Changes in Hydraulic Properties of Strata Over Active Longwall Mining, Illinois, USA

by Colin J. BOOTH[1] and Erik D. SPANDE[2]

[1] Department of Geology, Northern Illinois University,
DeKalb, Illinois 60115, USA
[2] Now with: CH2M-Hill, 1890 Maple Avenue-Suite 200,
Evanston, Illinois 60201, USA

ABSTRACT

This study has examined potentiometric and hydraulic property changes caused by active longwall mining at two sites in Illinois, USA. At site 1, over two longwall panels 221 m deep, the overburden was mainly shale but included a minor sandstone aquifer overlain by shale and by thin glacial deposits. Subsidence of about 2 m occurred within two months of undermining. With subsidence and fracturing, the permeabilities increased an order of magnitude in the sandstone, locally more in the shales. The sandstone piezometric levels declined gradually as the mine approached and then rapidly with subsidence, probably due to tensile dilation of fractures. The heads have mostly recovered. There was no significant inflow to the mine, and well water levels in the glacial drift were unaffected by mining. The observed ground-water response was clearly due to local changes of hydraulic properties in the bedrock. At site 2, over a 122-m-deep active longwall panel, the overburden was less permeable and subsided more coherently. Subsidence caused minor increases in permeability and sharp drops in bedrock potentiometric levels, but recovery has been limited.

INTRODUCTION

In the central Illinois Basin coalfield (US eastern interior), ground water for farms and rural homes is commonly obtained from low-yielding shallow Pennsylvanian sandstones or sand-and-gravel aquifers in the glacial drift. Room-and-pillar mines in the poorly permeable bedrock have had few inflow problems and little effect on wells. However, longwall mining has recently been introduced to the coalfield. The possible impact of longwall subsidence on aquifers is a concern of the Illinois Mine Subsidence Research Program (IMSRP), a multidisciplinary program of research toward efficient extraction of the state's coal resources while protecting its prime farmland.

Longwall mining produces rapid subsidence of the overburden over the extracted panel of coal. The associated fracturing and dilation and compression of joints and bedding planes alter the hydraulic properties of the strata, thus changing the hydraulic heads and gradients in overlying aquifers. Several studies have reported potentiometric and hydraulic property changes above longwall panels; a few examples are cited here from the UK[1] and from the US Appalachian coalfield[2,3,4,5,6,7].

The general picture from these studies is that longwall-induced subsidence causes a rapid initial decline in potentiometric levels, because of (1) increased leakage losses; (2) increased permeability within aquifers (changing hydraulic gradients); (3) increased storativity from fracture dilation (creating temporary head drops). Aquifer potentiometric levels usually recover, at least partially. These effects of subsidence on shallow aquifers may be entirely separate from the effects of drainage into the mine.

The Illinois Basin is a new setting for hydrogeological studies related to longwall mining. The only study of this type here prior to IMSRP was by Pauvlik and Esling[8], who observed only slight hydraulic changes in a shallow unconsolidated aquitard over a subsiding longwall panel. The present paper describes an IMSRP study of the hydrogeological effects of two longwall panels in southern Illinois.

INVESTIGATIONS AT SITE 1

SITE DESCRIPTION

Site 1 is located in Jefferson County in south-central Illinois. The study was conducted over a longwall mine operating at about 221 m depth in the 3-m-thick Herrin (No. 6) Seam. The site is gently rolling and has a cover of glacial drift, 3-9 m thick, comprising loess overlying till with a thin, discontinuous, basal sand-and-gravel aquifer. The bedrock above the mined coal comprises mainly shales and siltstones with thin limestones, coals, clay and sandstones. At a depth of about 24 m there is a minor aquifer, the 26-m-thick Mt. Carmel Sandstone, which is overlain by a shale aquitard.

Longwall panels Nos. 3 and 4, each 183 m wide and 1524 m long, separated by a 61-m-wide double-pillar barrier, were mined east to west in 1988-1989 during this study. Other panels had been mined to the south before the study began. In related IMSRP studies[9,10], the Illinois State Geological Survey (ISGS) installed bedrock and drift piezometers and survey monument lines over panels 3 and 4 and their barriers. Detailed strain measurements and hydraulic testing were conducted over panel 4, at a site which was undermined in February, 1989. Each panel produced approximately 2 m of subsidence during the two-month period following undermining. The subsidence was accompanied by tension cracks evident at the surface and by subsurface fracturing and bedding-plane separation evident in borehole studies.

CHANGES IN HYDRAULIC PROPERTIES

METHODS. Several methods were used to determine the hydraulic properties of the bedrock aquifer (the Mt. Carmel Sandstone) over panel 4 before and after subsidence. Because the potentiometric level in the sandstone aquifer was below the top of the aquifer - probably because of the effects of prior mining - methods of analysis appropriate for unconfined aquifers were selected.

(1) Straddle-packer tests were conducted in deep 7.6-cm-diameter boreholes drilled (at angles of 10° to vertical) for the ISGS studies. The hydraulic conductivities of isolated intervals were determined by the commonly used equation of Hvorslev[11], from the volume of water injected at controlled pressures. Pre-mining tests were conducted in a 213-m-deep hole using 6-m injection intervals in the sandstone and selected other sections. Because this hole was then grouted for strain measurements, post-mining tests were made in a different hole, drilled approximately 30 m away (also on the panel 4 centerline), using 3-m packer intervals. This hole showed many fractures and was finished at only 158 m depth because of drilling difficulties.

(2) Slug tests were conducted in piezometers before subsidence and just after the site was undermined, when the site had developed visible cracks but had not yet subsided. A small volume of water was rapidly poured into the piezometer and the potentiometric response was recorded by transducer and analyzed for hydraulic conductivity using the Bouwer and Rice method[12].

(3) Pumping tests were conducted in well P350, a 15.2-cm-diameter well over the centerline of panel 4, drilled to a depth of 47.2 m in the Mt. Carmel aquifer. The potentiometric response to a discharge of about 0.3 l/s was monitored in the test well and nearby piezometers, and aquifer properties were determined using Neumann's modification[13] of Boulton's method.

RESULTS. No single test provided complete results. The before-and-after packer tests are informative but not absolutely comparable, since different holes and different injection intervals were used. Because of subsidence damage, the piezometers could not be used for post-mining testing but they do provide pre-subsidence background permeability data. The pump-test well was usable after subsidence; before-and-after hydraulic conductivity comparisons were made from analysis of the recovery phases of the pumping tests.

The hydraulic conductivities of the Mt. Carmel Sandstone determined from the piezometers prior to undermining (Table I) were in the range 10^{-5} to 10^{-4} cm/s. Values remained the same just before site subsidence. The hydraulic conductivity of the 91-m-deep piezometer in the underlying shale increased from 10^{-6} to 6×10^{-4} cm/s at the onset of subsidence.

TABLE I: HYDRAULIC CONDUCTIVITIES DETERMINED IN PIEZOMETERS

PIEZOMETER OBS.	SCREENED INTERVAL m depth	SLUG TEST DETERMINATIONS BEFORE SUBS. Hydraulic Conductivity (cm/s)	START SUBS.	PRE-SUBSIDENCE FROM P350 TESTS
Sandstone				
P303	31.1-34.1	1.8×10^{-5}	1.8×10^{-5}	6.4×10^{-5}
P302	41.5-44.5	2.1×10^{-4}	2.0×10^{-4}	2.6×10^{-4}
P304	43.3-46.3	3.0×10^{-4}	1.7×10^{-4} Av. of 3 tests	1.4×10^{-4}
Shale				
P305	90.8-93.8	1.3×10^{-6}	6.2×10^{-4}	N/A

Analysis of the recoveries from pumping in well P350 shows some variation in the hydraulic conductivities of the sandstone determined from test to test (Table II). Considering the latest, longest test in each set as most reliable (well-developed well), the hydraulic conductivity increased about one order of magnitude (3×10^{-6} to 4×10^{-5} cm/s). The permeability values from the test well (open hole 26 m) are lower than those from the observation piezometers (screens 3 m), probably because of interval averaging effects. Pre-subsidence storativity of the sandstone aquifer was around 10^{-5} to 10^{-4}, based on piezometer observations during the pumping tests. No post-subsidence storativities could be determined, but the potentiometric results discussed below suggest increases in storage coefficient.

TABLE II: AQUIFER TESTS OVER PANEL 4
Results from Test Well Recovery Analysis

PRE-SUBSIDENCE TEST No.	DURATION mins.	HYDR. COND. cm/s	POST-SUBSIDENCE TEST No.	DURATION mins.	HYDR. COND. cm/s
2	13	2.0×10^{-6}	6	32	4.9×10^{-5}
4	68	1.7×10^{-5}	7	66	3.4×10^{-5}
5	239	3.3×10^{-6}	8	258	3.7×10^{-5}

The pre-subsidence packer tests (Figure 1) showed hydraulic conductivities of the sandstone between 10^{-6} and 10^{-4} cm/s. Tests of selected intervals lower in the bedrock indicated conductivities of less than 10^{-6} cm/s, while the tightest shales had conductivities lower than the measurable limit of about 10^{-8} cm/s.

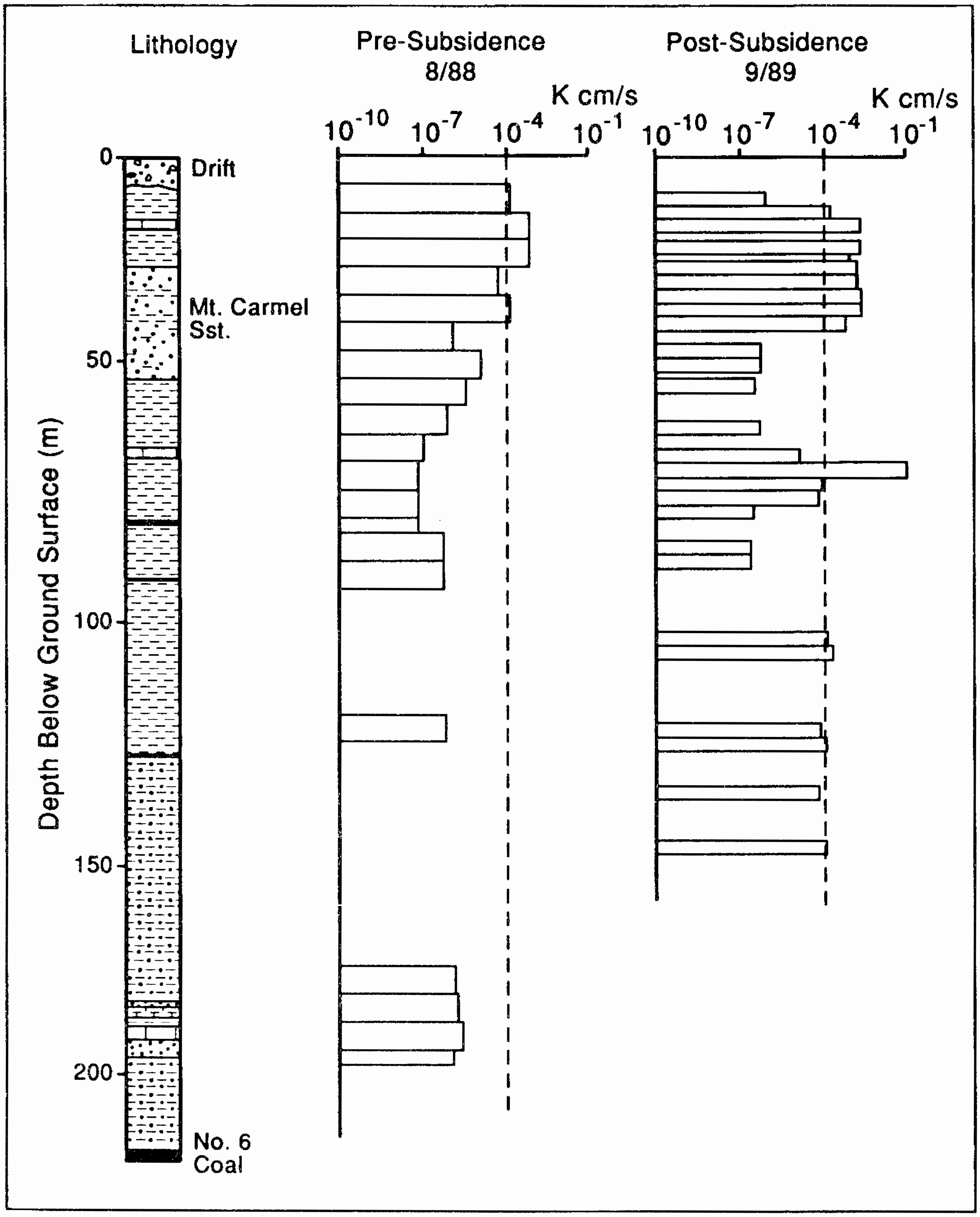

Figure 1. Packer Tests at Site 1.

In the post-subsidence borehole, lost circulation, core characterization and geophysical logging by the ISGS[9,10] revealed new fracturing and bedding plane separation. Packer testing indicated increases in hydraulic conductivities of the sandstone of an order of magnitude. In the lower bedrock, new local permeable zones had developed, with permeability increases of several orders of magnitude. The post-subsidence testing was conducted seven months after subsidence, so that the permeability changes can be considered permanent.

POTENTIOMETRIC CHANGES

Potentiometric levels in the Mt. Carmel Sandstone, recorded in piezometers by ISGS, were about 21 m below ground before subsidence, possibly already lowered by the previous mining of panels 1 and 2. The ISGS studies[9,10] showed that the water levels of Mt. Carmel Sandstone piezometers located over panel 3 then declined as the panel approached, reaching a minimum when the site went into tension (30 m behind the mine face), with a maximum head drop of about 11 m. The levels recovered gradually after the face passed, then declined slightly in December 1988 to January 1989 in apparent response to adjacent panel 4, then stabilized.

At the study site over panel 4, heads in the Mt. Carmel Sandstone declined in 1988 in apparent response to panel 3. After recovering to about 27 m depth, they began in December a gradual decline of about 5 m as panel 4 approached (Figure 2: P304, P350), then dropped sharply a further 11 m in February when the site subsided. In surviving well P350 the potentiometric level recovered within about a month from the steep drop, then continued a slow recovery. It is now about 23 m below ground, close to initial levels.

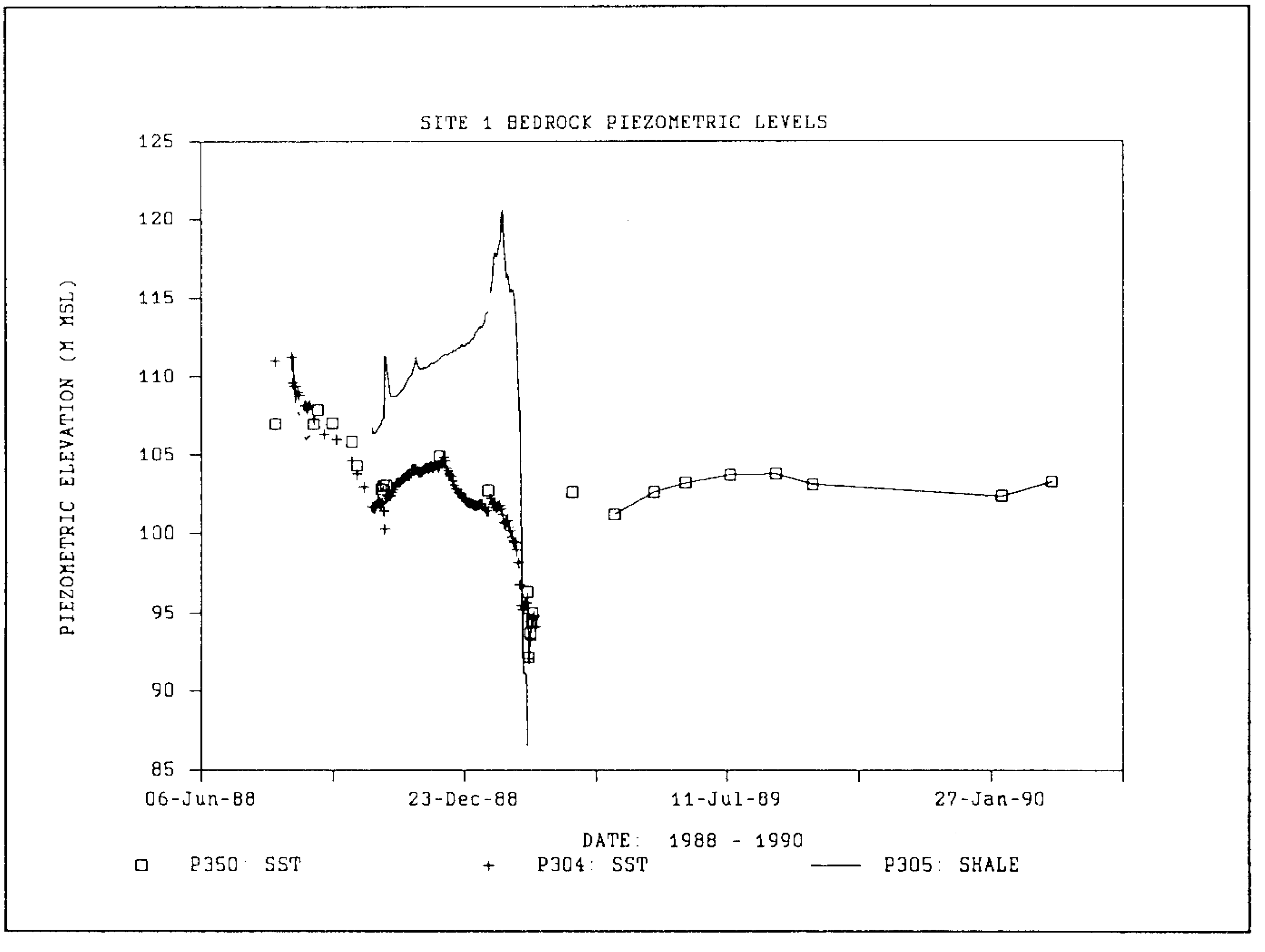

Figure 2. Site 1 Bedrock Potentiometric Levels

Piezometer P305 over panel 4 was screened into shale at a depth of 91-94 m, and responded differently. After a post-development recovery in 1988, the potentiometric level rose sharply in January, 1989, just before the site subsided, possibly because of compaction in response to lowered pore water pressures beneath (F.J. Getchell, personal conversation). When the site subsided, the shale piezometer rapidly dewatered.

The steepest declines in head thus occurred when the site went into tension. They are probably due to increased void storage created by dilation of joints and bedding planes. The earlier, gradual declines are probably drawdown responses around the potentiometric low centered over the approaching tensile zone.

Farm and domestic wells in the glacial drift and upper bedrock in the vicinity of the longwall panels were monitored and sampled regularly from spring 1988 through spring 1990. The water table in the drift was 0 to 3 m below ground; unimpacted heads in the upper bedrock were 5 to 10 m deep. Figure 3 shows example hydrographs from farm wells. Wells in the drift aquifer (e.g. RW1 over panel 3) showed no response to mining. (Rapid fluctuations in drift water levels with subsidence were recorded by transducer in a 3-m-deep piezometer in a related IMSRP study[14], but may have been missed by our less frequent readings, or were masked by the large storage and/or vertical averaging effects of the wells.)

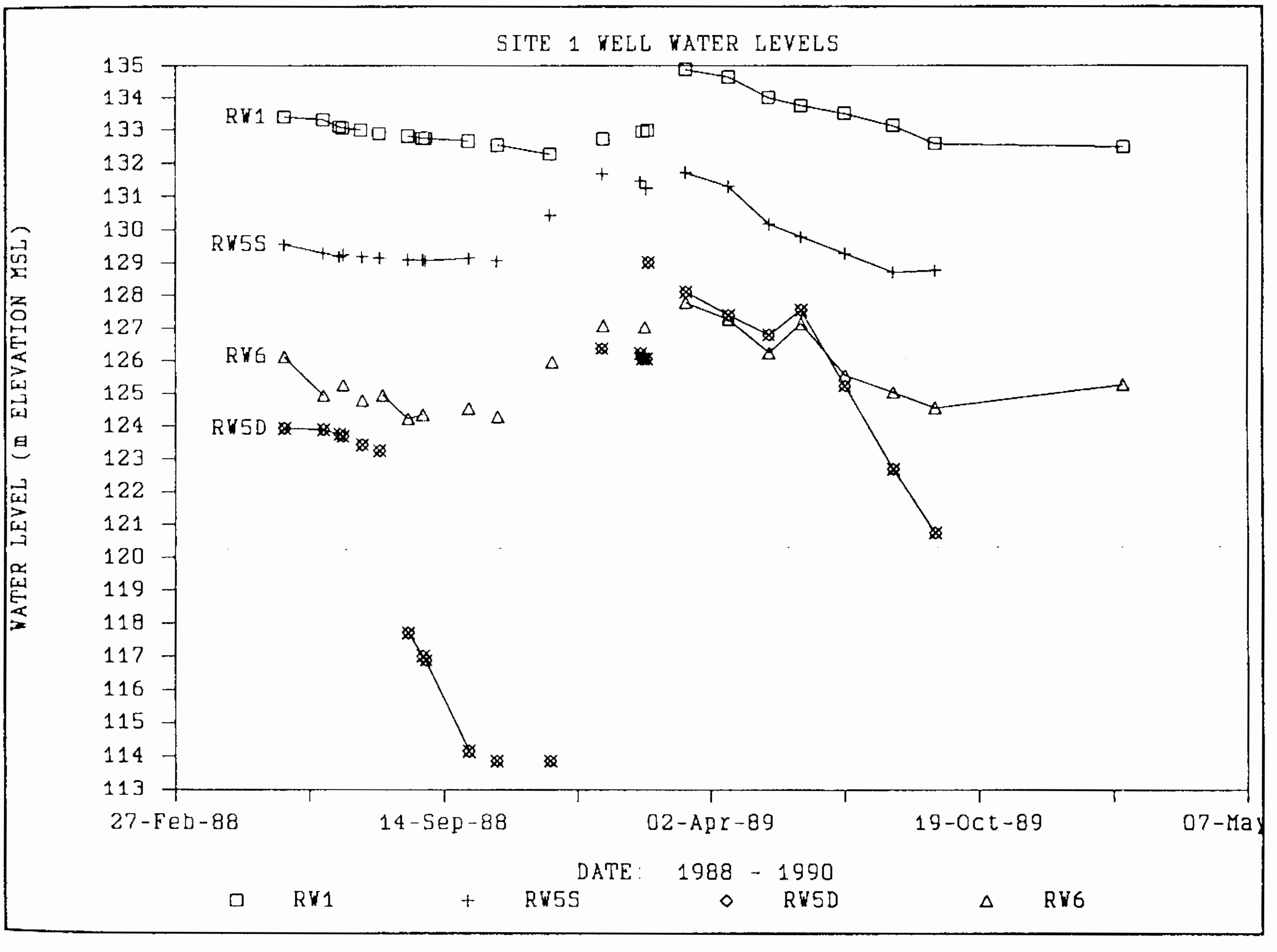

Figure 3. Site 1 Well Water Levels

Upper-bedrock wells (e.g. RW6) located 150 m north of panel 4 did not respond to mining, but a sharp response was seen in bedrock well R5D (19 m deep), on the north edge of the panel 3 subsidence trough. RW5D is nested in drift well RW5S (4 m deep); when panel 3 subsided in summer 1988, R5D dewatered, whereas R5S did not respond. R5D recovered within about three months, and chemical analyses show that it was at least partially recharged by fresh drift water before reverting to brackish bedrock water.

INVESTIGATIONS AT SITE 2

Site 2 is located in Saline County in southeastern Illinois over an active mine extracting the 1.7-m-thick Herrin Coal at a depth of about 122 m. The overburden consists of shales, siltstones, thin limestones, sandstones and coals. A minor bedrock aquifer at a depth of 54 m, the Trivoli Sandstone, is laterally discontinuous to 8 m thick across the site. The glacial drift cover is 18 to 28 m thick and consists of till, glacilacustrine deposits, and local sand and gravel. Longwall panel No. 1 (204 m wide, 2400 m long) was mined in 1989-90 and produced a maximum subsidence of 1.4 m within a few weeks of undermining; the overburden subsided with little bedding separation [10].

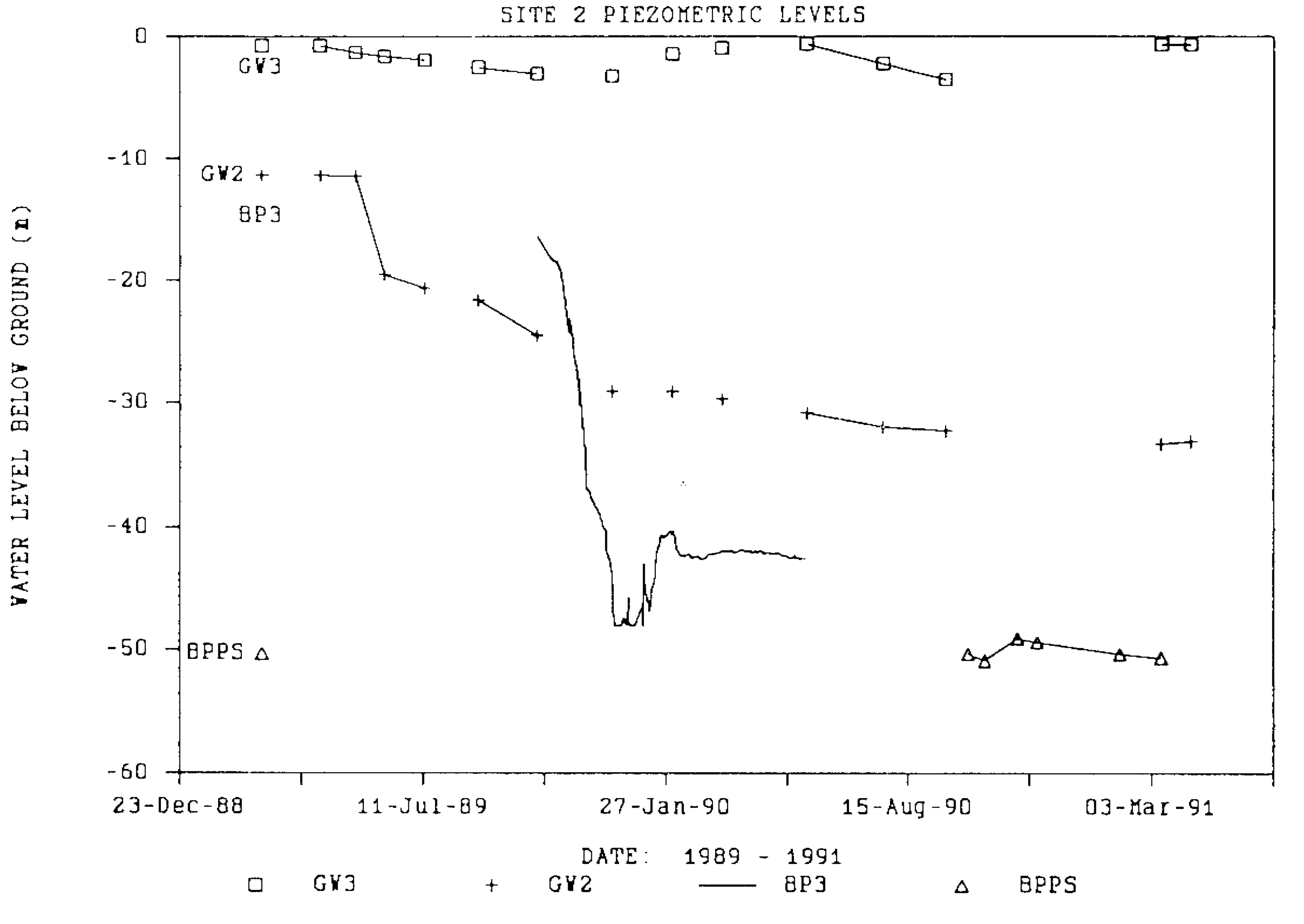

Figure 4. Site 2 Potentiometric Levels

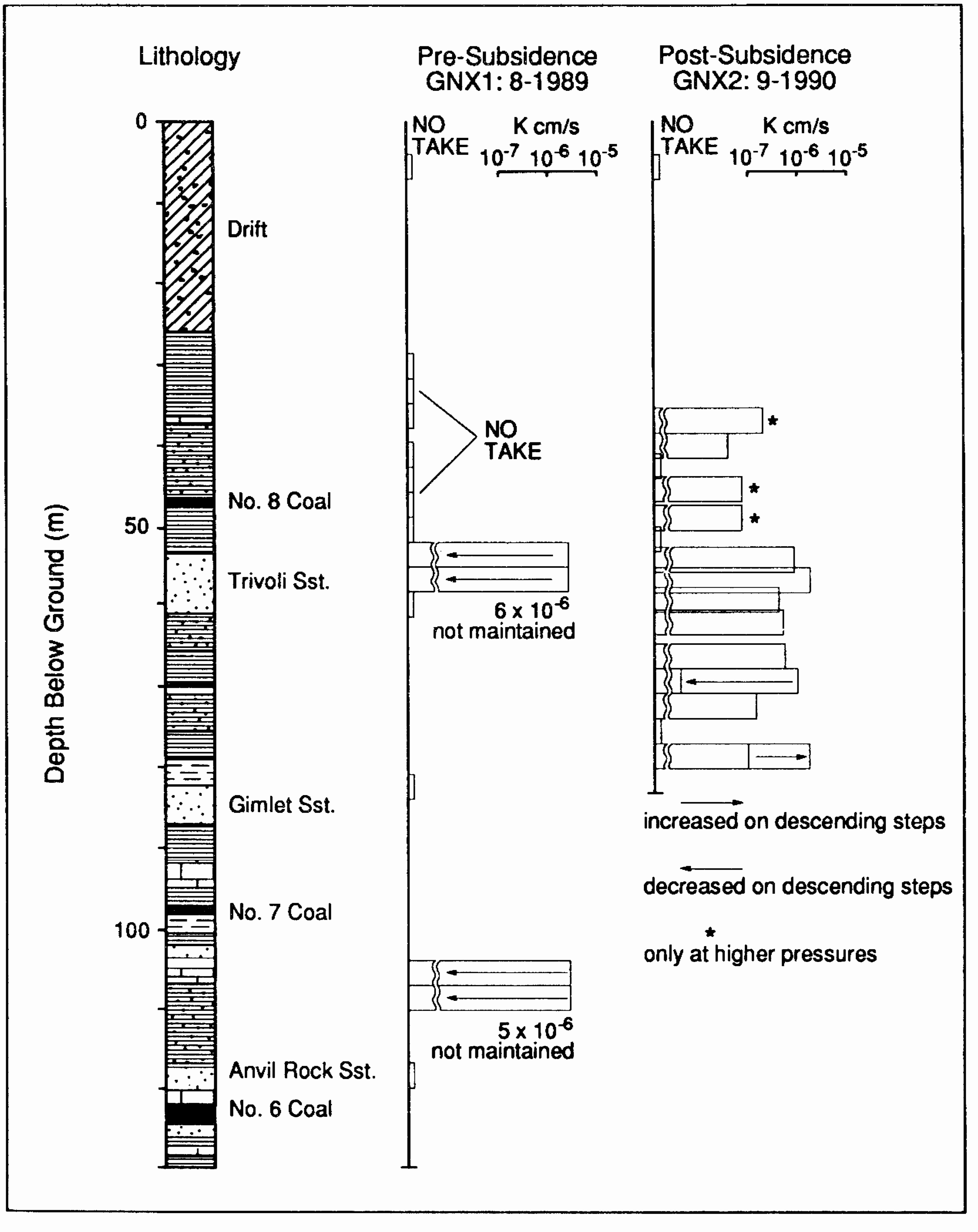

Figure 5. Site 2 Packer Test Results

At neither site did the mine experience significant inflow. The shale overburden maintained overall confining properties and the observed ground-water response was primarily an internal effect of the local changes in the hydraulic properties in the bedrock.

The ISGS[10] installed and monitored piezometers at the site. The drift piezometers were screened into sand and gravel at 18-23 m depth and displayed minor (2 to 3 m) declines in water level in response to mining. Trivoli Sandstone piezometers over the panel displayed major potentiometric declines of about 22 m just ahead of the mining and a further 8 m with site subsidence in January, 1990 (BP3 in Figure 4). The latter 8 m recovered quickly with the compressional wave, but no further recovery has occurred.

Water levels were also measured (Figure 4) in wells about 300 m north of the panel. The head in Trivoli Sandstone well GW2 began to drop when mining began, about 1 km away, and ultimately declined about 20 m without recovery. Water levels in the large-diameter wells (e.g. GW3) that penetrate only about 6 m into the drift responded very little to mining.

Packer tests before and after mining were conducted in deep angle boreholes drilled over the center of the panel (Figure 5). The pre- and post-subsidence holes were adjacent and both sets of tests were run with 3-m injection intervals. In the 130-m-deep pre-subsidence borehole, most of the selected intervals tested were too poorly permeable (less than about 10^{-8} cm/s) to accept any take of water at practical pressures. Intake in the Trivoli Sandstone was maintained less than five minutes, suggesting that the apparent permeability of 6×10^{-6} cm/s was a localized effect of the test.

The 84-m-deep post-subsidence borehole was drilled and tested nine months after undermining. The permeabilities of most intervals had increased slightly to measurable levels of between 10^{-7} and 10^{-6} cm/s. Permeabilities of 5×10^{-6} cm/s were indicated by maintained intake in the Trivoli Sandstone.

CONCLUSIONS

Longwall mine subsidence increases bedrock permeabilities. At site 1, an apparently permanent increase of about one order of magnitude was observed in the sandstone aquifer, with limited zones of very high increases in the underlying shale-limestone sequence, probably at bedding separations.

Water levels in wells in the surficial drift aquifer were largely unaffected by subsidence, but bedrock water levels fell sharply. In the sandstone aquifer, heads declined in two stages: gradually as the mine approached, and sharply when the site subsided. The rapid head drop is attributed to loss of water into new void space opened by tensile dilation of fractures and bedding planes. The earlier decline is a drawdown response to the potentiometric depression centered on the tensile zone, and is only seen in transmissive units. The dilational head drop in the sandstone recovered rapidly, as the voids were partly closed during recompression. The remaining depression recovered more slowly.

At site 2, the initially low permeabilities were increased slightly with subsidence. Drift water levels were little affected, but bedrock aquifer heads declined greatly. The dilational head drop over the panel recovered quickly with recompression. Overall recovery has been poor, probably because of limited inflow to this laterally restricted, less permeable aquifer.

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REFERENCES

1. Aston, T.R.C. and R.N. Singh. A reappraisal of investigations into strata permeability changes associated with longwall mining. Inter. Jl. Mine Water, Vol. 2, no. 1, pp. 1-14 (1983).

2. Hasenfus, G.J., K.L. Johnson, and D.W.H. Su. A hydrogeomechanical study of overburden aquifer response to longwall mining. Proc. 7th Inter. Conf: Ground Control in Mining, West Virginia University, Aug. pp. 149-162 (1988).

3. Schulz, R.A. Ground-Water Hydrology of Marshall County, West Virginia, with Emphasis on the Effects of Longwall Coal Mining. US Geological Survey, Water Resources Investigation Report 88-4006 (1988).

4. Dixon, D.Y. and H.W. Rauch. Study of quantitative impacts to ground water associated with longwall coal mining at three mine sites in the northern West Virginia area. Proc. 7th International Conf: Ground Control in Mining, West Virginia Univ., August, pp. 321-335 (1988).

5. Hill J.G. and D.R. Price. The Impact of Deep Mining on an Overlying Aquifer in Western Pennsylvania. Ground Water Monitoring Review, Vol. 3, no. 1, pp. 138-143 (1983)

6. Tieman G.E. and H.W. Rauch. Study of dewatering effects at an underground longwall mine site in the Pittsburgh seam of the northern Appalachian coalfield. Eastern Coal Mine Geomechanics, US Bureau Mines Information Circular 9137, pp. 72-89 (1986).

7. Walker, J.S. Case Study of the Effects of Longwall Mining Induced Subsidence on Shallow Ground Water Sources in the Northern Appalachian Coalfield. US Bureau Mines Report Inv. 9198, 17 p. (1988).

8. Pauvlik C.M. and S.P. Esling. The Effects of Longwall Mining Subsidence on the Groundwater Conditions of a Shallow Unconfined Aquitard in Southern Illinois. Proc. 1987 National Symp: Mining, Hydrology, Sedimentology and Reclamation, Springfield IL, Dec. pp. 189-196 (1987).

9. Mehnert, B.B., D.J. Van Roosendaal, R.A. Bauer, and D.F. Brutcher. Effects of Longwall Coal Mine Subsidence on Overburden Fracturing and Hydrology in Illinois. Proc. AEG Symposium: Mine Subsidence-Prediction and Control, 33rd Annual AEG Meeting, Pittsburgh, PA, Oct., pp. 105-112 (1990).

10. Kelleher, J.T., D.J. Van Roosendaal, B.B. Mehnert, D.F. Brutcher and R.A. Bauer. Overburden Deformation and Hydrologic Changes Due to Longwall Coal Mine Subsidence in the Illinois Basin. Land Subsidence, Proc. Fourth Inter. Symp. on Land Subsidence, Houston, May, IAHS Pub. 200, pp. 195-204 (1991).

11. Hvorslev, M.J. Time Lag and Soil Permeability in Groundwater Observations. Bulletin 36, US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MI, 50 pp. (1951).

12. Bouwer H. and R.C. Rice. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells. Water Resources Research, Vol. 12, no. 3, pp. 423-428 (1976).

13. Neumann, S.P. Analysis of Pumping Test Data from Anisotropic Unconfined Aquifers Considering Delayed Gravity Response. Water Resources Research, Vol. 11, no. 3, pp. 329-342 (1975).

14. Darmody, R.G. Illinois Mine Subsidence Research Program: The Agronomic Contributions. in: Proc. AEG Symp: Mine Subsidence-Prediction and Control, 33rd Annual AEG Meeting, Pittsburgh, PA, Oct. p 119-129, (1990).