes	1	
T-57	do	NW¼SW¼ Sec. 27, T. 18 S., R. 3 W.	1932	No		Do.
T-60	do	SE¼SE¼ Sec. 17, T. 19 S., R. 3 W.	1941	No		Do.
T-61	do	NW¼NW¼ Sec. 20, T. 19 S., R. 3 W.	1941	No		Do.
T-62	do	NW¼NE¼ Sec. 26, T. 19 S., R. 3 W.	1941	No		Do.
T-66	do	SE¼SW¼ Sec. 8, T. 19 S., R. 3 W.	1941	Yes	1	
T-68	do	NE¼NW¼ Sec. 34, T. 18 S., R. 3 W.	1942	No		Do.
T-71	do	SE¼NW¼ Sec. 11, T. 19 S., R. 3 W.	1943	No		Do.
T-72	do	NW¼SE¼ Sec. 25, T. 18 S., R. 3 W.	1943	No		Reported flowing when drilled. Gas present (H_2S).
T-75	do	SW¼SE¼ Sec. 6, T. 19 S., R. 2 W.	1944	Yes	2	Utilized as domestic supply. Gas present (H_2S).
T-P	do	NE¼SW¼ Sec. 22, T. 19 S., R. 3 W.	1914	Yes	2	Flow test 1957. Gas present (H_2S).
U-2	U.S. Pipe & Foundry Co.	SW¼NE¼ Sec. 32, T. 19 S., R. 3 W.	1921	Yes	2.5	Do.
W-12	Woodward Iron Co.	NE¼SE¼ Sec. 27, T. 18 S., R. 3 W.	1913	Yes	4	Utilized as domestic supply.
W-34	do	SE¼NW¼ Sec. 26, T. 18 S., R. 3 W.	1949	Yes	4	Pressure hydrograph. Flow test 1957; flow estimated at 50 gpm when first drilled.
W-36	do	NE¼NE¼ Sec. 26, T. 18 S., R. 3 W.	1949	No		Flowed when depth of hole reached 221 ft. Gas present (H_2S).

area, and ground water moves down the dip of the structure from these areas of recharge toward the northeast. Water in these formations confined below the Floyd Shale occurs under artesian conditions in the Pyne and Shannon mines.

Figure 21 is a pressure-head map constructed from pressure-gage readings in the mines along the Shannon fault in the "Big Seam" and shows the approximate altitude of water to be expected at various points along the fault zone (fig. 20).

The structure contours on the geologic map (pl. 1) show that the Dickey Springs anticline has been sheared along its northwestern flank by the Shannon fault. The anticline has a distinctive northeast plunge in subparallel alinement with the fault. As diamond drilling was extended in the underground workings of the Pyne mine, the holes penetrated rocks containing water under progressively higher hydrostatic pressures, both in the main fault zone and in a subsidiary fault that extends about 1,000 feet southeast of the main fault (figs. 20, 22). The higher hydrostatic pressures toward the northeast are the result of structural plunge. The low pressures and varying ground-water discharges in Pyne mine are the result of drainage and decreased permeabilities caused by the partial filling of the water-bearing openings with deposits of calcite and pyrite.

The structure contours indicate gradients down which water would flow provided the rocks were permeable. Water movement would be from the northeast as well as from the southeast; hence another recharge area may

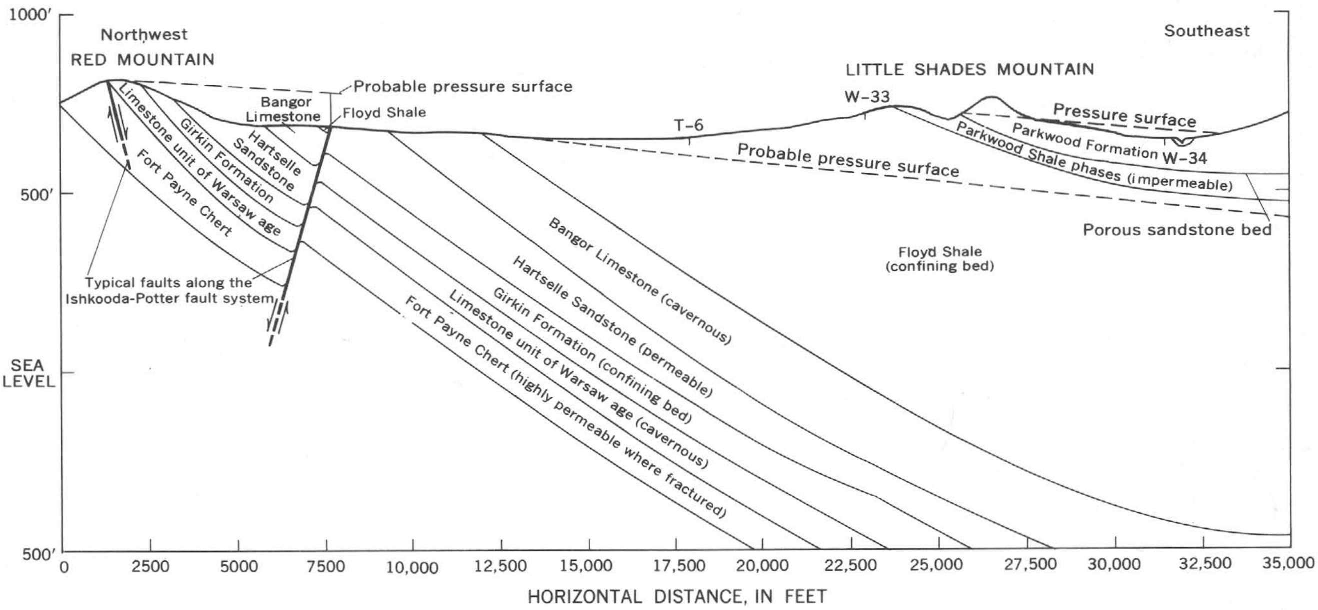


FIGURE 17.—Generalized geologic section in the northeastern part of the Birmingham red-iron-ore district, showing hydrologic conditions.

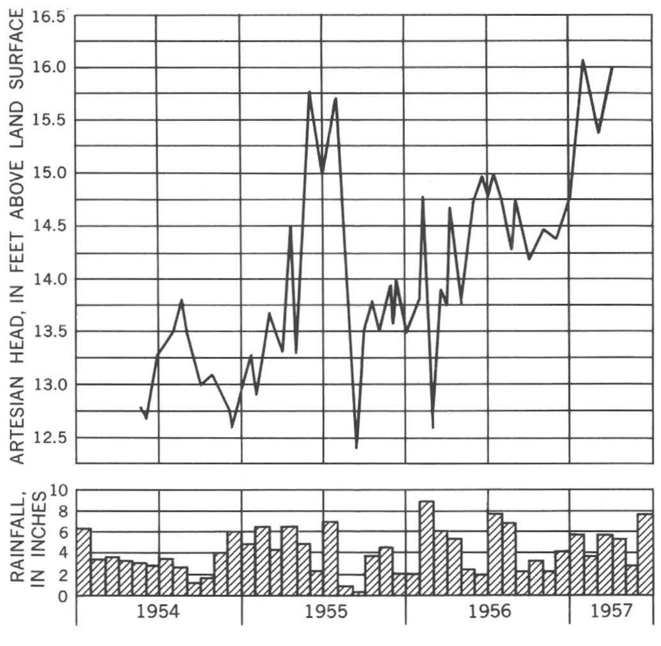


FIGURE 18.—Artesian pressure in diamond-drill hole W-34, and precipitation.

lie beyond the northeastern boundary of the area of investigation. The Shannon mine is in the main structural low between the Shannon fault system and the Dickey Springs–Patton system and, therefore, would receive flows from all directions.

GROUND-WATER RECHARGE

The ground-water reservoirs of the mining district receive most of their recharge from rainfall and an occasional light snowfall, part from influent streams, and the remainder from deep-subsurface underflow from the northeast.

RECHARGE FROM RAINFALL

The average annual rainfall in the district is about 53 inches (U.S. Weather Bureau, 1958), but only a part of this reaches the ground-water reservoir. Most of it flows directly into the surface-drainage system as runoff, and part of it is lost by evaporation and transpiration.

Many factors affect the amount of recharge from rainfall. Seasonal effects in the district are readily apparent in the rise and fall of the water levels in wells. During the hot, dry fall months, soil moisture is very low and, before water seeping downward through the

FIGURE 19.—Sinkhole resulting from collapse of solution cavity in the Bangor Limestone in the NW¼SE¼ sec. 23, T. 18 S., R. 3 W.

soil zone reaches the zone of saturation, the requirements of the root zone must be satisfied. When the heavy winter rains of long duration begin in November and December, the rise in water levels is slow until the demands of the soil are satisfied. After a period of time the response is quicker and the rise in water levels becomes rapid. After the soil has become saturated and the ground-water reservoir has been filled to capacity, additional rainfall added to the soil zone is rejected and runs off on the land surface or at the base of the soil overlying the bedrock, particularly in areas underlain by chert and limestone.

Pumpage from the mines increases as a result of increased recharge after the beginning of the winter rains (fig. 23). A total of 5.83 inches of rain fell during the period April 1–13, 1955, and, because of recharge caused by the rains, the inflow rate to Songo mine increased by 170 gpm. The first increased flow appeared in the mine 2 to 3 days after the rains started.

RECHARGE FROM SURFACE WATER

Discharge measurements were made along Shades and Patton Creeks and their tributaries to detect any gain or loss in their flows, particularly where the streams crossed faults (fig. 16). Because open-channel measurements of this type are subject to gaging errors, considerable care must be used in the selection and preparation of the sites as well as in making the measurements. Generally, a stream section was prepared 24 hours before a series of measurements was to be taken in order to insure a uniform velocity and clear channel above and below the gaging site. The measurements were made during periods of low flow because losses would be a large percentage of the total flow at these times.

Shades Creek is a sluggish stream and has dense vegetation along its banks. Its flood-plain deposits consist of sandy loam and fragments of chert and sandstone. Organic debris is scattered along the stream course, and the channel bottom is seldom uniform. Although the stream channel is frequently a series of large pools, the stream does not recharge the ground-water reservoir except in areas where it crosses outcrops of limestone and chert. The channel bottom over shale and sandstone is well silted with clay particles and organic debris and is therefore relatively impermeable. Discharge measurements along Shades Creek are given in table 5.

In the upper reaches, Patton Creek is cut through dipping well-jointed beds of sandstone and shale (fig. 24) and flows rapidly in a narrow, almost uniform well-cut channel. The lower reaches of the creek were not investigated because they extend beyond the area of study.

Losses due to transpiration are difficult to determine but may be considerable during the growing season. Evaporation from the surface of the stream is probably negligible owing to the dense cover afforded by the overhanging growth along the banks.

Another factor in the gain-and-loss study was the variation in streamflow resulting from sewage effluent and mine discharge. Data were insufficient for a quantitative evaluation of their effect.

Measurements were made in downstream order, and generally a day was required to complete a series or run. Where the stream was known to cross a fault, simultaneous measurements were made at upstream and downstream sites as near the fault as possible.

Figure 25 shows graphically the results of discharge measurements on Shades Creek. After June 20, 1956, the discharge measurements were confined to the lower reaches because the upper reaches indicated consistent gains in the previous series of measurements. The graph consistently shows losses between sites 5 and 9; here, the stream is underlain by shale, limestone, and chert, as well as thick deposits of alluvium.

The discharge at site 5 was plotted against the discharge at site 1 in cubic feet per second in figure 26. The drainage areas of sites 1 and 5 are 60 and 76.6 square miles. A line drawn through 60 on the site 5 scale and through 76.6 on the site 1 scale at a 45 degree angle represents the line of equal yield for both sites. The graph shows the corresponding discharge, in cubic feet per second per square mile, for each site; the deviation represents a change in the drainage characteristics of the downstream basin. The fact that all the points but one plot to the left of the equal-yield line indicates that site 5 is discharging more water per square mile than is site 1.

Simultaneous measurements on Rice Creek above and below the Dickey Springs fault are shown below; each pair, except one, shows losses that range from 0.014 to 0.280 cfs (cubic feet per second). On November 22, 1955, a flow of 0.01 cfs was estimated above the fault, whereas below the fault the channel was dry owing to percolation into the fault zone.

Losses between sites 2_1 and 2_2 on Rice Creek

Date of measurement	Discharge above fault (cfs)	Discharge below fault (cfs)	Loss (cfs)
June 3, 1953	0.076	0.062	0.014
November 22, 1955	.01	.000	.01
December 6, 1955	1.540	1.260	.280
June 20, 1956	.130	.084	.046
November 28, 1956	.152	.079	.087
June 4, 1957	.266	.219	.047
October 29, 1957	.560	.520	.040
Average loss			0.0856

A series of measurements made on Patton Creek in 1956 indicated areas of loss of streamflow. There is opportunity for losses to occur, for most of the channel is cut along strongly jointed and permeable sandstone beds of the Pottsville Formation (fig. 24).

Seepage measurements, in cubic feet per second, on Patton Creek

[Gains and losses include measurements on tributaries discharged into main-creek flow (fig. 16)]

Gaging station	Distance from upper measuring point (miles)	June 21, 1956		November 27, 1956	
		Discharge	Gain (+) or loss (−)	Discharge	Gain (+) or loss (−)
1	------------	0.005	------------	0.014	------------
2	0.7	.580	+0.575	.922	+0.908
7	3.4	.640	−.090	------------	−.684
8	4.2	.460	−.180	------------	+.053

The gain and loss studies on Shades Creek, Patton Creek, and Rice Creek show only typical figures but indicate that the streams are recharging the ground-water reservoir along parts of their courses.

RECHARGE FROM DEEP-SUBSURFACE UNDERFLOW

The fracture zones adjacent to faults of large displacement, particularly in beds of limestone and chert, afford permeable openings through which water can migrate for long distances. Some of the water flowing through the fracture zones is derived from sources outside the area of investigation.

Recharge to the northeastern ends of the Shannon and Patton faults probably is derived partly from areas lying northeast of the area of this investigation. The faults near the southwestern end of the Ishkooda-Potter system probably receive some water from areas southwest of the area of this investigation. The data collected were inadquate to provide any quantitative estimates of the amount of underflow moving into the district from deep-subsurface sources.

TRANSFER OF WATER BETWEEN FORMATIONS

The structural and hydrologic conditions in the area create head differentials which favor the transfer of water from one formation to another. When the water becomes impounded against impermeable fault zones under sufficient head, some of the movement is up and some is down. In places, water is transmitted laterally across a fault zone from one formation to another. The interformational movement of ground water makes quantitative studies extremely complex.

Some vertical leakage occurs as the result of pressure-head differences between the impermeable and permeable formations. Should attempts be made to dewater artesian aquifers in mining operations, the withdrawals of water under high pressure heads will

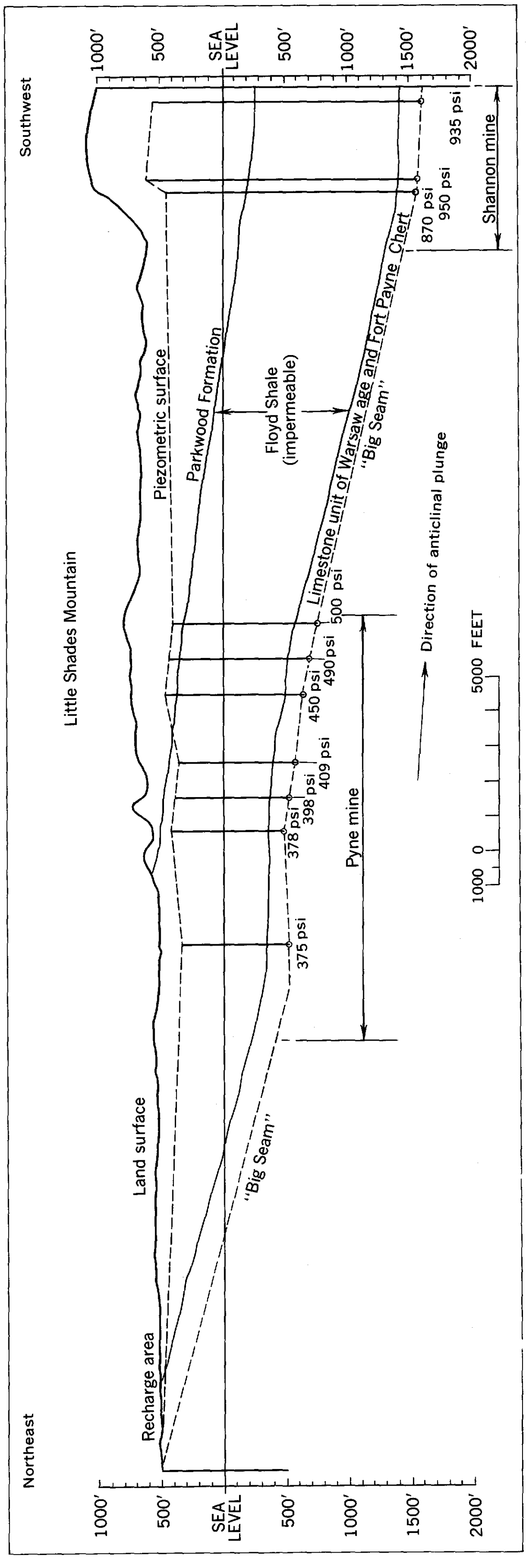


FIGURE 20.—Geologic section showing piezometric surface in the Shannon fault zone along the Dickey Springs anticline. Vertical line, artesian head, in feet; circle at bottom of vertical line, depth of observation; water pressure at depth of observation, in pounds per square inch. Datum is mean sea level.

TABLE 5.—*Discharge measurements along Shades Creek, in cubic feet per second*

Gaging site	22	19	16	14A	13	12	5	8	9	1
Distance below initial point (miles)	0	2.4	4.6	7.0	8.4	9.6	14.0	16	17	18.9
June 3, 1953										
Discharge at site	10.3	10.5	10.8	10.9	11.0	11.4	26.4	24.0	28.4	26.0
Inflow between sites	.08	.30	0	.25	0	15.5	.01	.06	0	
Discharge at next site	10.5	10.8	10.9	11.0	11.4	26.4	24.0	28.4	26.0	
Net gain	.12	0	.1		.4			4.34		
Net loss				.15		.5	2.41		2.4	
June 23, 1955										
Discharge at site	5.51	10.9	11.1	10.5	10.8	9.59	24.9	23.6	23.3	25.6
Inflow between sites	.30	.21	0	.22	0	15.81	0	.07	0	
Discharge at next site	10.9	11.1	10.5	10.8	9.59	24.9	23.6	23.3	25.6	
Net gain	5.36	.01		.08					2.3	
Net loss			.6		1.21	.50	1.3	.37		
Dec. 6–7, 1955										
Discharge at site	13.0	20.7	23.6	24.6	24.7	25.7	32.6	34.2	32.0	35.7
Inflow between sites	.64	1.22	0	.80	0	12.31	0	1.49	0	
Discharge at next site	20.7	23.6	24.6	24.7	25.7	32.6	34.2	32.0	35.7	
Net gain	7.06	1.63	1.0		1.0		1.6		3.7	
Net loss				.70		5.41		3.69		
June 18–19, 1956										
Discharge at site	14.4	31.2	33.4	38.4	42.7	13.3	20.0	19.2	18.3	18.6
Inflow between sites	.22	.07	0	.08	0	8.52	0	.09	0	
Discharge at next site	31.2	33.4	38.4	42.7	13.3	20.0	19.2	18.3	18.6	
Net gain	16.58	2.13	5.0	4.22					.3	
Net loss					19.4	1.82	.8	.99		
Nov. 28, 1956										
Discharge at site							[1] 12.0	16.3	13.8	16.8
Inflow between sites						2.85	0	.08	0	
Discharge at next site						[1] 12.0	16.3	13.8	16.8	
Net gain							4.3		3.0	
Net loss								2.58		
June 4, 1957										
Discharge at site							[1] 22.4	24.0	21.2	23.1
Inflow between sites						4.82		0	.22	
Discharge at next site						[1] 22.4	24.0	21.2	23.1	
Net gain							1.6		1.68	
Net loss								1.8		
Oct. 29, 1957										
Discharge at site							[1] 20.6	22.3	22.8	22.9
Inflow between sites						3.36	0	.62	0	
Discharge at next site						[1] 20.6	22.3	22.8	22.9	
Net gain							1.7		.1	
Net loss								.12		

[1] Alternate site, 13.5 miles below initial point.

probably induce vertical leakage from overlying less permeable beds. As a result, the mines would remain "wet" from "roof drippers," and small flows would issue from open joints and along bedding planes.

GROUND-WATER DISCHARGE

Water is lost from the ground-water reservoirs of the mining district by evaporation and transpiration, by effluent seepage into streams, by discharge from springs and wells, by mine pumpage, and by outflows from deep-subsurface sources.

DISCHARGE BY EVAPORATION AND TRANSPIRATION

In places, plants draw water directly from the zone of saturation and discharge it into the atmosphere by transpiration. The rate of transpiration varies with the type of plant, depth to the water table, character of the soil, climate, and season of the year. Transpiration is most active during the growing season, which averages about 239 days, beginning in March and ending the last of October. Abundant phreatophytes along the banks of the streams probably draw heavily from the water table during this lengthy growing season. Evaporation from the ground-water reservoirs is confined to areas where the water table is near the land surface, such as marshes and swamplands; however, these losses are probably small owing to the small areal extent of the swamplands.

SEEPAGE INTO STREAMS

The base or fair-weather flow of streams in the Birmingham district is generally derived from ground water. The seepage of ground water into the surface streams probably is one of the largest natural sources of groundwater discharge in the area of study.

DISCHARGE BY SPRINGS

Depression springs are common in the low-lying areas, and they discharge water throughout the year. The flow from these springs ranges from 1 gpm during

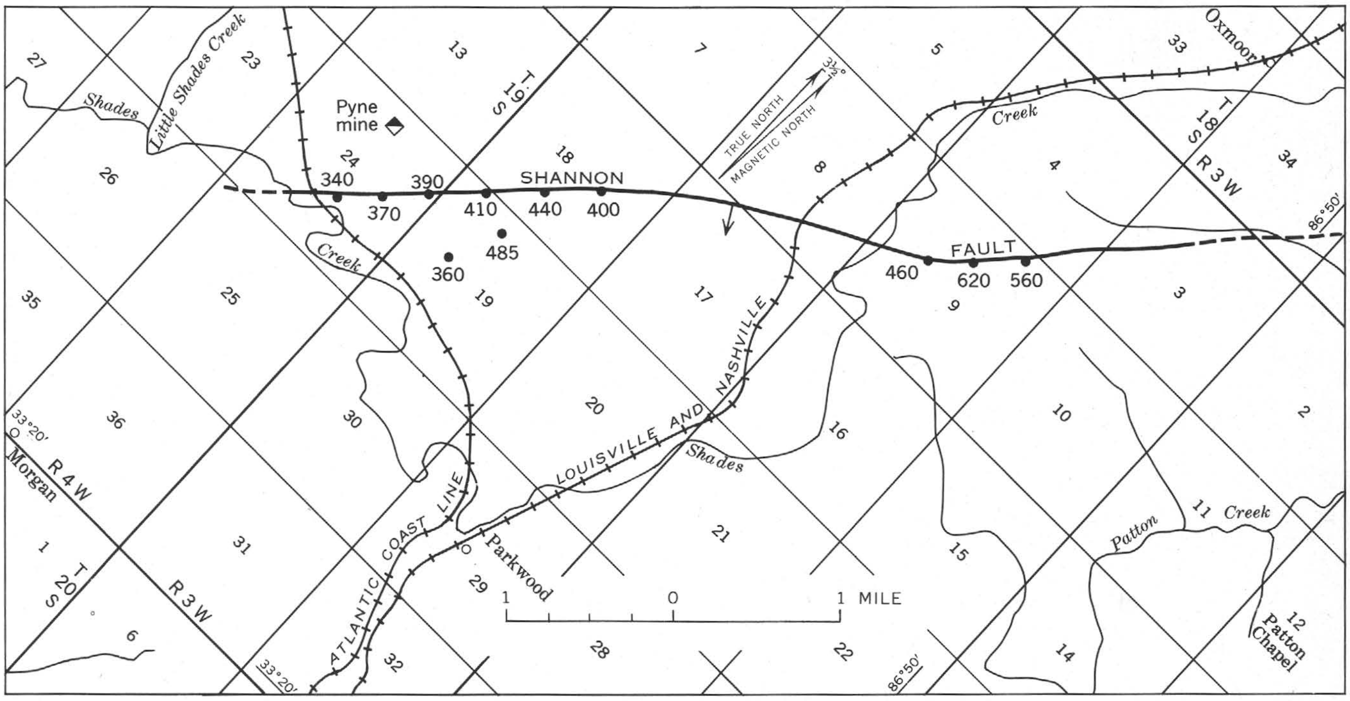


FIGURE 21.—Pressure head of water along the Shannon fault. ●, altitude of water in mine, in feet above mean sea level.

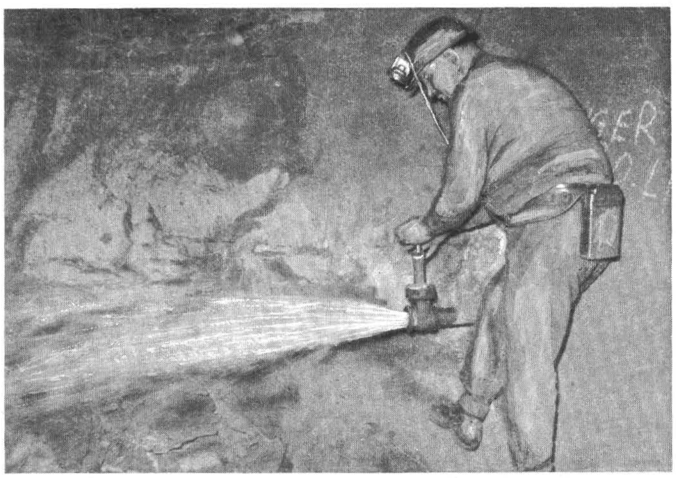


FIGURE 22.—Discharge of water from diamond-drill hole in Pyne mine under a pressure head of 430 psi.

dry periods to 10 gpm during the wet periods. Contact springs in the higher areas have relatively large discharges during the winter and spring months, but decline to little or no flow during the late fall months. Contact springs in the lower areas, along the fault zones, generally flow from tubular openings in the limestone and chert formations and maintain a rather uniform annual flow.

DISCHARGE BY WELLS

Another large source of ground-water discharge is from wells. Most of the wells are used for domestic and stock supply; however, wells at Greenwood and Rocky Ridge furnish municipal supplies for about 300 users.

During the course of the well inventory, data were obtained on 1,070 wells, which is about 85 percent of the total number of wells in the area of study; 700 are drilled wells ranging from 40 to 500 feet in depth, and the remainder are dug wells ranging from 12 to 50 feet in depth. The flow of 11 diamond-drill holes averages 2.8 gpm annually, and 4 of these holes are used for domestic supply. The estimated discharge from pumped wells, flowing wells, and springs is about 1,500 gpm.

DISCHARGE BY MINE PUMPAGE

An artificial source of ground-water discharge is by mine pumpage. The rate of pumping from each mine changes considerably. However, not all of the pumpage is ground water; some is surface water that flows down the slopes from the portal, and some is waste from water that is pumped into the mines for drinking and drilling purposes. The ground water is derived from

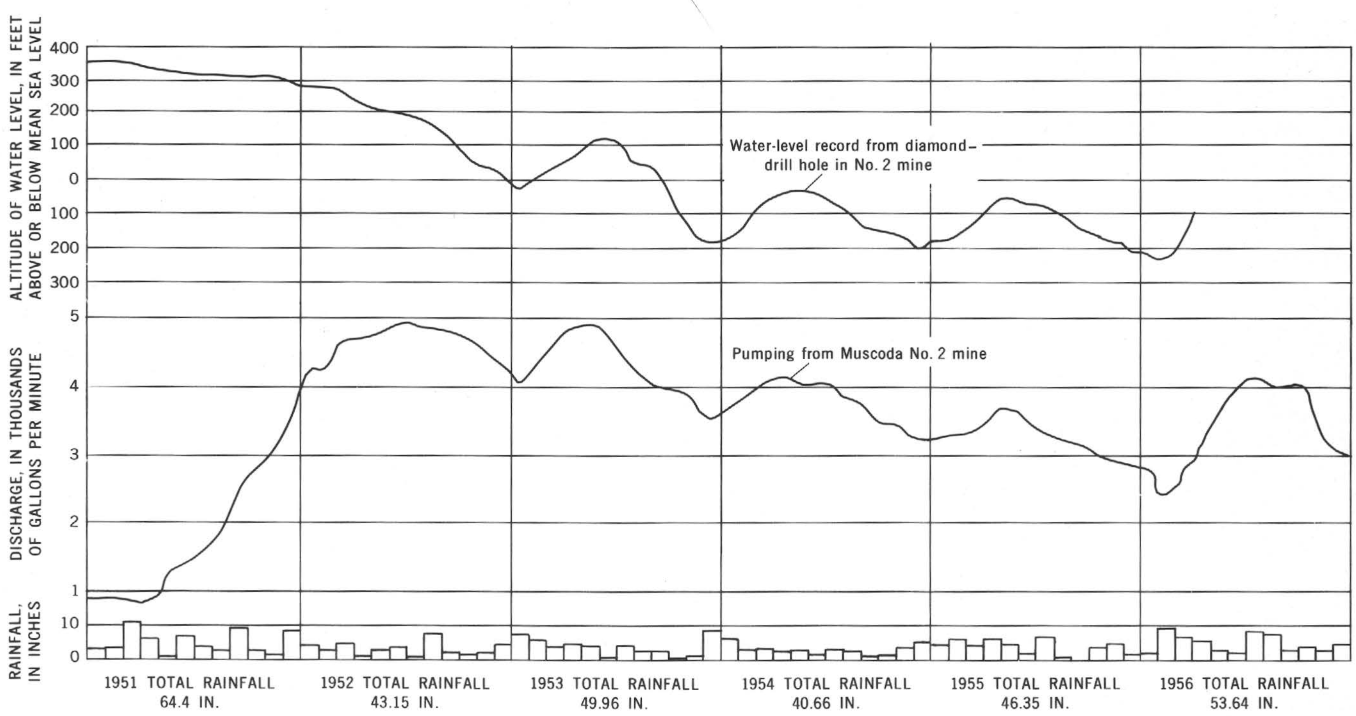


FIGURE 23.—Correlation of pumping and water level near Muscoda mine.

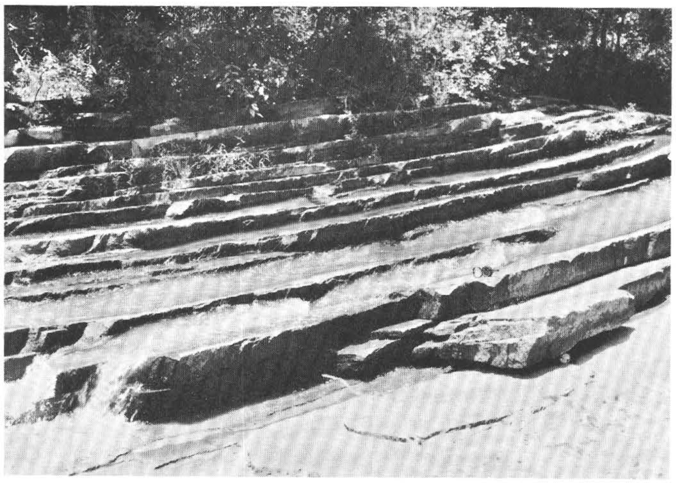


FIGURE 24.—Exposure of the Pine Sandstone Member of the Pottsville Formation in Patton Creek in the NE¼NW¼ sec. 14, T. 19 S., R. 3 W.

"roof drippers," seeps along the bedding planes and joints, and large inflows from roof falls.

The pumpage from the slope mines is greater than the pumpage from the shaft mines that underlie the valley floor. The deeply weathered, highly folded, and fractured rocks overlying the slopes allow rapid seepage into the mines. The fracturing caused by subsidence is more conspicuous along the slopes where the mine workings are older and more extensive.

The pumpage from mines in the district is estimated to be 9,500 gpm. Detailed pumpage records are not available.

DISCHARGE BY DEEP-SUBSURFACE OUTFLOWS

Some ground water is probably being discharged through deep-subsurface fracture systems along the shear zones of major faults in the district. The depth below land surface of the fracture systems is not known, but the water-bearing fractures penetrated in the Shannon fault in the Shannon mine indicate the fracture systems exist to depths of at least 3,000 feet.

Evidence of ground-water discharge from deep-subsurface fracture systems exists about 7 and 20 miles south and southwest of the district, in the vicinities of Green Pond and Centreville. Springs and wells near these towns are developed in solution channels, joints, and bedding planes of limestone, dolomite, and chert of Cambrian and Ordovician ages. Ground water from the Cambrian and Ordovician formations probably rises upward into the overlying basal sands and gravels of the Tuscaloosa Group of Cretaceous age. Johnston (1933, p. 140) reported spring flows of a few to several hundred gallons per minute from the Cambrian and Ordovician dolomites.

GROUND-WATER HYDRAULICS

The occurrence of ground water in the Birmingham red-iron-ore district may be classified according to three

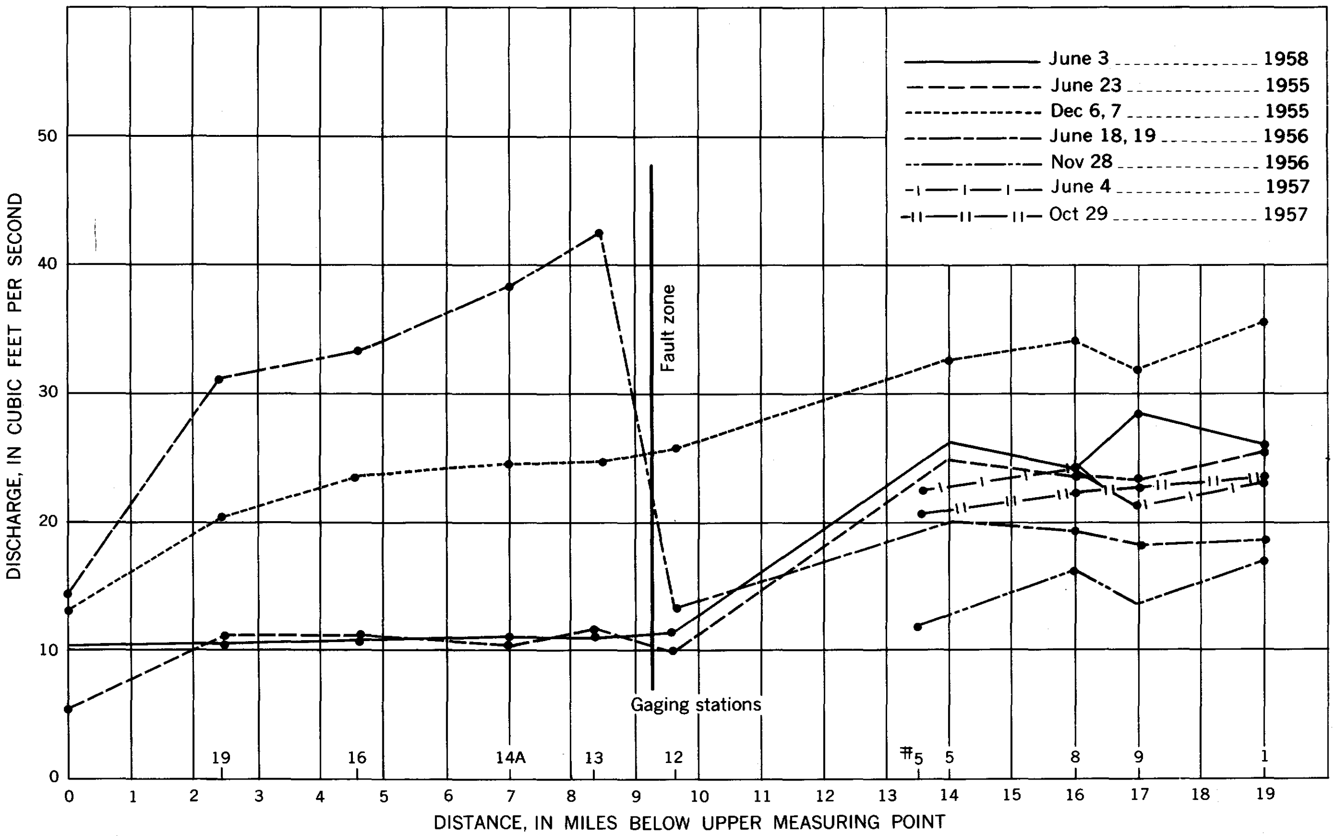


FIGURE 25.—Cumulative gains and losses in flow of Shades Creek.

zones: (1) the upper or water-table zone, (2) an intermediate artesian zone, and (3) a deeper water-table and artesian zone.

The movement of ground water in the upper or water-table zone is controlled primarily by the slopes and drainage of the land surface. Therefore, the general direction of flow is downslope in a lateral direction from points of recharge to lower points of natural discharge. Flow in this zone is termed "saturated flow" and the movement is very slow and uniform. The flow, because of this slow and uniform motion, obeys well-defined laws of laminar flow.

The water table is generally fairly close to the land surface in the areas underlain by shale and interbedded sandstone strata. In the areas underlain by limestone and chert, the water table is deeper, poorly defined, and subject to seasonal changes in position of as much as 130 feet.

On the southeastern slopes of Red Mountain in areas underlain by mine openings, the water table has been lowered owing to the drainage of deeply weathered chert and limestone formations through openings caused by mine subsidence and cave-ins.

Generally, the flow of ground water within the saturated rocks of the water-table zone occurs under flat gradients. Ground water can percolate downward and laterally between dipping layers of relatively impermeable strata and become confined because of the successive layers of different rocks within one formation. This occurs in the intermediate zone, and the flow of water is controlled by the differential head between the points of recharge and discharge. Motion in this zone is still principally lateral, moving from points of high pressure head to points of low pressure head; however, some gradients may be quite steep owing to the structure.

In the deeper zone, ground water moves through an extensive well-defined conduit system in shear zones associated with the major faults of the district. The fracture system runs parallel and subparallel to the fault trends and is a complex system of diversely oriented, interconnected openings. Because of drainage outlets in the mines, some sections of this zone have water under unconfined conditions such as a true water table.

Most of the major fault systems of the district extend through the Floyd Shale, Parkwood Formation, and Pottsville Formation. These rocks contain thick shale units which are relatively impermeable. Where the fault zones cut these formations, the sheared edges of

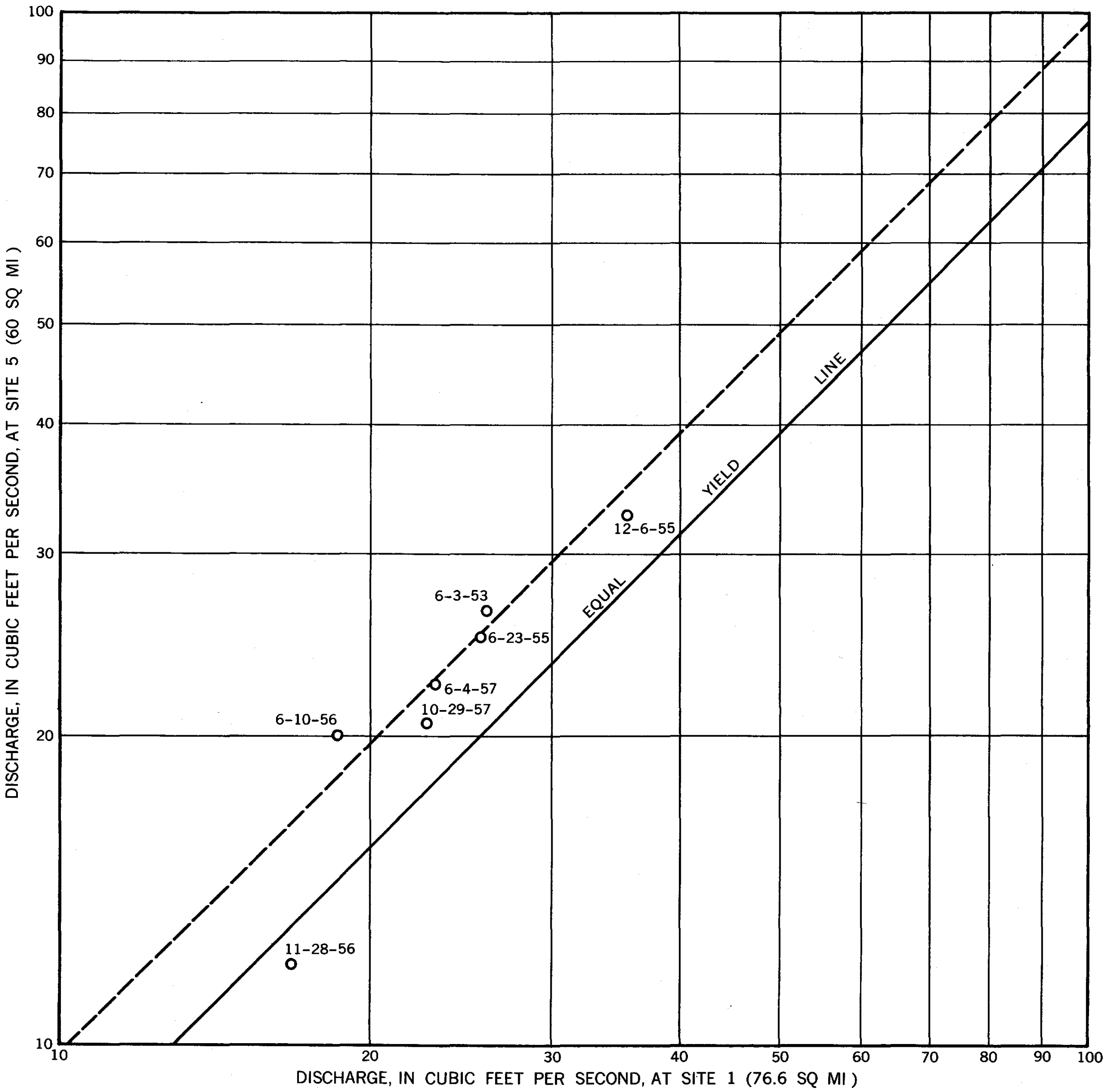


FIGURE 26.—Discharge of Shades Creek at sites 1 and 5, in terms of equal yield.

the fractured formations tend to be sealed with shale gouge and they are thus made impermeable to the flow of water. However, because of the sandstone units in these formations, some transfer of water across the fault zones may occur. Most of the water probably enters the zones from the ends and flows through the fracture conduit down to the deeper formations to become confined water under artesian head. Owing to the circuitous route the water must follow, some of the motion may be vertical and therefore may not follow the well-defined laws of laminar flow.

The preceding discussion and also examination of the fence diagram (pl. 2) and the structure contours (pl. 1) show that the flow of ground water in the area is a combination of horizontal, vertical, and inclined flow.

AQUIFER TESTS AND HYDRAULIC FACTORS

The following discussion on aquifer tests and hydraulic factors of formations is brief; more comprehensive explanations may be found in Ferris (1948), Ferris and others (1962), Muskat (1949), and Theis (1935). Several other texts and papers listed in the "Selected references" afford additional background on specific ground-water problems. However, some of the basic formulae presently in use are given for purposes of familiarity and application to the water problems in the Birmingham district.

When water is withdrawn from a formation by a well, the water levels decline in the vicinity of the point of withdrawal and accordingly the water surface assumes the shape of an inverted cone (cone of depression) whose apex is at the point of withdrawal. The shape and extent of the cone of depression depend mainly on time and on the aquifer's coefficient of transmissibility and storage. Increasing the rate of discharge will not affect the lateral growth of the cone but will cause it to deepen in proportion to the increase. In other words, the drawdown in the well is proportional to the rate of pumping. When a well is pumped, the cone of depression will continue to expand and deepen, although at a diminishing rate, until it either expands to an area where recharge can be induced in an amount equal to that being pumped or expands to an area where the water being discharged from the formation can be salvaged at a rate equal to that being pumped.

The pattern of flow to a well in an essentially homogeneous unconsolidated formation with a horizontal water surface would be radial. In expressing a general equation for analyzing the effects of dewatering, certain basic assumptions must be made: (1) the aquifer must be constant in thickness, (2) it must be infinite in areal extent, (3) it must be homogeneous and isotropic (transmits water with equal facilities in all directions), and (4) water removed from storage must be discharged instantaneously with decline in head. It is further assumed that the well penetrates, and receives water from, the entire thickness of the aquifer.

BOUNDARY CONDITIONS

One of the limiting assumptions in aquifer-test conditions is that the aquifer is infinite and isotropic. However, after prolonged pumping, particularly from wells that penetrate aquifers in folded and faulted rocks, departures from the infinite-aquifer drawdown curve commonly appear, which are indicative of hydraulic boundary conditions. These boundaries represent either recharge or barrier conditions. Boundary conditions are more obvious on the semilogarithmic plots, but careful analysis of logarithmic plots will also show boundary conditions by a decided departure from the type curve when the interval of testing is long.

The effects of boundaries must be considered in the extensions of drawdown and recovery curves in order to make an accurate analysis of future trends in an aquifer. These boundaries may be simulated mathematically by the introduction of hypothetical image wells. Their effects as recharge or barrier boundaries may be determined by summation of the drawdowns caused by the image wells, which are pumped wells for barrier boundaries and are recharge wells for recharge boundaries (Ferris, 1948). Having an image well at a point beyond the boundary equal to the distance from the real well to the boundary and pumping an equal amount to the real well will simulate mathematically the effects of the barrier boundary. Thus, an aquifer of infinite extent is transformed hypothetically into an aquifer of finite extent. For the impermeable boundary or barrier, such as an impermeable fault zone or unconformity between sediments and bedrock, the drawdown produced within the real cone of depression is the sum of the drawdown of the real well plus that of the imaginary discharging well. The situation produced by a recharging boundary—such as an influent stream on a permeable fault zone—is similar, except the image well is a recharge well and the imaginary cone is "building-up" instead of "drawing-down," and is thus producing no drawndown at the recharging boundary.

FLOW CONDITIONS NEAR CIRCULAR OPENINGS

The relation of the hydraulic properties of a formation, the rate and duration of pumping, and the change in water level caused by the withdrawal of water from a circular opening, is expressed in the following formula developed by Theis (1935, p. 519–524).

$$s=\int_{\frac{1.87r^2S}{Tt}}^{\infty}\frac{e^{-u}du}{u} \qquad (1)$$

where s = drawdown, in feet, at any observation point in the vicinity of the circular opening from which water is withdrawn at a uniform rate,

Q = rate of withdrawal of water in gallons per minute,

T = coefficient of transmissibility, in gallons per day per foot (gpd per ft),

r = the distance, in feet, from the point of withdrawal to the point of observation,

S = coefficient of storage, a dimensionless decimal fraction, and

t = time, in days, since the withdrawal of water begun.

This formula can be used for a vertical well or circular opening of a large radius which penetrates the whole formation.

FLOW CONDITIONS NEAR A LINEAR OPENING

A formula for the relations among the hydraulic properties of a formation near a linear opening such as a long open trench or infiltration gallery was developed by Stuart and others (1948, p. 46–47). The formula is stated as

$$s=\frac{Qx}{2T}\left[\frac{e^{-u^2}}{\sqrt{\pi}u}-1+\frac{u}{\sqrt{\pi}}\int_0^u e^{-u^2}du\right] \quad (2)$$

in which $u=1.3675\,x\sqrt{S/Tt}$ (2*a*)

where s=drawdown in feet, at distance x and time t,
Q=quantity discharged from trench, in gallons per day per foot of trench,
x=distance of point of observation from the trench, in feet,
t=time since discharge started, in days,
T=coefficient of transmissibility, in gallons per day per foot, and
S=coefficient of storage, a dimensionless decimal fraction.

This formula can be applied to withdrawals from a large open trench, an infiltration gallery, or a long narrow fault zone—hence, its practical use in mine-dewatering problems.

An aquifer test involves measuring the rate of drawdown or recovery of water level in a pumped well and in one or more observation wells in its vicinity. The data are plotted on logarithmic graphs, and the curves obtained are analyzed to determine the coefficients of transmissibility and storage. When these coefficients have been determined, it is then possible to extrapolate the data to determine the effects of longer periods of pumping at various distances and different rates of discharge.

The departure of the observed data from the hypothetical curve is an indication of the departure of the aquifer-test conditions from the theoretical conditions upon which the Theis solution is based. It is obvious that a thorough knowledge of the geology is necessary before a proper interpretation of the data can be obtained.

METHODS OF DETERMINING TRANSMISSIBILITY AND STORAGE

In the Birmingham red-iron-ore district, values for the coefficients of transmissibility and storage were obtained by the methods of Theis (1935, p. 519–524) and of Cooper and Jacob (1946, p. 526–534). In the Theis method the exponential integral of equation 1 is replaced by the term $W(u)$, which is read "well function of u," and the equation is rewritten

$$s=\frac{114.6\,Q}{T}W(u) \quad (1)$$

The integral expression of equation 1 cannot be solved directly, but its value can be obtained from the series:

$$W(u)=(-0.577216-\log_e u+u-\frac{u^2}{2.2!}+\frac{u^2}{3.3!} \quad (2)$$

in which

$$u=\frac{1.87\,r^2S}{Tt} \quad (3)$$

A modified method of using the Theis formula, developed by Cooper and Jacob (1946, p. 526–534), involves plotting the field data on semilogarithmic paper. This method is based on the knowledge that the value of u decreases for large values of t and that the terms beyond $_eu$ in the exponential series may be neglected. The equation may then be written as

$$s=\frac{114.6}{T}Q\left[\log_e\left(\frac{1}{u}\right)-0.5772\right]$$

After performing the algebraic computations and converting to logarithms to the base 10, the equation is

$$T=\frac{264}{\Delta s}Q \quad (4)$$

where Δs is the change, in feet, in the drawdown or recovery over one logcycle of time. The coefficient of storage may be obtained by the equation expressed as

$$S=\frac{0.3\,Tt_0}{r^2} \quad (5)$$

where t_0 is the time intercept, in days, on the zero-drawdown axis.

Both methods of solving the nonequilibrium formula (log and semilog plots) were used in analyzing pump-test data for the district because each has advantages not possessed by the other.

The Theis formula, equation 1 (p. C32), can be further modified to analyze the recovery curve of a pumped well (Theis, 1935). It is based on the assumption that if a well is pumped or allowed to flow for a known period, the residual drawdown, at any instant after the discharge has stopped, will be the same as if the discharge of the well had continued but a recharge well with the same flow had been introduced at the same point in the flow system at the instant the discharge stopped. The same hydrologic and geologic conditions that are assumed for the nonequilibrium formula are appliable to the recovery formula, which is written as

$$T=\frac{264Q}{\Delta s'} \quad (6)$$

where $\Delta s'$ is the change in residual drawdown, in feet, per log cycle of time. The residual drawdown is the difference between the observed water level and the nonpumping (static) water level extrapolated from the observed trend prior to the pumped period.

The recovery formula is applied in the same manner as the modified nonequilibrium formula. The residual drawdown, s', is plotted on the arithmetic scale on semilogarithmic-coordinate paper against the values of t/t' on the logarithmic scale. The time since pumping started is indicated by t, whereas the time since pumping stopped is indicated by t'.

The recovery formula was used to determine transmissibility of the diamond-drill holes flowing on the surface because no observation wells were available.

Values of the coefficients of transmissibility as computed from pumping tests on wells in the formations overlying the iron-ore mines in the district are given below. The coefficient of storage was not obtained from measurements on the pumped wells because the effective radius of the pumped well is indeterminant.

Coefficients of transmissibility determined for the formations overlying the iron-ore mines

[Formations penetrated: Mw, limestone unit of Warsaw age; Mfp, Fort Payne Chert; Mp, Parkwood Formation; Mf, Floyd Shale; ℙp, Pottsville Formation]

Date of test	Well (pl. 1; fig. 16)	Coefficient of transmissibility (gpd per ft)	Duration of test (days)	Formations penetrated
11- 3-54	9	6, 240	0. 35	Mw, Mfp
10- 8-57	W-34	4, 120	. 39	Mf
10-10-57	T-52	50	. 36	Mf
10-16-57	T-P	690	. 30	Mp, ℙp
11- 6-57	U-2	2, 060	. 35	Mf
11-11-57	W-12	1, 050	. 33	Mf, Mp
1- 4-58	10	365	. 24	Mp, ℙp
3-15-58	5	224	1. 98	Mp, Mf

The tests on wells 9, 5, and 10 were made on drilled wells used for a municipal and domestic water supply. The remaining tests were made on flowing diamond-drill exploration holes drilled by the mining companies.

The considerable range of transmissibilities was expected owing to the variations in lithologies within the formations as well as the complexities of structure. The high transmissibility of the formations adjacent to well 9 is due to the fact that the well is developed in solution cavities in the Fort Payne Chert of Mississippian age and the limestone unit of Warsaw age (fig. 27). The lower transmissibilities of the formations adjacent to wells 5, 10, T-P, and T-52 are indicative of the relative impermeability of the shale and sandstone beds of the Floyd Shale and Parkwood Formation of Mississippian age and the Pottsville Formation of Pennsylvania age. The transmissibilities of the formations adjacent to wells W-12, U-2, and W-34 were higher owing to the presence of nearby faults with large interconnected openings which allowed water to flow fairly unrestricted to the wells. Data from the pumping tests on these last three wells show that a recharge-type boundary occurs within the cone of influence of the pumped wells.

PYNE MINE PUMPING TEST

An aquifer test, using the methods previously presented, was applied to determine the hydraulic factors near the water-bearing fault in Pyne mine. The plan of the test area is shown in figure 28.

Diamond-drill hole 179 was a horizontal hole drilled into the rib in mine heading 2-east crosscut right from station 19 plus 07. A water-bearing fracture with a pressure head of 450 psi was penetrated about 110 feet from the collar.

Diamond-drill hole 186 was a horizontal hole drilled into the rib in mine heading 6-east crosscut right from station 22 plus 37; about 60 feet from the collar a water-bearing fracture with a pressure head of about 450 psi was penetrated.

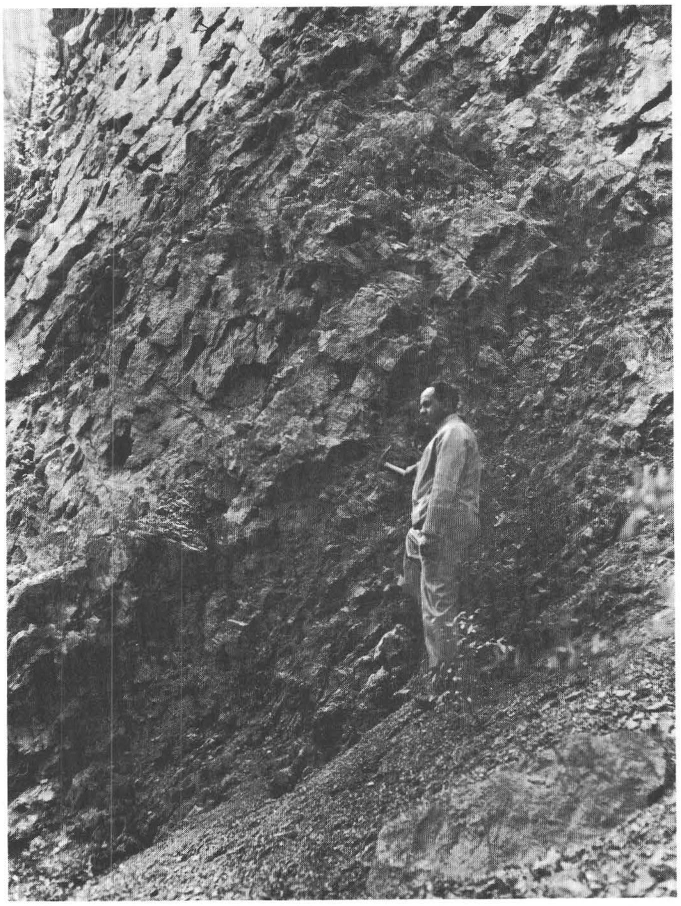


FIGURE 27.—Outcrop of Fort Payne Chert, showing cavities, Clear Branch Gap, SW¼NW¼ sec. 5, T. 20 S., R. 4 W.

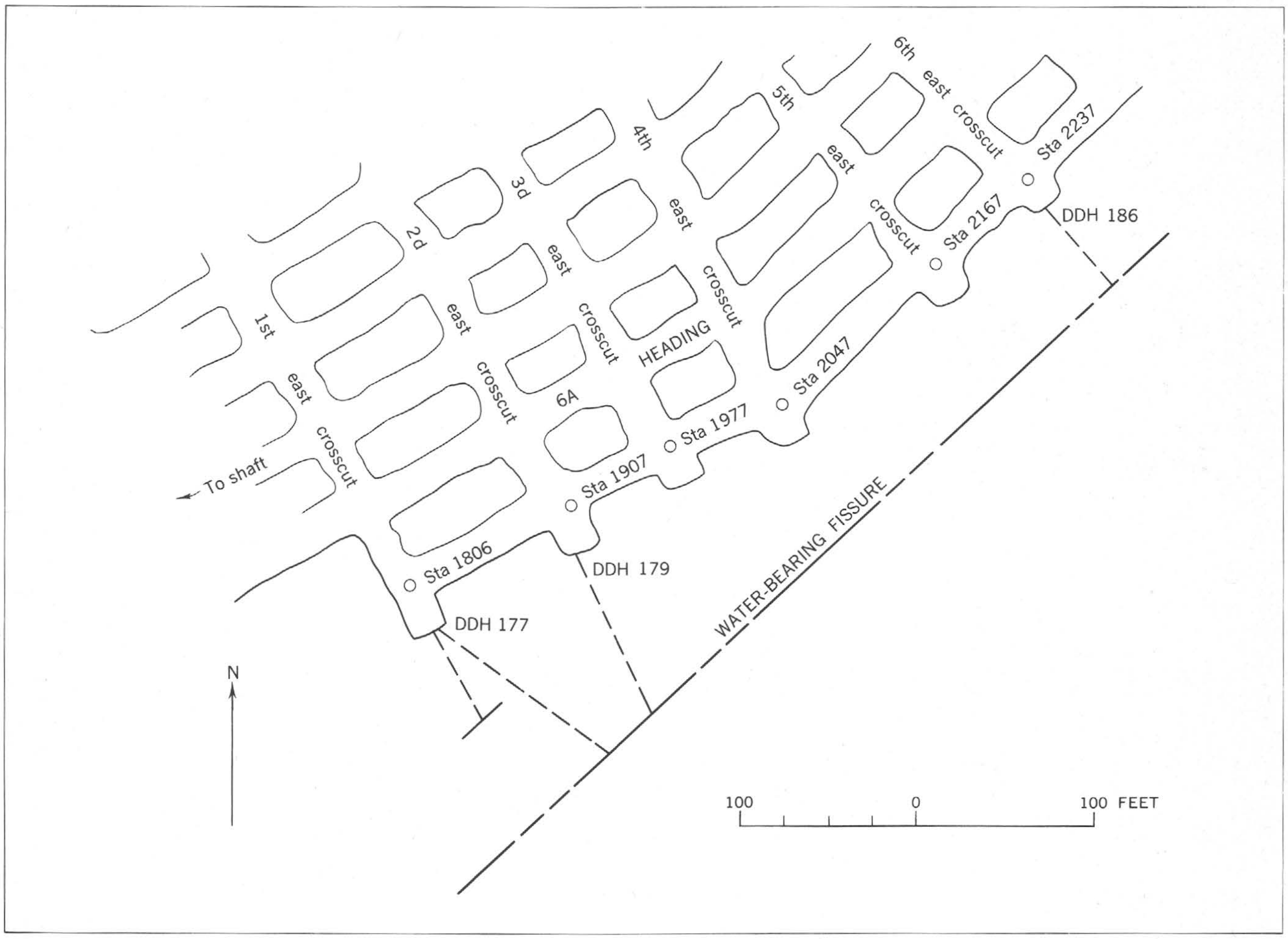


FIGURE 28.—Pumping-test area in Pyne mine (workings on south side of Shannon fault). Diamond-drill holes 179 and 186 are, respectively, a flowing well and an observation well. Sta (station), surveyor's reference point.

Both diamond-drill holes 179 and 186 had penetrated openings which later mining proved to be a shear fracture branching off the main Shannon fault. Samples of water from this fracture and the Shannon fault show the same chemical characteristics (table 2).

Diamond-drill hole 179 was allowed to flow uniformly, and the discharge was about 400 gpm. Drawdown and recovery measurements were made on diamond-drill hole 186 by using an automatic-recording pressure gage. The pressure data from the gage charts were converted from pounds per square inch to feet, and the time was read directly from the charts. The hydrograph of the test is shown in figure 29.

The drawdown and recovery curves shown in figures 30, 31, 32, and 33 were constructed from the hydrograph shown in figure 29. Both methods of solving the nonequilibrium formula (log and semilog plots) were used in analyzing the test.

Examination of the graphs show considerable dispersion of the plotted data. Some of the dispersion is the result of human and instrumental error because the recorder chart could be read only to the accuracy of ±5 pounds or 11.55 feet. Some of the dispersion is also due to boundary conditions within the chaotic structure of the shear zone. Although the boundaries were considered, it was believed that an effective transmissibility was desired for calculation purposes; hence, the line drawn through the drawdown and recovery plots would provide the basis for a calculation of an average effective transmissibility.

The calculation of transmissibility coefficients (in gpd per ft) for the fault is given below:

	Drawdown	*Recovery*
Log	3, 920	4, 250
Semilog	3, 840	4, 330

The storage coefficients are 0.000122 from the log plot of the drawdown and 0.000079 from the log plot of the recovery. Both values are indicative of conditions arising from elastic deformation.

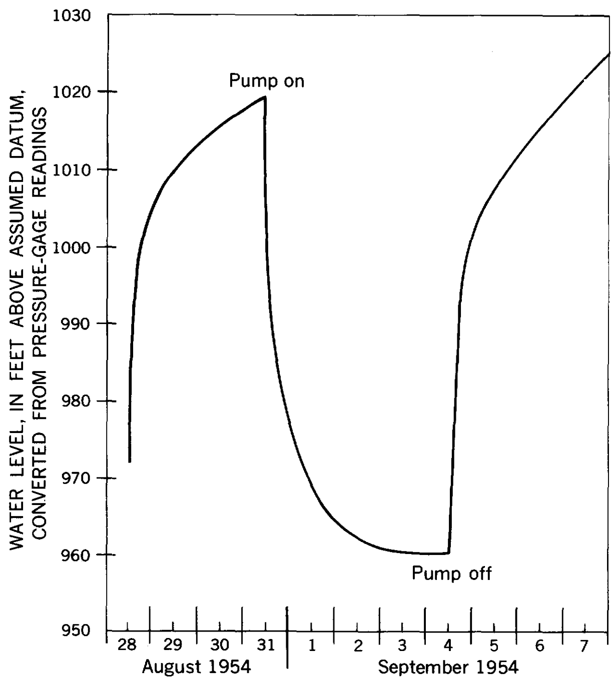


FIGURE 29.—Interference on diamond-drill hole 186 in Pyne mine caused by withdrawal of water from drill hole 179.

METHODS OF CONTROL OF GROUND WATER IN MINES

The value of a mining property is determined from the number of tons of measured and indicated ore that can be extracted at a predetermined cost over a period of years. Damage caused by mine floodings can be so extensive that the cost of overcoming the damage will limit the margin of profit, and continued operation would be unprofitable. Although measures for the prevention of mine floodings require high initial outlay, they may prove profitable when amortized against the larger quantities of ore that could be mined.

Few mines are absolutely dry. Pumping in the red-ore mines will always be necessary owing (1) to recharge from rainfall, (2) to pumping of water into the mines for drilling and drinking purposes, and (3) to flowing of surface water down the slopes from the portal. The present system of mine drainage seems to be adequate, although it may be desirable to replace some of the older, outmoded, inefficient pumps. Pumps with automatic water-level switches and electric counters that show pump-operating times have been installed in most of the mines.

INTERCEPTION OF WATER FLOWS

The prevention of inflow of water before it reaches the mine workings is the easiest way to reduce pumping costs. Before this prevention can be accomplished, it is necessary to know the sources from which the water is flowing; then, the most efficient method of reducing the flows can be selected. Grouting, drainage wells, drainage ditches, and flumes are commonly used as standard engineering methods for prevention or interception of inflows.

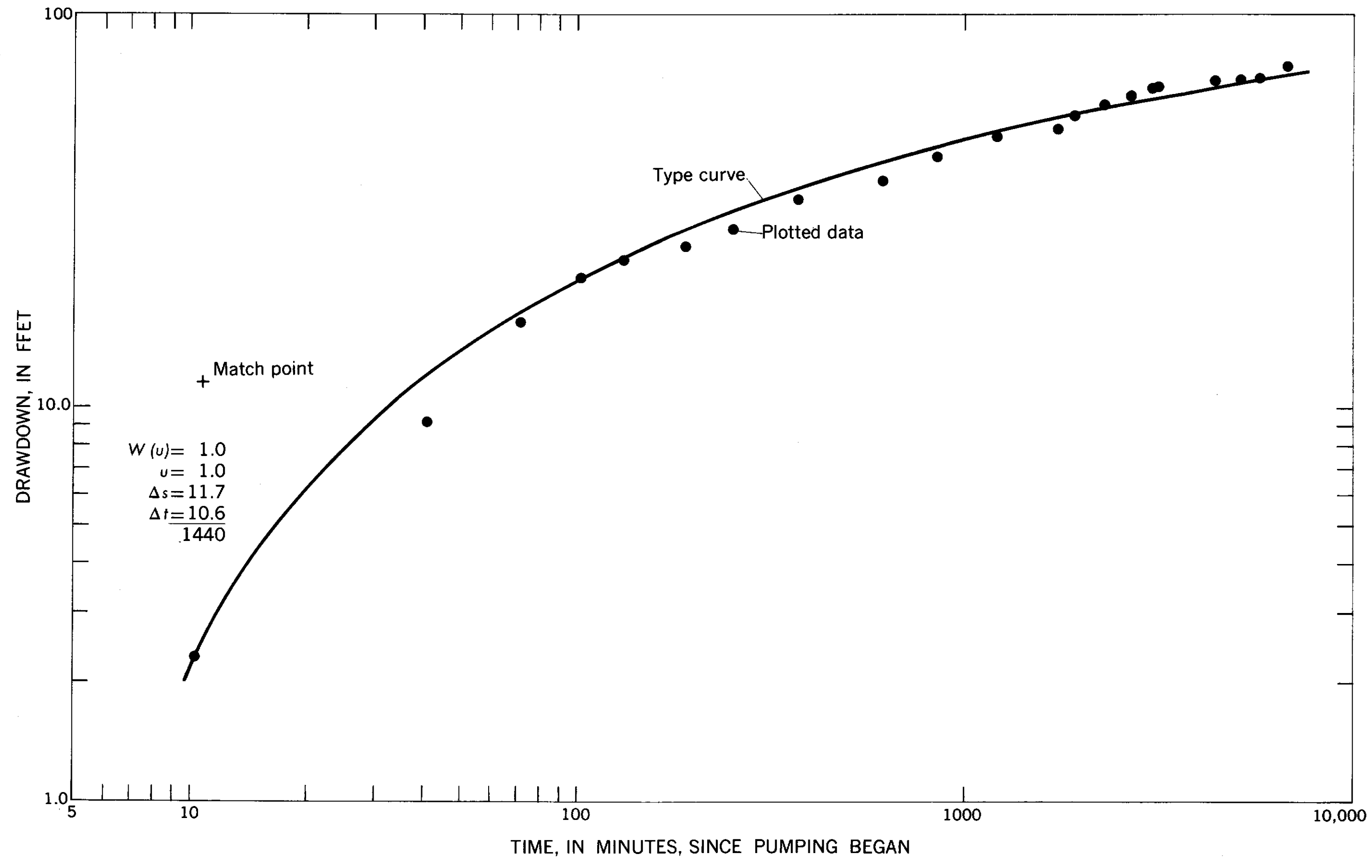
GROUTING

Grouting involves the injection, under pressure, of a mixture of portland cement, water, and sand or gravel in proportions that best fit the particular conditions. Small fissures might require just a mixture of portland cement and water, called "neat cement," plus additives that hasten setting and permit greater penetration of the fissures. Bitumens, grains, and straw have been successfully used in the grouting of larger fractures. The choice of grouting method and materials to be used depends on the cost and availability of materials and the nature of the openings to be grouted.

Pressure grouting has been used in the red-iron-ore district with different degrees of success. The grouting operations, although successful in plugging some of the water-bearing openings, locally have caused the drainage water to be diverted and to overflow into previously dry areas.

Mine openings in the Pyne mine through the Shannon fault were successfully constructed without excessive inflows by the use of grouting. A series of diamond-drill holes placed radially around and ahead of the tunnel bore were used to pump grout into the water-bearing fissures and seal them. Before grouting, the water flowed from 1 to 200 gpm under pressures that ranged from 150 to 335 psi. After the tunnel was constructed, it was lined with concrete, and a concrete and steel bulkhead with a door (which could be closed in the event of sudden inflows) was placed between the fault and the shaft of the mine (fig. 34).

Muscoda mine had a serious water problem in 1950, and attempts were made to seal off the inflow. At mine heading 1st-left in Muscoda No. 4 mine, 44 diamond-drill holes were drilled into the shear zone of a fault; gage pressures in these holes ranged from 415 to 480 psi, and water flows ranged from 3 to 250 gpm. About 25,000 sacks of cement, 160 sacks of bentonite, and 44 sacks of rock dust were pumped into the holes under injection pressures that ranged from 500 to 1,900 psi. An AX-size (1⅛-in.) diamond-drill hole, drilled horizontally into the rib at mine heading 7th-right of the No. 5 limestone mine, intercepted a flow of 250 gpm at a depth of 542 feet in the shear zone of the same fault. About 12,518 sacks of cement, 45 sacks of bentonite, 690 sacks of rock dust, 1 sack of lumnite, and a quantity of grain were injected into the fault zone. Either the cavities were so large that the grout would not fill



Computations

$$T=\frac{114.6\times400\times1.0}{11.7}=3{,}920 \text{ gpd per ft}$$

$$S=\frac{3{,}920\times1.0\times10.6}{1.87\times1{,}440\times(357)^2}=0.000122$$

FIGURE 30.—Logarithmic graph of time drawdown of water level in diamond-drill hole 186 in Pyne mine.

the opening or the pressure of the water was too great for the small grout-block to dam the opening.

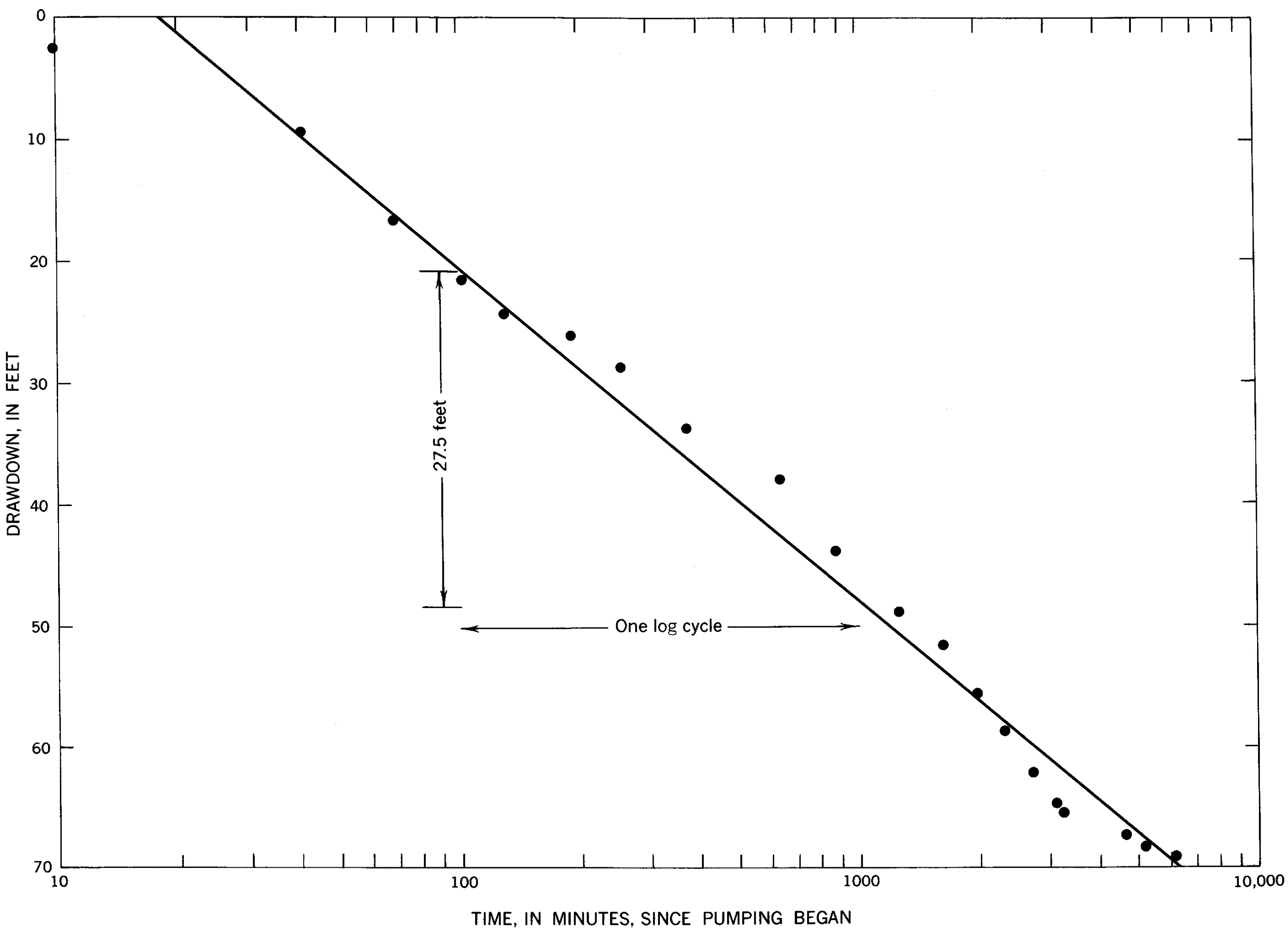
Another possibility of eliminating water flow in mines appears to be the emplacement of a grout sheet or a grout curtain across an area through which the flow passes to the mined area. This procedure probably can be done effectively from the surface through large-size churn-drill holes of 4 to 6 inches in diameter. After the grout has been allowed to set, the effectiveness of the grouting can be determined by drilling a number of small-diameter diamond-drill holes between the large holes. The most likely position for a grout curtain would be across shallow-trough areas, such as are present in the Greenwood-Morgan area, and across the ends of faults that are known to be water conduits. Perhaps the most effective depths would be from 300 to 800 feet. Once the grout curtain has been emplaced, withdrawals of water by wells or drainage tunnels could effectively lower the head on the side of the curtain nearest the mine.

DEEP WELLS

Dewatering by wells is generally effective in areas where the water-bearing rocks are extensively weathered and fractured and large flows may be obtained. In the red-ore district, however, the water problems in the deeper mines are confined to extensively fractured narrow fault zones, which in places are as much as 2,000 feet below the land surface. The use of wells as drainage structures in this district would be practical only in those areas where the water-bearing rocks are extensively fractured and do not exceed about 800 feet in depth.

DRAINAGE DITCHES AND FLUMES

Little use has been made of drainage ditches and flumes as drainage structures in this district. The main uses for these structures are to divert surface flows away from the mine openings or to convey surface water across permeable rocks. Flumes are usually constructed of wood, concrete, or metal and require constant maintenance to keep them from leaking. Drainage ditches



$$T=\frac{264\times400}{27.5}=3{,}840 \text{ gpd per ft}$$

FIGURE 31.—Semilogarithmic graph of time drawdown of water level in diamond-drill hole 186 in Pyne mine.

also usually require some sort of lining to prevent seepage. Long ditches or flumes are costly to construct and maintain.

INFILTRATION GALLERIES

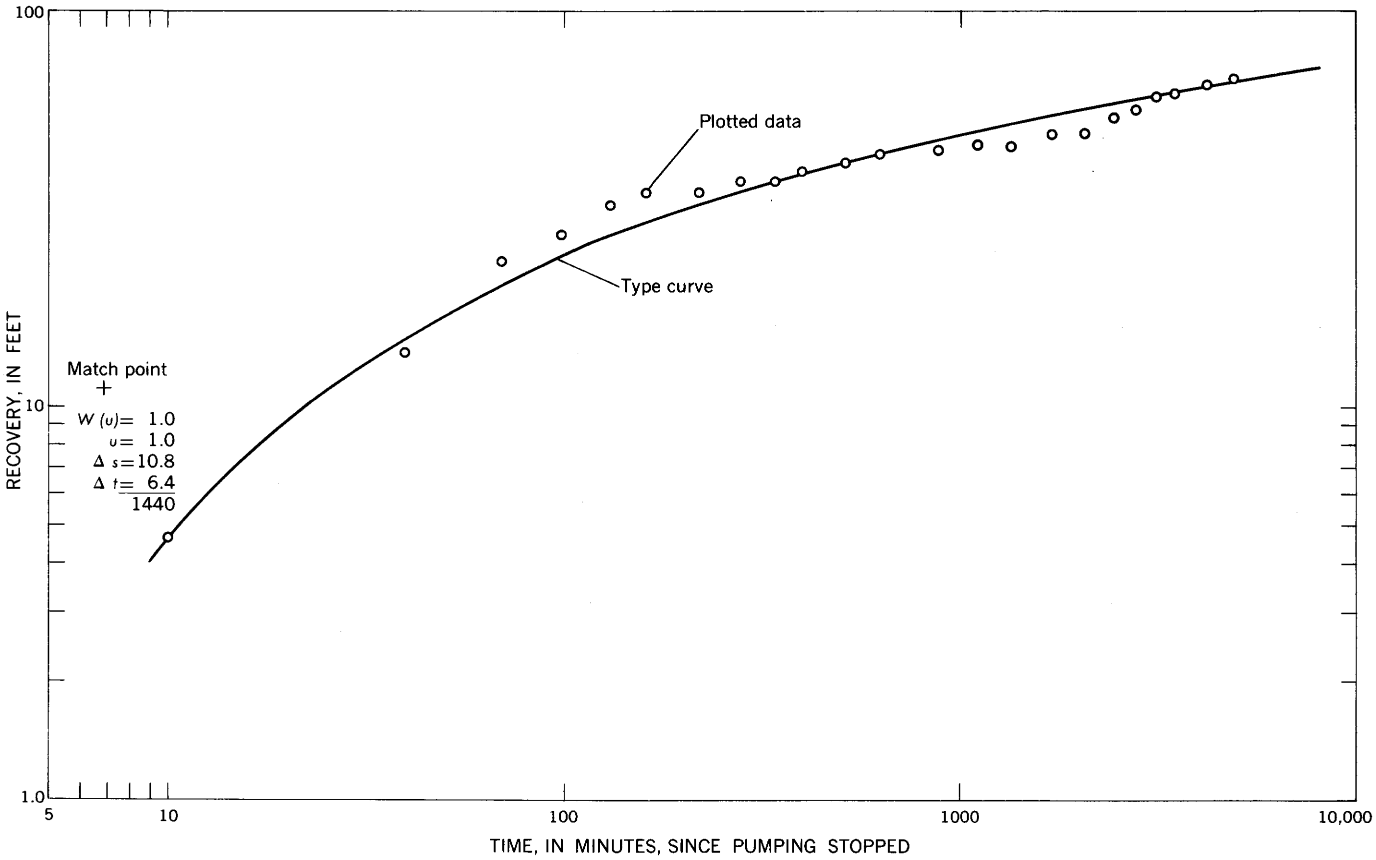
Infiltration galleries have been used successfully as a means of dewatering highly permeable rock near some of the iron-ore mines in northern Michigan (Stuart and others, 1948). Their effectiveness lies in the fact that they intercept the flow from a more complete section of an aquifer, whereas a well can tap only a part of an aquifer and not necessarily the most permeable part.

The infiltration gallery may be an effective method of drainage, but driving a lengthy drift near faulted ground may be very hazardous and costly. As an alternative, a drainage structure is proposed that would perform the function of a well, in that the structure would withdraw from a point source. This type of structure is termed a "water-interceptor drift."

WATER-INTERCEPTOR DRIFTS

The use of water-interceptor drifts is suggested as a means of dewatering or controlling the inflow of deeply circulating water in extensively faulted and fractured rocks in the red-iron-ore district, particularly along the Shannon fault (fig. 35). The drift as a number of advantages over the previously discussed drainage-type structures. It would take less time to develop and be less expensive than the other type structures, and it could be located near the section to be mined so as to accomplish complete dewatering.

Prior to installation of an interceptor drift, pressure and flow studies should be made to determine the initial static pressure and the amount of flow in the tap holes. From these data, premilinary drawdown and recovery curves should be plotted and the values of transmissibility and storage computed. The data could then be extrapolated to show what rate of withdrawal and amount of time would be needed to dewater the area.



Computations

$$T=\frac{114.6\times400\times1.0}{10.8}=4,250 \text{ gpd per ft}$$

$$S=\frac{4,250\times1.0\times6.4}{1.87\times(357)^2\times1.440}=0.000079$$

FIGURE 32.—Logarithmic graph of time recovery of water level in diamond-drill hole 186 in Pyne mine.

The installation of an automatic-recording flow meter and pressure gage on the discharge pipe would keep a constant check on the progress of dewatering. The drill holes that had been used in previous observations to determine the T and S values should also be equipped with automatic-recording pressure gages for an additional check on the progress of dewatering.

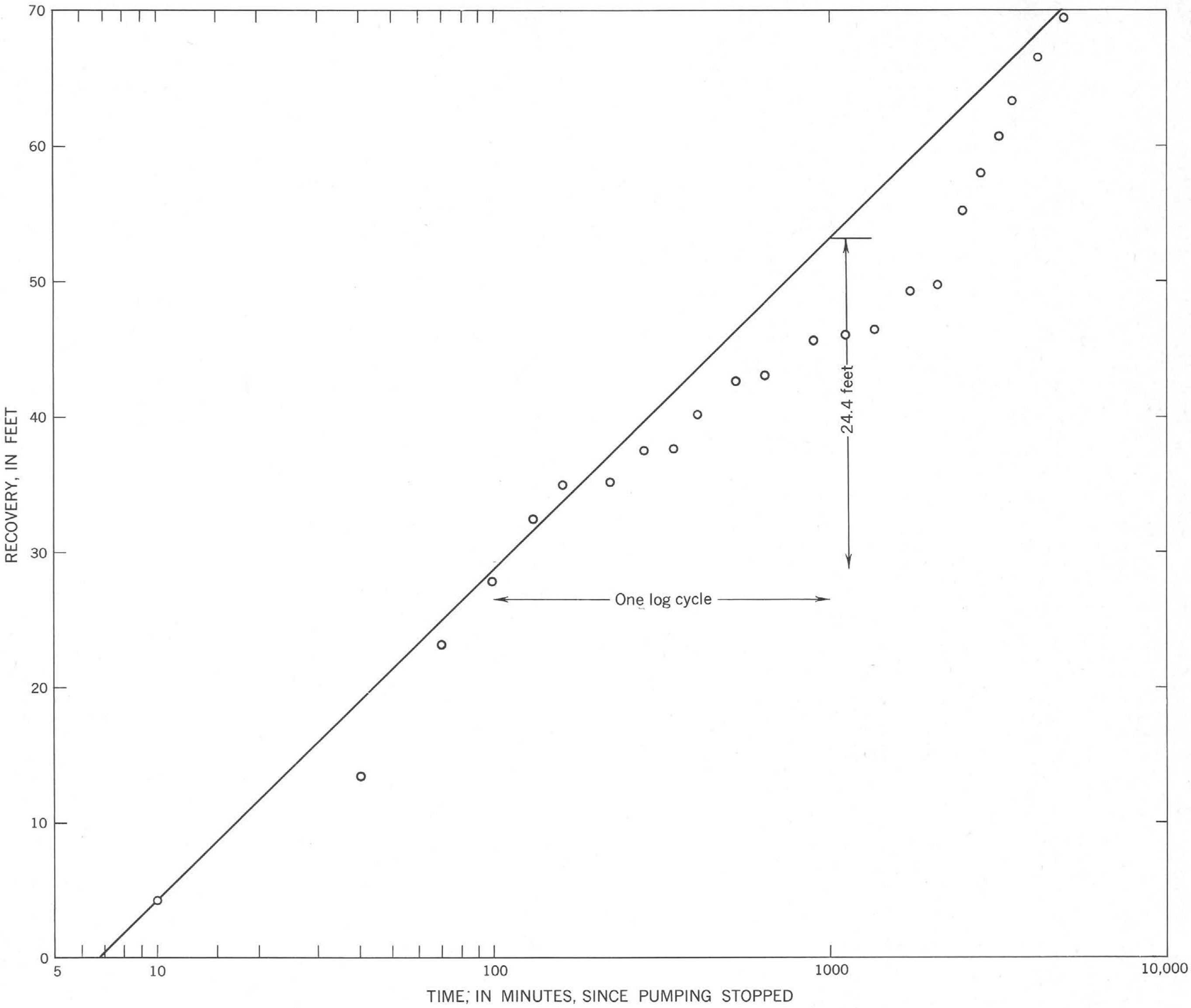
DEWATERING THE SHANNON FAULT

The following discussion describes a method for dewatering the Shannon fault. The necessary assumptions and limitations are presented and explained according to present-day concepts of ground-water hydraulics.

Hydrogeologic data collected from field tests and observation indicate that ground-water inflow into the Pyne mine is from an extensive system of interconnected fractures associated with the main fault of the Shannon fault system. The water in this fracture system is confined by overlying shale formations above the shear zone and is recharged by open-fracture systems and tubular openings at the ends.

The problem is to dewater completely this water-bearing zone so that mining operations can proceed without being hampered by hazardous water conditions. Dewatering will also alleviate the problem of leaving a thick barrier pillar against the water-bearing zones. The volume of ore left in such a barrier pillar along the Shannon fault is approximately 12 million long tons of iron ore.

Although some of the hydrogeologic factors have been determined, a number of basic assumptions still have to be considered before a method of dewatering is developed. The pumping test made on diamond-drill hole 186 indicated that the coefficient of transmissibility of the rocks adjacent to the water-bearing fault in the east workings would be about 4,000 gpd per foot and the coefficient of storage would be about 0.0001. Because the determined value for the transmissibility was for a branch of the main fault, it seems reasonable to



$$T = \frac{264 \times 400}{24.4} = 4{,}330 \text{ gpd per ft}$$

FIGURE 33.—Semilogarithmic graph of time recovery of water level in diamond-drill hole 186 in Pyne mine.

assign a value of at least 10,000 gpd per foot for the main fault. The coefficient of storage will approach the specific yield of the formation if the fault zone is completely drained. Muskat (1949, p. 172–173) gave values of porosities and permeabilities for about 1,200 dolomitic limestone specimens. On the basis of this value, an average porosity of about 12 percent was picked as representative of the porosity for the fault zone. The value of specific yield will be slightly lower because of water retained in the pore spaces of the rock by capillary and molecular forces; 0.10 is therefore assumed as the value for S in the calculations.

The shape of the zone to be dewatered is assumed to be a rectangular prism or trench about 200 feet wide, 300 feet deep, and 43,000 feet long. Water will flow to this trench along the top from both sides and from the ends of the prism.

The trench will be drained by a water-interceptor drift or drifts near the center on the downthrown side of the fault about 2,000 feet below the land surface.

Because of the lack of data and the necessity of assigning many unknown variables, three possible cases are described and the merit and feasibility of each are discussed.

FIGURE 34.—Concrete and steel bulkhead emplaced in Pyne mine to prevent the spread of floodwater. Photograph courtesy of Woodward Iron Co.

CASE 1A

Flow to the fault zone in this case is considered to be across the sides and ends into the rectangular prism or trench. The trench is assumed to be of sufficient size to accept all water that the overlying formations are capable of transmitting. The vertical permeability is equal to the horizontal permeability, and the flow to the trench will therefore be almost linear but perpendicular to it.

The total transmissibility of the different formations overlying the trench is about 10,500 gpd per foot. (See p. C33.) The coefficient of storage is assumed to be about 0.10, as previously stated. The thickness of the formation to be dewatered is about 2,000 feet. The factors in standard units of nomenclature previously described for the drain formulas are given as follows:

T=10,500 gpd per ft	x=100 feet
S=0.10	W=200 feet
s=2,000 feet	t=100, 500, 1,000 days

To determine the amount of water available from the overlying formations which will flow to the trench, the equation for flow conditions near a linear opening is applied as follows:

$$s=\frac{Qx}{2T}D(u). \qquad (2)$$

Where $D(u)$ is read "drain function of u" and

$$u=1.3675x\sqrt{\frac{S}{Tt}}, \qquad (2a)$$

equation 2 is rewritten

$$Q=\frac{2Ts}{xD(u)}. \qquad (2b)$$

Substituting in equation 2*a* and performing the indicated operation gives:

where t is 100 days, u=0.0422;
where t is 500 days, u=0.0189;
where t is 1,000 days, u=0.0134.

From a published table (Ferris, 1950), the values of $D(u)$ corresponding to the u values are found to be:

u	$D(u)$
0.0422	12.25
.0189	29.00
.0134	42.20

Substituting in equation 2*b* and performing the indicated operations, the flow is calculated to be:

for 100 days, Q=1,023,000 gpm;
for 500 days, Q=432,000 gpm;
for 1,000 days, Q=297,000 gpm.

The preceding values for Q, in gallons per minute, at 100, 500, and 1,000 days, neglected the flow into the ends of the trench. This can be calculated by using the equation for flow near circular openings because the flow is assumed to be radial—that is, the flow pattern will converge to the point of withdrawal.

Assuming the same values for T, S, and t as stated previously but using a radius (r=100 feet) for a circular well, the equation is:

$$s=\frac{114.6QW(u)}{T} \qquad (1)$$

where

$$u=\frac{1.87r^2S}{Tt} \qquad (2)$$

Substituting in equation 2 and performing the indicated operation gives:

where t is 100 days, u=0.00178;
where t is 500 days, u=0.000356;
where t is 1,000 days, u=0.000178.

Referring to a published table (Wenzel, 1942), values of u give the corresponding values of $W(u)$:

u	$W(u)$
0.00178	5.7560
0.000356	7.3639
0.000178	8.0569

Substituting in equation 1 and performing the indicated operations for Q, the computation indicates the flow to be:

for 100 days, Q=32,000 gpm;
for 500 days, Q=25,000 gpm;
for 1,000 days, Q=23,000 gpm.

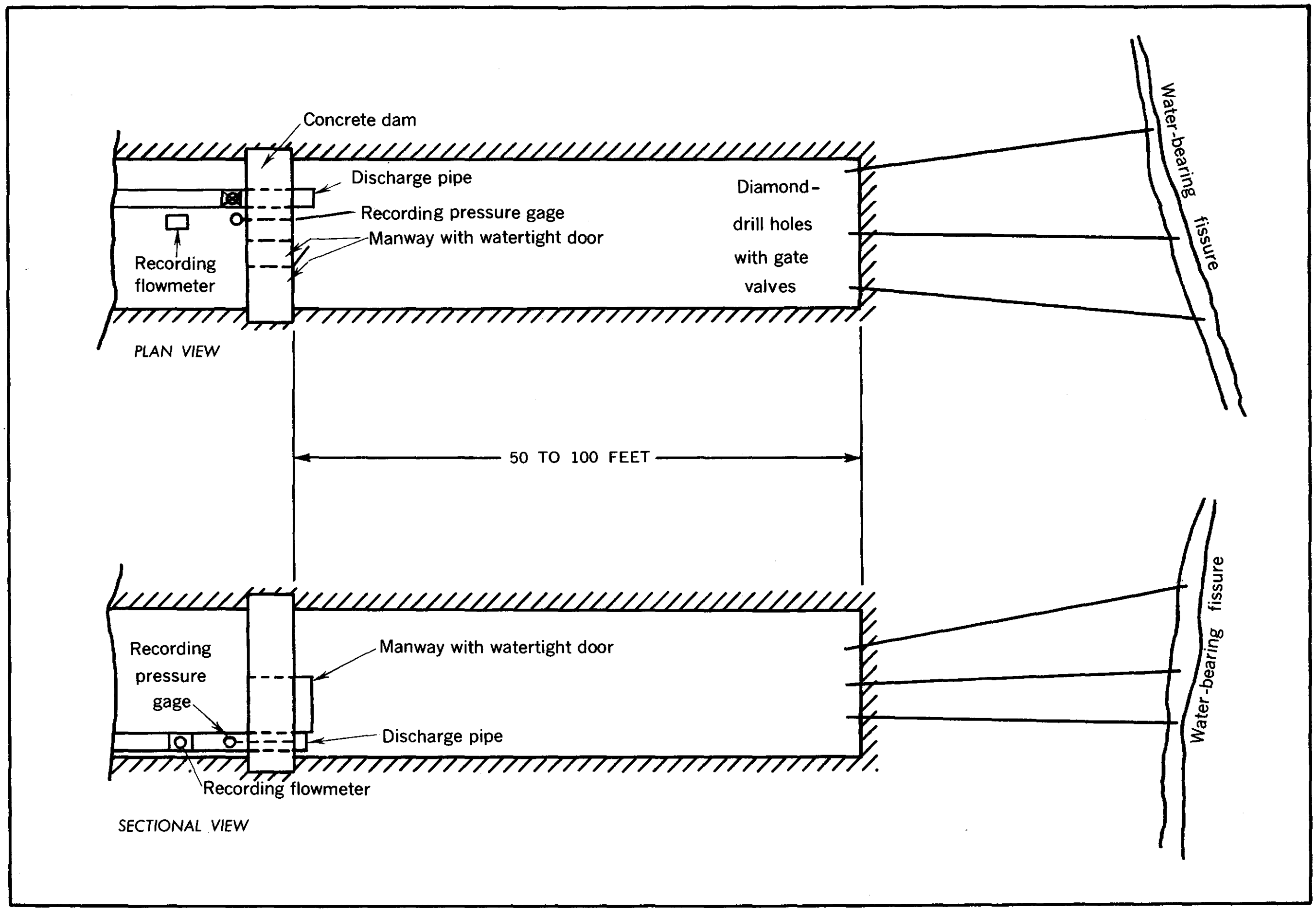


FIGURE 35.—Proposed water-interceptor drift.

If the flow from the sides and ends of the trench is added, the average rate of withdrawal for the indicated time periods is:

for 100 days, $Q=1{,}055{,}000$ gpm;
for 500 days, $Q=457{,}000$ gpm;
for 1,000 days, $Q=320{,}000$ gpm.

CASE 1*B*

As the fault zone becomes dewatered, a new equilibrium condition appears owing to the decline in pressure head, and T decreases correspondingly. The time when this decrease occurs is unknown and present-day formulas and methods cannot cope with more than one variable. In order to compensate for this change, case 1*A* becomes 1*B* and a new value of T is introduced. All previous data remain the same but T is assumed now to be 5,000 gpd per foot.

Flow from the sides of the trench under this new condition is calculated to be:

for 100 days, $Q=721{,}000$ gpm;
for 500 days, $Q=297{,}000$ gpm;
for 1,000 days, $Q=205{,}000$ gpm.

For the ends of the trench, the flow is calculated to be:

for 100 days, $Q=17{,}000$ gpm;
for 500 days, $Q=13{,}000$ gpm;
for 1,000 days, $Q=12{,}000$ gpm.

The total flow to the trench from the sides and ends will then be equal to:

for 100 days, $Q=738{,}000$ gpm.
for 500 days, $Q=310{,}000$ gpm;
for 1,000 days, $Q=217{,}000$ gpm.

CASE 1*C*

As dewatering continues, T will decrease even further and a new value of T becomes necessary. T is now assumed to be 1,000 gpd per foot.

Using the same data as for the two previous phases of case 1 under the new condition that $T=1{,}000$ gpd per foot, flow from the sides of the trench is calculated to be:

for 100 days, $Q=372{,}000$ gpm;
for 500 days, $Q=144{,}000$ gpm;
for 1,000 days, $Q=98{,}000$ gpm.

For the ends of the trench, the flow is calculated to be:

for 100 days, Q=5,000 gpm;
for 500 days, Q=3,000 gpm;
for 1,000 days, Q=3,000 gpm.

The total flow to the trench from the sides and ends will then be equal to:

for 100 days, Q=377,000 gpm;
for 500 days, Q=147,000 gpm;
for 1,000 days, Q=101,000 gpm.

The value of T will decrease even further, but at what time and to what extent it will decrease is not known nor can it be computed.

CASE 2

The flow in the fault zone is now considered under a different set of conditions. In case 1 the flow was assumed to be derived from the rocks at the sides and ends of the fault; in case 2 it is assumed that the sides do not contribute flow because impermeable beds are displaced opposite permeable beds and the fault is sealed to vertical flow from the sides. In case 2 the flow is at right angles to the flow considered in case 1 and involves dewatering a zone 200 feet wide between impermeable beds in the fault that is 43,000 feet long. The drainage structure is at the midpoint between the ends of the fault and, although there are impermeable beds above, the drawdown is assumed to be 2,000 feet, which is the distance the drainage structure lies below the water table in the surrounding rocks.

The value of T is assumed to be 10,000 gpd per foot; S, 0.10; x, 1 foot; and drawdown (s), 2,000 feet; time (t) interval the same as used previously (100, 500, 1,000 days).

Substituting these values in the equation for flow to a linear opening gives the following results for each foot of width:

	u	D(u)	Q, *in gpd per ft*
for 100 days	0.000434	1,290	31,000
for 500 days	0.000194	2,940	14,000
for 1,000 days	0.000137	4,150	10,000

The flow for the 200-foot width of the fault zone is calculated, in gallons per minute, to be:

for 100 days, Q=4,300 gpm;
for 500 days, Q=1,950 gpm;
for 1,000 days, Q=1,390 gpm.

The preceding calculations neglect any recharge from the top and ends to the fault zone, a source not prevalent under these conditions.

In cases 1 and 2, flow from the bottom which has not been considered in the calculations, should affect the flow by increasing the amount of water to accomplish the same amount of drawdown over the same interval of time. However, this condition is not included in the calculations because the field data were not sufficient to indicate that this would occur.

There is little doubt that withdrawal of water from the fault zone would induce infiltration from the sides and top of the dewatered zone. Some drainage by transfer of water from one formation to another, caused by the difference in head, would most likely occur, but the amount would be difficult or impossible to determine even with more refined data.

CASE 3

Case 3 considers an alternate method of computation for dewatering the fault zone based strictly on the extensions of the Pyne mine pumping-test data. The method involves extending the drawdown and recovery of water levels during the controlled test to other drawdown or recoveries on the assumption that they are directly proportional to a second rate of pumping. In this method, it is necessary to assume that the hydrogeologic factors remain constant throughout the water-bearing zone during the period of drawdown or recovery. Figure 36 is a time-drawdown graph for the actual pumping rate of 400 gpm and a convenient calculated rate of 1,000 gpm at the point of withdrawal. The graph shows that pumping at the rate of 400 gpm will lower the water level about 133 feet in 1,000 days. However, this rate is not rapid enough to be economical to mining operations. Increasing the rate to 1,000 gpm shows a lowering of 333 feet in 1,000 days, 312 feet in 500 days, and 266 feet in 100 days. If it is desired to lower the pressure head 2,000 feet in the fault zone in 100 days, the pumping rate must be increased by 2,000:266, or 7.5 times, to dewater the area in 100 days. Similarly the rate must be increased by 2,000:312, or 6.33 times, for 500 days, and by 2,000:333, or 6.0 times, for 1,000 days. The drawdowns in figure 36 are each for the rate of 1,000 gpm; the increased rates of pumping to accomplish the dewatering in 100 days, 500 days, and 1,000 days would be 7,500 gpm, 6,330 gpm, and 6,000 gpm, respectively.

DISCUSSION OF CASES

In considering all the cases previously mentioned, it must be remembered that the formulas presently in use apply to linear flow and that their application generally pertains to fairly flat gradients met in normal ground-water studies. The application of these formulas to mining-hydrology problems has only been tried since the early fifties. Their successful application to problems involving the dewatering of ore bodies lies in the ability to foresee and predict changes in the hydro-

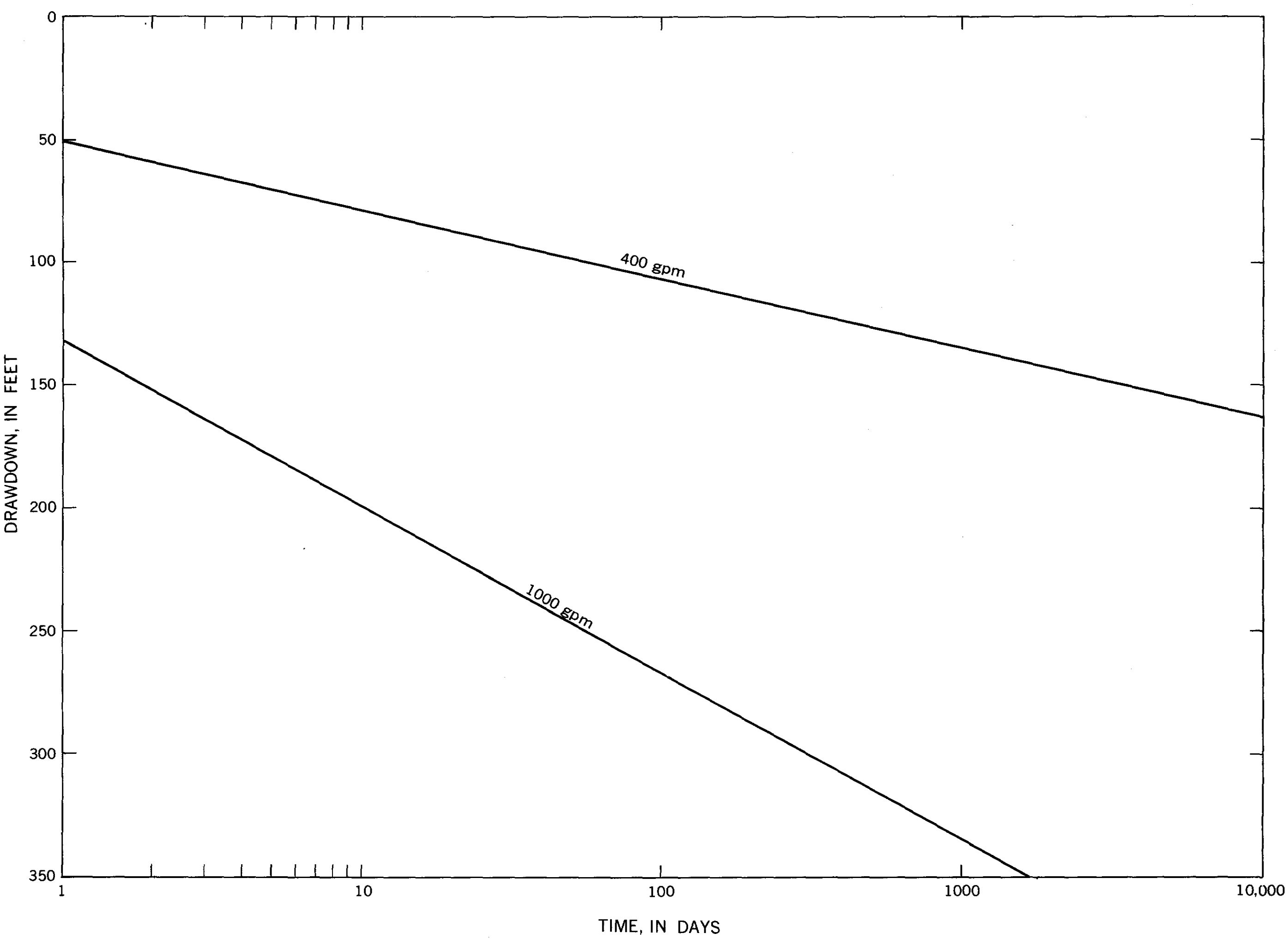


FIGURE 36.—Time drawdown of water level in diamond-drill hole 186 in Pyne mine.

geologic conditions which would tend to affect the regimen of flow. The necessary prerequisites, then, are a detailed knowledge of the geology and hydrology within the mining district. By their very nature, dewatering problems involve complex geologic block drainage with steep hydraulic gradients and, very likely, high velocities of flow through solution tubes or open fractures, which would tend to invalidate most of the assumptions given for their use.

For case 1, the shape of the rock formation overlying the trench which contributed water to the Shannon fault zone was assumed to be a distorted wedge. The line of outcrop of the Red Mountain Formation along Red Mountain is of zero thickness, and the southwestern edge is a triangle that ranges from 0 to 300 feet in thickness. The southeastern edge is a prism that ranges from 300 to 3,000 feet in thickness, and the northeastern edge is a triangle that ranges from 0 to 3,000 feet in thickness. The measured surface area represented by the wedge is about 33 square miles or 21,120 acres. Using an average thickness of 825 feet for the wedge and assuming a specific yield of 0.10 give 1,742,000 acre-feet of water, or 568 billion gallons, in storage. Converting this figure to gallons per minute over a 1,000-day pumping period gives 407,000 gpm of water to be pumped from storage. In addition, the water added from seasonal recharge would have to be pumped also. This calculated volume of water in storage and an unknown quantity for recharge appear to be excessive in terms of dewatering the fault zone. However, it is believed that the dewatering will not drain the overlying formations completely and that leakage within formations from induced infiltrations will be minor.

The calculations for case 1, are based on the assumption that the fault zone is capable of receiving water from all the overlying formations. This condition would be applicable for the first short period of pumping, but as drainage progresses the formations would be dewatered and the transmissibility would become smaller. As the transmissibility decreases, the flow to the mine opening decreases; for example, during the 1,000-day period of dewatering when the transmissibility decreases from 10,500 to 5,000 and to 1,000, the flow decreases from 321,000 gpm to 217,000 gpm and to 101,000 gpm, respectively. This decrease in transmissibility is to be expected, but our present methods of calculations do not permit the determination of the rate of decrease of the transmissibility with time. As the drawdown increases, the transmissibility decreases in proportion to the rate at which the formations are dewatered. The calculations were made for three conditions that were considered to be possible for the area, and the flows were determined for these conditions. It is not known if these assumptions are representative for any period of time, but the highest values used are believed to be similar to the conditions during early pumping. The lower values of flow are for later times when the area becomes completely dewatered and the flow into the fault zone approaches the average rate of recharge to the zone.

Another factor which limits the flow of water through the formations has not been discussed in this computation; it is the boundary conditions caused by the drainage of the fault blocks in the formations adjacent to the Shannon fault.

The southeasterly dipping formations are not continuous and are greatly disturbed by the faults that cross the district. As a result, the permeability of the formations ranges from one extreme to the other. The faults usually would act as barriers to the flow of water across them; hence, the volume of water to be pumped from them is limited to the recharge and the amount of storage.

The Songo mine area, for example, was dewatered after a rockfall which produced an inflow of about 2.5 billion gallons of water. The water levels in several test wells, which were bored on the surface and cased off in the formations immediately overlying the mine, were observed for a period of about 1 year. These wells showed that the formations overlying the Fort Payne Chert and limestone unit of Warsaw age all contained water at a level which responded rapidly to seasonal variations in rainfall, barometric effects, and evapotranspiration conditions. Therefore, even with leakage from these aquifers into the mines below, the formations were still saturated and were not dewatered.

For case 2, it was assumed that the fault zone was sealed along both sides and that no vertical recharge could occur through the top of the fault zone, although recharge would occur at the ends. Case 2 showed a much lower volume to be pumped than did case 1*A*, *B*, and *C*. However, vertical recharge likely would occur, owing to the saturated formations overlying the fault zone.

Case 3 assumes that the test conducted on diamond-drill hole 186 met the requirements of the equation for flow to a circular opening in that the drawdowns occurring at a point are proportional to the rates of withdrawals of water. The values calculated for the expected flow to the drainage structure were slightly higher than those calculated in case 2 but much lower than those of case 1.

Because case 3 is based on extensions of observed data without calculations involving transmissibility and storage considerations, this case may be the most applicable and feasible approach to dewatering the fault zone, but the results in cases 1 and 2 may offer some clue as to the maximum and minimum amounts of water to be expected in dewatering.

As previously stated, however, none of the methods include an indeterminate flow of water from the bottom of the trench.

PILOT STUDY

Before a detailed plan of dewatering can be considered, more data on the hydrogeologic conditions in and adjacent to the Shannon fault zone must be obtained. To get these data, it is suggested that more complete testing be done, by the procedures applied at drill hole 186 in Pyne mine—namely, that of a small-scale dewatering or pilot study using larger rates of withdrawal and observing the progressive dewatering of the fault zone.

The suggested pilot study for the district should begin in Pyne mine where mine headings are near the Shannon fault system. Diamond-drill holes should be spaced along the entire length of the fault where it has been revealed by headings. The holes to be tested should be in areas where the joint systems are strongest and along parts of the fault zone that show a curved surface facing generally northeast. Additional pumping tests should be made and extended over longer periods of time; in fact, some of the pumping tests should be for a period of 90 to 180 days.

To determine the rate of dewatering in the formations near the surface, observation wells should be so located on the surface overlying the discharge points underground that any effects from the underground pumping can be detected and noted. Some of the wells should be at least 800–1,000 feet deep so that the effects in the deeper formations can be noted. Pumping tests should be conducted on these surface wells for comparison with the underground-test results.

Other mine operators in the district may have driven headings close enough to the Shannon fault that a similar pilot study could be conducted by them.

The pumping-test analyses should be the same as the nonequilibrium methods used in this report, especially as those used in case 3.

If the data obtained from this pilot study are sufficient to prove the feasibility of dewatering the Shannon fault, then a detailed master plan should be considered and a unit plan of operation compiled.

Until this pilot study is made, the operators in the district should maintain a current file of all hydrologic data obtained from mining operations. Any diamond-drill holes, both surface and underground, should be accurately logged and capped for possible future use.

CONCLUSIONS AND SUMMARY

The investigation clearly indicates that water problems in the mines are of two general types: (1) ground water flowing into the mine openings through broken and caved ground overlying the mine slopes along Red Mountain and (2) ground water flowing into the deeper mines through a system of interconnected fractures associated with the tight folds and faults having large throw. The water in the fracture systems is under high-pressure heads and artesian conditions.

The source of all ground water in the district is from rainfall, influent-stream seepage, and deep-seated inflows from areas adjacent to the area of investigation. Seepage investigations along Shades, Little Shades, and Patton Creeks showed losses of 40 to 2,500 gpm. Shades Creek, the main drainage stream, loses water along its lower reaches near Greenwood where the creek flows across outcrops of the Fort Payne Chert and limestone unit of Warsaw age.

The Red Mountain Formation of Silurian age contains the iron-ore seams and is overlain by about 200 feet of Mississippian formations, the Fort Payne Chert and the limestone unit of Warsaw age. These formations crop out along the southeastern slopes of Red Mountain and have been extensively weathered and fractured. As a result, these formations are capable of storing and transmitting large amounts of ground water. Along the slopes of the mountain a number of mine roofs have collapsed, and large cracks and sinkholes have occurred on the surface because of the age of the workings and lack of adequate support in the upper and middle slopes of the mines. Large inflows of ground water have had access to the mine workings from the saturated formations above because of this subsidence.

Mine floodings and pumpage from the slope mines over the past 50 years have resulted in the nearly complete dewatering of the largest part of the overlying weathered and fractured zones. Small pockets containing as much as 1 to 2 million gallons of water probably remain trapped against impermeable barriers such as faults and the contact between the weathered zone and solid rock. It is doubtful that any sudden inundation capable of large sustained flow will occur in the upper or middle slope mines.

Ground-water problems in the mines along the bottom slopes and underneath deeper cover are attributed to an extensive system of interconnected fractures in the shear zones and splays of major faults. More water-bearing faults and fracture systems probably will be found as the mining progresses to the southeast and under deeper cover.

The investigation has also revealed that the direction of movement of ground water is parallel and subparallel to the structural features, especially where localized stress conditions have caused strong and numerous joint systems. The general direction of movement is northeast and southwest according to the local structure.

The structure contours (pl. 1), drawn on the base of the Fort Payne, show several structural basins that may be reservoirs for ground water. One underlies nearly all of sec. 27, T. 19 S., R. 4 W. Another underlies parts of secs. 11, 12, 13, and 14, T. 19 S., R. 4 W. This area may have been drained by previous breakthroughs in the Muscoda, Sloss, and Red Ore mines, but it warrants some additional investigation to determine its hydrologic potential.

The largest area which may present a serious water problem is the low point of the structure that lies between the Shannon and Patton faults and northeast of the Dickey Springs anticline. At the level of the mine workings, water pressures as high as, 1,000 psi and large flows may be present in this area.

The transmissibility of the formation overlying the ore mines has been determined from pumping tests on three municipal and domestic wells and five flowing diamond-drill holes. The transmissibility of the shale and sandstone units in the Floyd Shale and the Parkwood and Pottsville Formations is low, ranging from 50 to 4,000 gpd per foot, whereas the transmissibility of the Fort Payne Chert and limestone unit of Warsaw age was determined to be 6,000 gpd per foot. The transmissibilities for three of the flowing diamond-drill holes were determined to be considerably higher than usual for shale and sandstone units in the Floyd, Parkwood, and Pottsville. For example, W–12, U–2, and W–34 showed transmissibilities of 1,000, 2,000, and 4,000 gpd per foot, respectively, which are due to extensive fracture systems adjacent to fault zones that were penetrated by the drill holes.

From the pumping test on diamond-drill hole 186 in Pyne mine, the transmissibility was determined to be about 4,000 gpd per foot and the storage coefficient about 0.0001. These hydraulic factors reflect the conditions of flow in a sympathetic fault of the major Shannon fault.

Generally, ground-water flow under shallow water-table conditions in the district is essentially linear and horizontal. However, flow within the deep fracture zones, especially during dewatering, is a combination of horizontal, vertical, and inclined flow probably having higher velocities than generally realized.

Discussion of three cases under conditions of flow assumed for the dewatering of the Shannon fault zone indicated there are problems that remain to be solved. The methods used in these cases utilize most of the flow equations presently in use. All are based on nonequilibrium conditions and are restrictive because they deal primarily with linear and radial flow, and the assumptions for their use are based on homogeneous and isotropic geologic formations. However, the test in Pyne mine probably was sufficient to extend the observed data and predict possible flow conditions that might be expected in dewatering the Shannon fault. For 100, 500, and 1,000 days the volume of water to be pumped would be: 1,055,000, 475,000, and 320,000 gpm, respectively, for case 1*A*; 738,000, 310,000, and 217,000 gpm for case 1*B*; 372,000, 148,000, and 101,000 gpm for case 1*C*; 4,300, 1,950, and 1,390 gpm for case 2; and 7,500, 6,330, and 6,000 gpm for case 3.

Geochemical studies indicated that the water in the mines is largely the calcium bicarbonate type and has moderate amounts of temporary hardness. No definite correlation of water from the wells, springs, mines, and streams could be made with the rock types.

The suggested pilot-study program should be directed toward supplementing and improving existing data. The detailed quantitative study should include a well-planned test-drilling program in areas of tight folding and faulting, supplemented by adequate observation wells and pumping tests to determine the hydraulic factors of the water-bearing formations.

Should the pilot study show that the Shannon fault can be dewatered, a master unit plan can be prepared and followed which would probably entail the participation of all the companies in the area. It appears likely that the dewatering of the Shannon fault would produce water of adequate quality and sufficient quantity for industrial use.

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