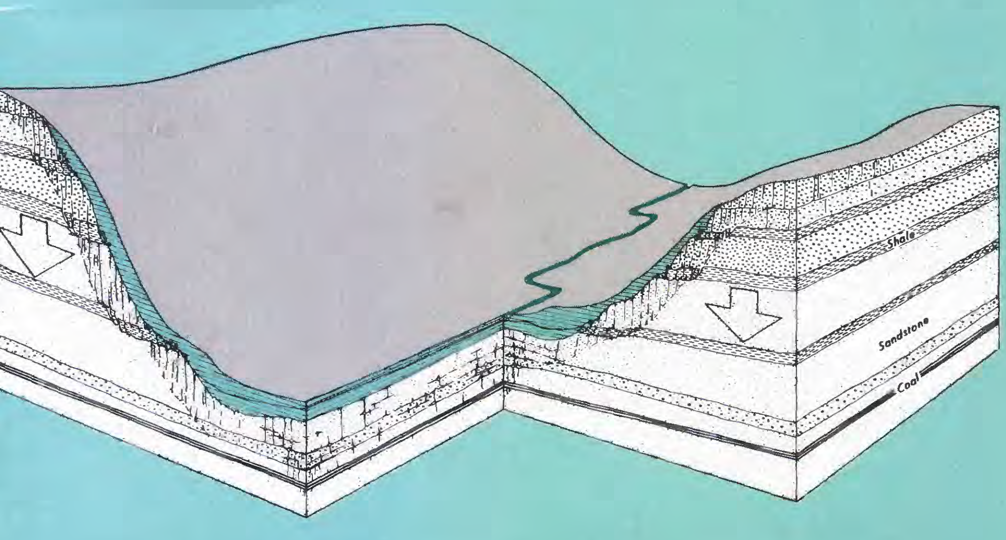
Hydrologic Effects of Stress-Relief Fracturing In an Appalachian Valley



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Hydrologic Effects of Stress-Relief Fracturing In an Appalachian Valley

By GRANVILLE G. WYRICK and JAMES W. BORCHERS

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

The following factors may be used to convert the inch-pound units published herein to the International System of Units (SI):

Multiply inch-pound	By	To obtain SI units
	Length	
inches (in)	25.4	millimeters (mm)
	0.0254	meters (m)
feet (ft)	0.3048	meters (m)
miles (mi)	1.609	kilometers (km)
	Area	
square miles (mi^2)	2.590	square kilometers (km^2)
	Volume	
gallons (gal)	3.785	liters (L)
	3.785	cubic decimeters (dm^3)
	3.785×10^{-3}	cubic meters (m^3)
million gallons (10^6 gal)	3785	cubic meters (m^3)
	3.785×10^{-3}	cubic hectometers (hm^3)
cubic feet (ft^3)	28.32	cubic decimeters (dm^3)
	0.02832	cubic meters (m^3)
	Flow	
cubic feet per second (ft^3/s)	28.32	*liters per second (L/s)
	28.32	cubic decimeters per second (dm^3/s)
	0.02832	cubic meters per second (m^3/s)
gallons per minute (gal/min)	0.06309	liters per second (L/s)
	0.06309	cubic decimeters per second (dm^3/s)
	6.309×10^{-5}	cubic meters per second (m^3/s)
million gallons per day (10^6 gal/d)	43.81	cubic decimeters per second (dm^3/s)
	0.04381	cubic meters per second (m^3/s)

*The unit liter is accepted for use with the International System (SI). See NBS Special Bulletin 330, p. 13, 1977 edition.

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HYDROLOGIC EFFECTS OF STRESS-RELIEF FRACTURING IN AN APPALACHIAN VALLEY

By G.G. Wyrick and J.W. Borchers

ABSTRACT

A hydrologic study at Twin Falls State Park, Wyoming County, West Virginia, was made to determine how fracture systems affect the occurrence and movement of ground water in a typical valley of the Appalachian Plateaus Physiographic Province. Twin Falls was selected because it is generally unaffected by factors that would complicate an analysis of the data. The study area was the Black Fork Valley at Twin Falls. The valley is about 3 miles long and 400 to 600 feet wide and is cut into massive sandstone units interbedded with thin coal and shale beds. The study was made to determine how aquifer characteristics were related to fracture systems in this valley, so that the relation could be applied to studies of other valleys.

Two sites were selected for test drilling, pumping tests, and geophysical studies. One site is in the upper part of the valley, and the second is near the lower central part. At both sites, ground water occurs mainly in horizontal bedding-plane fractures under the valley floor and in nearly vertical and horizontal slump fractures along the valley wall. The aquifer is under confined conditions under the valley floor and unconfined conditions along the valley wall. The fractures pinch out under the valley walls, which form impermeable barriers. Tests of wells near the valley center indicated a change in storage coefficient as the cone of depression caused by pumping reached the confined-unconfined boundaries; the tests also indicated barrier-image effects when the cone reached the impermeable boundaries. Drawdown from pumping near the center of the valley affected water levels at both sites, indicating a hydraulic connection from the upper to the lower end of the valley. Stream gain-and-loss studies show that ground water discharges to the stream from horizontal fractures beneath Black Fork Falls, near the mouth of Black Fork. The fracture systems that consititute most of the transmissive part of the aquifer at Twin Falls are like those described as being formed from stress relief. As stress-relief fractures have been described in other valleys of the Appalachian Plateaus, the same aquifer conditions may exist in those valleys.

1.0 INTRODUCTION

The Investigations at Twin Falls State Park Provide Better Understanding of Ground-Water Occurrence and Movement

The investigations at Twin Falls State Park in Wyoming County, W.Va., provided a better understanding of the occurrence and movement of ground water in the valleys of the Appalachian Plateaus. Originally, the investigative method consisted of drilling three test wells and making a pumping test at Test Site 1 (fig. 1.0-1) as part of the Guyandotte basin study; later, however, other methods were used, including additional drilling and testing, geophysical investigations, and gain-and-loss studies, all of which aided in providing a better understanding of the ground-water hydrology.

The investigations at Twin Falls State Park, Wyoming County, W. Va., were undertaken in an effort to improve the knowledge of the occurrence and movement of ground water in valleys of the Appalachian Plateaus. Analysis of pumping-test data from many studies in the past had not been satisfactory because of a lack of understanding of how fracture systems affect ground-water hydrology; as a part of the Guyandotte basin study, therefore, it was determined that pumping tests in a small valley in the Appalachian Plateaus would be tightly controlled.

Three test wells were drilled at Test Site 1 (fig. 1.0-1), as a part of the Guyandotte basin study, by the U.S. Geological Survey in cooperation with the West Virginia Geological and Economic Survey. Upon completion of the Guyandotte basin study, the remainder of the study at Twin Falls State Park was done as a part of a Federally funded research project on mine hydrology by the U.S. Geological Survey.

Methods of study originally included only the drilling of observation wells and aquifer testing at Site 1. As a better understanding of the ground-water hydrology developed, however, more holes were drilled and tested, along with geophysical testing and stream gain-and-loss studies. All aided in a better understanding of the hydrology of the valley.

The organizational system used in the preparation of this report is known as **STOP** (an acronym for Sequential Thematic Organization of Publications). The STOP technique was adapted from industrial publications for use in earth-science publications by the West Virginia Geological and Economic Survey in 1973. For more information, contact the West Virginia Geological and Economic Survey, P.O. Box 879, Morgantown, West Virginia 26505, for the reprint titled "STOP: A path to more useful Earth science reports," by James A. Carte and Ronald A. Landers.

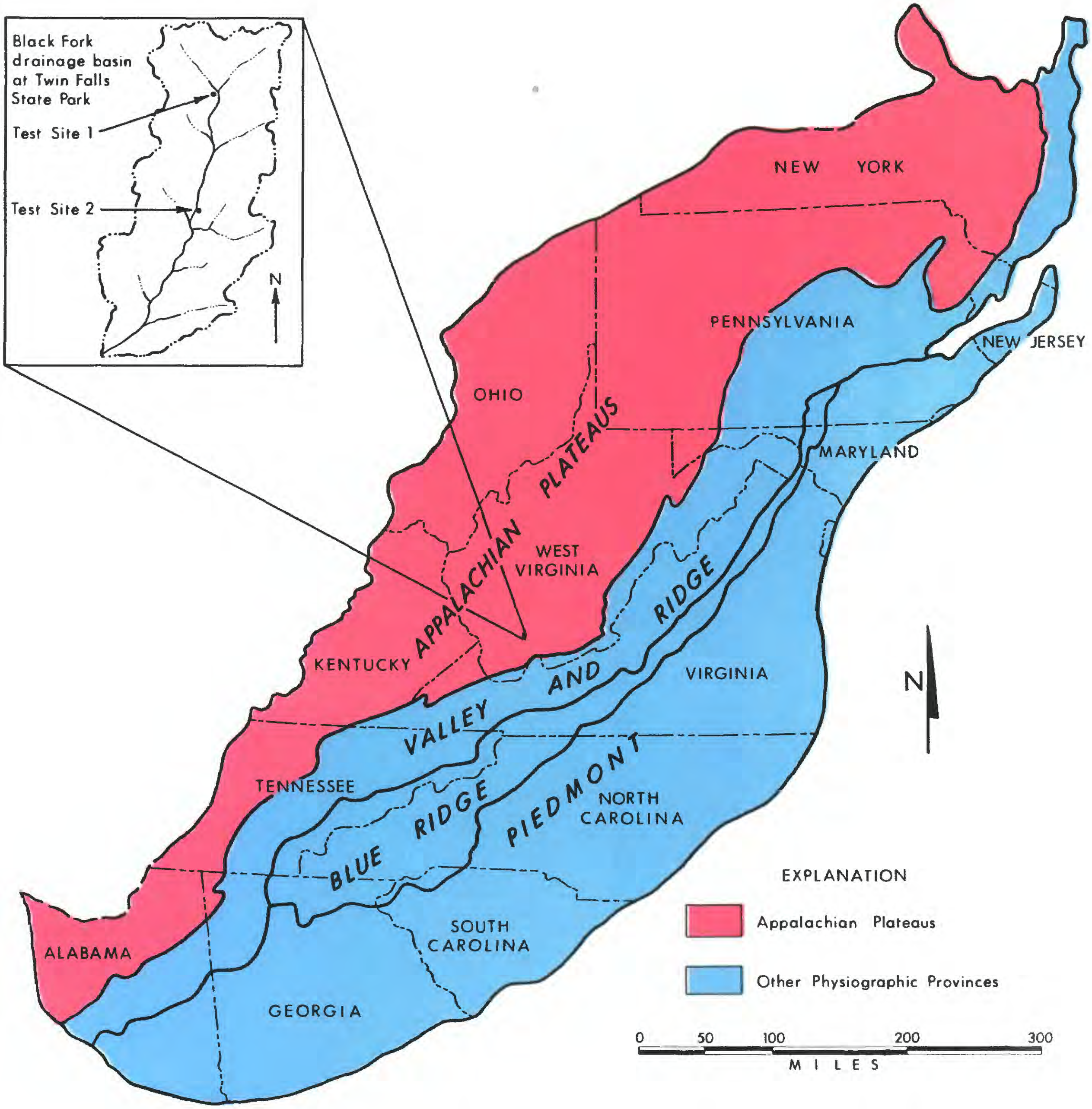

Figure 1.0-1. Appalachian Plateaus and study area at Twin Falls State Park

2.0 CONCLUSIONS AND APPLICATIONS

Stress-Relief Fractures Are Most Transmissive Part of Aquifer and Affect Surface-Water Hydrology of a Valley in Appalachian Plateaus

Stress-relief fractures constitute the most transmissive part of the aquifer and affect the surface-water hydrology of a valley in the Appalachian Plateaus. The predictable pattern of fractures and the associated hydrologic effects resulting from stress relief may have wide transfer value in interpreting the hydrology of other, similar valleys. Applications of the hydrologic effects of stress-relief fracturing may prove useful in developing ground-water supplies, in monitoring the hydrologic effects of surface and deep mining, and in understanding relations between surface water and ground water in small valleys.

The stress-relief fractures at Twin Falls constitute the most transmissive part of the aquifer shown as the blue area on figure 2.0-1. This area is underlain by horizontal fractures under the valley floor and slump fractures along the valley walls. The fractures are interconnected at the base of the valley walls. The aquifer is recharged along the valley walls, where the aquifer is unconfined and where fractures may intercept surface runoff. The aquifer is discharged where the fracture system crops out in the stream channel at the change in stream gradient below Black Fork Falls. Because of the ground-water discharge below the falls, the streamflow characteristics above and below the falls are quite different.

The transfer value of the interpretations in this report can be tested by investigating other valleys. Engineering reports have described stress-relief fracturing in valleys in the Appalachian Plateaus and elsewhere in the United States and foreign countries. Also, study of hydrologically more complicated valleys—valleys affected by deep mining beneath them or by fractures associated with anticlines, synclines, and regional fracture systems—could refine the interpretations in this report. The concept of stress-relief fracturing may be used to interpret the aquifer characteristics in many valleys.

Some applications of knowing the the hydrologic effects of stress-relief fracturing are:

- Better well sites can be selected if fracture patterns resulting from stress relief are understood.

- Dispersion of contaminants from landfills, injection wells, septic tanks, and the like into aquifers might be better understood and monitored by knowledge of the hydrology of stress-relief fractures.

- Water losses from reservoirs and seepage under locks and dams may be understood and explained, in some places, by interpreting the hydrologic effects of stress-relief fractures.

- Inflow to deep mines underlying valleys may be estimated by testing overlying aquifers affected by stress-relief fractures.

- Strip-mine benches in the Appalachian Plateaus are cut through the slump-fracture zone along valley walls, which can affect hydrology significantly. First, aquifer recharge may be increased in several ways during mining by uncovering slump fractures, so that they intercept more surface runoff. The strip-mine bench may be so sloped that it retains more runoff water, facilitating aquifer recharge. Second, reclamation regulations require backfilling benches. Such backfilling can seal slump fractures and reduce aquifer recharge if impermeable fill material is used. Third, exposing rocks to weathering and solution on the strip-mine bench can change the chemical quality of aquifer recharge markedly. As these effects must all be monitored, an understanding of stress-relief fracturing can help in designing monitoring systems.

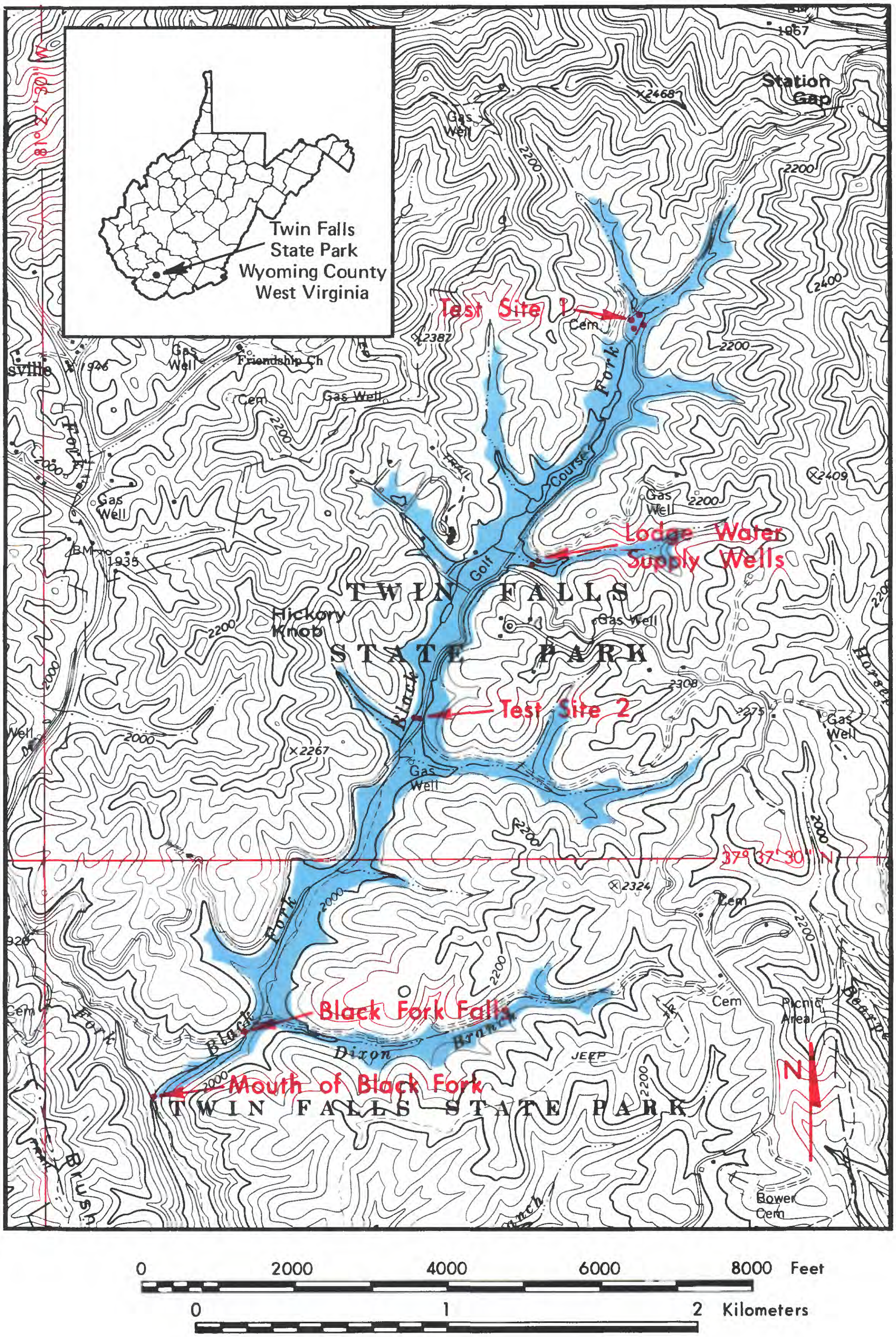

Figure 2.0-1. Topographic map showing the aquifer at Twin Falls State Park

3.0 PERMEABILITY AND STRESS RELIEF

3.1 Primary and Secondary Permeability

Secondary Permeability Generally More Significant Than Primary Permeability in Aquifers of Appalachian Plateaus

Permeability is a measure of the ease with which a liquid will move through a rock. Primary permeability refers to movement through intergranular pore spaces, and secondary permeability refers to movement through rock fractures. Intergranular pore spaces in rocks in the Appalachian Plateaus are generally filled with cementing material, and the rocks have been fractured by earth movement; therefore, secondary permeability is generally more significant to the occurrence and movement of ground water in the plateaus than primary permeability.

Sedimentary materials–such as sand, silt, clay, and organic material–are generally deposited as individual particles in layers. These layers, or beds, may be covered by subsequent beds that compact them. Permeability in bedded material is a measure of the ease with which a liquid will move through intergranular pore spaces and their interconnections. Unconsolidated rocks will generally flex without fracturing; consequently, their only permeability is primary permeability.

Water infiltrating unconsolidated rocks may deposit cementing materials in pore spaces and their interconnections. Deposited material, such as carbonate or silicate, in unconsolidated rocks reduces the intergranular pore space and their interconnections and causes the rocks to consolidate, making them more brittle and subject to fracturing. Fracturing, in turn, causes openings in the rocks through which a liquid may move. This type of permeability is referred to as secondary permeability. The features of both primary and secondary permeability are shown in figure 3.1-1.

Rocks may have both primary and secondary permeability in varying degrees. Surficial rocks in the Appalachian Plateaus seem to have low primary permeability and much higher secondary permeability. Generally, wells that do not penetrate fractures will not produce usable amounts of water, indicating negligible primary permeability. Wells that penetrate numerous fractures will generally have higher yields, per foot of water-level drawdown, than those penetrating few fractures. The yield of a well, in gallons per minute per foot of drawdown, for a given period of pumping, is called the "specific capacity" of the well.

An analysis of the probability of high specific capacity in the Greenbrier-Upper New River basin was made by Clark and others (in press) who found two factors significant in high specific capacity. These are related to topography and major structural features. Wells along major anticlines had significantly higher specific capacity than those along synclines or in undisturbed rocks. Wells in valleys had higher specific capacity than those on hillsides or hilltops. Fractures along the axis of an anticline may be numerous, of course, because of stress, and they may also be numerous under valley floors because of relief of stress.

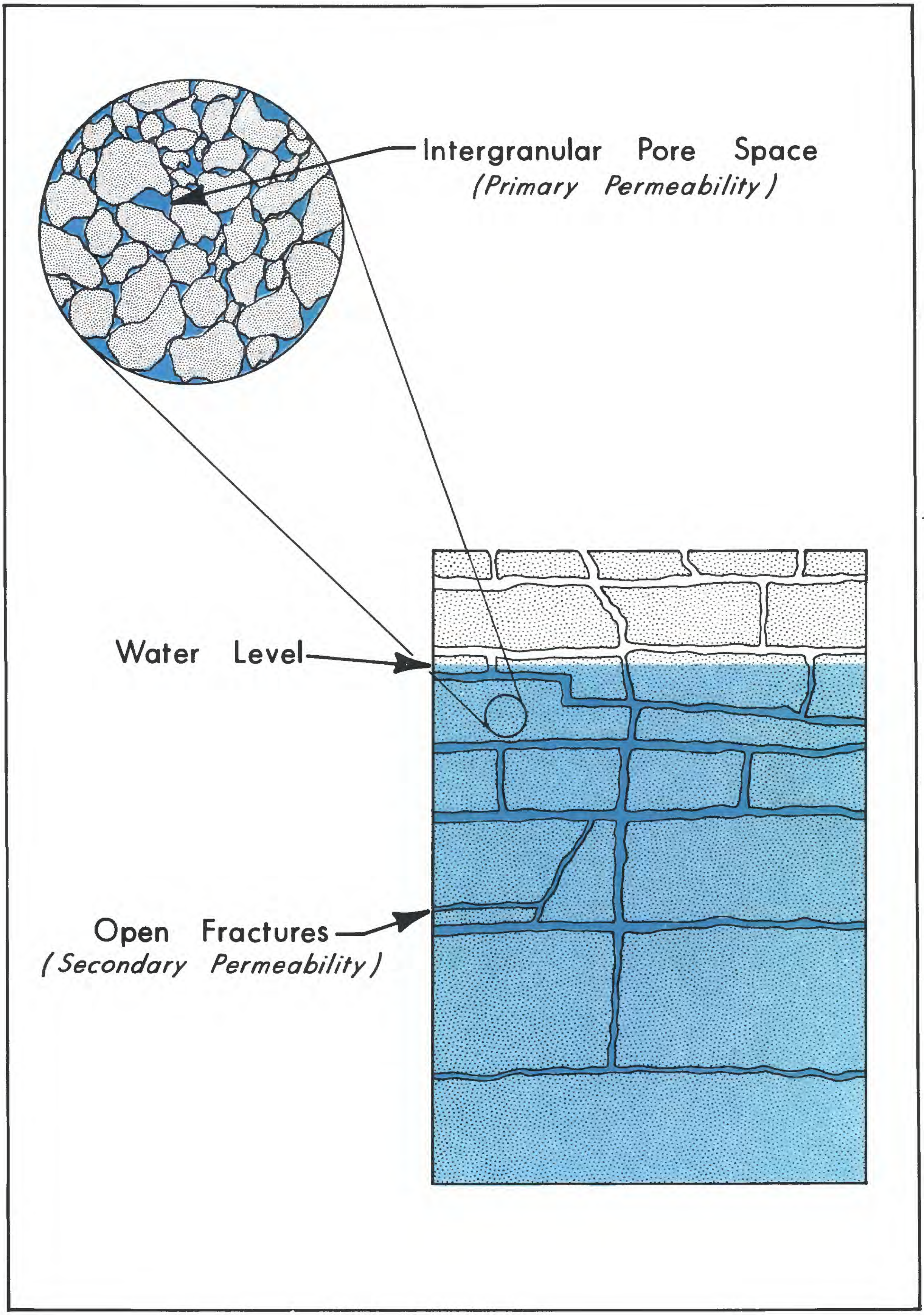

Figure 3.1-1. Features of primary and secondary permeability

3.2 Stress Relief

Predictable Fracture Patterns Are Result of Stress Relief

Stress relief, the removal of compressional stress on underlying rocks by erosion of overlying rocks, results in predictable fracture patterns in valleys. The fractures are generally horizontal under valley floors and are generally vertical along valley walls, where the rocks are nearly flat-lying, as in the Appalachian Plateaus.

When rocks are buried by younger rock material, they are subjected to compressional stress by the weight of overlying rock material. After an uplift, the compressional stress on rocks of a valley floor will be relieved where weighty overlying rocks are removed by erosion. Other rocks of the same unit that forms the valley floor remain under compressional stress beneath adjacent hills. The large black arrows in figures 3.2-1 and 3.2-2 indicate compressional stresses, and the large red arrow represents the resultant stress. One result of this imbalance of forces is the upward arching of rocks in the valley floor.

Unequal arching of beds, the upper beds arching more than the lower, results in slippage and fracturing along horizontal planes of weakness. These planes of weakness are generally the bedding planes, but weakness may also prevail along planes where grain size or lithology differs slightly. In this report, horizontal openings are referred to as bedding-plane separations, bedding-plane fractures, or bedding-plane openings. Arching also causes minor vertical fracturing near the axis of the arch.

Another result of unequal stress distribution is vertical and horizontal fracturing along valley walls. Where material is eroded from a valley, its walls are subjected to unequal horizontal stresses. These stresses result in vertical tensile fractures along the valley walls. The vertical fractures allow the valley walls to slump downward, causing compressional fractures at the base of the valley walls. The horizontal and vertical fracture systems are interconnected and thus become conduits for the movement of ground water.

The geologic setting in figures 3.2-1 and 3.2-2 has been modified to conform to a generalization of the geologic setting observed at outcrops and during test drilling at Twin Falls State Park. The rocks are composed mainly of hard sandstone and interbedded shale and coal. The main features of stress-relief fracturing in these illustrations were taken from Ferguson (1974). That report applies to valleys of the Appalachian Plateaus. Reports by others discuss stress-relief fracturing in many parts of the world. References to stress relief in the United States, Great Britain, Germany, Romania, India, and Canada are listed in Section 7.2 of this report.

Theories on the formation of valleys have led to many controversies. The authors recognize that valleys must initially form along weaknesses in rock. The weaknesses may result from any number of causes. This paper, however, is not concerned with the origin of valleys but, rather, with the effects of stress-relief fracturing on ground-water hydrology.

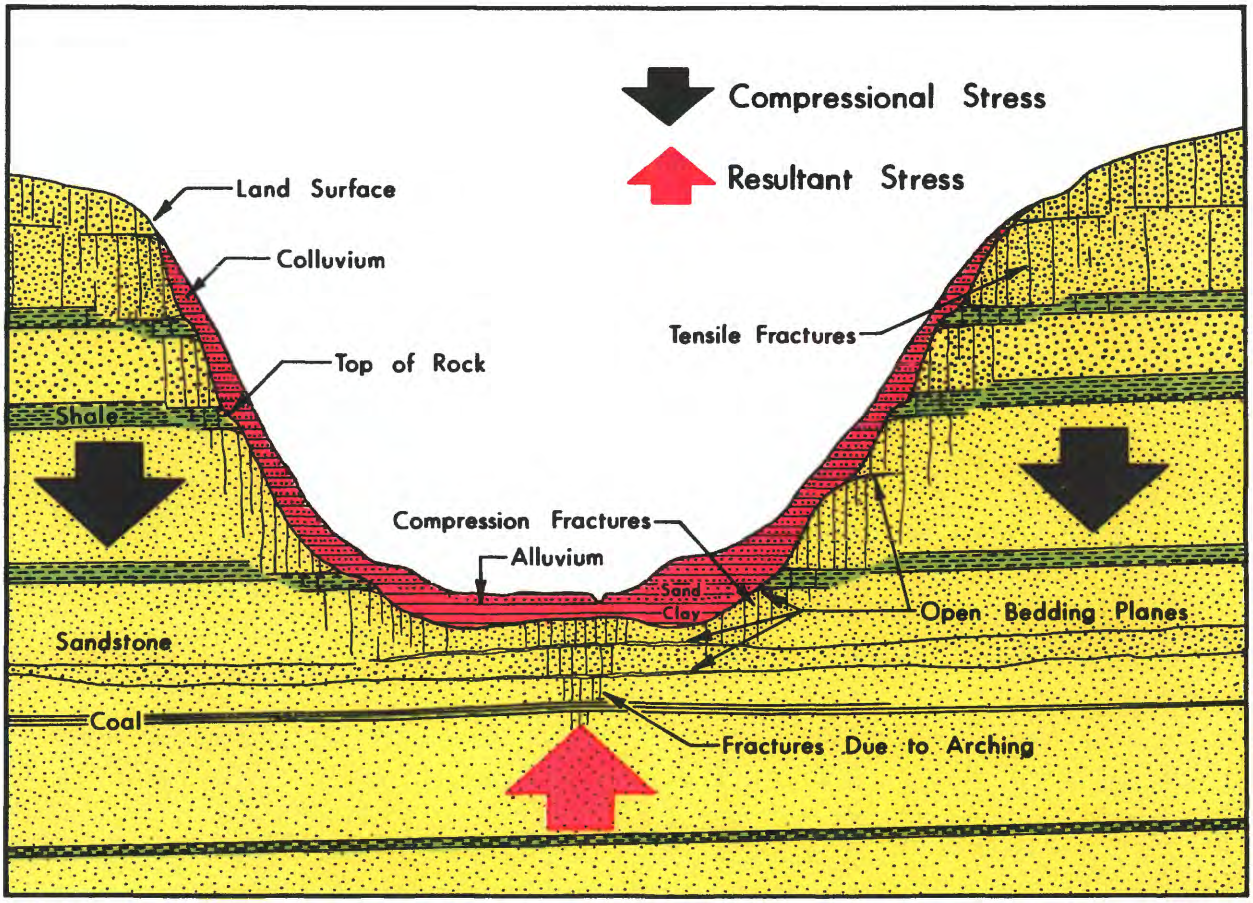

Figure 3.2-1. Generalized geologic section showing features of stress-relief fracturing [after Ferguson (1974)]

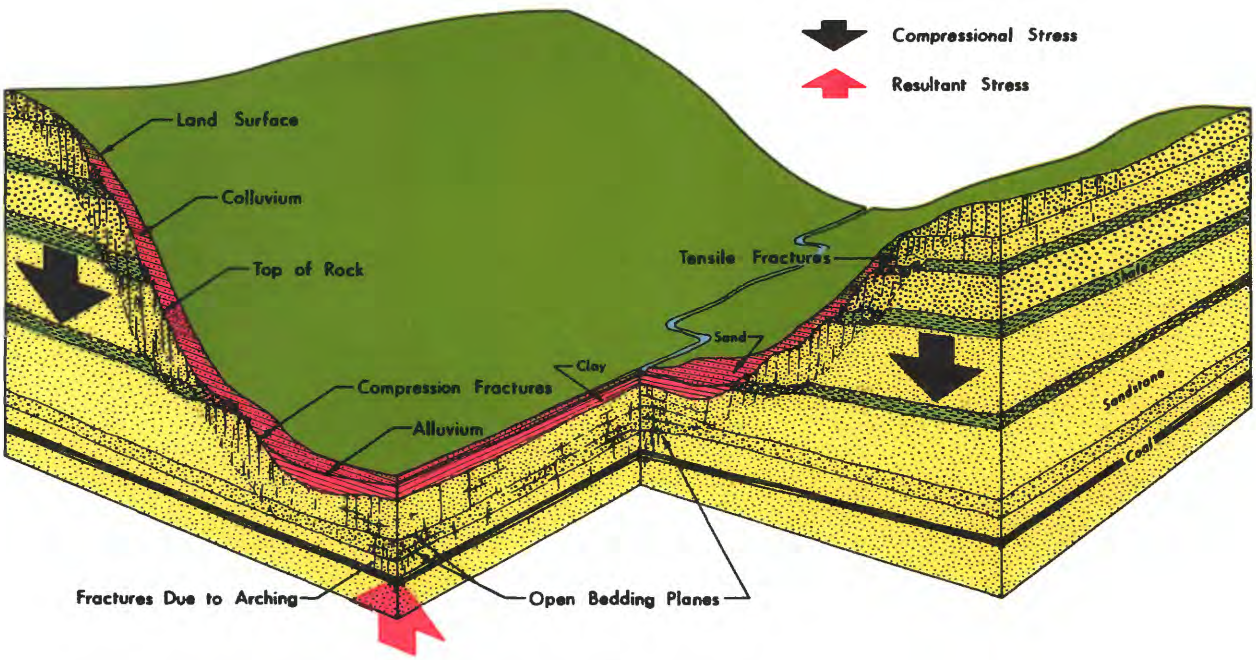

Figure 3.2-2. Block diagram of generalized geologic section showing features of stress-relief fracturing [after Ferguson (1974)]

4.0 SELECTION OF TEST AREA

4.1 Location of Area

Twin Falls State Park Selected Because It Meets Strict Criteria for Test Area

Twin Falls State Park in east-central Wyoming County, W.Va., was selected because it meets the strict criteria established for a test area. These criteria were established to eliminate problems that were encountered in analyzing pumping-test data from previous tests in other valleys of the Appalachian Plateaus.

The strict criteria established for a test area consist of selecting an area that: (1) is relatively unaffected by man's activities, (2) is not situated along major tectonic features, and (3) is geologically and topographically similar to other valleys in the Appalachian Plateaus. Twin Falls State Park is in the heavily mined southern coal fields of West Virginia, but no coal has been mined in the Park. Park personnel control all pumping in the valley, which provides hydrologic control during tests. The main valley in the Park is parallel to and about 5 miles northeast of the nearest significant tectonic feature, an anticline. This distance is considered to be adequate for the Park to be unaffected by fracturing along the axis of the anticline. The Park is similar in topography and geology to many other small valleys in the Appalachian Plateaus and is well within the boundaries of the Appalachian Plateaus. (See fig. 4.1-1.) For these reasons, the park met most, if not all, criteria for a test area.

Pumping tests of wells in valleys of the Appalachian Plateaus have been unsatisfactory in some previous studies. Indicated aquifer characteristics have been unrealistic. Aquifer characteristics such as transmissivity and storage coefficient are determined by matching water-level drawdown curves to type curves. Departures of drawdown curves from type curves, which make interpretation difficult, have variously been attributed to interference caused by nearby pumping wells, interference from nearby mine dewatering or, possibly, the unpredictable hydrologic effect of irregular fracture patterns. As all of these factors could be controlled or accommodated at Twin Falls State Park, the park met the criteria for a test area.

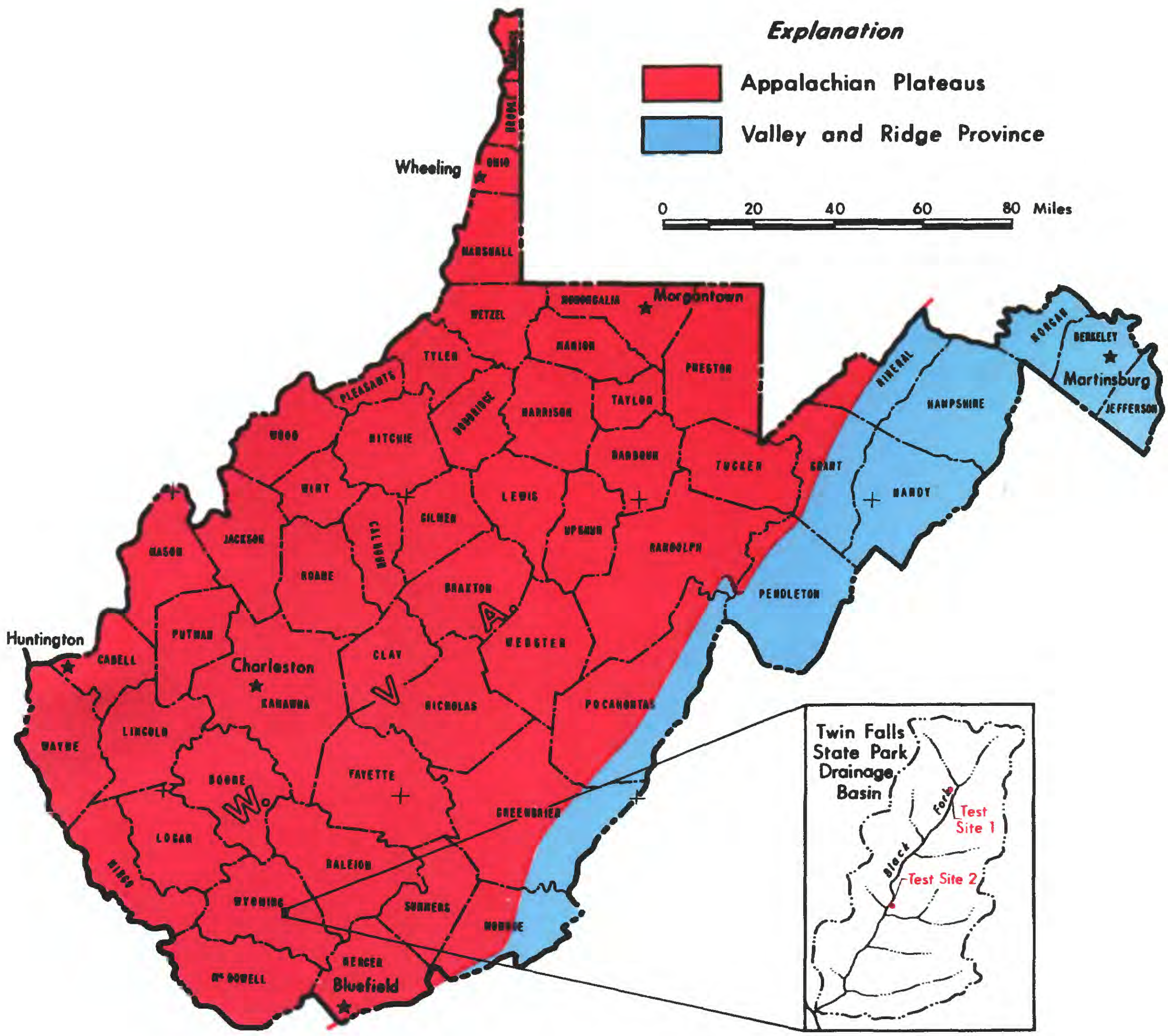

Figure 4.1-1. Appalachian Plateaus and Test Sites at Twin Falls State Park

4.2 Description of Area

Black Fork Is Nearly Straight Stream that Flows from Headwaters Near Test Site 1 to Mouth at Cabin Creek

Black Fork is a nearly straight stream, about 3 miles long, trending southwestward from headwaters near Test Site 1 to its mouth at Cabin Creek. (See fig. 4.2-1.) The stream flows through massive sandstone formations interbedded with thin shale and coal beds. The stream channel and the valley parallel the strike of the geologic formations. Relief in the park is about 400 feet from hilltops to the stream channel. The stream channel drops about 200 feet from Test Site 1 to the mouth at Cabin Creek.

Black Fork valley has an average width of about 400 feet. The valley floor is generally flat from Test Site 1 to Black Fork Falls, with a gradient of about 25 feet per mile. In contrast, the gradient from Black Fork Falls to the mouth is much steeper (approximately 450 feet per mile).

The valley floor above Black Fork Falls is composed of alluvium, mainly sand and clay. Below Black Fork Falls alluvium is absent, and the stream channel is cut mostly in hard sandstone. The hilltops and valley walls are covered by colluvium, mostly sand and gravel. The colluvium covers massive sandstone formations, which dip gently to the northwest at about 100 feet per mile.

Test drilling and surface-geophysics studies indicate that the alluvium in the valley floor is composed of sandy clay near the land surface that grades to dense clay at depth. Surface-resistivity profiles and surface-magnetometer studies indicate that the vertical fractures near the center of the valley are clay-filled from the overlying clay beds.

The hilltops, valley walls, and valley floor below Test Site 2 are heavily wooded. The valley floor from near Test Site 2 to above Test Site 1 is grass-covered and is used for a golf course.

Intermittent springs near the base of the valley walls are common. These springs flow for a short time, immediately after heavy rains, when the water levels in the unconfined aquifers are at or above the valley floor.

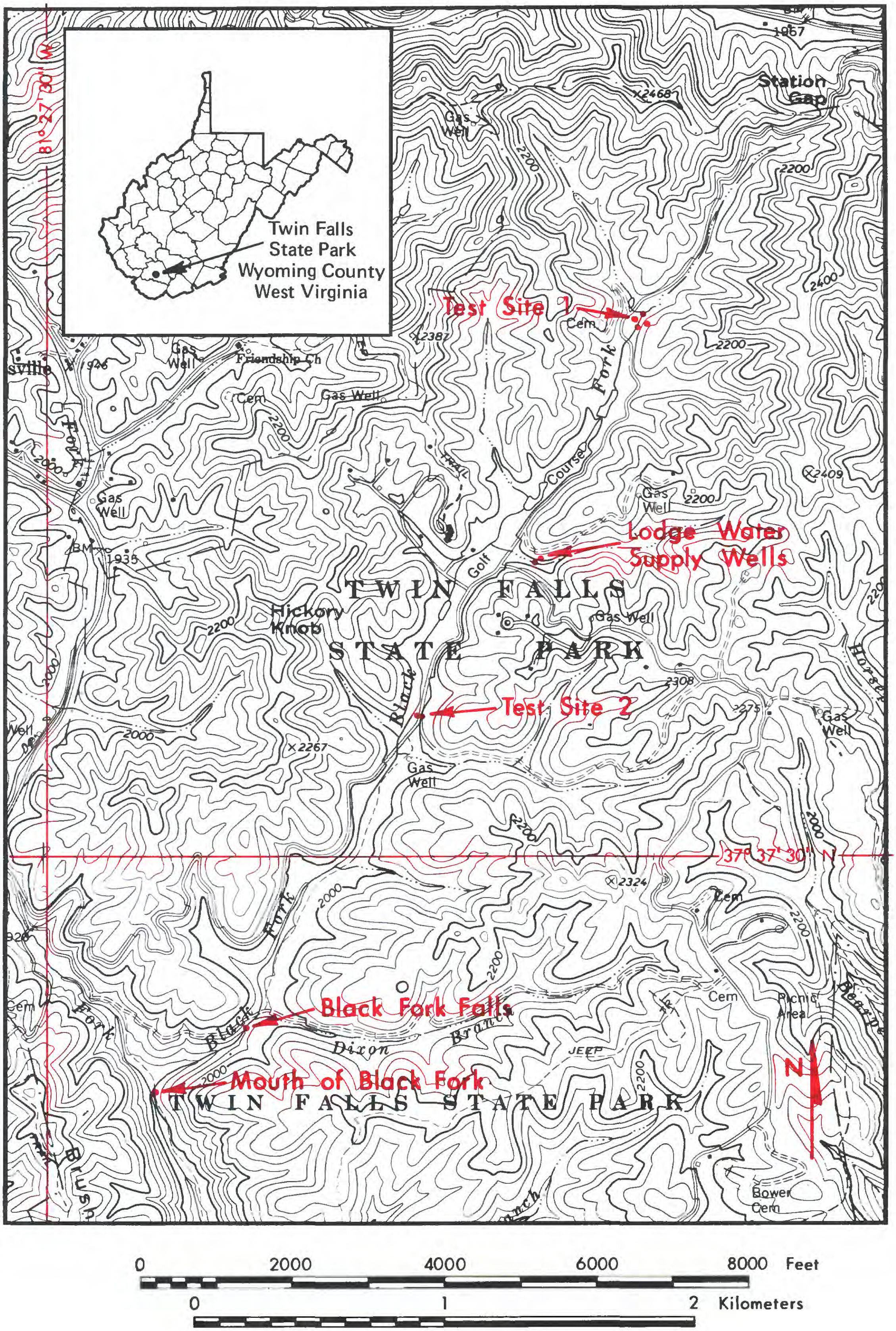

Figure 4.2-1. Topographic map of Twin Falls State Park

5.0 HYDROLOGY AT TEST SITES

5.1 Hydrology at Test Site 1

5.1.1 Introduction and description of Test Site 1

Four Well Locations Were Selected at Test Site 1 So Directional-Permeability Formulas Could Be Used

The well field at Test Site 1 was designed at a time when it was believed that ground water in the Appalachian Plateaus occurred in random high-angle fractures. In such a fracture system, differences in permeability parallel to and perpendicular to the major fracture system would be large. Four 80-foot wells at Site 1 were located so that formulas related to directional permeability could be used in analyzing the test data.

Test Site 1 (see fig. 4.2-1) near the upper end of Black Fork Valley is the location of irrigation wells, used seasonally, for the golf course. Well J68 (see fig. 5.1.1-1) is an irrigation well equipped with a pump capable of pumping more than 80 gal/min (gallons per minute). The locations of the observation wells—Wells 001, 002, and 003—were selected so that the width of the valley would be monitored during tests and so that none of the wells were at 90- or 180-degree angles to any other well (Papadopulos, 1965).

The observation wells were drilled, and well J68 was pumped at 70 gal/min for 24 hours. Data from the pumped well and observation wells could not be analyzed for the aquifer characteristics—transmissivity (T) and storage coefficient (S)—because the effect of multiple images and other effects interfered with computations. Although values for T and S could not be computed, two significant things were learned about Test Site 1 from the test: (1) the drawdowns in Wells 002 and 003 were approximately equal throughout the test, indicating that permeability in those directions was probably equal and (2) the multiple-barrier effects were felt early in the test, indicating a narrow aquifer bounded by impermeable barriers.

Based upon what was learned from the first test, additional physical and geophysical data were collected at Test Site 1, and a second pumping test was designed to pump at a lower rate near the center of the valley, so that values for T and S could be determined before measurable image effects interfered with the data analysis.

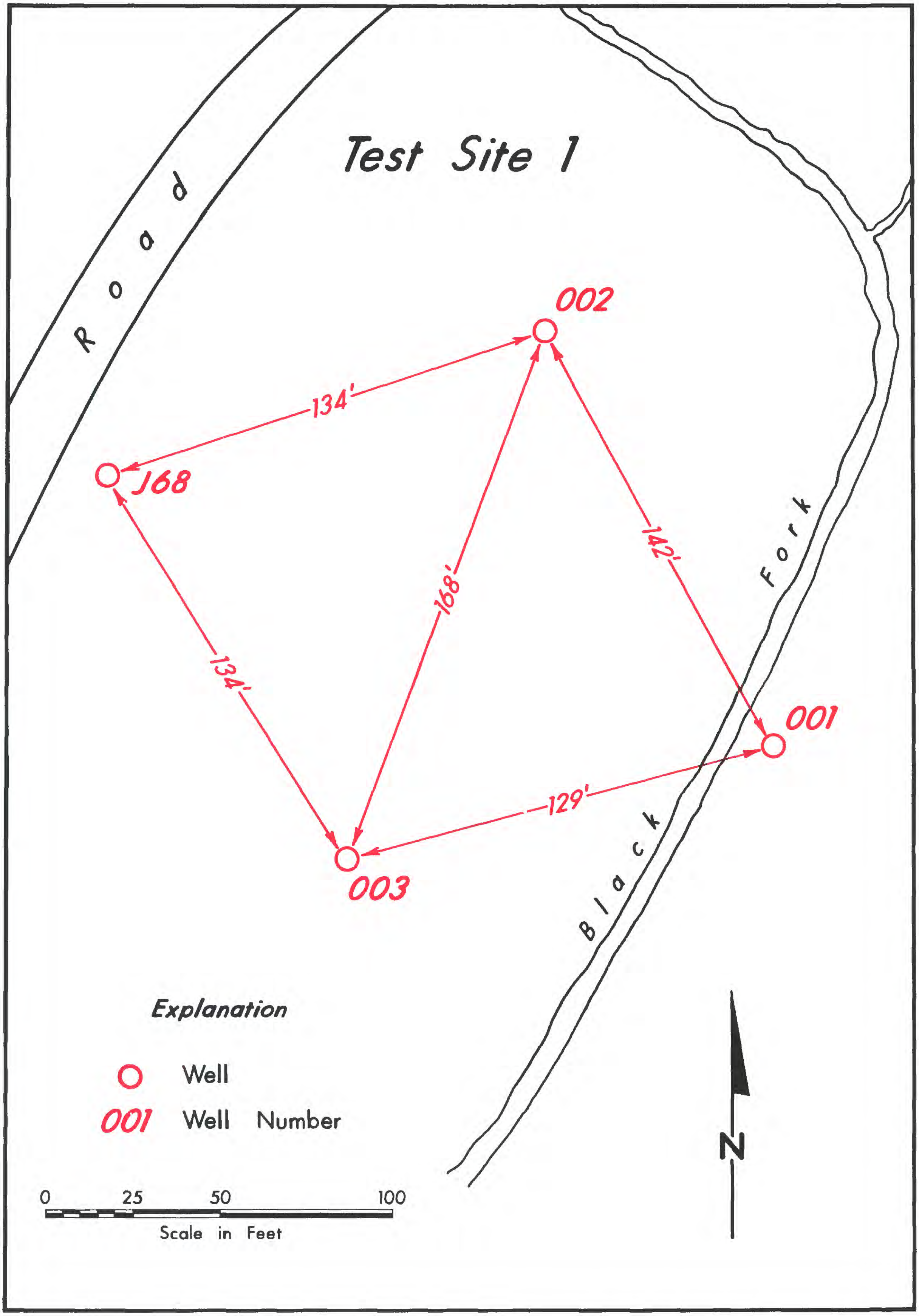

Figure 5.1.1-1. Well locations at Test Site 1

5.1.2 Well data

Wells Near Valley Center Obtain Water from Bedding-Plane Separations; Well Near Valley Wall Obtains Water from Shallow Slump Fractures

The lithology of the consolidated rock units correlates closely from well to well at Site 1. The depths of water inflow to the wells drilled near the valley center do not correlate with the depth of inflow to a well near the valley wall. Geophysical logs and current-meter studies indicate that water is derived from bedding-plane separations at depths between 40 and 65 feet near the center of the valley and from fractures between 30 and 40 feet deep in the slump zone near the valley walls.

The lithologic logs (fig. 5.1.2-1) were compiled after examination of well cuttings collected during well drilling. Wells 001, 002, and 003 were drilled by the cable-tool method, and the well cuttings were collected at intervals of 2 to 5 feet. The lithology correlates closely from hole to hole for units more than 2 feet thick.

The relative velocity of flow is a measure of the flow of water in the wells from points of inflow, up the well, to a pump intake in the casing. Flow was not measurable in the wells when they were not pumping. When they were pumped at about 20 gal/min, the relative velocity of flow in the hole showed where water entered. If the wells had tapped rocks of uniform permeability and if the hole diameter had been constant, the relative-velocity curve would have been a smooth curve, showing a gradual increase in velocity from the bottom of the well to the bottom of the casing. Because the water entered at fractures, the relative velocity of flow increased abruptly where the meter came up past a water-bearing fracture and decreased when the hole diameter increased because of caving of poorly indurated rock. The curves for Wells 002 and 003 show abrupt increases between 50 and 65 feet, where they intercepted water-bearing fractures. Both curves showed a marked decrease at 40 to 45 feet, where the shale bed caved and enlarged the hole diameter during drilling. Well 001 had no inflow below the shallow fractures between depths of 30 to 40 feet. A comparison of the data indicates that the bedding-plane fractures at Wells 002 and 003 did not occur in the same rock units at Well 001 and that the shallow fractures at Well 001 did not occur in the same rock units at Wells 002 and 003.

The down-hole relative-resistivity logs and the surface-resistivity depth-probe logs correlate with major lithic changes and also, to some extent, with fracture depths indicated by the relative-velocity curves. Resistivity increased abruptly at fractures because the open, water-filled fractures offer more resistance to the flow of electric current than the rocks.

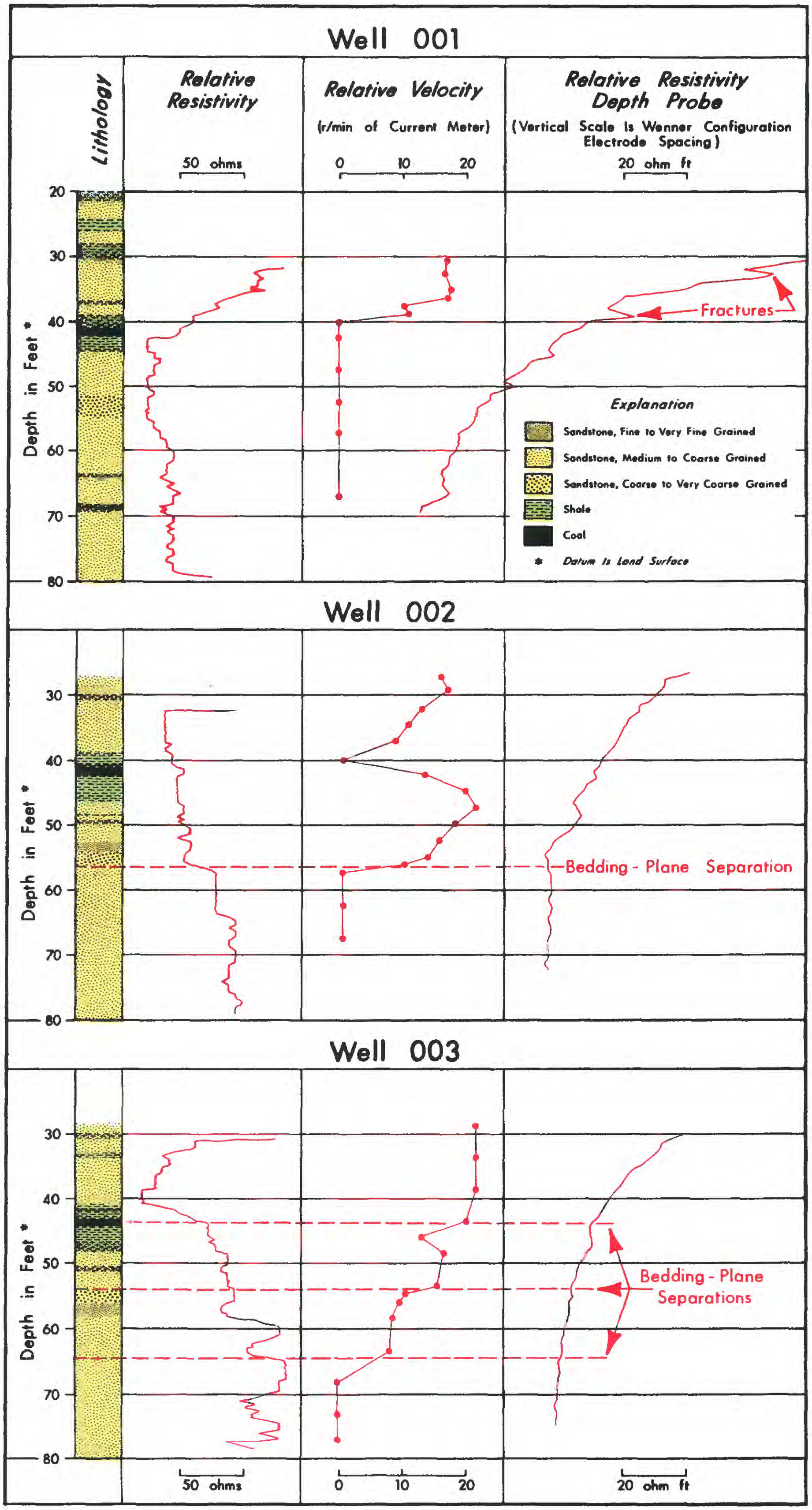

Figure 5.1.2-1. Physical data for Wells 001, 002, and 003 at Test Site 1

5.1.3 Hydrograph of Well 002

Well 002 Hydrograph Shows Changes in Water Level Before and After Pumping Test on October 26, 1977

A hydrograph of the water level in Well 002 shows effects of the pumping test itself, the regional water-level trend, and interference effects of pumping other wells before and after the pumping test on October 26, 1977.

The hydrograph, a graph of water level related to time, shows changes in water level in Well 002 for about 4 days. (See fig. 5.1.3-1.) The pumping test was made during the middle of this period. Data shown on the hydrograph were recorded each hour.

The hydrograph shows the effects of pumping about 3,300 feet from Site 1 on October 24 and 27. Pumping at the Lodge wells started at about 8 a.m. and lasted for 9 hours, until the storage tanks were filled. The pumping rate was 17 gal/min. This pumping lowered water levels at Site 1 about 0.2 foot after 9 hours. The Lodge well was not pumped during the test on October 26.

Rain was heavy on October 25, recharging the aquifer and causing regional ground-water levels to rise. The rise began about noon on the 25th and, except for during the time of control-pumping of Well 003 on the 25th, continued until about 8 a.m. on the morning of the test. The rising trend in water level was hardly measurable by 9 a.m. on the 26th. By this time, the aquifer had also recovered from pumping on the 25th. As the water level would have continued to rise (if the test had not been made) only about 0.005 foot during the time of the test on October 26, correcting for the rise was considered unnecessary in analyzing the test data. Well 003 was pumped at 6 gal/min, starting at about 9 a.m. on October 26.

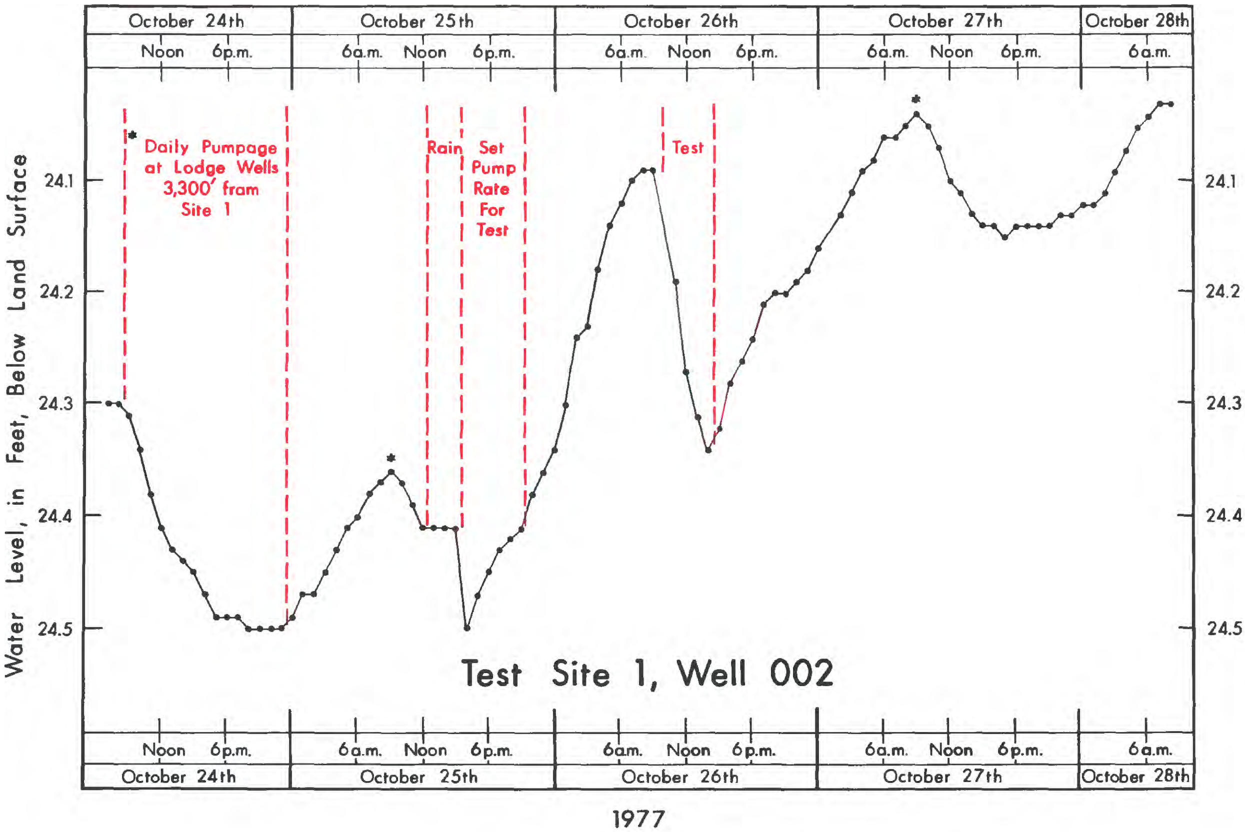

Figure 5.1.3-1. Hydrograph of Well 002 at Test Site 1

5.1.4 Analysis of pumping-test data

Convergence of All Drawdown Curves Near End of Test Indicates Water Level in All Wells Draws Down Same Amount at Same Time

Water-level drawdowns in the pumped and observation wells during the pumping test on October 26, 1977, are plotted on figure 5.1.4-1. The drawdown plotted for observation Wells 002 and J68 (solid-red circles and solid-blue circles, respectively) and pumped Well 003 (solid-black circles) indicates that these wells tap an aquifer of extremely high transmissivity—only 0.3 foot of drawdown in 3.3 hours. On the other hand, the drawdown curve for Well 001 (solid-black triangles) indicates that this well taps an aquifer of lower transmissivity. The convergence of all the drawdown curves near the end of the test indicates that the water level in all the wells is drawing down the same amount at about the same time, which would happen if the aquifer system were bounded laterally by impermeable barriers.

The drawdown curves for Wells 002, J68, and 003 illustrate the drawdown of water level in these wells caused by pumping Well 003 at 6 gal/min. Drawdown in Wells 002, 003, and J68 began 10 to 35 seconds after pumping began. These wells tap the aquifer formed by open fractures below the valley floor. The nearly equal amount of drawdown at almost the same time in the pumped and observation wells indicates extremely high transmissivity. The water level in Well 001 responded to pumping Well 003 considerably later in the test, and, initially, its drawdown was much less. This well taps the aquifer formed by slump fractures along the valley wall, where transmissivity is much lower. As pumping continued, drawdown of water level in all the wells became nearly equal, as would happen if an interconnected aquifer system bounded by two or more impermeable barriers were to be pumped. The situation would be analogous to pumping from a lake or reservoir. Drawdown of lake or reservoir level would be the same, under pumping, no matter where on the lake or reservoir the level was measured.

The profiles of the water level from Well J68 through Well 003 to Well 001, under pumping, are shown in figure 5.1.4-2. As may be seen by the near parallelism of the connecting lines, the water level in Wells J68 and 003 declined at approximately the same rate in the same time intervals. During the first hour of the test, the drawdown in Well 001 lagged behind drawdown in other wells because Well 001 is in the unconfined aquifer, which has a larger storage coefficient and is not as transmissive as the aquifer below the valley floor. After the first hour, the image effects caused by the impermeable boundaries had increased to the extent that the water level in all wells was declining at the same rate.

Two methods were used to try to determine T and S values of the aquifers: (1) a mathematical model of the valley constructed by S.S. Papadopulos was used, and (2) computations through the use of the image-well theory were used to reproduce the drawdown measured at Well 002 while Well 003 was being pumped. In both methods, it was found that a large number of values for transmissivity (T) would produce drawdown curves that matched the measured drawdown if the proper storage-coefficient (S) values were used. Thus, it was concluded that the shapes of the curves indicate an aquifer with an extremely high T value bounded by aquifers with lower T values, which, in turn, are bounded by impermeable barriers. The above is an interpretation of the ground-water part of the hydrologic system in the valley. This is the type of hydrologic system that would result from stress-relief fracturing. Until equipment capable of measuring extremely small changes in water level over extremely short time intervals becomes available, T and S values cannot be quantitatively determined in a valley of this size.

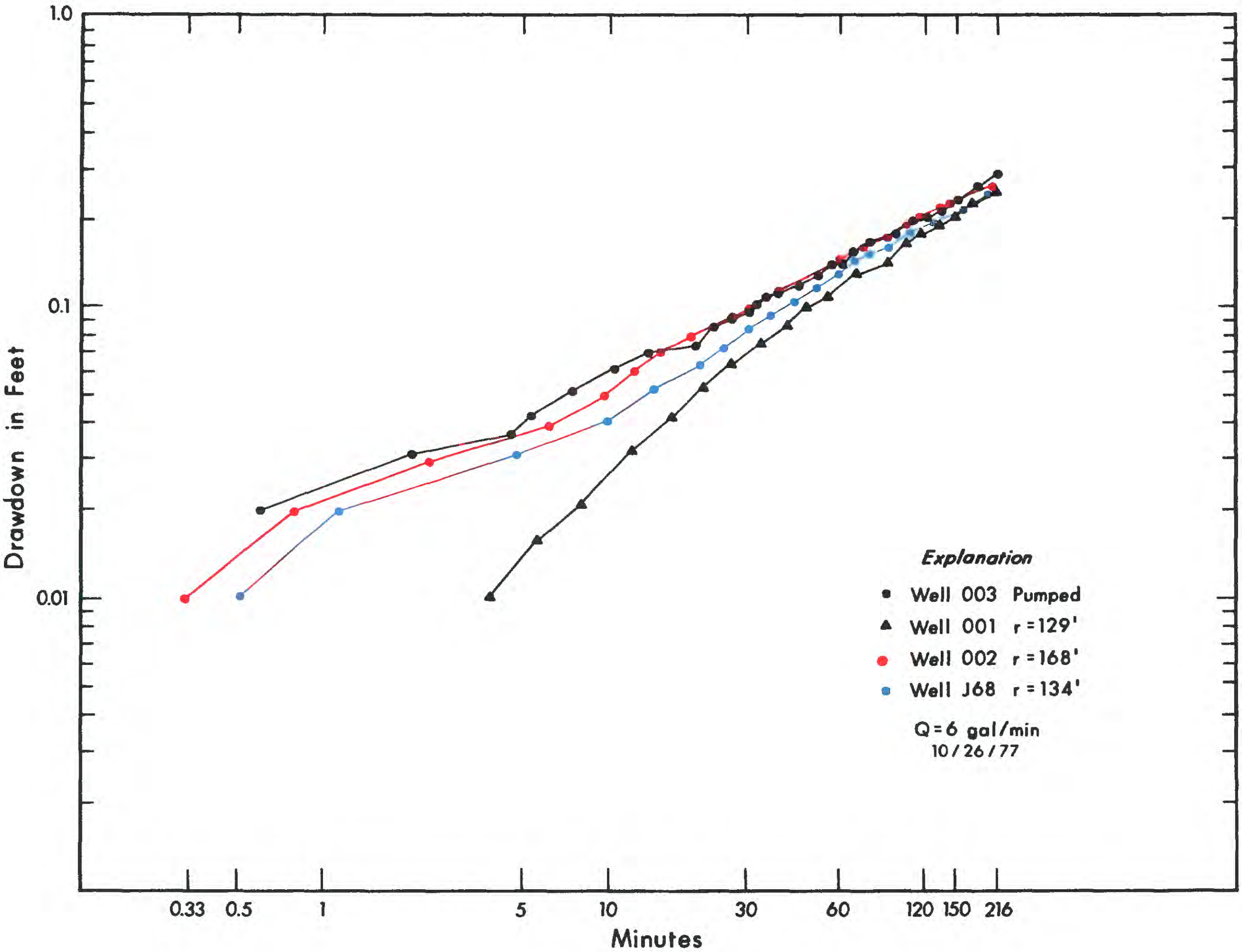

Figure 5.1.4-1. Pumping-test data for Test Site 1

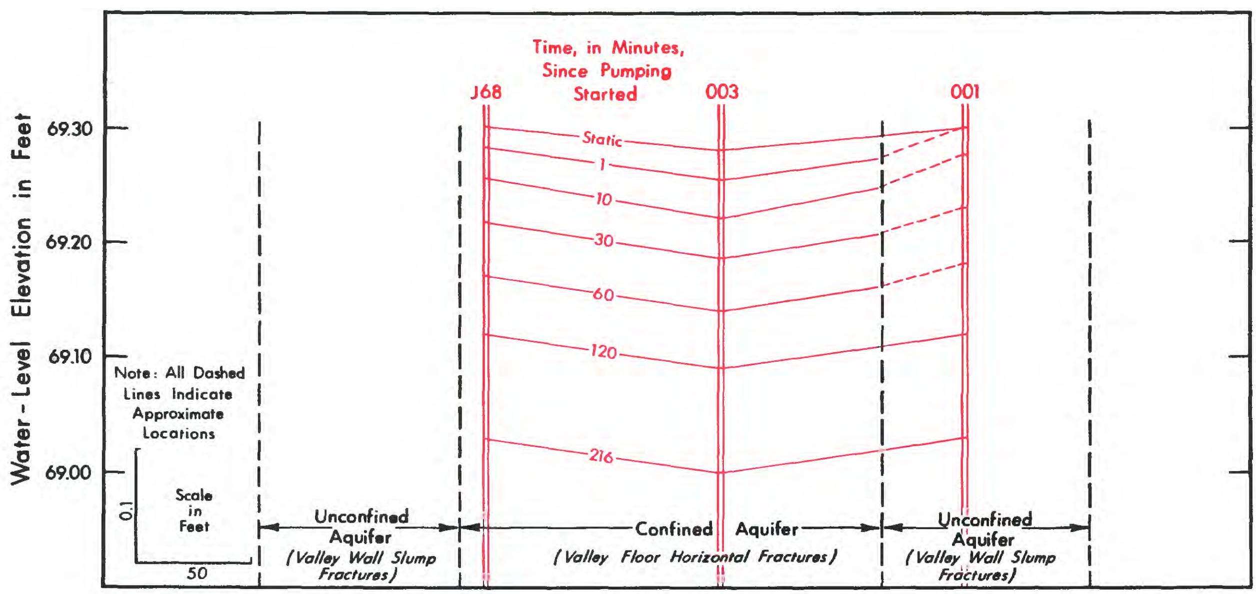

Figure 5.1.4-2. Water-level profiles during pumping tests at Test Site 1

5.1.5 Interpretation of data

Data Interpretation Indicates that Aquifer At Site 1 Is Stress-Relief Fracture System

Interpretation of all the data from Test Site 1 indicates that the aquifer incorporates a system of stress-relief fractures. Wells tap bedding-plane fractures under the valley floor where water is under confined conditions. Near the valley walls, the water is under unconfined conditions in the valley-wall slump fractures. The horizontal bedding-plane fractures pinch out under the valley walls, effectively forming impermeable barriers. Stress-relief fracturing accounts for the aquifer characteristics at Test Site 1.

The aquifer is confined by alluvial clay under the valley floor. (See fig. 5.1.5-1.) As can be seen, the water levels in wells cased through the clay layer will rise above the bottom of the confining clay layer. Near the valley walls, at Well 001, the water is unconfined in fractures formed by valley-wall slump. Black Fork flows in a channel in the sand and clay bed, which is about 20 feet above the head in the aquifer. There is no indication of hydrologic connection between Black Fork and the aquifer under the valley at Test Site 1.

The distance estimated from Well 001 to the effective barriers defines the width of the aquifer and thus the width of the fractured zone. The width of the fractured zone would include both the bedding-plane fractures and the slump-zone fractures (see fig. 5.1.5-2), as the sets of fractures are hydraulically interconnected. All the data indicate that the fracture system resulting from stress relief constitutes most of the transmissive part of the aquifer system at Test Site 1.

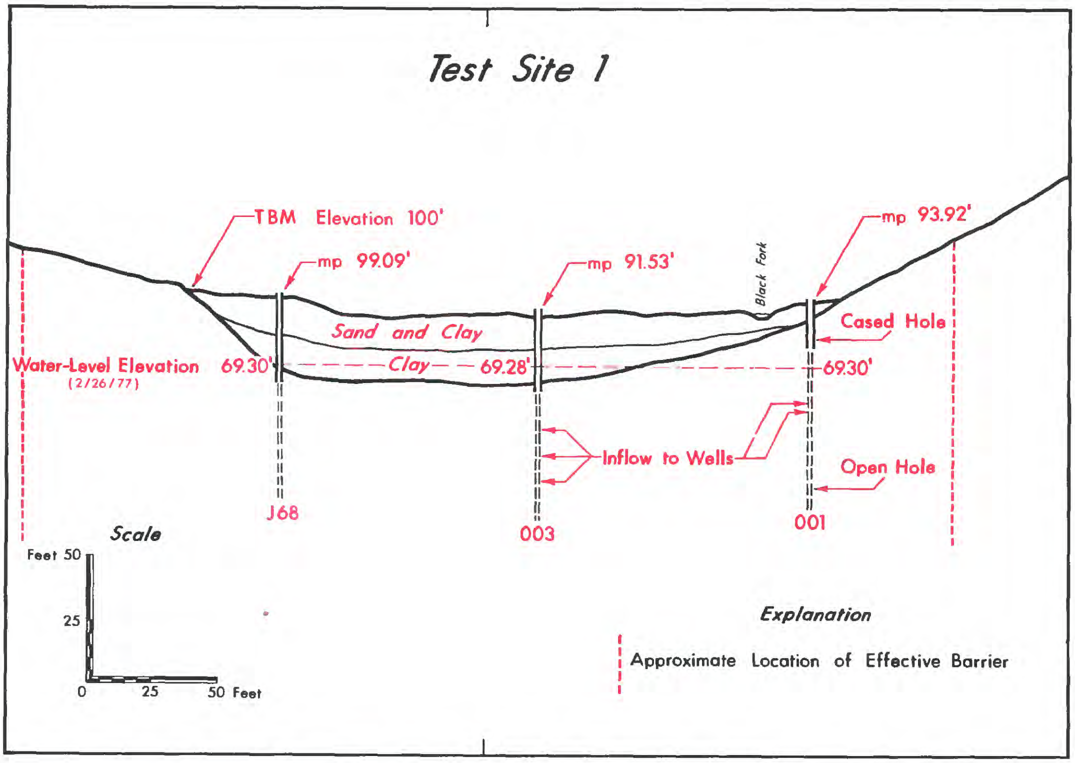

Figure 5.1.5-1. Scaled cross section at Test Site 1

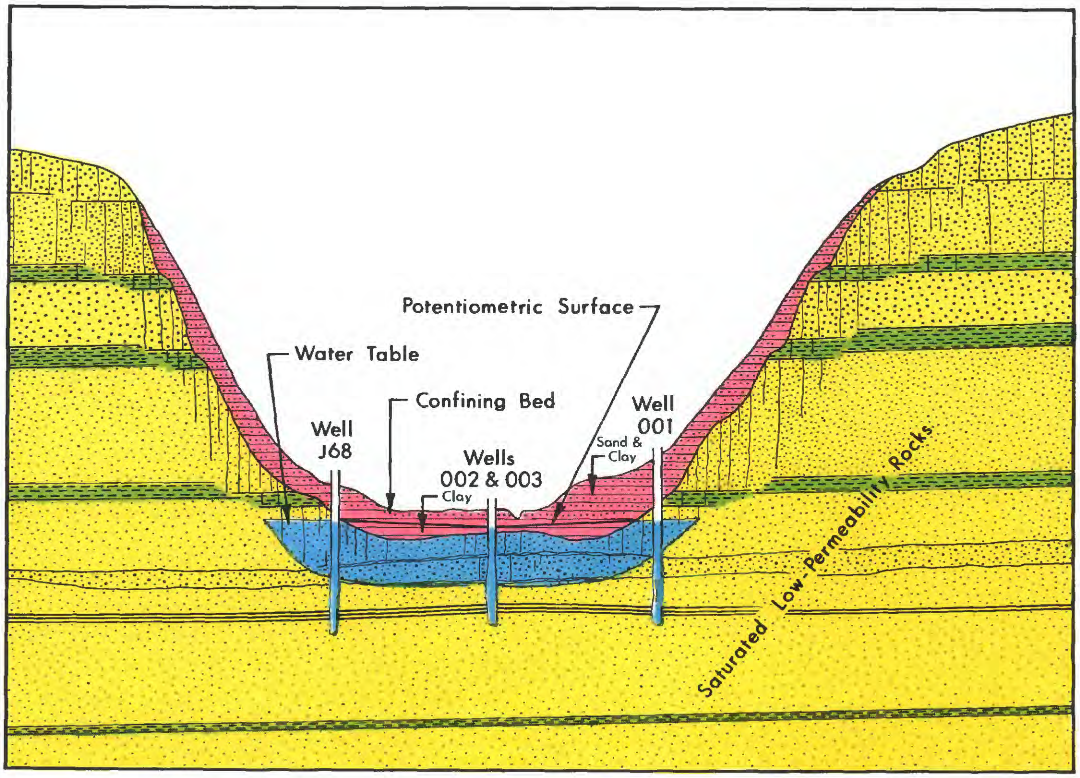

Figure 5.1.5-2. Generalized cross section of aquifer at Test Site 1

5.2 Hydrology at Test Site 2

5.2.1 Introduction and description of Test Site 2

Site 2 Location Selected to Correlate Lower-Valley and Upper-Valley Aquifer Conditions

The location of Test Site 2 was selected to determine if aquifer conditions in the lower part of the valley are the same as those in the upper part of the valley at Test Site 1.

Test Site 2 is in a narrow part of the valley about halfway between Test Site 1 and Black Fork Falls. (See fig. 4.2-1.) The location of Test Site 2 allows a comparison of aquifer conditions in the lower-central part of the valley with those at Test Site 1 in the upper part of the valley and with those observed in outcrops below Black Fork Falls near the mouth of the valley.

Two wells were drilled at Test Site 2. (See fig. 5.2.1-1.) Well A is near the center of the valley near Black Fork, and Well B is about halfway between Well A and the east wall of the valley. Test Site 2 is in a constriction in the valley where the valley is about 200 feet wide.

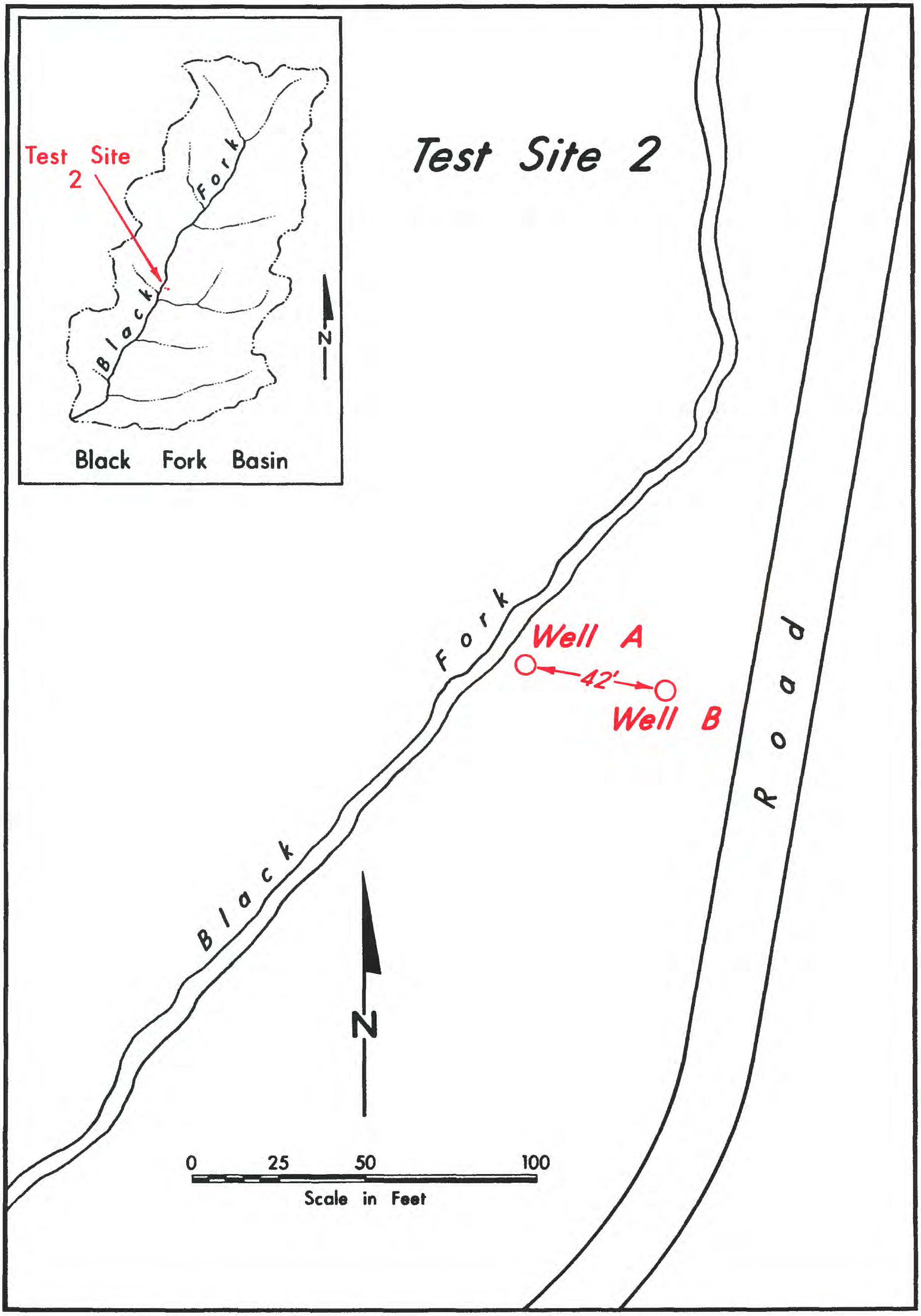

Figure 5.2.1-1. Well locations at Test Site 2

5.2.2 Well data

Well A Data Indicate Similar Geologic Conditions as at Site 1

The data collected at Well A indicate the same general type of geologic conditions as those at Test Site 1. Inflow to the well is derived from three bedding-plane separations between 20 and 60 feet below land surface. These three openings may be correlated with changes in bedding indicated by changes in drilling rate and relative resistivity. The well data indicate that water occurs under the same type of aquifer conditions at Test Site 2 as were determined for wells in the confined aquifer at Test Site 1.

The correlation of lithology, drilling time, relative resistivity, and relative velocity for Well A is excellent. The drilling time, in feet drilled per hour, is an indication of the relative hardness of the rock penetrated by the drill bit during drilling and indicates where the rock type changes with depth. The relative velocity indicates where water enters the well when the well is pumped at about 20 gal/min. The relative resistivity is a measure of the resistance of the rock to the flow of an electric current, thus indicating changes in rock type.

The lithologic log (see fig. 5.2.2-1) shows a change from fine-grained sandstone to coarse-to-very coarse-grained sandstone at a depth of 33 feet. The drilling rate decreased abruptly at this depth, and the relative velocity indicated an abrupt increase in flow to the well at this depth. The relative resistivity shows a decrease in resistance in the fine-grained sandstone section. These would be interpreted as a bedding-plane fracture at 33 feet, which supplies water to the pumping well.

The data indicate three bedding-plane fractures that supply water to the well. These are shown on figure 5.2.2-1 at depths of 22, 33, and 52 feet. Well data and interpretation indicate similar ground-water conditions at Test Sites 1 and 2.

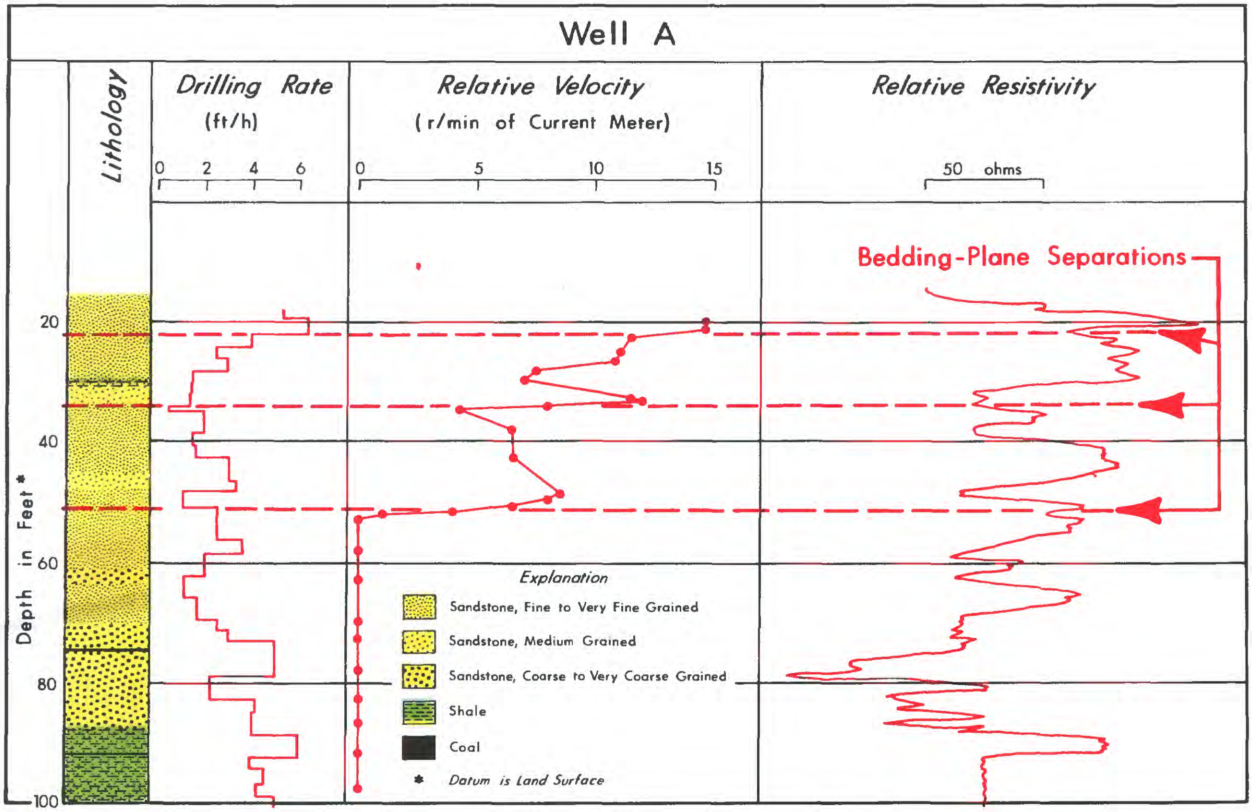

Figure 5.2.2-1. Physical data for Well A at Test Site 2

5.2.3 Analysis and interpretation of slug-test and pumping-test data

Test-Data Analysis Indicates Aquifer Characteristics At Test Site 2 Are Similar to Those at Test Site 1

An analysis of the slug-test data shows the multiple-image effects of impermeable barriers at Test Site 2. These aquifer conditions are similar to those at Test Site 1.

Slug tests were made at Well A and Well B at Test Site 2 on November 28 and 29, 1978, respectively. Each test consisted of dumping 55 gallons of water into the well and measuring the decay of the head built up by the dumped water. The head effects of adding water to the aquifer system are the exact opposite of pumping water from the aquifer. The effects of impermeable barriers are to delay the decay of the residual head, which results in departure of the measured curve above the type curve.

The type curves used were developed by Cooper and others (1954) and Papadopulos and others (1973). The early measurements matched to the curve show an almost horizontal shift from the curve for $\alpha = 10^{-1}$ to the curve for $\alpha = 10^{-10}$ (fig. 5.2.3-1). The measured curve departed above the type curve, indicating impermeable-boundary effects. Because of these departures of the measured curve, values for transmissivity and storage coefficient could not be determined at Test Site 2. However, the shape of the measured curve, compared with the type curves, does indicate the same aquifer conditions at Test Site 2 as at Test Site 1.

When Well A was pumped at 8 gal/min on November 29, 1978, the drawdown in Wells A and B was the same at the same time intervals throughout the test. This indicates an extremely high transmissivity in the horizontal fractures, as at Test Site 1 (fig. 5.2.3-1). Because image effects from the barriers were significant before the first 10 seconds of the test, T and S cannot be computed.

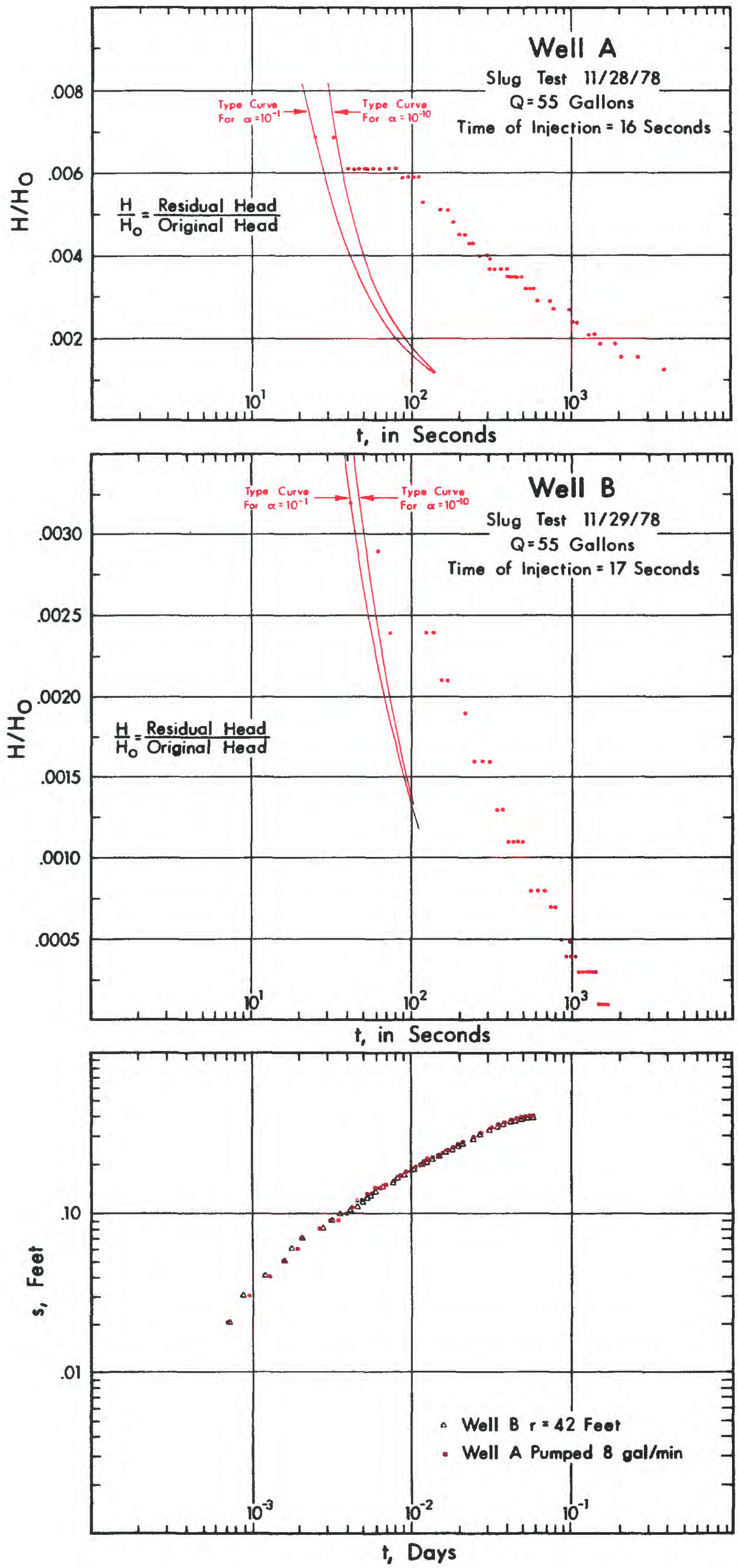

Figure 5.2.3-1. Data from slug test and pumping test at Test Site 2

6.0 HYDROLOGY OF THE VALLEY

6.1 Pumping Lodge Water-Supply Well

Pumping Well at Lodge Shows that Aquifer Is Continuous from Test Site 1 to Test Site 2

The water-supply well for the Lodge was pumped for about 5 hours to see if levels were lowered at both Test Sites 1 and 2. Well 002 at Test Site 1 and Well A at Test Site 2 both had measurable drawdown, indicating that the aquifer is continuous from Test Site 1 to Test Site 2.

The Lodge well was pumped at 17 gal/min for about 5 hours on February 21, 1979 (fig. 6.1-1). The water levels in the pumped well, Well 002, and Well A were measured during the pumping. The resulting drawdowns in all three wells are shown in figure 6.1-1. Well 002 is about 3,300 feet upvalley from the Lodge well, and Well A is about 2,400 feet downvalley. As wells at both sites, more than a mile apart, were affected, the aquifer is concluded to be continuous between the test sites. Because of the interference of impermeable-boundary effects and changes in aquifer shape at tributary valleys, no attempt was made to analyze for values of transmissivity (T) and storage coefficient (S) in this test. Changes in the slope of the curves for Wells 002 and A at about 11 a.m. are attributed to the influence of changes in aquifer width at tributary valleys.

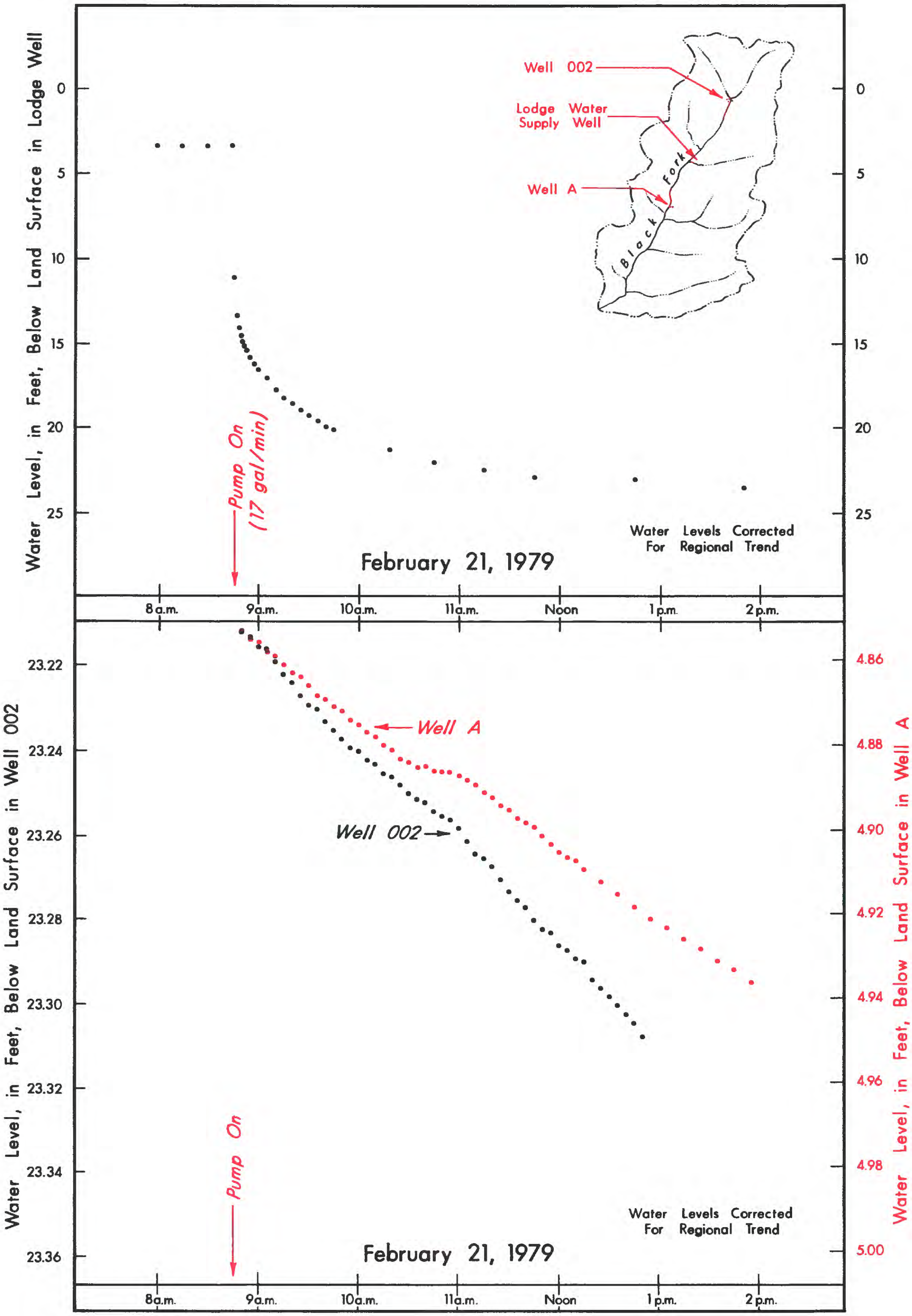

Figure 6.1-1. Drawdown at pumped Lodge well and at Wells 002 (Test Site 1) and A (Test Site 2)

11 to 6 Times Greater Stream Runoff Per Square Mile Below Falls Than Above Falls Caused by Ground-Water Discharge

The stream runoff per square mile below Black Fork Falls is 11 to 6 times as much as above the falls because of ground-water discharge to the stream at the falls. The ground water is discharged through horizontal bedding-plane fractures that crop out in the stream under the falls.

Runoff in Black Fork is a combination of overland runoff and ground-water discharge to the stream. As can be seen in figure 6.2-1, the runoff per square mile of drainage area below Black Fork Falls is about 11 times greater than above the falls during periods of low flow and more than 6 times greater during higher flow. The illustration also shows the stream profile and the results of a stream gain-and-loss study made downstream from near Test Site 2 to the mouth in November 1978. The flow nearly doubles from immediately above the falls to just below the falls. The bedding-plane fractures below the stream channel above the falls crop out in the zone of large increase in streamflow below the falls. Some fractures may be observed cropping out along the face of the falls and below it. Also, numerous iron oxy-hydroxide deposits can be seen on the rocks below the falls where iron-rich ground water is discharged.

The aquifer that contains stress-relief fractures at Black Fork Falls discharges water into the stream at the falls through bedding-plane fractures where there is no confining alluvium.

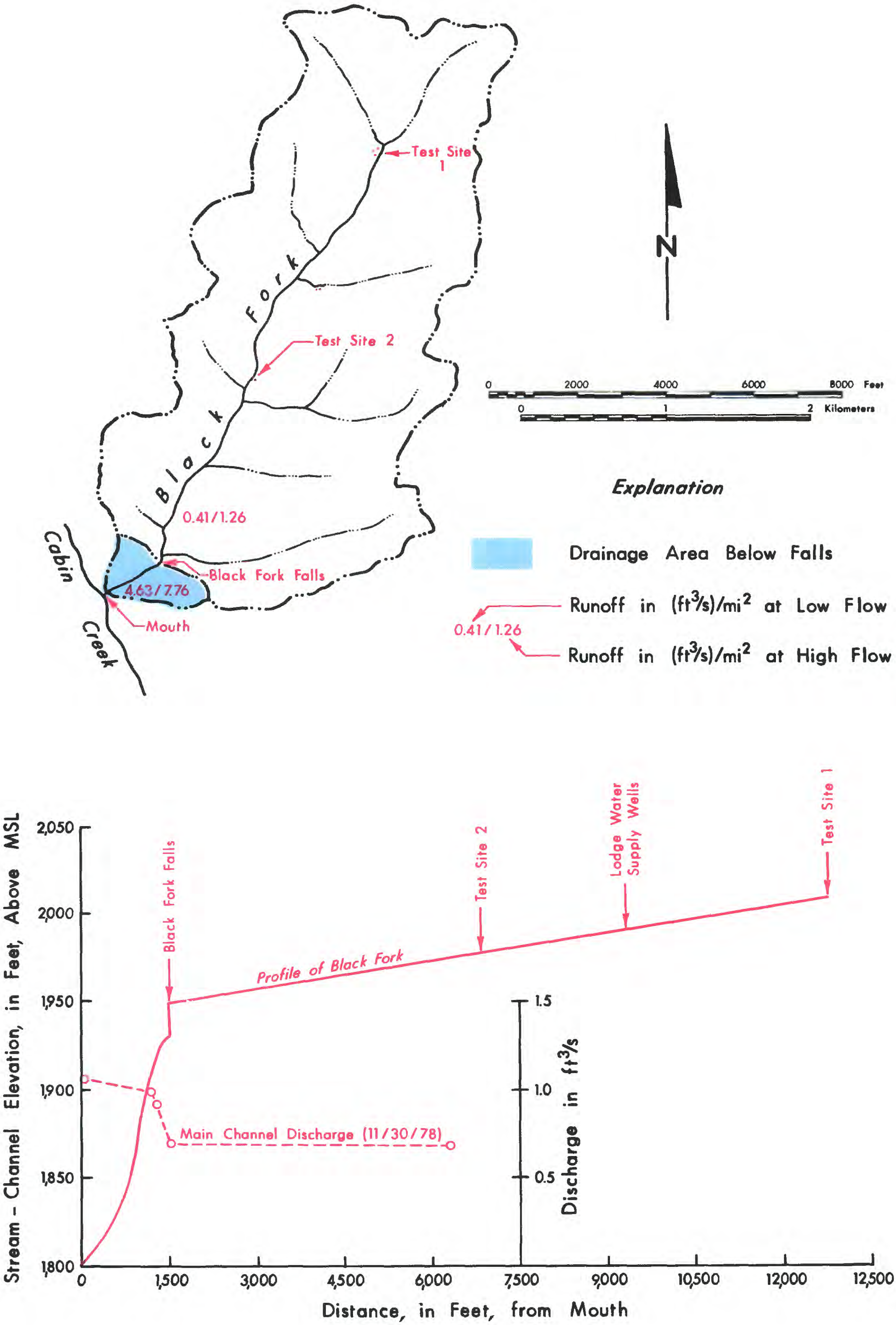

Figure 6.2-1. Profile and runoff map for Black Fork

Change in Rate of Ground-Water Discharge Below Falls Is Directly Related to Changes in Ground-Water Level

The change in rate of ground-water discharge below Black Fork Falls is directly related to the changes in ground-water levels at Test Sites 1 and 2. As water levels in Well 002 (Site 1) and Well A (Site 2) rise or decline, the ground-water discharge to the stream below Black Fork Falls increases or decreases.

One form of Darcy's Law states that, if aquifer characteristics remain constant, discharge from an aquifer is directly proportional to head at a given point. In Black Fork Valley, the size and shape of the aquifer and transmissivity are constant with time. The only variables with time are head and discharge. The relation of these variables is shown in figure 6.3-1. Well 002 is 9,200 feet from the discharge point at the falls, and Well A is 4,600 feet from the discharge point. Note that Well 002 is about twice the distance from the discharge point and has about twice the head for the same discharge. This implies that the fracture zones are relatively uniform throughout the valley.

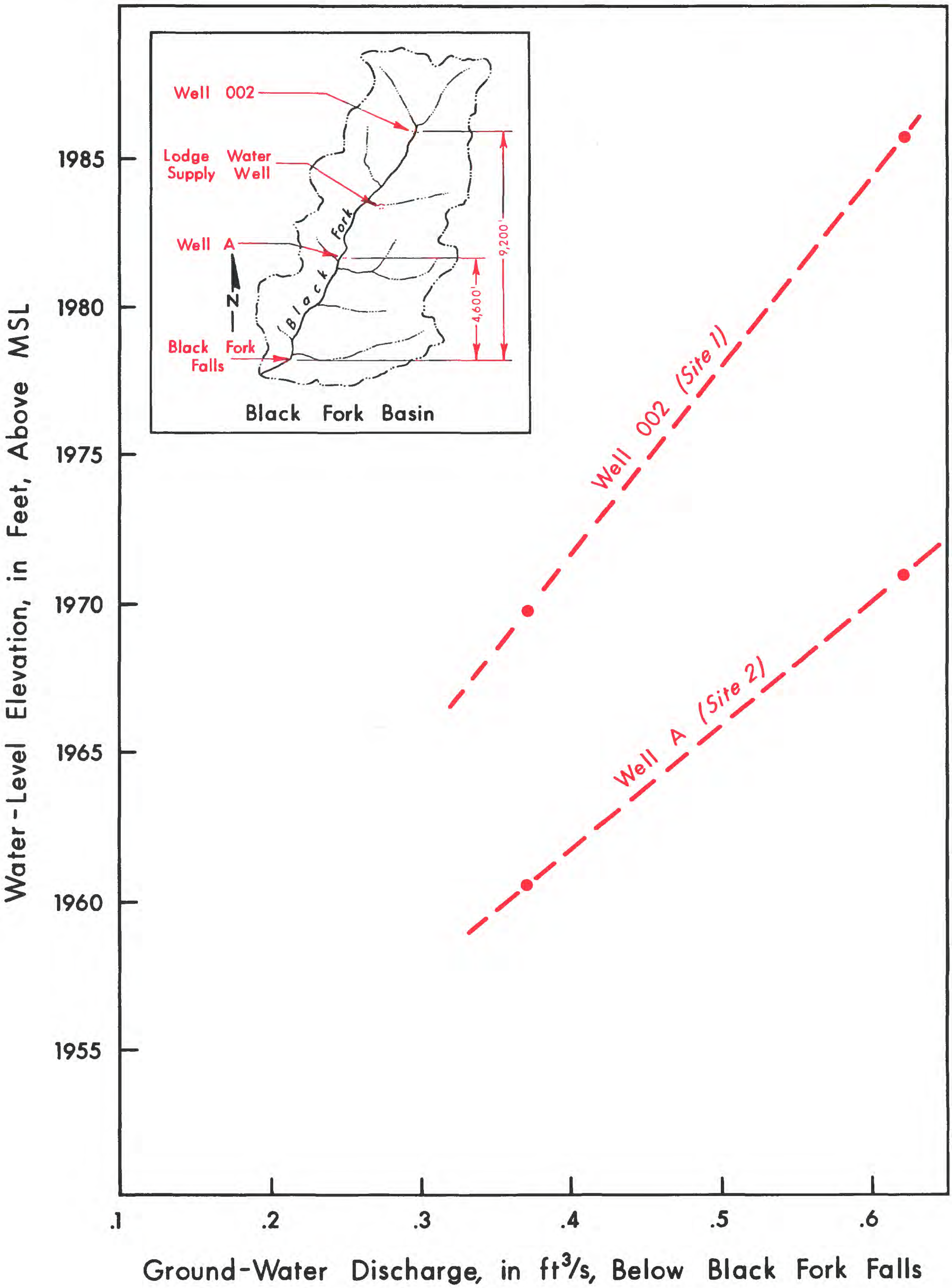

Figure 6.3-1. Ground-water level and discharge relationship in Black Fork Valley

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***"I.S." Papadopulos and "S.S." Papadopulos referred to throughout this report are the same person, and both "I.S." and S.S." are correct where used.**

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