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Using Remote Sensing and Inclined Drilling to Locate High-Yield Water Wells in the Eastern Kentucky Coal Field

Robert E. Andrews[1], David R. Wunsch[2], James. S. Dinger[1], and Glenn A. Dunno[3]

Abstract

The Kentucky Geological Survey has developed a method using lineament analysis in conjunction with inclined exploration boreholes to identify subsurface fractures in the Eastern Kentucky Coal Field. Wells are then drilled to intersect these fractures, with the hope that the wells will be high yielding (greater than 30 gal/min). Lineaments were selected from Landsat TM imagery, side-looking airborne radar (SLAR) imagery, and two enhanced Landsat TM images for over 6,400 square miles of eastern Kentucky. Lineaments were replotted on 7.5-minute topographic quadrangle maps, and field reconnaissance identified locations where lineaments correlated with straight-line topographic features and fracture zones. Subsequent application of an inclined drilling technique at six sites has resulted in four production wells with yields ranging from 47 to 72 gal/min. All production wells intersected fractured rock.

According to data from the Kentucky Groundwater Data Repository through October 2002, the yields of these four production wells are greater than the yields of 95 percent of the wells drilled in the Eastern Kentucky Coal Field.

This study suggests that to minimize the chances of encountering salty groundwater, the best sites for high-yield wells are in first- or second-order stream valleys with fracture zones.

Introduction

Analysis of water-well yield data collected from the Kentucky Groundwater Data Repository indicates that 93.1 percent of the 7,453 wells drilled in the Eastern Kentucky Coal Field (Fig. 1) from January 1985 through October 2002 have yields less than 30 gal/min (Fig. 2). These yield data were summarized from well completion records submitted by water-well drillers. Wells producing 30 gal/min or greater, considered high-yielding wells, represent only 6.9 percent of the wells drilled in the region. Hydrogeologic studies conducted in eastern Kentucky over the past 40 years have indicated that these higher yields are the result of the wells intersecting secondary permeability features: namely, fractures.

One tool available to geologists for locating fractures is remote-sensing imagery such as satel-

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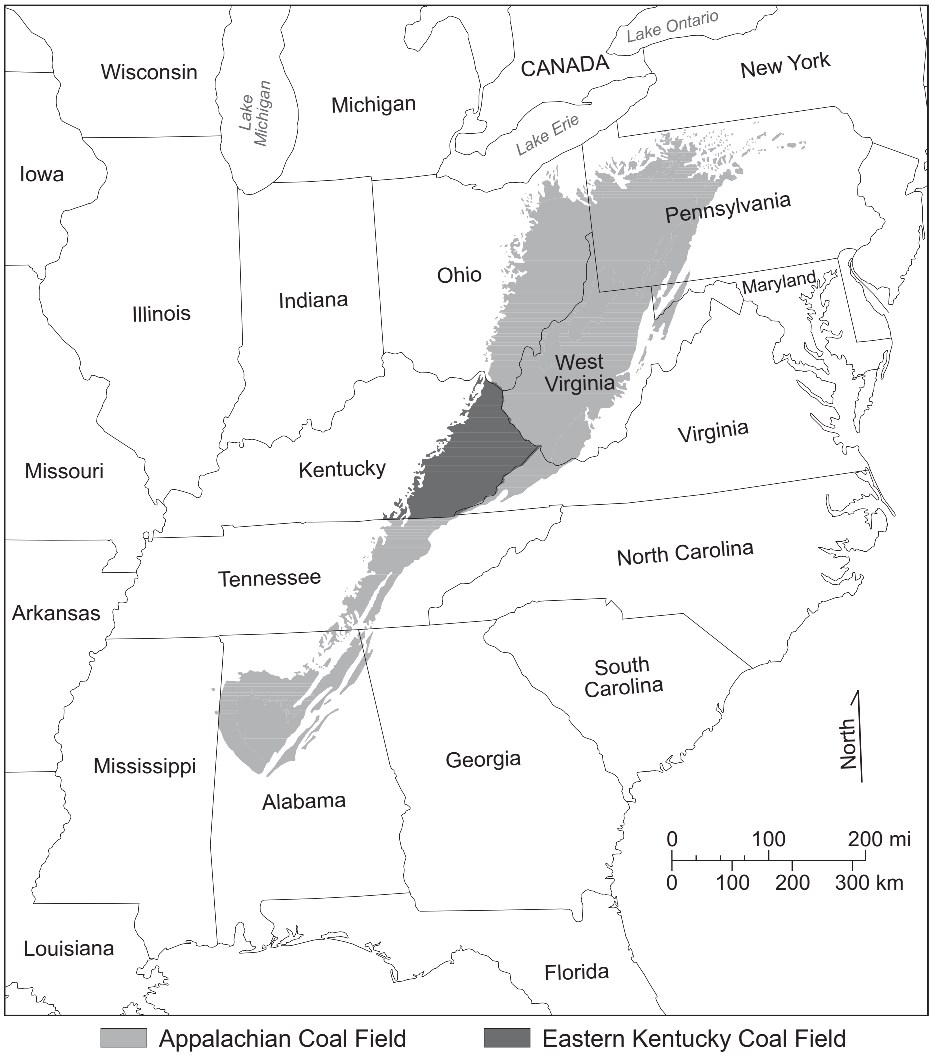


Figure 1. Location of the Eastern Kentucky Coal Field within the Appalachian Coal Field.

lite imagery, low-altitude radar, and aerial photographs. This imagery can be examined for linear features (appearing as "lines" on the imagery), which can represent roads, power lines, pipelines, and railroad tracks, as well as fracture zones on the order of a few feet to several hundred feet wide, or surface features such as straight-line stream valleys, which form along fractures.

The use of linear features to locate fracture zones and groundwater supplies was pioneered by Lattman and Parizek (1964). They found that linear features selected from aerial photographs reflect underlying fracture concentrations in the folded and faulted sandstone-interbedded carbonates of central Pennsylvania. They also found that water wells located along or at the intersection of these linear features were likely to have yields 60 times greater than wells located in between these features. The technique of using linear features to locate fractures and water supplies has been successfully used in other parts of the United States and the world (Parizek and Gold, 1997).

In 1996, the Kentucky Geological Survey began using linear features delineated from remote-sensing imagery to identify fracture zones in the Eastern Kentucky Coal Field. As a part of this study, KGS conducted field reconnaissance and exploratory drilling at locations of linear features in order to identify water-producing fractures within fracture zones and determine the quality and quantity of the water available from these fractures. KGS developed a technique of using inclined exploration boreholes to identify the subsurface fractures and accurately site high-yield, vertical production wells to intersect them.

Regional Geology and Hydrogeology

The Eastern Kentucky Coal Field is part of the Appalachian Coal Field, which extends from Pennsylvania to Alabama (see Figure 1). The coal field is a large, intricately dissected upland characterized by narrow, crooked valleys and narrow, irregular, steep-sided ridges. Most of the smaller creeks have narrow valley floors, whereas larger streams have floodplains of moderate width. Local relief increases from 300 ft in the north near the Ohio River to about 2,500 ft in the south along Pine Mountain, near the Tennessee-Kentucky border (Price and others, 1962).

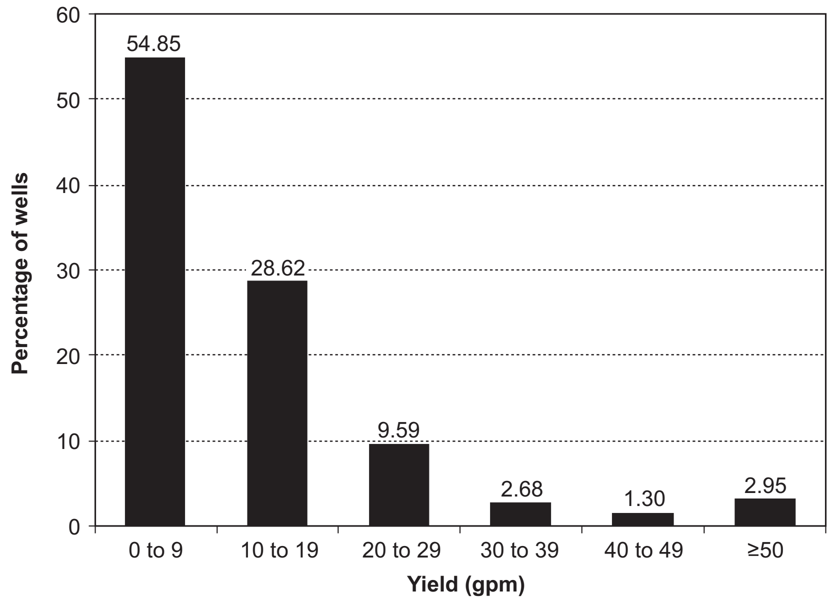


Figure 2. Distribution of reported well yields in the Eastern Kentucky Coal Field, compiled from the Kentucky Groundwater Data Repository. The total number of wells is 7,453, drilled from January 1985 through October 2002.

More than 90 percent of the bedrock underlying the coal field belongs to the Upper to Middle Pennsylvanian Breathitt Group (Fig. 3) (Chesnut, 1992). The rocks of the lower part of the Breathitt Group (Grundy Formation down to the Pacahontas Formation) consist mainly of quartzose sandstone formations separated by shale, sandstone, and coal. The rocks of these formations are exposed mainly along the western edge of the coal field. The quartzose sandstones are characteristically fine to medium grained, conglomeratic in places, well sorted, massive, and crossbedded (Price and others, 1962). The quartzose sandstones of the lower part of the Breathitt Group were previously classified as part of the Lee Formation. The upper part of the Breathitt Group (Pikeville Formation up to the Princess Formation; see Figure 3) contains most of the coal-bearing strata in eastern Kentucky (Chesnut, 1992). The coal beds and associated underclays are interbedded in layers with discontinuous lenses of sandstone, shale, and siltstone (Price and others, 1962). The sandstones are medium to very fined grained, poorly sorted, and contain rock fragments, clay, and siderite within the pore spaces (Price, 1956; Price and others, 1962).

Ferguson (1967), Wyrick and Borchers (1981), and Harlow and LeCain (1991) have documented a network of fractures superimposed on the strata of the Appalachian Coal Field. Kipp and Dinger (1991) documented a near-surface fracture zone in the hillside and valley bottom of an unmined part of a basin in northwestern Knott County. Within this fracture zone were both vertical and horizontal (bedding plane) fractures. From a study of joints at four large roadcuts in Perry County, Sirek (1995) concluded that the controlling factors for fracture development in eastern Kentucky are topography, bed thickness, and hydraulic fracturing produced by the emplacement of the Pine Mountain Overthrust Block.

Studies prior to 1987 documented the permeability of the rocks in the Breathitt Group. Because of the low permeability of the Breathitt sandstones, groundwater flow primarily occurs in secondary permeability features such as fractures and joints (Price and others, 1962; Kirkpatrick and others, 1963). The quartzose sandstones of the lower part of the Breathitt Group were found to transmit much more water than the sandstones in the upper part of the Breathitt Group (Price and others, 1962).

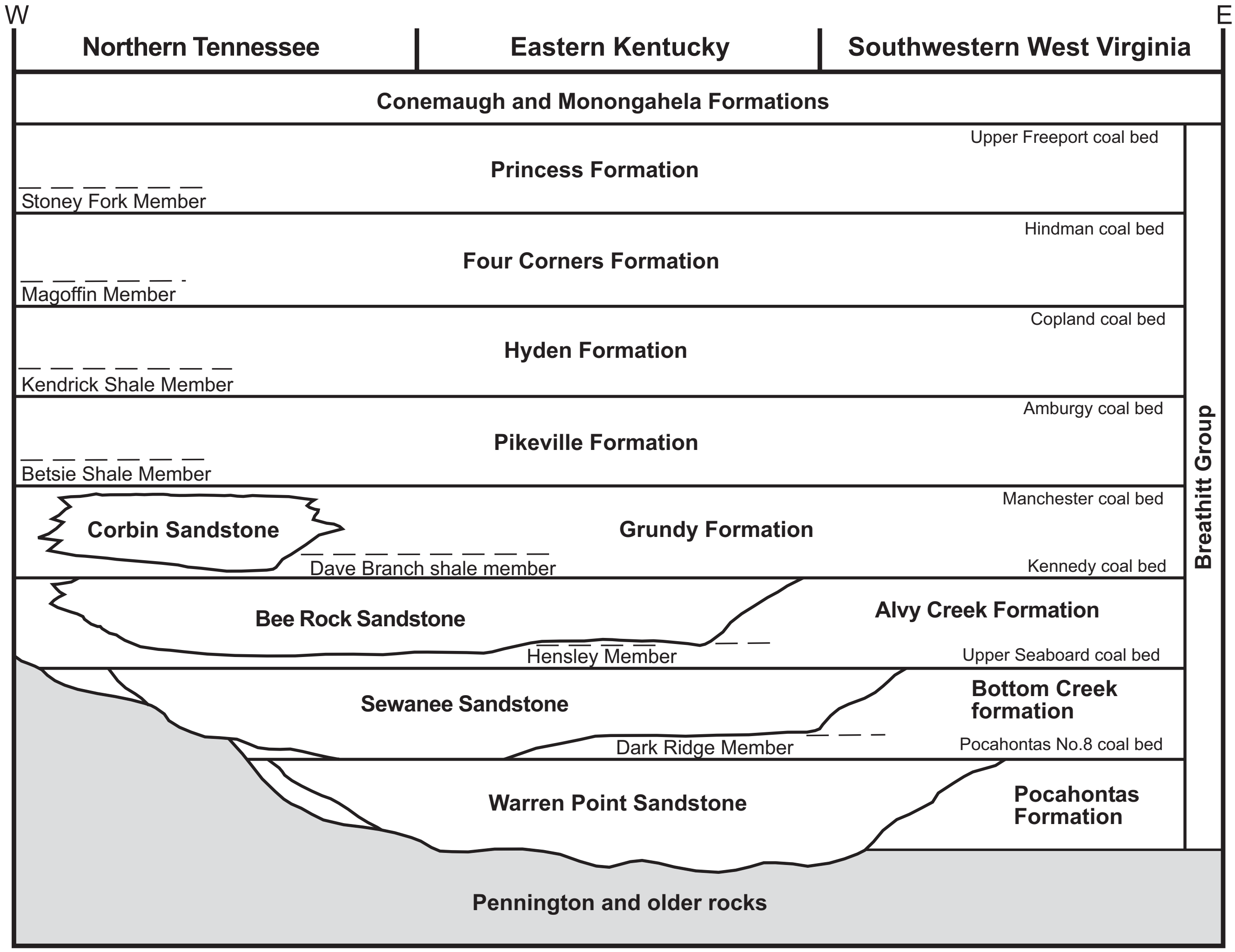


Figure 3. Stratigraphic framework of Pennsylvanian rocks in the Eastern Kentucky Coal Field (Chesnut, 1992).

Kipp and Dinger (1987), Minns (1993), and Wunsch (1993) conducted constant-head pressure-injection tests in order to further document the hydraulic conductivity of eastern Kentucky rocks. These tests were conducted on four cored holes at three sites in eastern Kentucky and encompassed strata in the upper part of the Breathitt Group. Minns (1993) conducted tests spanning 10-ft intervals, whereas Kipp and Dinger (1987) and Wunsch (1993) conducted tests spanning 5-ft intervals. The results of testing on more than 150 intervals are summarized in Table 1.

Intervals consisting predominantly of sandstone and shale/sandy shale had the lowest hydraulic conductivities. For sandstones, the median hydraulic conductivity values determined from Minns (1993) and Wunsch (1993) were 7×10^{-7} ft/min and 2.0×10^{-6} ft/min, respectively (see Table 1). For shales/sandy shale, the median hydraulic conductivity values determined from Minns (1993) and Wunsch (1993) were 4×10^{-7} ft/min and 1.4×10^{-6} ft/min, respectively. Among other lithologies, the intervals with the highest hydraulic conductivity were coals and fractured rock. Minns (1993) found the highest median conductivity in fractured rock (9×10^{-4} ft/min). Wunsch (1993) found the highest median conductivity in coals (1.2×10^{-3} ft/min).

Harlow and LeCain (1991) conducted pressure-injection tests in the Appalachian Coal Field. They tested 349 intervals, each spanning 9 ft, in 43 core holes in southwestern Virginia. The results of their tests (see Table 1) are consistent with the findings of Kipp and Dinger (1987), Minns (1993), and

Table 1. Summary of hydraulic conductivity (K) values determined from pressure-injection tests of cored holes in the Appalachian Coal Field.

Reference	Location	Dominant Lithology	Minimum	Maximum	Median
Kipp and Dinger (1987)	eastern Kentucky	sandstone	4.0×10^{-7}	6.0×10^{-6}	NC[2]
		shale	1.0×10^{-5}	3.2×10^{-6}	NC[2]
Minns (1993)	eastern Kentucky	coal (above drainage)	1×10^{-6}	2×10^{-4}	9×10^{-6}
		coal (below drainage)	8×10^{-7}	2×10^{-6}	6×10^{-7}
		fractured rock	2×10^{-5}	4×10^{-3}	9×10^{-4}
		sandstone	2×10^{-7}	3×10^{-5}	7×10^{-7}
		shale/sandy shale	3×10^{-7}	6×10^{-4}	4×10^{-7}
Wunsch (1993)	eastern Kentucky	coal	2.3×10^{-4}	1.8×10^{-3}	1.2×10^{-3}
		fracture rock	2.5×10^{-6}	3.4×10^{-4}	6.1×10^{-6}
		sandstone	6.8×10^{-7}	7.2×10^{-4}	2.0×10^{-6}
		shale	8.5×10^{-7}	3.3×10^{-4}	1.4×10^{-6}
Harlow and LeCain (1991)	southwestern Virginia	coal[3, 4]	7.7×10^{-8}	4.6×10^{-3}	1.2×10^{-5}
		sandstone[3, 5]	7.7×10^{-8}	1.2×10^{-2}	7.7×10^{-8}
		siltstone and shale[3, 5]	7.7×10^{-8}	1.3×10^{-2}	7.7×10^{-8}

[1] Rock types are classified as dominant either by composing a large percentage of the interval or by being the most important conductor of water flow (i.e., fracture class).

[2] NC=median values were not calculated because of the limited number of data used in this study.

[3] Minimum value (7.7×10^{-8} ft/min) represents lower limit of analytical method and equipment used (Harlow and LeCain, 1991).

[4] Generally, hydraulic conductivity was found to decrease with increasing depth. A small number of tests exhibited low hydraulic conductivity (< 7.7×10^{-8} ft/min) at shallow depths.

[5] Generally, hydraulic conductivity was found to be higher at shallower depths (< 100 ft). Harlow and LeCain (1991) attributed these higher hydraulic conductivities to fractures.

Wunsch (1993). Harlow and LeCain (1991) found that coal intervals had the highest median hydraulic conductivity (1.2×10^{-5} ft/min) and intervals consisting of sandstone, siltstone, and shale had the lowest median hydraulic conductivity (7.7×10^{-8} ft/min). Generally, the hydraulic conductivity of the sandstone, siltstone, and shale intervals was higher at shallower depths (less than 100 ft). Harlow and LeCain (1991) attributed these higher hydraulic conductivities to fractures.

Minns (1993) and Wunsch (1993) developed conceptual models of groundwater flow in eastern Kentucky. The groundwater flow system consists of two components: local and regional flow (Fig. 4). In the local flow system, water infiltrates into the subsurface in first-order stream valleys through the bedrock and shallow fracture zone. The shallow fracture zone may extend from 50 to 200 ft into the subsurface (Kipp and Dinger, 1991; Minns, 1993; Wunsch, 1993). The water travels downward until it comes in contact with a coal seam, where it may be preferentially transmitted horizontally to outslopes and discharged as seeps and springs. Wunsch (1993) concluded that at these outslopes the water may (1) remain on the surface and move to lower elevations as surface runoff, (2) be transpired in the evapotranspirative process, or (3) re-enter the groundwater system at or below the spring or seep, working its way through the shallow fracture zone into major stream valleys (third-order or greater). In the regional flow system, groundwater not directed to the outslopes by the coal seams moves down through the bedrock, discharging at third-order stream valleys (Kipp and Dinger, 1991; Minns, 1993; Wunsch, 1993).

From the analysis of a third-order watershed in Perry County, Wunsch (1993) developed a

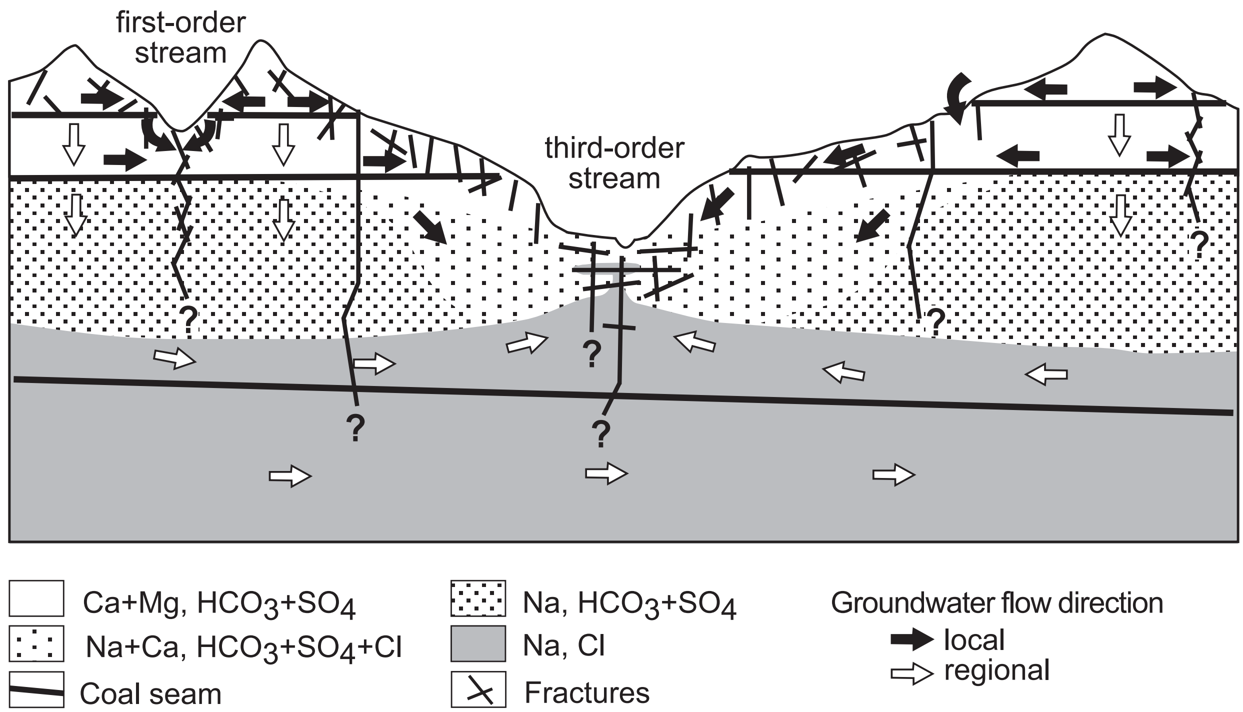


Figure 4. Conceptual groundwater flow and hydrochemical facies model for the Eastern Kentucky Coal Field (modified from Wunsch, 1993).

hydrochemical facies model applicable to the Eastern Kentucky Coal Field and large parts of the Appalachian Coal Field (Callaghan and others, 1998, 2000). The model consists of four hydrochemical zones (see Figure 4). In the first zone, located within and just below the near-surface fracture zone, calcium (Ca), magnesium (Mg), bicarbonate (HCO_3), and sulfate (SO_4) are the dominant cations and anions. The second zone, which is located in the center of upland ridges, is characterized by sodium (Na), HCO_3, and SO_4 as the major ions. The dominant ions in the third zone are Na and chloride (Cl). Beneath third-order streams, the Na and Cl zone is generally thought to be less than 150 ft deep, and fractures may provide pathways for salt water to migrate to even shallower depths. The fourth zone, a mixing zone located below and along the flanks of third-order stream valleys, has Ca, Cl, HCO_3, Na, and SO_4 as its major ions. Wunsch (1993) concluded that this zone results from a mixing of water from the previous three zones in varying percentages as it moves from ridge interiors and the shallow fracture zone toward the major stream valleys. The distinct hydrochemical facies result from water-rock interactions over time. Groundwater reaches a relative equilibrium through chemical (e.g., dissolution) and physical (e.g., cation exchange) reactions with aquifer materials with which it has contact along its flow path. Tritium data show that some water types, such as those with Na-Cl and Na-HCO_3 as the dominant cation-anions, usually represent water that has a long residence time and may be from decades to hundreds of years old, if not older (Wunsch, 1993).

Methods of Linear Features Analysis

Regional fractures in eastern Kentucky are believed to contain and transmit large quantities of groundwater. Minns (1993) suggested that these regional fractures are mostly found below third-order stream valleys. Because of the steep topography in eastern Kentucky, we hypothesized that linear features longer than 1 mi or lineaments according to the classification of Parizek and Gold (1997) (Table 2) could best be used to identify these regional fractures. Fracture and joint traces (linear features less than 1 mi long) are believed to repre-

Table 2. Classification of linear features types and the type of remote-sensing imagery from which they are typically selected (Parizek and gold, 1997).

Linear Feature Type	Length of Linear Feature	Remote-Sensing Typically Selected From:
lineaments	> 1 mi	satellite imagery
fracture trace	330 ft–1 mi	aerial photographs (scale 1:20,000)
joint trace	inches–330 ft	aerial photographs (scale 1:20,000)

sent only localized fracture zones in eastern Kentucky. For these reasons, we examined satellite and low-altitude radar imagery for lineaments in the hope of identifying water-producing fractures that would yield more than 30 gal/min.

The satellite imagery used in this study was collected from the thematic mapper (TM) onboard Landsat 5. This satellite, launched in 1984, orbits the earth at an altitude of 438 mi. The Landsat satellite is considered a passive remote-sensing system because it detects available energy reflected or radiated from terrain. A TM image is separated into six spectral bands, each having a ground cell resolution of 98 ft and one thermal band having a ground cell resolution of 394 ft (Sabins, 1997). We used two December 1991 scenes, each covering a 116 by 109 mi area. Scenes from this time of year were chosen because of the low sun angle, which helps illuminate the lineaments (Dunno, 1998). The two scenes were acquired in digital form from the Kentucky Office of Geographic Information.

The low-altitude radar used in this study was side-looking airborne radar (SLAR). SLAR imagery is collected from aircraft using a beam of microwave energy that is transmitted to the ground at an angle perpendicular to the aircraft's flight path. This results in an obliquely illuminated view of the terrain that enhances subtle features. This type of imagery is considered to be active remote sensing because it emits its own source of energy. The advantage of SLAR over Landsat TM is that it is not dependent upon daylight or optimal weather conditions such as a cloudless day (Sabins, 1997). SLAR imagery consists of a single band that has an average ground cell resolution of 39 ft; each image covers an area 65 mi long by 28 mi wide. We used both analog and digital SLAR imagery, which was collected in 1984 and acquired from the U.S. Geological Survey EROS Data Center in Sioux Falls, S. Dak. The analog imagery consisted of 1 x 2° mosaics of 10 individual SLAR images. The digital imagery consisted of individual images.

All imagery was imported into Imagine, a remote-sensing software package developed by ERDAS, Inc. The digital imagery was imported directly into Imagine, but the analog SLAR data were first scanned using a color drum scanner and then imported into Imagine. The Landsat images were georeferenced to 7.5-minute topographic quadrangle maps, and the SLAR images were georeferenced to the Landsat images.

Using Imagine, two spectral enhancements were applied to the Landsat TM data in order to accentuate the lineaments or make them easier to select. The first enhancement was a red-green-blue/intensity-hue-saturation/red-green-blue (RGB-IHS-RGB) transformation. This transformation was used to improve the interpretability of the image by reducing the six spectral bands of data into a three-band combination that has the most information with the least duplication. The second enhancement was a principal component analysis, which reduced the six spectral bands into one band by eliminating the redundant information between the bands (Dunno, 1998). A separate image was created as a result of applying each of these enhancements.

We delineated lineaments for over 6,400 mi^2 of eastern Kentucky from the original Landsat TM image, the two Landsat images enhanced by RGB-IHS-RGB transformation and principal component analysis, and the SLAR images (Fig. 5).

Lineament delineation is recognized as a subjective process. Many researchers have suggested that in order to make the process more objective or reproducible, more than one person should independently select lineaments from the same image for a given area. Lineaments determined to be coincident between each person are then considered real (Lattman, 1958; Mabee and others, 1994; Parizek and Gold, 1997). In this study, only one person delineated lineaments for a given area at one time. But in order to make the process more objective, lineaments were independently selected

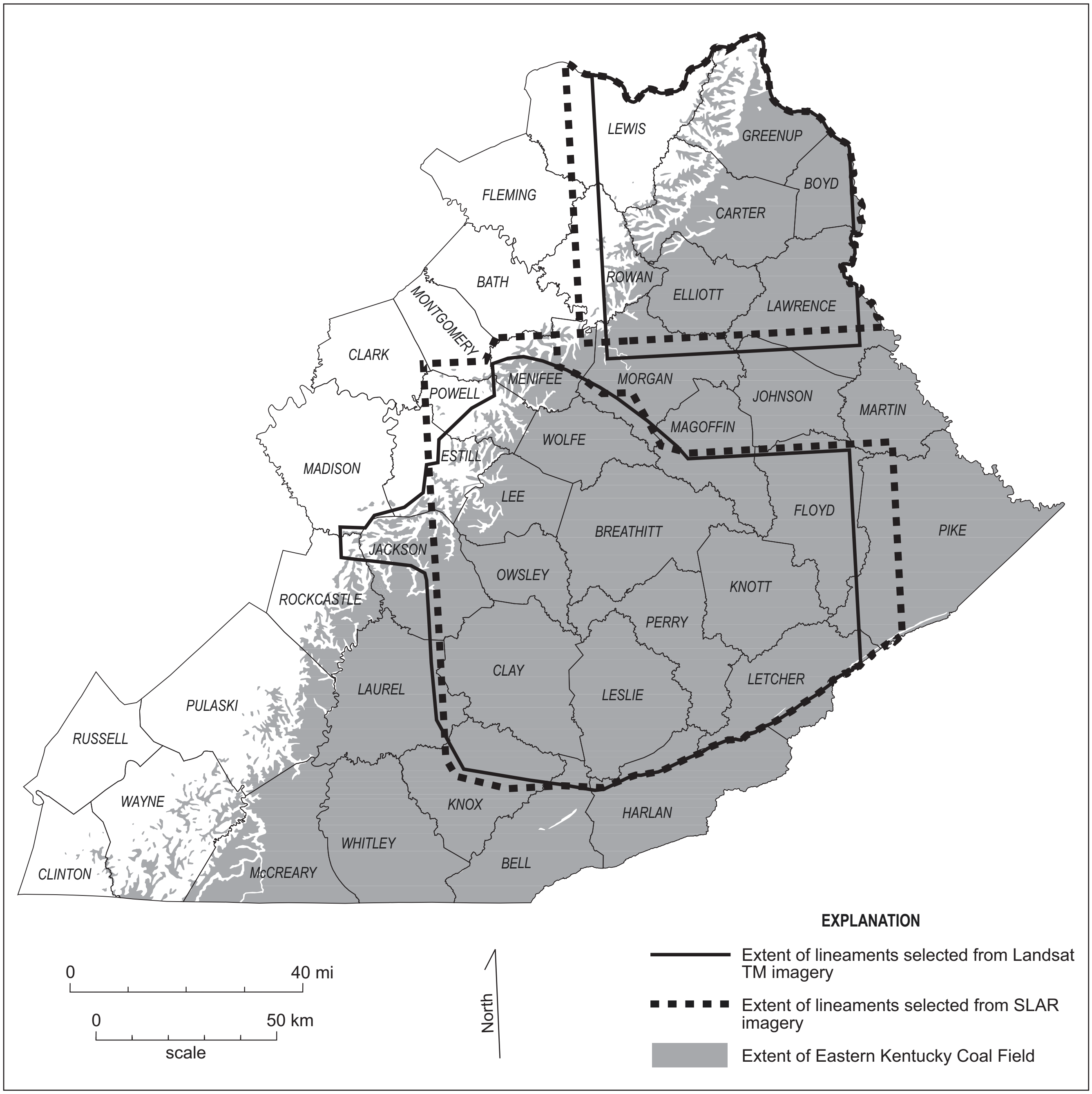


Figure 5. Aerial extent of lineaments selected from Landsat TM and SLAR imagery in the Eastern Kentucky Coal Field.

from all four image types. Another objective of this study was to determine which image type would produce lineaments that best represented structural geologic features of eastern Kentucky.

All selections were completed via on-screen digitizing in Imagine so that the lineaments could be easily exported to geographic information system (GIS) coverages. Lineaments were dilineated at view scales of 1:250,000 and 1:125,000 so that only lineaments were identified. Smaller scales would have resulted in identifying shorter linear features. Periodically these images were rotated in 45^{o} increments to refresh the viewing perspective. Histogram equalization and spatial filtering were applied to all images in order to make delineating the lineaments easier. Lineament selections for each image were limited to 1-hr intervals in order to avoid eye fatigue (Dunno, 1998).

Lineaments derived from the four image types discussed here often appear to be separate and offset when plotted on the same map. This gives the impression that there are several lineaments in close proximity to one another. These lineaments more likely represent the same linear feature and are offset because of different image resolutions and errors in replotting the lineaments at scales larger than the original view scale.

Field Checking of Lineaments

In any lineament delineation study, two relevant questions arise: (1) do the selected linear features relate to the structural geology of the area being studied, and, if so, (2) how do they relate? To answer both questions, we visited the selected lineaments in the field to correlate them to the structural features of the coal field. Eastern Kentucky terrain was reviewed for surficial expressions of fractures, outcrops were examined, and field measurements of structural features such as rock fracture patterns were collected. To date, over 70 sites have been examined in Breathitt, Carter, Clay, Knott, Leslie, Letcher, Perry, and Wolfe Counties, and over 150 fracture orientation and structural measurements have been taken. Field sites were identified and located by overlaying the lineaments onto 7.5-minute topographic quadrangle maps, using GIS software and a handheld global positioning system (GPS) unit.

During these field visits, we found many locations where the delineated lineaments correlated to straight-line topographic features. Stream valleys that develop along fractures contain straight linear segments, which appear on remote-sensing imagery as linear features. A good example of a straight valley correlating with selected lineaments is in Oakdale, along Clover Branch Road and Bowman Branch Road at the intersection with Ky. 52 (Fig. 6). At this site, the north–south-trending lineaments selected from the original Landsat TM image, the RGB/IHS/RGB enhanced Landsat image, the principal component enhanced Landsat image, and the SLAR image correlated with the north–south-trending Clover Branch and Bowman Branch Roads.

Lineaments were also found to correlate with high fracture density, evidenced at highway roadcuts or other locations with extensive rock outcrops. Although not all lineaments and rock exposures that were examined revealed higher than normal fracture densities, some outcrops yielded exciting and dramatic results. One such example is in Knott County along Ky. 80, 3 mi northeast of Hindman (Fig. 7). At this site, two lineaments (A and B) were delineated from the original Landsat TM image. Both have an orientation of N85°W and are separated by 600 ft. In the vicinity of lineament A, two dramatic fractures extend throughout the entire thickness of the roadcut along Ky. 80 (Fig. 8). The southern fracture (on the right side of Figure 8), which is filled in with weathered shale, has an orientation of N85°W. The northern fracture (on the left side of Figure 8) has an orientation of N60°E. Between the two fractures, which are separated by 85 ft, are smaller joints with orientations of N85°W. The two major fractures at this roadcut are not exact expressions of the two lineaments delineated from the Landsat image, but rather represent one fracture zone, which may be expressed as lineament A on the imagery. Lineament B appears to represent a ridgeline, and not a fracture zone that might have large quantities of groundwater.

Exploratory Drilling

After determining that lineaments delineated from Landsat and SLAR imagery can represent fracture zones in eastern Kentucky, we then focused on locating discrete fractures in the subsurface that would produce significant groundwater of suitable quality. In order to identify the discrete fractures, we embarked on a program to drill wells and boreholes in eastern Kentucky at sites identified from the lineament analysis.

Criteria were developed to identify and evaluate suitable drilling sites. This screening process consisted of two phases: a preliminary evaluation and a final evaluation. GIS technologies were used to conduct the preliminary evaluation. Lineament maps were created using 7.5-minute topographic

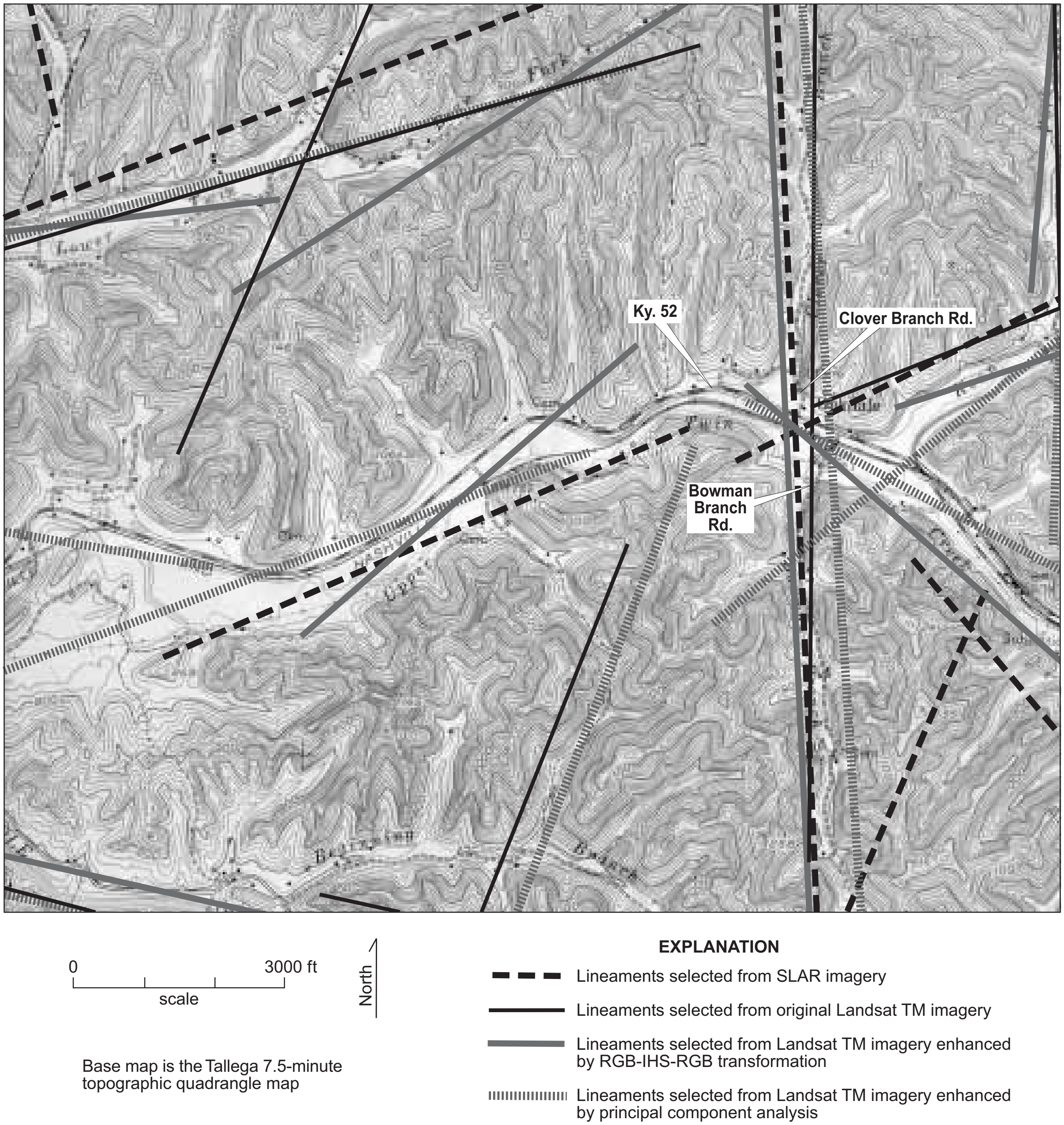
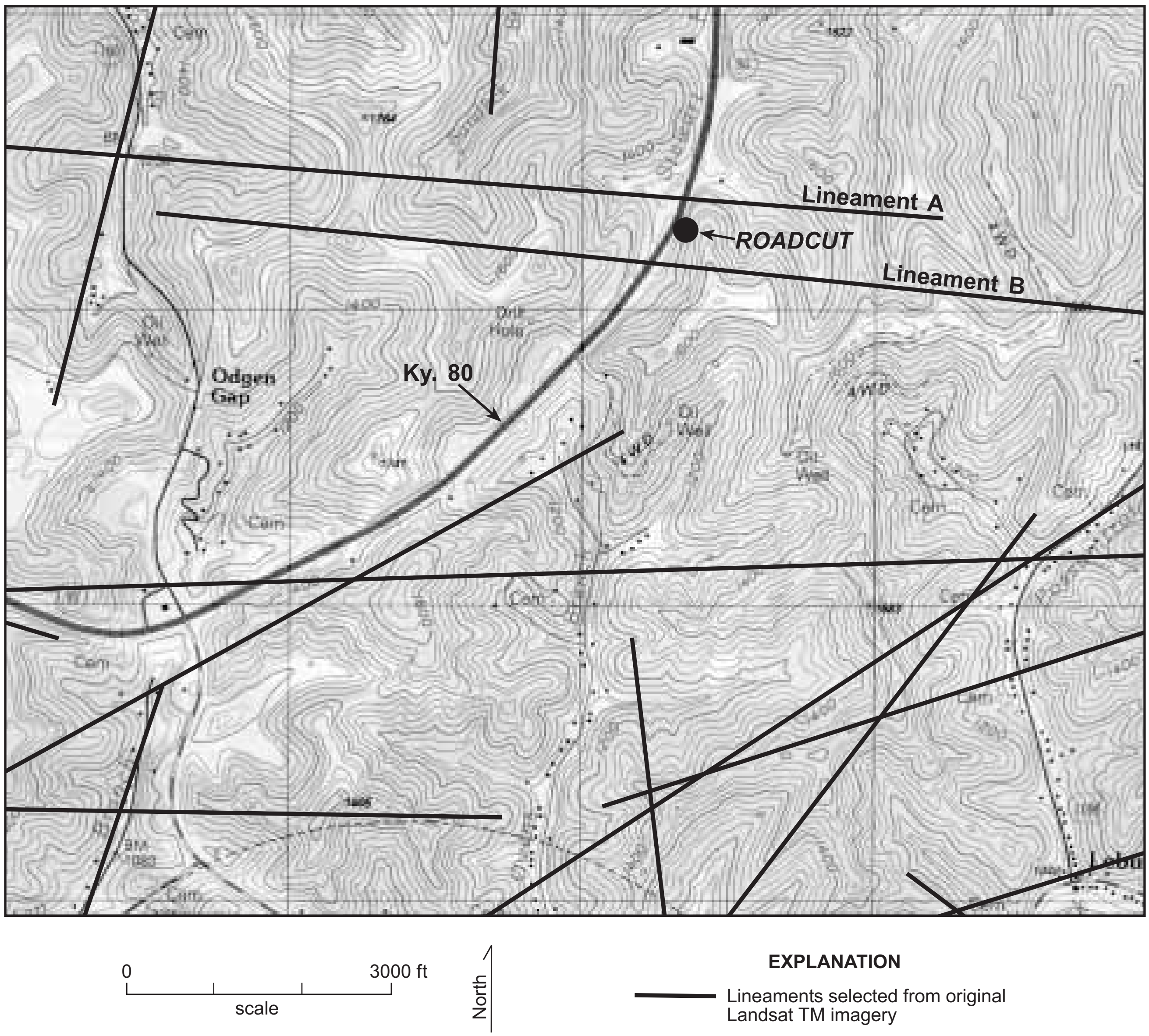


Figure 6. Lineaments selected from Landsat TM and SLAR imagery correlating with straight-line stream valleys at Oakdale, in Breathitt County.



Base map is the Hindman 7.5-minute topographic quadrangle map

Figure 7. Original Landsat TM lineaments and location of roadcut along Ky. 80, north of Hindman.

Figure 8. Fracture zone along Ky. 80 roadcut identified by Landsat TM lineaments (looking east).

quadrangle maps as a base. Sites were identified at or near valley bottoms where crossing lineaments were delineated from more than one image type. Previous work by Parizek and Gold (1997) demonstrates that optimal drilling locations are where lineaments cross, because of their potential to represent the juncture of two fracture zones. In eastern Kentucky, valley bottoms are the principal discharge zones for groundwater and provide the greatest potential for intersecting larger quantities of water.

For the final evaluation, the selected sites were visited to observe the surface geology and topography and look for indications of fractures. Existing subsurface geologic data (geologic maps and borehole data) were also examined for any indication of subsurface fractures and groundwater occurrence. In addition, the sites were evaluated to determine accessibility to drilling equipment.

Initially, vertical production wells were installed in the vicinity of lineament intersections to identify water-producing fractures. Fracture and joint orientation measurements were taken from surrounding roadcuts to assess which lineaments represented the dominant fracture orientations of the area. In addition, electrical resistivity profiles were conducted to aid in the location of the subsurface fractures at each site (Graham and others, 1999). Finally, GPS surveys were used to located wells as closely as possible to site-specific lineaments selected from the georeferenced images.

At two sites in Breathitt and Carter Counties, six vertical production wells were drilled. Even though all the wells intersected fractures, the highest-yielding well produced only 20 gal/min, and the remaining wells yielded less than 10.5 gal/min; two wells yielded as little as 1.5 gal/min (Andrews, 2002a). A well yielding 20 gal/min is significant in eastern Kentucky (this is more than the yields of 83 percent of drilled wells in eastern Kentucky; see Figure 2), but the goal of this research was to locate wells yielding more than 30 gal/min.

Because the targeted yield of 30 gal/min was not achieved, and because of a limited drilling budget, we adopted a technique of using inclined exploration boreholes to identify water-producing fractures and locate drilling sites for production wells. A schematic diagram of the technique is shown in Figure 9. The first step is drilling a 6-in. inclined exploration borehole (approximately 40 to 60° from horizontal) using a pneumatic ham-

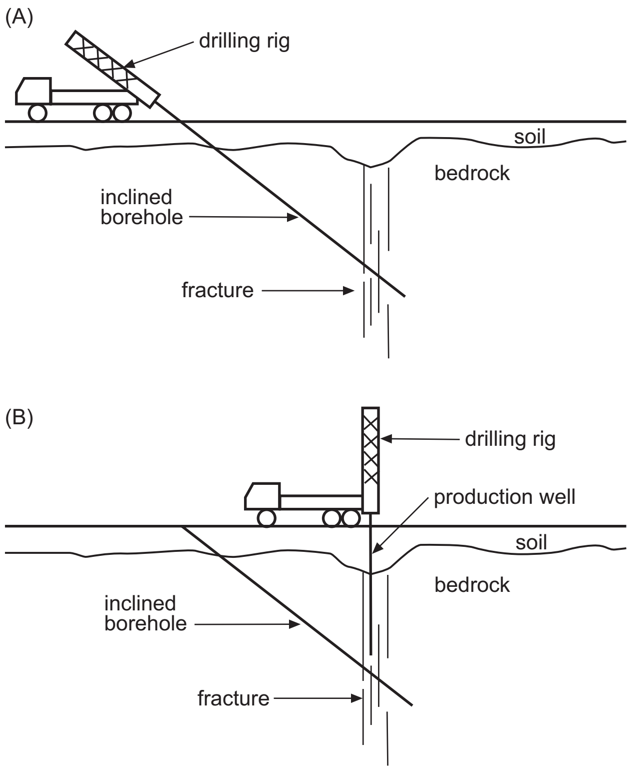


Figure 9. How an inclined exploration borehole is used to locate discrete water-producing fractures. (A) An inclined exploration borehole is drilled to locate a discrete fracture in a fracture zone. (B) A production well is drilled over the fracture discovered from the inclined borehole.

mer and bit (Fig. 9A). While the drill bit advances, water production rates, pH, temperature, and specific conductance are monitored. At the conclusion of drilling, a video camera is advanced down the borehole in order to identify fractures. The video log of the borehole and the water quality and quantity data are used to locate an optimal fracture zone producing groundwater. The drill rig is then placed over the target zone at a point determined by surveying and triangulation, and a vertical production well is installed (Fig. 9B). The total depth of the production well is predetermined by the geochemical monitoring.

The advantage of drilling an exploration borehole inclined from horizontal is that it can be used to examine more of the subsurface at a lower cost than drilling multiple vertical boreholes in the same area. One borehole inclined 40° from horizontal with a length of 250 ft (depth of 161 ft) covers 192 lateral ft. In order to cover the same lateral area, 38 vertical boreholes, each 161 ft deep and located on 5-ft centers, would have to be drilled. At a rate of $10/ft, vertical drilling would cost $61,180, compared to a single inclined borehole that would cost only $6,500 (at $26/ft).

Once a production well was installed, the inclined borehole was abandoned by plugging it with bentonite grout. Even though the inclined borehole identified a significant water-producing fracture, it is not recommended to supply water because of the increased potential of borehole collapse, which could trap the pump. Moreover, most pumps are designed for optimal operation in the vertical position.

For thin fracture zones, the inclined boreholes were abandoned using standard techniques: filling the holes with a bentonite grout slurry. For boreholes that encountered a fracture zone of significant size (greater than 1 ft wide), we filled the boreholes but tried to leave the fracture zone open so as not to interfere with the production well. This goal was accomplished by filling the bottom of the borehole below the water-producing fracture zone with bentonite grout (Fig. 10). A rubber or polypropylene packer was installed just above the fracture zone, and 5 ft of bentonite pellets were placed above the packer. The remainder of the borehole was filled with bentonite grout. The packer assembly consisted of a double-locking well seal packer with a 4-in.-diameter polyvinyl chloride (PVC) cap on the bottom and a 4- to 2-in.-diameter PVC reducer on top. The packer was advanced down the borehole using a 2-in.-diameter PVC pipe that rested on the reducer cap. Once the packer was installed, the PVC pipe was removed.

For video logging of the inclined boreholes, the best method was to place the downhole video camera in threaded sections of 2-in.-diameter PVC pipe (Fig. 11). At the camera end of the pipe, centralizers were used to keep the camera centered in the borehole. The camera was advanced down the borehole by adding sections of pipe. This method protected the camera and allowed ease of movement. For the best identification of potential fractures, the downhole camera survey was conducted at least 12 to 24 hrs after the borehole was completed to allow time for suspended particles in the groundwater to settle in the hole. The camera was lowered slowly into the hole so that sediment was not suspended again in the water.

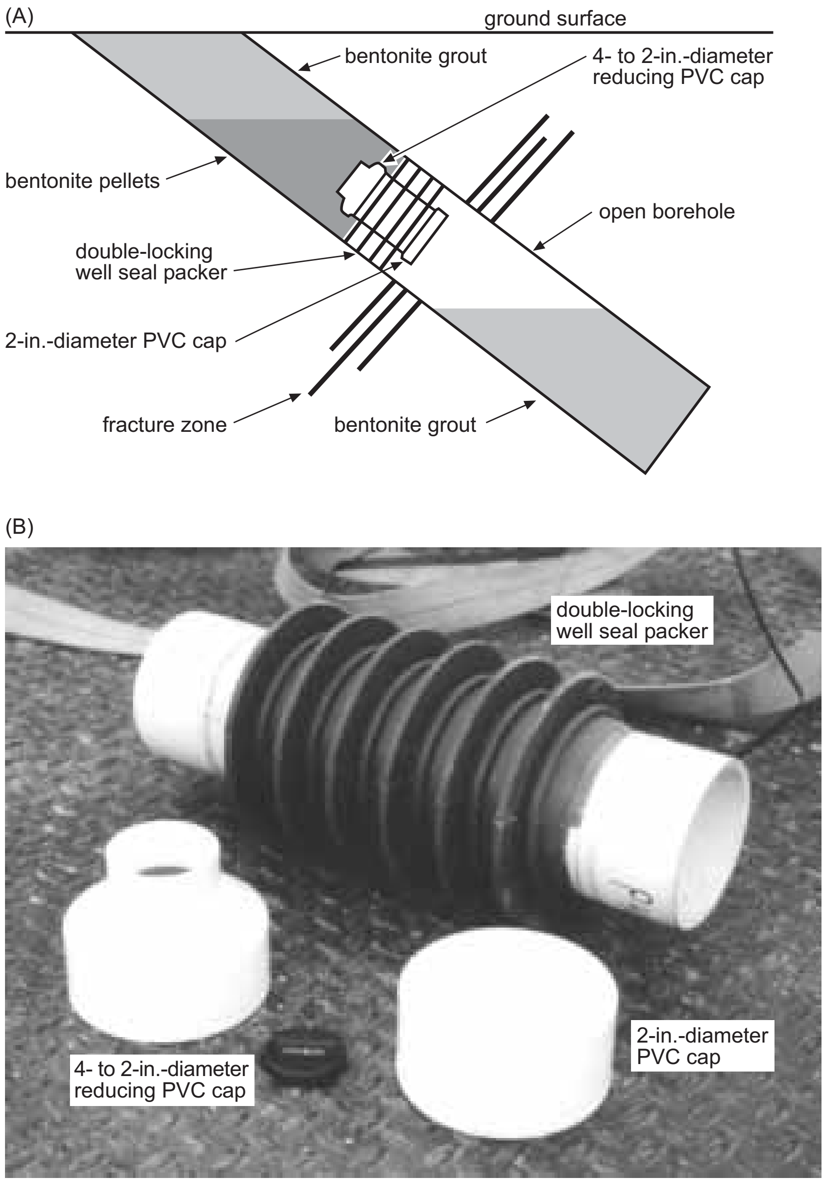


Figure 10. How to abandon an inclined exploration borehole that intersected a fracture zone greater than 1 ft thick. (A) Materials used. (B) Individual parts of the packer assembly. Lens cap for scale.

The inclined boreholes should be oriented perpendicular to lineament orientations so as to intersect as many fractures as possible. Also, the vertical production well should be offset a sufficient distance (a minimum of 5 ft) from the inclined borehole to avoid sealing off the production well with bentonite grout when the borehole is abandoned.

Results of Drilling

Since 1998, the inclined drilling technique has been used at six sites in eastern Kentucky (Fig. 12), and production wells have been installed at four of the sites. Constant-rate aquifer tests, which had a duration of 12 or 48 hrs, showed that the yield of these production wells ranged from 47 to 72 gal/min, surpassing the project goal of 30 gal/min. Water levels in production wells at the Vest and Isom sites recharged to their initial elevations within 32 hrs after pumping stopped (Andrews, 2002a, b). At Oakdale, the water level in the production well recharged to its initial elevation within 80 hrs after pumping stopped (Andrews, 2002c), and at Creekville, complete recharge occurred within 13 days.

Water samples were collected at the beginning, midpoint, and end of each aquifer test. These samples were analyzed for total and dissolved metals and the following anions: bicarbonate, chloride, fluoride, nitrate-nitrogen, and sulfate. The chemical data collected from these samples are presented in Appendix A. Figure 13 shows Stiff diagrams, which illustrate the average water type of the groundwater derived from the 12- and 48-hr tests. The groundwater from Creekville, Oakdale, and Vest had a total dissolved solids (TDS) concentration of less than 500 mg/L, which is the U.S. Environmental Protection Agency's secondary standard for drinking water. Water with a TDS concentration less than 500 mg/L is considered to be of good quality.

Both the Oakdale and Vest wells produced Na-HCO_3 type water, and the Creekville well produced Ca-HCO_3 type water. The Isom well produced Na-Cl type water. Typically, Na-HCO_3 water is older and is usually encountered in the interior of upland areas (see Figure 4), which have undergone extensive cation exchange along with contemporaneous dissolution of carbonate miner-

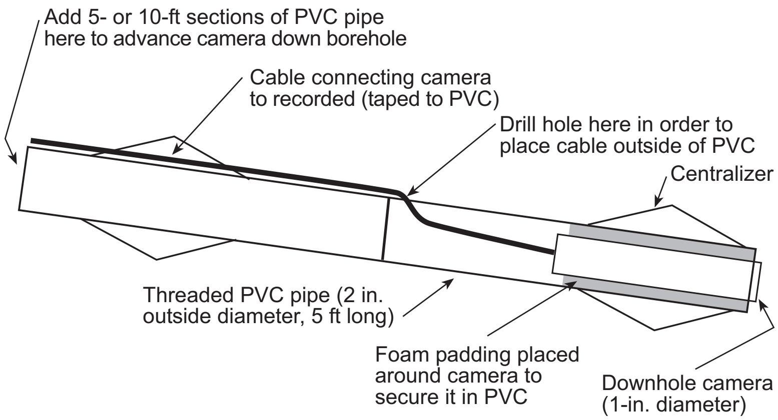


Figure 11. Cross section of the apparatus used to advance a camera down inclined boreholes.

als (calcite, siderite) and sulfate reduction (Wunsch, 1993). Na-HCO_3 water suggests that the source of recharge into these wells is along fractures connected to upland interior ridges surrounding the valley where each well was drilled. The Ca-HCO_3 water encountered at Creekville is usually the youngest water type in a region; this may indicate that recharge into this well is relatively local. The Na-Cl type water at Isom indicates that recharge into this well is from a deep regional source (Wunsch, 1993).

The water samples collected during the aquifer tests also give insight into the source of recharge into these wells. During the 48-hr tests, Na and Cl concentration increased slightly over time in all wells, suggesting that an improperly managed well could ultimately draw salty water beyond tolerable limits over extended pumping times. Other cation ratios appeared to change with pumping as well. For example, during the course of the aquifer test the Ca concentration in the Creekville well remained relatively unchanged, while the Na concentration doubled from approximately 17 to 38 mg/L. Chloride and HCO_3 increased as well. These data suggest that the fracture systems controlling the groundwater flow in the studied areas are in sufficient hydraulic connection to allow the wells to capture water from various hydrochemical facies zones identified for the Eastern Kentucky Coal Field (see Figure 4).

Because 48-hr tests are not long enough to determine the long-term trends that will occur during the useful lives of the wells, a 30-day aquifer test was conducted on the Vest well. For the first 27 days, the well was pumped at 55 gal/min, and for the remaining 72 hrs it was pumped at 75 gal/min. The water level recovered to 10 percent of its initial depth within 3 days after completion of the test (Andrews, 2002b). Water samples were collected weekly during the 30-day test and analyzed for the same constituents as for the shorter tests. Figure 14 shows Stiff diagrams illustrating the water type at the beginning, middle, and end of the test. The chemical data collected from these samples are presented in Appendix B.

Some similar hydrochemical trends were observed during the 30-day test as occurred during the 48-hr test. At the conclusion of the 30-day test, the Vest well continued to produce Na-HCO_3 type water (see Figure 14). The Na and Cl concentrations decreased slightly over the course of the 30-day test, opposite to what was observed during the 48-hr test, when a slight increase was recorded. Over the course of the 30-day test, the ratio of cations changed with pumping. Calcium and Mg concentrations increased by factors of 6 and 26, respectively. In addition, SO_4 concentration increased by a factor of 5 over the course of the test. During the 48-hr test, Ca and Mg concentrations increased only slightly, and SO_4 concentration decreased only slightly.

Lessons Learned from Applying Inclined Drilling Technique

The application of the inclined drilling technique at the six sites in eastern Kentucky has been a learning experience. The different geologic and hydrogeologic situations encountered at each site enabled further refinement of the technique.

At the Isom site, inclined drilling indicated that we were in a fracture zone (Fig. 15). The water-producing fracture in the production well was at about 25 ft, however, above the depth of surface casing required by Kentucky regulations. Although no water-producing fractures were encountered below the depth of the inclined borehole (97 ft),

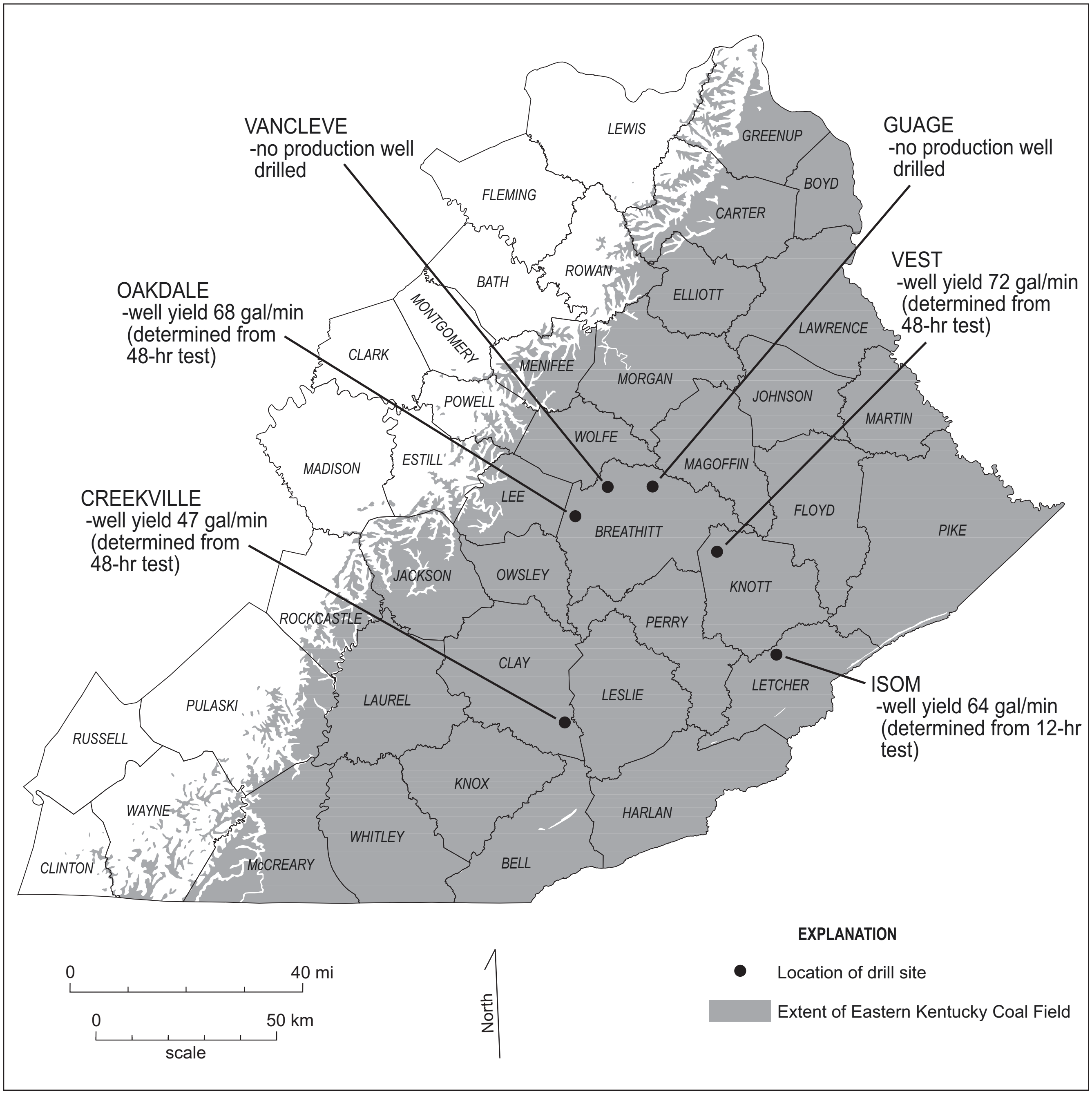
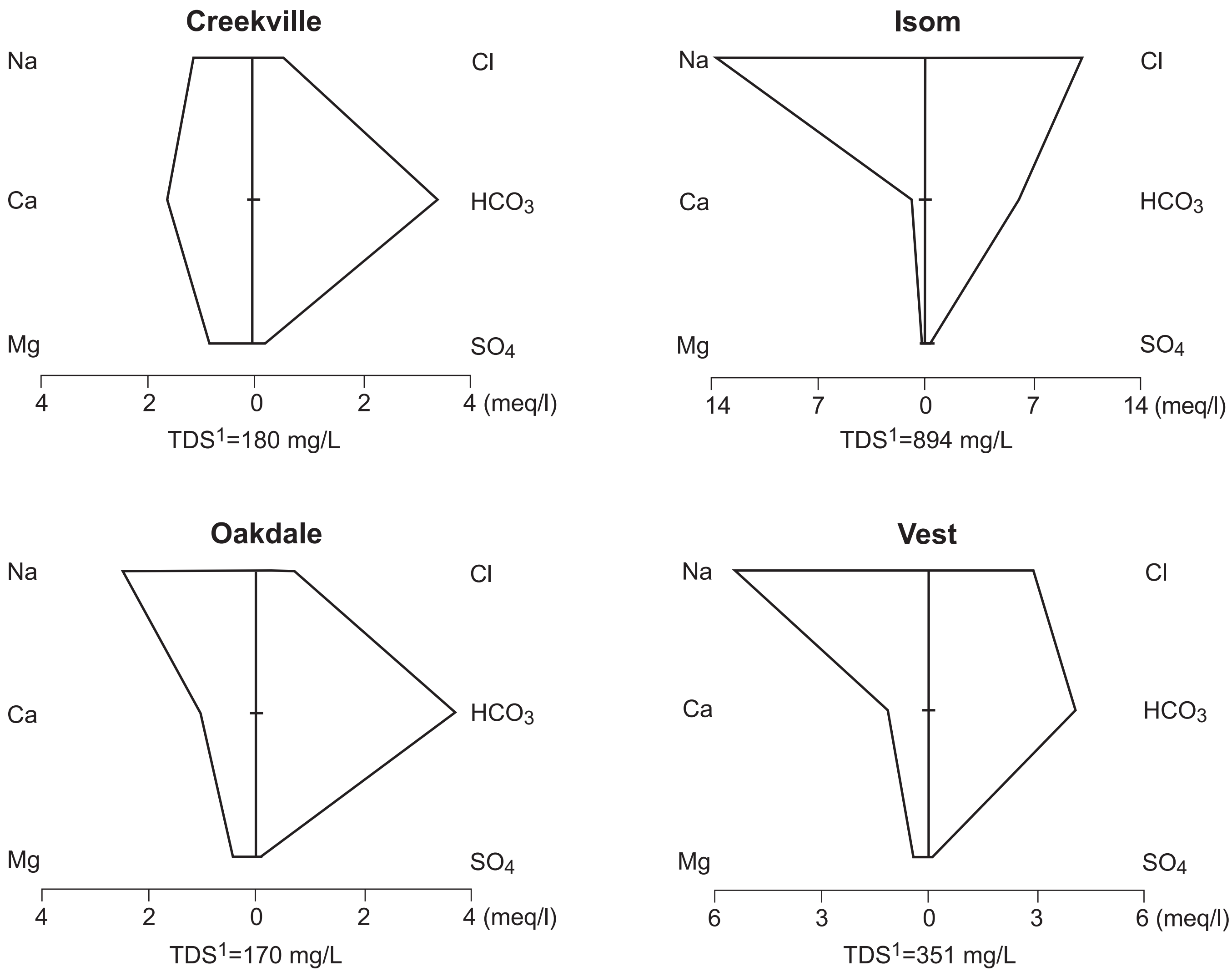
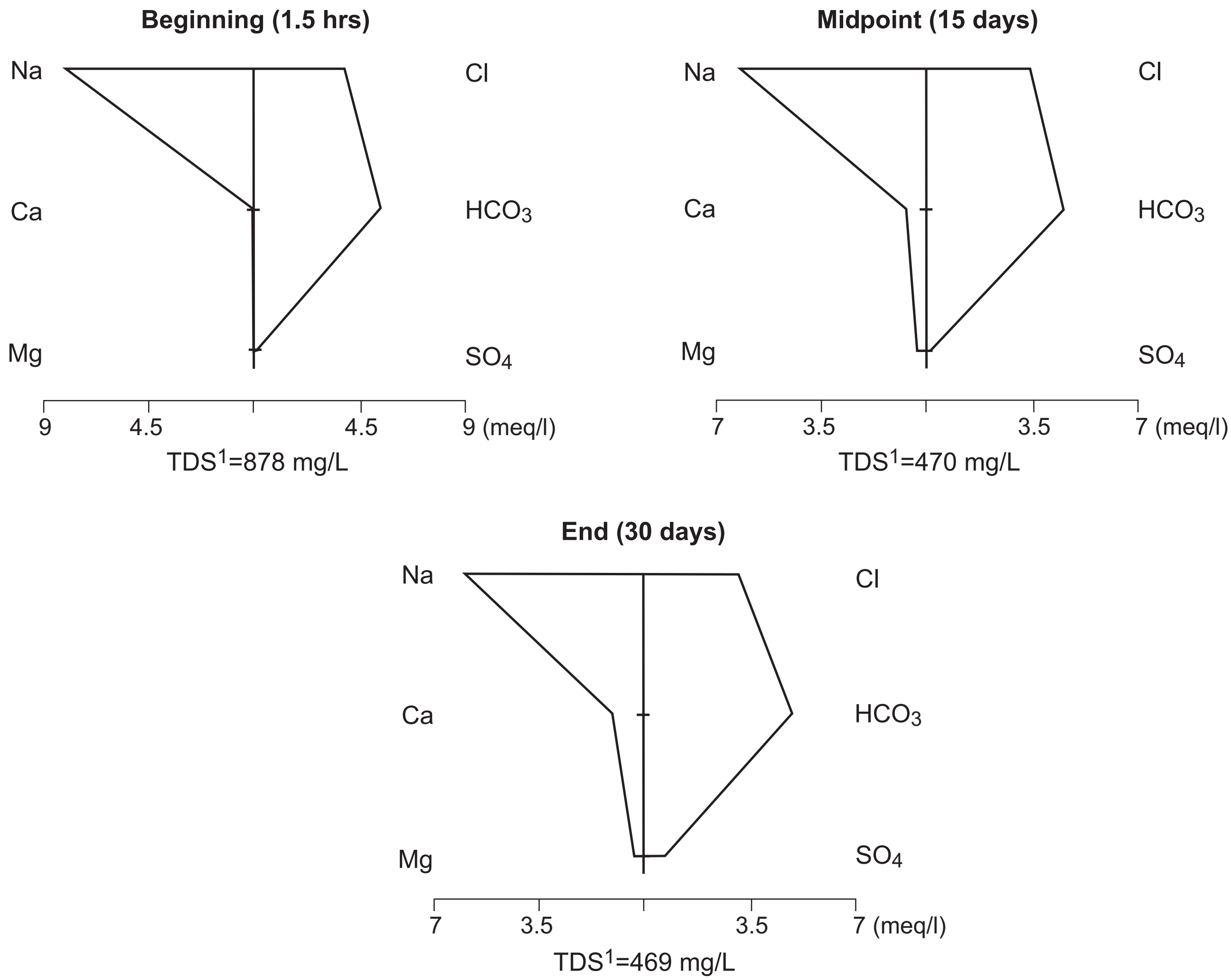


Figure 12. Locations and yields of production wells drilled in the Eastern Kentucky Coal Field using the inclined drilling technique.



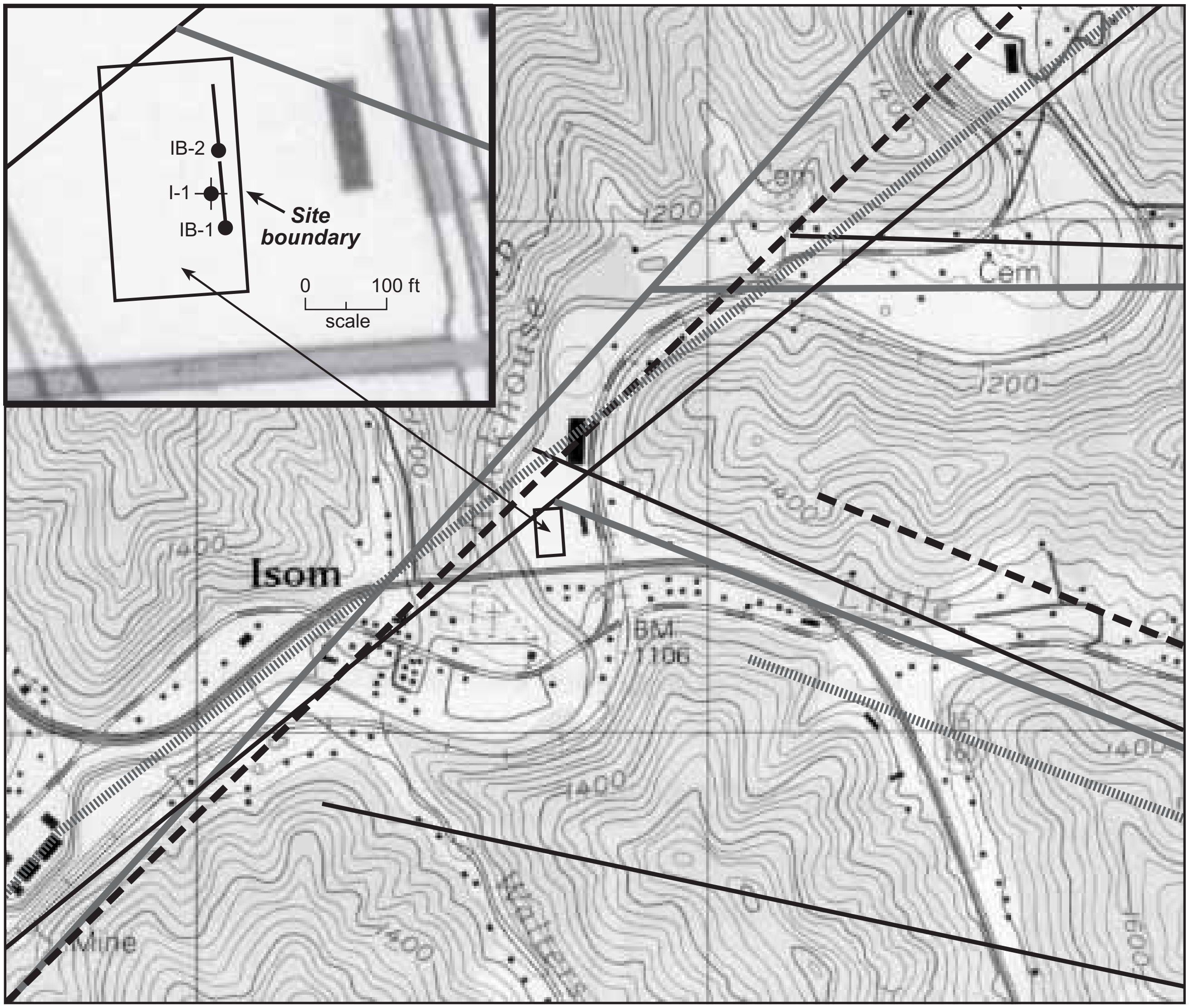
[1]Total dissolved solid (TDS) concentration calculated with HCO_3 converted by gravimeteric factor (HCO_3 (mg/L) x 0.4917) to CO_3 (Hem, 1992).

Figure 13. Stiff diagrams summarizing the water qualify of the wells located using inclined drilling technique (meq/l=milliequivalence per liter).



[1]Total dissolved solid (TDS) concentration calculated with HCO_3 converted by gravimeteric factor (HCO_3 (mg/L) x 0.4917) to CO_3 (Hem, 1992).

Figure 14. Stiff diagrams summarizing the water qualify of the Vest well during the 30-day aquifer test.



EXPLANATION

I-1 Production well

IB-1 Length and location of inclined exploration boreholes (dot indicates top of borehole)

0 2000 ft
scale

North

Lineaments selected from SLAR imagery

Lineaments selected from original Landsat TM imagery

Lineaments selected from Landsat TM imagery enhanced by RGB-IHS-RGB transformation

Lineaments selected from Landsat TM imagery enhanced by principal component analysis

Base map is the Isom 7.5-minute topographic quadrangle map

Figure 15. The Isom drilling site.

we were encouraged to drill the production well deeper because we knew we were in a fracture zone, and anticipated that we would encounter a fracture zone with water. At 113 ft, a 1.5-ft-thick fractured gray sandstone was intersected, resulting in a yield of 64 gal/min.

Experience gained from this study strongly suggests that inclined drilling should be done in the center of valleys and perpendicular to identified lineaments. The Vancleve drilling site (see Figure 12) was located near lineament intersections on a previously graded bench, 50 ft above the surface of a fourth-order valley floor (Fig. 16). This site was chosen to test the hypothesis that by drilling on a bench along a hillside, water-producing fractures identified by the lineaments could be intersected and the shallow saltwater (NaCl) interface in the center of the valley could be avoided. Two inclined boreholes were drilled 200 ft at an inclination of 40° from horizontal (128.6 ft deep). These boreholes penetrated about 80 ft below the valley floor, but they were subparallel and offset to the major identified lineaments for the valley. No water-producing fractures were identified in either of these boreholes; therefore, no production well was drilled at this site.

At subsequent drilling sites (Creekville, Guage, Oakdale, and Vest) all inclined boreholes were located in valley bottoms and oriented across and perpendicular to a linear valley identified by the lineaments. Given the mostly horizontal strata of eastern Kentucky, orienting the boreholes across the center of a valley provides the best chance of intercepting the fracture zone represented by the valley. Because a linear valley is most likely an erosional expression of a fracture zone, orienting the inclined borehole perpendicular to a linear valley will allow more fractures to be encountered than drilling parallel to the valley.

We believe that, whenever possible, the inclined borehole should be located as close as possible to the mouth of the valley where it empties into a higher-order valley. This limits the targeted width of the fracture zone and subsequently reduces the length of the inclined borehole. A good example of following this guideline was at the Oakdale site (see Figure 12), where the targeted lineament was oriented north–south (Fig. 17). The drilling site was located at the mouth of the narrow north valley rather than in the large valley bottom to the south. This was done because the north-oriented valley was an erosional expression of a fracture zone, and only one inclined borehole was needed to identify the water-producing fracture zone. Selecting a drilling site in the broader valley to the south probably would have required more than one inclined borehole to identify the fracture zone that created the valley.

A major concern for obtaining potable water from wells drilled in valley bottoms in the Eastern Kentucky Coal Field is the shallow saltwater interface. Wunsch (1993) documented that the freshwater-saltwater interface generally occurs 150 ft below major stream valleys (third-order or greater). In the center of valleys, salt water can occur at depths less than 150 ft (see Figure 4). A specific conductance greater than 1,000 microSiemens/cm (µS/cm) often indicates the presence of high chloride in groundwater.

A shallow saltwater interface was observed at three sites: Creekville, Guage, and Vest (see Figure 12). The Creekville site (Fig. 18) was located along a fourth-order stream valley and the Vest site (Fig. 19) was located close to the mouth of a first-order valley near a fourth-order valley. By monitoring the specific conductance during the installation of the inclined boreholes at these sites, we were able to identify the water-producing fractures that did not contain salt water and therefore determine the suitable depth and location of production wells. At each of these sites, wells located in fractures near the hillside did not contain salt water. Even though no salt water was encountered during the installation and testing of the production wells, continued use of the wells might cause salt water to be drawn into the well.

At the Guage site, which was located at the intersection of a fourth-order and a fifth-order stream, two inclined boreholes were drilled (Fig. 20). In the first hole (GB-1), the first water encountered (at a depth of 64 ft) had a specific conductance of 1,840 µS/cm. Even though the second hole (GB-2) was located closer to a hillside, the first water encountered in it (at a depth of 51 ft) was also salty, with a specific conductance of 1,480 µS/cm. Laboratory analysis of the water from this borehole indicated a Cl concentration of 324 mg/L. Because salt water was encountered during the

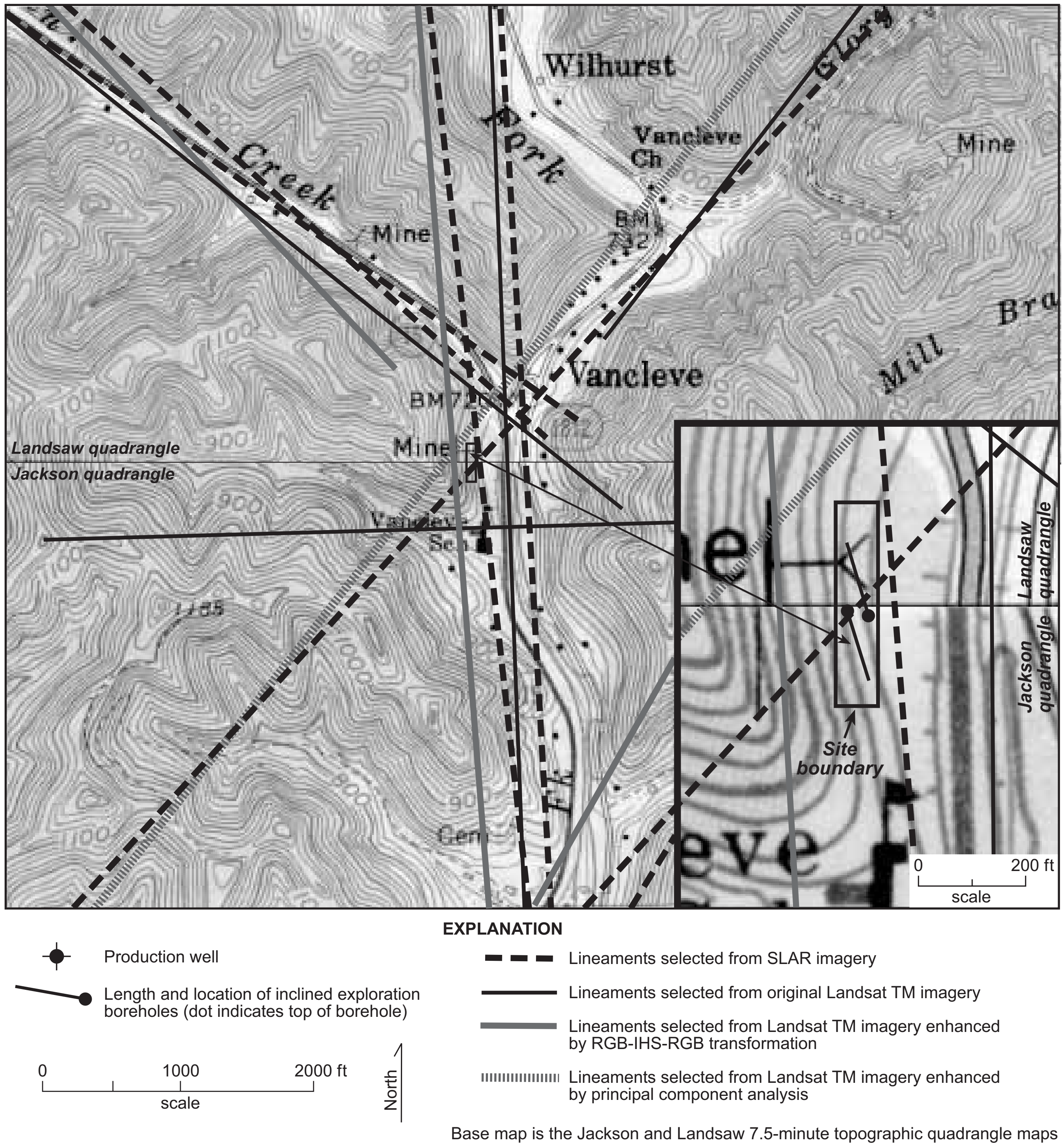


Figure 16. The Vancleve drilling site.

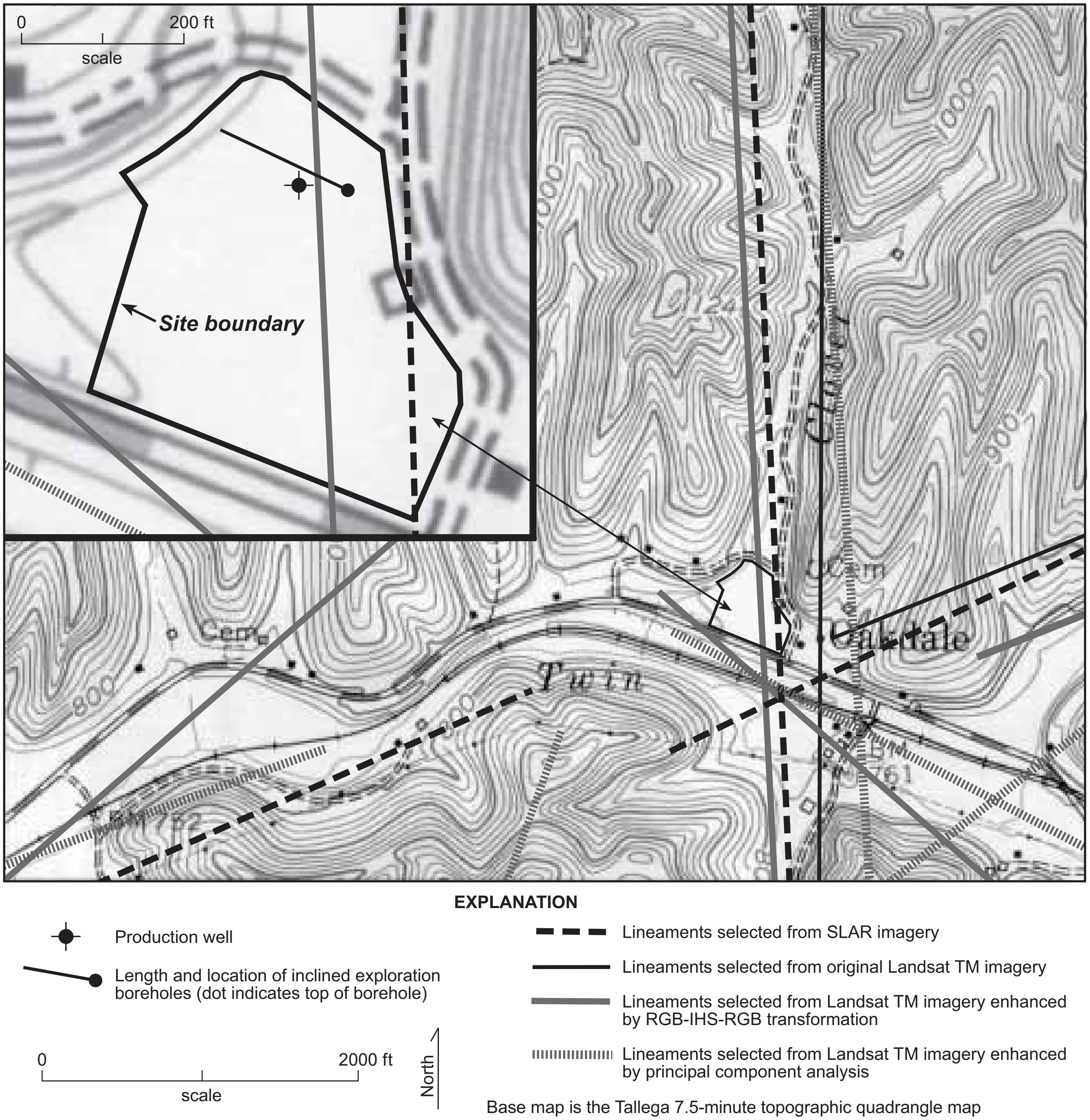


Figure 17. The Oakdale drilling site.

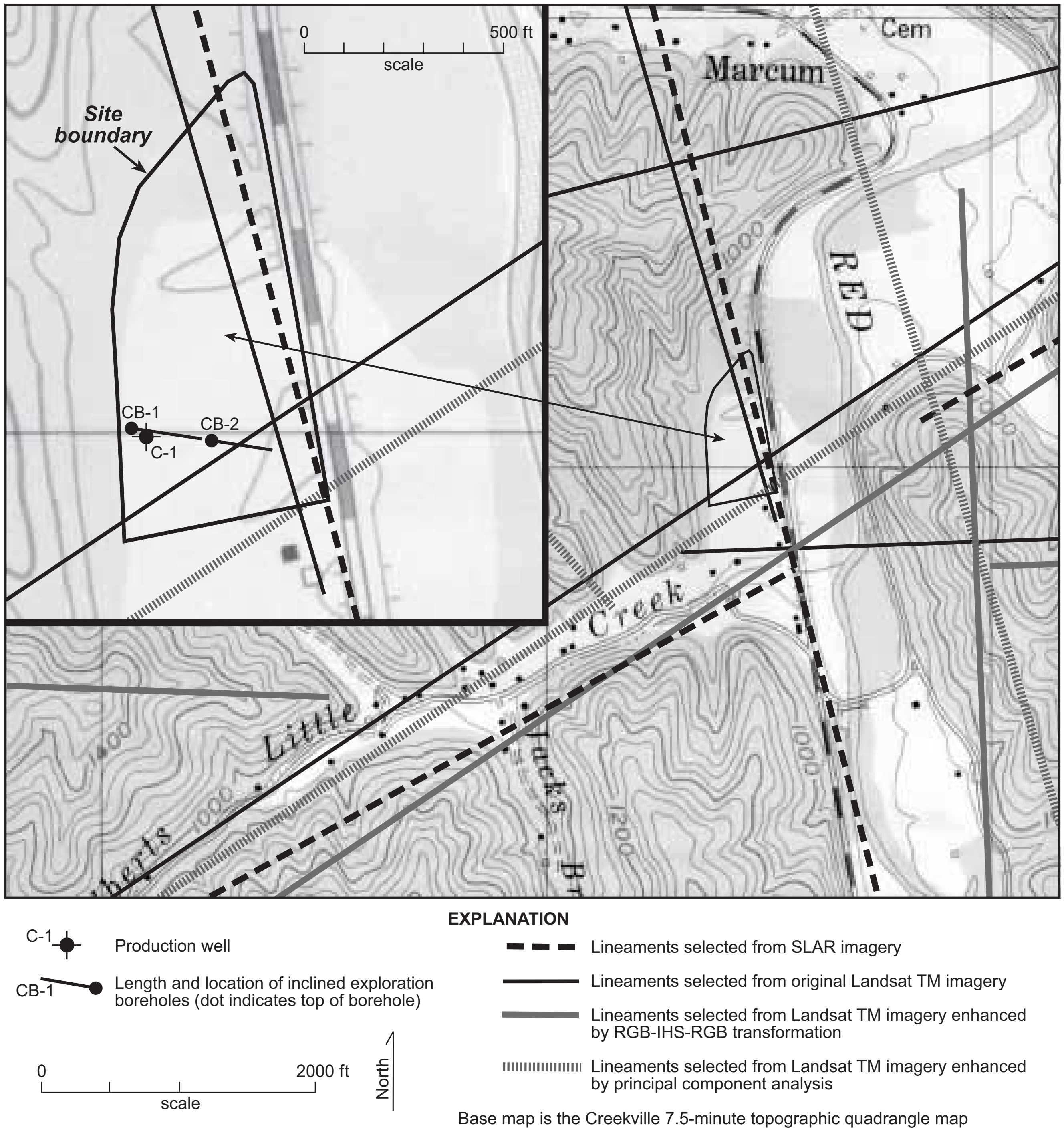


Figure 18. The Creekville drilling site.The location of production well C-1 was selected based on fractures found in inclined borehole CB-1.

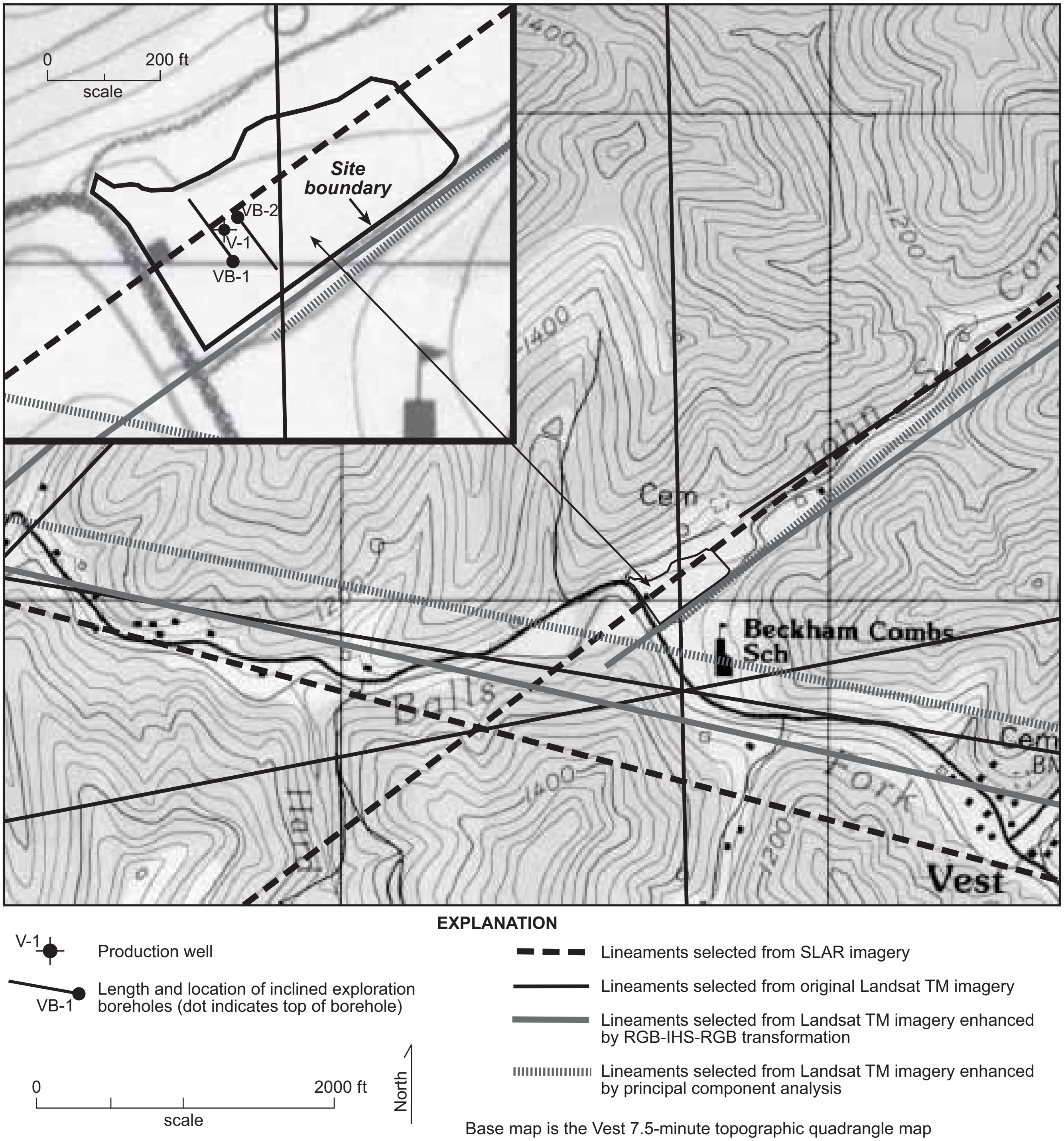


Figure 19. The Vest drilling site. The location of production well V-1 was selected based on fractures found in inclined borehole VB-1.

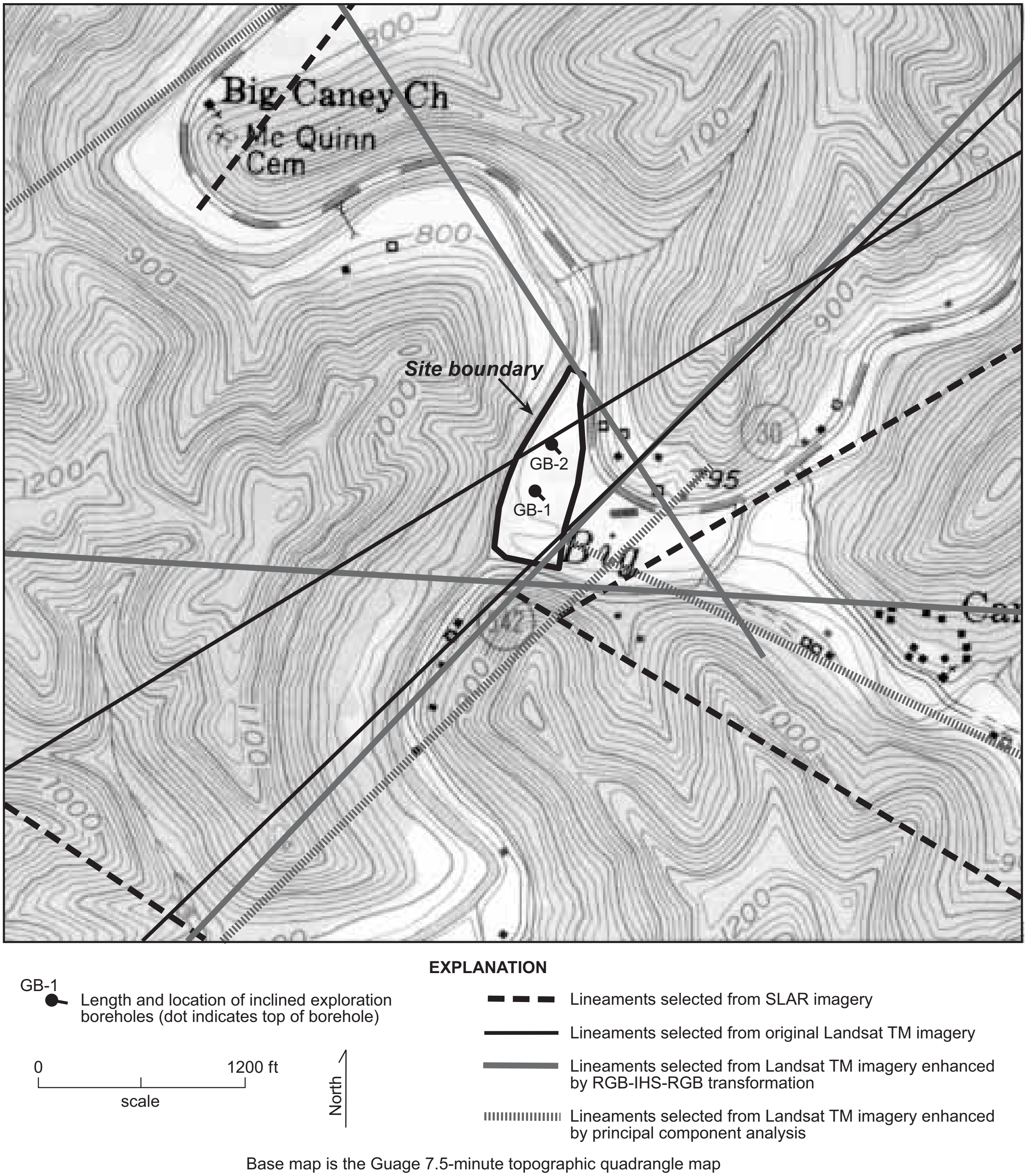


Figure 20. The Guage drilling site.

drilling of the borehole, we decided not to install a production well at this site.

Statistical Analysis of Inclined Drilling Technique

The yields of the four wells located using the inclined drilling technique were compared to yields reported in well completion records available from the Kentucky Groundwater Data Repository in October 2002 (the same data used in Figure 1). The yields of the wells drilled in each county in this study were greater than the yields of 95 percent of all the other wells drilled in each county (Fig. 21). In fact, the yields of the wells in this study were greater than the yields of 95 percent of the wells drilled in the entire Eastern Kentucky Coal Field (Fig. 22).

Future Research Needed

The findings of this study suggest that the application of remote-sensing and inclined drilling techniques improves the chances of locating high-yielding wells in the Eastern Kentucky Coal Field. Because of the varying geologic, hydrogeologic, and topographic settings of the coal field, however, additional research needs to be conducted to refine the techniques. The inclined drilling technique needs to be applied at more sites in eastern Kentucky, particularly in first- and second-order stream valleys, to determine if these locations in upland areas can produce significant groundwater with suitably low salinity. Additional long-term pumping of the production wells located by these methods is needed to assess their long-term water quality and quantity characteristics. Results of these long-term tests will affect the potential use of these wells. More field studies, incorporating outcrop measurements and geophysical techniques, are needed to better correlate lineaments to the structural features of the region. Results of these field studies will greatly enhance our ability to use lineaments to identify fracture zones and possibly eliminate lineaments identified from images that do not represent eastern Kentucky structural features important to groundwater supply. Finally, this technique should be tested in other regions of Kentucky where hydrogeologic conditions include karst, low-permeability shales, and semiconsolidated sediments.

Acknowledgments

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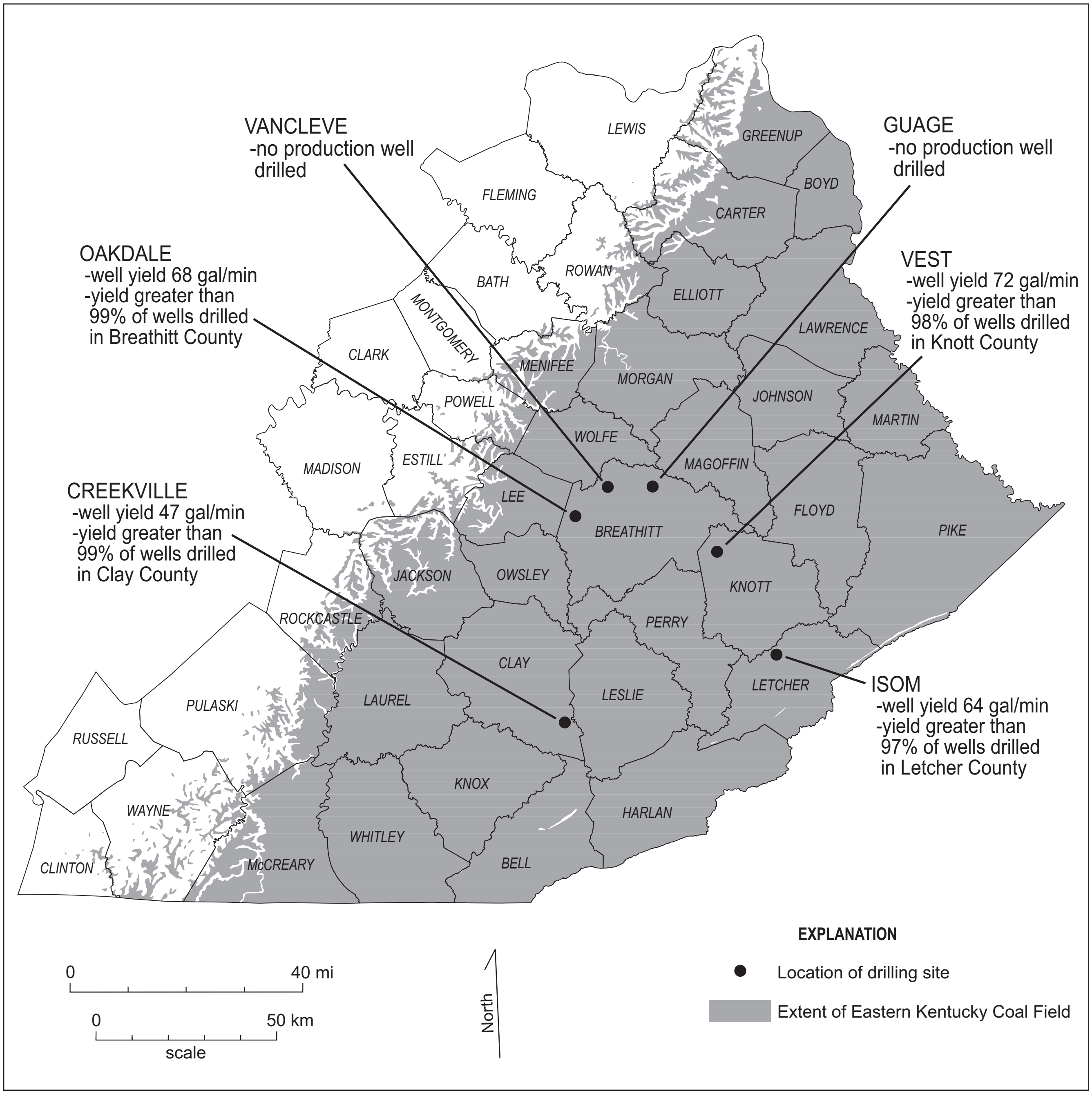

Figure 21. Comparison of yields of production wells drilled in the Eastern Kentucky Coal Field using the inclined drilling technique to yields of wells in Breathitt, Clay, Knott, and Letcher Counties. County data from the Kentucky Groundwater Data Repository, January 1985 to October 2002.

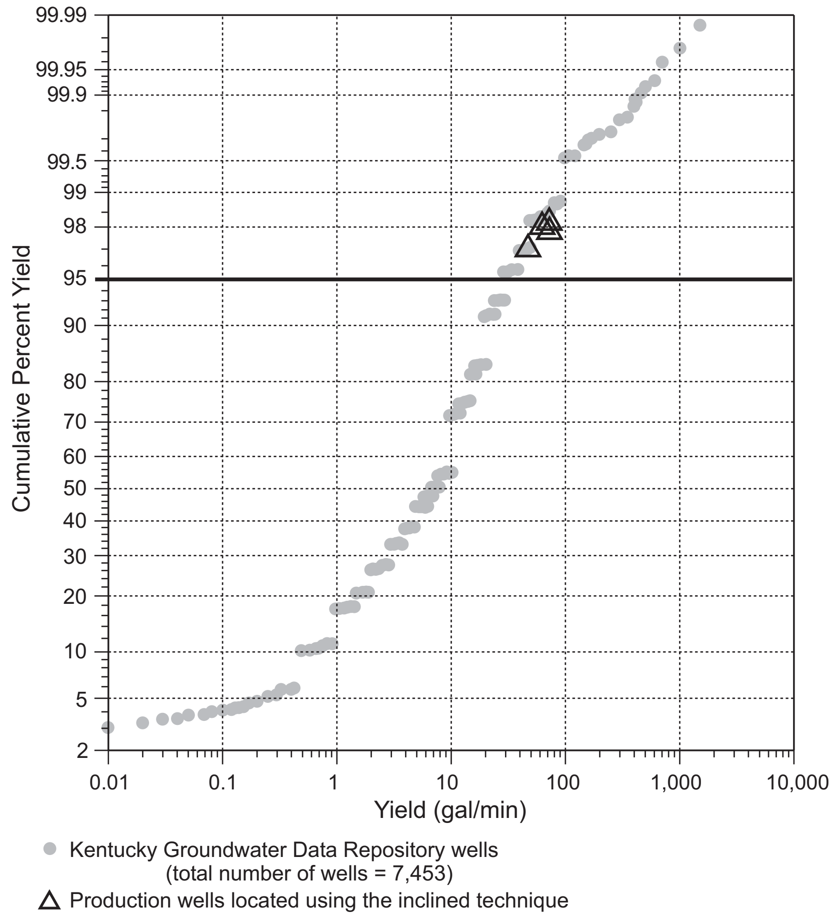

Figure 22. Comparison of the yield of production wells located using remote sensing and inclined drilling technique to yields of all reported wells in the Eastern Kentucky Coal Field. Data from the Kentucky Groundwater Data Repository, October 2002.

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Appendix A: Water Quality Data Collected During Aquifer Tests

Creekville (48-hour test)

All values in mg/L unless otherwise noted. Values with the “<”symbol indicate that the concentration is below the method’s detection limit.

Sample ID	C-1 START	C-1 MID	C-1 FINAL
Collection date & time	6/12/00 3:45 PM	6/13/00 2:00 PM	6/14/00 12:30 PM
Time since start of test	1.7 hours	23.9 hours	46.5 hours
pH (std. units)[1]	6.65	6.72	6.87
Conductivity (µS/cm)	0.317	0.354	0.427
Temperature (°C)[1]	14.3	15.2	14.6
Bicarbonate	193	204	218
Chloride	8.6	17.4	32.7
Fluoride	0.47	0.45	0.43
Nitrate	< 0.02	< 0.02	< 0.02
Nitrate-N	< 0.004	< 0.004	< 0.004
Sulfate	6.8	6.3	6.1
Total dissolved solids	154	180	206
Dissolved metals by ICP			
Aluminum	< 0.041	< 0.041	< 0.041
Antimony	< 0.060	< 0.060	< 0.060
Arsenic	< 0.012	< 0.012	< 0.012
Barium	0.27	0.37	0.45
Beryllium	< 0.0002	< 0.0002	< 0.0002
Boron	< 0.002	< 0.002	< 0.002
Cadmium	< 0.008	< 0.008	< 0.008
Calcium	32.27	32.58	32.98
Chromium	< 0.014	< 0.014	< 0.014
Cobalt	0.003	0.003	< 0.002
Copper	< 0.009	< 0.009	< 0.009
Gold	< 0.002	0.01	0.004
Iron	1.98	1.74	1.69
Lead	< 0.020	< 0.020	< 0.020
Lithium	< 0.006	0.007	0.01
Magnesium	11.07	10.42	10.33
Manganese	0.17	0.15	0.14
Nickel	0.006	< 0.005	< 0.005
Phosphorus	0.11	0.12	0.13
Potassium	0.76	0.90	1.06
Selenium	< 0.011	< 0.011	< 0.011
Silicon	10.42	10.40	9.85
Silver	< 0.010	< 0.010	< 0.010
Sodium	16.94	25.09	38.34
Strontium	0.28	0.40	0.48
Sulfur	1.93	1.77	1.68

Note:
[1] Parameter measured in the field.

Creekville (continued)

Sample ID	C-1 START	C-1 MID	C-1 FINAL
Thallium	< 0.075	< 0.075	< 0.075
Tin	< 0.138	< 0.138	< 0.138
Vanadium	< 0.013	< 0.013	< 0.013
Zinc	0.008	< 0.002	< 0.002
Sodium	16.94	25.09	38.34
Total metals by ICP			
Aluminum	0.32	< 0.041	< 0.041
Antimony	< 0.060	< 0.060	< 0.060
Arsenic	< 0.012	< 0.012	< 0.012
Barium	0.28	0.37	0.46
Beryllium	< 0.0002	< 0.0002	< 0.0002
Boron	< 0.002	< 0.002	< 0.002
Cadmium	< 0.008	< 0.008	< 0.008
Calcium	32.23	32.57	33.59
Chromium	< 0.014	< 0.014	< 0.014
Cobalt	< 0.002	< 0.002	< 0.002
Copper	< 0.009	< 0.009	< 0.009
Gold	0.009	< 0.002	0.004
Iron	2.83	1.75	1.83
Lead	< 0.020	< 0.020	< 0.020
Lithium	0.007	< 0.006	0.01
Magnesium	10.92	10.32	10.59
Manganese	0.18	0.15	0.15
Nickel	0.0053	< 0.005	< 0.005
Phosphorus	0.20	0.13	0.15
Potassium	0.69	0.87	1.11
Selenium	< 0.011	< 0.011	< 0.011
Silicon	10.77	10.32	10.12
Silver	< 0.010	< 0.010	< 0.010
Sodium	16.79	25.06	39.13
Strontium	0.29	0.39	0.48
Sulfur	1.97	1.77	1.73
Thallium	< 0.075	< 0.075	< 0.075
Tin	< 0.138	< 0.138	< 0.138
Vanadium	< 0.013	< 0.013	< 0.013
Zinc	0.006	< 0.002	< 0.002

Note:
[1] Parameter measured in the field.

Isom (12-hour test)

All values in mg/L unless otherwise noted. Values with the "<"symbol indicate that the concentration is below the method's detection limit.

Sample ID	I-1 START	I-1 MID	I-1 FINAL
Collection date & time	9/8/98 3:35 PM	9/8/98 9:05 PM	9/8/98 3:00 AM
Time since start of test	0.5 hours	6.0 hours	11.9 hours
pH (std. units)[1]	8.18	8.15	8.24
Conductivity (µS/cm)	1.95	1.77	1.71
Temperature (°C)[1]	16.7	14.9	14.6
Bicarbonate	380	354	351
Chloride	407	353	330
Fluoride	1	0.92	0.94
Sulfate	< 0.02	< 0.02	< 0.02
Nitrate	0.1	< 0.1	< 0.1
Nitrate-N	0.02	< 0.02	< 0.02
Total dissolved solids[2]	982	877	824
Dissolved metals by ICP			
Aluminum	< 0.022	< 0.022	< 0.022
Antimony	< 0.049	< 0.049	< 0.049
Arsenic	< 0.051	< 0.051	< 0.051
Barium	2.24	1.96	1.76
Beryllium	0.0006	0.0006	0.0006
Boron	0.096	0.099	0.081
Cadmium	<0.007	<0.007	<0.007
Calcium	19.5	15.9	14.4
Chromium	< 0.022	< 0.022	< 0.022
Cobalt	< 0.011	< 0.011	< 0.011
Copper	0.01	0.006	0.007
Gold	< 0.021	< 0.021	< 0.021
Iron	0.314	0.218	0.19
Lead	< 0.052	< 0.052	< 0.052
Lithium	0.069	0.064	0.06
Magnesium	4	3.41	3.09
Manganese	0.026	0.012	0.01
Nickel	< 0.021	< 0.021	< 0.021
Phosphorus	0.085	< 0.054	< 0.054
Potassium	3.13	2.85	2.63
Selenium	< 0.034	< 0.034	< 0.034
Silicon	5.18	5.35	5.19
Silver	not analyzed	not analyzed	not analyzed
Sodium	349	316	291
Strontium	2.59	2.26	2.03

Notes:

[1] Parameter measured in the field.

[2] Total dissolved solid (TDS) concentration calculated with HCO_3 converted by gravimetric factor (HCO_3 [mg/L] x 0.4917) to CO_3 (Hem, 1992).

Isom (continued)

Sample ID	I-1 START	I-1 MID	I-1 FINAL
Total metals by ICP			
Aluminum	< 0.022	< 0.022	< 0.022
Antimony	< 0.049	< 0.049	< 0.049
Arsenic	< 0.051	< 0.051	< 0.051
Barium	2.24	1.96	1.76
Beryllium	0.0006	0.0006	0.0006
Boron	0.096	0.099	0.081
Cadmium	< 0.007	< 0.007	< 0.007
Calcium	19.5	15.9	14.4
Chromium	< 0.022	< 0.022	< 0.022
Cobalt	< 0.011	< 0.011	< 0.011
Copper	0.010	0.006	0.007
Gold	< 0.021	< 0.021	< 0.021
Iron	0.314	0.218	0.190
Lead	< 0.052	< 0.052	< 0.052
Lithium	< 0.069	0.064	0.060
Magnesium	4.0	3.41	3.09
Manganese	0.026	0.012	0.010
Nickel	< 0.021	< 0.021	< 0.021
Phosphorus	0.085	< 0.054	< 0.054
Potassium	3.13	2.85	2.63
Selenium	< 0.034	< 0.034	< 0.034
Silicon	5.18	5.35	5.19
Silver	not analyzed	not analyzed	not analyzed
Sodium	349	316	291
Strontium	2.59	2.26	2.03
Sulfur	0.895	0.566	0.431
Thallium	< 0.035	< 0.035	< 0.035
Tin	< 0.139	< 0.139	< 0.139
Vanadium	< 0.005	< 0.005	< 0.005
Zinc	0.008	< 0.007	< 0.007

Notes:

[1] Parameter measured in the field.

[2] Total dissolved solid (TDS) concentration calculated with HCO_3 converted by gravimetric factor (HCO_3 [mg/L] x 0.4917) to CO_3 (Hem, 1992).

Oakdale (48-hour test)

All values in mg/L unless otherwise noted. Values with the "<"symbol indicate that the concentration is below the method's detection limit.

Sample ID	**O-1START**	**O-1MID**	**O-1FINAL**
Collection date & time	4/17/00 6:50 PM	4/18/00 4:00 PM	4/19/00 4:00 PM
Time since start of test	1.7 hours	22.8 hours	46.8 hours
pH (std. units)[1]	6.87	7.13	7.01
Conductivity (µS/cm)	0.353	0.432	0.427
Temperature (°C)[1]	13.5	13.7	14.9
Bicarbonate	190	240	240
Bromide	< 1.0	< 1.0	< 1.0
Chloride	17.8	25.0	25.7
Fluoride	0.19	0.29	0.30
Nitrate (NO_3)	< 0.02	< 0.02	< 0.02
Nitrate-N (NO_3-N)	< 0.004	< 0.004	< 0.004
Sulfate	7.3	< 5.0	< 5.0
Total dissolved solids	148	196	166
Dissolved metals by ICP			
Aluminum	< 0.022	< 0.022	< 0.022
Antimony	< 0.059	< 0.059	< 0.059
Arsenic	< 0.006	< 0.006	< 0.006
Barium	0.16	0.19	0.18
Beryllium	< 0.0006	< 0.0006	< 0.0006
Boron	0.007	0.04	0.04
Cadmium	< 0.006	< 0.006	< 0.006
Calcium	19.96	22.3	22.53
Chromium	< 0.016	< 0.016	< 0.016
Cobalt	< 0.002	< 0.002	< 0.002
Copper	< 0.008	< 0.008	< 0.008
Gold	0.01	0.007	< 0.004
Iron	6.32	2.92	2.37
Lead	< 0.006	< 0.006	< 0.006
Lithium	< 0.007	< 0.007	< 0.007
Magnesium	5.75	5.79	5.77
Manganese	0.26	0.13	0.12
Nickel	< 0.033	< 0.033	< 0.033
Phosphorus	0.49	0.30	0.23
Potassium	2.34	2.56	2.53
Selenium	0.02	0.02	0.02
Silicon	7.91	7.42	7.33
Silver	< 0.006	< 0.006	< 0.006
Sodium	44.59	63.48	66.16
Strontium	0.18	0.20	0.20
Sulfur	2.15	1.38	1.23
Thallium	< 0.023	< 0.023	< 0.023
Tin	< 0.081	< 0.081	< 0.081
Vanadium	< 0.024	< 0.024	< 0.024
Zinc	< 0.003	< 0.003	< 0.003

Note:
[1] Parameter measured in the field.

Oakdale (continued)

Sample ID	O-1START	O-1MID	O-1FINAL
Total metals by ICP			
Aluminum	3.39	0.17	0.18
Antimony	< 0.059	< 0.059	< 0.059
Arsenic	0.008	< 0.006	< 0.006
Barium	0.18	0.19	0.19
Beryllium	< 0.0006	< 0.0006	< 0.0006
Boron	0.04	0.08	0.07
Cadmium	< 0.006	< 0.006	< 0.006
Calcium	20.46	21.97	22.22
Chromium	< 0.016	< 0.016	< 0.016
Cobalt	< 0.002	< 0.002	< 0.002
Copper	< 0.008	< 0.008	< 0.008
Gold	0.01	0.005	0.005
Iron	7.85	2.50	2.97
Lead	< 0.006	< 0.006	< 0.006
Lithium	< 0.007	< 0.007	< 0.007
Magnesium	6.25	5.63	5.83
Manganese	0.27	0.11	0.13
Nickel	< 0.005	< 0.005	< 0.005
Phosphorus	0.55	0.24	0.28
Potassium	2.91	2.48	2.55
Selenium	0.02	< 0.009	< 0.009
Silicon	14.36	7.29	7.61
Silver	< 0.006	< 0.006	< 0.006
Sodium	45.45	64.47	63.64
Strontium	0.18	0.19	0.19
Sulfur	2.16	1.09	1.12
Thallium	< 0.023	< 0.023	< 0.023
Tin	< 0.081	< 0.081	< 0.081
Vanadium	< 0.024	< 0.024	< 0.024
Zinc	< 0.003	< 0.003	< 0.003

Note:
[1] Parameter measured in the field.

Vest (48-hour test)

All values in mg/L unless otherwise noted. Values with the “<”symbol indicate that the concentration is below the method’s detection limit.

Sample ID	**V-1START**	**V-1MID**	**V-1FINAL**
Collection date & time	5/15/00 4:15 PM	5/16/00 1:00 PM	5/17/00 1:00 PM
Time since start of test	1.5 hours	22.3 hours	46.3 hours
pH (std. units)[1]	7.42	7.40	7.49
Conductivity (μS/cm)	0.684	0.719	0.742
Temperature (°C)[1]	13.7	14.3	13.8
Bicarbonate	250	260	260
Bromide	< 1.0	< 1.0	< 1.0
Chloride	93.1	109	117
Fluoride	0.63	0.56	0.55
Nitrate (NO_3)	< 0.02	< 0.02	< 0.02
Nitrate-N (NO_3-N)	< 0.004	< 0.004	< 0.004
Sulfate	7.6	6.2	6.2
Total dissolved solids	328	360	364
Dissolved metals by ICP			
Aluminum	0.16	0.12	0.13
Antimony	< 0.060	< 0.060	< 0.060
Arsenic	< 0.012	< 0.012	< 0.012
Barium	0.52	0.69	0.73
Beryllium	< 0.0002	< 0.0002	< 0.0002
Boron	< 0.002	< 0.002	< 0.002
Cadmium	< 0.008	< 0.008	< 0.008
Calcium	18.4	20.71	21.27
Chromium	< 0.014	< 0.014	< 0.014
Cobalt	< 0.002	< 0.002	< 0.002
Copper	< 0.009	< 0.009	< 0.009
Gold	< 0.002	< 0.002	< 0.002
Iron	0.45	0.77	0.85
Lead	< 0.020	< 0.020	< 0.020
Lithium	0.02	0.02	0.02
Magnesium	4.16	4.66	4.79
Manganese	0.04	0.04	0.05
Nickel	< 0.005	< 0.005	< 0.005
Phosphorus	1.54	0.51	0.22
Potassium	2.25	2.53	2.66
Selenium	0.02	0.02	0.02
Silicon	8.10	7.97	7.89
Silver	< 0.010	< 0.010	< 0.010
Sodium	116.5	127.7	129.9
Strontium	0.65	0.84	0.88
Sulfur	2.63	3.32	3.43
Thallium	< 0.075	< 0.075	< 0.075
Tin	< 0.138	< 0.138	< 0.138
Vanadium	< 0.013	< 0.013	< 0.013
Zinc	0.004	0.003	0.004

Note:
[1] Parameter measured in the field.

Vest (continued)

Sample ID	V-1START	V-1MID	V-1FINAL
Total metals by ICP			
Aluminum	3.68	1.54	0.26
Antimony	< 0.060	< 0.060	< 0.060
Arsenic	< 0.012	< 0.012	< 0.012
Barium	0.56	0.63	0.67
Beryllium	< 0.0002	< 0.0002	< 0.0002
Boron	0.04	0.05	0.05
Cadmium	< 0.008	< 0.008	< 0.008
Calcium	18.13	18.86	19.26
Chromium	< 0.014	< 0.014	< 0.014
Cobalt	< 0.002	< 0.002	< 0.002
Copper	< 0.009	< 0.009	< 0.009
Gold	< 0.002	< 0.002	< 0.002
Iron	2.04	1.21	0.83
Lead	< 0.020	< 0.020	< 0.020
Lithium	0.02	0.02	0.02
Magnesium	4.45	4.4	4.35
Manganese	0.05	0.04	0.04
Nickel	< 0.005	< 0.005	< 0.005
Phosphorus	1.58	0.46	0.17
Potassium	2.18	2.14	2.40
Selenium	< 0.011	0.01	< 0.011
Silicon	16.28	10.41	7.15
Silver	< 0.010	< 0.010	< 0.010
Sodium	109.3	115.2	118.8
Strontium	0.62	0.75	0.80
Sulfur	2.18	1.76	1.72
Thallium	< 0.075	< 0.075	< 0.075
Tin	< 0.138	< 0.138	< 0.138
Vanadium	< 0.013	< 0.013	< 0.013
Zinc	0.01	0.02	0.01

Note:
[1] Parameter measured in the field.

Appendix B: Water Quality Data Collected During the Vest 30-Day Aquifer Test

All values in mg/L unless otherwise noted. Values with the "<"symbol indicate that the concentration is below the method's detection limit.

Sample ID	V1W1	V1W2	V1W3	V1W4	V1W5
Collection date & time[1]	10/16/01 3:00 PM	10/24/01 12:45 PM	10/31/01 12:00 PM	11/7/01 12:30 PM	11/15/01 11:45 PM
Time since start of test	1.5 hours	8 days	15 days	22 days	30 days
pH (std. units)[2]	8.27	8.16 [3]	7.96	8.12	7.85
Conductivity (μS/cm)[2]	0.926	0.874 [3]	0.908	0.902	0.942
Temperature (°C)[2]	13.6	15.6	15.6	14.7	13.8
Bicarbonate	330	241	280	280	300
Bromide	< 1	< 1	< 1	not tested	< 1
Chloride	136	96.8	124	119	112
Fluoride	0.69	0.52	0.46	not tested	0.5
Nitrate (NO_3)	< 0.02	< 0.02	< 0.02	not tested	< 0.02
Nitrate-N (NO_3-N)	< 0.004	< 0.004	< 0.004	not tested	< 0.004
Sulfate	< 5	< 5	6.2	not yested	29.6
Total dissolved solids	878	580	470	457	469
Dissolved metals by ICP					
Aluminum	< 0.087	< 0.087	0.17	0.17	0.16
Antimony	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Arsenic	< 0.021	< 0.021	< 0.021	< 0.021	< 0.021
Barium	0.34	0.52	0.57	0.62	0.73
Beryllium	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Boron	0.07	0.07	0.07	0.06	0.076
Cadmium	< 0.008	< 0.008	< 0.008	< 0.008	< 0.008
Calcium	3.64	12.53	14.1	15.5	21.1
Chromium	< 0.015	< 0.015	< 0.015	< 0.015	< 0.015
Cobalt	< 0.004	< 0.004	< 0.004	< 0.004	< 0.004
Copper	< 0.009	< 0.009	< 0.009	< 0.009	< 0.009
Gold	< 0.022	< 0.022	< 0.022	< 0.022	< 0.022
Iron	0.05	0.56	0.72	0.87	1.13
Lead	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Lithium	0.06	0.04	0.14	0.13	0.06
Magnesium	0.17	1.43	3.90	4.37	4.37
Manganese	0.007	0.026	0.03	0.04	0.05
Nickel	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Phosphorus	0.08	0.117	0.11	0.12	0.11
Potassium	2.92	3.09	2.98	3.11	2.86
Selenium	< 0.016	< 0.016	< 0.016	< 0.016	< 0.016
Silicon	4.77	6.24	6.26	6.28	7.01
Silver	< 0.017	< 0.017	< 0.017	< 0.017	< 0.017
Sodium	185.6	150.4	141.6	141.8	138
Strontium	0.51	0.71	0.79	0.87	0.97
Sulfur	0.38	1.11	2.55	5.44	9.81
Thallium	< 0.051	< 0.051	< 0.051	< 0.051	< 0.051
Tin	< 0.138	< 0.138	< 0.138	< 0.138	< 0.138
Vanadium	< 0.019	< 0.019	< 0.019	< 0.019	< 0.019
Zinc	0.005	< 0.003	< 0.003	< 0.003	0.004

Notes:

[1] Prior to October 31, 2001, collection date and time referenced to daylight saving time.

[2] Determined in field unless otherwise noted.

[3] Determined at KGS laboratory.

Sample ID	V1W1	V1W2	V1W3	V1W4	V1W5
Total Metals by ICP					
Aluminum	< 0.087	0.09	0.20	not tested	0.19
Antimony	< 0.05	< 0.05	< 0.05	not tested	< 0.05
Arsenic	< 0.021	< 0.021	< 0.021	not tested	< 0.021
Barium	0.34	0.51	0.58	not tested	0.74
Beryllium	< 0.001	< 0.001	< 0.001	not tested	< 0.001
Boron	0.07	0.066	0.06	not tested	0.07
Cadmium	< 0.008	< 0.008	< 0.008	not tested	< 0.008
Calcium	3.73	12.58	14.2	not tested	21.3
Chromium	< 0.015	< 0.015	< 0.015	not tested	< 0.015
Cobalt	< 0.004	< 0.004	< 0.004	not tested	< 0.004
Copper	< 0.009	< 0.009	< 0.009	not tested	< 0.009
Gold	< 0.022	< 0.022	< 0.022	not tested	< 0.022
Iron	0.11	0.56	0.72	not tested	1.13
Lead	< 0.02	< 0.02	< 0.02	not tested	< 0.02
Lithium	0.07	0.05	0.15	not tested	0.06
Magnesium	0.15	1.44	3.94	not tested	4.79
Manganese	0.008	0.026	0.03	not tested	0.051
Nickel	< 0.005	< 0.005	< 0.005	not tested	< 0.005
Phosphorus	0.09	0.11	0.12	not tested	0.12
Potassium	3.21	3.20	3.29	not tested	2.93
Selenium	0.02	< 0.016	< 0.016	not tested	< 0.016
Silicon	4.83	6.21	6.31	not tested	6.94
Silver	< 0.017	< 0.017	< 0.017	not tested	< 0.017
Sodium	185.8	150.8	145.2	not tested	140
Strontium	0.53	0.72	0.80	not tested	0.97
Sulfur	0.32	1.10	2.54	not tested	9.87
Thallium	< 0.051	< 0.051	< 0.051	not tested	< 0.051
Tin	< 0.138	< 0.138	< 0.138	not tested	< 0.138
Vanadium	< 0.019	< 0.019	< 0.019	not tested	< 0.019
Zinc	0.04	0.004	< 0.003	not tested	0.011

Notes:

[1] Prior to October 31, 2001, collection date and time referenced to daylight saving time.

[2] Determined in field unless otherwise noted.

[3] Determined at KGS laboratory.

Kentucky Geological Survey, Series XII, Report of Investigations 10, 2004—Using Remote Sensing and Inclined Drilling to Locate High-Yield Water Wells in the Eastern Kentucky Coal Field—Andrews, Wunsch, Dinger, and Dunno

In much of eastern Kentucky, municipal sources of water are limited and there are no underground mines to supply water. Geologic and remote-sensing technologies are being used to identify areas that could yield large amounts of groundwater. Eastern Kentucky wells producing significant amounts of water (more than 30 gallons per minute) are usually near fractures or faults, which may be expressed as linear features on aerial photographs, satellite imagery, and topographic maps.

About the senior author:

Robert Andrews is a hydrogeologist in the Water Resources Section at the Kentucky Geological Survey. He received his bachelor's degree in geology from the College of Wooster (Ohio) in 1989, and his master's degree in geology from the University of Kentucky in 2002. Andrews is a member of the National Ground Water Association, the Kentucky Society of Professional Geologists, and the Geological Society of America.