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JULY 1986

CHARACTERIZATION OF SUBSIDENCE OVER PILLAR EXTRACTION PANELS

Contract J0233920
GAI Consultants, Inc.

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

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NOTICE

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An investigation was made of ground response to pillar re-treatment mining in a 5.5-foot thick seam at 600 foot depth at a site in northern West Virginia. This paper describes mining-related stress changes and movements at mine level, displacements within the overburden, ground surface subsidence and ground water level variations. Hydraulic properties of the rock strata changed and water levels declined in certain deep-lying strata.				
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FOREWORD

This report was prepared by GAI Consultants, Inc., Monroeville, Pennsylvania under U.S. Department of Energy [DOE] Contract DE-AC22-80 PC 30120 and U.S. Bureau of Mines [USBM] Contract J0233920. Between 1980 and 1982, it was administrated under the technical direction of The DOE Carbondale Energy Research Center, with William Eichfeld serving as the Technical Project Officer; between 1982 and 1983, under the technical direction of the USBM Denver Mining Research Center, with Timothy Hackett serving as the Technical Project Officer; and since 1983, under the technical direction of the USBM Bruceton Mining Research Center, with Vladimir Adamek serving as the Technical Project Officer. Ronald Simonich was the Contract Administrator for the Bureau of Mines. This report is a summary of the work completed under this contract during the period 1980-1985.

This report was submitted by the authors in July, 1986.

The writers gratefully acknowledge Kitt Energy Corporation (particularly Mr. Franklin Miller and Ms. Jodi Rulli) without whose cooperation this work could not have been accomplished. The writers also thank Professor Syd Peng of West Virginia University for the use of drilling equipment required to install certain mine level instrumentation.

Mr. Kenneth Wardell, mining consultant, Leeds, England, Professor Syd Peng, West Virginia University, Morgantown, and Professor Z. T. Bieniawski, Pennsylvania State University, University Park, served as consultants to GAI and reviewed the instrumentation plan prior to its implementation. The writers accept sole responsibility for the analyses, the views and conclusions in this report.

EXECUTIVE SUMMARY

INTRODUCTION

Pillar extraction has a long history of use in U.S. coal fields and, although longwall mining is becoming increasingly popular, still accounts for a sizable proportion of the coal mined. Ground movements associated with pillar extraction are sometimes large enough to disrupt the ground water and surface water regimes as well as damage buildings and other surface structures. The federal government has recognized the need for a better understanding of subsidence processes so that a greater compatibility can be achieved between coal mining and current and future land use. To further that understanding, GAI Consultants, Inc., under contract to the U.S. Bureau of Mines and U.S. Department of Energy, has conducted a study of ground response to pillar retreat mining at Kitt Energy Corporation's Kitt No. 1 Mine in northern West Virginia. The specific aim of the study was to describe, as completely as possible, the physical response of the overburden strata to the mining of coal by the pillar extraction method in the Northern Appalachian Coal Field and the changes in ground water levels and quality that accompanied the mining process. This report presents the findings.

SITE DESCRIPTION

The monitoring site occupies approximately 250 acres of rolling grasslands having a maximum relief of 135 feet. The mine is located in the nearly flat-lying 5.5 foot thick Lower Kittanning Coal approximately 600 feet below ground surface. Overburden strata (Figure 1) are of the Pennsylvanian age Allegheny, Glenshaw and Casselman Formations and consist of alternating units of claystone, shale, siltstone and sandstone, along with a few units of limestone and coal. Five to fifteen feet of residual soils mantle much of the site. Alluvial sediment 10 to 15 feet thick occupies the topographically low, south-central portion of the site.

MINING

The room-and-pillar system employed at the mine permitted almost total (>90 percent) removal of coal from the panel. Developmental (advance) mining consisted of driving a series of 17-foot wide entries on 60-foot centers from the mains to the far end of the panel, joining them on 90-foot centers with cross-cuts of the same width. Ventilation entries were driven along the south and east margins of the panel. Pillar recovery (retreat mining) began with Pillar 1 (Figure 2) and progressed row by row toward the main entries. Pillars were extracted in pairs. All coal was removed with a single continuous miner. Developmental mining took 9.5 months; retreat mining 6 months. The retreat rate was relatively steady. Coal in adjoining panels was unmined. No prior mining had been conducted in seams above or below the panel.

INSTRUMENTATION

A variety of devices were installed at the monitoring site to measure displacements, stresses and water levels: at mine level -- convergence points, roof extensometers, instrumented roof bolts and stress meters; in the overburden -- inclinometers, time domain reflectometry cables, multiple position borehole extensometers, and piezometers; at ground surface -- survey monuments and benchmarks.

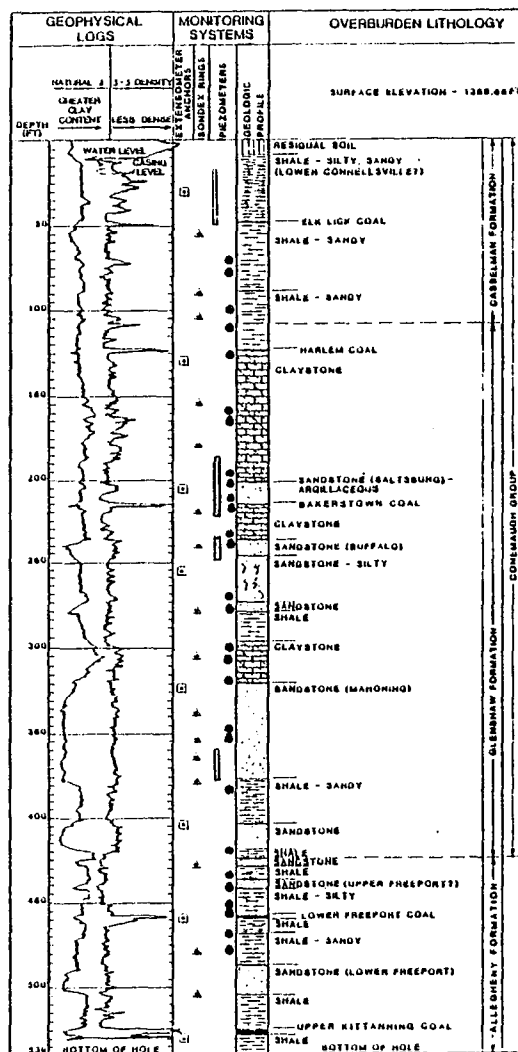


Fig. 1. Geologic Profile
Piezometer (□)
Slip Zone (●)

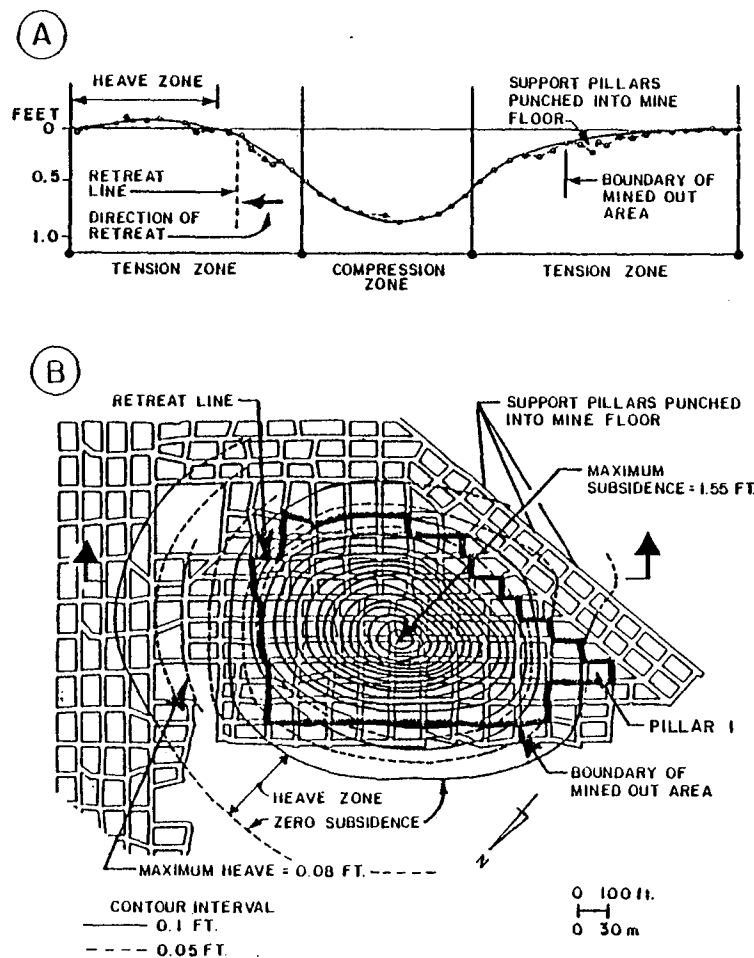


Fig. 2. Subsidence trough as mining nears completion. A. Profile; B. Plan View (1 ft. = 0.3m)

FINDINGS

The recovery of coal pillars led to redistribution of the overburden load, resulting in intensified stresses in remaining pillars, compression of the pillars, convergence of entries, and shearing, fissuring and deflection of the overburden strata. As a result, piezometric levels in certain water-bearing strata declined and a broad, shallow depression formed at ground surface, its areal extent and depth increasing with the dimensions of the mined-out area.

Stress Changes in the Coal Seam

Prior to existence of the mine, the primitive (virgin) vertical stresses existing in the 600-foot deep coal seam were probably about 600 psi (Figure 3A). Upon development of the entries and cross-cuts, the stresses at pillar locations presumably increased to about 1030 psi in conformance with a tributary redistribution of load. Then, upon extraction of coal pillars during retreat mining, the stresses in remaining pillars increased further due to load redistributions from the mined-out area. Stress meter measurements in pillars along the direction of mining defined a near exponential stress increase toward the retreat line. Stress increases as large as 825 psi were measured in pillars located along the retreat line. Additional stress increases of several hundred pounds per square inch accompanied the extraction of neighboring pillars in a particular row. Still higher stress levels were achieved during extraction of an individual pillar.

Although the Lower Kittanning Coal possesses an unconfined compressive strength of 1000-2800 psi (12 of 14 samples exceeded 1600 psi), pillar distress in the form of intense spalling and cracking was observed only in individual pillars as they were being extracted. Lateral confinement resulting from the broad, squat pillar geometry (5:1 width/height ratio) is believed to have contributed greatly to pillar strength.

Permanent pillars supporting the ventilation entries along portions of the south margin of the panel lost capacity as a result of bearing failure of the underclay floor and roof instability (Figure 3B). This ultimately influenced the geometry of the subsidence trough (Figure 2).

Mine Level Ground Movements

Roof

Downward deflections of 0.05 to 1.7 inches were measured in entries and cross-cuts during the five month period immediately preceding retreat mining -- the result primarily of degradation of the roof shale brought about by extreme atmospheric conditions (95°F, 100 percent relative humidity) over a two-week period in July. Roof deflections accompanying retreat did not exceed 4 inches and were generally less than 1 inch amidst pillars that had not yet been removed. Roof strata movements, measured by roof extensometers, were confined almost exclusively to the lowermost 8 feet of rock, which included the 5 foot interval of roof bolt support.

Coal Pillars

Vertical deflections resulting from retreat-imposed stresses did not exceed 0.3 inch by the time the retreat line had met the back (gob-side) face of a row of pillars. The

pillars were in no danger of failing. The in-place elastic modulus of the coal was 2.8×10^5 psi, essentially the same as measured in the laboratory.

Floor

Generally, floor deflections in entries and cross-cuts were not perceptible to the naked eye, but were estimated to range from a few tenths of an inch to perhaps 1.6 inches. Noticeable floor heave of 4 to 6 inches with upwarping and cracking of the underclay took place only in the ventilation entries along the south margin of the panel. There, the deterioration of floor and roof prompted mine personnel to augment roof bolts with timber cribbing.

Convergence

Roof, pillar and floor movements during retreat mining combined to produce 0.05 to 4 inches of vertical closure (convergence) of entries and cross-cuts amidst pillars that had not yet been removed. Convergence increased with approach of the retreat line in a manner similar to pillar stress (Figure 4) and was slightly greater in four-way intersections than in entries or cross-cuts between intersections. The relative contributions of roof, pillar and floor to convergence were variable, probably due to local variations in geology, mechanical properties and stress field. These local variations in convergence of mine openings are considered less important to the subsidence process than are variations in the load-carrying capacity of the roof/pillar/floor system, particularly those deriving from local bearing failure of the mine floor such as occurred along the south margin of the panel.

Rock Strata Movements

The sandstone, siltstone, claystone and coal units appear to have behaved as a sequence of weakly bonded plates of differing thicknesses and mechanical properties supported on a foundation of coal pillars. Progressive withdrawal of this support by mining resulted in the downward flexure of the strata into the mined-out area, accompanied by lateral slippage and fissuring. Slippage zones were pervasive throughout the overburden, developing at vertical intervals of 5 to 50 feet, primarily along bedding planes (Figures 1 and 5A). Slippage tended to follow the progress of mining, as indicated by inclinometers installed within the panel. Motion in the 106- to 126-foot depth interval in Inclinometer 1, for example, first was southerly toward the initial extraction, then easterly as pillars alongside were removed, and later more northerly as the retreat line moved towards the mains (Figure 5B). Directional motion was also evidenced at other depths and locations in the panel.

Local strata dislocations of 1 inch or more limited the inclinometer sonde to successively lesser depths as mining progressed. Owing to the large spans and the low tensile and shear strengths along slip surfaces, bedding separations may have occurred at or below the slip surfaces. The strata dislocations precluded detection of any separations using the wire extensometers or Sondex (magnetic induction) device.

Groundwater Response

Piezometric levels in the seven piezometers located above the mine panel -- two in each of three water-bearing strata and one in a fourth (Figure 1) -- remained unchanged during the 9.5 month period of developmental mining. Later, during retreat mining

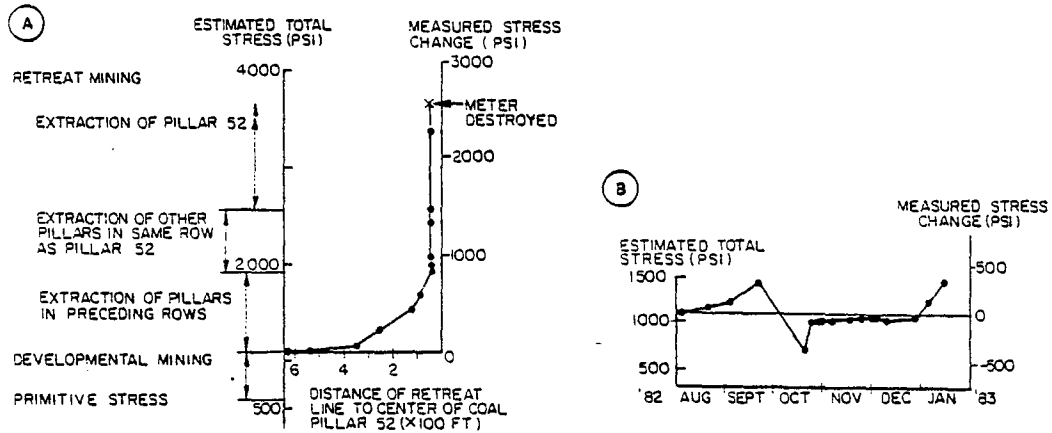


Fig. 3. Vertical stress in coal pillars.
 A. Pillar 52 within panel.
 B. Support pillar along south ventilation entries that experienced bearing failure.
 (1 psi = 6.895 kPa)

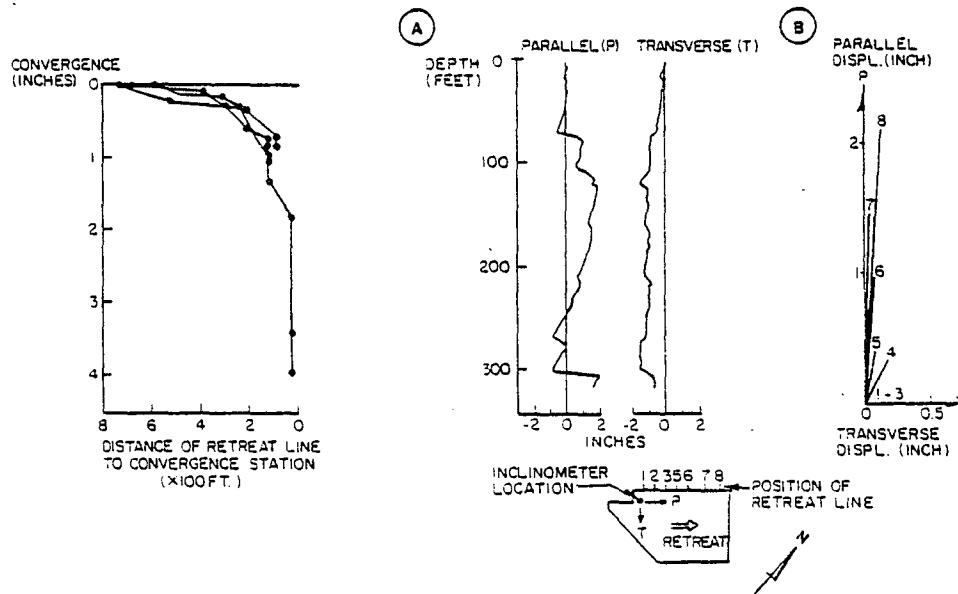


Fig. 4. Convergence of mine openings
 (1 in. = 25.4mm)

Fig. 5. Lateral movements within overburden, Inclinator 1.
 A. Displacements with depth.
 B. Slip in the 106-126 ft. (32-38 m.) interval. (1 ft. = 0.3m)

(Figure 6)*, piezometric levels in the Lower Connellsville Sandstone at 30-foot depth again remained unchanged. Piezometric levels in the Saltsburg and Mahoning Sandstones began declining almost as soon as retreat mining began. Those in the Saltsburg Sandstone at 210 foot depth declined 70 feet and then recovered to elevations 35 to 50 feet below premining levels where they remained following mining. Piezometric levels in the Mahoning Sandstone at 350 foot depth dropped 270 feet and remained depressed over the one year post-mining monitoring period. These observations are consistent with a characterization of the overburden as a downward deflecting, thick sequence of plates whose upper fibers are in compression and whose lower fibers are in extension.

Field permeability tests conducted before and after retreat mining indicated order of magnitude increases in hydraulic conductivity in the Lower Connellsville and Saltsburg sandstone strata. Flexure, slippage and fissuring probably caused at least local increases in the hydraulic conductivities of intervening beds of claystone, shale and siltstone, as well. Casing damage from mining prevented post-retreat testing of the Mahoning Sandstone.

Water inflows to the mine panel were first recognized a month-and-one half after retreat mining began and continued up to and beyond the completion of mining four-and-one half months later. The rate of flow into the panel was virtually constant over the period of observation. Six and one-half months after mining ended, mine personnel reported water emanating from the panel at the main entries.

Ground Surface Movements

Developmental mining produced no perceptible movement of the ground surface. Retreat mining produced a dish-shaped depression, or trough, that increased in depth and areal extent as the mined-out area enlarged and eventually encompassed the entire mine panel (Figure 2B).

At no time was subsidence evident to the naked eye. No ground cracks appeared, even in zones of known ground extension. No modifications to ground slope or lowering of the ground surface could be discerned within the mildly hilly topography of this typical Northern Appalachian site. Subsidence was detected by survey only after the mined-out area had reached dimensions of approximately 380 feet square. Maximum subsidence at that time was 1 inch. Maximum subsidence at the completion of retreat mining was 1.75 feet, corresponding to 32 percent of the mined thickness. Movements in the horizontal plane were as great as 3.5 inches.

Bounding the mined-out area to a distance of approximately 350 feet ($0.58H$) was a heave zone whose amplitude was at most 1 inch (Figure 2B). The heave zone is consistent with the characterization of the overburden as a broad, thick plate spanning across elastic abutments.

The mine panel was not of critical dimensions. Consequently, additional subsidence would be expected if the dimensions of the panel were increased. However, similarities in subsidence data from survey to survey in the direction of retreat mining suggested,

* For simplicity, data from only three of the piezometer installations are shown. The others show similar trends.

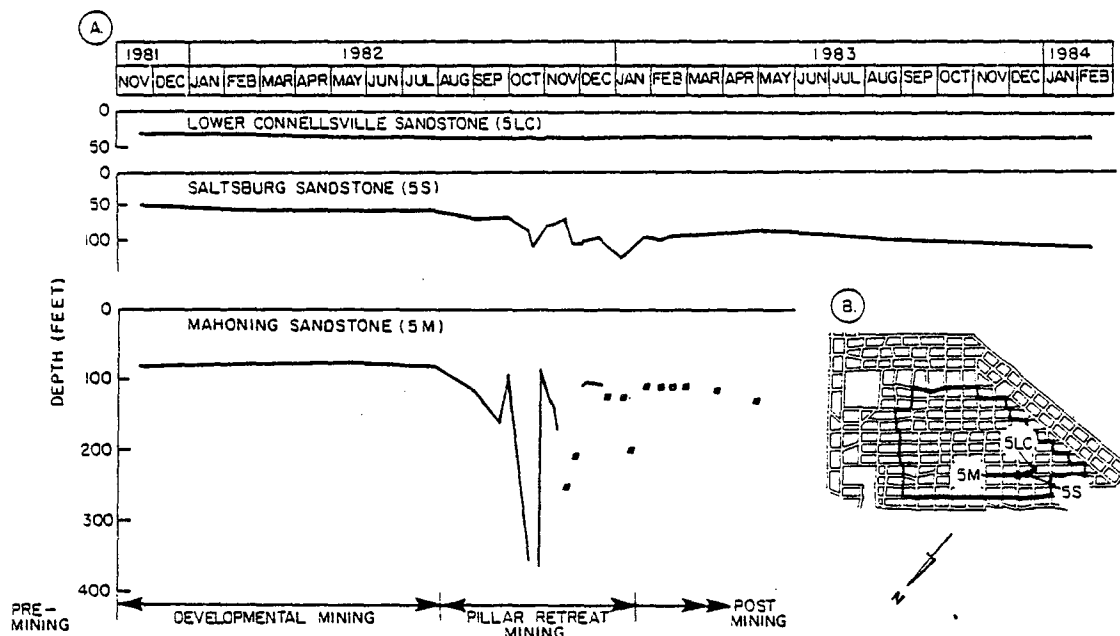


Fig. 6. Water level variations during mining
 A. Water Levels B. Piezometer Location Map
 Stratum locations are shown in Fig. 1.
 Piezometer casing dislocation depths are denoted by ■.

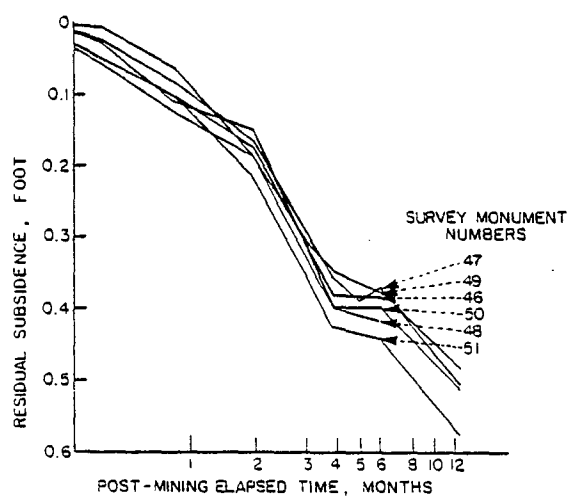


Fig. 7. Residual subsidence at center of trough.

after the mined-out area had reached a length of 360 feet (0.6H), that limiting conditions were being approached relative to the 600-foot width of the panel.

Subsidence parameters, such as angle of draw, ground strain, etc. depended both on location above the panel and the stage of mining. Tensile and compressive ground strains approached 0.005 locally. At the end of mining, the angle of draw ranged from 5 degrees where the margin of the panel remained firm to 40 degrees (or more) where the margin experienced bearing failure.

Time-dependent ground movements took place while mining was underway. At least some of the time-dependent movements were the result of pillars along the margin of the panel punching into the mine floor. The rate of "residual" subsidence--subsidence occurring after the completion of mining--first appeared to diminish about four months after mining had ceased (Figure 7). By that time, maximum subsidence had increased 0.4 foot (about 24 percent) in excess of the 1.75 feet measured at the completion of mining. Further observations showed subsidence to be continuing.

CLOSURE TO EXECUTIVE SUMMARY

This report has presented the findings of a study of ground response to pillar retreat mining in a 5.5-foot thick seam at 600-foot depth in northern West Virginia. These data and observations promise to improve the engineering community's understanding of the subsidence process and its ability to deal with the potential impacts of subsidence on surface structures and the environment.

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1.0 INTRODUCTION

This report summarizes work performed for the U.S. Bureau of Mines and the U.S. Department of Energy by GAI Consultants, Inc. The period of the contract was September, 1980 through March, 1985.

OBJECTIVES OF THE STUDY

The activities performed during this study were directed towards describing, as completely as possible, the physical response of the overburden strata to the mining of coal by the pillar extraction method in the Northern Appalachian Coal Field and the changes in ground water levels and quality that accompanied the mining process. The data from this and other studies furnishes input for the development of empirical and analytical subsidence models that promise to improve the state of subsidence prediction.

The objectives of the study were met by collecting subsidence, overburden and mine level data from the C-3 panel of Kitt Energy Corporation's Kitt No. 1 Mine and establishing relationships between the mining sequence, induced pillar stresses, ground movements, piezometric levels and hydraulic parameters. The Kitt No. 1 Mine is located in Barbour County, West Virginia, 17 miles southeast of Clarksburg and five miles northwest of Philippi, where West Virginia Route 76 intersects U.S. Route 119.

The study involved six tasks:

- Task 1 - Site Selection,
- Task 2 - Development of an Instrumentation Plan for the Mine Panel,
- Task 3 - Instrument Installation,
- Task 4 - Monitoring,
- Task 5 - Data Analysis, and
- Task 6 - Reports and Meetings

ORGANIZATION OF THE REPORT

The following pages elaborate on these tasks. Section 2 of the report (the next section) describes the geologic setting in which the work was performed, including the regional geology as well as stratigraphic data collected on-site by drilling and downhole geophysics. Section 3 discusses the mining program--the manner in which the mine panel was developed, the method in which pillars were extracted and the sequence of retreat. Section 4 outlines the instrumentation program, the types and locations of measuring devices and the methods of installation. Sections 5 through 9 deal with the ground response to mining and with mining-related effects on the ground water regime. Section 5 discusses the vertical pillar stresses, the manner in which they redistribute during developmental mining and pillar recovery and the load capacity of the coal pillars and mine floor. Section 6 describes the convergence of the mine openings during developmental mining and pillar recovery that occurred as a result of weathering and the redistribution of stresses around the openings. Section 7 describes the manner in which the overburden strata responded to pillar recovery, as determined by a series of inclinometers and other devices installed in drill holes above the mine panel. The discussion of overburden response is continued in Section 8, where the effect of mining on the piezometric levels in four strata overlying the mine panel is described along with comparisons of hydraulic parameters and water chemistry before and after pillar recovery. Section 9 presents the results of the ground survey program. The evolution of the subsidence trough is described in reference to the position of the retreat line and the size of the mined-out area. The subsidence trough existing at the end of mining is

characterized in terms of geometric parameters which are compared with estimates based upon available empirical prediction techniques. Section 10 presents a summary, conclusions and recommendations.

2.0 GEOLOGIC SETTING

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REGIONAL GEOLOGY AND TOPOGRAPHY

Barbour County, West Virginia, is situated along the eastern boundary of the Appalachian Plateau physiographic province (Figure 2.1), which is characterized by gently folded and essentially flat-lying sedimentary rock strata. The eastern border of Barbour county follows the Allegheny Front -- the escarpment that separates the Appalachian Plateau physiographic province from the more highly folded and faulted Valley and Ridge physiographic province to the east.

Barbour County is also located near the southern limit of West Virginia's Northern Coal Field (Figure 2.2), where the coal seams are younger in age (higher in the Pennsylvanian sequence), generally more flat-lying, less numerous, and more evenly distributed through the stratigraphic column than coal seams in the state's Southern Coal Field (Figure 2.3).

Within Barbour County, coal seams actively mined include the Redstone, Pittsburgh, Bakerstown, Upper Freeport, and Upper, Middle, and Lower Kittanning. The Bakerstown and Upper Freeport coals are strip-mined only and the Lower Kittanning coal is mined solely by underground methods. The other coals are exploited by both strip and underground methods. The greatest number of active mines are in the Pittsburgh Coal. The Kitt No. 1 Mine is one of several underground mines in the Lower Kittanning Coal.

The Kitt Mine is located between the northeast-southwest trending axes of the Hiram anticline, 4.5 miles east of the site, and an unnamed syncline 3.5 miles west (Figure 2.4). These folds are broad and open, and the rock strata in the locality of the mine dip only 1.5 degrees to the west. No large-scale, regional faulting has been documented within Barbour County by state geologic reports.

The generalized stratigraphic sequence of Barbour County is illustrated in Figure 2.4. At the Kitt Mine and to the west, rock strata of the Monongahela Group (which include the Redstone and Pittsburgh Coals) outcrop in the topographically higher areas, and rock strata of the Conemaugh Group in the lower areas. (The Conemaugh Group includes the Elk, Lick, Harlem and Bakerstown Coals.) To the east of the mine site, in a band centering along the axis of the Hiram anticline, rock strata of the

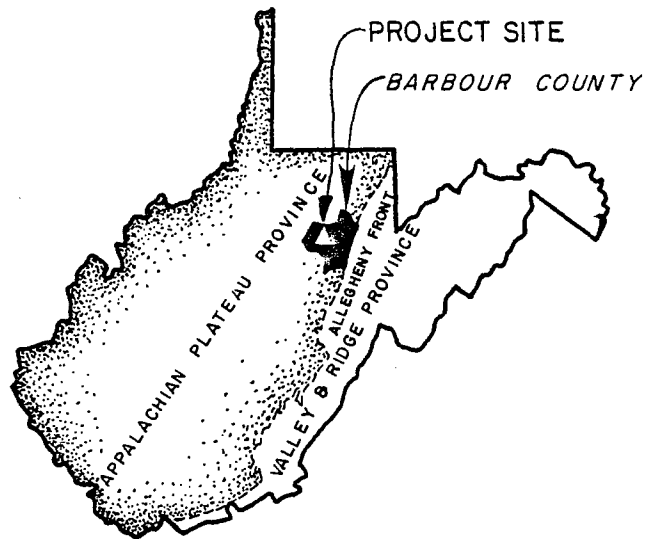


FIGURE 2.1 POSITION OF BARBOUR COUNTY, WEST VIRGINIA
IN THE APPALACHIAN PLATEAU PHYSIOGRAPHIC
PROVINCE (modified from Arkle and Brock, 1968)

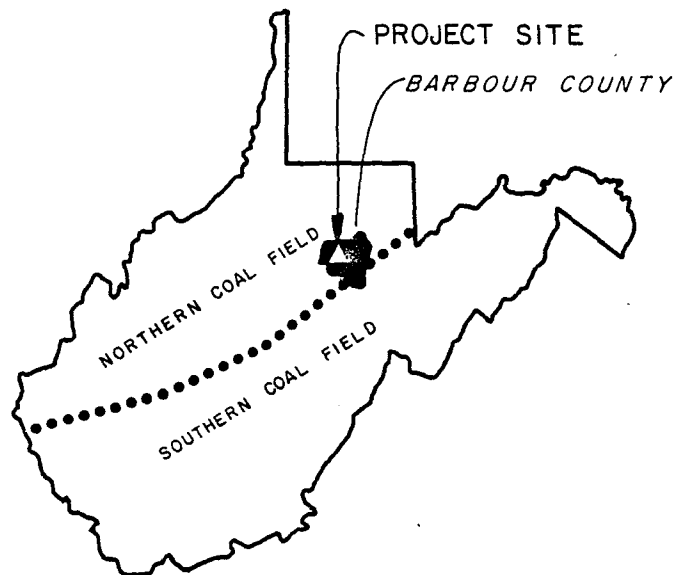


FIGURE 2.2 POSITION OF BARBOUR COUNTY IN THE NORTHERN
COAL FIELD OF WEST VIRGINIA (modified from
Barlow, 1974)

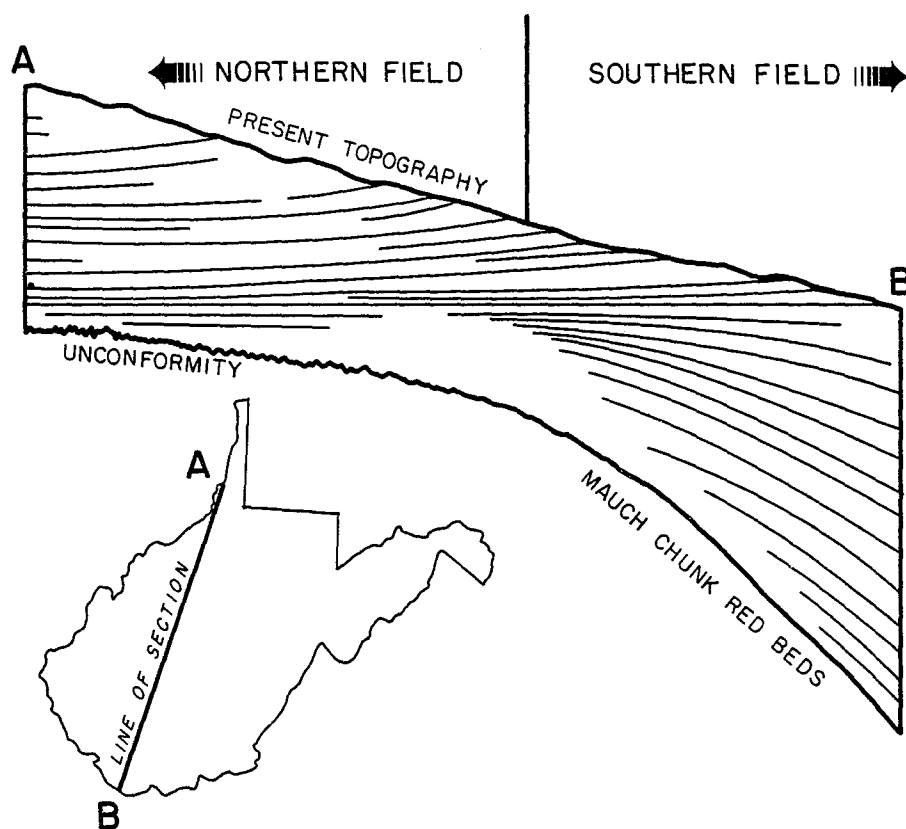


FIGURE 2.3 GENERALIZED CROSS-SECTION THROUGH NORTHERN AND SOUTHERN COAL FIELDS OF WEST VIRGINIA (after Barlow, 1974)

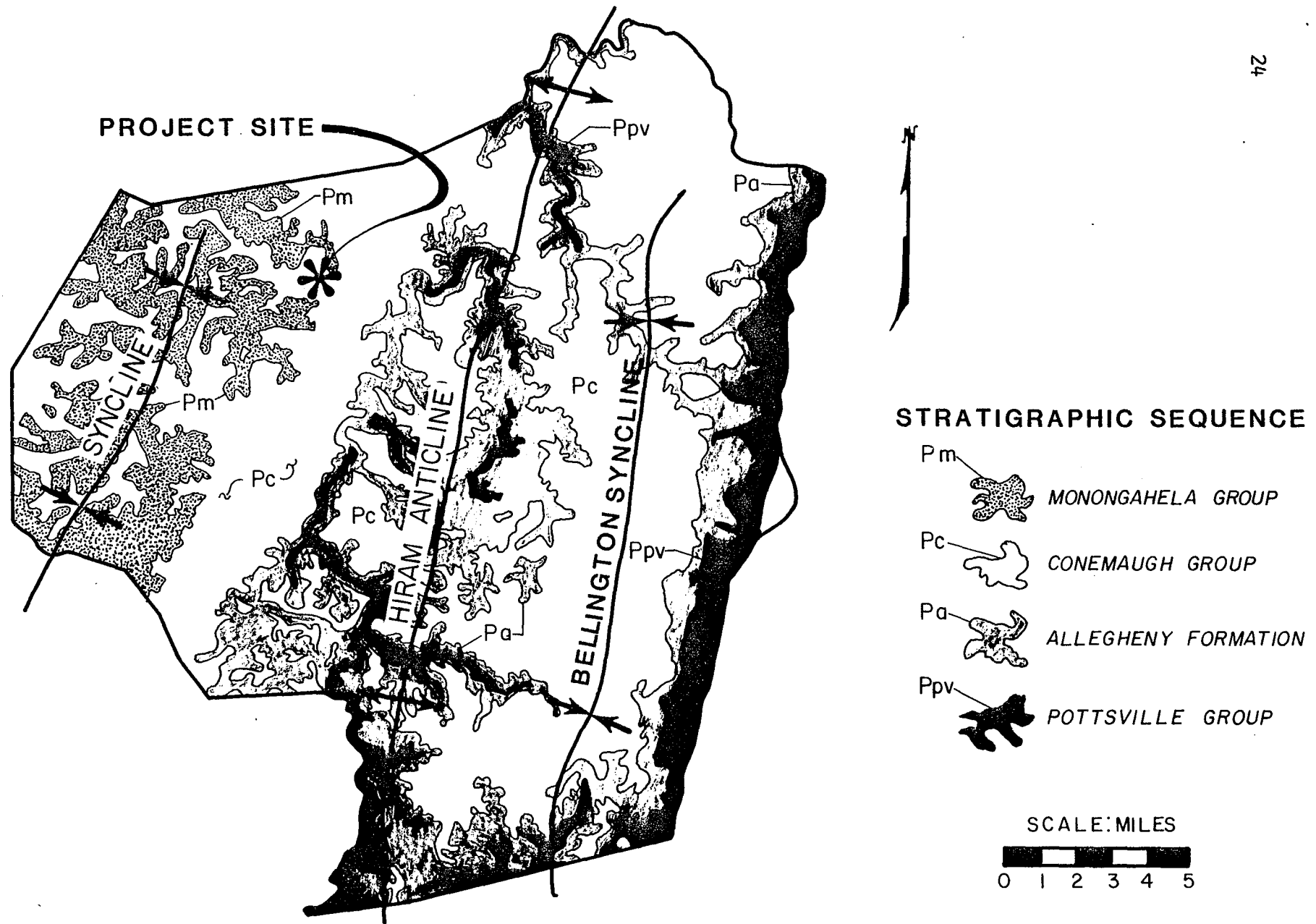


FIGURE 2.4 GEOLOGIC MAP OF BARBOUR COUNTY, WEST VIRGINIA

Conemaugh Group outcrop at the higher elevations and those of the Allegheny and Pottsville Groups in the topographically lower areas, particularly along river and stream courses. (The Allegheny Group coals include the Upper Freeport; the Upper, Middle, and Lower Kittanning; and the Clarion).

SITE GEOLOGY AND TOPOGRAPHY

Ground Surface Conditions

The project site is bounded on three sides by moderately hilly terrain*. Local relief is 135 feet. Hill slopes average 13 degrees, but reach 30 degrees locally. Essentially level ground occupies the valley floor from the center to the south end of the mine panel.

Swamp conditions exist in the low area, fostered by small springs issuing from the northeast hillside. Water in the swamp rarely exceeded 18 inches in depth over the duration of the study.

At the beginning of the project, all brush and trees on the site were cleared. Grass now covers most of the site.

Soil Cover

Except for two small rock outcrops, soil mantles the site and is of three types: (1) residual (saprolitic) soil, (2) alluvial soil, and (3) man-placed fill. Residual/saprolitic soil blankets the majority of the site and is a clayey, sandy silt with rock fragments. The residual soil was termed "saprolite" where the structure of the parent rock was visible. Because the boundary between saprolitic soil and poorly lithified bedrock is gradational, the soil/bedrock contact was taken as the depth at which the rate of roller-bit advance decreased noticeably. As defined by this criterion, residual soil/saprolite varies in thickness from 5 to 15 feet.

Alluvial soil is found only in the low-lying and swampy areas. The material is primarily clayey, silty sand and is estimated to be 10 to 15 feet thick. The man-placed fill is located along a haul road constructed by the Kitt Energy Corporation at the northeastern extremes of the longitudinal survey lines. The fill is composed of a mix of waste mine-rock and residual soil and is at least 3.5 feet thick where the survey monuments are located.

Rock Overburden

Continuous NX drill core was recovered from the D-5 borehole at depths from 15 feet below ground surface to 25 feet below the mine-level--a total of 608 feet. Eight other borings were air rotary drilled using rock roller-bits and consequently were not sampled. Logs are presented in Figures 2.5 A-D.

Lithologies in the unsampled boreholes were ascertained by downhole geophysical methods, the logging being performed by the Kitt Energy Corporation and the interpretation by the writers.

*A plan view of the site showing topography is presented in Figure 4.3, Section 4.0, Instrumentation Program.

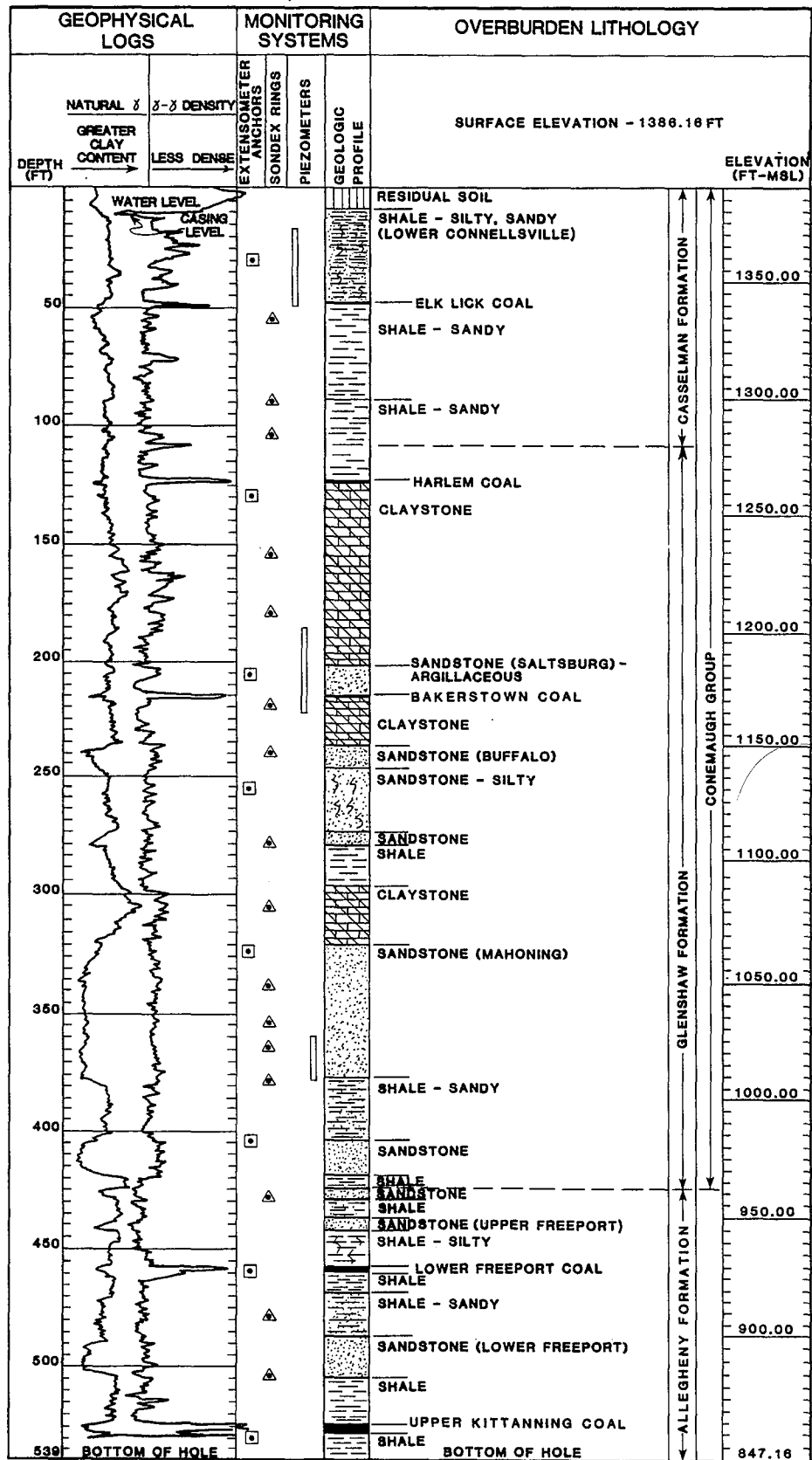


FIGURE 2.5A BORING D-1
OVERBURDEN LITHOLOGY AND
MONITORING INSTRUMENT LOCATIONS

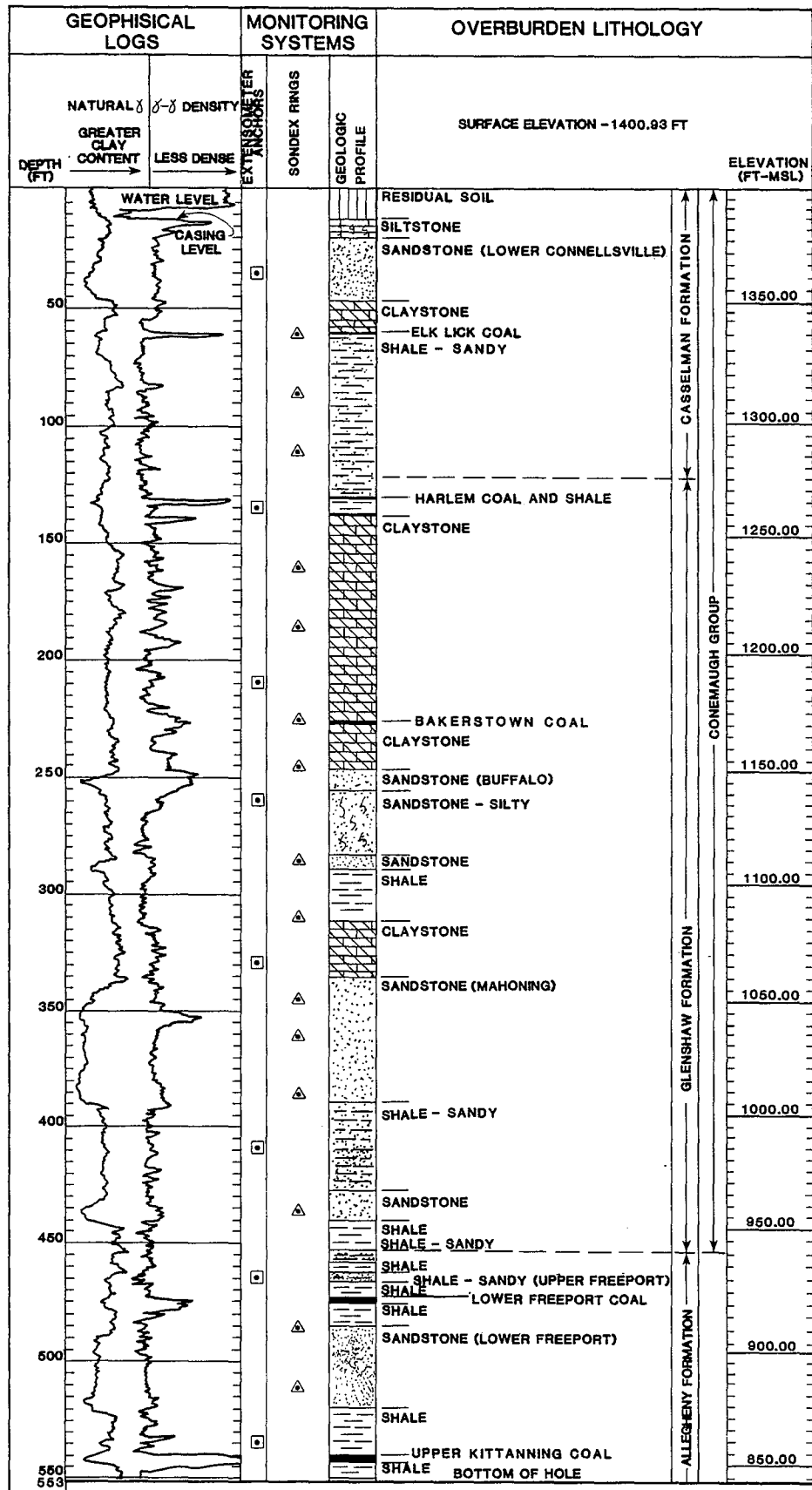


FIGURE 2.5B BORING D-2
OVERBURDEN LITHOLOGY AND
MONITORING INSTRUMENT LOCATIONS

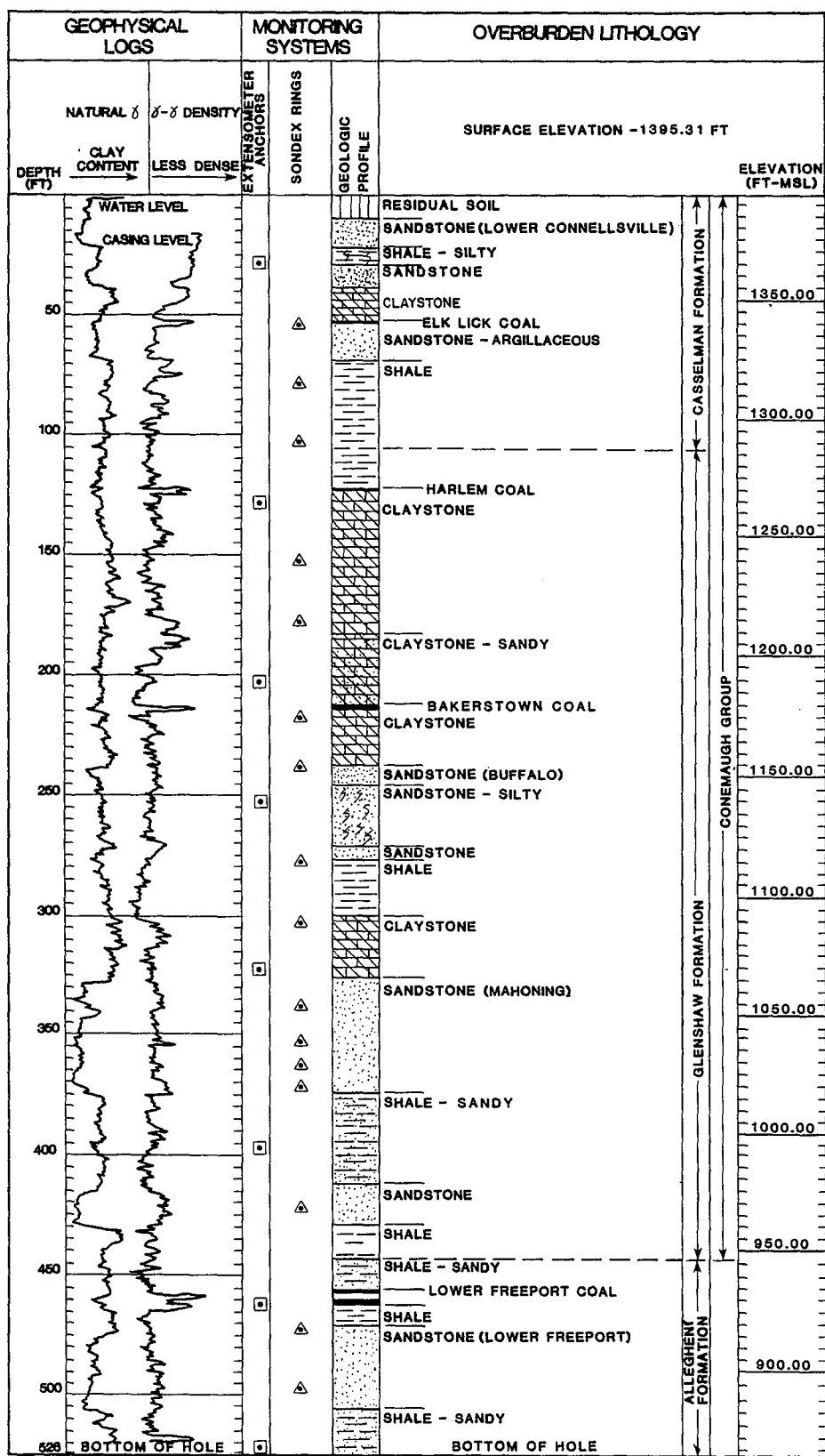


FIGURE 2.5C BORING D-3
OVERBURDEN LITHOLOGY AND
MONITORING INSTRUMENT LOCATIONS

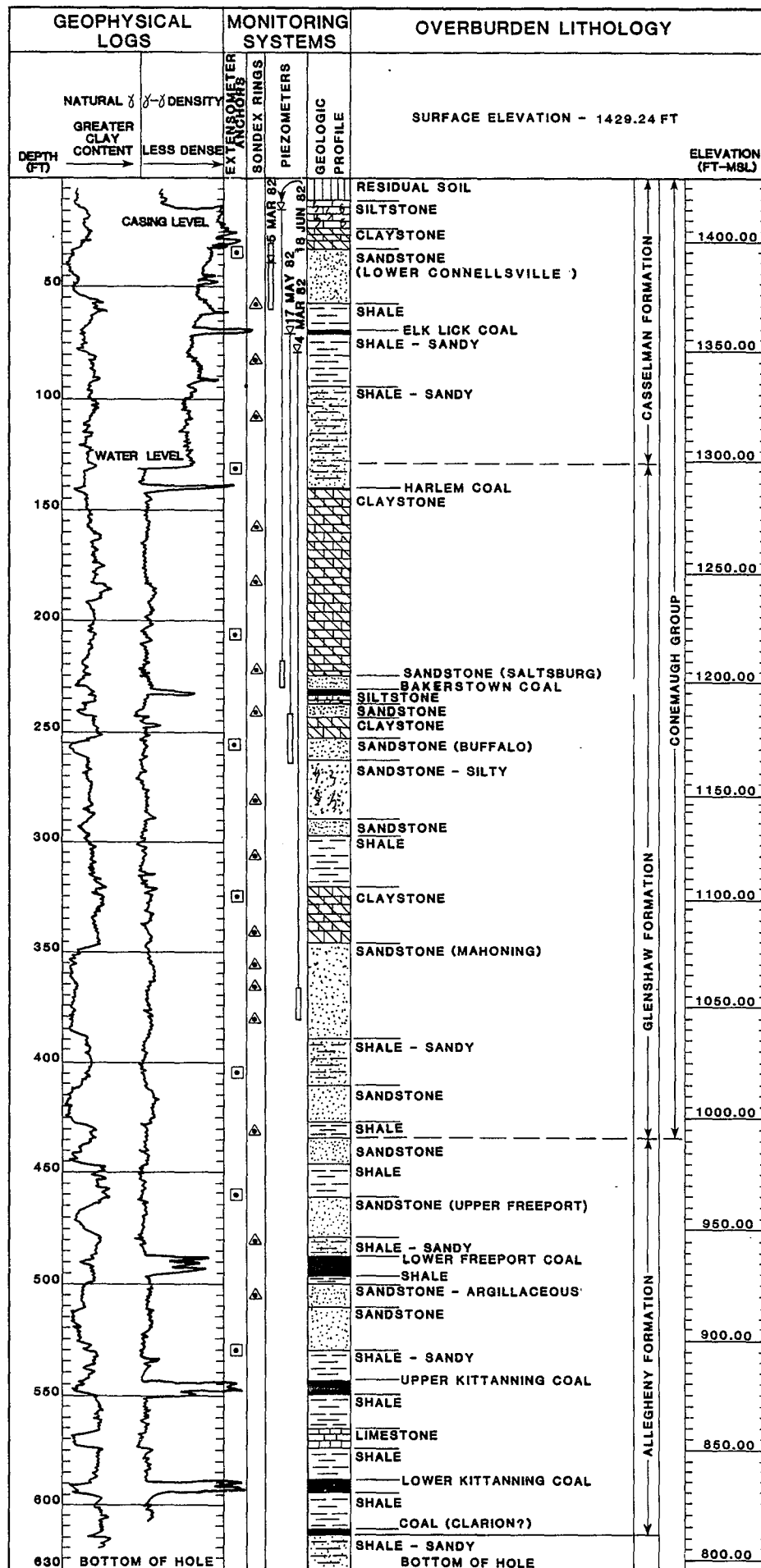


FIGURE 2.5D BORING D-4
OVERBURDEN LITHOLOGY AND
MONITORING INSTRUMENT LOCATIONS

**FIGURE 2.5E BORING D-5
OVERBURDEN LITHOLOGY**

The geophysical interpretations were guided by two basic principles: (1) coal is less dense than surrounding rock strata, enabling its detection by a gamma-gamma density logging tool; and (2) claystone and shale possess higher clay contents than surrounding rock strata, enabling their detection by a natural gamma logging tool, which senses gamma radiation that emanates from potassium ions in the clay. The correlation made in Borehole D-5 between the geophysical log and the rock core served as a guide in interpreting the geophysical logs from the unsampled boreholes.

Cross sections between Borings D-2, D-3 and D-5 (Figure 2.6 A) and between Borings D-1, D-3 and D-4 (Figure 2.6 B) illustrate the general continuity of rock units across the site, with certain self evident lateral changes in strata thicknesses and continuity that are typical of such a sedimentary sequence. Figure 2.7 illustrates the broader continuity of rock units between the C-3 panel and the D-3 longwall panel 1200 feet northeast.

Rock overburden at the project site is composed of Pennsylvanian-age sedimentary strata from three formations: the Casselman, which represents the uppermost 20 percent of the overburden; the Glenshaw, the middle 50 percent; and the Allegheny, the lowermost 30 percent.

a. Casselman Formation--varies in thickness from 107 to 135 feet across the mine panel and consists 62 percent shale and siltstone, 21 percent sandstone, 16 percent claystone and 1 percent coal, the coal being the one-foot thick Elk Lick located at mid-depth in the formation.

The principal sandstone is the 10- to 25-foot thick Lower Connellsville, which occupies the midsection of the upper half of the formation. The Lower Connellsville Sandstone is thickest to the east and north and grades to a sandy shale to the southwest (Figure 2.6). Whereas the Lower Connellsville Sandstone is massive in nature, the overlying and underlying shales, claystone, and siltstones are very broken, as indicated by low Rock Quality Designation (RQD) values (Figure 2.5 E)--a phenomenon that is typical of near-surface rock. The Casselman rock units below the Elk Lick Coal are less broken.

Sandy shales occupy most of the 52 to 69 feet of Casselman Formation below the Elk Lick Coal, although argillaceous sandstone occupies the first 16 feet immediately below the Elk Lick Coal in Boring D-3. Due to its stratigraphic position, this sandstone is probably the Morgantown. In Boring D-5, the lower 23 feet of the sandy shale zone is occupied by a silty sandstone/silty claystone/sandy siltstone sequence. This sequence, below where the Morgantown Sandstone would be located, may correspond to the Grafton sandstone found elsewhere in Barbour County. The base of the Casselman formation is defined by the top of the fossiliferous, marine Ames shale, which directly overlies the Harlem coal.

b. Glenshaw Formation -- varies in thickness from 300 to 340 feet across the mine panel and consists of about 45 percent sandstone, 40 percent claystone, 15 percent shale and siltstone, and minor amounts of limestone and coal.

*Rock Quality Designation (RQD) is defined by Deere et al. (1967) as the percentage of a core run that is composed of lengths of solid core exceeding 4-inches in length.

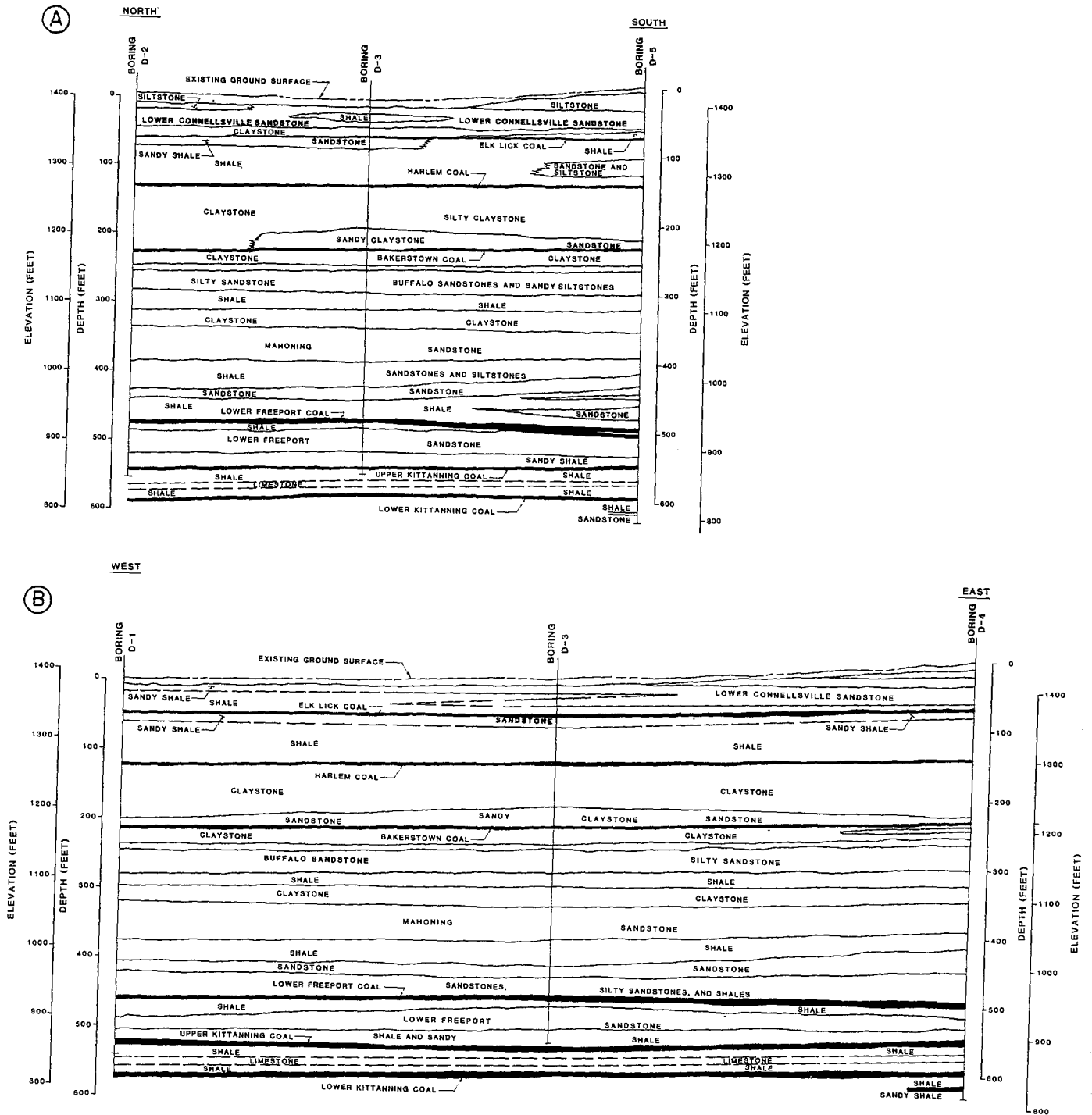


FIGURE 2.6 GEOLOGIC CROSS SECTIONS ACROSS C-3 PANEL
A. NORTH - SOUTH
B. EAST - WEST

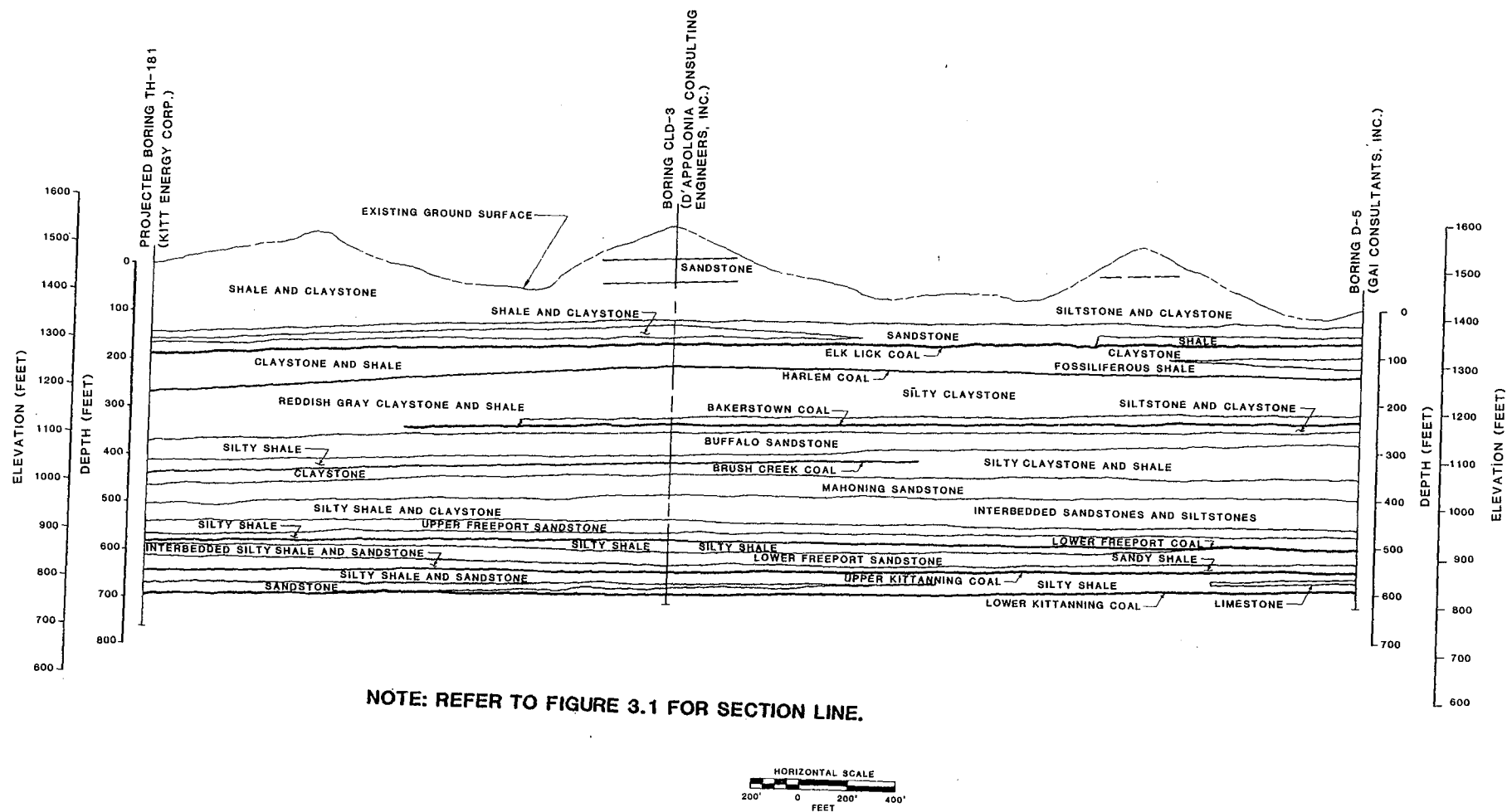


FIGURE 2.7 GEOLOGIC CROSS SECTION BETWEEN C-3 AND D-3 PANELS

Coal units within the formation are the 1- to 2-foot thick Harlem Coal near the top of the formation and the foot-thick Bakerstown Coal located 105 feet below, near the middle of the formation. At 285 foot depth in Boring D-5, a coal-like response on the gamma-gamma density log appeared opposite a calcareous and slightly carbonaceous claystone--possibly indicating a thin, unsampled coal at this elevation, such as the Brush Creek Coal, which has been found in a similar stratigraphic position in the central portion of the mine property, north of the project site. The Mahoning Coal may be represented by irregularly-shaped coal partings found at the 413 to 430 foot depth in a 17-foot thick sandstone in Boring D-5. The base of the formation is defined by the top of the Upper Freeport Coal (Reger, 1918). In Boring D-5, the correlative of this coal is probably the sandstone at the 442- to 449-foot depth which contains thin, irregular and discontinuous streaks or partings of coal distributed throughout.

Distinctive sandstone units in the Glenshaw Formation are (1) the 10-foot thick Saltsburg Sandstone, located immediately above the Bakerstown Coal, but evident only in Borings D-1, D-4, and D-5; (2) the 28- to 36-foot thick Buffalo sandstone, a series of sandstone, silty sandstone, and sandy siltstone units located 20 feet below the Saltsburg Sandstone near the middle of the formation; and (3) the 79- to 104-foot thick Mahoning Sandstone, a series of massive sandstones, shaly siltstones, and sandy shales located in the lower third of the formation.

c. Allegheny Formation -- the interval from the base of the Glenshaw Formation to the top of the Lower Kittanning coal varies in thickness from 140 to 160 feet and consists of 55 percent shale and siltstone, 30 percent sandstone, 10 percent coal and 5 percent limestone. The interval contains no claystone.

The Allegheny Formation is capped by a 7-foot thick sandstone with irregularly-shaped coal partings, which are probably equivalent to the Upper Freeport coal. Identification of the coal partings by geophysical methods was not possible. Consequently, the location of the top of the Allegheny Formation is somewhat uncertain at locations other than Borehole D-5. Two distinct, evenly spaced coal units lie between the coal partings and the Lower Kittanning coal, the stratigraphically highest being the Lower Freeport coal and the other being the Upper Kittanning Coal. The Lower Freeport Coal varies from three to eight feet in thickness and, where thickest, is separated into two or three benches by 1- to 3.5-foot intervals of carbonaceous shales. The Upper Kittanning Coal is 3- to 4-feet thick. Prominent sandstones in the Allegheny Formation are (1) the 12-foot thick Upper Freeport Sandstone, which lies between the top of the formation and the Lower Freeport Coal, and (2) the 28-foot thick Lower Freeport Sandstone which lies between the Lower Freeport Coal and the Upper Kittanning Coal. Approximately 40 feet of rock strata separate the Upper Kittanning Coal from the Lower Kittanning Coal. The top 15 feet are calcareous shale. Below the shale is a limestone and below the limestone are rock units forming the immediate mine roof. These are described below.

MINE ROOF

Mine roof strata are illustrated in Figure 2.8. Medium hard, silty and calcareous shales form the immediate mine roof, which is overlain at a height of 16 feet above mine level by a hard, gray 6- to 7-foot thick limestone. Medium soft clay partings are distributed throughout the 3.5 feet of shale located immediately below the limestone. Rock core from the mine roof exhibited fracture spacings varying from two inches to three feet. The silty shale with clay partings was the most broken; the limestone unit

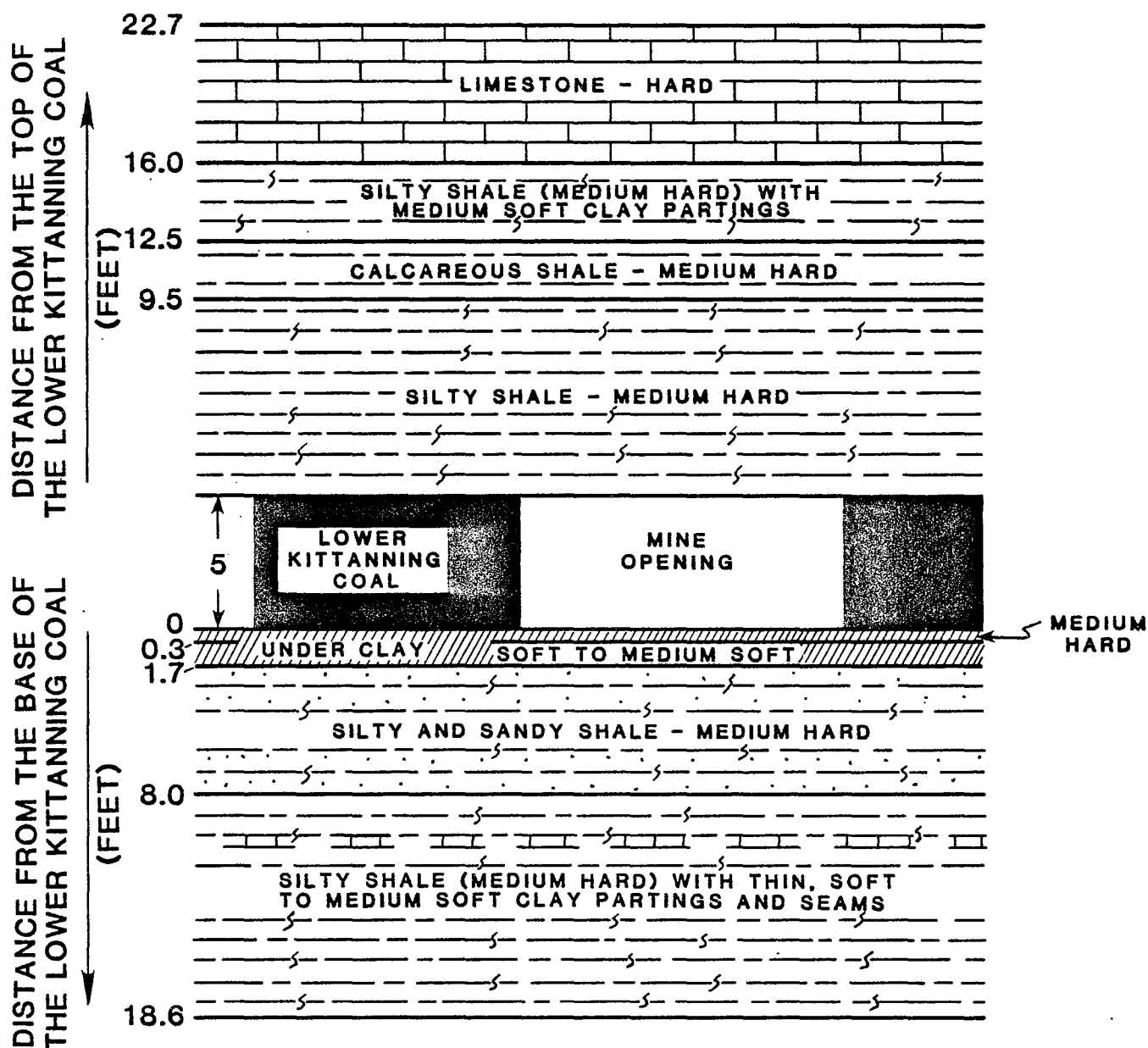


FIGURE 2.8
STRATIGRAPHY OF THE IMMEDIATE MINE ROOF
AND FLOOR AT THE LOCATION OF BORING D-5

and the silty shale just above mine-level were less broken. RQD values for these strata varied from 69 to 88 percent (Boring D-5, Figure 2.5 E), which indicate the rock quality to be fair to good.

LOWER KITTANNING COAL

Within the C-3 mine-panel, the thickness of the Lower Kittanning coal (measured at mine level) varies from 4.7 to 6.2 feet. A 1- to 2-inch thick bed of "bony" or argillaceous coal divides the Lower Kittanning Coal into two units, the upper of which generally represents 1/2 to 2/3 the thickness of the entire coal seam. Vertically oriented, hard, clay dikes 1- to 3-feet wide were occasionally encountered in the coal during mining.

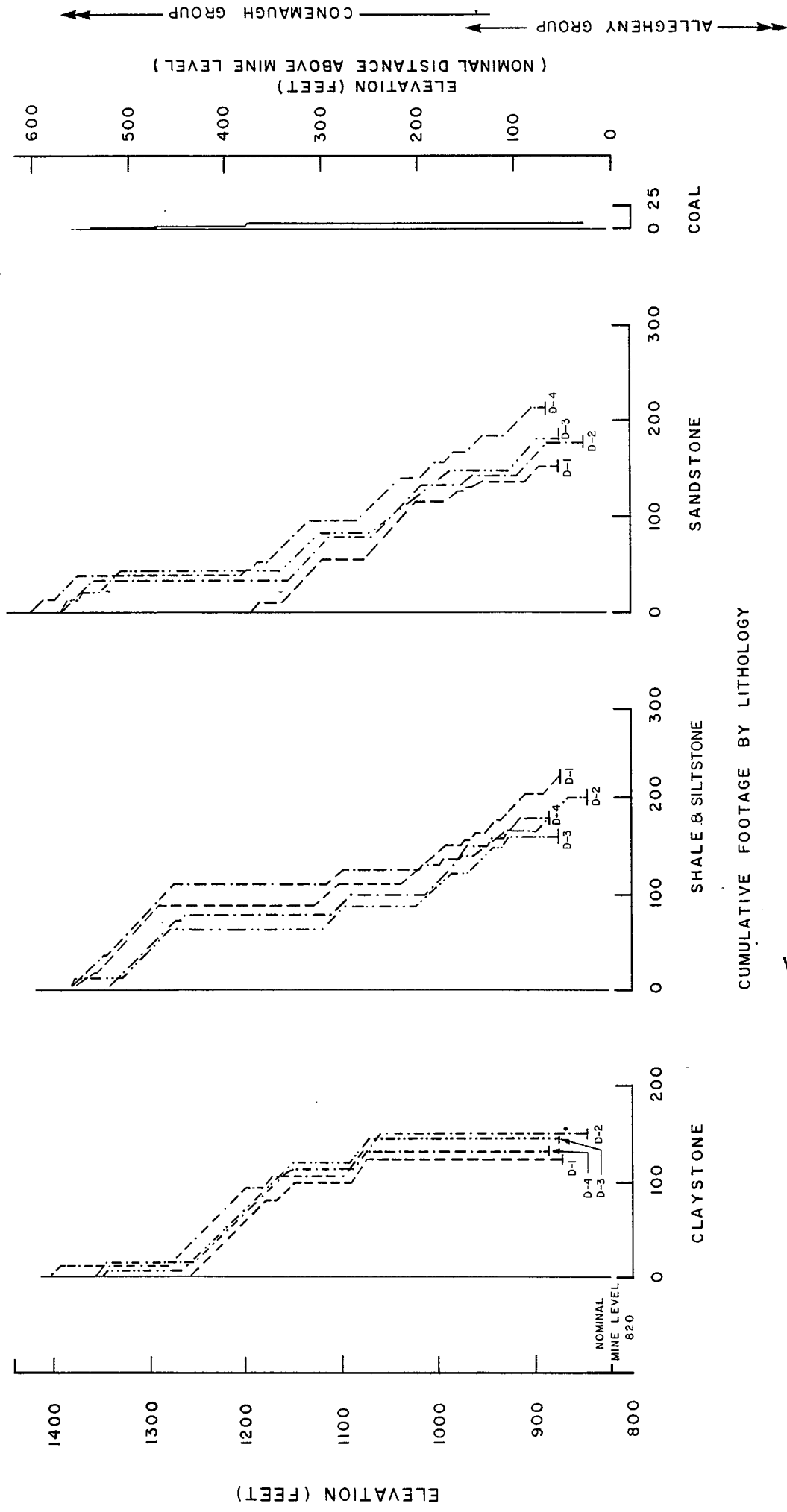
MINE FLOOR

The immediate mine floor is composed of 1.7 feet of underclay at the location of Boring D-5, the only sampling point (Figure 2.8). The upper 0.3 feet of the underclay is medium hard and the lower 1.4 feet is soft to medium soft. Silty and sandy shales of medium hardness with occasional thin, clay seams separate the underclay from the one-foot thick Clarion Coal located about 17 feet below the mine floor. The Clarion Coal, in turn, is underlain by clayey, sandy shale to undetermined depth.

LITHOLOGIC DISTRIBUTION

Figure 2.9 summarizes the vertical distribution of overburden lithologies above the C-3 panel based upon tabulations from Borings D-1 through D-4. The four sets of curves portray the cumulative footages of claystone, shale-siltstone, sandstone and coal between ground surface (Elevation 1400±) and any specified elevation below ground surface. A particular lithology is present in that interval where the cumulative footage curve slopes to the right and is absent where the curve is vertical. The curves show that (1) the overburden, as a whole, is composed of approximately 37 percent sandstone, 37 percent shale-siltstone and 25 percent claystone, with minor amounts of limestone and coal; and (2) the lithologies are not distributed uniformly with depth. The sandstone units are confined primarily to the lower half of the overburden, the shale and siltstone to the upper and lower thirds of the overburden, and the claystone to the middle third; and (3) the vertical distribution of lithologies is relatively uniform across the site, indicating a general lateral continuity of the strata across the mine panel, with exceptions as noted above and in Figures 2.6 and 2.7.

The character of the overburden is discussed further in subsequent sections of the report.



Note: Limestone $\leq$ 5%

FIGURE 2.9— DISTRIBUTION OF OVERBURDEN LITHOLOGIES, C-3 PANEL

3.0 MINING PROGRAM

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MINE PLAN*

Figure 3.1 represents the Kitt Mine when the C-3 monitoring program was conducted. The nearest total extraction mining to the C-3 panel prior to or during the monitoring program was that in the D-3 longwall panel, 1200 feet northeast. Both the C-3 and D-3 panels were mined at approximately the same time in 1981-1983. The A-mains and C-mains had been driven earlier. During the monitoring program, the A-mains were buffered from the C-3 panel by a 180-foot wide barrier pillar and from the C-mains by a 300-foot wide series of barrier pillars. More than 2000 feet of unmined coal lay between the A- and C-mains to the west of the C-3 panel.

MINING SEQUENCE

Mining was conducted using a single Joy 14 CM continuous miner, along with a scoop and two 21 SC shuttle cars.

Figures 3.2A-L illustrates the mining sequence, which can be described as follows:

1. Developmental Mining (Advance Mining)
 - a. Driving the Mains. In developing the Kitt Mine, eight main entries [a]†-the C-mains--were driven into the unmined coal adjoining and parallel to the section of the mine property that was to become the C-3 panel. To connect the main entries, cross-cuts were introduced at regular intervals, forming seven parallel, northwest-southeast bearing lines of coal pillars (chain pillars). Those chain pillars in the vicinity of the C-3 panel measured 53 feet by 83 feet in plan, the long dimension being oriented parallel to the entries. Each entry and cross-cut measured 17 feet in width and 5.5 feet in height. The system of eight main entries and seven chain pillars totalled 510 feet in width.
 - b. Driving the Ventilation Entries. Development of the C-3 panel began with driving the C-1 bleeder (or ventilation) entries [b] from the

* To simplify the discussion, north ("project north") is assumed to be directed parallel to the long axis of the C-3 panel in the direction of the C-mains.

† Bracketed letters [a] - [e] are keyed to Figure 3.2A

-  MINE CONFIGURATION AS OF AUGUST, 1983
-  AREAS OF TOTAL COAL EXTRACTION
-  AREAS OF PROJECTED FUTURE MINING
-  BORING LOCATIONS AND CROSS SECTION TRACE, FIGURE 2.7



SCALE: 1"=1000'

0 500 1000 2000 3000

GROUND SURFACE
CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

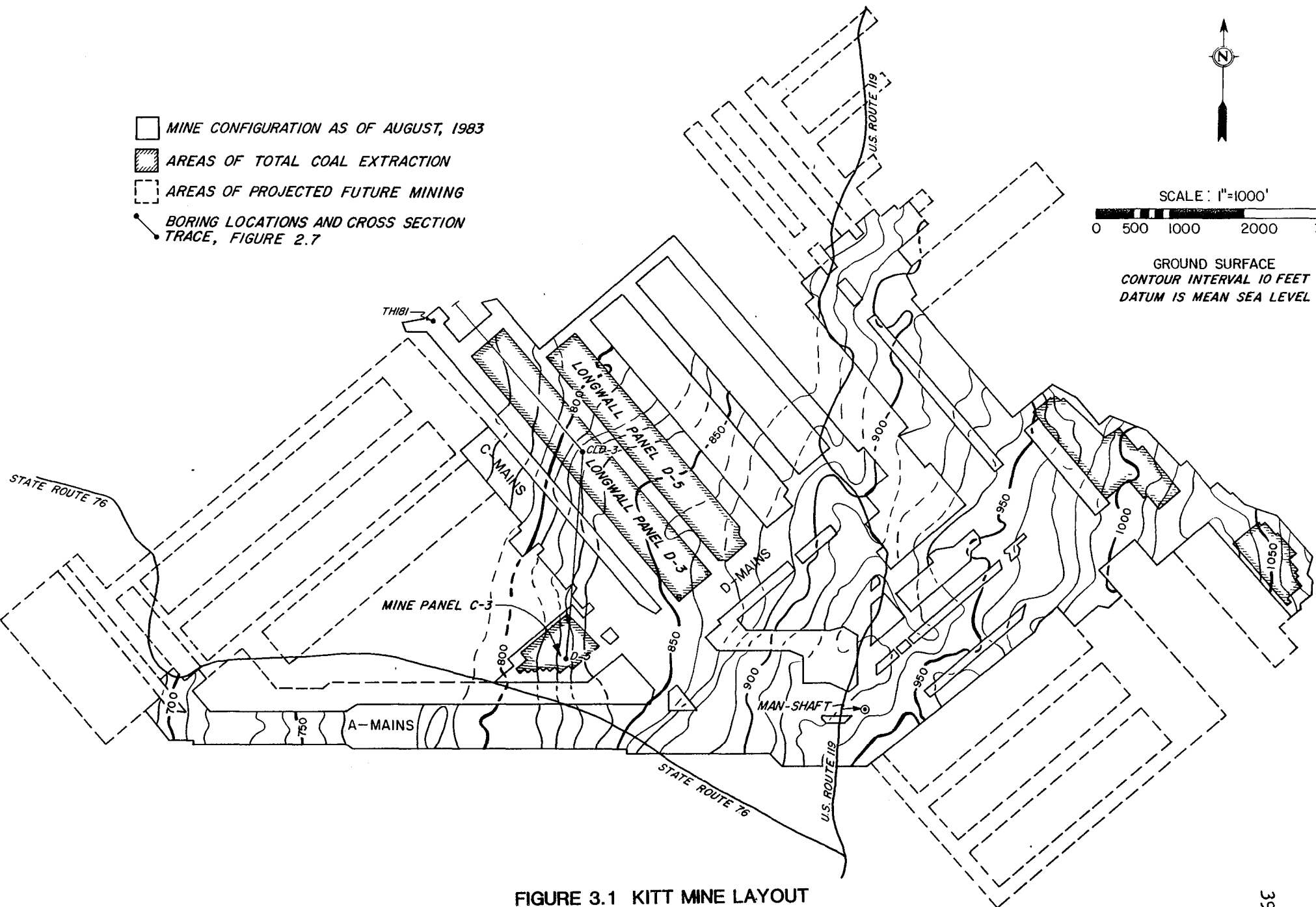
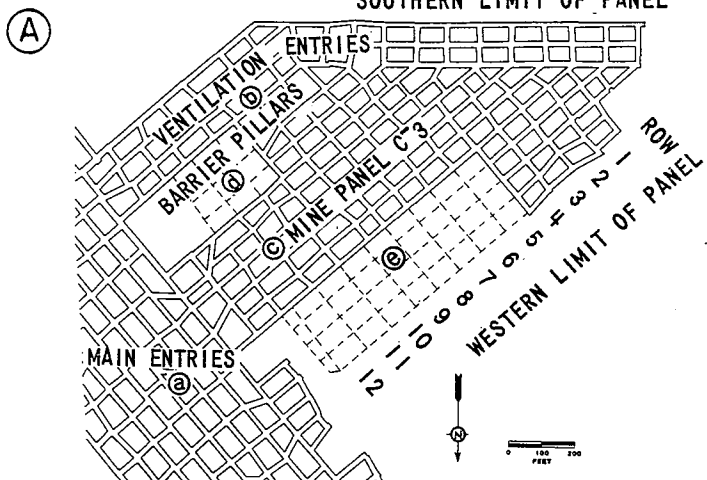
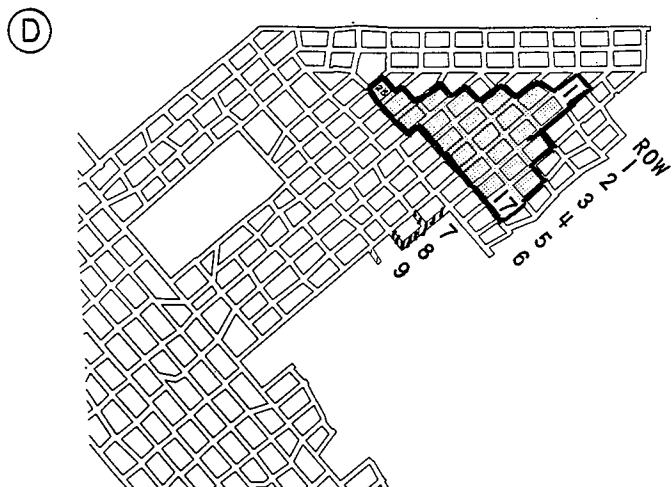


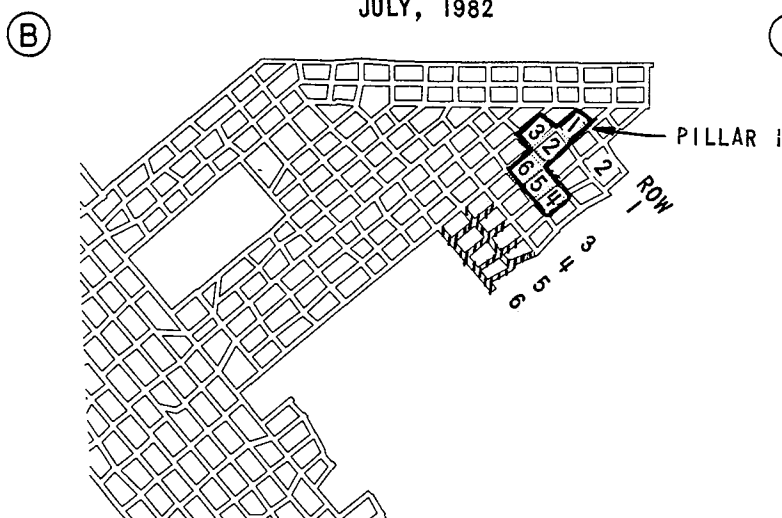
FIGURE 3.1 KITT MINE LAYOUT



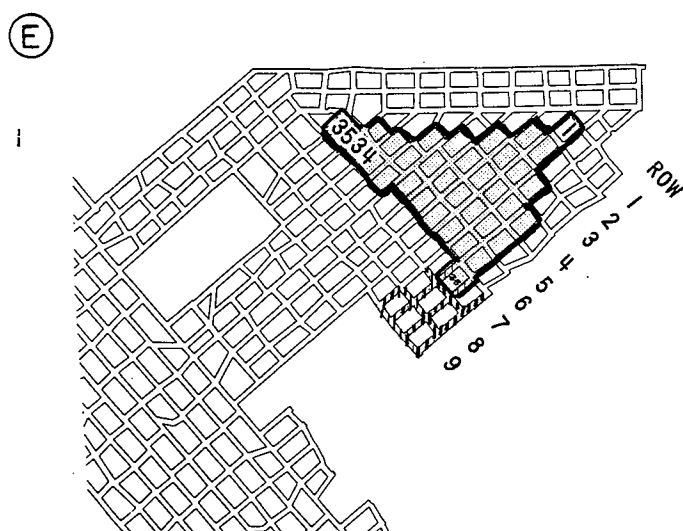
C-3 PANEL CONFIGURATION
AFTER ADVANCE MINING &
BEFORE RETREAT MINING
JULY, 1982



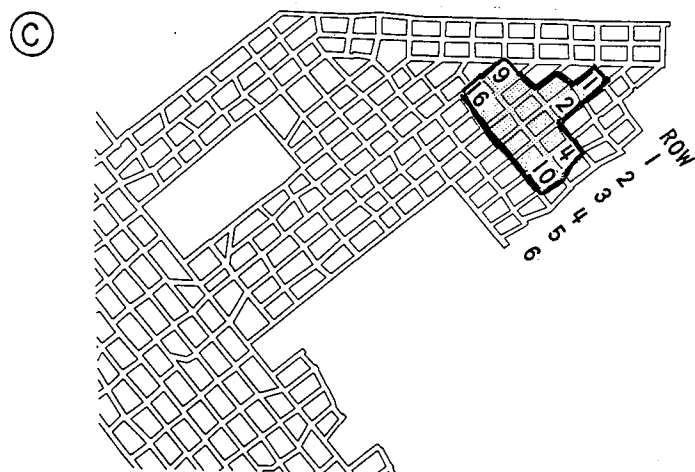
SURVEY NO. 8, SEPTEMBER 21, 1982



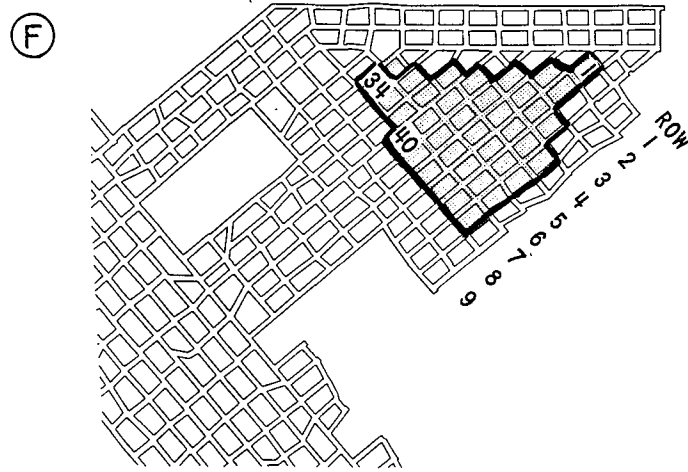
SURVEY NO. 6, AUGUST 21, 1982



SURVEY NO. 9, OCTOBER 18, 1983



SURVEY NO. 7, SEPTEMBER 3, 1982



SURVEY NO. 10, OCTOBER 25,



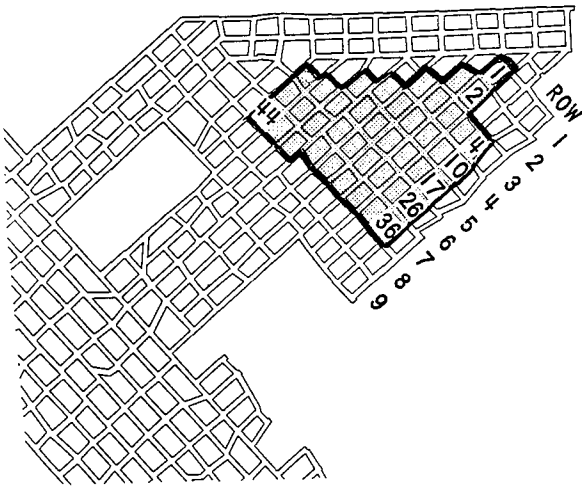
NEWLY DEVELOPED ENTRY OR CROSS CUT;



MINED OUT; PILLARS EXTRACTED

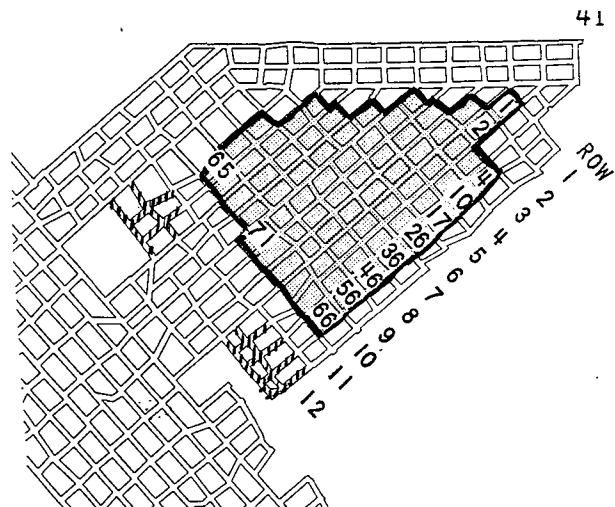
FIGURE 3.2 SEQUENCE OF MINING OF THE C-3 PANEL

(G)



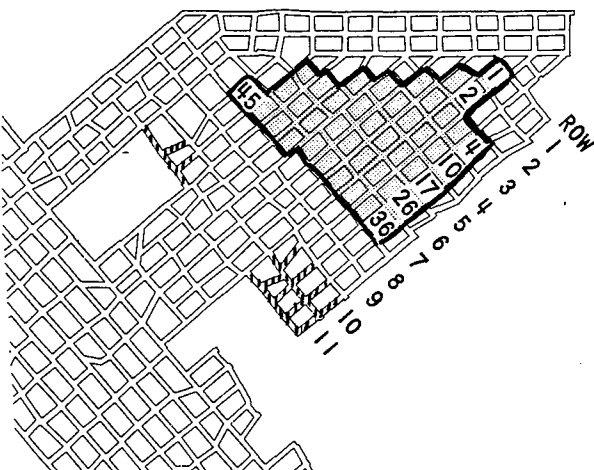
SURVEY NO. 11, OCTOBER 28,

(J)



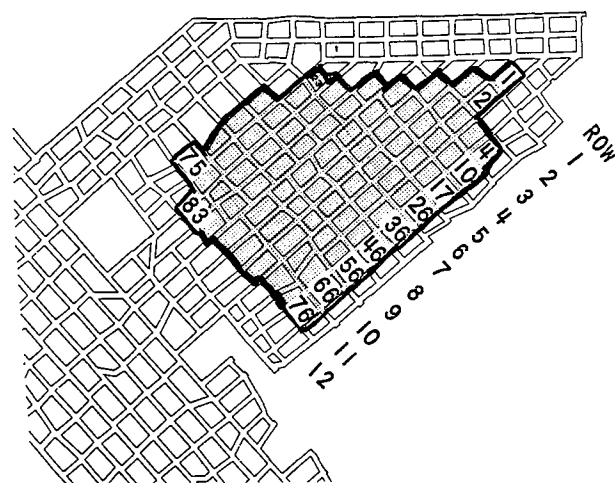
SURVEY NO. 14, JANUARY 4, 1983

(H)



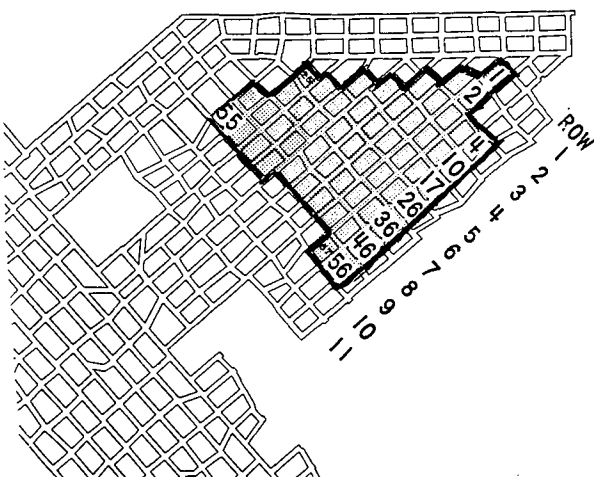
SURVEY NO. 12, NOVEMBER 16, 1982

(K)



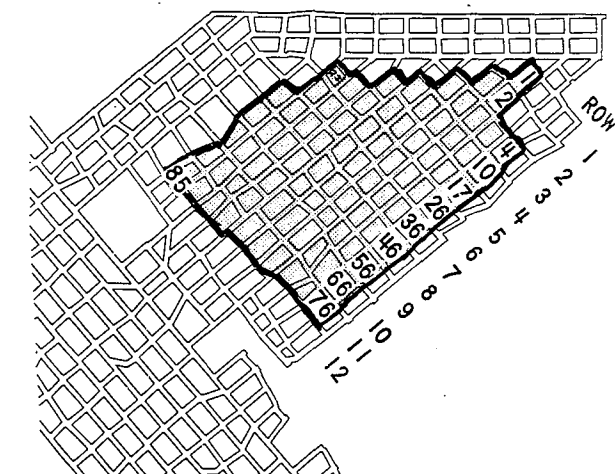
SURVEY NO. 15, JANUARY 13, 1983

(I)



SURVEY NO. 13, DECEMBER 2, 1982

(L)



SURVEY NO. 16, FORWARD JANUARY 26, 1983

C-mains along the southeast margin of the mine panel. Part was driven prior to developmental mining elsewhere in the C-3 panel and part was driven coincidental with developmental mining in the panel.

- c. Developing the Pillar Extraction Area. The C-3 panel, as developed and mined by Kitt Energy Corporation, encompassed an area that was 950 feet wide and 1600 feet long. Before Kitt Energy's change of ownership (and change in mine plan), this area was to have been occupied by two adjacent panels, C-3 and C-5 (Figure 3.3). As part of the change in mine plan, which took place after the current monitoring program had been developed and partially implemented, the width of the revised C-3 panel was made two pillar rows narrower than the combined width of the original C-3 and C-5 panels. The offset in pillar rows along the longitudinal axis of the C-3 panel demarcates the boundary between the two earlier panels. The revised mining plan also included the utilization of large barrier pillars along the east and west flanks of the panel during developmental mining.

In developing the C-3 panel, six panel entries [c] were driven perpendicular to the main entries for the entire length of the panel and were joined at regular intervals by cross-cuts, forming five parallel lines of pillars. Individual coal pillars varied somewhat in size and shape (Figure 3.2A), but generally approximated the design dimensions of 43 feet by 73 feet. Cross-cut and entry widths measured 17 feet on average.

A 200-foot wide barrier pillar [d] was maintained between the ventilation entries and the panel entries and, at several locations 260 feet from the mains and beyond, was transected by entries and cross-cuts extending to the ventilation entries.

When developmental mining reached the far (south) end of the mine panel, several entries and cross-cuts were also driven into the block of coal [e] occupying the west flank of the panel at its south end. This created additional pillars of the usual 43 by 73 foot size and extended the first four rows of pillars to the western limit of the panel. The configuration of the C-3 panel upon completion of developmental mining in late July, 1982, was as shown in Figure 3.2A. Further developmental mining was conducted in association with retreat mining, as discussed below.

2. Retreat Mining and Pillar Recovery. Retreat mining began at the south end of the panel with the extraction of Pillar 1 (Figure 3.2B) and proceeded systematically row by row, west to east, across the short dimension of the mine panel leaving in place the western-most column of pillars along the solid coal. Pillars were extracted in pairs using a "split-and-fender" sequence as illustrated by Figure 3.4 so as to provide sufficient work places for the continuous miner and the bolter to operate concurrently.

In mining a pair of coal pillars, an 18-foot long cut was first made by the continuous miner along the longitudinal axis of the more westerly of the two pillars. The miner then made a similar cut in the easterly pillar, as the

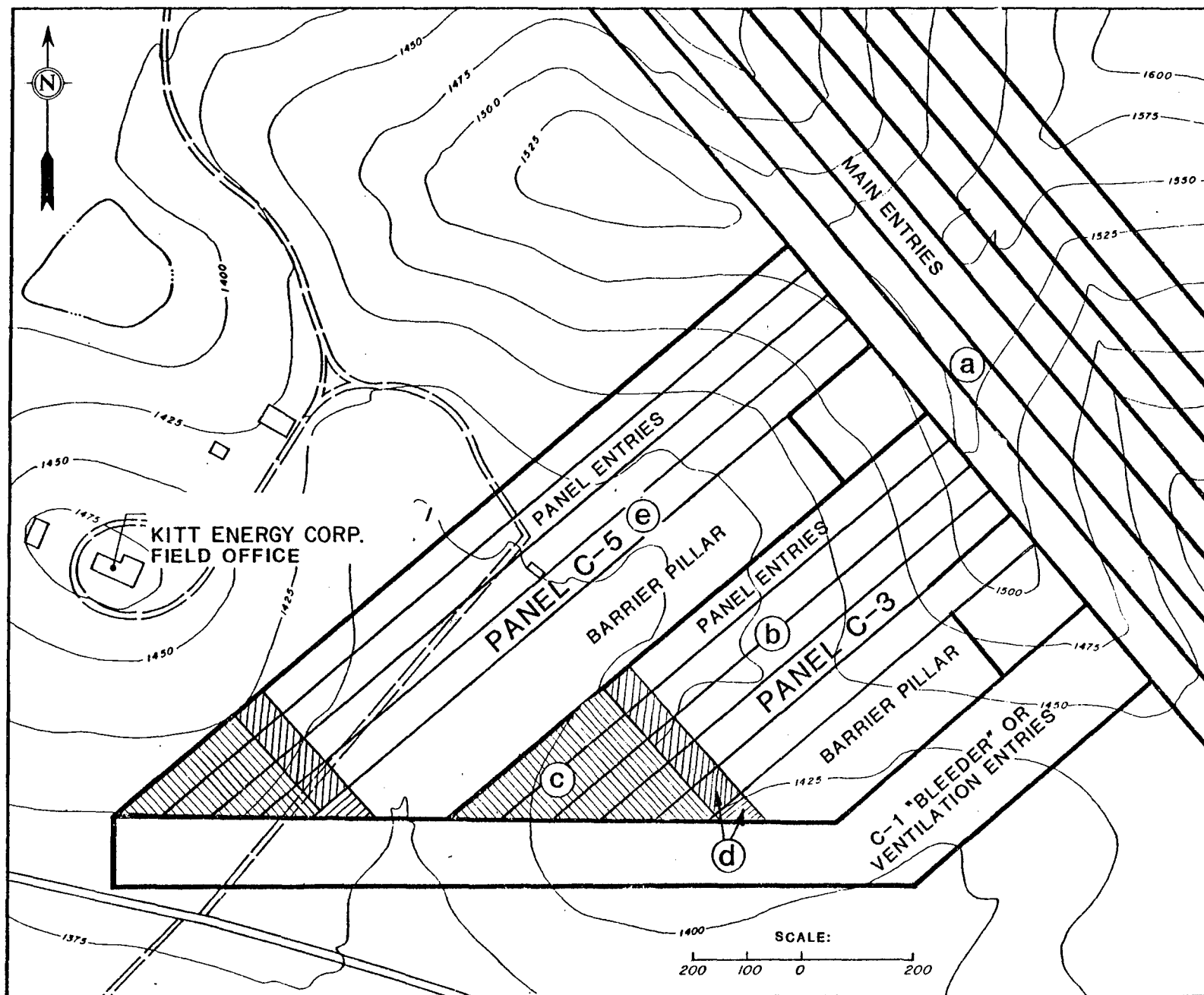
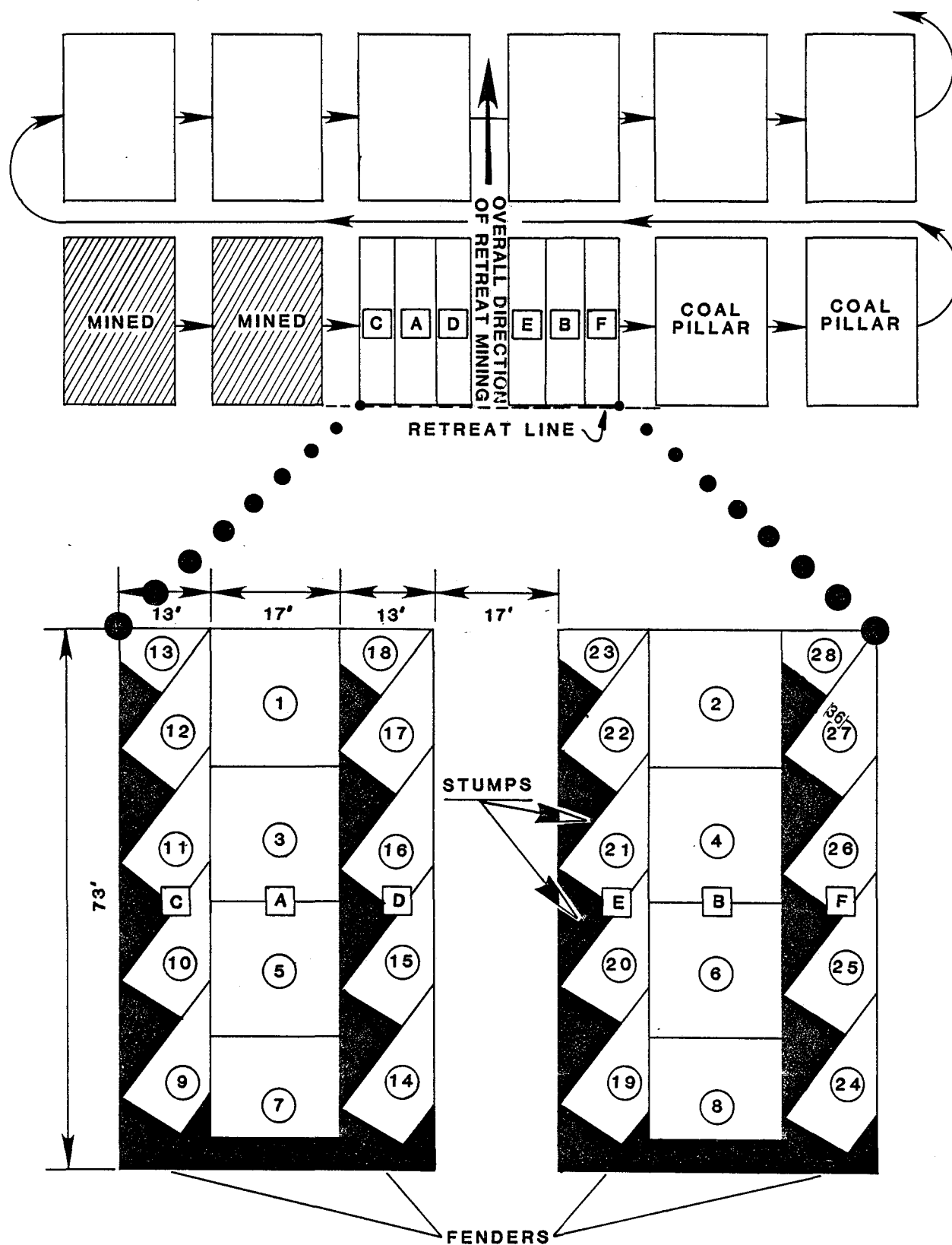


FIGURE 3.3 ORIGINAL C-3/C-5 PANEL CONFIGURATION



A, ① - Order in which portions of each pair of coal pillars is removed by a continuous miner.

Note: Posts and other support are not shown.

FIGURE 3.4 SEQUENCE OF PILLAR EXTRACTION AT THE KITT MINE

bolter installed roof support within the westerly pillar. This dual operation--advancing the cut and bolting -- alternated between the pair of pillars until only a 3- to 5-foot interval of coal separated each cut from the gob. The miner then moved to the western-most of the four fenders created by splitting the two pillars and proceeded to remove that fender by cutting a series of contiguous angled pockets beginning at the end nearest the gob. Each of the four fenders was removed in succession by this method. The area around the continuous miner was heavily timbered to prevent roof falls as the angle cuts were made, and, for further safety, was also supported by coal "stumps" of various widths left at the end of each cut by the mining machine operator based upon his judgment of local roof conditions. Determination of even approximate dimensions of the stumps was impossible. There is little doubt that they crushed out as retreat progressed along the panel.

Collapse of the mine roof as a result of the removal of coal pillars often occurred within several hours after pillar removal, if not sooner. Twice during retreat mining, the front half of the continuous miner was buried by roof falls, necessitating careful excavation to remove the machine from beneath the precariously piled, broken roof rock. Because roof failure depended on both the strength of the roof rock and local pillar support, expanses of uncollapsed mine roof measuring a few tens of feet on a side were sometimes observed in the gob area behind the retreat line. These areas collapsed with enlargement of the mined-out area.

Deviations from the usual split-and-fender sequence described above were sometimes necessitated by poor roof conditions:

- a. In Pillar Row 8, for example, extraction first progressed from west to east in the usual fashion, but ceased near the center of the row where roof conditions were poor. Extraction then resumed from the east side of the row and worked toward the center, in this way obviating the need for the shuttle car to pass unstable roof.
- b. In several areas of poor roof, a "Christmas tree" extraction procedure was employed, wherein both ribs of a pillar were extracted by driving pockets to each side from the center longitudinal cut through the pillar. This made maximum use of the support offered by the pillar itself and minimized activities beneath the "old" roof of the entry between the pillars. The method was not used on a regular basis because it required considerable maneuvering of the continuous miner.
- c. Several pillars in areas of poor roof (eg. Pillars 3 and 14) were cut transversely (across the short dimension) rather than longitudinally to maintain stout pillar support against the gob. This "pocket-and-wing" sequence was followed primarily in the early stages of retreat within the triangular south end of the panel.

Each time one or two rows of pillars were extracted across the width of the panel, additional entries and cross-cuts were

driven into the as yet undeveloped coal flanking the six panel entries. The hatching in Figure 3.2B-L identifies areas where developmental mining alternated with pillar extraction. Such development was confined to the west flank [e] until early November, 1982, but thereafter was also conducted in the solid block of coal along the east flank [d].

Twelve rows of pillars were to have been extracted. However, as retreat mining neared completion, Kitt Energy elected to leave the twelfth (last) row in place as a precaution against overstressing the C-mains. This was done in view of the fact that the D-3 longwall panel directly across the mains from the pillar retreat panel (Figure 3.1) was nearing completion at the same time and had been thought by mine personnel to be the source of some distress observed in the C-Mains roof. Altogether, 82 coal pillars were extracted over an area measuring 615 feet in width and 1015 feet in length (longest panel dimension). Somewhat more than 90 percent of the coal was removed within this area.

Figure 3.2B-L documents the retreat sequence within the C-3 panel on dates when the ground surveys were conducted. The stippled areas indicate the gob. At any point in time during the retreat sequence, the boundary between the gob and the pillars not yet extracted is denoted as the 'retreat line'. Table 3.1 lists the dates of extraction of groups of coal pillars, the development of pillars along the flanks and the dates of corresponding surveys of the ground surface. The surveys are discussed in Section 9.

Developmental mining began on November 9, 1981 and ended 9.5 months later on July 23, 1982. Retreat mining began on July 26, 1982 and was completed six months later on January 18, 1983.

ROOF CONTROL

Roof bolts provided most of the roof support within the C-3 panel and were installed with a Fletcher DD-015 twin boom roof bolter. During advance mining, 5-foot long resin bolts were installed in a square pattern on 4.5-foot centers, with steel straps extending from bolt head to bolt head across the width of each mine opening to provide some protection against ravelling of the roof strata. During retreat mining, 6-foot long conventional bolts were installed on 4.5-foot centers in new cuts where the coal pillars were being split. Supplemental bolting was also conducted where the mine roof had deteriorated appreciably subsequent to advance mining.

At the retreat line, two parallel rows of timber "breaker" posts were installed across the width of each entry where it intersected the mined-out area. This was done to control breakage of the roof into the gob during pillar extraction and prevent its propagation back into the area still to be mined.

In two or three small areas, timbers and crossbeams were used along principal entries (track and conveyor entries) where local roof hazards existed. And wood cribbing was constructed along almost the entire length of the ventilation entry directly adjacent

Table 3.1
SCHEDULE OF PILLAR EXTRACTION
IN MINE PANEL C-3

Figure 3.2	Mine Pillars Extracted by Calendar Interval	Pillar Numbers (Dates of Extraction)	Calendar Interval of Developmental Mining x	Date of Surface Survey† (Survey Number)
B	7/23/82 to 8/21/82	1, 2, 3, 5, 6* (7/23/82 to 8/12/82)	8/13/82 to 8/21/82	8/21/84 (6)
C	8/22/82 to 9/3/82	7, 8, 10-15* (8/22/82 to 9/3/82)	-	9/3/82 (7)
D	9/4/82 to 9/21/82	16-25 (9/4/82 to 9/19/82)	9/20/82 to 9/21/82	9/21/82 (8)
E	9/22/82 to 10/18/82	26-34, 36* (10/5/82 to 10/18/82)	9/22/82 to 10/4/82	10/18/82 (9)
F	10/19/82 to 10/25/82	37-40 (10/19/82 to 10/25/82)	-	10/25/82 (10)
G	10/26/82 to 10/28/82	41-44 (10/26/82 to 10/28/82)	-	10/28/82 (11)
H	10/29/82 to 11/16/82	45 (10/29 82 to 10/31/82)	11/1/82 to 11/15/82	11/16/82 (12)
I	11/17/82 to 12/2/82	46-57 (11/17/82 to 12/2/82)	-	12/2/82 (13)
J	12/3/82 to 1/4/83	58-71 (12/3/82 to 12/5/82) (12/18/82 to 1/4/83)	12/6/82 to 12/17/82	1/4/82 (14)
K	1/5/83 to 1/13/83	72-83 (1/5/83 to 1/13/83)	-	1/13/83 (15)
L	1/14/83 to 1/26/83	84, 85 (1/14/83 to 1/26/83)	-	1/26/83 (16)

* Pillars 4, 9 and 35 were left in place.

x Developmental mining that alternated with pillar extraction.

† Surface surveys are discussed in Section 9 in association with ground surface movements. Additional surveys were conducted during the post-mining (residual subsidence) phase.

to solid coal on the south and southeast margins of the panel. The cribbing served to protect the entries during retreat mining in an area of severe roof degradation and floor heave.

Changes in pillar stress and ground movements associated with mining are discussed in subsequent sections of the report.

4.0 INSTRUMENTATION PROGRAM

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INTRODUCTION

A variety of devices were installed at the monitoring site: at mine level--convergence points, roof extensometers, stress meters and instrumented roof bolts; in the overburden--inclinometers, time domain reflectometry cables, multiple position borehole extensometers and piezometers; at ground surface--survey monuments and benchmarks. Each group of instruments is discussed in turn.

MINE LEVEL INSTRUMENTATION

In-mine devices were designed to monitor: 1) changes in mine opening height (convergence); 2) deflections of the roof strata; 3) changes in vertical pillar stress; and 4) changes in roof bolt load. Locations of these instruments are shown in Figures 4.1 and 4.2.

Stress Measurements

A total of 22 vibrating wire stress meter units were installed--21 in coal pillars, with active axis oriented vertically, and one in the mine roof adjacent to a multi-instrumented pillar with active axis oriented parallel to the entries. Thirteen of the units were installed in coal pillars that were ultimately extracted and eight in permanent pillars (or solid coal) around the perimeter of the extraction area.

Installation holes were drilled horizontally into the pillars at midheight using an electric auger. The holes were 2-inches in diameter from the pillar face to a point five feet from the deep end of the hole and 1.5-inches in diameter over the final five feet.

Each vibrating wire stress meter (manufactured by Irad) consisted of a hollow steel cylinder which, after insertion into the borehole, was preloaded diametrically by means of a sliding wedge and platen assembly. Stress changes in the surrounding rock medium induced small changes in diameter of the cylinder, which, in turn, induced commensurate changes in the natural frequency of vibration of a highly tensioned wire stretched across the internal diameter of the cylinder in the preload direction. The period of vibration of the wire was determined by connecting the leads to a portable readout box.

The stressmeter cables were routed back towards the C-mains on spads in the coal pillars or on roof bolt plates; cables from pillars to be extracted were terminated in junction boxes two- and one-half cross-cuts back toward the mains. Cables for the six

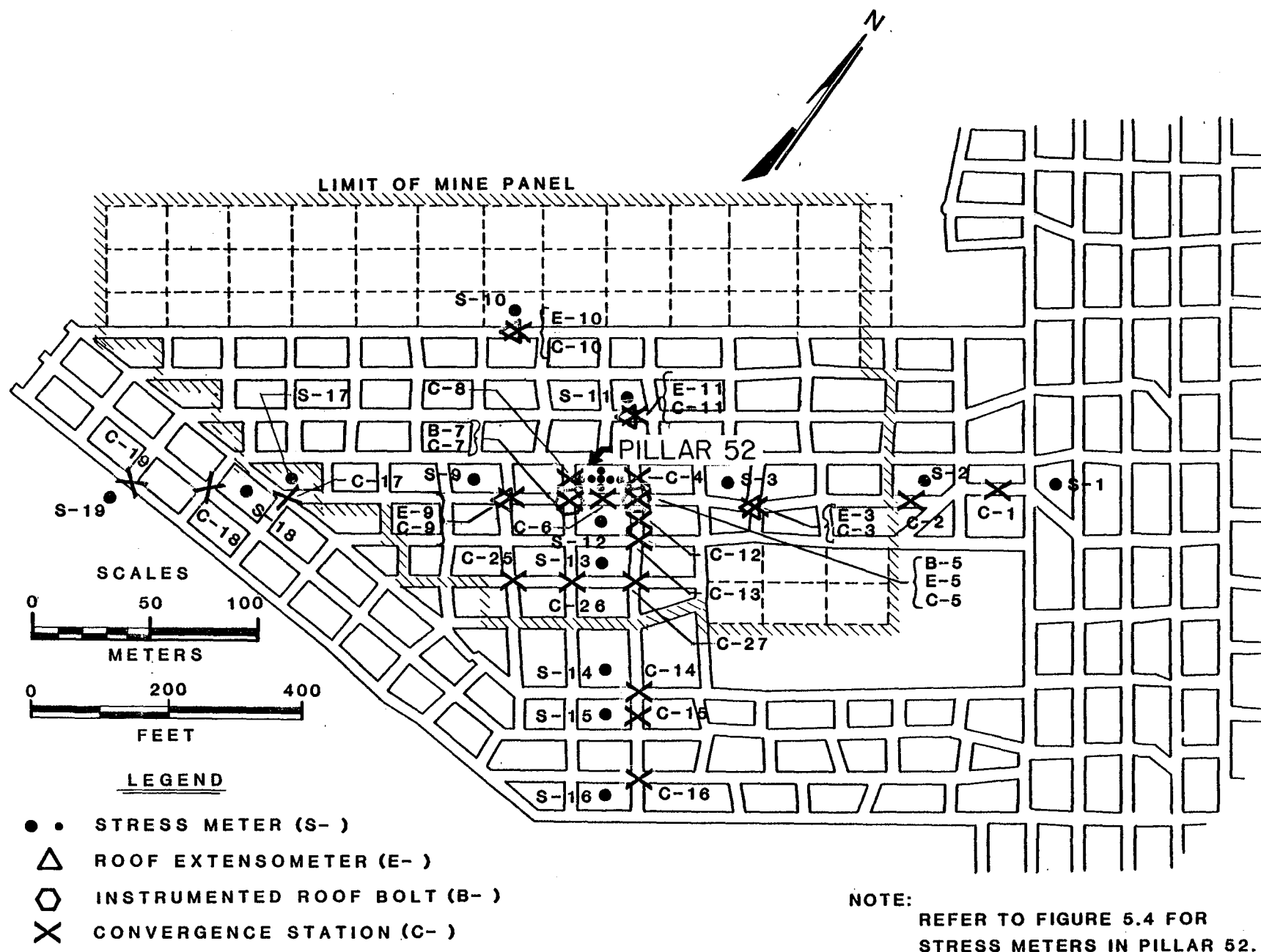


FIGURE 4.1 LOCATIONS OF MINE LEVEL INSTRUMENTATION

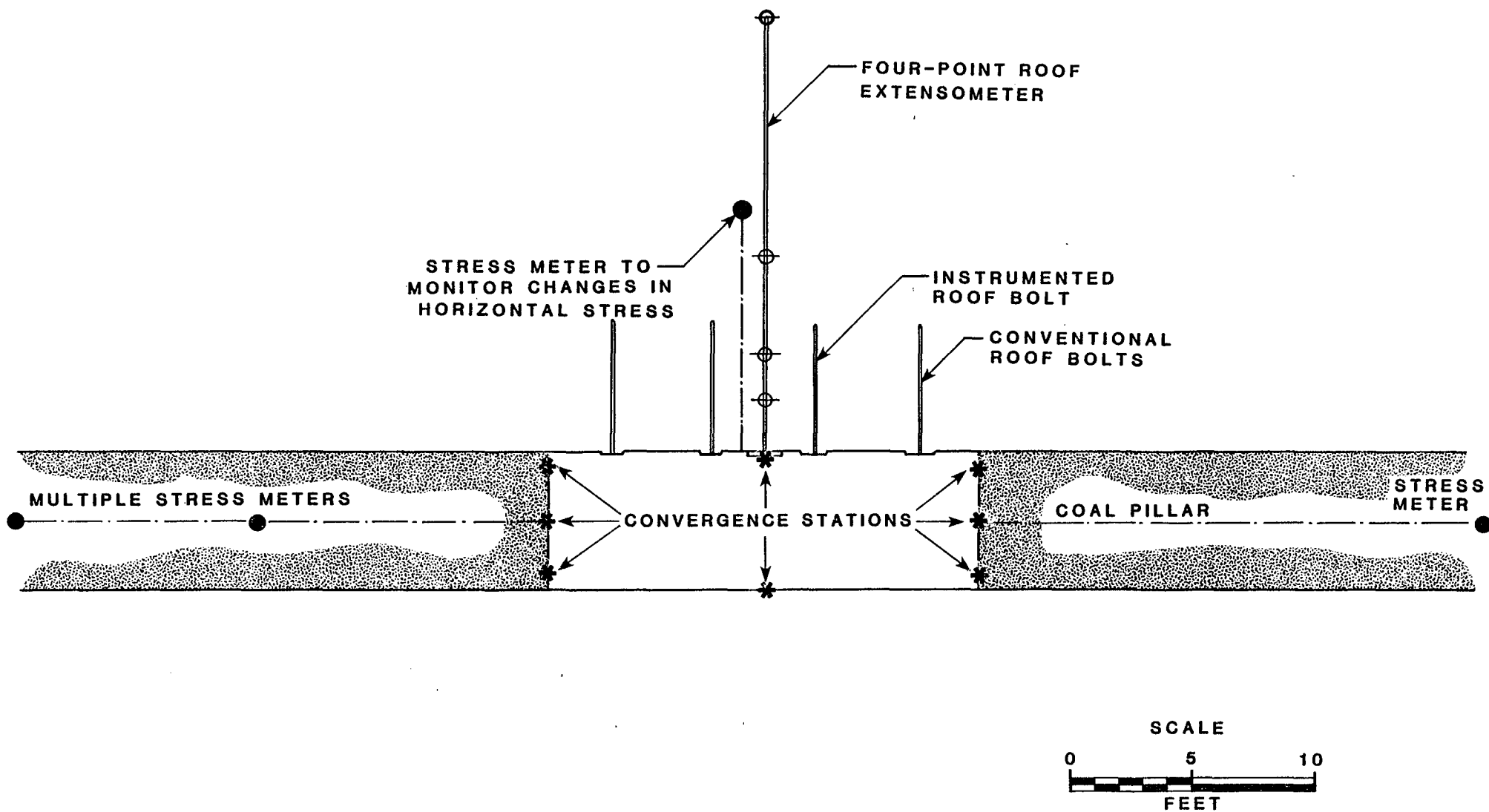


FIGURE 4.2 ELEVATION VIEW, INSTRUMENTED MINE OPENING

stressmeters in permanent pillars that were to remain functional after the completion of retreat mining were routed along the ventilation entries toward the C-mains and terminated in a junction box in an entry carrying intake air. The stress meter data are discussed in Section 5.

Instrumented Roof Bolts

Two inch diameter, six foot long load-indicating rock bolts manufactured by Irad were installed in the mine roof adjacent to the instrumented coal pillar. These bolts supplemented rather than replaced bolts in the conventional roof support pattern. Like the stress meters, the load indicating bolts operated on the vibrating wire principle. Each bolt was hollow and fitted with a coil, a magnet and a highly tensioned wire along its longitudinal axis. The bolts were installed in 1.375-inch diameter, 6-foot long holes drilled by the roof bolter and were secured by conventional expansion anchorages. The bolts were tensioned with a torque wrench by manually applying 150 foot-pounds to the nut at the collar of the hole. Changes in tension brought about by roof deflection altered the natural frequency of the wire, which was measured by means of a portable probe in combination with the read-out box.

Convergence

Changes in mine opening height were measured at 22 locations in the panel. Fifteen were located at the center of four-way intersections; one at a three-way intersection and six at the center (midspan) of entries or cross-cuts between intersections. Three of the locations at four-way intersections and two in entries were coincident with roof extensometer stations. A schematic of a convergence station is shown in Figure 4.2.

Each convergence station consisted of a pair of diametrically opposed 1/4-20 eyebolts, which were fastened, as appropriate, to existing roof bolt plates, or to expansion anchors secured to the floor or the coal pillar with epoxy. Eyebolts in the floor were installed in shallow holes and between readings were covered with steel plates. Measurements of distance between the points were made with a SINCO tape extensometer. Convergence was recorded as the difference between initial and subsequent readings.

Roof Movements

Vertical deflections of the roof strata were measured at five locations in the panel using multiple position borehole extensometers. The extensometers were installed in 1.5 inch diameter holes drilled by the roof bolter to a height 18 feet above mine level--higher than the expected zone of caving. Additional extensometers planned for the floor were deleted from the program due to the inability to drill vertically downward holes with available equipment.

Each extensometer consisted of four mechanical C-ring anchors positioned at points nominally 2, 4, 8 and 18 feet above mine level (Figure 4.2). A stainless steel rod extended from each anchor through a guide hole in the reference plate at the collar of the drillhole. A depth micrometer was used to measure the position of the lower end of each rod relative to the reference plate. Differences in rod position from reading to reading yielded a measurement of vertical anchor displacement. Vertical stratum displacements were computed from these readings assuming that the topmost (18-foot

anchor) remained stationary during retreat mining. The findings are discussed in Section 6.

SUBSURFACE INSTRUMENTATION

Strata Movement

Instruments to measure strata movements during mining were installed in five vertical borings drilled from ground surface to a depth of approximately 550 feet, 50 feet above mine level. Hole locations (denoted D-1 through D-5) are shown in Figure 4.3. Boring D-1 is located in the southerly half of the panel from which pillar extraction began. Borings D-2 and D-4 are located near the midpoints of the long and short sides of the panel, 100 feet and 200 feet, respectively, from the solid coal. Boring D-3 is located along the centerline of the mine panel near the expected location of maximum subsidence resulting from pillar extraction. Boring D-5, cored by NX-wire line methods, is located on the southeast hillslope and passed through the complete stratigraphic section at the mine site. The other four borings were drilled by air rotary methods and were 6-inches in diameter. GAI monitored the drilling of all holes so that intervals of water loss and other details could be properly interpreted. Stratigraphic correlations between the non-cored holes and core hole D-5 were made on the basis of downhole geophysical logs, as discussed in Section 2.

The borings were fitted variously with the following devices: multiple position borehole extensometers (MPBX's) and Sondex rings for measuring vertical deflections of strata; slope indicator casing for measuring lateral deflections of strata; time domain reflectometry cables to identify intervals where significant shearing, strata separation or breaks took place; and piezometers to measure piezometric levels in selected strata. Specific instrumentation installed in each boring is summarized in Table 4.1.

Multiple Position Borehole Extensometers (MPBX's)

Each MPBX comprised an eight anchor, constant tension wire system. The anchors consisted of two-foot lengths of #8 steel (1-inch diameter) reinforcing bar attached at prescribed locations along the outside of a central spine of plastic inclinometer casing.

A 1/16 inch diameter, 1 x 19 stranded stainless steel cable extended from each anchor to the readout head. Each wire was encased in an individual 1/4 inch diameter nylon tube filled with hydraulic fluid that served as a lubricant and corrosion inhibitor.

The extensometer readout heads were specially designed for the project by Soil and Rock Instrumentation and incorporated an independent spring tensioning and readout system for each anchor. The springs provided a constant 22 pounds of tension on each wire for the design travel of the extensometer--2 feet of upward movement and 8 feet of downward movement for each anchor. At the reference head, the top of each wire was permanently marked and labeled at one foot intervals with nine, steel crimp-markers. A 1-foot scale graduated in 0.01 foot intervals was positioned under each wire for reading each wire marker. Figure 4.4 presents a schematic of the MPBX system and Figures 4.5 and 4.6 present details of the reference head and a typical anchor.

Table 4.1
BOREHOLE SUBSURFACE INSTRUMENTATION

<u>Boring</u>	<u>MPBX^w</u>	<u>Inclinometer</u>	<u>TDR^x</u>	<u>Monitoring Well[‡]</u>
1	X	X	X	X
2	X	X	X	
3	X	X		
4	X	X	X	X
5			X	

w Multiple position borehole extensometer

x Time domain reflectometry cable

‡ Piezometer installations in the Mahoning Sandstone (Refer to Section 8 for details)

LEGEND

- MPBX-INCLINOMETER
- ◐ MPBX-INCLINOMETER-TDR
- NX CORE BOREHOLE WITH TDR
- GROUNDWATER MONITORING WELLS
- SURVEY MONUMENT
- ◻ STRAIN TRIANGLE MONUMENT CONFIGURATION

D2 BORING NUMBER

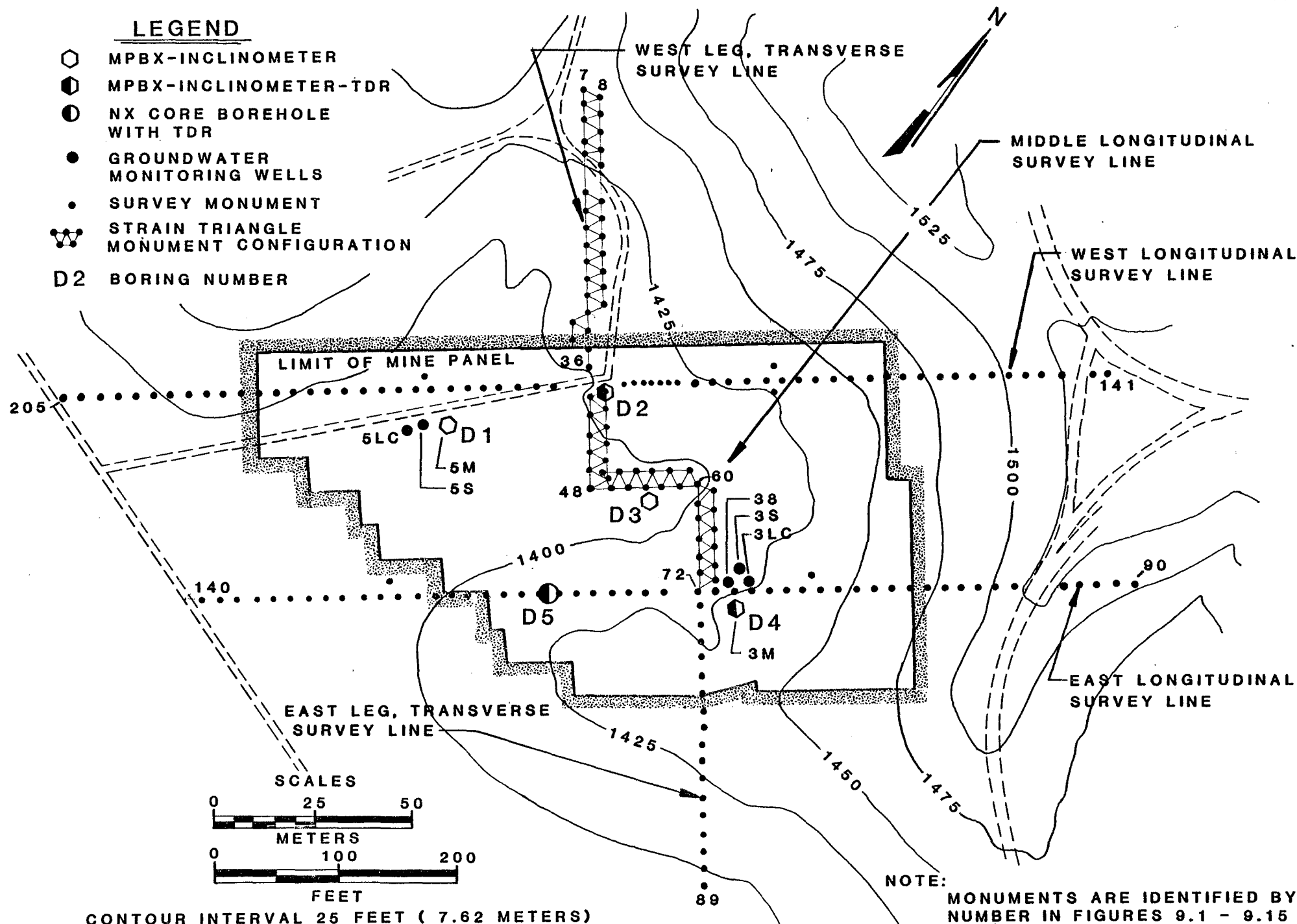


FIGURE 4.3 LOCATIONS OF SUBSURFACE AND SURFACE INSTRUMENTATION

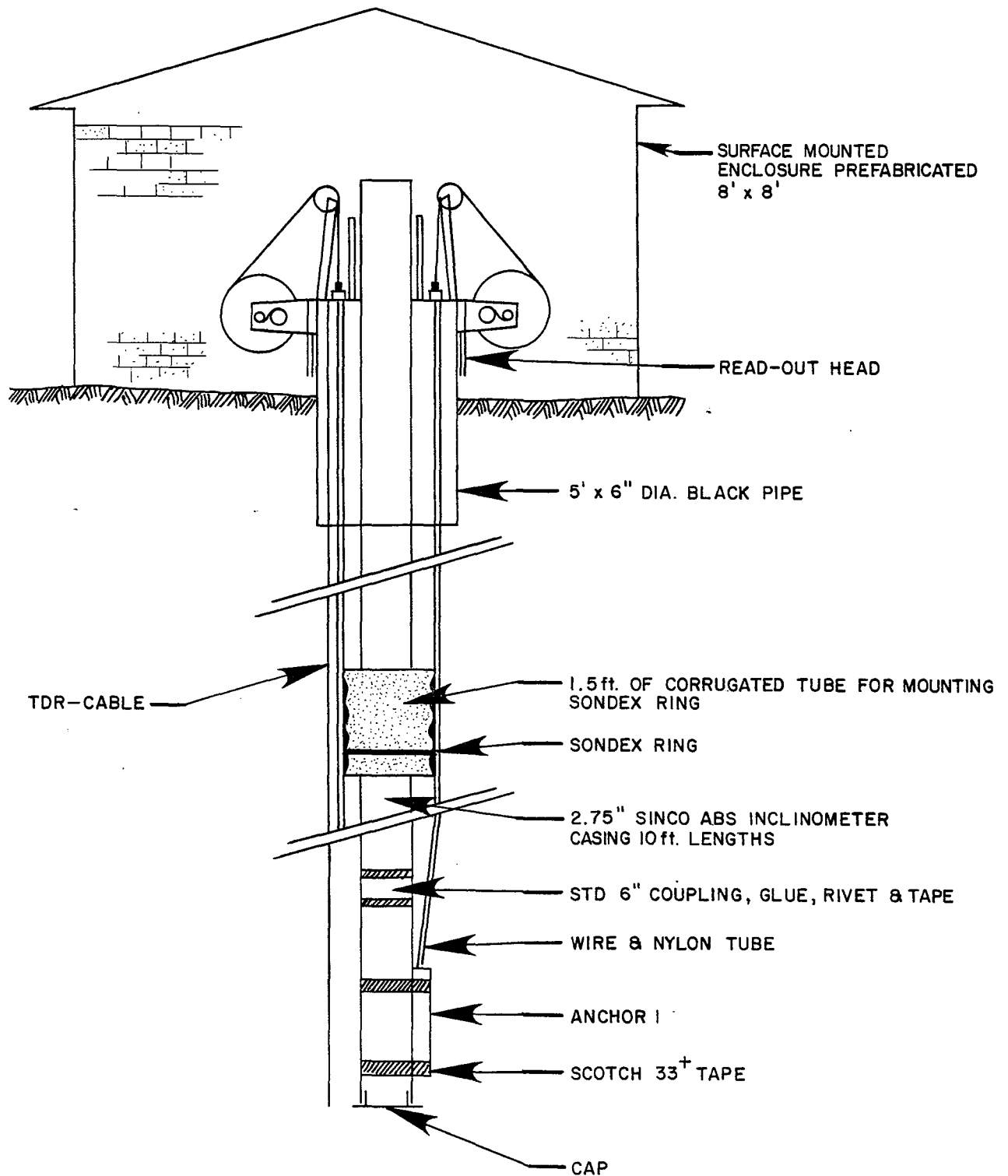
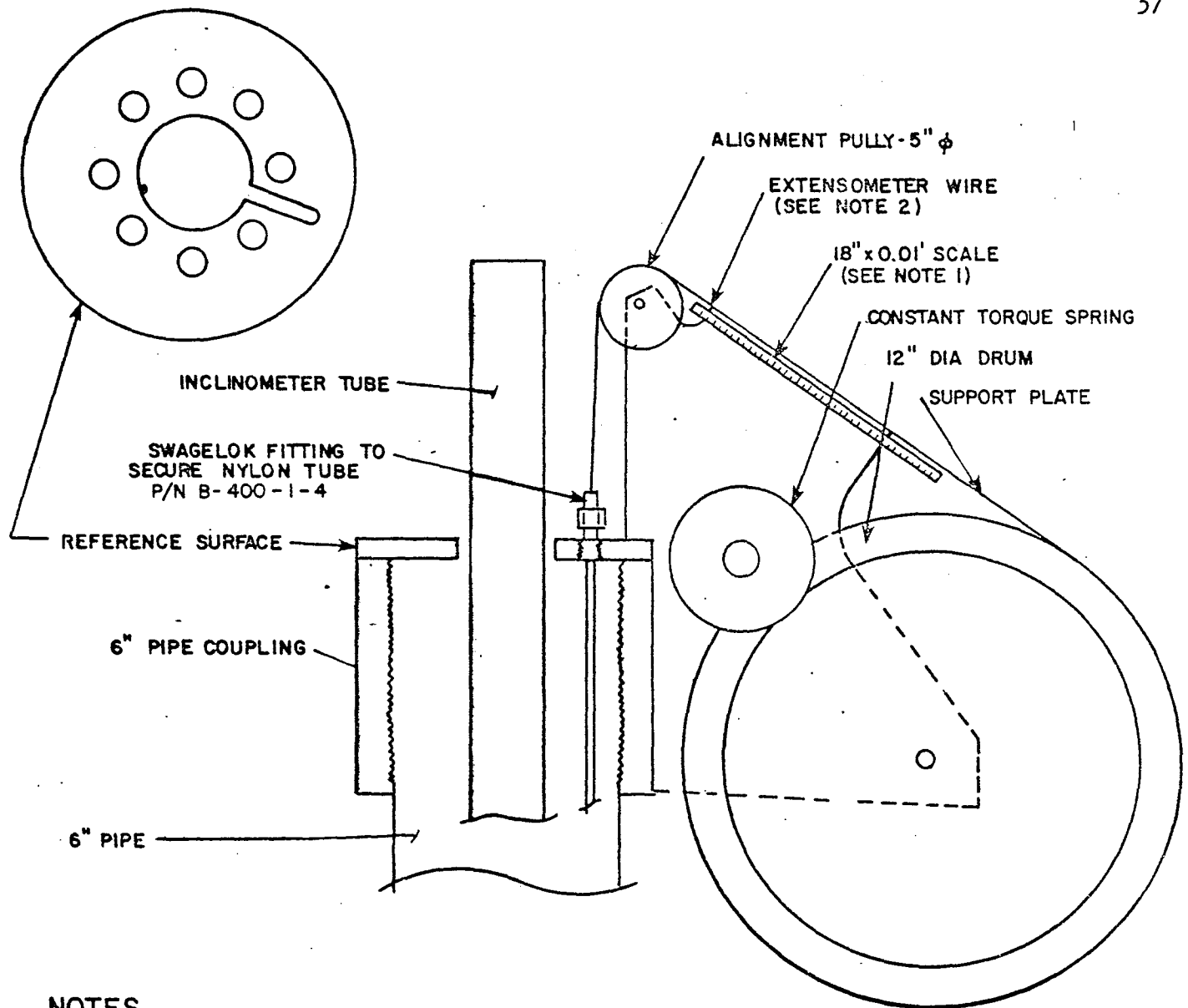


FIGURE 4.4 MULTIPLE POSITION BOREHOLE EXTENSOMETER, ELEVATION VIEW, GROUND SURFACE INSTALLATION



NOTES

1. AN INDIVIDUAL 0.01 ft. SCALE IS SUPPLIED WITH EACH WIRE. ADDITIONALLY A STEP IS PLACED AT THE BASE OF THE SCALE TO POSITION A SECOND SCALE SHOULD THE FIRST BECOME DAMAGED.
2. THE WIRE IS MARKED IN ONE FOOT INTERVALS
3. ONLY ONE OF 8 WIRE TENSIONING SYSTEMS ILLUSTRATED.

FIGURE 4.5 MULTIPLE POSITION BOREHOLE EXTENSOMETER
REFERENCE HEAD

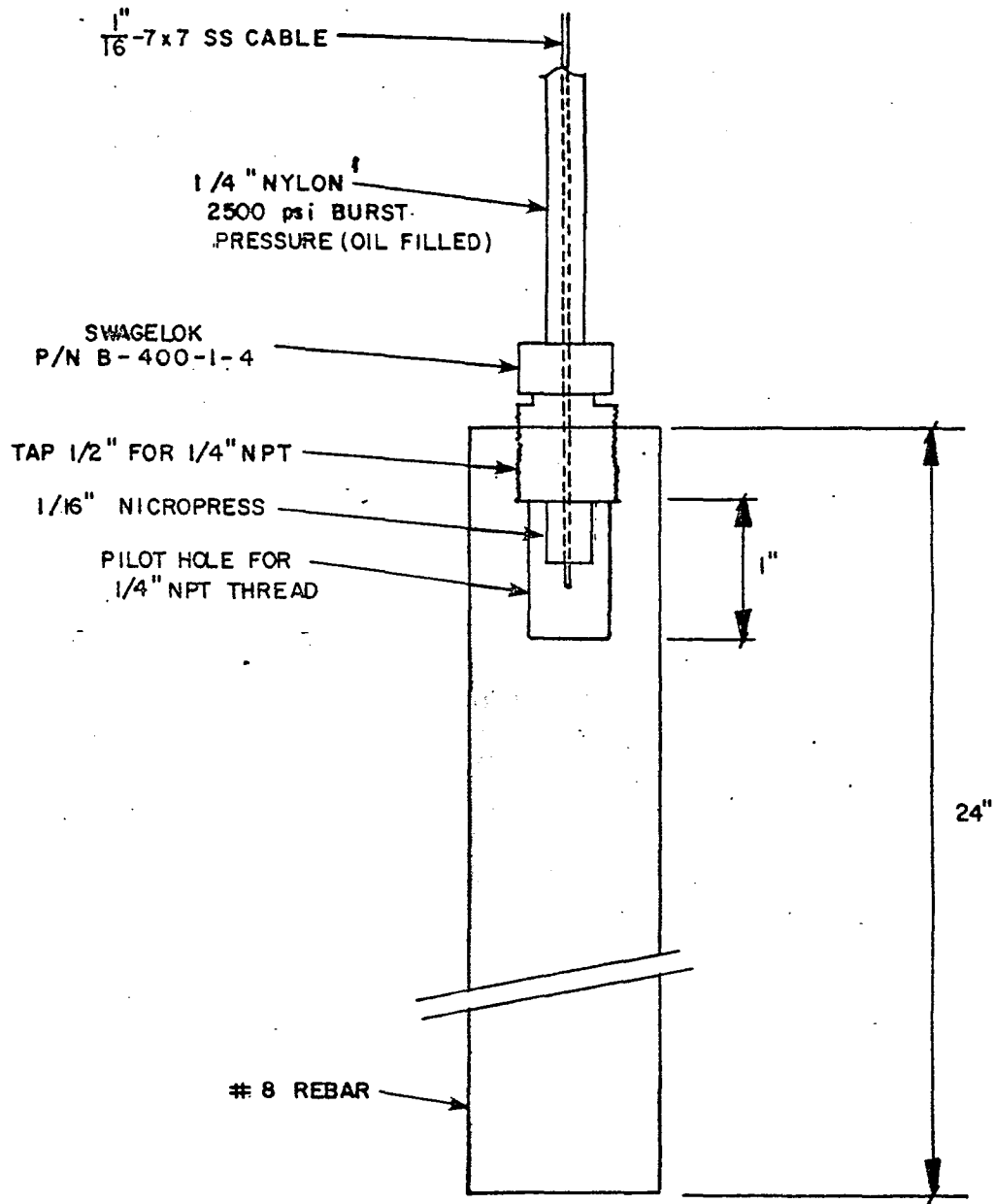


FIGURE 4.6 MULTIPLE POSITION BOREHOLE
EXTENSOMETER ANCHOR

Sondex System

Manufactured by Slope Indicator Company (SINCO), the system operates on the magnetic induction principle and utilizes an electronic probe attached to a survey tape in combination with a series of markers, each marker consisting of a stainless steel ring taped to the outer surface of the inclinometer casing. When lowered down the inclinometer casing, the probe activates a buzzer as it passes each marker. The marker rings were positioned at nominal intervals of 20 feet along the length of the casing and were supplemented by the MPBX anchors (also steel), which similarly served as markers.

Time Domain Reflectometry (TDR) System

The TDR consists of a 1/4-inch diameter RG58 c/u coaxial cable extending from ground surface to the bottom of a boring. Reference points produced by crimping the cable were introduced at 10 foot intervals of depth. Electric pulses sent down the cable by the readout box, a Tektronix Model 1500 cable tester, were reflected at any break in the cable, the depth of which was computed from the travel time of the pulse recorded on the paper strip chart.

Inclinometer System

Standard flush coupled, 2.75-inch diameter, grooved, ABS casing supplied by SINCO was utilized for each inclinometer installation. All joints were glued, riveted and taped to prevent grout intrusion during placement. The inclinometer casing also served as the spine around which the MPBX and Sondex systems were constructed.

A field survey consisted of determining the vertical orientation of each inclinometer casing at depth intervals of five feet using a SINCO Model 50309 Digitilt inclinometer probe. The passage of the probe up and down the hole was guided by the sidewall grooves of the casing. Each survey comprised two traverses of a hole from bottom to top--the inclinometer probe engaging one set of the diametrically opposed grooves in the first traverse and the mutually perpendicular set of grooves in the second traverse. The lateral position of the inclinometer casing with depth was computed incrementally from a knowledge of the inclination of the inclinometer probe in each depth interval and the gage length of the instrument. Downhole spiraling of the inclinometer casing grooves resulting from the manufacturing and installation processes was compensated for using the data gathered from a post-installation, pre-mining twist survey conducted in each inclinometer casing with a SINCO downhole device designed for this purpose.

The findings from the subsurface instrumentation program are presented in Section 7.

Piezometers (Water Wells)

Seven piezometers were installed above the mine panel (Figure 4.3), the southerly group of three (the 5-series) near Boring D-1 and the northerly group (the 3-series) near Boring D-4. One piezometer in each group extended to the Lower Connellsville Sandstone, another to the Saltsburg Sandstone and a third to the Mahoning Sandstone. The Mahoning installations were incorporated into Borings D-1 and D-4. A piezometer was also installed to the Buffalo Sandstone near Boring D-4 under a program sponsored by Los Alamos Scientific Laboratory. Details of piezometer construction and the findings

of the ground water program are discussed in Section 8. (Note that the monitoring devices are called piezometers because they monitor water pressures in individual rock units).

GROUND SURFACE INSTRUMENTATION

Surface Monuments

A network of 197 subsidence monuments was constructed to permit measurement of ground surface movements parallel and perpendicular to the panel axes (Figure 4.3). The monument network was constructed for the initially-planned two panel (C-3/C-5) arrangement shown in Figure 3.3. One longitudinal line of monuments coincided with the centerline of each of the two initially-planned mine panels and a transverse monument line approximately bisected each panel in a perpendicular direction. The two transverse monument line segments were offset 120 feet between the proposed C-3 and C-5 panels in order to accommodate the unequal panel lengths, with a short longitudinal segment connecting the two segments. The west leg of the transverse survey line was constructed as a series of equilateral strain triangles 30 feet on a side, as was the short longitudinal segment connecting the two transverse legs and the segment of the east leg of the transverse survey line lying between the middle and east longitudinal survey lines. This was to permit an evaluation of principal ground strains.

The longitudinal survey lines extended about 420 feet (0.7 times the overburden thickness) beyond the north end of the panel in the direction of the mains. The transverse survey line extended a similar distance beyond the lateral panel boundaries in accordance with recommendations in the NCB Subsidence Engineer's Handbook, 1975, p. 13. The longitudinal survey lines extended south to the limits of the Kitt Mine property, 270 feet to 320 feet beyond the property line. A monument spacing of 0.05 times the overburden thickness (30 feet) was used to achieve satisfactory definition of curvature and tensile and compressive zones within the subsidence profile, in accordance with recommendations given by the NCB Subsidence Engineers' Handbook, 1975, p. 34.

Four individual strain triangles were also constructed--two each along the east and west longitudinal survey lines--to check estimates of ground motion in each panel quadrant predicted from movements of monuments situated on the main axes.

Benchmarks

Four permanent benchmarks were positioned at least one panel depth (600 feet) beyond the closest edge of the pillar extraction panels in stable ground unaffected by prior or ongoing mining.

Subsidence monuments consisted of 5-foot lengths of 0.75-inch diameter steel reinforcing bars set to a depth of 4 feet below ground surface and anchored in 12 inches of concrete at the bottom on the hole. A stiffer 2-inch diameter, concrete-filled steel pipe was substituted for the reinforcing bar in the strain triangle monuments. A 36-inch long, 4-inch diameter PVC pipe was placed over each reinforcing bar to isolate it from frost heave and other potential movements of the surrounding soil. The space between the PVC pipe and the reinforcing bar was filled with a thick slurry mixture of bentonite and oil. This permitted free movement of monument components and sealed off all but the top 10-inch protruding section of the monument from the elements. Benchmarks were similar to subsidence monuments.

Second Order surveys were conducted using a Keuffel & Esser AutoRanger electronic distance measuring device and a Vectron electronic theodolite. Horizontal and vertical displacements were monitored at monuments and benchmarks.

Additional details and findings concerning the ground surveys are presented in Section 9.

5.0 PILLAR STRESSES AND PILLAR CAPACITY

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Stress Distribution in Individual Pillars	69
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INTRODUCTION

The average vertical stress acting within a coal pillar is, in this discussion, termed the 'pillar stress' and represents the sum of the pre-mining vertical stress (the primitive vertical stress) σ_{vo} and the induced vertical stress σ_{vi} arising from mining activity:

$$\sigma_v = \sigma_{vo} + \sigma_{vi} \quad (5.1)$$

The evolution of stresses at each pillar location took place in four stages --

1. Before Mining

The primitive vertical stress acting in the 600-foot deep coal seam prior to existence of the mine was probably about 600 psi, an estimate based simply on the weight of rock overlying the seam.

2. During Developmental Mining

Excavation of the entries and cross-cuts removed about 42 percent of the coal in the areas of development, increasing the vertical stress at pillar locations in those areas to perhaps 1030 psi, an estimate based on a tributary redistribution of overburden load.

3. During Retreat Mining

Pillar extraction removed most of the remaining 58 percent of the coal in the panel, increasing by several hundred pounds per square inch the stresses in pillars that had not yet been extracted, as well as in permanent pillars located around the perimeter of the panel. (Locally in the ventilation entries, pillar stresses actually decreased due to bearing failure of the mine floor and instability of the mine roof).

Vertical stresses are thought to have increased in the gob area as rubble and overburden came to rest upon the mine floor where pillars had been extracted. These gob stresses were not measured.

4. After Mining

Pillar and gob stress changes almost certainly accompanied residual subsidence that followed retreat mining. Sealing of the mine panel precluded the long term measurement of stresses in barrier and ventilation entry pillars that remained along the perimeter of the panel after mining.

Pillars appeared to be in no danger of failure by crushing or shearing. Pillar distress in the form of intense spalling and cracking was observed only in individual pillars as they were being extracted. Permanent pillars supporting the ventilation entries along portions of the south margin of the panel lost capacity as a result of bearing failure of the underclay floor and roof instability. This ultimately influenced the geometry of the subsidence trough.

In keeping with custom, the distribution of pillar stresses in the C-3 panel is discussed in terms of three transitory zones (Figure 5.1):

1. The front abutment -- the pillars still to be mined ahead (north) of the moving retreat line;
2. The rear abutment -- the barrier pillars, the ventilation entry pillars, the solid coal and the gob trailing (south of) the retreat line; and
3. The side abutments -- the barrier pillars, the ventilation entry pillars and the solid coal alongside (east and west of) the mined-out area.

Induced pillar stresses were measured with 22 vibrating wire stress meters at 15 locations in the mine panel (Figure 4.1) -- seven in the area of pillar extraction; six in the ventilation entries and two in the permanent pillars in the direction of the mains. Stresses were not measured in the gob.

The principal findings and comments concerning pillar stresses and pillar load capacity are presented in the following paragraphs. Pillar load capacity is discussed first, followed by the stress distributions in individual pillars, and finally by the distribution of vertical stresses in pillars across the mine panel during mining.

LOAD CAPACITY OF PILLARS/FLOOR/ROOF

Overview

The ability of a pillar to support the weight of the overburden depends upon the strength of the coal itself, the geometry of the mine pillar, and the respective bearing capacities of the mine floor and mine roof.

Pillars in the C-3 panel displayed few signs of distress during mining, except for minor spalling. None of the pillars crushed or threatened to do so.

Laboratory tests conducted during the study (Table 5.1) indicate unconfined compressive strengths for the Lower Kittanning Coal of 1000 to 2800 psi. Strengths of 12 of the 14 samples exceeded 1600 psi. Three samples were NX-wireline core secured from Boring D-5; eleven were cubes of nominal 2-inch edge length, sawed from block samples carried from the mine workings. Scatter in strength data is attributed primarily to intrinsic variations in coal strength and to small variations in sample dimensions.

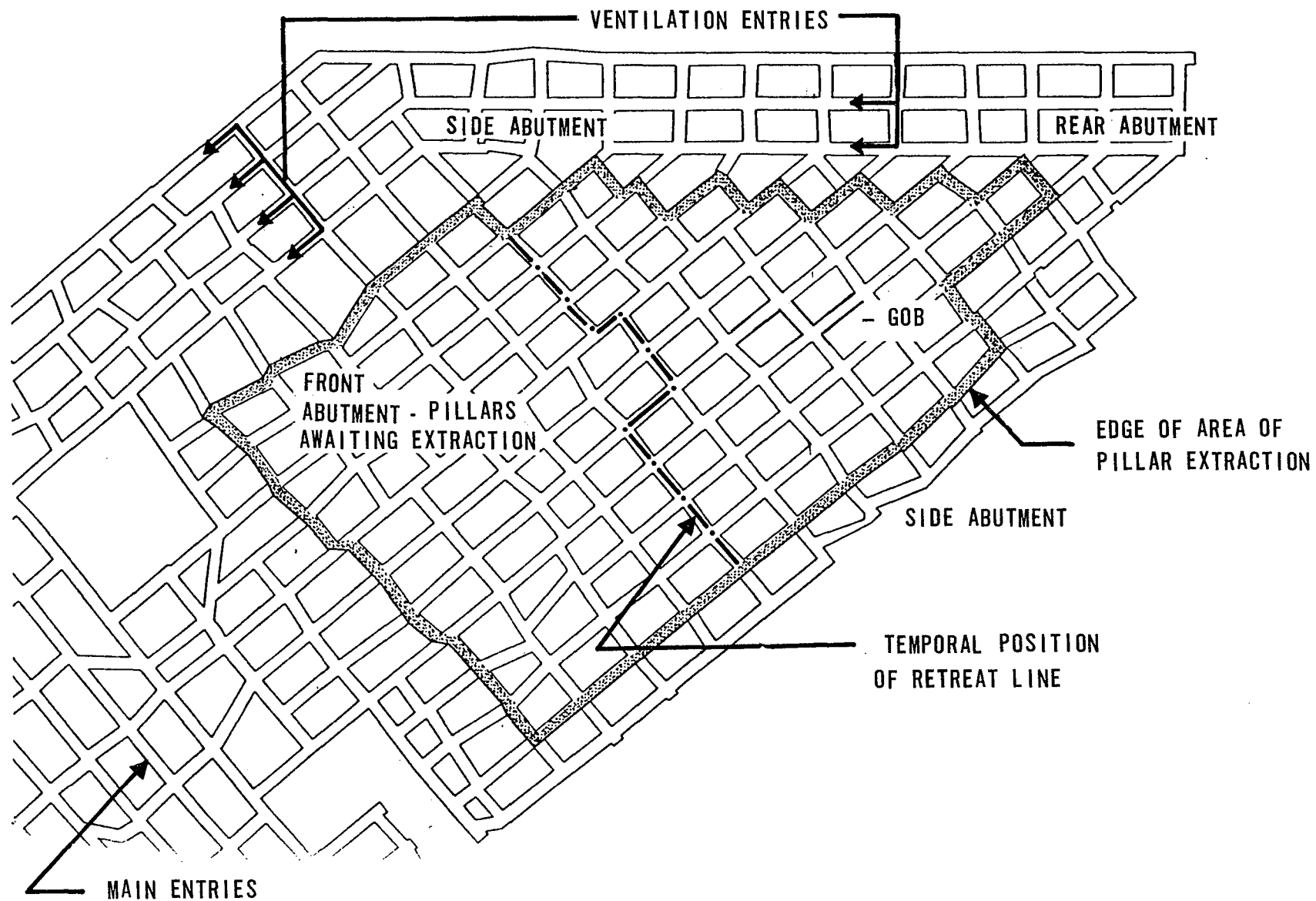


FIGURE 5.1 ZONES COMPOSING C-3 PANEL

Table 5.1

Laboratory Compressive Strength Tests
Lower Kittanning Coal
C-3 Panel, Kitt No. 1 Mine

<u>Cylinders^x</u>	<u>Unconfined Compressive Strength</u>	<u>Axial Strain at Peak Stress</u>	<u>Tangent E-Modulus</u>	<u>Water Content</u>	<u>Unit Weight</u>
1.	1099 psi	7.3×10^{-3}	2.78×10^5 psi	1.3%	87.5 pcf*
2.	1616	10.3×10^{-3}	2.78×10^5	1.0	80.6
3.	1866	9.4×10^{-3}	2.78×10^5	1.2	97.8*

<u>Cubes^Δ</u>	<u>Unconfined Compressive Strength</u>
1.	1314 psi
2.	1627
3.	1765
4.	1765
5.	1885
6.	2408
7.	2452
8.	2497
9.	2599
10.	2686
11.	2756

Δ Nominal 2-inch edge length

x NX-wireline core (2.0 inch diameter); length/diameter=2.2 to 2.5

* Contains pyrite nodules

Overall, the strengths appear to be consistent with those of other eastern U.S. coals (cf. Hustrulid, 1976).

As shown by Bieniawski and Hustrulid (1976), among others, the strength of coal decreases with increasing size of the block of coal. Yet, the lateral confinement offered by competent mine roof and mine floor can significantly enhance coal pillar capacity (Wilson and Ashwin, 1972). Lateral confinement of the broad squat pillars (5:1 width/height ratio) across much of the C-3 panel is believed to have contributed significantly to the load carrying capacity of these coal pillars, while less competent floor and roof rock is believed to have limited the pillar capacity in localized areas.

Evaluation of Mine Floor Bearing Capacity

As discussed in Section 2, the C-3 panel mine floor is composed of about 20 inches of claystone, which is underlain by silty and sandy shale at least 14 to 15 feet thick. The claystone governs the bearing capacity of the mine floor.

The claystone, or "underclay" as it is sometimes called, is a massive, relatively soft rock that lacks the laminations typically found in other sedimentary strata, but is dissected by smooth, curved slickensides resulting from differential movements that took place while the material was still in a soft state. These slickensides, spaced at a fraction of an inch to a foot or two, weaken the rock and promote its deterioration when exposed to air and moisture for prolonged periods of time. Upon weathering, the rock assumes the character of an overconsolidated clay soil. According to the Unified Soil Classification System, the underclay can be classified by composition as a low plasticity clay (CL).

At locations where the bearing capacity of the floor is exceeded, the claystone shears and heaves upward into the mine opening, much as would a clay block squeezed between two parallel plates -- one plate being the underside of the pillar and the other being the top surface of the stratum beneath the clay.

Few strength data are available for underclays in the eastern United States and little detailed information is available concerning drying and rewetting effects. A single (unbroken) sample of underclay secured from Boring D-5 at the Kitt Mine site indicated a pre-mining unconfined compressive strength q_u at natural water content of 2700 psi. Although this value is consistent with limited data available from other underclays, additional tests would, of course, have led to a more reliable estimate of strength. Despite the limited data, some interpretation of the bearing capacity of the mine floor can be made. The interpretation is based on the fact that, whereas a series of ventilation entry pillars along the south margin of the panel experienced bearing capacity failure, the great majority of pillars in the panel did not. Consider, first, the pillars that did not experience bearing capacity failure.

Measurements made in Pillar 52, for example, indicate that vertical induced stresses at the center of the pillar reached as high as 1470 psi during mining. In recognition of the roughly parabolic stress distribution across the pillar (to be discussed below), the average induced vertical stress is estimated to be approximately 600 psi. Since the floor had not failed at that location, the bearing capacity of the floor beneath Pillar 52 must have been at least 1600 psi. This figure represents the estimated 600 psi primitive vertical stress and the estimated 430 psi transferred during developmental mining plus the estimated 600 psi average stress induced during retreat mining.

Assuming the undrained shear strength S_u of the claystone to be 1350 psi $\ddagger$, the bearing capacity of the mine floor would have been at least 6900 psi**. If this is true, then the factor of safety of Pillar 52 against general bearing failure of the floor -- factor of safety being defined as the ratio of bearing capacity to applied vertical stress -- would have been about 4.3*. It seems reasonable to conclude from available information, that the bearing capacity of the floor beneath a typical pillar in the C-3 panel was at least 1600 psi and may have ranged to 6900 psi or more.+ These pillars were in a 'dry' area, where no water puddled or ponded on the mine floor.

The pillars in the south ventilation entry that experienced bearing failure were in a 'wet' area at the downdip end of the panel where water intruding the mine area from overlying strata first collected. The maximum induced vertical stress measured in these pillars prior to the drop in load was between 230 psi (Stress Meter 18) and 320 psi (Stress Meter 17). Figure 5.2 shows the stresses measured by Stress Meter 17. After bearing failure (apparently) ensued, the stress cycled up and down -- the pillar seemingly settling and shedding its load to neighboring pillars each time the applied vertical stress exceeded the bearing capacity--the bearing capacity after failure being governed by a reduced (residual) strength. One cannot be certain of the stress distribution in the pillar, particularly whether or not the measured stress is above or below the average. However, the investigation of the stress distribution in Pillar 52 (discussed below) suggests that an induced stress of 200-350 psi measured at the center of a pillar may be associated with an average pillar stress of 90-130 psi^x. Taking these average values as failure stresses, the bearing capacity of the mine floor in the vicinity of the failed ventilation entry pillars would have been about 1120 to 1160 psi, taking into account the pre-retreat stresses. These values possibly underestimate the bearing capacity of the floor inasmuch as higher stress levels may have been attained between the dates on which measurements were made.

The ability to predict the bearing capacity failure before mining might have been improved had an extensive mine floor investigation been conducted concurrent with mine development. However, our information is limited to the basic rock property data that have been reported herein. Given the uncertainty in stress distributions in the pillars, the probable variations in underclay strength and thickness across the panel and other factors, assessment of the bearing capacity of the mine floor cannot be accomplished with a high degree of confidence.

$\ddagger S_u = q_u/2$ (Lambe and Whitman, 1969, p. 451, Footnote 2)

** $Q_u = N_c \cdot S_u$ (Lambe and Whitman, 1969, p. 486)

*This assumes, conservatively, that the shear strength of the claystone and underlying shale are the same. The bearing capacity factor N_c is then 5.14.

+The shear strength of the shale is almost certainly greater than that of the claystone. If so, the bearing capacity factor is higher than the value above, as is the factor of safety.

^xClearly, this estimate disregards possible differences in the stress distribution that might result from reduced competence of the mine roof and mine floor.

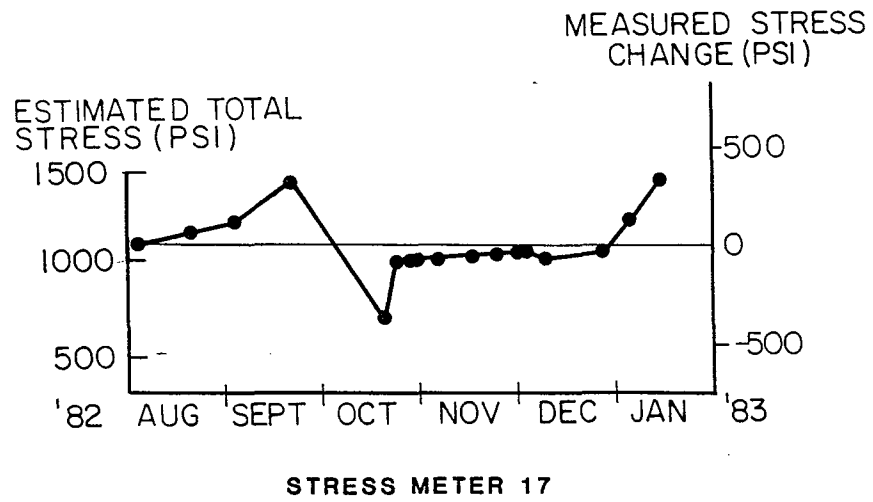


FIGURE 5.2 STRESSES MEASURED IN BARRIER PILLAR AT SOUTH END OF PANEL THAT EXPERIENCED BEARING CAPACITY FAILURE

STRESS DISTRIBUTIONS IN INDIVIDUAL PILLARS

Developmental Mining

Since stress meter installation necessarily followed developmental mining, the distribution of vertical stress across an individual pillar produced by driving entries and cross-cuts during panel development can only be estimated.

The inspection of pillars as entries and cross-cuts were being driven revealed some indications of stress relief, particularly at corners (Figure 5.3A) and occasionally on pillar faces (Figure 5.3B). Overall, however, evidence of stress relief in pillars was limited. Any fracturing that may have occurred behind pillar faces was, of course, hidden from view.

Retreat Mining.

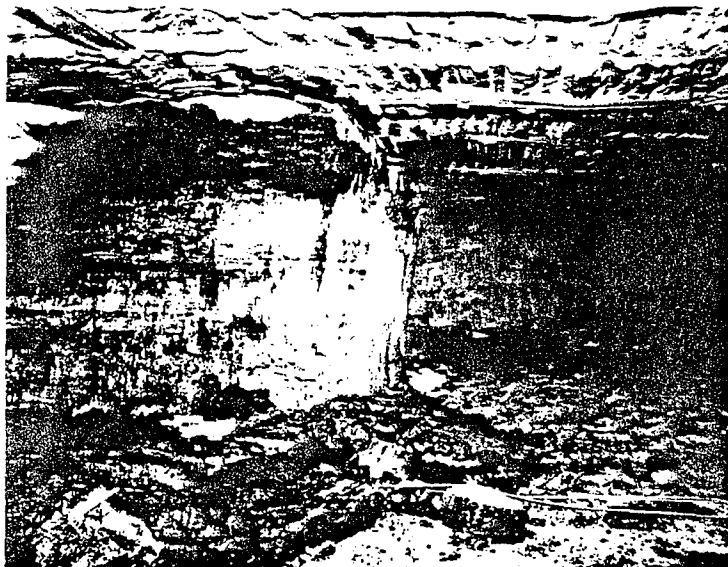
The distribution of induced vertical stress across an individual pillar produced by retreat mining was found to be non-uniform, with the stress measured at the centroid of the pillar being an apparent maximum in cases where the retreat line lay closer than 300 feet to the pillar.

Induced vertical stresses were measured during retreat mining along the major and minor axes of Pillar 52 at seven mid-height locations. In addition to the center, stress meters were located at distances one-sixth and one-third the pillar length from the end faces of the pillar and one-sixth the pillar width from the lateral faces of the pillar. The pillar length was 73 feet and the pillar width, 43 feet.

Figure 5.4 presents idealized sketches of the distribution of vertical stresses across the pillar at particular stages of retreat mining. The following observations are made:

1. In the early stages of retreat mining when the retreat line lay approximately 600 feet distant (August 19, 1982), the vertical stresses were slightly elevated in the near and middle sectors of pillar. The highest stress was in the meter nearest the gob. The transverse stress profile across the mid-section of the pillar appeared to be parabolic.
2. When the retreat line lay approximately 300 feet from the pillar (September 2), the distribution of induced vertical stresses continued to resemble that observed on August 19, although now the centroidal stress meter indicated the highest stress.
3. When the retreat line lay approximately 100 feet from the pillar (October 19), the distribution of induced vertical stresses had adopted a distinctly non-uniform, although approximately symmetric pattern in both the longitudinal and transverse directions. The transverse induced stress distribution at the pillar midsection appeared bell-shaped. The longitudinal centerline profile indicated a maximum induced stress near the center of the pillar, with local maxima in the near and far third sectors of the pillar--the stress in the sector nearest the retreat line being slightly higher than that in the far sector.
4. When the retreat line lay at the gob-side face of the pillar and all other pillars in the row had been extracted except for one pillar alongside (November 29), the distribution of induced vertical stress remained elevated

(A)



(B)



FIGURE 5.3 STRESS RELIEF IN PILLARS

- A. SPALLING AT CORNERS AND FACE**
- B. CRACKING ON FACE**

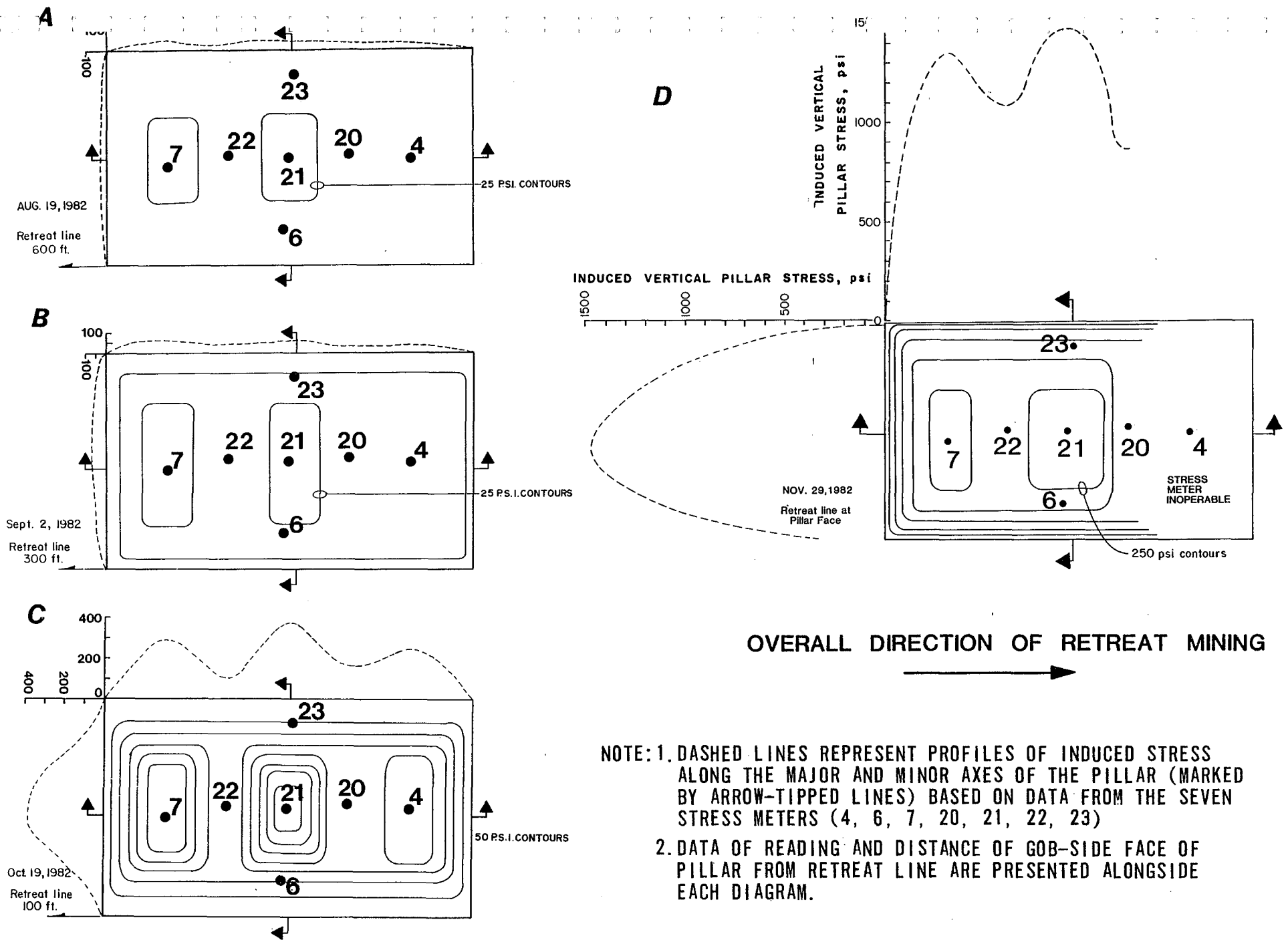


FIGURE 5.4 IDEALIZATION OF INDUCED VERTICAL STRESS DISTRIBUTION IN PILLAR 52 AT PARTICULAR STAGES OF MINING

near the center of the pillar. The stress meter farthest from the gob no longer operated so the longitudinal stress profile could not be determined as completely as in the other cases. The transverse stress profile at the midsection of the pillar appeared to be parabolic.

These idealizations are indicative of a three-dimensional stress distribution whose maximum had adjusted centerward in the pillar with approach of the retreat line. Additional stress meters would doubtlessly have revealed further details of the stress distribution (e.g. Wagner, 1980) and, in fact, may have revealed both tensile and compressive zones, such as have been reported in laboratory samples by Peng (1970). The existence of a three-dimensional stress distribution can be attributed in measure to variations in coal properties, non-uniformity in vertical stress application from adjoining strata, shear stresses induced along the top and bottom surfaces of the coal pillar by a mismatch in mechanical properties (e.g. Poisson's Ratio) between the coal and adjoining strata, and other factors (Jaeger and Cook, 1969).

Assuming the idealizations of vertical stress distribution for Pillar 52 are reasonable first approximations, they suggest for the C-3 panel that: (1) the induced stress measured at the center of a pillar as the retreat line draws near is generally higher than is a hypothetical average, uniformly distributed vertical stress computed by dividing pillar load by cross-sectional area. (This is an important consideration with regard to interpreting load levels in other pillars, each of which have only a single centrally-located stress meter); and (2) the vertical stress distribution amongst the pillars along the retreat line -- the "front abutment pressure" -- reaches its maximum value not directly at the edge of the gob, but rather about 35 feet back, near the center of the pillar closest to the retreat line.

STRESS DISTRIBUTION ACROSS THE MINE PANEL

Developmental Mining

The driving of entries and cross-cuts through the coal seam causes local transfers of overburden weight to the pillars thus created, elevating the vertical stress in the coal seam near the openings above pre-mining levels.

Customarily, the increase in vertical stress is assumed to be proportional to the percentage of coal extracted in the immediate vicinity of the pillar--the tributary area concept. The introduction into the C-3 panel of 17-foot wide entries on 60-foot centers extending from the mains to the far end of the panel, and joined on 90-foot centers by cross-cuts of the same width, resulted in the removal of 42 percent of the coal. The tributary area concept predicts the vertical stress acting over a typical 43 x 73 foot pillar to be 1030 psi, assuming the pre-mining vertical stress to be 600 psi. The estimated vertical stress induced by developmental mining is therefore 430 psi, 72 percent above the estimated pre-mining stress.

Given the difficulties in measuring vertical pillar stresses induced by developmental mining or reliably computing them under complex boundary conditions, the 430 psi estimate based on the tributary area theory is accepted as a conservative (high) value of the development-induced vertical pillar stress.

Retreat Mining

Retreat mining began with the extraction of Pillar No. 1 in the far south corner of the panel and progressed systematically northward toward the main entries. As the mined-out area enlarged, first as a triangle, then as a trapezoid, the overburden weight redistributed three dimensionally in such a way as to maintain force and moment equilibrium. Zones of relaxation that developed in certain areas were compensated for by zones of higher stress elsewhere.

The distribution of vertical stresses in the front, the rear, and the side abutments is discussed in turn in the context of Figures 5.5-5.7.

1. Front Abutment Pressure

All of the stress meters, except Nos. 17 through 19 located at the south end of the panel, measured front abutment pressures during some period within the monitoring program. As retreat mining progressed, Stress Meters 14 through 16 eventually became positioned in a more rearward position relative to the retreat line and thereupon measured side abutment pressures. Ultimately, each of Stress Meters 3 through 13 were mined through and lost.

During mining, each pillar in the area where extraction was performed experienced a load history similar to that of Pillar 52 described below:

Prior to existence of the mine, the primitive vertical stresses existing in the 600-foot deep coal seam were probably about 600 psi (Figure 5.5). Upon development of the entries and cross-cuts, the stresses at pillar locations presumably increased to about 1030 psi in conformance with a tributary redistribution of load. Then, upon extraction of coal pillars during retreat mining, the stresses in remaining pillars increased further due to load redistributions from the mined-out area. Stress meter measurements in pillars along the direction of mining defined a near exponential stress increase toward the retreat line. Stress increases as large as 800 psi were measured in pillars located along the retreat line. Additional stress increases of several hundred psi accompanied the extraction of neighboring pillars in the same row. Still higher stress levels were achieved during extraction of an individual pillar.

The stress meter layout in the panel permits some observations to be made concerning the distribution of stresses transverse to and along the direction of mining.

a. Front Abutment Pressure Across Panel Width

Profiles of pillar stress from west to east across the panel were provided by Stress Meters 10 through 16, and 21 (Figure 5.6. Refer to Item B in legend). Stress Meters 12 through 16 and 21 lay in the same pillar row; Stress Meter 10, one-and-one half pillars (130 feet) forward; Stress Meter 11, one-half pillar (45 feet) behind. Because of their respective locations in relation to the section line of the figure and to the retreat line, Stress Meter 10 read somewhat high and Stress Meter 11 somewhat low compared to other stress meters defining the stress profiles.

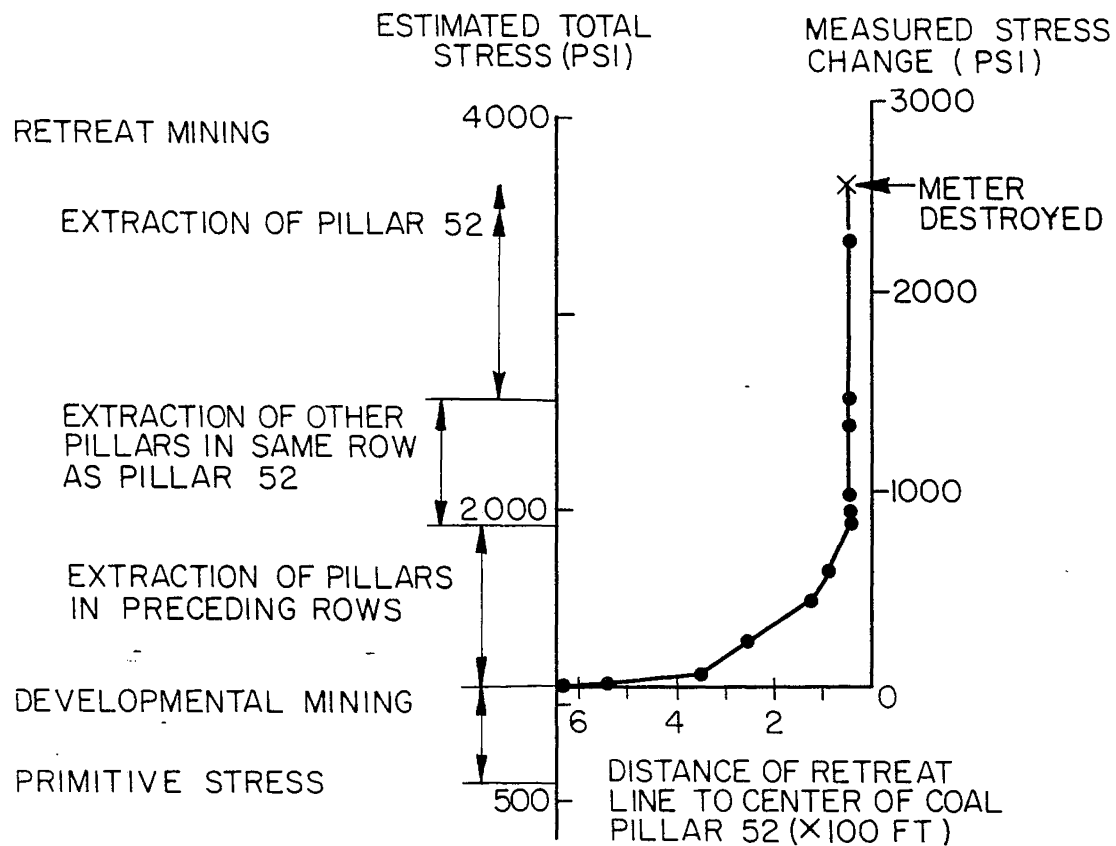
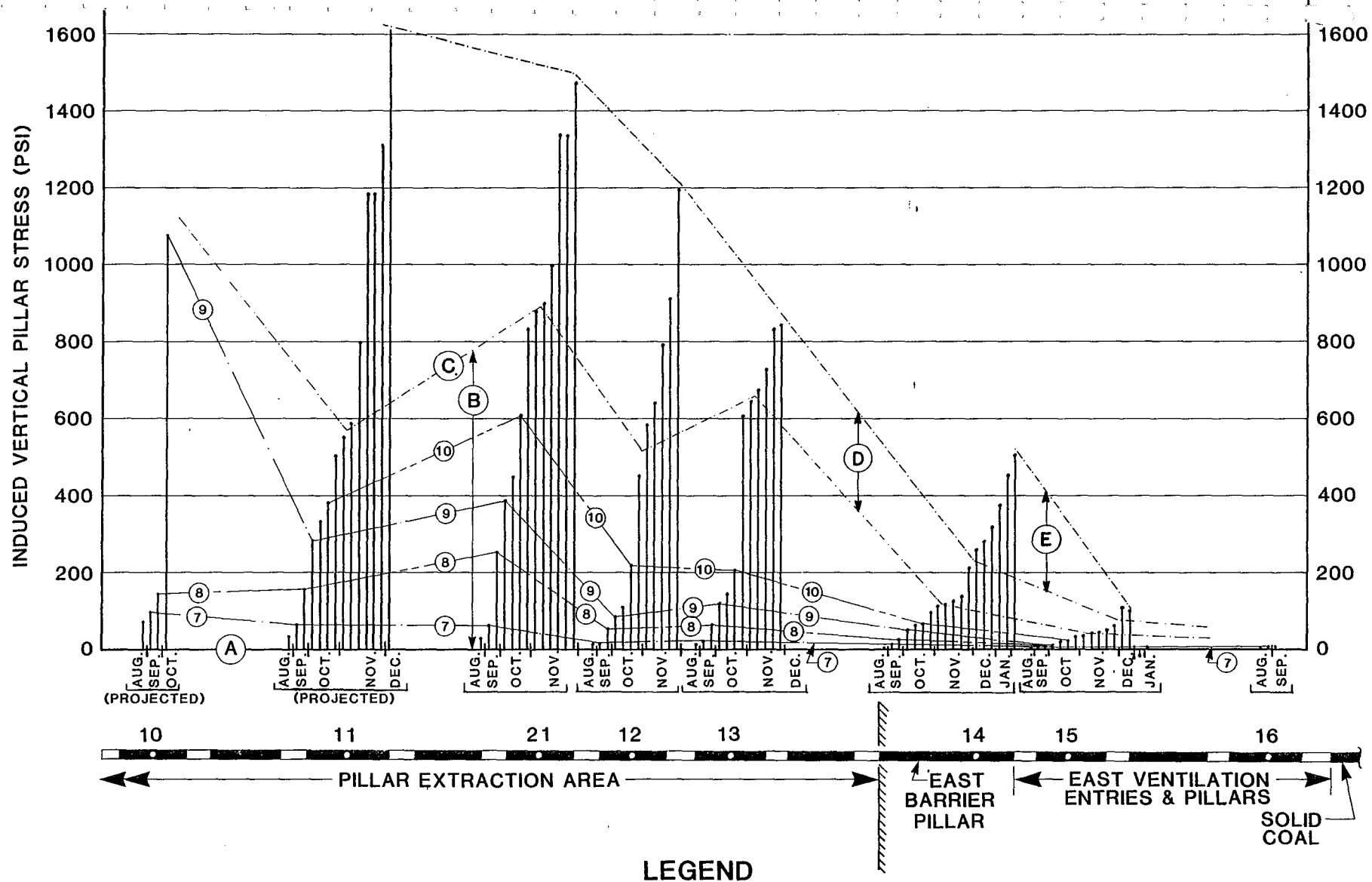


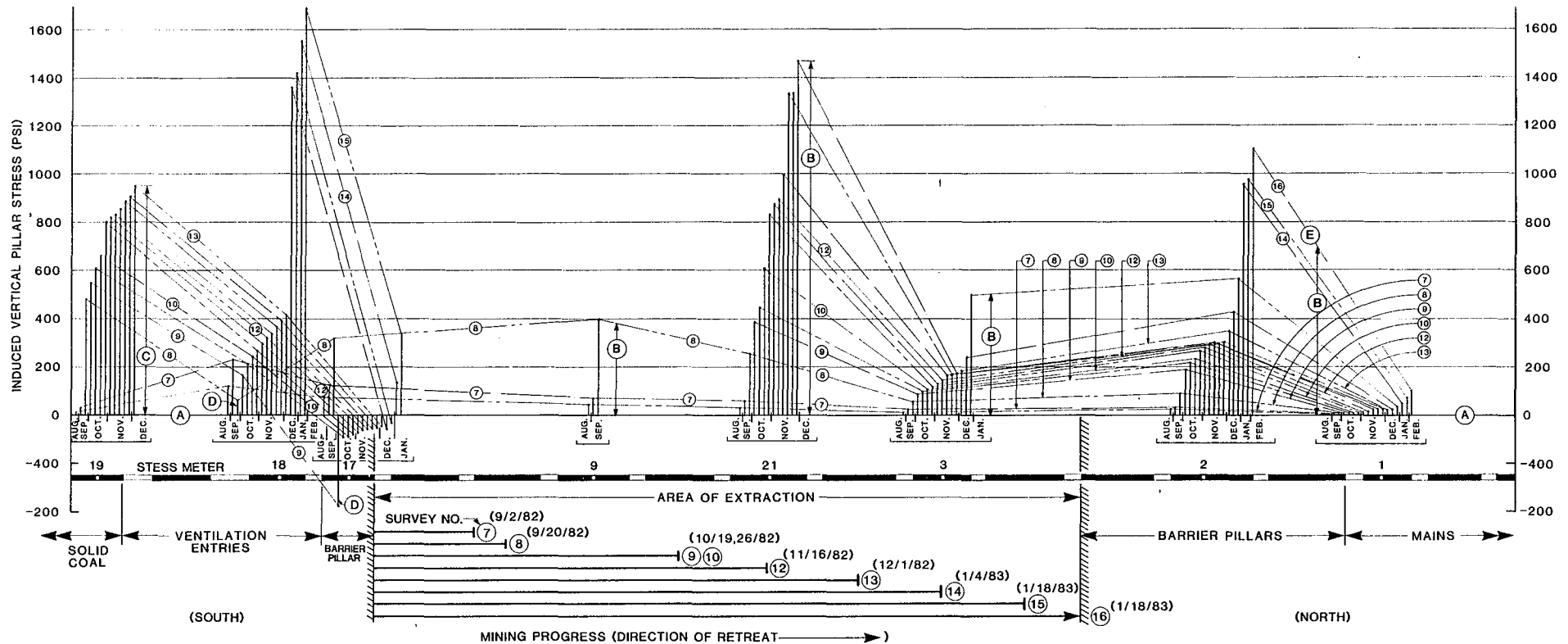
FIGURE 5.5 STESSES MEASURED IN PILLAR IN FRONT ABUTMENT AREA PRIOR TO ITS EXTRACTION



LEGEND

- (A) PRIOR TO RETREAT MINING, INDUCED VERTICAL PILLAR STRESSES ARE ZERO.
- (B) INCREASE IN STRESSES WITH APPROACH OF THE RETREAT LINE. STRESSES REPRESENT PART OF 'FRONT ABUTMENT PRESSURE.'
- (C) STRESSES IMMEDIATELY PRIOR TO EXTRACTION MINING ALONG THE TRANSVERSE SECTION LINE (PILLAR ROW 8).
- (D) STRESSES DEVELOPED DURING EXTRACTION MINING ALONG THE TRANSVERSE SECTION LINE.
- (E) STRESSES DEVELOPED AFTER EXTRACTION MINING HAD PROGRESSED BEYOND THE TRANSVERSE SECTION LINE. MEASURED STRESSES REPRESENT PART OF 'SIDE ABUTMENT PRESSURE'.
- (F) REFER TO FIGURE 5.7 FOR DEFINITION

FIGURE 5.6 PROGRESSION OF INDUCED VERTICAL PILLAR STRESSES WITH RETREAT MINING-- TRANSVERSE SECTION (LOOKING NORTH) (PILLAR ROW 8)



LEGEND

- (A) PRIOR TO RETREAT MINING, INDUCED VERTICAL PILLAR STRESSES ARE ZERO.
- (B) INCREASE IN STRESSES WITH APPROACH OF THE RETREAT LINE. STRESSES, REPRESENT PART OF 'FRONT ABUTMENT PRESSURE'.
- (C) INCREASE IN STRESSES WITH DEPARTURE OF THE RETREAT LINE. STRESSES REPRESENT PART OF 'REAR ABUTMENT PRESSURE'.
- (D) DECREASE IN STRESS DUE TO BEARING FAILURE OF MINE FLOOR OR OTHER UNLOADING MECHANISMS.
- (E) FINAL STRESSES MEASURED PRIOR TO SEALING OFF MINE PANEL.

- (n), 7 to 16-CORRELATIVE GROUND SURVEY NUMBER. NON-NUMBERED STRESS MEASUREMENTS WERE MADE AT INTERMEDIATE TIMES

NOTE: AREA OF EXTRACTION EXTENDS FARTHER SOUTH TO THE WEST OF THE SECTION LINE. (REFER TO FIGURES 3.2 AND 4.1)

FIGURE 5.7 —PROGRESSION OF INDUCED VERTICAL PILLAR STRESSES WITH RETREAT MINING — LONGITUDINAL SECTION (LOOKING WEST)

The transverse stress profile indicates that:

1. For any position of the retreat line
 - a. the stresses in extraction pillars tended to decrease to the east (Stress Meters 10-13 and 21); and
 - b. the stresses in the barrier and support pillars diminished away from the mined-out area (Stress Meters 14-16).
2. As the retreat line approached, the stresses in the extraction pillars, the barrier pillar and the ventilation entry pillars increased without interruption. The pillars did not lose capacity.

The lesser pillar stresses to the east are attributed to the triangular shape of the mined-out area in the early stages of mining. Overburden spans across the mined-out area near the east apex of the triangular area are much shorter than the more westerly spans across the mined-out area near the long side. Consequently, one would expect lesser pillar extraction-induced load transfers to the easterly pillars, particularly in the early stages of mining. And one would expect the pillar stresses to become more uniform as the retreat line progressed further northward toward the row of instrumented pillars and extraction extended across the full width of the panel.

The rather low stress levels attained by the ventilation entry pillars (Stress Meters 15 and 16) as the retreat line approached suggest that relatively little load was transferred to the solid coal during this period, a condition that would be fostered by the east barrier pillar.

The extraction pillars along the retreat line experienced no measurable load loss during retreat mining even though they apparently sustained stresses as high or higher than ventilation entry pillars of nearly the same dimensions that did lose load due to mine floor/roof degradation. Perhaps this is because the extraction pillars were generally required to carry high loads for only limited periods of time -- at most a few weeks -- and were not located in areas where mine water collected.

b. Front Abutment Pressure Along the Panel Length

Profiles of pillar stress from south to north along the panel are provided by Stress Meters 9, 21, 3, 2 and 1 (Figure 5.7. Refer to Item B in legend). The stress meters along this section line are situated four columns of pillars from the east edge of the pillar extraction area. Measuring along the section line in the direction of retreat, Stress Meter 9 is 230 feet from the south margin of the panel; 21, 400 feet; 3, 590 feet; 2, 865 feet and 1, 1050 feet. Stress Meters 1 and 2 are located beyond the north margin of the eleven pillar row extraction area: 1, 320 feet beyond; and 2, 140 feet beyond. The longitudinal stress profile indicates that the build-up in stress with approach of the retreat line varied somewhat from pillar to pillar, yet the pillar stress tended to: (1) be highest in the pillar located directly at the retreat

line; (2) decrease in the direction of the pillars still to be mined; and (3) attain peak values that were progressively higher the more distant the retreat line from the south barrier and ventilation entries.

The apparent tendency for the maximum pillar stress at the retreat line to increase as the mined-out area enlarged presumably resulted from the transfer of overburden weight to the pillars along the perimeter of the panel being proportionately larger than the additional panel perimeter created by each increment of pillar extraction. An increasingly higher load per lineal foot produced along the perimeter of the mined-out area would produce a correspondingly higher maximum pillar stress along the retreat line as the mined-out area enlarged. This would take place, of course, if only a limited proportion of the overburden weight was transferred to the gob.

The rate of stress increase in individual pillars may have been influenced by individual pillar sizes and stiffnesses, local mining details, and other factors. Stress Meter 3, for example, was located near the large solid block of coal along the east flank of the panel. This block was not subdivided into pillars until November and December, 1982. Until then, Stress Meter 3 recorded a relatively limited build-up in stress as the retreat line approached.

Figure 5.8 presents a summary plot of induced pillar stress with position of the retreat line, using all stress meters in the program. Position of the retreat line is expressed in terms of the parameter X/H , where, as before, X is the horizontal perpendicular distance between the retreat line and the stress meter, and H is the overburden thickness at the stress meter station. The data reflect the exponential nature of the induced stress/retreat line relationship in both the longitudinal and the transverse directions. Two points are to be noted:

1. The datum in Figure 5.8 is the initiation of retreat mining. Pre-retreat stresses -- those occurring between the installation of instruments during developmental mining and the initiation of retreat mining -- have been deducted.
2. Stress measurements could be made only as access to the mine permitted. Consequently, each curve in Figure 5.8 no more than approximates the relationship at a particular point in the mine panel between pillar stress and position of the retreat line. An idealization of the complete relationship for a stress meter station is shown in Figure 5.9. Stress Meter 21 (Pillar 52) is used as an example. Each point in the figure specifies the amount of vertical stress at the stress meter station after retreat mining had progressed to the point in the mine panel indicated by the figure. An array of such plots -- one for each point in the panel -- would be required to completely define induced stress characteristics within the panel.

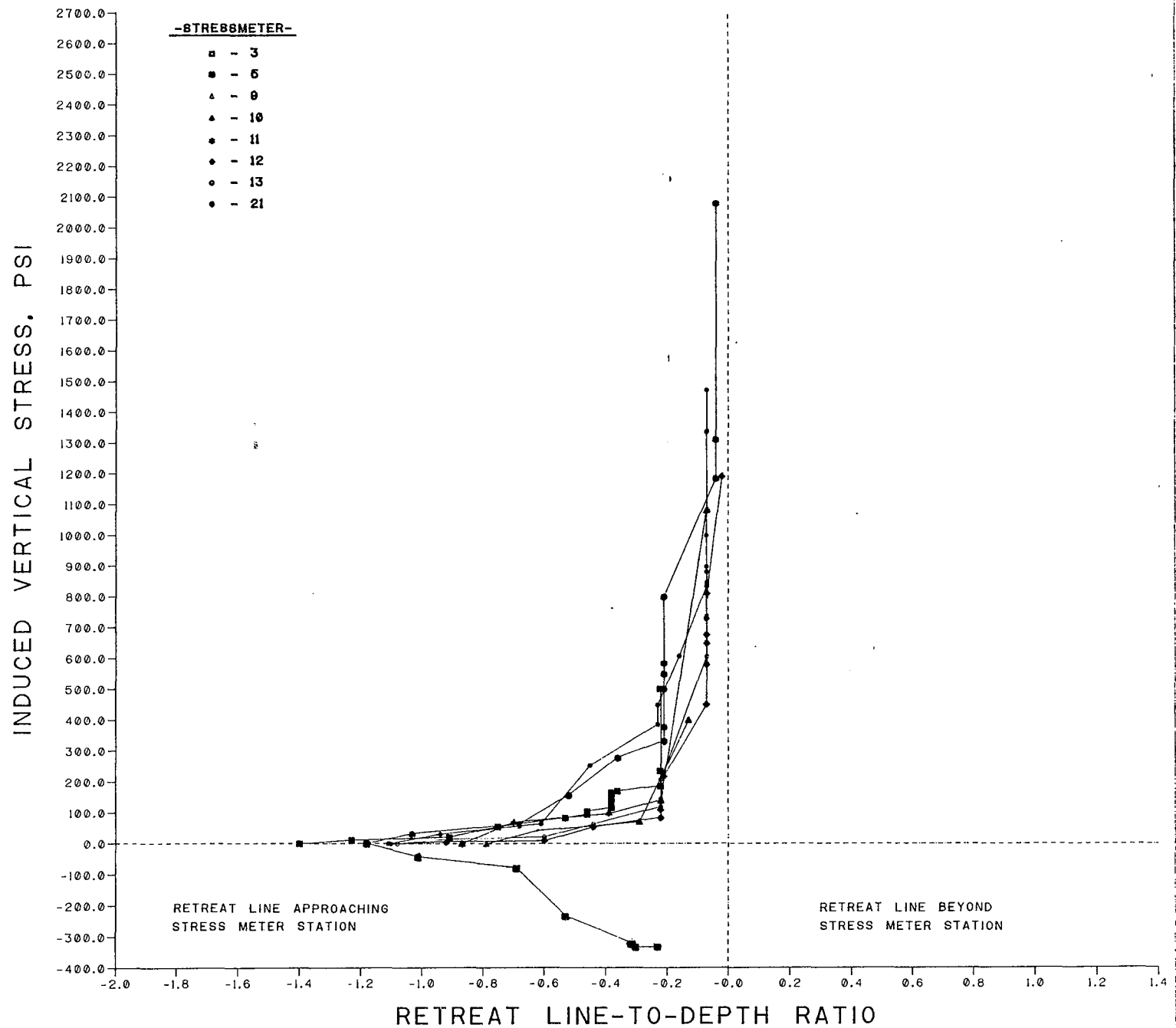


**FIGURE 5.8 -INDUCED PILLAR STRESS AS A FUNCTION OF POSTION OF THE RETREAT LINE
A. STRESSMETERS IN PILLARS AWAITING EXTRACTION**

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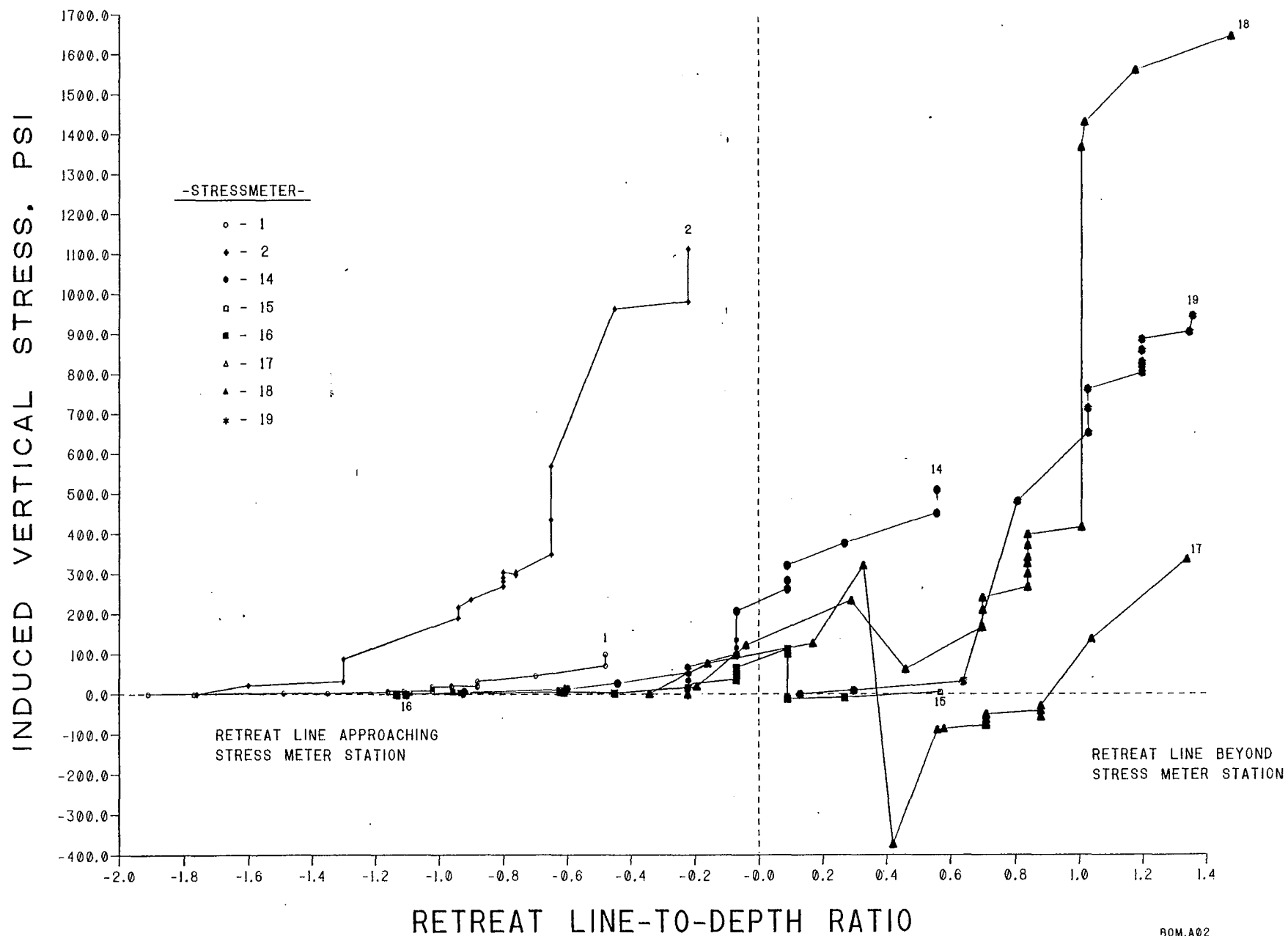
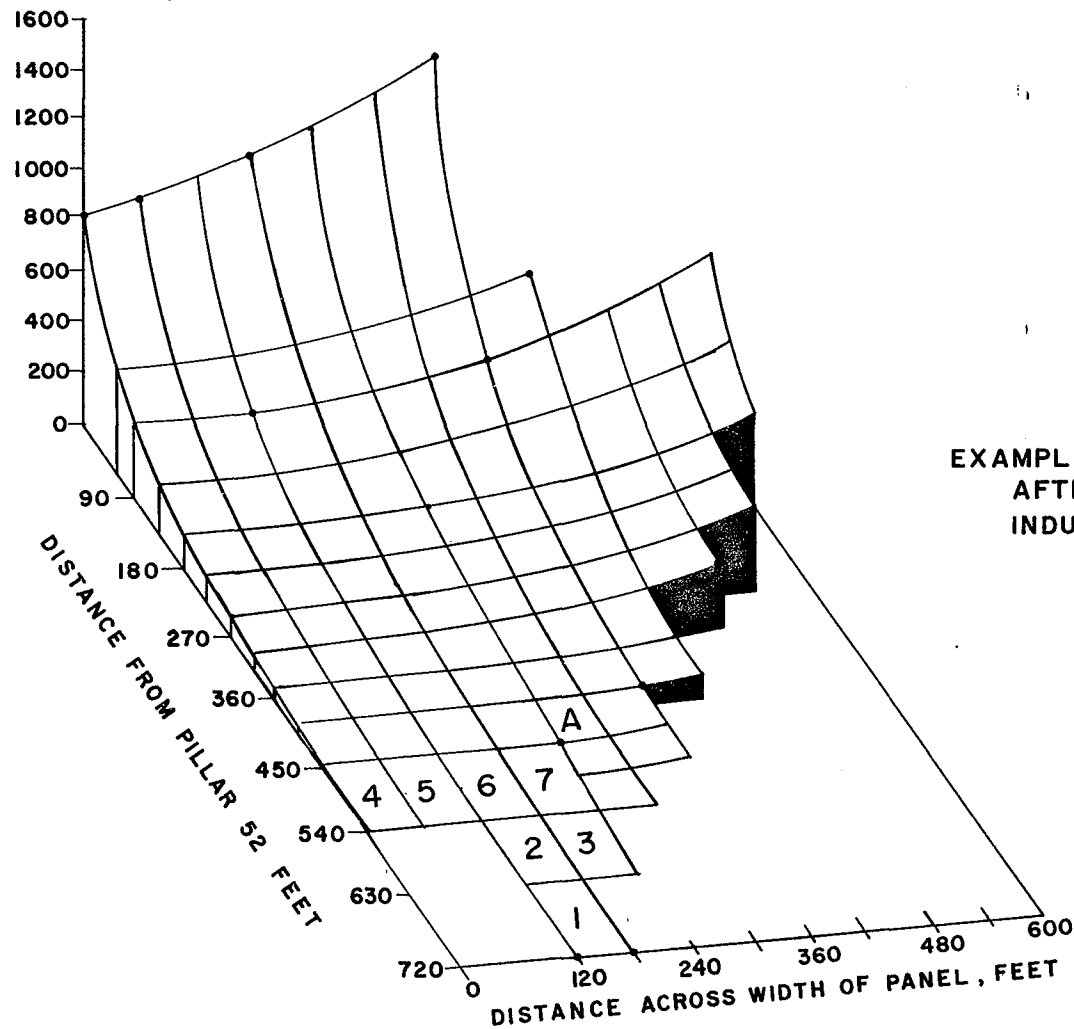


FIGURE 5.8 - CONTINUED

B. STRESSMETERS IN PILLARS OUTSIDE AREA OF PILLAR EXTRACTION

INDUCED
PILLAR STRESS, P.S.I.



EXAMPLE :

AFTER EXTRACTION OF PILLARS 1-7 (POINT A),
INDUCED VERTICAL STRESS IN PILLAR 52 = 22 P.S.I.

FIGURE 5.9 IDEALIZED PLOT SUMMARIZING THE VERTICAL STRESS INDUCED AT THE CENTER OF PILLAR 52 - AT EACH STAGE OF RETREAT MINING.

2. Rear Abutment Pressure

Stress Meters 17, 18 and 19, aligned in the direction of mining (Figure 5.7), provided an indication of rear abutment pressure. Stress Meter 17 was located in the barrier pillar directly adjacent to the mined-out area; Stress Meter 18 in the neighboring ventilation entry pillar, and Stress Meter 19 in the solid coal. Logistics prevented placing stress meters in or beneath the gob. Consequently, the rear abutment pressure measured in this monitoring program is that component associated with arching over the gob onto the coal along the perimeter of the mined-out area.

Two principal observations are made:

- a. The vertical stress in the solid coal climbed without interruption as the mined-out area increased in size, whereas stresses in the barrier pillar and ventilation entry pillar dropped to lower values on more than one occasion.
- b. Vertical stresses tended to increase in the direction of the mined-out area during the early stages of mining, but later increased in a direction away from the mined-out area toward the solid.

Specifically, the data indicate the following:

Between August 8 and September 2, 1982, the stresses at all three rear abutment monitoring points climbed steadily as the mined-out area increased in size. Then, at some point between September 2 and 20, when extraction mining first moved from the south apex of the panel to the areas north and east of the rear abutment monitoring points, the induced stress in the ventilation entry pillar dropped from 237 to 65 psi, while stresses in the barrier pillar and solid increased dramatically -- the stress in the solid from 53 psi to 503 psi and the stress in the barrier pillar from 129 psi to 324 psi -- signalling a redistribution of weight on the rear abutment. Then, between September 20 and October 10, as one more row of pillars was extracted, the stress in the barrier pillar dropped dramatically (a change of 695 psi), while the stresses in both the ventilation entry pillar and the solid continued upward. The drop in barrier pillar stress appears to coincide with the first measured subsidence above the panel in mid-October, 1982.

As extraction continued, the stresses at all three stress monitoring points climbed. By January 13, 1983, the last available reading before the panel was sealed off, the barrier pillar stress had slightly exceeded the preceding September's level of 338 psi and the stress in the ventilation entry pillar had risen to 1647 psi, far exceeding the previous peak of 237 psi reached on September 2. The stress in the solid reached 965 psi on January 2, 1983 before the stress meter malfunctioned, possibly the result of inundation by the rising mine pool.

The principal mechanisms that might lead to the stress reductions described above are: (1) settlement of the pillar, such as from punching into the mine floor, and (2) local uplift of the mine roof, such as from the upward leverage of a sequence of rock strata acting over a barrier

pillar fulcrum. Both may have contributed to the behavior observed in the C-3 panel. However, pillar settlement (pillar punching) is believed to be the more prominent cause of pillar unloading. Floor heaving was observed in the rear abutment area as early as September, 1982 and, as weeks passed, appeared from mine level observations to be more than a superficial phenomenon. Quantitative evidence of pillar settlement was furnished by survey of the ground surface above the rear abutment. The ground surface profile there was found to be highly irregular and suggestive of more than the usual amount of subsidence. This is discussed further in Section 9.

By late November, 1982, the ventilation entry pillar stress far exceeded the September peak stress of 237 psi. This is not inconsistent with bearing failure having taken place in September -- if, as bearing failure ensued, the floor material around the perimeter of the pillar became less competent, and the load shifted farther and farther toward the center of the pillar. This could have raised the measured vertical stress, even though the load carrying capacity of the pillar may actually have been less due to a reduced bearing area. During this period, there appears to have been an overall transfer of weight back toward the solid (away from the mined-out area).

During the retreat mining process, convergence in the gob area took three general forms (as described in Section 6): collapse of the immediate roof, flexure of the immediate roof, or no closure. The flexure and no closure conditions would be expected to produce local arching between the pillars and the gob some distance back from the retreat line -- 20 to 30 feet in the case of flexure, or farther in the case of no closure. These conditions were temporary and were eventually supplanted by collapse at each location. Collapse would be expected to level out the "rear abutment" pressure in the gob. Even so, it seems unlikely that the vertical stress in the gob area reestablished at pre-mining levels until months, if not years, after retreat mining had been completed. This is because subsidence continued for at least twelve months after mining had been completed. The continuing subsidence suggests that the overburden during this period was receiving at least partial support from pillars and solid coal surrounding the mined-out area. Consequently, the vertical stress delivered to the mine floor by the overburden during this period, although probably greater than zero was almost certainly less than the original overburden pressure.

3. Side Abutment Pressure

Stress Meters 14, 15 and 16 aligned transverse to the direction of mining (Figure 5.6) yielded information concerning the east abutment pressure. Stress Meter 14 was located in the barrier pillar directly adjacent to the mined-out area; Stress Meter 15 in the neighboring ventilation entry pillar and Stress Meter 16 in the ventilation entry pillar nearest the solid. Extremely hazardous roof conditions and obstructions prevented the installation of stress meters in the solid along this alignment. Lack of access also prevented the installation of stress meters in the west abutment. Entries and cross-cuts were not driven into that area until shortly before extraction began.

Like the rear abutment stresses, the east abutment stresses:

1. Climbed as the mined-out area increased in size, but experienced some declines; and
2. Increased in the direction of the mined-out area.

Unlike the rear abutment stresses, the east abutment stresses:

1. Remained highest in the barrier pillar throughout the period of monitoring; and
2. Did not drop until early December, 1982, two months after surface subsidence had first been recorded.

Stress Meters 14-16 were in a position to measure the front abutment pressure until late November, 1982, when pillar extraction began in the row adjoining these pillars. During the July to mid-November 'front abutment' period, stresses in these pillars increased as extraction drew nearer and were greatest in the east barrier pillar adjacent to the mined-out area. In late September, 1982, Stress Meter 16, nearest the solid, was rendered inaccessible by a rock fall. Stress Meters 14 and 15 functioned throughout the program and continued to indicate rising stresses as extraction progressed in the row of pillars directly alongside. The stress in the ventilation entry pillar reached its maximum value as extraction in this row of pillars neared completion and thereafter decreased. By the completion of extraction of the next row of pillars, the stress had dropped below its initial pre-retreat mining level. As pillar extraction continued, the pillar stress began to climb once again, and by late February, 1983, had increased to the pre-retreat value (zero induced stress). During this period the barrier pillar stress continued to rise.

On the basis of observations at mine level, pillar punching appears to be the source of the stress reduction in the ventilation entry pillar. However, the peak stress there was significantly lower than were stresses in the rear abutment when those pillars are thought to have experienced bearing failure. Furthermore, there were no indications of irregularity in the ground surface profile above the east abutment to support the suspicion of significant pillar punching. It is possible that the strata arched over the distressed ventilation entry pillar(s) from east barrier pillar to the solid. In essence, the east ventilation entry pillars may have behaved as yield pillars. If so, pillar punching may have taken place with the principal evidence being concentrated at mine level.

The pillar stresses reported here for the east abutment were almost certainly influenced by the close proximity of the monitoring stations to the rear abutment along the south boundary of the panel. Had the monitoring stations been located farther north from the end of the panel, the measured stresses may have been higher.

The redistribution of stresses in and around the coal pillars and mine openings as mining progressed resulted in deflections of the mine openings. The vertical component of that deflection -- the convergence -- is discussed in the next section.

6.0 MINE LEVEL MOVEMENTS

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INTRODUCTION

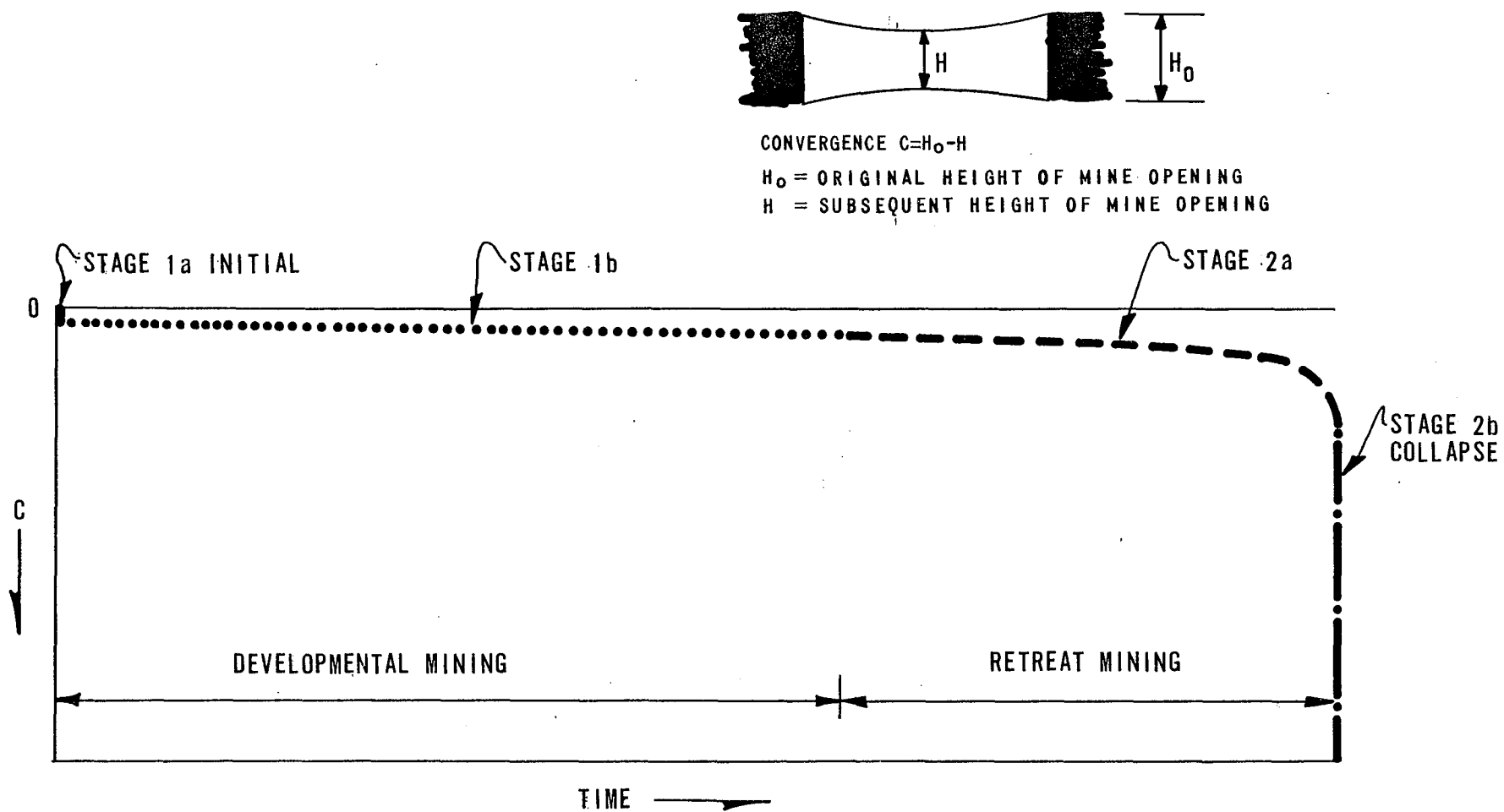
The change in height of a mine opening is termed 'convergence' (or closure) and is the sum of deflections of the roof C_R , the coal pillars C_p and the floor C_F :

$$C = C_R + C_p + C_F \dots\dots\dots(6.1)$$

Convergence of the mine openings took place in several stages which are shown schematically in Figure 6.1:

1. Developmental Mining (Advance Mining)
 - a. Initial convergence of a fraction of an inch to possibly several inches occurring immediately upon excavation of the mine opening as stresses within the bounding rock were relieved; and
 - b. Convergence of a fraction of an inch to several inches occurring over a period of months as the rock bounding the mine opening fractured, deteriorated and adjusted in the mine atmosphere.
2. Retreat Mining
 - a. Convergence of a fraction of an inch to several inches as the rock bounding the mine opening responded to stresses imposed by the extraction of pillars some distance from the opening; and
 - b. Collapse of the mine opening. Roof falls occurred in a few locations in permanent entries and in entries not yet reached by the retreat line; eventually caving of the roof occurred everywhere in the gob area as the retreat line passed through.

Some information concerning initial convergence (Stage 1a) was obtained by means of a borescope survey conducted in two entries during developmental mining. Information concerning convergence during Stages 1b and 2a was obtained by convergence measurements made at 22 stations located as shown in Figure 4.1. Fifteen stations were located in the area of pillar extraction; five in the bleeder entries and two near the main entries. Fifteen stations were located at four-way intersections; one at a



NOTE: SCHEMATIC - NOT TO SCALE.

FIGURE 6.1 STAGES IN THE CONVERGENCE OF A MINE OPENING

three-way intersection; four in entries midway between cross-cuts; and two in cross-cuts midway between entries. Nineteen stations consisted of eye-bolts installed in the roof and floor along the centerline of the entry or cross-cut (Figure 4.2). Three stations consisted of eye-bolts installed at the roof and floor lines of coal pillars. Five of the centerline stations included eighteen foot long, four-position, rod-type, borehole extensometers installed vertically in the mine roof (Figure 4.2). (Logistics prevented the installation of similar extensometers in the mine floor.) Information concerning the final stage of convergence (2b) was obtained by visual observations of the gob area from the retreat line and by an examination of roof falls that occurred outside the gob area.

Convergence is discussed in the context of the three zones cited earlier in relation to the pillar stresses (Figure 5.2): the front abutment, the rear abutment and the side abutments.

FRONT ABUTMENT: AREA WHERE PILLARS AWAIT EXTRACTION

1. Convergence During Developmental (Advance) Mining

- a. Initial convergence in entries and cross-cuts. A significant amount of convergence appeared to occur within a short time after (if not at the same time that) an entry or cross-cut was driven. This convergence is at least partially the result of stress relief around the mine opening.

An assessment of the amount of initial convergence was made during developmental mining in mid-January, 1982 by employing a borescope (periscope) to examine the roof strata in sections of two entries that had been driven one month earlier. Ongoing developmental mining at the time of the borescope survey was 200 or more feet away. A 10-foot long borescope was used to examine first one side and then the opposite side of roof extensometer Boreholes 5B and 11E adjacent instrumented Pillar 52 (Figure 4.1) and in the process measure the widths of the roof fractures. The presumption was that the fractures were closed or did not exist prior to mining and their cumulative width at the time of inspection was a measure of the downward deflection of the roof strata into the mine opening as a result of driving the entry. The aperture of each observed fracture was measured against a standard grid etched on the borescope lens. Observed fracture locations and widths are shown in Figure 6.2.

In the examination, only low angle (essentially horizontal) fractures were found in the roof strata. These were primarily along bedding planes, but included several narrow zones of crushed rock. Differences in the numbers and spacing of fractures on opposite sides of each borehole perhaps were due to the inability of the observer to detect very narrow apertures; no fractures less than 0.05 inches in width were identified. But because the width of a fracture is customarily variable along its length, it is possible that at least some of the "discontinuous" fractures fully transected the borehole. Certainly, the total vertical roof movement must have been the same along opposite sides of each borehole and any apparent differences in cumulative crack width from side to side could have been due only to inaccuracies in measurement. The results of the investigation indicate

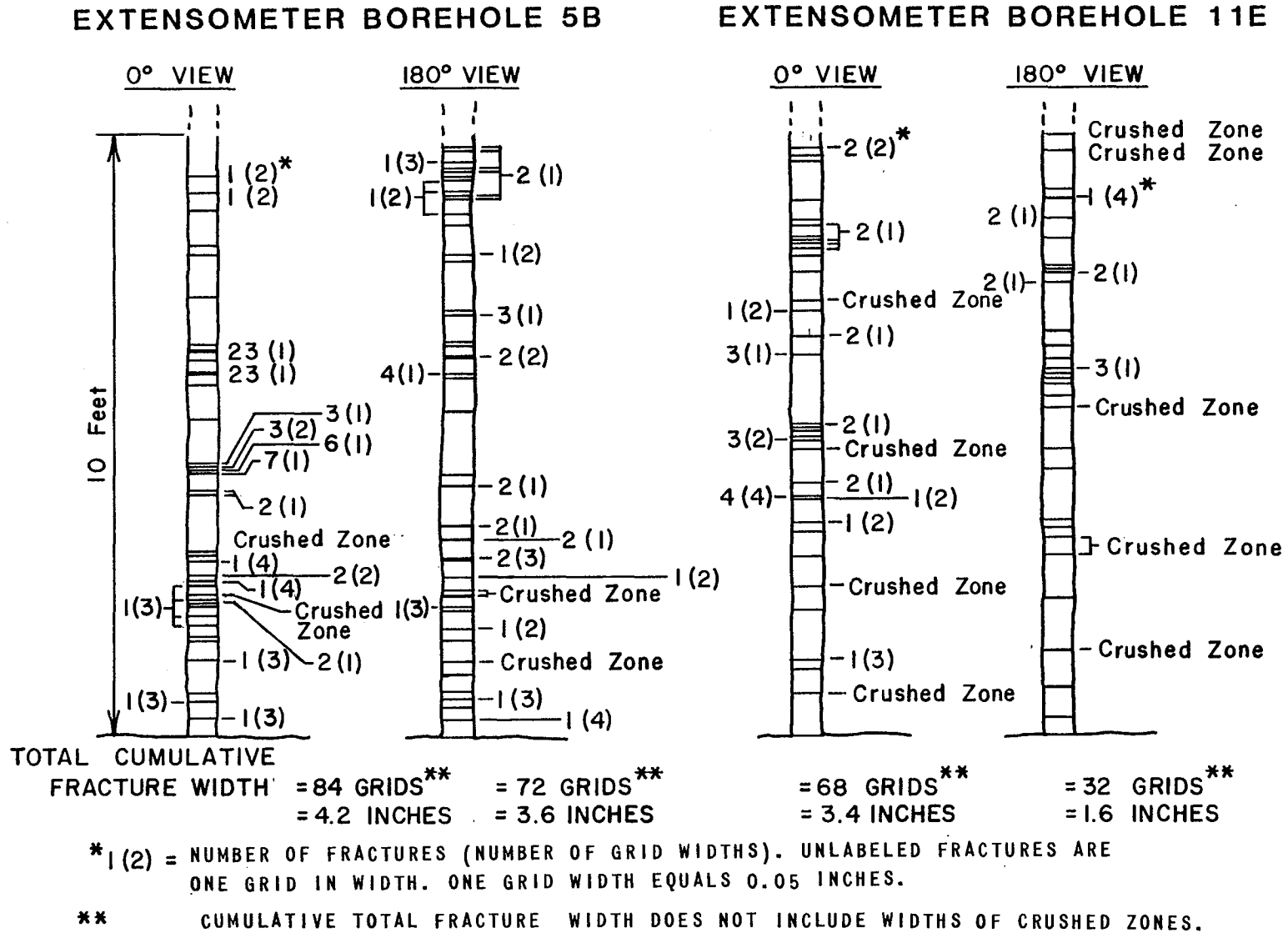


FIGURE 6.2
LOCATIONS AND WIDTHS OF HORIZONTAL FRACTURES IN THE LOWER
10 FEET OF ROOF EXTENSOMETER BOREHOLES 5B AND 11E

a cumulative fracture width of 3.6 to 4.2 inches and a mean fracture spacing of 3 inches in the lower 10 feet of Borehole 5B, and a cumulative fracture width of 1.6 to 3.4 inches and a mean fracture spacing of 3.75 inches in the lower 10 feet of Borehole 11E. The cumulative fracture width would have been greater and the fracture spacing smaller had the crushed zones been taken into account. Moreover, judging from the distribution of cracks in the lower 10 feet of the two boreholes, additional cracks probably opened higher in the roof and, if so, would be evidence of even greater amounts of initial convergence, as would cracks of the same origin in the mine floor. What cannot be established is how much of the deformation occurred instantaneously upon driving the entry and how much occurred during the intervening month prior to conducting the borescope investigation. Regardless, it appears that the convergence that took place during the first month after a section of entry had been opened may have equalled or exceeded the convergence taking place throughout the remainder of developmental and retreat mining phases (with the exception of collapse of the entry). Although, only two boreholes were surveyed by borescope, the data are thought to be representative of deformations that accompanied the early stage of developmental mining at other locations in the panel and are believed consistent with the concept of stress relief.

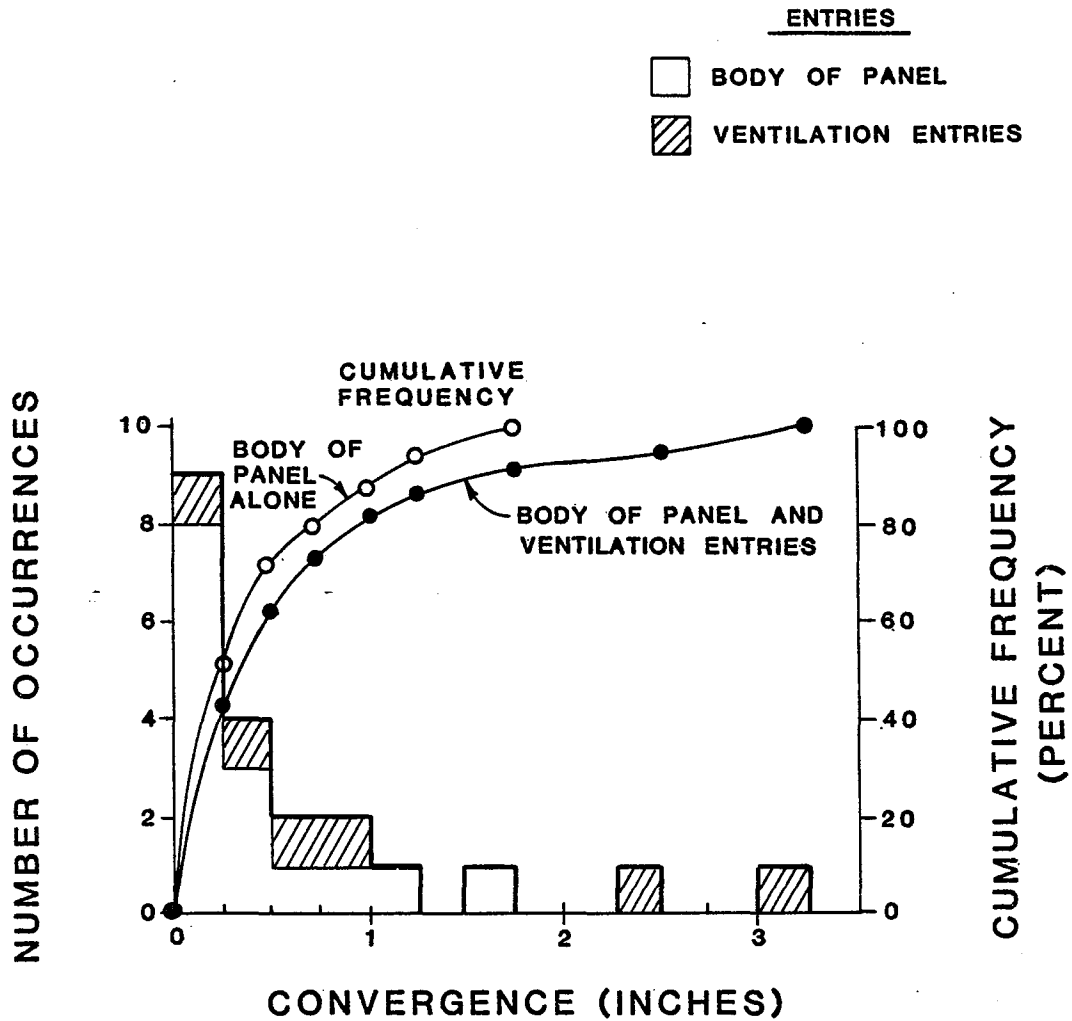
b. Convergence in entries and cross-cuts in the area awaiting pillar extraction during the period between convergence station installation and the initiation of retreat mining, early March-late July, 1982.

The convergence stations were established during a two-week interval in March, 1982, zero to 17 weeks after the entries and cross-cuts had been driven past the respective stations, three-quarters of them within 10 weeks. Convergence measured between the time of installation in March and the initiation of retreat mining in late July ranged from 0.05 inch to 1.7 inches, the value being 0.9 inch or less in 90 percent of the cases (Figure 6.3).

Roof extensometers at five convergence stations indicated that most downward roof movements during the five month period following instrument installation and preceding retreat were concentrated in the lowermost 8 to 8.5-foot interval of strata, which included the 5-foot interval of roof bolting (Table 6.1).

Roof movements during this period are attributed to redistributions of stress in the panel arising from developmental mining, to degradation (weathering) of the roof strata and to general relaxation of the roof strata under the force of gravity.

During advance mining, continuous, vertical fractures ("cutters") often formed in the newly exposed mine roof usually at the mine face, but occasionally not until the mine face had moved at least one pillar row beyond. The cutters initially appeared as tight, but continuous fractures, often paralleling the sides of coal pillars, but occasionally trending diagonally across entries and cross-cuts (Figure 6.4). Crushed



NOTE: EXCLUDES 'INSTANTANEOUS' CONVERGENCE ACCOMPANYING
CREATION OF A MINE OPENING

**FIGURE 6.3 CONVERGENCE OCCURRING
DURING DEVELOPMENTAL MINING
MARCH-AUGUST, 1982**

Table 6.1

ROOF DEFLECTIONS MEASURED BY EXTENSOMETERS
DURING DEVELOPMENTAL AND RETREAT MINING

A. Developmental
Mining^x

Height Above Mine Level (feet)	MPBX									
	3A		5B@		9C		10D		11E@	
	inchΔ	%*	inch	%	inch	%	inch	%	inch	%
13.9-17.9	0.010	1	-0.105	-8	-0.162	-10	0.003	5	0.003	4
8.4-13.9	0.146	13	-0.214	-16	-0.211	-13	-0.074	-117	-0.001	-1
3.9- 8.4	0.585	54	0.749	58	1.496	90	0.074	117	0.003	4
0- 3.9	0.344	32	0.855	66	0.549	33	0.060	95	0.067	93
Net Roof Deflection ⁺	1.085	100	1.285	100	1.672	100	0.063	100	0.072	100

B. Retreat
Mining^x

(feet)	inchΔ	%*	inch	%	inch	%	inch	%	inch	%
13.9-17.9	-0.030	-6	-0.004	36	-0.017	-7	-0.027	-150	-0.019	-12
8.4-19.9	0.034	7	-0.014	127	0.004	2	0.049	272	-0.020	-12
3.9- 8.4	0.191	38	0.029	-263	0.241	98	-0.064	-355	0.045	28
0- 3.9	0.305	61	-0.022	200	0.016	7	0.060	333	0.155	96
Net Roof Deflection ⁺	0.500	100	-0.011	100	0.244	100	0.018	100	0.161	100
Date of Final Reading	11/29/82		11/29/82		9/02/82				11/29/82	
X/H _v	0.42		0.15		0.36				0.05	

Δ Deflection within each interval: + = extension; - = compression

x Developmental Mining (3/1/82 [instrument installation] - 8/3/82); Retreat Mining (8/3/82 - Date of Reading)

* Percentage of Net Roof Deflection

+ Movement of the mine roof relative to the anchor 18 feet above mine level.

v Distance at the time of the final reading of Convergence Station to Retreat Line as a fraction of overburden thickness

@ Borescope examinations were made of the lower 10-foot intervals of Boreholes 5B and 11E, as discussed under Item 1a, initial convergence, in this section of the report. Note that the roof deflection that occurred during the March-August, 1982 period after the roof extensometers had been installed is much smaller than what apparently occurred initially, based upon the borescope examination of the two boreholes.

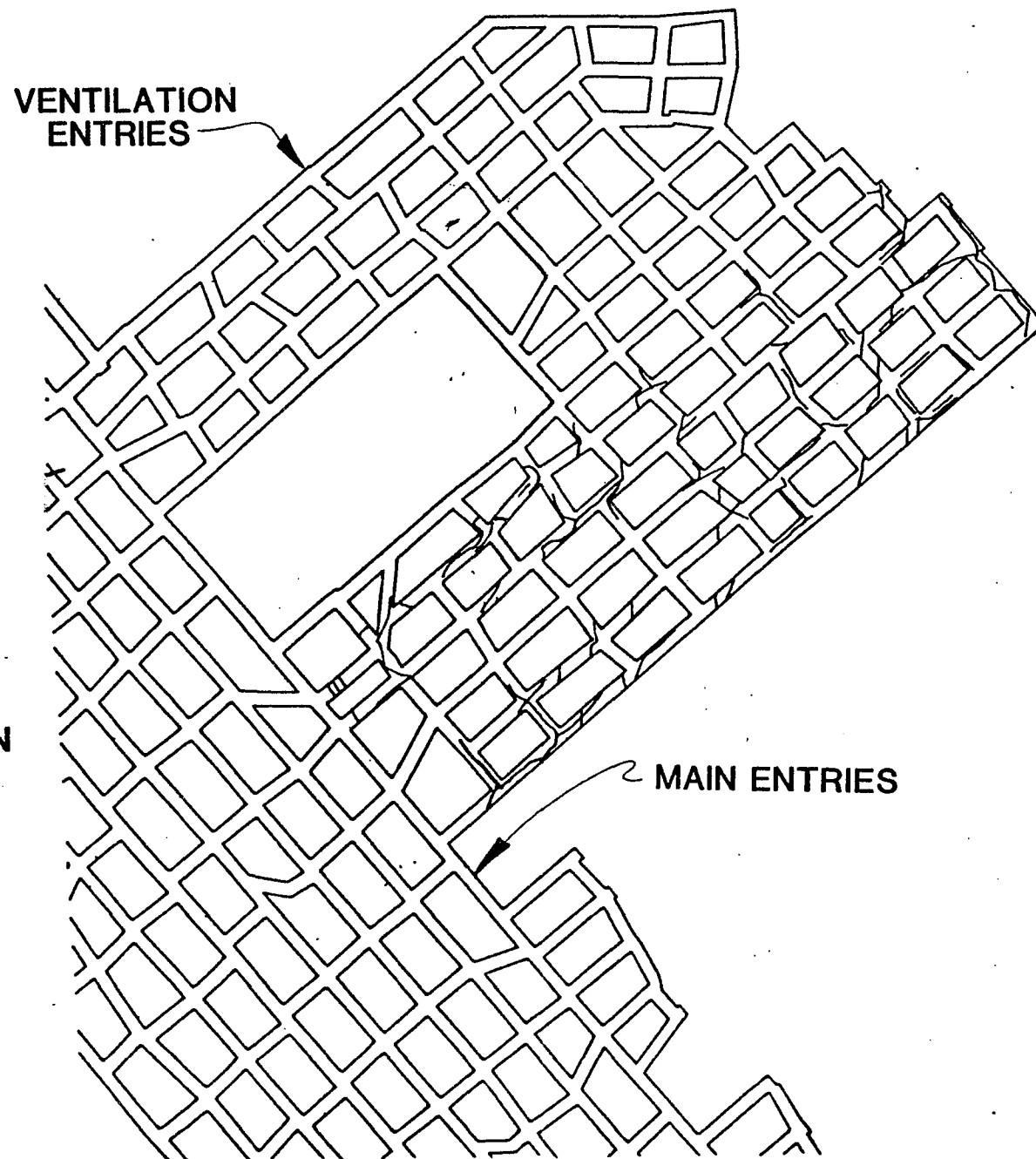


FIGURE 6.4
LOCATION AND ORIENTATION
OF "CUTTER" FRACTURES IN
THE MINE ROOF OF THE
PARTIALLY ADVANCED MINE
PANEL

and buckled zones developed in association with some of the cutters, a possible result of high horizontal compressive forces. Such deformation was initially confined to rock at the roof line, but in time, appeared to propagate upward. If the broken rock did not fall piece by piece into the mine opening as the crushed zone enlarged, the entire crushed rock section fell as a unit, leaving an inverted v-shaped void in the mine roof along the length of the fracture. The height above the roof line was generally not more than three feet.

In addition to effects like those described above, weathering of the roof rock also appeared to contribute to convergence. In July, 1982, during a period of extremely high temperature and relative humidity, significant amounts of condensation formed underground as air from ground surface was drawn into the cooler portions of the mine. Rapid degradation and widespread slaking of the mine roof resulted, littering the mine floor with slabs of roof shale (Figure 6.5). Slaking and raveling of the roof was particularly active where cutters and zones of crushed, deformed rock had developed.

Some shearing occasionally took place in the floor of this section of the C-3 panel, particularly along pillar faces. The shears, associated with pillar punching, were commonly referred to as "floor heave" because the fraction of an inch greater settlement on the pillar side of the crack gave the remainder of the floor the appearance of having heaved.

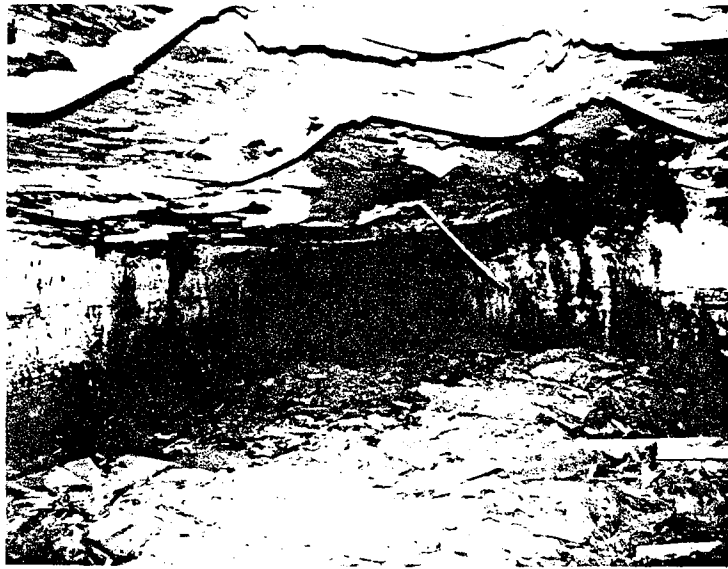
2. Convergence During Retreat Mining in the Area Where Pillars Awaited Extraction.

Convergence increased in magnitude and rate in a nearly exponential fashion with approach of the retreat line to the convergence station (Figures 6.6A, B). Based on final readings, convergence during retreat reached 0.06 to 5.6 inches at minimum at the 15 convergence stations in Zone A1 (Figure 6.7A). This represents 0.1 to 8 percent of the nominal 5.5 foot mined thickness of coal. (As discussed below, the maximum convergence was probably larger.) The estimated maximum convergence during retreat mining was approximately 2 inches (excluding collapse of the mine opening). The roof extensometers (Table 6.1) indicate that downward movement of the roof during retreat mining was concentrated in the lowermost 8 to 8.5 feet of strata, as it was during developmental mining.

Two items are to be noted:

- (1) Datum. The zero point in Figure 6.6 is the initiation of retreat mining. Pre-retreat convergence has been deducted.
- (2) Estimated Maximum Convergence (excluding collapse). Convergence measurements could be made only as access to the mine permitted. Consequently, at several of the convergence stations, the maximum convergence attained immediately prior to extraction of the pillars adjoining the station was almost certainly greater than the last reading obtained. This can be appreciated by

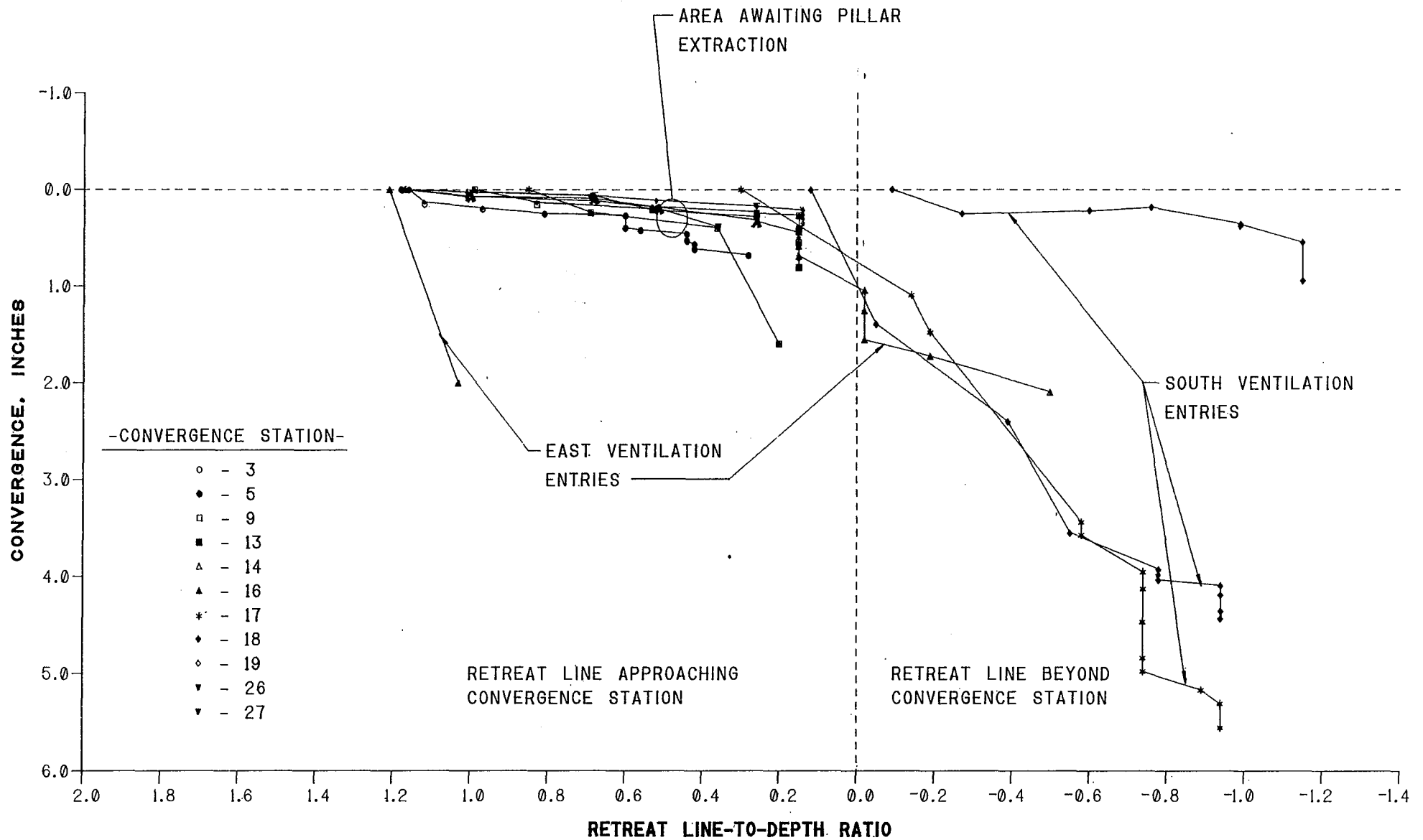
A



B



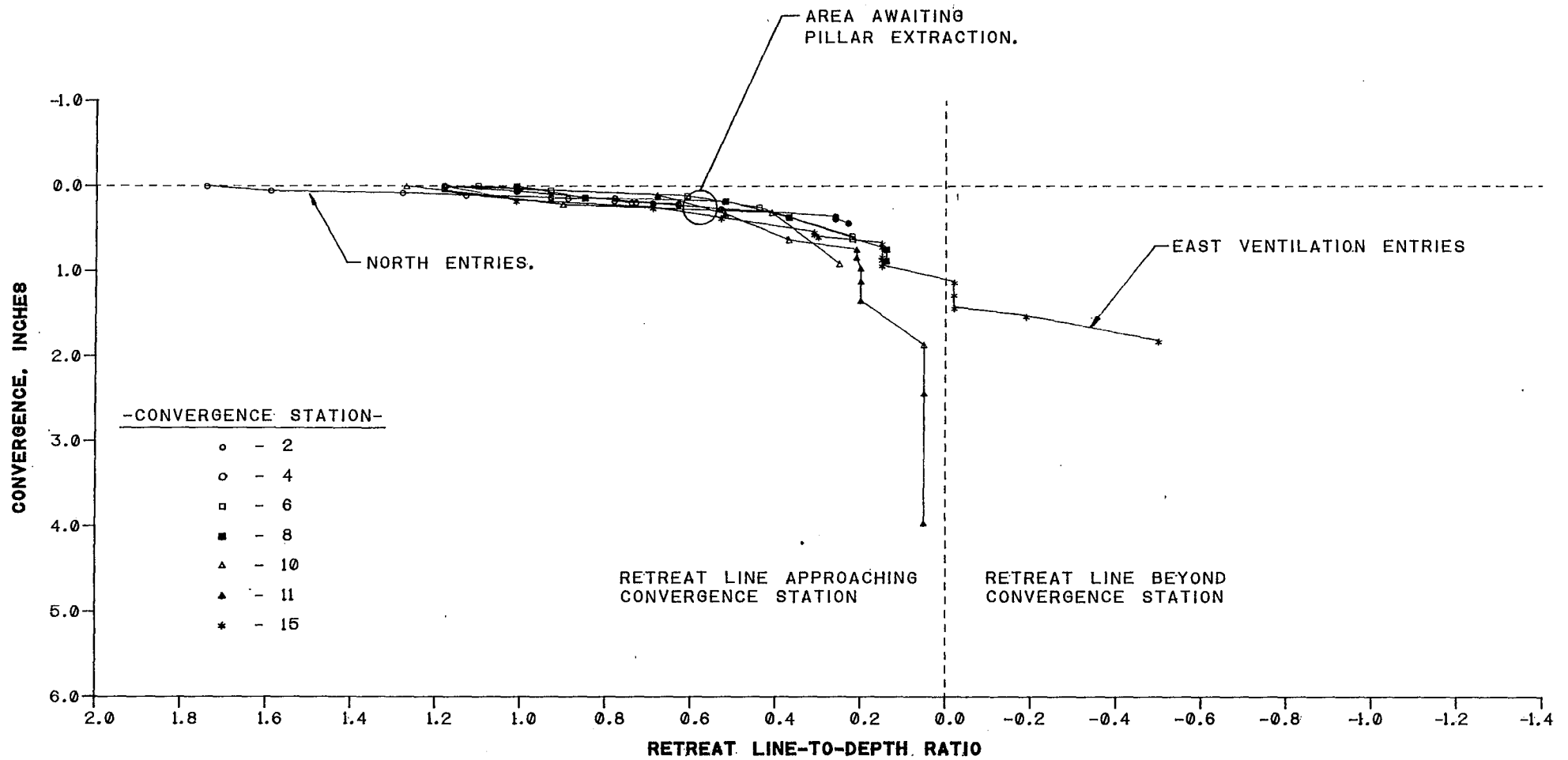
FIGURE 6.5 PHOTOGRAPHS OF ROOF DEBRIS, A AND FLOOR HEAVE B



BOM.A01

FIGURE 6.6 - CONVERGENCE IN RELATION TO POSTION OF THE RETREAT LINE

A. INTERSECTIONS



BOM.A94

FIGURE 6.6 - CONTINUED

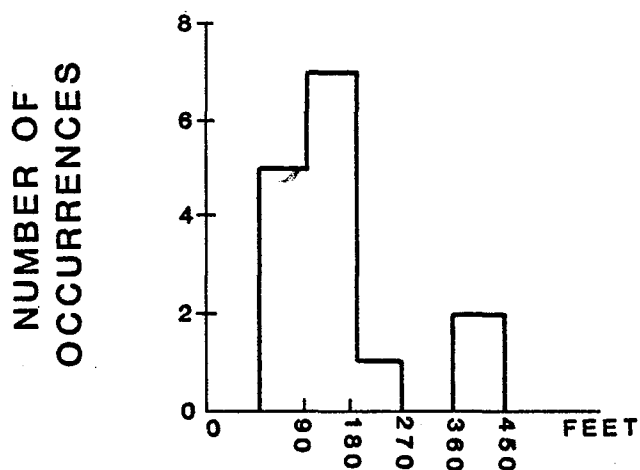
B. ENTRIES AND CROSS CUTS

A

NUMBER OF
OCCURRENCES

CONVERGENCE DURING RETREAT (INCHES)
BASED ON FINAL READINGS

B



DISTANCE BETWEEN CONVERGENCE STATION
AND RETREAT LINE AT FINAL READING

(90 FEET IS THE NOMINAL CENTER-TO-CENTER
DISTANCE BETWEEN CROSS CUTS)

FIGURE 6.7
CONVERGENCE OCCURRING DURING RETREAT MINING

noting the distance between the convergence station and the retreat line at the time the final reading was taken (Figure 6.7B). The 2-inch value, cited above as being 'representative' of the maximum convergence that occurred during retreat mining, is judgmental based upon inferred trends in the convergence curves in Figure 6.6. It should be recognized that each curve in Figure 6.6 no more than approximates the relationship between convergence at a particular point in the mine panel and the position of the retreat line. (This is analogous to the situation described earlier for induced pillar stress.) An idealization of the complete relationship for a specific convergence station is shown in Figure 6.8. Convergence Station 5 is used as an example. Each point in the figure specifies the amount of vertical closure that had taken place at the convergence station between the time retreat mining began and the time it had progressed to the particular point in the mine panel indicated by the figure. An array of such plots--one for each point in the panel--would be required to completely define convergence characteristics within the panel.

The rate of convergence during retreat in many of the entries, cross-cuts and intersections was virtually the same as the rate of compression of the pillars bounding the mine opening, particularly for the lower ranges of convergence (less than 0.5 inch for entries and cross-cuts and 0.75 inch for intersections). This is shown in Figure 6.9A, B, where mine opening convergence is plotted against induced vertical stress in the neighboring pillars. The estimated pillar compression is shown along the left boundary of the two plots. Convergence values at zero induced pillar stress are those occurring before retreat mining began. In the upper ranges of convergence, the rate of closure at many of the stations increased, as indicated by a flattening of in slope of the pillar stress-convergence curve. The onset of the slope change varied from station to station in the panel. For example, at Convergence Station 27 (in an intersection), the convergence rate appeared to increase as pillars were extracted in the row immediately ahead of the station, whereas at Convergence Station 4 (in an entry), the convergence rate appeared to increase as pillars were extracted three rows ahead of the station. At some locations, such as Convergence Stations 15 and 18, the rate of convergence exceeded the rate of pillar compression throughout the retreat mining phase. The increases in convergence rate are indicative of intensified movements of the mine roof and floor.

Vertical segments of the convergence curves shown in Figure 6.6 occur where more than one reading was taken during pillar extraction in a particular pillar row and do not necessarily imply accelerated or abnormal convergence. This is consistent with Figure 6.8.

The variable contributions of roof, pillar and floor to convergence is illustrated in Figure 6.10 based on data collected at five locations in the panel where borehole extensometers had been installed in the mine roof. At these five locations, the contribution of the roof to

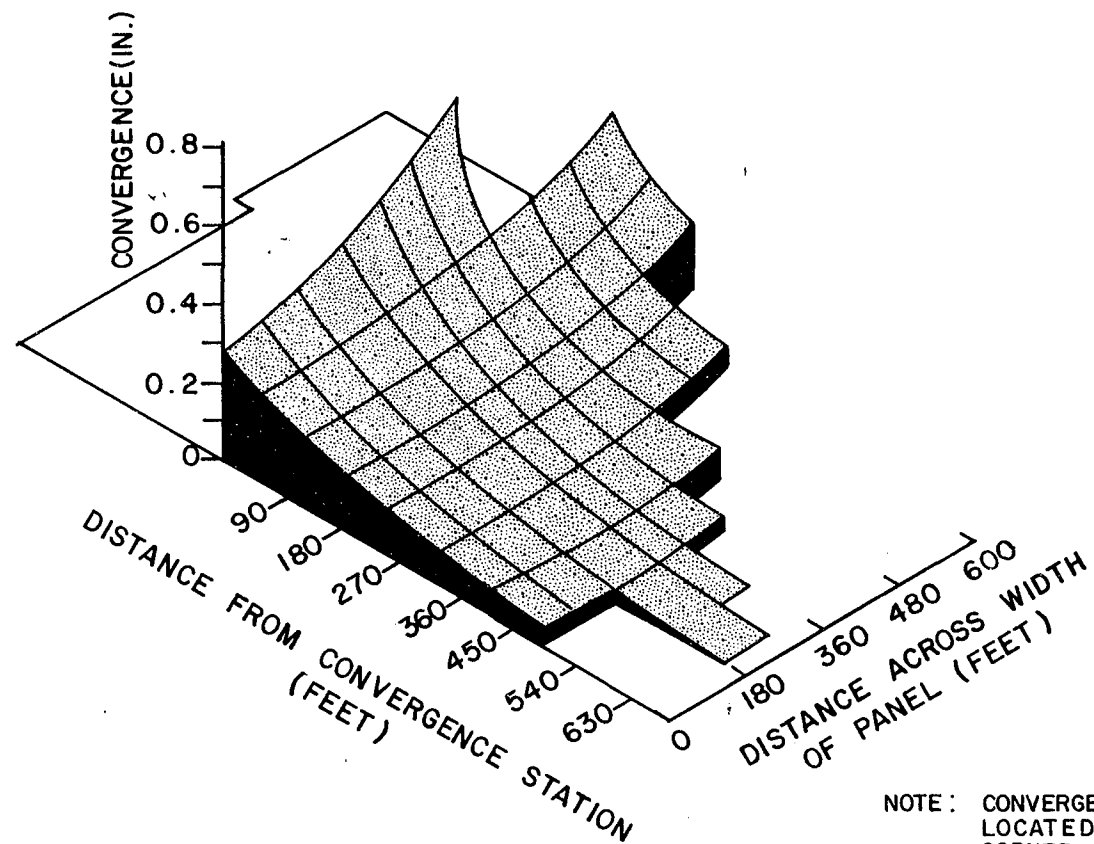
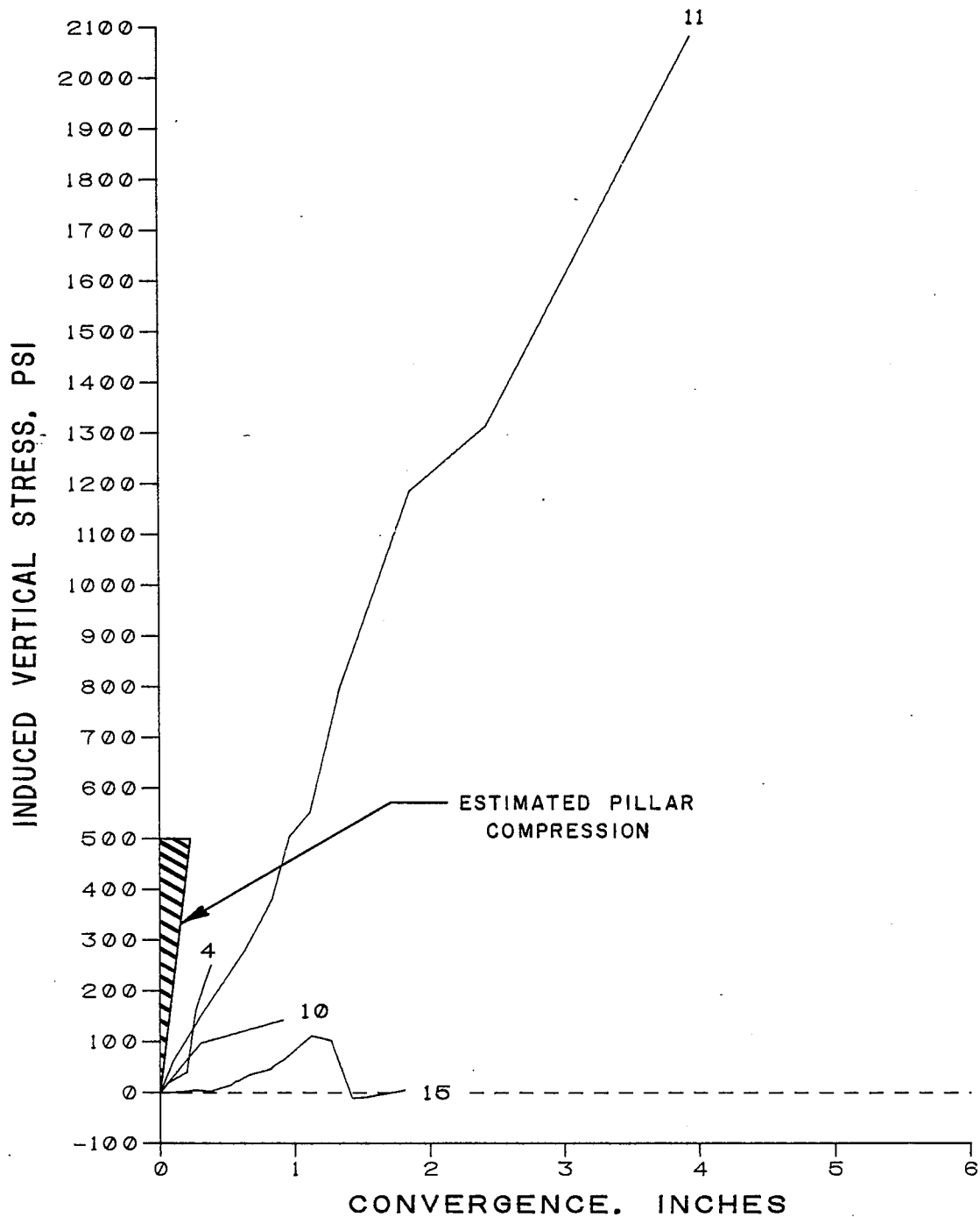
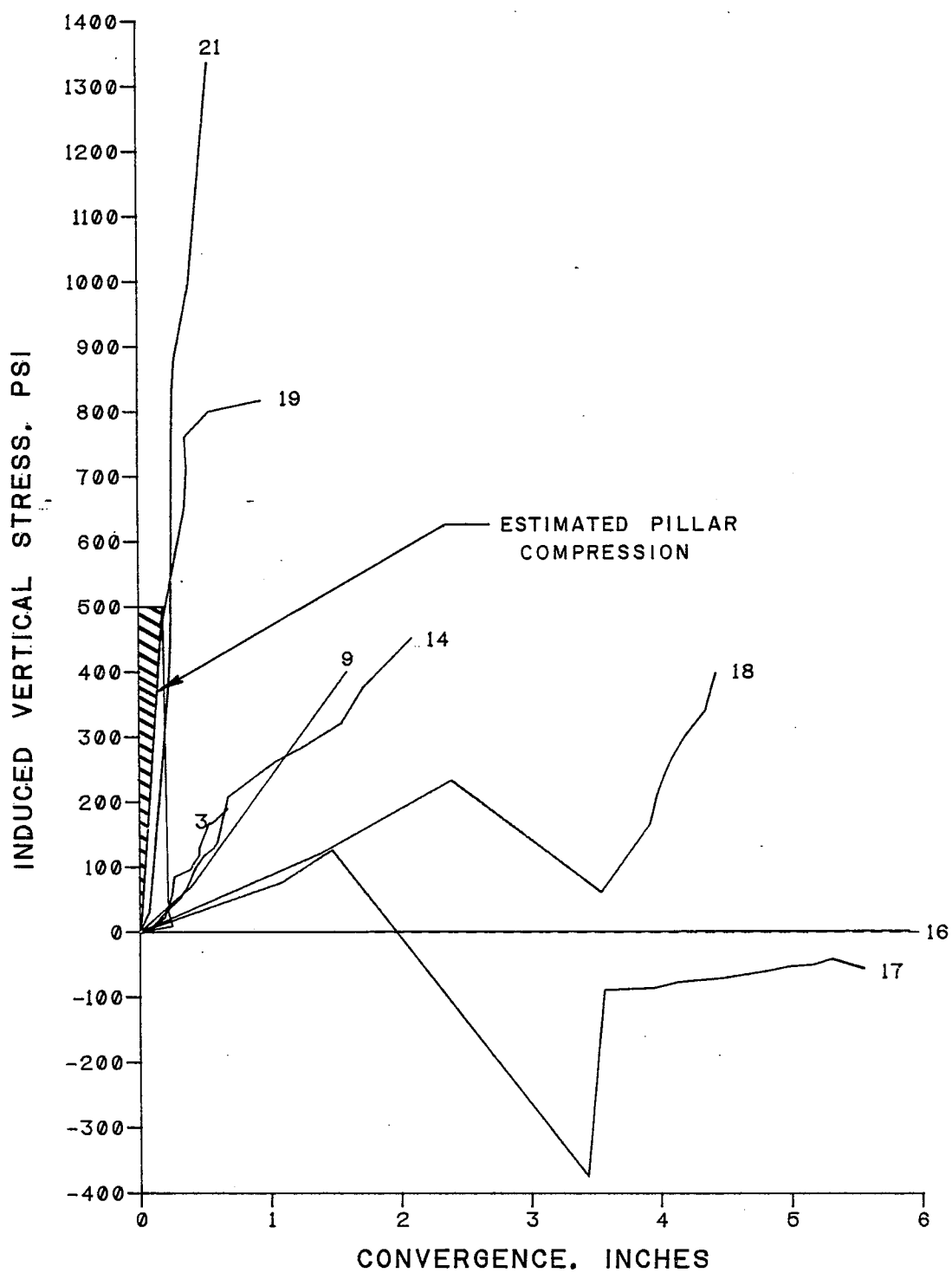


FIGURE 6.8 IDEALIZED PLOT SUMMARIZING THE CONVERGENCE AT STATION 5 AT EACH STAGE OF RETREAT MINING



BOM.A10

FIGURE 6.9
CONVERGENCE VERSUS INDUCED VERTICAL STRESS IN NEIGHBORING PILLARS
A. INTERSECTIONS CONTINUED



BOM.A11

FIGURE 6.9 B. ENTRIES AND CROSS CUTS

NORMALIZED DISTANCE BETWEEN CONVERGENCE STATION AND RETREAT LINE X/H

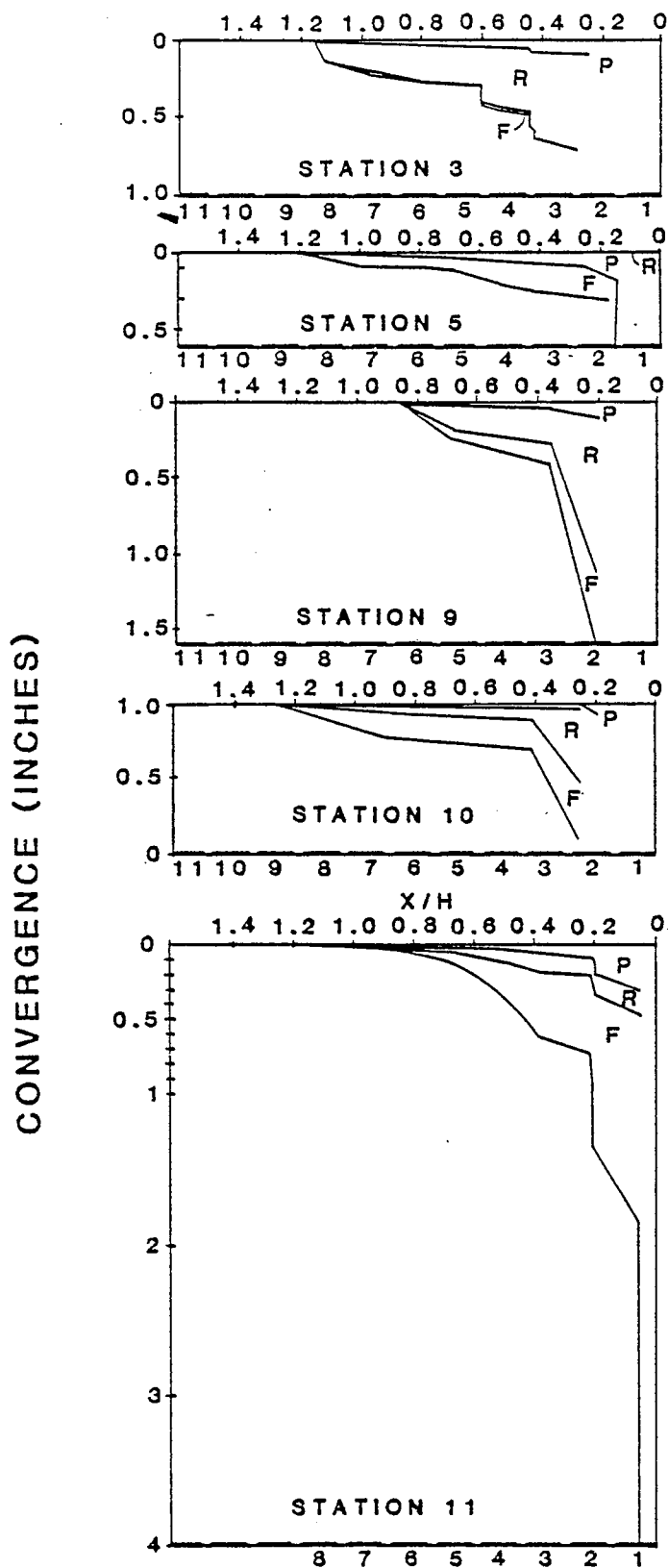


FIGURE 6.10
CONTRIBUTIONS OF ROOF, FLOOR AND PILLARS TO
CONVERGENCE AT FIVE STATIONS

convergence is the deflection indicated by the roof extensometer referenced to its top anchor; the contribution of the deformation of the neighboring pillars is based upon measurements of vertical stress change; and the contribution of the floor is taken as the difference between the total convergence and the individual contributions of the roof and pillars. On this basis, roof deflections apparently exceeded floor and pillar deflections at Convergence Stations 3, 9 and 10, whereas floor movements apparently dominated at Convergence Stations 5 and 11. Floor movement was almost nil at Station 3; roof movement was almost nil at Station 5; and, in most cases, pillar deflections were small both in an absolute and a relative sense. These data attest to the variability in response of the mine level strata to the stresses imposed during retreat mining. This variability in response is almost certainly related to cracks and fissures that developed in the rock strata as pillar extraction progressed.

Some of the cracks appeared typical of extension (Figure 6.11A) and others of shearing (Figure 6.11B), the latter particularly at roof/pillar junctions where stress concentrations would be expected. Cracks doubtlessly developed in the floor as well as the roof, but could not often be seen owing to ruts and other floor irregularities caused by mining activities. Details and locations of cracks varied from location to location in the panel, probably reflecting local variations in geology, mining procedure and stress field. Crack development is assuredly related to strain level and convergence, but data were insufficient to relate progress of cracking to deformation of the mine opening.

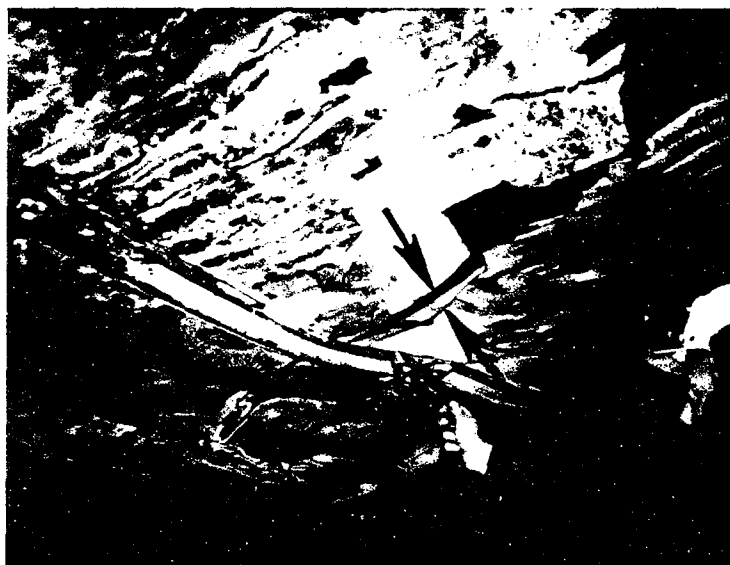
Only two roof falls (as distinct from ravelling and slaking) occurred in the area awaiting pillar extraction during the life of the panel, one of them in the entry between Pillars 81 and 82, the other in the four-way intersection between Pillars 34, 35, 44 and 45 at Convergence Station 25. At the latter, the last reading taken 2.5 weeks prior to the fall indicated a convergence of 1.6 inches. This convergence had taken place over a two week period in August. The occurrence of a fall at this location was not particularly surprising given the rate of closure. Even so, there was no assurance to the observer that a fall would occur before the adjoining pillars were extracted. By general appearance, the two places that failed were no different from others where the total convergence was only an inch or two.

REAR ABUTMENT: GOB AREA

Convergence in the gob area as the retreat line traversed the panel was not always so gradual as in the area where pillars awaited extraction. Convergence in the gob took one of three basic forms, as viewed from the row of pillars nearest the gob:

- a. Continuation of the roof line from the area awaiting pillar extraction for an indefinite distance into the gob area with no perceptible downward movement (Figure 6.12A). This condition--apparently temporary and observed primarily during extraction of the first three rows of pillars--was promoted by occasional remnant coal pillars and by the nearby barrier pillars along the boundaries of the mine panel;

A



B



FIGURE 6.11 PHOTOGRAPHS OF CRACKS IN MINE ROOF
A. TENSILE CRACKS NEAR MIDSPAN OF INTERSECTION
B. EXPOSED FACE OF 'CUTTER' IN ROOF DIRECTLY ABOVE PILLAR FACE

NORMALIZED DISTANCE BETWEEN CONVERGENCE STATION AND RETREAT LINE X/H

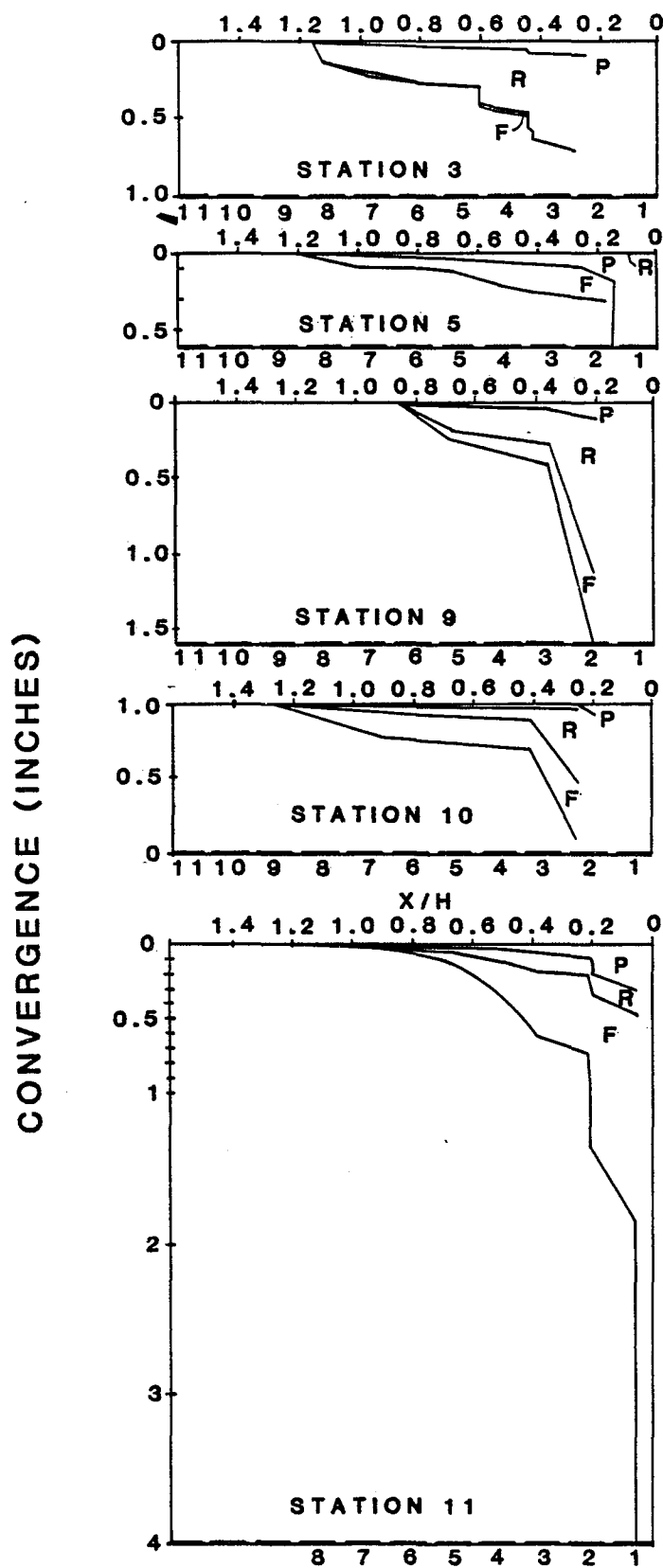


FIGURE 6.12
CONTRIBUTIONS OF ROOF, FLOOR AND PILLARS TO
CONVERGENCE AT FIVE STATIONS

- b. Downward flexure of the mine roof in a smooth arc extending from atop the coal pillars to the floor 20 to 30 feet beyond the retreat line (Figures 6.12B and 6.13A); or
- c. Collapse of the mine roof resulting in an abrupt, complete closure of the mine entry (total convergence) at the pillar line (Figure 6.12C and 6.13B).

The form of convergence occurring along the length of a particular entry sometimes changed with successive positions of the retreat line--for example, from no perceptible movement to flexure to collapse.

Overall, roof collapse was the most common form of convergence in the gob area and was doubtlessly promoted by the presence of fractures that had developed in the roof strata during the mining process. Obviously, observations of convergence during this program were confined to the relative movement of the immediate mine roof and the mine floor; there is no assurance that these were necessarily representative of movements of rock strata further above the mine opening, which were hidden from view. Determination of these movements requires independent measurements that are described in a subsequent section of the report.

REAR AND SIDE ABUTMENTS: PERMANENT (VENTILATION) ENTRIES ALONG THE PERIMETER OF THE MINE PANEL

Convergence in the permanent entries occurred much like in the area awaiting pillar extraction and consisted of deflection of the pillars, the mine roof and the mine floor. For obvious reasons related to panel geometry, convergence did not always bear the same relationship to position of the retreat line along the perimeter areas as in the area awaiting pillar extraction (Figure 6.6).

Owing apparently to the wet floor conditions and high abutment pressures acting along the south ventilation entries for an extended period of time, a greater proportion of convergence along the south ventilation entries consisted of floor heave and roof deflection. For apparently the same reason, the rate of convergence relative to stress increase in neighboring pillars was much greater in the ventilation entries than in the area awaiting pillar extraction. Floor heave is clearly seen in Figure 6.5B, a photo view near Station 17 in the south ventilation entries adjacent to the barrier pillar. Note how conventional roof support was augmented by cribbing in an effort to maintain the entries.

The maximum convergence measured in the ventilation entries was 5.6 inches, recorded at Station 17 in early December, 1982. (This was the last reading obtained.) Convergence measured in the ventilation entries along the east side of the panel (Stations 14 and 15) approached or exceeded 2 inches by January, 1983, when the panel was sealed off and by now has presumably been exceeded at this and other locations in the ventilation entries.

A



B

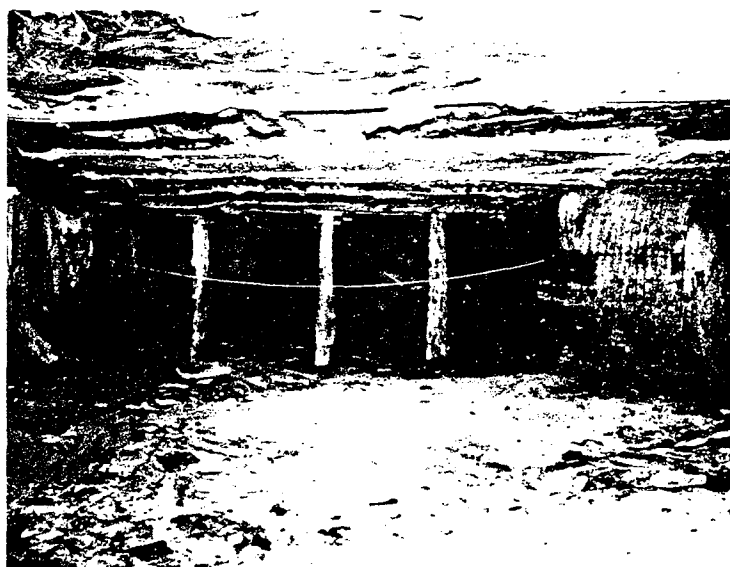


FIGURE 6.13 PHOTOGRAPHS OF CONVERGENCE IN GOB AREA

- A. CLOSURE BY ROOF FLEXURE
- B. CLOSURE BY ROOF COLLAPSE

7.0 OVERBURDEN MOVEMENTS

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General Characteristics of Overburden Movements	109
Inclinometer Observations Station-by-Station	110
Deformation Mechanisms	120

INTRODUCTION

The overburden during full extraction mining is often envisioned in terms of three zones, based on mode of deformation (Peng and Chiang, 1984):

1. The caved zone--the interval extending from the top of the coal to a height 2 to 8 times the mined thickness of coal, where the immediate roof collapses to the mine floor, breaks and bulks to a volume somewhat larger than its original volume.
2. The fractured zone--the interval extending from the top of the caved zone to a height 30 to 50 times the mined thickness, where the strata are envisioned as a series of beams decoupled from one another along bedding surfaces and formed of blocks bounded by vertical fractures and bedding surfaces.
3. The continuous deformation zone--the interval extending from the top of the fractured zone to ground surface, where the strata are envisioned as a continuous beam, without major cracks.

In an attempt to define these (or other) zones in the overburden above the C-3 panel, three types of instruments were installed in four 550-foot deep drill holes whose locations are shown in Figure 4.3:

1. Time domain reflectometry cables to identify locations at depth where significant vertical or horizontal deformations had taken place.
2. Multiple position borehole extensometers (MPBX) and Sondex markers to measure vertical differential movements of the strata;
3. Inclinometer casing to measure lateral differential movements of the strata.

Details of the instrument installation are discussed in Section 4. Specific instrument configurations in each drill hole are summarized in Table 4.1.

As retreat mining and monitoring progressed, it became apparent that the sandstone, siltstone, shale, claystone and coal units could be characterized as a sequence of weakly bonded plates of differing thickness and mechanical properties supported on a foundation of coal pillars. Progressive withdrawal of this support by mining resulted in

the downward flexure of the strata into the mined-out area, accompanied by lateral slippage and fissuring. The lateral slippage was so pronounced even from the beginning of retreat mining as to clamp if not shear off the MPBX wires, rendering the MPBX systems inoperative for the measurement of vertical strata movements. The backup--the Sondex system--was similarly rendered inoperative by lateral dislocations of the inclinometer casing, which limited the Sondex probe to successively shallower depths as retreat mining progressed. Any vertical differential movements of the strata that may have taken place during retreat mining were located below the depth to which the Sondex probe could penetrate.

Information provided by the TDR installations was largely ambiguous. The several breaks that developed in the TDR cables during retreat mining could not be attributed with certainty to any specific cause--shearing, bedding separation, crushing--nor with any definable amount of movement. Thus, information concerning deformation of the overburden was provided primarily by the inclinometers, although they too were limited to successively shallower depths as retreat mining progressed.

GENERAL CHARACTERISTICS OF OVERBURDEN MOVEMENTS

The following behavioral characteristics of the overburden were evident from the inclinometer observations:

1. The sequence of strata movements was much the same at all four inclinometer stations, although differences in detail were evident.
2. The differences in detail appeared to be due to the progressive nature of the deformation process and to the relative instrument positions within the panel.
3. The overburden deformation process consisted variously of flexure (bending and rotation of rock strata), displacement (differential slippage of rock strata) and presumably fracturing, including bedding separation.
4. In view of these deformation processes, the existence was suggested of two major zones overburden--a lower zone above the mined-out area where the rock strata had displaced laterally, bent downward, separated along bedding surfaces and sometimes failed; and an upper zone extending to ground surface from the top of the first zone, where displacement and flexure took place, but where, it is suspected, bedding plane separation and significant fracturing were absent. The thickness of the upper zone may have lessened as mining progressed.

Strata movements common to all four inclinometer stations were these:

1. As the retreat line approached, but was still several pillar rows distant from an inclinometer station, the overburden began to rotate downward more or less monolithically into the area that had been mined out.
2. By the time the retreat line lay approximately one pillar row from an inclinometer station, rock strata within 100 to 200 feet of mine level had shifted laterally toward the mined-out area, the movement being concentrated in zones spaced at 20- to 50-foot vertical intervals.

3. As pillars were extracted in the same row as an inclinometer, the overburden rotated in the vertical plane of the pillar row as the support points changed and the overburden span increased. At the same time, lateral displacements of the strata continued to increase at lower elevations and became more pronounced higher in the overburden, some of them within 100 feet of ground surface. Rotation of the overburden toward the mined-out area also increased.
4. As extraction progressed beyond the inclinometer station, overburden rotations and lateral displacements increased still further. The greatest depth to which the inclinometer sonde could pass became progressively less, finally becoming no more than 60 to 100 feet at the completion of retreat mining. This apparently resulted from excessive lateral dislocations of the casing and from separations of the casing at certain horizons. The precise cause generally could not be determined.

INCLINOMETER OBSERVATIONS STATION-BY-STATION

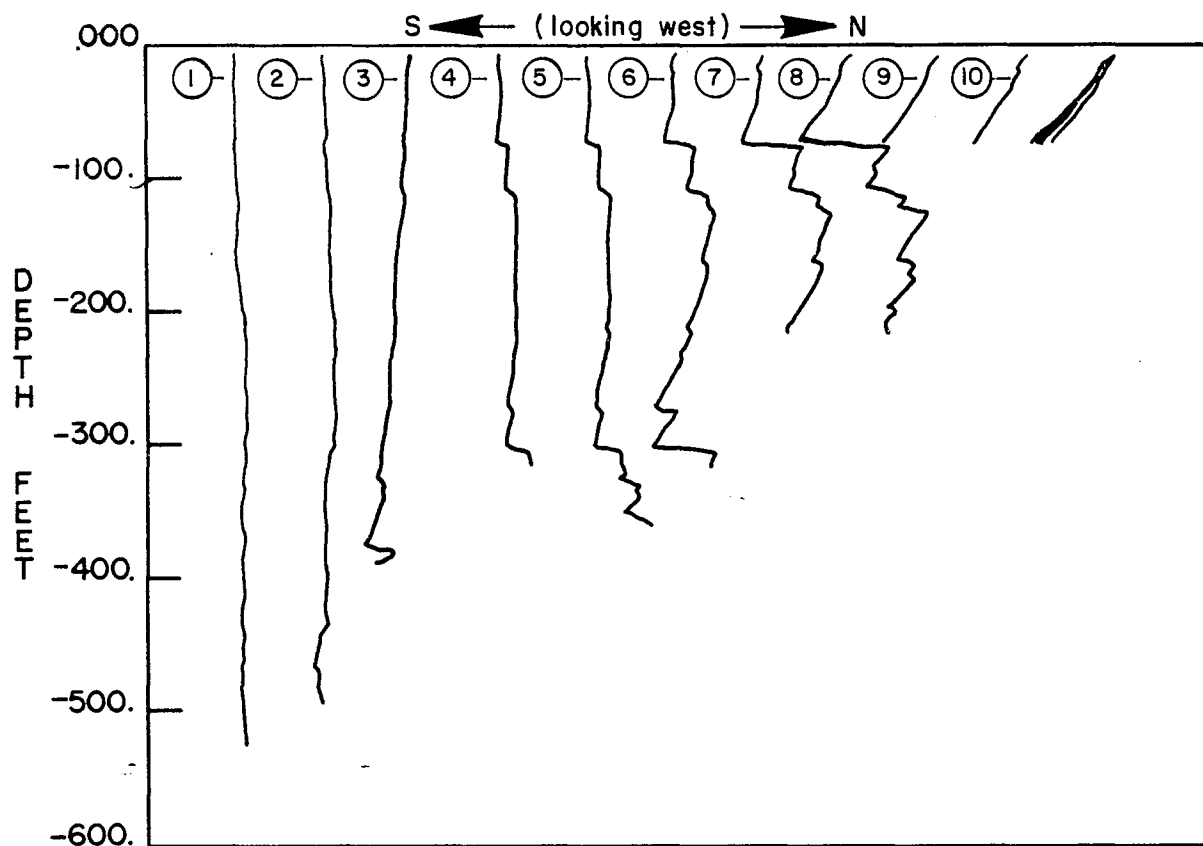
Casing deflections at each of the four inclinometer stations illustrate these characteristics in more detail. Figure 7.1 presents profiles of the lateral displacements for each instrument by survey based upon measurements made at five foot intervals of depth. Displacements are resolved into components parallel to retreat mining (looking west) and transverse to retreat mining (looking north).

Inclinometer 1 in Boring D1 is located above an entry at a distance two extraction pillars and one ventilation pillar east of the solid coal and four pillars from the south end of the C-3 panel. (Refer also to Figures 2.5A, 4.3, and 7.1A).

Inclinometer Survey (IS1), August 20--To this date, only six pillars had been extracted from the panel, all to the south and east of the inclinometer. Subsidence was not yet measurable by ground survey. Deflections of the inclinometer casing were still slight and changes in slope of the casing were barely discernable. A rather pronounced displacement took place in the 466-476 foot depth interval near the boundary between two shale units. This displacement seemed to indicate an eastward shift toward the mined-out area of rock strata below a depth of 466 feet and a downward rotation to the east.

IS2, September 2--Extraction had extended northward beneath, but not yet beyond, the inclinometer. Lateral movement had continued primarily eastward toward the mined-out area along several discrete zones below a depth of 400 feet (within 200 feet of mine level). Dislocations were primarily in shale zones and along the Upper Freeport and Lower Freeport Coal horizons. The inclinometer sonde could not pass below a depth of 496 feet, which may or may not have been caused by a casing separation at this level (a shale horizon). No subsidence had yet been measured.

IS3, September 30--Extraction had progressed beneath the inclinometer and to the second pillar row beyond (north). The first subsidence had been measured (about 0.50 inch). Overall, the inclinometer casing had tilted 0.016 degree to the vertical in the north-south plane and 0.0025 degree in the east-west plane, indicating a downward deflection of the strata to the northeast of the inclinometer. Casing was impassable by the sonde below a depth of 391 feet (shale near a sandstone interface). The zone of pronounced lateral displacements had reached a depth of 300 feet (a claystone).



EAST-WEST DISPLACEMENT TRANSVERSE TO MINING

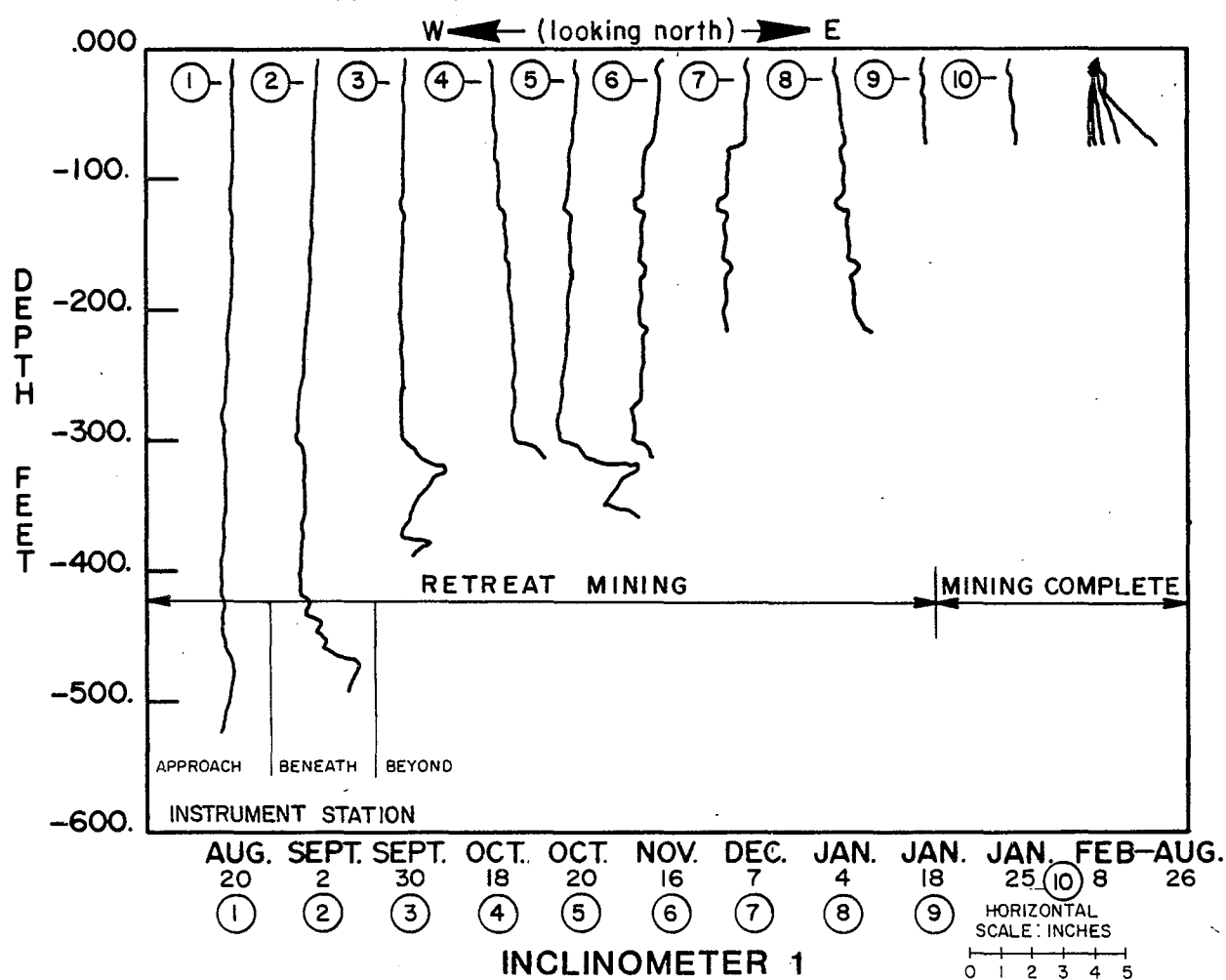


FIGURE 7.1A INCLINOMETER PROFILES AT VARIOUS STAGES OF RETREAT MINING

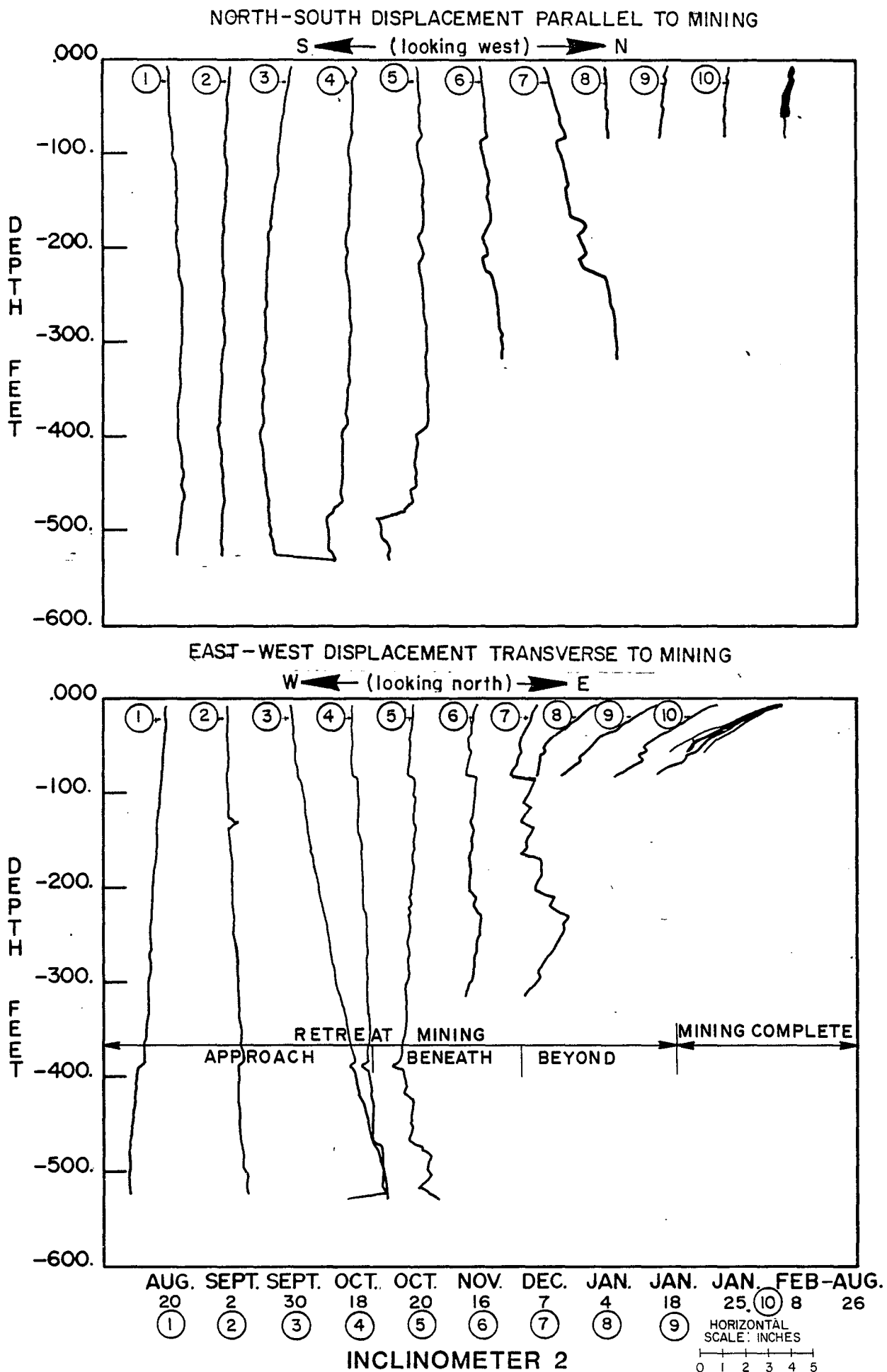
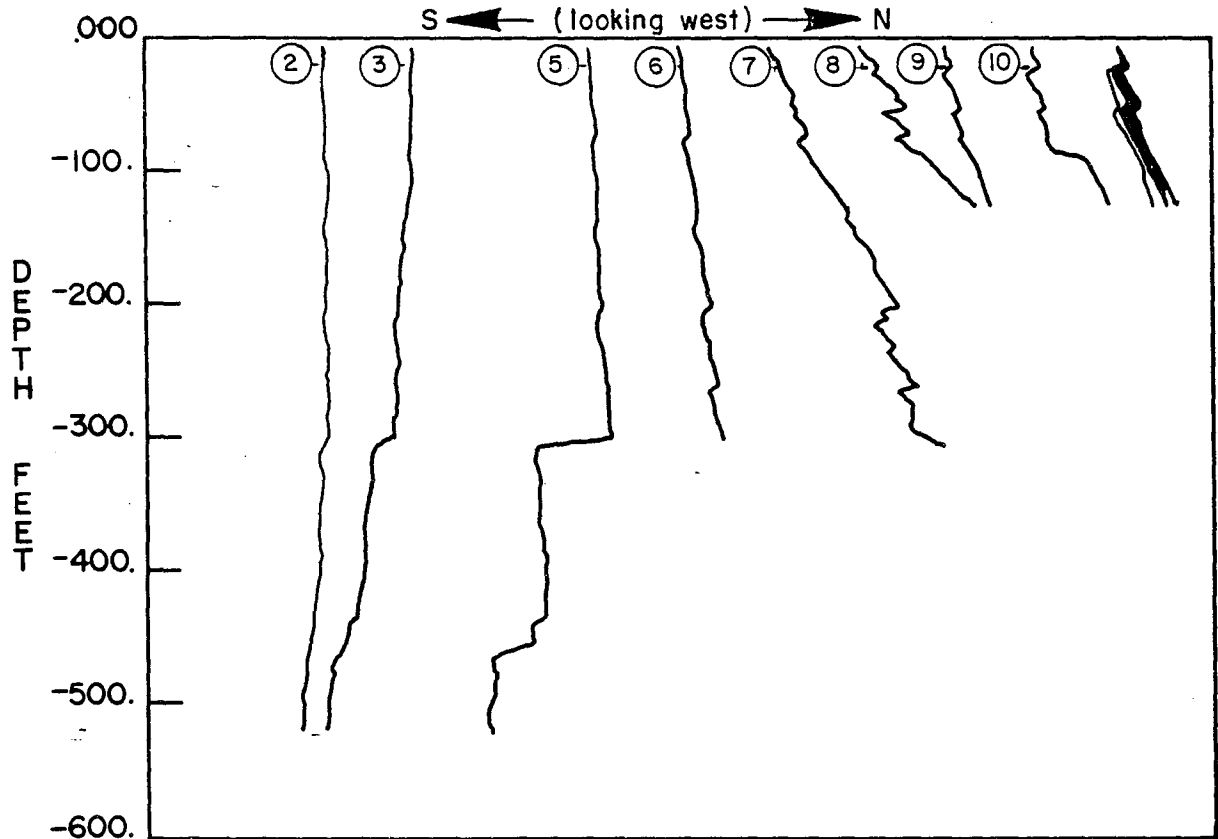


FIGURE 7.1 B INCLINOMETER PROFILES AT VARIOUS STAGES OF RETREAT MINING



EAST-WEST DISPLACEMENT TRANSVERSE TO MINING

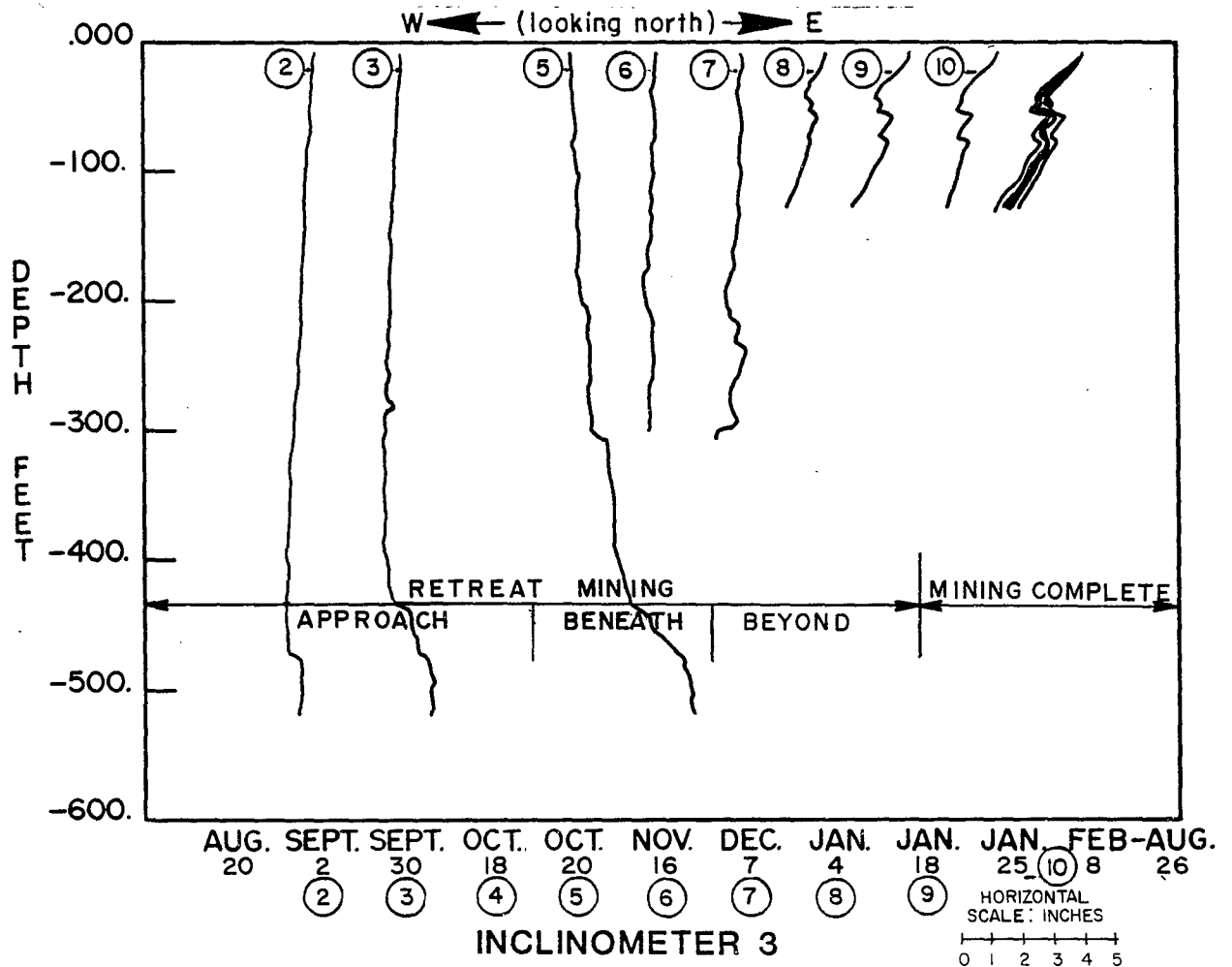


FIGURE 7.1C INCLINOMETER PROFILES AT VARIOUS STAGES OF RETREAT MINING

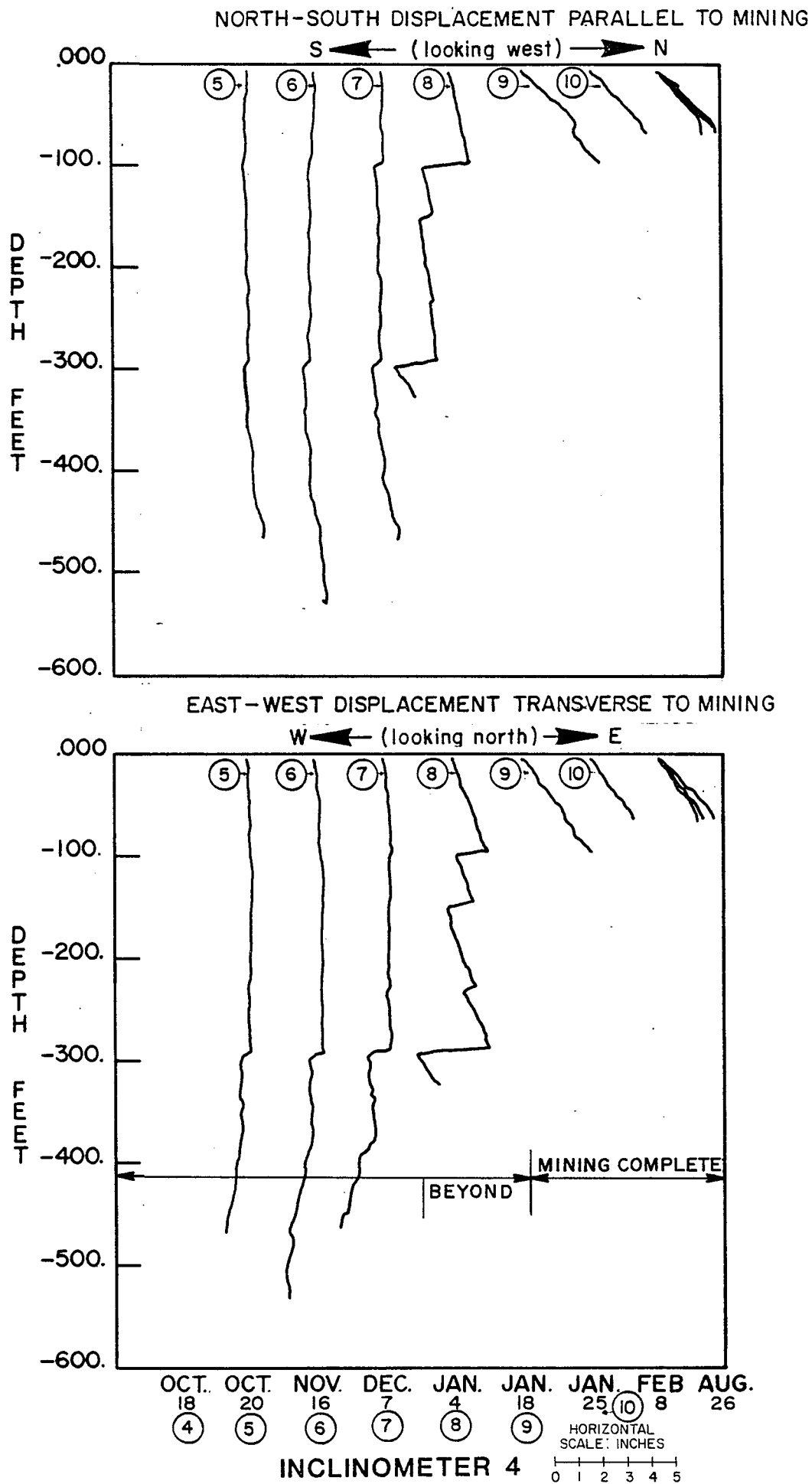


FIGURE 7.1D INCLINOMETER PROFILES AT VARIOUS STAGES OF RETREAT MINING

IS4, October 18--Extraction had progressed to the third pillar row beyond (north of) the inclinometer. The casing had become impassable below a depth of 316 feet (a claystone). Pronounced lateral displacements could now be recognized to within 71 feet of ground surface. The strata continued to deflect downward to the north as before, but now also to the west.

IS5, October 20--Extraction had progressed four additional pillars to the east in the third pillar row beyond the inclinometer. Strata realigned to the extent that the inclinometer sonde could once again reach a depth of 356 feet, 40 feet deeper than during IS4, two days earlier. Strata continued to displace, largely at horizons where movements had occurred earlier. At the 111-116 foot depth interval, a reversal of lateral displacement had occurred, as indicated by the "C"-shaped hook in the north-looking profile. The strata continued to deflect downward to the north, but now also to the east rather than to the west, apparently in response to translation of the center of the span farther east to the opposite side of the inclinometer.

IS6, November 16--Extraction had progressed three full pillar rows beyond the inclinometer. The casing once again became impassable below a depth of 316 feet. Lateral displacements had become much pronounced at higher elevations, and the casing had adopted a distinct curvature, apparently the result of increasing tilt of the strata downward to the northeast. Additional reverse lateral displacements had become apparent in the 161-171 foot depth interval, as well as near the 216 and 300 foot depths.

IS7, December 7--Extraction was underway in the fifth row beyond the inclinometer. Displacements had continued much as observed during IS6, but were sufficiently large at the Bakerstown Coal horizon (216 foot depth) to prevent passage of the inclinometer sonde.

IS8, January 4, 1983--Extraction had progressed to the sixth pillar row beyond the inclinometer. The casing remained passable to a depth of 216 feet, although lateral displacements had increased at the horizons identified earlier. The northward tilt of the strata became more pronounced, but tilt in the east-west plane had now shifted to the west.

IS9, January 18--Extraction had reached six full pillar rows beyond the inclinometer and was now complete. Tilt was strongly northward, with virtually no component to the east or west. The casing had become impassable beyond a depth of 71 feet.

IS10, January 30 forward--Over the seven months of monitoring following the completion of mining, the tilt increased slightly to the north as well as to the east, reflecting the time-dependent deepening of the subsidence trough, that is, residual subsidence.

Inclinometers 2-4 responded to mining much the same as Inclinometer 1, the differences in direction and magnitude of movement being apparently due to the particular position of the instrument in relation to the boundaries of the area being mined. Movements recorded by them are briefly described below.

Inclinometer 2 is located one extraction pillar and one ventilation pillar from the west (solid) boundary of the panel and seven pillars from the south corner where pillar retreat began (Refer to Figures 2.5B, 4.3 and 7.1B).

With retreat mining still three to four rows from the inclinometer (IS1, August 20), the strata appeared to be deflecting downward to the south and east in the direction of the mined-out area. Later (September 2, September 30 and October 18), slight displacements occurred to the south and west as the retreat line approached, and a marked swing of the casing had taken place by September 30, when subsidence was first measured. As extraction progressed in the pillar row due south between the instrument and the gob (October 18), southeastward lateral movements took place in a few zones near and below the 400 foot depth, as well as near the 100 foot depth. With pillar extraction taking place directly beneath the instrument (October 20), lateral displacements to the southwest became much more pronounced along the zones identified on October 18, and were now measured along several new zones as well. Overall tilt of the strata changed from northwest to southeast. As retreat mining began in the first pillar row beyond the instrument (November 16), the inclinometer casing was found impassable below a depth of 316 feet, eliminating from survey the lowermost 200 feet of casing traversed in the preceding (October 20) survey. Displacement zones not observed earlier had become apparent near the 200 foot depth. By December 7, pillar extraction was progressing in the second pillar row beyond the instrument. Pronounced displacement zones had developed at depths between 80 feet and 316 feet, the latter representing the bottom of the open length of casing. Lateral movements appeared to be southeastward. By January 4, as retreat mining neared completion, the casing had become impassable below a depth of 86 feet. The 86-foot uppermost section of casing continued to tilt eastward, but now only very slightly southward. After mining had been completed (January 18 forward), eastward tilt increased slightly and was joined by a northward component. Thus, displacements of the strata appeared to respond to progress of mining--tilting first to the southeast, then to the northwest, then to the southeast and finally to the northeast, all accompanied by lateral displacements at various horizons as documented above.

Inclinometer 3 is located near the center of the panel, five pillars from the west (solid) boundary and seven pillars from the south end of the panel (Refer to Figures 2.5C, 4.3 and 7.1C).

Strata movements recorded by Inclinometer 3 were very similar to those described for Inclinometers 1 and 2. By September 2, retreat mining had approached no closer than three pillar rows to the instrument. An overall eastward tilt of the strata had become evident, as had a southward lateral movement of the lowermost 300 feet of strata. By September 30, with retreat mining approaching in the second row from the instrument, displacements had continued southeastward toward the mined-out area along trends established earlier. By October 20, pillar extraction had begun to the west of the inclinometer in the row separating the inclinometer from the gob. Southeasterly lateral displacements had become increasingly pronounced, and the tilt of the strata had become southwesterly, evidently in response to the pillar extraction immediately west. Notably, these displacements for Inclinometer 3, located near the center of the panel, were much more pronounced for corresponding positions of the retreat line than were the displacements measured by Inclinometers 1 and 2, located near the west side of the panel. By November 16, the retreat line lay directly beneath the inclinometer, and retreat mining had begun from the west in the first row beyond (north of) the inclinometer. The casing had become impassable below a depth of 300 feet (claystone near a shale interface), where significant lateral displacement had earlier taken place.

Tilt of the overburden had increased somewhat in a southerly direction toward the mined out area, but had changed from westerly to easterly along the row being mined,

evidently in response to an eastward transfer of the center of deflection of the strata as the mined-out width of the pillar row increased. By December 7, retreat mining was progressing in the second pillar row beyond the inclinometer. Tilting had continued in a southeasterly direction, the greatest increase being in the southerly component. The same trend continued up to and beyond the completion of mining, although from January 4 forward, the casing became impassable below a depth of 131 feet.

Inclinometer 4 is located toward the northeast corner of the panel in a location reached only in the latter stages of retreat mining. (Refer to Figures 2.5D, 4.3 and 7.1D).

Movement that had taken place by October 18, when retreat mining was approaching in the third row south of the inclinometer, was limited primarily to small southerly displacements and the downward deflection of strata to the west of the instrument, both below 300 foot depth. By November 16, with pillar extraction approaching within two rows of the instrument, casing movements continued along the trends established earlier. By December 7, with extraction approaching in the row directly in front of the instrument, a visible displacement had occurred as shallow as 100 feet. By January 4, extraction had progressed directly beneath and to the first row beyond (north of) the instrument, and the casing had become impassable below a depth of 326 feet (claystone near a shale interface). Southwesterly displacements as great as 2.5 inches had taken place in several zones below the 100 foot depth, correlating with a shale/shale interface, with claystone near an interface with the Harlem Coal, with siltstone and with sandstone near a shale interface. By January 18, pillar extraction had progressed two rows beyond the inclinometer and mining was complete. Only the uppermost 96 feet of the casing could be monitored and this section had become more steeply tilted to the southwest--toward the center of the subsidence trough. By the time subsequent surveys were conducted, the casing had become impassable below a depth of 66 feet. As time passed, this section of the casing tilted slightly farther to the southwest.

A plan view of lateral inclinometer deflections furnish further insight into overburden movements during retreat mining. Lateral deflections recorded by Inclinometer 1 are shown in Figure 7.2. The instrument traces are convoluted from the many changes in direction taken by the casing as it responded to displacements of the strata. Interpretation of these traces is made more difficult by the progressive shortening of the casing during retreat mining. Even so, close examination of the data reveals a pattern of movements. Consider, for example, the 106-126 foot depth interval--20 feet of sandy shale bounded at its base by the Harlem coal in contact with a claystone--an interval that in the latter stages of mining is demarcated in Figure 7.1A by distinct knickpoints at top and bottom. Figure 7.3 presents a plot of differential displacement of the base of this interval relative to the top of the interval (holding the top of the interval stationary) and reveals that motion was first southerly toward the initial extraction, then easterly as pillars alongside were removed, and later increasingly more northerly as the retreat line moved toward the mains (Figure 7.3).

A vectorial, interval-by-interval presentation of the remainder of the data would reveal additional characteristics of the ground movements, as would a presentation of data in terms of absolute displacements, where movements of both overlying strata and collar of the hole are taken into account.

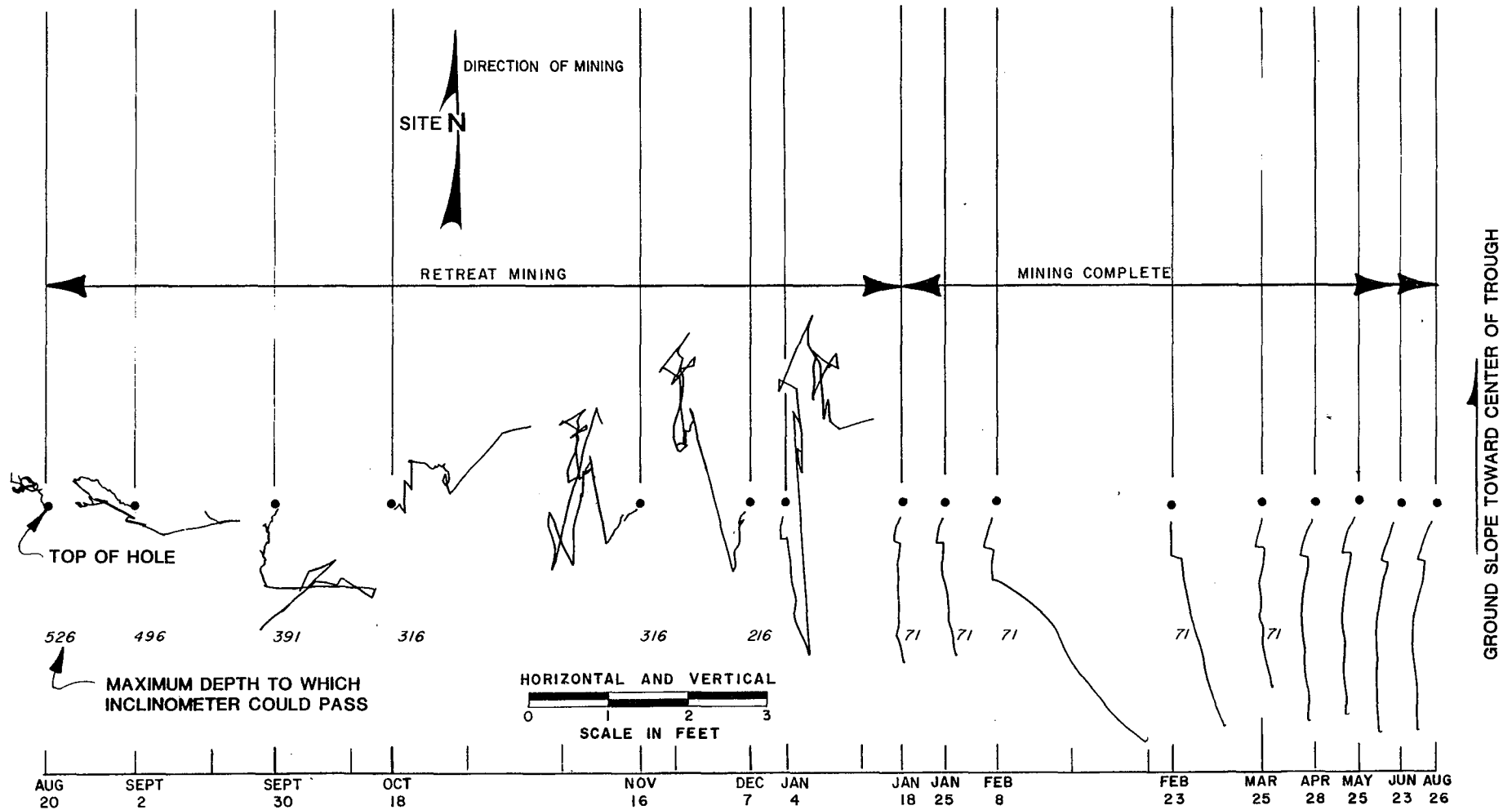
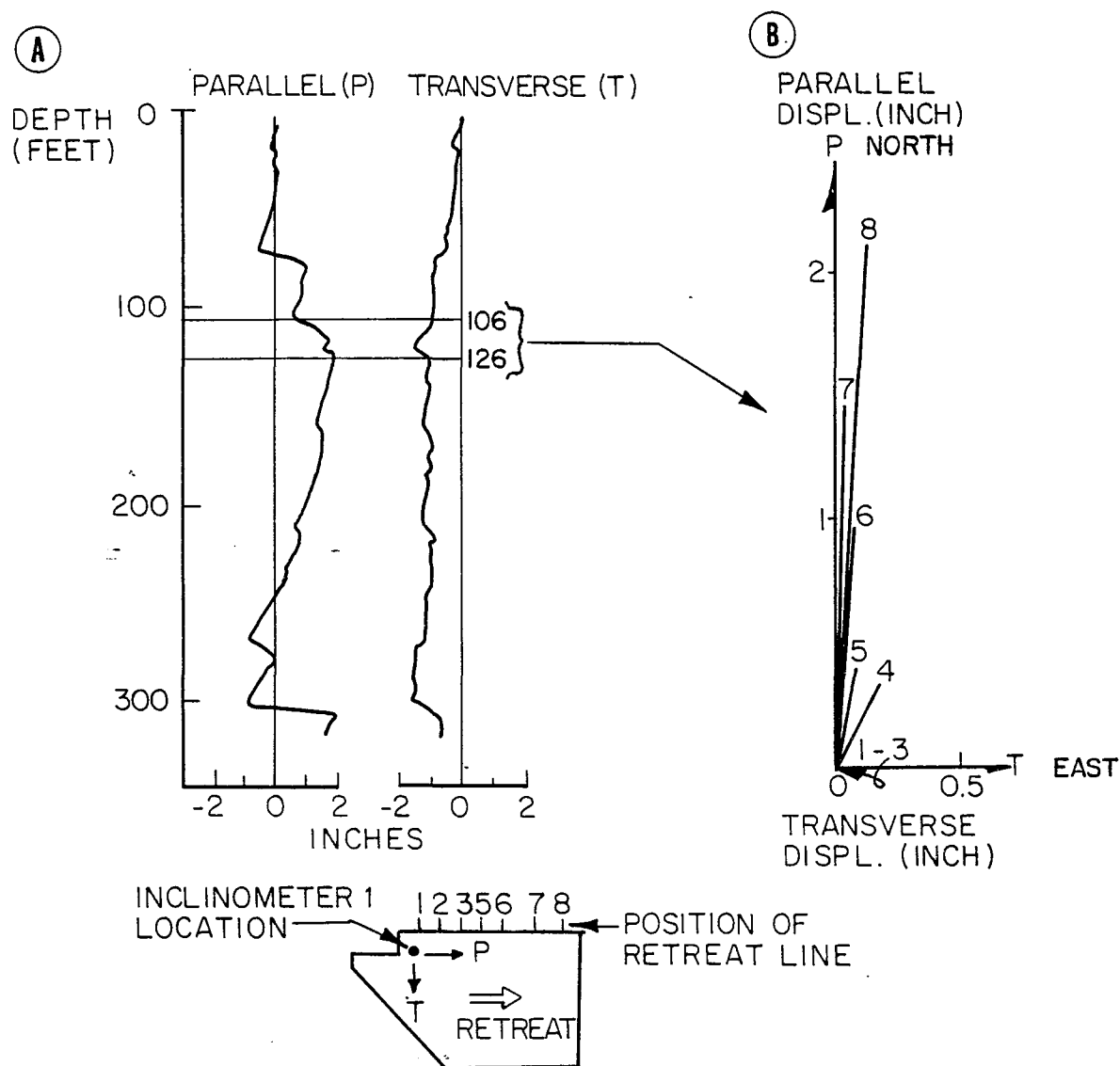


FIGURE 7.2 LATERAL MOVEMENTS AT INCLINOMETER 1 RECORDED IN A SERIES OF PLAN VIEWS AT VARIOUS STAGES OF RETREAT MINING



- NOTE: 1) REFERENCE NUMBERS IN PLAN VIEW SHOW POSITION OF RETREAT LINE AT VARIOUS STAGES OF RETREAT MINING
- 2) FIG. A SHOWS VERTICAL PROFILE REPRESENTATIVE OF A SINGLE POINT IN TIME
- 3) FIG. B SHOWS VECTORS OF HORIZONTAL MOVEMENT OF THE BASE OF THE 106-126 FOOT DEPTH INTERVAL IN RELATION TO THE TOP OF THAT INTERVAL (HELD STATIONARY)

FIGURE 7.3 RELATIVE DIFFERENTIAL DISPLACEMENT OF ROCK STRATA PARALLEL AND TRANSVERSE TO THE DIRECTION OF MINING, DEPTH 106-126 FT. , INCLINOMETER 1.

DEFORMATION MECHANISMS

As alluded to above, deformation of the overburden during retreat appears to have taken place by displacement along bedding planes and other surfaces of weakness, and by flexure and block rotation, probably accompanied by separation along bedding planes and fracturing.

The surfaces of weakness along which lateral movements were concentrated, were common throughout the overburden, developing at vertical intervals of 3 to 50 feet, often along bedding planes such as shown in Figure 7.4 for Inclinator 1.

In recognition that the inclinometer casing was installed perpendicular to bedding surfaces and, being grouted in place, remained so during mining, the occurrence of bedding plane separations above the mined-out area is suggested at locations where the inclinometer casing adopted a pronounced curvature toward mine level, such as shown in Figure 7.1A, Transverse Displacement, August 20. If this interpretation is correct, then a zone of bedding separation trailed the retreat line and may have reached an inclinometer station after the retreat line had progressed a few pillar rows beyond the station.

Casing breaks at bedding separations are believed responsible for blocking passage of the inclinometer sonde, particularly at lower elevations. Obviously, significant casing separations had not occurred within any interval through which the inclinometer passed; and if the casing had not separated, then the strata had not separated since the casing was grouted to the rock. Figure 7.5 presents a vertical section through Inclinator 1, 3 and 4, marked for each survey, with lines connecting the lowest points to which the sonde could pass in each inclinometer casing. According to this rationale, bedding separations would not have been present above each line, but may have been present at or below. It is probable that many of the casing obstructions preventing passage of the inclinometer sonde represented offsets along bedding planes or surfaces of weakness that were still in contact. As will be discussed in the next section, the fact that the Mahoning Sandstone at 350 foot depth was dewatered by retreat mining, whereas the shallower Buffalo, Saltsburg and Lower Connellsville Sandstones were not, may be evidence that the boundary between strata having separations and those not lies roughly at mid-depth in the overburden. A core drilling and borehole TV investigation would be required to more precisely define any boundary between these two zones.

The overburden response to retreat mining is further considered in Section 8, where mining related changes in the piezometric levels are discussed, along with changes in the hydraulic properties of four sandstone strata.

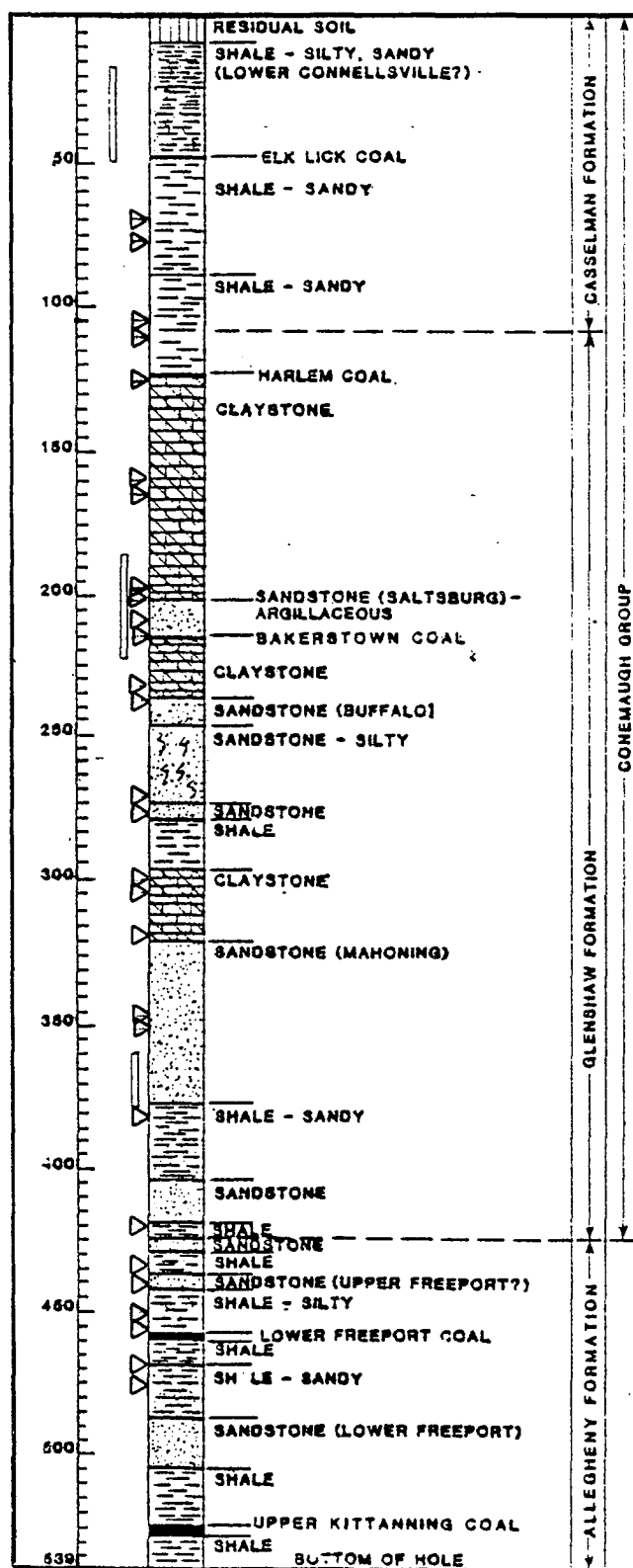


FIGURE 7.4 LOCATIONS OF ZONES OF PROMINENT LATERAL DISPLACEMENTS IN D1 (DENOTED BY ▷)

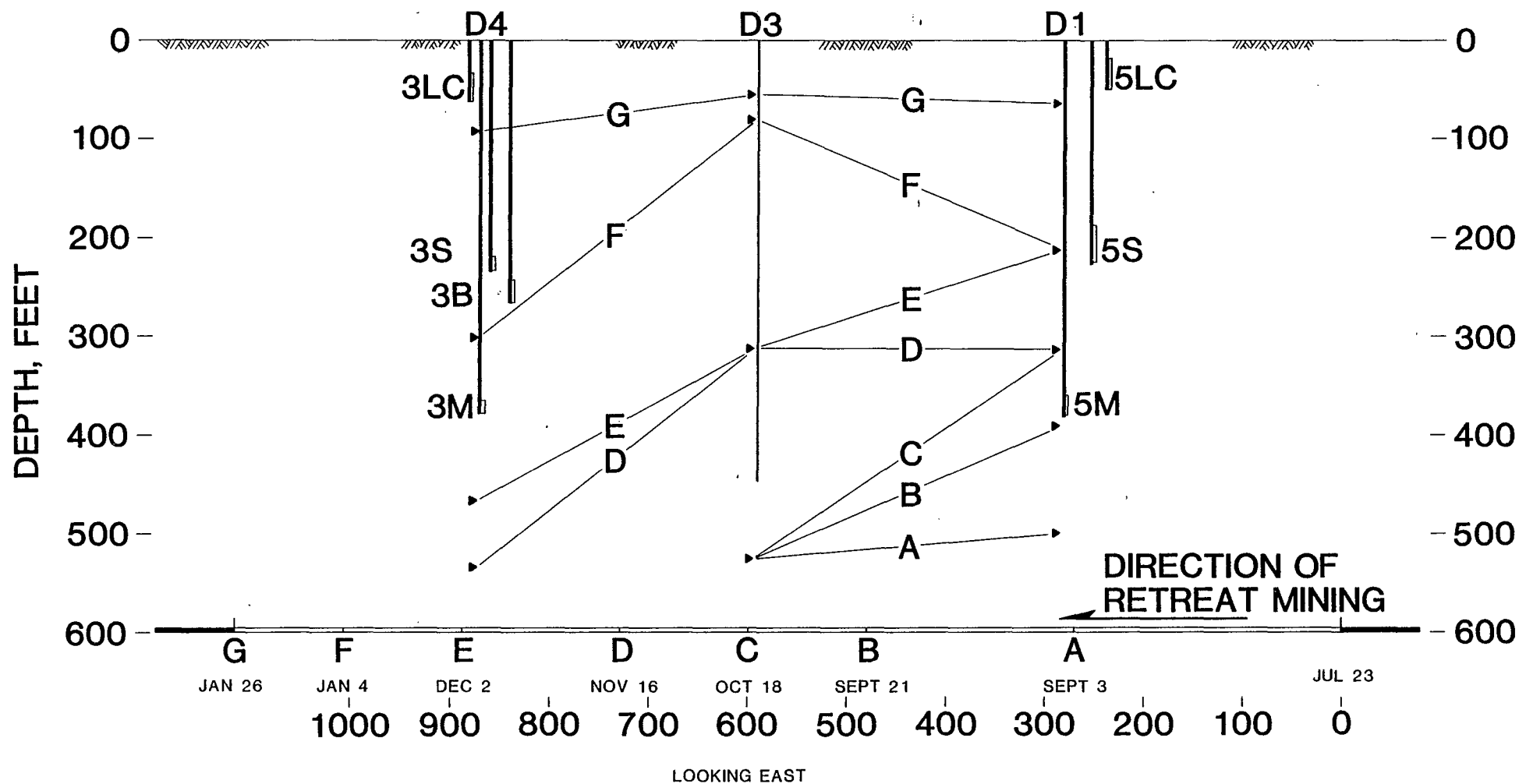


FIGURE 7.5 RELATIONSHIP OF MAXIMUM PENETRATION OF INCLINOMETER SONDE TO STAGE OF RETREAT MINING

8.0 GROUND WATER

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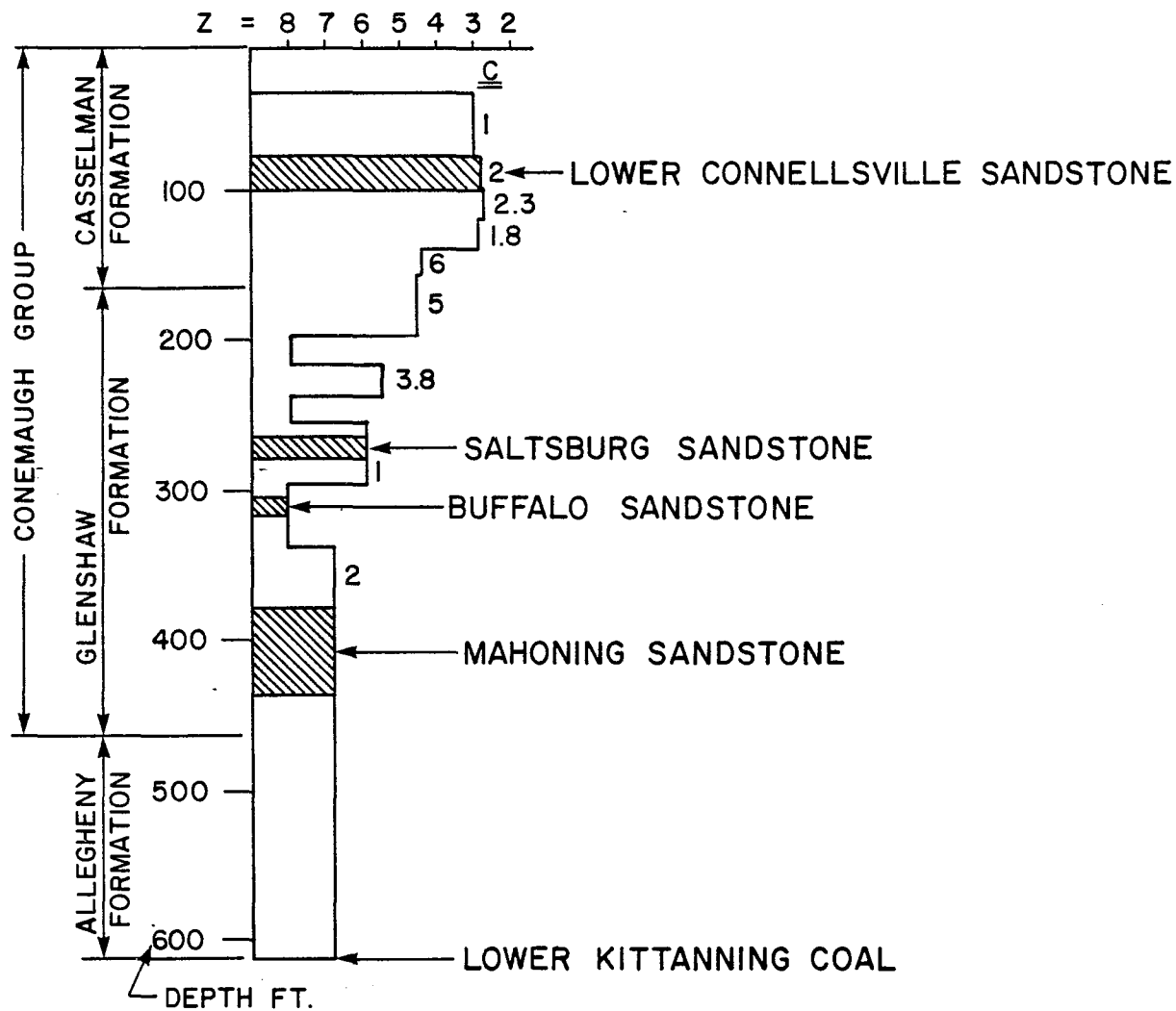
INTRODUCTION

The C-3 mine panel and surrounding area have been virtually unaffected by mining-related surface activities. Land has been used primarily as pasture and woodland. In the past, perennial grasses have been cultivated for cattle feed over about twenty five percent of the area. Farming has not been practiced at the site in recent years.

The nearly flat-lying, overburden strata of the Pennsylvanian-age Allegheny, Glenshaw and Casselman Formations--an alternating sequence of claystone, shale, sandstone and siltstone units, with a few thin coal seams--outcrop in eastern Barbour County and, because of dip, bedding and topography, are subject to recharge from precipitation and surface water.

As determined by a contiguous series of packer tests conducted by GAI and Kitt Energy in a 3-inch diameter boring approximately 2000 feet south of the C-3 panel in association with construction of a shaft (Figure 8.1), the top 150 feet of rock strata are relatively pervious, having hydraulic conductivities on the order of 10^{-3} cm/sec. (1 cm/sec = 1.97 ft./min.). This interval of shales, claystones, sandstones and siltstones includes the 25-foot thick Lower Connellsville Sandstone, a local source of water that lies within 50 feet of ground surface. Wells in the Lower Connellsville Sandstone reportedly yield 15 to 20 gallons of water per minute.

Below the relatively pervious upper zone and extending to a depth of about 300 feet (half the depth to the mine) is an interval of claystones, sandstones and shales having hydraulic conductivities between 10^{-4} and 10^{-8} cm/sec, one to five orders of magnitude less than those in the upper zone.



$$\text{HYDRAULIC CONDUCTIVITY (CM/SEC)} = C \times 10^{-Z}$$

NOTE:

- VALUES OF Z ARE GIVEN BY THE TOP HORIZONTAL SCALE.
- VALUES OF C ARE LISTED ALONGSIDE THE RESPECTIVE STRATA.

FIGURE 8.1 PROFILE OF HYDRAULIC CONDUCTIVITY FROM TOP OF ROCK TO MINE LEVEL DETERMINED BY A SERIES OF PACKER TESTS IN A BOREHOLE 2000 FEET FROM THE C-3 PANEL.

Between 300-foot depth and 600-foot depth (mine level) is an interval of sandstones, shales and claystones whose hydraulic conductivities are most often on the order of 10^{-7} cm/sec or less.

The hydraulic properties of the overburden units are governed primarily by joints and fractures whose frequency and spacing are influenced by lithology and vary laterally as well as vertically within a particular stratum. Because these discontinuities often cross rock boundaries, the hydraulic properties of shale and claystone units--rock types commonly assumed to be "impervious"--may not be distinctly different, locally, from those of the sandstones, which are commonly assumed to be "pervious." Because weathering is less intense with depth and joints are less numerous and more tightly closed (prior to mining), the hydraulic properties of the rock units diminish with increasing distance below ground surface.

Objectives of the ground water study were to determine the effects of underground mining on:

1. Ground water levels (piezometric levels) in specific water-bearing strata overlying the mine panel, including the rate of piezometric level decline and rate of restoration.
2. Hydraulic properties of the rock strata, including hydraulic conductivity and storativity.
3. The rate of water inflow to the mine panel and the manner in which this inflow might be related to changes in ground water levels and hydraulic properties of the rock strata.
4. Ground water chemistry.

To observe ground water responses to pillar extraction mining, seven ground water piezometers were constructed in two clusters above the mine panel--three near Boring D-1 and four near Boring D-4 (Figure 4.3). Each piezometer tapped one of four different sandstone strata--the Lower Connellsville at 30-foot depth (570 feet above mine level); the Saltsburg at 210-foot depth (390 feet above mine level); the Buffalo at 240-foot depth (360 feet above mine level); and the Mahoning at 350-foot depth (250 feet above mine level). These are representative depths of the top surfaces of the respective sandstone strata, which are used to simplify discussions. Variations in depths and stratum thicknesses are discussed below.

The findings of the monitoring program indicate that total extraction mining produced significant water level declines in deep-lying strata but had little effect on water levels at shallower depths. Changes in hydraulic properties appear to have occurred throughout the overburden. Determination of the changes in the deep-lying strata was thwarted by rupture of the piezometer casing. Water that drained from the deep-lying strata collected in the mine workings, forming a pool whose level increased steadily throughout the monitoring program and eventually reached the main entries. Water chemistry changes that occurred during mining in the strata monitored were insignificant. These findings are elaborated on in the following paragraphs.

ROCK UNITS MONITORED

In the section of Barbour County where the Kitt Mine is located, ground water is most commonly secured from shallow sandstone units of the Pennsylvanian-age Casselman and Glenshaw formations, both of the Conemaugh Group. Yields from these units are typically low to moderate--1 to 400 gallons per minute, the average being about 16 gallons per minute (Ward and Wilmoth, 1968).

The Lower Connellsville Sandstone represents the most prominent shallow water-bearing unit in the area. The Saltsburg, Buffalo and Mahoning Sandstones represent several of the more prominent deeper water-bearing units. Strictly, only the Lower Connellsville Sandstone can be termed an aquifer in the immediate vicinity of the mine site, since it alone is used as a water supply. The Lower Connellsville sandstone ranges in thickness from 10 to 25 feet across the site. Core recovered from Boring D-5 indicates that the rock is micaceous and fine-grained near its upper boundary and medium/coarse-grained toward its base. Several 0.1- to 1.0-foot thick shale partings occur near the top of the unit. Above the southwestern portion of the mine panel (at Boring D-1), the unit is represented by a sandy shale.

The Saltsburg Sandstone is located approximately 165 feet below the base of the Lower Connellsville Sandstone. In the southern half of the site (at Borings D-1, -4 and -5), the unit varies from 8 to 11 feet in thickness and lies approximately 200 to 225 feet below ground surface. At core Boring D-5, the unit grades from a fine-grained sandstone near its upper boundary to coarse-grained at its base. At Boring D-1, the unit is argillaceous. In the northern half of the site, at Borings D-2 and D-3, the geophysical logs yield no evidence of a sandstone at the Saltsburg stratigraphic horizon. The Saltsburg Sandstone lies directly above the 1- to 2-foot thick Bakerstown coal.

The Buffalo Sandstone lies approximately 21 to 24 feet below the Saltsburg Sandstone (approximately 235 to 255 feet below ground surface) and includes a series of silty sandstones and sandy siltstones that are collectively 40 to 44 feet thick. The sandstones vary from coarse- to fine-grained. The silty sandstones and sandy siltstones are thinly laminated and interbedded.

The 35- to 60-foot thick Mahoning Sandstone lies approximately 350 feet below ground surface and is the deepest water-bearing unit that was monitored. It is located at the top of a sequence of alternating units of sandstones, siltstones and shales that extends to the 525- to 550-foot deep Upper Kittanning Coal. The Mahoning Sandstone is massive and predominantly coarse-grained throughout its thickness.

All of the monitored water-bearing units outcrop in eastern Barbour County and, because of dip of bedding and topography are subject to local surface recharge resulting from precipitation and surface waters.

PIEZOMETER (MONITORING WELL) CONSTRUCTION

Borings for the piezometers were drilled by air rotary methods. Drill cuttings assisted in determining piezometer stratigraphy as did the geophysical logs of nearby Borings D-1 and D-4. Figure 4.3 shows the location of each piezometer, identified by a number-letter combination (eg. 5LC), the number referring to the original panel (3 or 5) over which the piezometer was located and the one or two letters referring to the stratum monitored (LC=Lower Connellsville, S=Saltsburg, B=Buffalo, M=Mahoning).

Piezometers 5LC, 5S and 3LC were installed in 6-inch diameter borings and Piezometers 3S' and 3B in ten-inch diameter borings. The ten-inch diameter borings were intended to accommodate an acoustic tomography program to be conducted by the Los Alamos National Laboratory (LASL). Six-inch diameter Piezometer 3S served as a replacement for Piezometer 3S', which was found defective in its construction, and was constructed by the drilling subcontractor after cancellation of the acoustic tomography program by LASL.

Piezometers 3M and 5M were incorporated into the 6-inch diameter instrumentation Borings D-1 and D-4. Piezometers 3M and 5M utilized 3/4-inch inside diameter standpipes.

The details of piezometer construction are presented in Figure 8.2 and Table 8.1. A single interval in each piezometer was isolated for monitoring, thus distinguishing the installation as a piezometer rather than an ordinary water well, where several strata would be tapped simultaneously. After each boring was drilled, clean water was circulated through the drill rods to the bottom of the hole until the water outflow at ground surface appeared to be free of soil particles.

The bottom-most 10- to 30-feet of each PVC casing was perforated at 3-inch vertical intervals with 0.125-inch diameter holes at quarter points around the casing circumference. After installation of the PVC casing, the annulus between the borehole wall and the PVC casing was filled with clean (washed) pea gravel to within 2 feet of the top of the rock unit to be monitored. Three feet of sand was placed above the gravel zone and one foot of bentonite pellets was placed above the sand. The remainder of the hole was filled with a cement grout and bentonite slurry. The top of each standpipe was provided with a threaded cap.

The piezometers enabled (1) monitoring piezometric levels of the four strata during mining, (2) measuring hydraulic properties of the four strata, and (3) securing samples for water chemistry determinations. Each of these topics is discussed in the following paragraphs.

RELATIONSHIP OF PIEZOMETRIC LEVELS TO MINING

The piezometric level (also called potentiometric level) is the level to which water rises in a piezometer cased to a confined aquifer. The piezometric surface of a confined aquifer is an imaginary surface coinciding with the pressure level of water in the aquifer (Todd, 1980).

Piezometric levels measured in each piezometer during the monitoring program are summarized in Figure 8.3 and are reviewed below in the context of the mining sequence.

Developmental Mining (January-July, 1982).

Structurally, the overburden strata were little affected by the introduction of entries and cross-cuts into the panel. Subsidence was virtually nil. Piezometric levels remained at their pre-mining elevations except (presumably) near mine level. Measured piezometric level variations were minor and no more than might be expected from seasonal variations and the residual effects of hydraulic conductivity tests performed at various times during this period.

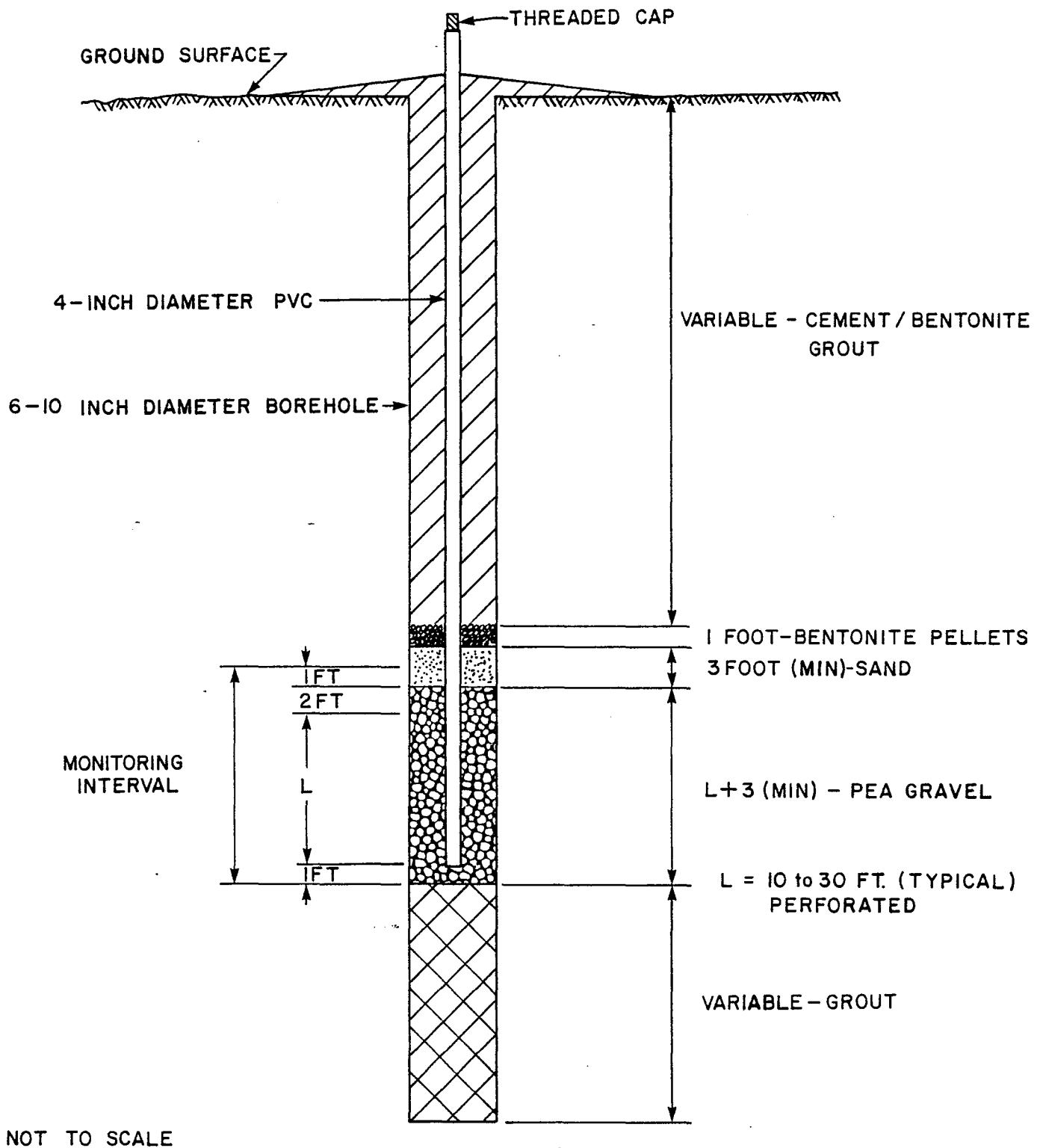


FIGURE 8.2 TYPICAL WELL (PIEZOMETER) INSTALLATION AT MINE SITE.

Table 8.1
PIEZOMETER INSTALLATIONS^x

	5LC	5S	5M	3LC	3S	3B	3M
1. Pre-Subsidence Ground Surface Elevation (feet)	1387.5	1387.3	1386.4	1430.5			1429.6
2. Diameter							
a. Drill Hole (inches)	6	6	6	6	6	10	6
b. Casing ^v (inches)	4	4	3/4	4	4	8	3/4
3. Casing Stickup above ground surface (feet)	4.7	1.5	3.67	4.1	4.6	3.7	2.5
4. Gravel Pack ^o							
a. Interval Height (feet)	32.3	35	19.3	27.5	11.3	22.0	13.5
b. Depth below ground surface (feet)	17.2-50	18.6-222	347.2-377	34-61.5	219.7-231	24.3-265	364.9-279.3
5. Screen							
a. Interval Height (feet)	30	15	5	20	9.5	20	5
b. Depth below ground surface (feet)	21.5-51.5	207-222	372.5-377.5	39.5-59.5	221.5-231	245-265	373.3-378.3
6. Bottom of Drill Hole Depth below ground surface (feet)	51.5	223.5	380.0	61.5	233.8	267.0	382.3

^xLC = Lower Connellsville Sandstone; S = Saltsburg Sandstone; B = Buffalo Sandstone; M = Mahoning Sandstone

[†]Grout: 150 gallon water + 200 lb. bentonite + 75 lb. Type I Portland Cement

^oWashed Shot Gravel (3/8" to #10); Ottawa Sand Cap (2 feet)

^v Casing: 4" diameter, Schedule 80, Threaded Flush Joint PVC for most installations

Pillar Retreat (July, 1982-January, 1983)

The extraction of coal pillars produced a redistribution of the overburden load that resulted in intensified stresses in the remaining pillars, compression of the pillars, convergence of the entries and deflection of the overburden strata.

The individual units of claystone, shale, sandstone, siltstone and coal composing the overburden appear to have behaved as a sequence of weakly bonded plates of various thicknesses and mechanical properties, supported on a grid-work of coal pillars. As this support was systematically withdrawn by pillar extraction, the strata sagged downward into the mined area, accompanied by lateral slippage and fissuring. As discussed in Section 7, slippage zones were prevalent throughout the overburden and developed at vertical intervals of 3 to 50 feet, commonly along bedding surfaces.

The progression of strata dislocations from mine level upward as the mined-out area broadened is reflected by the successively shallower depths to which the inclinometer sonde was limited as mining progressed.

The following observations are made in relation to the piezometric levels during pillar retreat (Figure 8.3). - Depths cited below reference the top surfaces of the respective strata, consistent with the figures given in the first part of this section.

1. The progression of strata dislocations from mine-level upward as the mined-out area broadened resulted in piezometric level declines, first, in the Mahoning Sandstone, 250 feet above mine level, and later, in both the Buffalo and Saltsburg Sandstones, 360 and 390 feet above mine level, respectively. Piezometric levels in the Lower Connellsville Sandstone, 570 feet above mine level, were virtually unaffected.
2. Retreat mining, in progressing south to north from ventilation entries toward the mains, passed first beneath the "5-series" piezometers (5M, 5S, 5LC) and later beneath the "3-series" piezometers (3M, 3B, 3S, 3LC), 600 feet north. Strata in the vicinity of the 5-series piezometers were disturbed earlier and consequently began draining before those near the 3-series piezometers. (In Figure 8.3, compare 3M with 5M and 3S with 5S).

Piezometric level declines in the 3-series piezometers (3M, 3B and 3S) that first became apparent two to three months after retreat mining began are thought to be the result of southward-directed lateral seepage toward the 5-series piezometers, since little strata movement occurred at the north end of the panel until the final two to three months of retreat mining. By that time, the piezometric level declines in the 3-series piezometers may have been more directly the result of seepage through fractured strata in the immediate vicinity of the 3-series piezometers. This is discussed further below.

The following observations relate the piezometric levels in the 5-series piezometers (Figure 8.3) both to position of the retreat line and to the height above mine level where the inclinometer casing positioned nearest the piezometers had ruptured (Figure 8.4), the latter being an indicator of disturbance in the overburden:

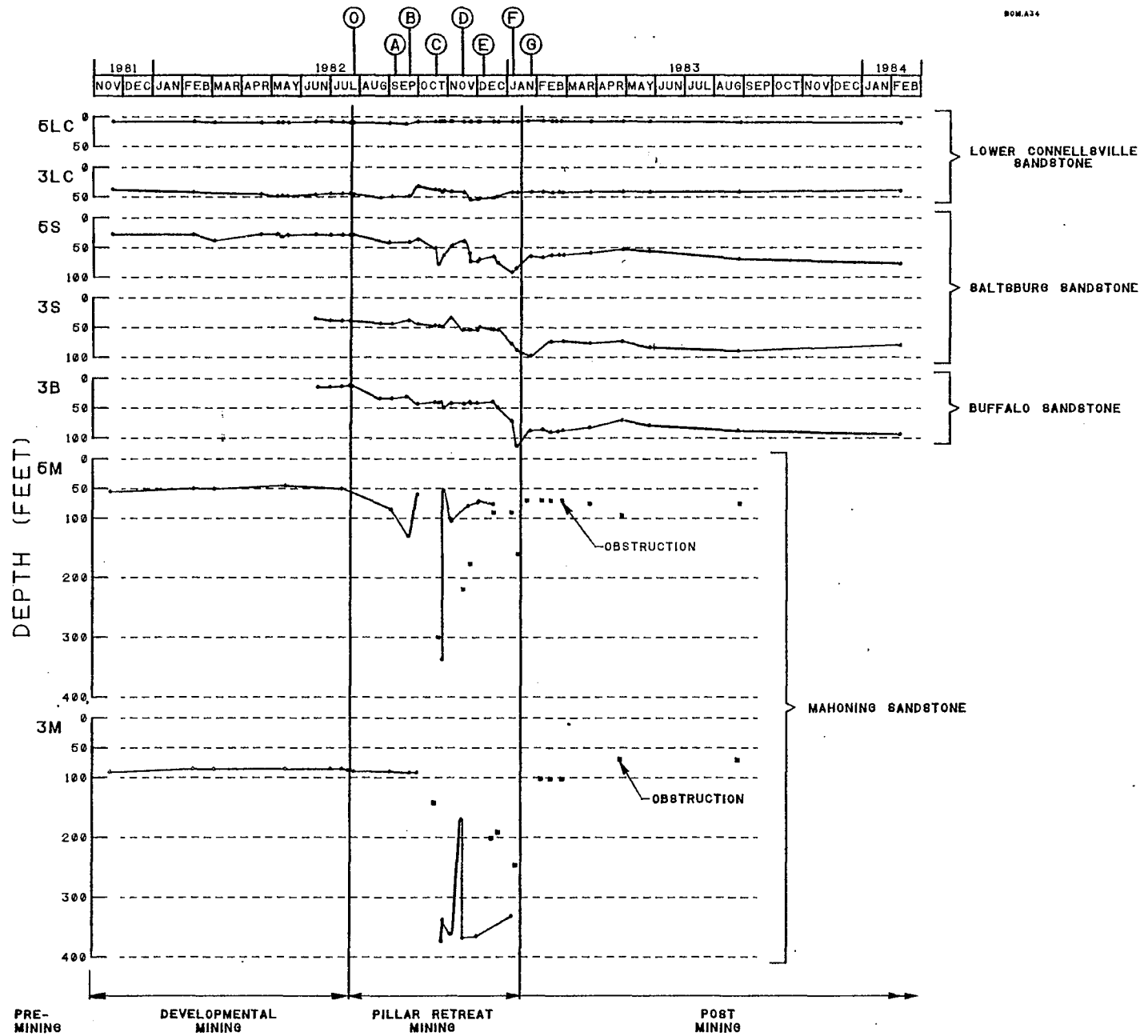
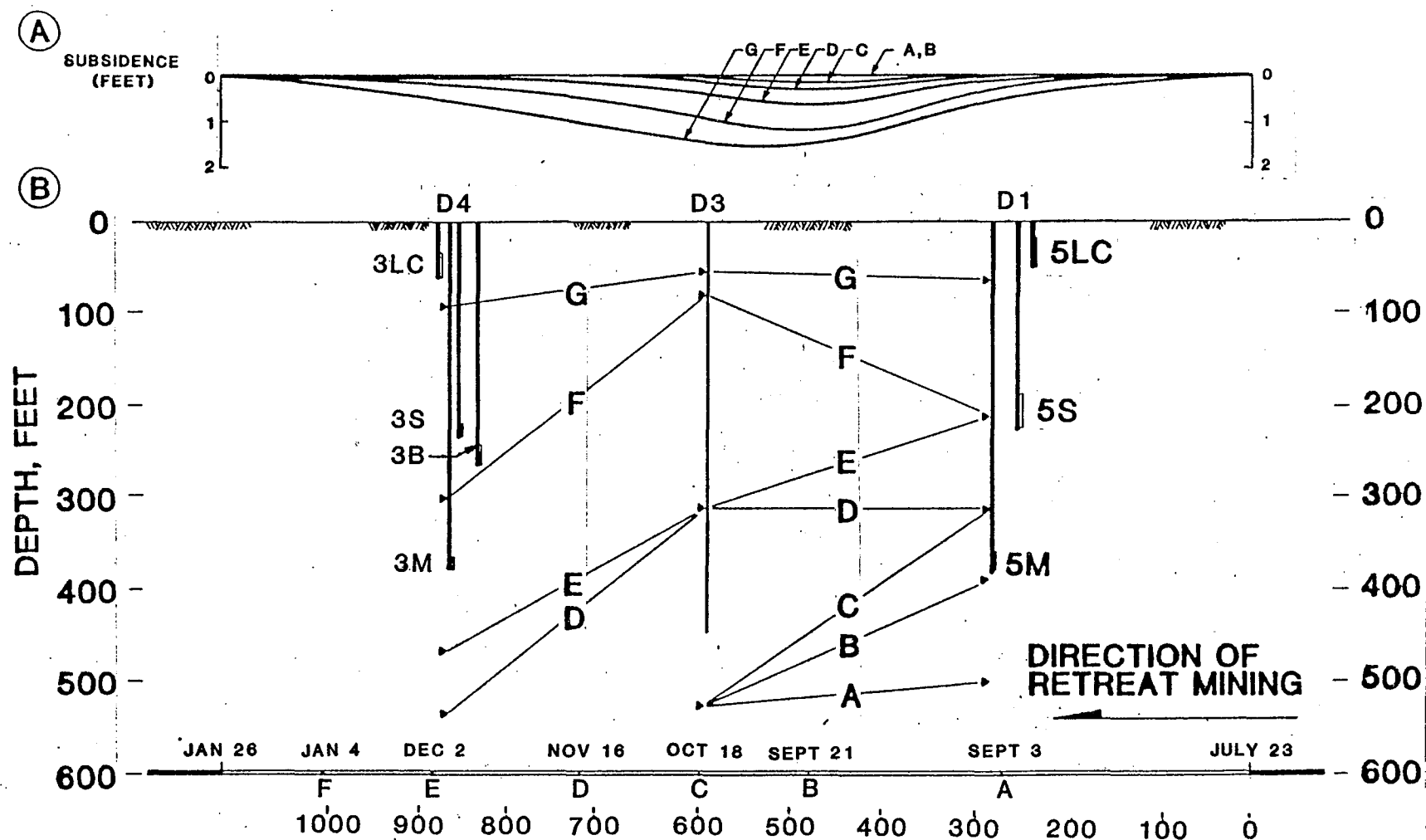


FIGURE 8.3 - SUMMARY OF WATER CHEMISTRY TESTS



NOTE: LETTERS AT MINE LEVEL DENOTE THE FURTHEST EXTENT OF RETREAT MINING ON THE DATE SHOWN.

FIGURE 8.4 RELATIONSHIP OF SUBSIDENCE AND STRATA DISLOCATIONS TO STAGE OF RETREAT MINING.

- A. SUBSIDENCE TROUGH DEVELOPMENT ALONG SECTION LINE THROUGH THE PIEZOMETER INSTALLATIONS.
- B. MAXIMUM DEPTH TO WHICH INCLINOMETER SONDE COULD PENETRATE AT EACH STAGE OF RETREAT MINING.

- a. Position O: Pillar extraction began; the retreat line was approaching the 5-series piezometers--Piezometric levels in both the Mahoning and Saltsburg Sandstones had begun to decline.
- b. Position A. Retreat line was located beneath the 5-series piezometers--The piezometric level in the Mahoning Sandstone had declined 10 feet below its pre-mining level and that in the Buffalo Sandstone to 25 feet below its pre-mining level. Bedding-plane slip had taken place at many locations, yet the inclinometer casing remained intact to a depth 250 feet below the Buffalo Sandstone and 120 feet below the Mahoning Sandstone.
- c. Position B. Retreat line was located 200 feet beyond the 5-series piezometers--The inclinometer casing had sheared off 15 feet below the base of the Mahoning Sandstone. The piezometric level in that stratum continued to decline. The piezometric level in the Saltsburg Sandstone remained unchanged.
- d. Position C. Retreat line was located 350 feet beyond the 5-series piezometers--The inclinometer had sheared off in a claystone unit above the Mahoning Sandstone and the piezometric level in the Mahoning sandstone (5M) had fallen 270 feet or more below its pre-mining level. (The piezometer casing had become obstructed and was possibly ruptured at a depth of 330 feet. No further reliable readings could be obtained from 5M.) The piezometric level in the Saltsburg Sandstone had fallen 50 feet below its pre-mining level.
- e. Position D. Retreat line located 450 feet beyond the 5-series piezometers--The inclinometer length remained unchanged from that observed at Position D. The piezometric level in the Saltsburg Sandstone rose slightly.
- f. Position E. Retreat line located 600 feet beyond the 5-series piezometers--The inclinometer had sheared off at the Saltsburg Sandstone and the piezometric level in that unit had declined to a local minimum comparable to that observed at Position D.
- g. Position F. Retreat line located 750 feet beyond the 5-series piezometers--The inclinometer length remained unchanged from that observed at Position E. The piezometric level in the Saltsburg Sandstone (5S) had fallen 60 feet below its original level, the lowest level recorded in this stratum during the monitoring program.
- h. Position G. Retreat line located 850 feet beyond the 5-series piezometers [end of retreat]--The inclinometer casing had sheared to within 65 feet of ground surface. The piezometric level in the Saltsburg Sandstone (5S) had recovered 15 feet from the elevation corresponding to Position F, and was soon to level off.
- i. Throughout retreat mining, the piezometric level in the Lower Connellsville Sandstone, 550 feet above mine level, remained essentially unchanged.

Piezometric levels in the 3-series piezometers (Figure 8.3) located 600 feet north of the 5-series piezometers experienced changes similar to those in the 5-series piezometers:

- a. Compare 3S with 5S (Saltsburg Sandstone)--Piezometric levels declined in July/August, early/mid-October, late November and late December; piezometric levels rose in late October/early November, early December and January. The range in water levels (highest to lowest) was 65 feet in both cases, but the intermediate fluctuations of Piezometer 3S were more subdued, possibly due to its being more distant than 5S from the center of mining activity and overburden disturbance.
- b. Compare 3M with 5M (Mahoning Sandstone)--Piezometric levels declined with the initiation of pillar extraction in late July and culminated in a dramatic drop in piezometric level in mid-October. The July-September decline in piezometric level at 3M was more subdued than at 5M, possibly (like the Saltsburg Sandstone) because the 3-series piezometers were at a greater distance from the center of mining activity and overburden disturbance.

Post-Mining (January 1983-June 1984)

Erratic piezometric fluctuations ceased and piezometric levels tended to stabilize at or below levels measured prior to retreat. Piezometric levels in the Lower Connellsville Sandstone, for example, remained at elevations attained at the end of retreat mining in January, 1983, levels that were the same as pre-mining levels (5LC) or very near (3LC).

Piezometric trends in the Buffalo and Saltsburg Sandstones were very similar to one another. For approximately one month after the completion of retreat mining, the piezometric level in the Buffalo Sandstone (3B) remained about 75 feet below its pre-mining level (about 30 feet above the lowest level it attained during pillar extraction). In the second and third months (March and April), the piezometric level rose gradually, and in the fourth through eleventh months (May-January) gradually declined to an elevation 85 feet below its premining level, which then maintained to the conclusion of monitoring in March, 1985.

For about a month after the completion of retreat mining, the piezometric level in the Saltsburg Sandstone (5S) remained approximately 40 feet below its pre-mining level (about 30 feet above the lowest level it had attained during pillar extraction). In the second and third months (March and April), the water level rose gradually, and in the fourth through the eleventh months (May-January) gradually declined to an elevation 50 feet below its pre-mining level, which maintained for the remainder of the monitoring program. (The post-mining piezometric level of 3S is governed by the piezometric level in the overlying Lower Connellsville Sandstone--the result of rupture of the piezometer casing and seal as retreat mining drew to a close. Note the December 1982-February, 1983 period in Figure 8.3).

Piezometric levels in the Mahoning Sandstone were indeterminate in the post-mining period owing to the rupture and dislocation of the piezometer casings that had

taken place during retreat mining. In the case of 5M, it is clear that the water level is more than 20 feet (and probably hundreds of feet) below pre-mining levels.

The foregoing paragraphs have dealt with piezometric levels in individual rock strata. The water level found in a conventional supply well, in contrast, would represent the cumulative effect of all the strata intercepted by the well. Consequently, the response of a well to retreat mining may be somewhat different than the response of the individual strata comprising the well or may be dominated by a single high yield rock unit in the well. The latter situation is illustrated by Piezometer 3S. There, after the piezometer casing had ruptured, the piezometric level rose to that of the Lower Connellsville Sandstone. It is conceivable, then, that if a water well were drilled through the Lower Connellsville Sandstone to one of the intermediate strata (the Saltsburg or the Buffalo Sandstone, for example), the well might exhibit no adverse effects from retreat mining, despite physical changes in certain strata intercepted by the well. The distinction between piezometer response and well response is important and must be borne in mind when comparing the data from this program with data collected from other programs where water wells were used.

MINE INFLOWS

The C-3 panel was regarded as "dry." During developmental mining, seepage from the roof, floor or coal was negligible.

In October 1982, about three months after retreat mining began, water was heard trickling into the gob area near the south end of the panel. The precise point(s) of entry could not be determined, although an investigation showed water to be ponding at the far south corner of the bleeder entries, the lowest point in the panel. (The coal seam slopes southward from the mains toward the bleeder entries at an average of 0.3 inch per foot--a dip of 1.6 degrees).

By October 19, water had ponded ankle deep in the bleeder entries in the first cross-cut outby the solid coal (Point A, Figure 8.5). The northward progression of the high water mark toward the mains was recorded on five subsequent occasions during the three month period ending in mid-January, 1983, at which time the C-3 panel was sealed off at the mains by a cinder block wall. The position of the mine pool on each occasion is shown in Figure 8.5, as inferred from the water level in the bleeder entries and the configuration of the mine floor.

The rate of rise of the mine pool during the three month period of observation within the panel was essentially constant at 0.108 feet per day. The rate of water inflow during this period is estimated at about 100,000 gallons per month or 2.9 cubic feet per minute and seemed not to vary significantly as the gob area enlarged. The volume of water in the panel on a given date was estimated by planimetry of a mine map of the flooded area, accounting for pillars and for areas where the water was not in contact with the roof and assuming a gob porosity of 10 percent. If the gob materials were absent, the estimated rate of mine inflow would be about 5 cubic feet per minute.

The mine panel is surrounded by solid coal on its downdip (south) and lateral (east and west) boundaries. Consequently, the estimates of inflow are not complicated by the possibility of significant seepage losses to or gains from adjacent mine panels.

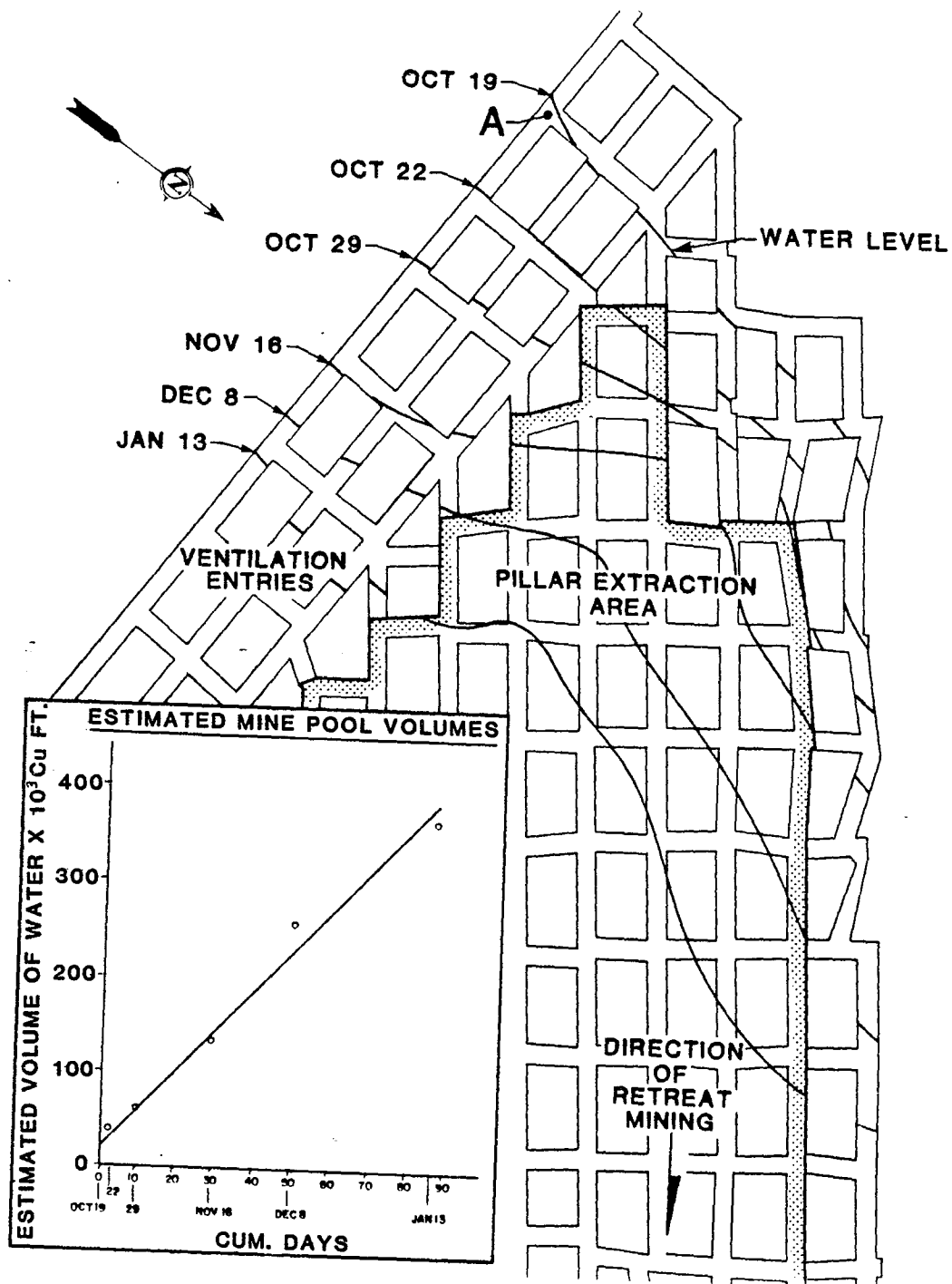


FIGURE 8.5 MINE POOL —OBSERVED WATER LEVEL AND ESTIMATED MINE POOL VOLUME AT VARIOUS STAGES OF RETREAT MINING. POINT A REPRESENTS THE LOCATION WHERE THE MINE POOL WAS FIRST OBSERVED.

Attesting to the near constancy of water inflow to the panel is the fact that during the week of August 8, 1983, water was observed seeping through the seal from the panel into the main entries (local mine floor elevation $834\pm$). A forward projection of the mine pool elevation regression line to this elevation suggested that seepage from the panel would occur within a few days of its actual occurrence.

PIEZOMETRIC PROFILES

The comparative water pressure distributions with depth before, during, and after mining, (Figure 8.6) summarize the piezometric data discussed in the foregoing paragraphs. Water pressure is related to piezometric level by the expression

$u = \gamma_w h_p$, where γ_w is the unit weight of water and h_p is the pressure head--the piezometric level being referenced to mid-height of the gravel zone in the piezometer.

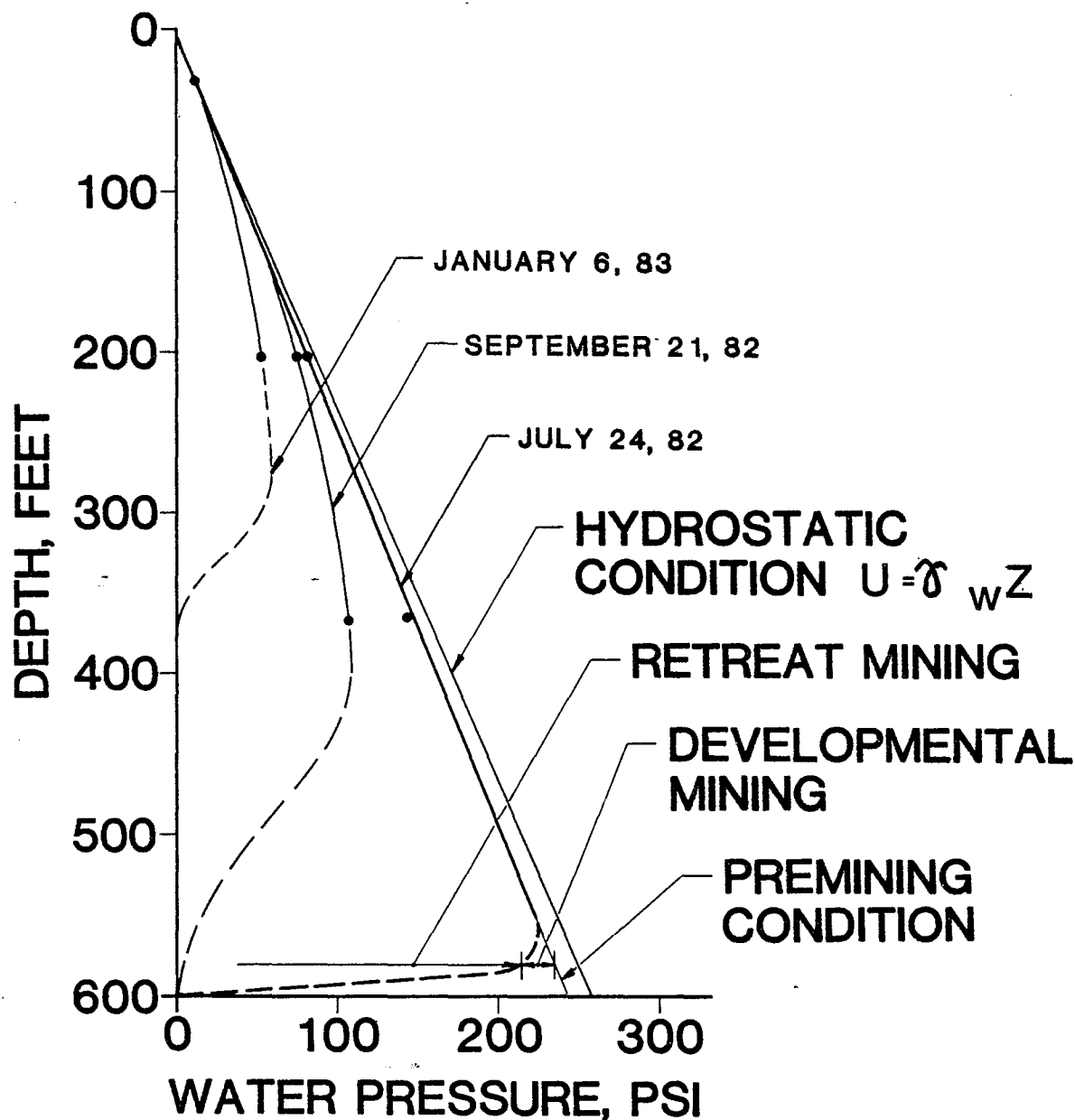
The piezometric profile during developmental mining is linear from a few feet below ground surface, where groundwater is first encountered, to the Mahoning Sandstone horizon at a depth of 360 feet and probably deeper. Prior to developmental mining, the line presumably extended to the level of the Lower Kittanning Coal horizon and below, possibly reflecting a regional flow condition that had developed over a long period of time. (Note that the premining profile departs slightly from the hydrostatic case for which $u = \gamma_w z$ and z is depth below the water table. This can be likened to the case of downslope ground water flow parallel to ground surface, where the water pressure is linear with depth but equals $\gamma_w z \cos i$, rather than $u = \gamma_w z$. Angle i is the inclination of the slope to the horizontal [Lambe and Whitman, 1969].)

With the introduction of mine entries into the coal seam, the water pressure at the coal horizon dropped to zero, inducing what must have been a local reversal of the profile--the decrease in water pressure denoted by the dashed line in Figure 8.6. (The point of reversal is not defined by the piezometer installations in this monitoring program.) The overburden strata were not disturbed by developmental mining and so the ground water conditions were probably affected only a short distance above mine level.

During retreat mining, dislocations in the overburden strata, initially most prominent near mine level, developed at increasingly higher elevations as mining progressed and produced further reductions in water pressures, particularly in the lower 400 feet of overburden. Adjustment of the overburden to pillar extraction produced fluctuations in water pressures, if not dewatering of the strata. Pressure reductions were more pronounced the closer the stratum lay to mine level, and were accompanied by water inflows to the mine panel. Over a period of several months the mine panel became flooded. An overflow in the mine panel limited the height to which the water level could rise.

During the first two years following mining, the piezometric levels appear to have achieved some degree of stability.

After an indefinitely long period of time has passed--after the entire mine has been abandoned--it might be expected that ground water will again occupy the lower strata and piezometric levels will approach their premining condition. The degree to which this is realized will depend upon the effectiveness of mine seals and other details of the mine, as well as the cumulative effect on the ground water regime of other mining in the region.



NOTE THAT THE DASHED SEGMENTS OF THE SEPTEMBER 21, 1982 AND JANUARY 6, 1983 PROFILES REFLECT THE PROGRESSIVE DEWATERING OF DEEPER LYING STRATA DURING RETREAT MINING.

FIGURE 8.6 PROFILE OF WATER PRESSURE IN THE OVERBURDEN AT VARIOUS STAGES OF MINING.

HYDRAULIC PROPERTIES

The permeability of a rock stratum and its capacity to store water are customarily defined in terms of the following parameters:

Hydraulic Conductivity, K --the rate at which water flows through a unit cross section of rock under a unit hydraulic gradient. (Dimensions: length/time.)

Transmissivity, T --the rate at which water flows through a unit width of aquifer of saturated thickness b under a unit hydraulic gradient. Transmissivity is related to hydraulic conductivity by the relationship $T = Kb$. (Dimensions: length²/time.)

Storage Coefficient (Storativity), S --the volume of water that an aquifer of saturated thickness b releases from or takes into storage per unit surface area of aquifer per unit change in head. (Dimensionless)

Specific Storage, S_s --the volume of water that a unit volume of aquifer releases from storage per unit decline in head. For a horizontal confined aquifer of thickness b , $S_s = S/b$. (Dimensions: 1/length.)

Downhole tests were conducted to determine the hydraulic properties of the four strata in which piezometers were constructed--single-piezometer pump tests (tests without observation piezometers) in the Lower Connellsville, Saltsburg and Buffalo Sandstones, to obtain values of transmissivity; and slug tests in the Lower Connellsville, Saltsburg and Mahoning Sandstones to obtain values of both transmissivity and storage coefficient. The slug test method is described in Appendix 8.1 at the end of this section and is based upon the work of Cooper et al (1963), with some type curve extensions developed by the writers. The pump test, where hydraulic conductivity is determined from the rate of recovery of the water level after the cessation of pumping, is based upon the work of Theis, as described by Todd (1980).

Test results are summarized in Table 8.2. Values of transmissivity have been converted to hydraulic conductivity and values of storage coefficient to specific storage to enable comparison of the hydraulic characteristics of the rock units independent of their respective thicknesses. The test data indicate the following:

Pre-retreat Mining

The Lower Connellsville Sandstone possessed a hydraulic conductivity between 10^{-3} and 10^{-5} cm/sec and a specific storativity between 10^{-6} and 10^{-9} prior to the initiation of pillar extraction. The slug tests suggested that the Lower Connellsville Sandstone is about 20 times more permeable near the south end (5LC) of the panel than near the north end (3LC), an interesting result inasmuch as the Lower Connellsville appears to be more shaly to the south, as discussed above under "Rock Units Monitored." Differences in the hydraulic characteristics of the Lower Connellsville Sandstone at the two locations was further demonstrated by the pump tests conducted in 3LC and 5LC. The pump test in 5LC indicated a hydraulic conductivity of 7.3×10^{-5} cm/sec, in reasonable agreement with the corresponding slug test in 5LC, which involved a far smaller radius of influence. However, the pump test in 3LC was significantly different from that in 5LC--in 3LC virtually no recovery was measured during the 48-hour monitoring period that followed drawdown, although, a month later, when the piezometer was next monitored, the piezometric level had recovered to its pre-test

Table 8.2
SUMMARY OF PIEZOMETER TESTS

Stratigraphic Unit	Well	Test Type	Hydraulic Conductivity, K		Specific Storativity ^x , S _s	
			Pre-retreat (cm/sec)	Post-retreat (cm/sec)	Pre-retreat (1/cm)	Post-retreat (1/cm)
Lower Connellsville Sandstone	3LC	Slug-Pump-	2.0 x 10 ⁻⁵ *	2.6 x 10 ⁻⁴ -	5.3 x 10 ⁻⁷ -	4.3 x 10 ⁻¹⁵ -
	5LC	Slug-Pump-	4.4 x 10 ⁻⁴ 7.3 x 10 ⁻⁵	2.4 x 10 ⁻⁴ 2.2 x 10 ⁻⁴	4.5 x 10 ⁻⁹ -	4.5 x 10 ⁻⁵ -
Saltsburg Sandstone	3S	Slug-Pump-	1.2 x 10 ⁻³ 3.0 x 10 ⁻³	- -	1.3 x 10 ⁻⁴ -	- -
	5S	Slug-Pump-	7.3 x 10 ⁻⁷ 8.5 x 10 ⁻⁴	4.6 x 10 ⁻⁵ 2.1 x 10 ⁻³	4.2 x 10 ⁻⁷ -	4.2 x 10 ⁻¹⁴ -
Buffalo Sandstone	3B	Pump-	7.4 x 10 ⁻⁴	1.1 x 10 ⁻³	-	-
Mahoning Sandstone	3M	Slug-	4.5 x 10 ⁻⁷	-	3.8 x 10 ⁻⁶	-
	5M	Slug-	4.0 x 10 ⁻⁹	1.4 x 10 ⁻⁸ †	2.6 x 10 ⁻⁵	2.6 x 10 ⁻⁷ ‡

*Indeterminate--Virtually no recovery after pumping

†Results are suspect due to uncertainty in position of piezometric level and integrity of casing.

^xFrom slug tests only. Single-well pump tests do not yield values of specific storativity.

elevation. The tests seem to indicate that although the hydraulic properties of the rock in the immediate vicinity of the 3LC and 5LC piezometer bores were somewhat similar, one piezometer (3LC) was constructed in a moderately high permeability zone of limited areal extent, whereas the other (5LC) was constructed in a zone of greater areal extent--one that could support sustained pumping for a period of several hours, and probably longer. This emphasizes the value of conducting pump tests as well as slug tests in assessing hydraulic characteristics.

The Saltsburg Sandstone possessed a pre-retreat hydraulic conductivity between 10^{-2} and 10^{-7} cm/sec and specific storativity between 10^{-5} and 10^{-7} /cm. The hydraulic conductivity of the Saltsburg Sandstone was greater to the north than to the south. The hydraulic conductivities indicated by the slug test and pump test for 3S are virtually identical, 1.2×10^{-3} cm/sec and 3×10^{-3} cm/sec, respectively. The hydraulic conductivity indicated by the slug tests at 5S, however, is approximately three orders of magnitude less than indicated by the corresponding pump test in 5S-- 7.3×10^{-7} cm/sec for the slug test and 8.5×10^{-4} cm/sec for the pump test. Both tests were considered reliable. The slug data were reproduced in three separate tests. The reason for the disparity is not evident, although may be due to increasing hydraulic conductivity away from the piezometer bore. In any case, the data suggest that the hydraulic conductivity of the Saltsburg Sandstone equals or slightly exceeds that of the more shallow-lying Lower Connellsville Sandstone.

The Buffalo Sandstone, lying 40 feet below the Saltsburg Sandstone, possessed a pre-retreat hydraulic conductivity of 7.4×10^{-4} cm/sec, similar to that of the Saltsburg and Lower Connellsville Sandstones. Slug tests were not conducted in 3B due to other ongoing tests by Los Alamos Scientific Laboratory.

The Mahoning Sandstone at 360 foot depth was significantly less permeable than the other three rock units. It possessed a pre-retreat hydraulic conductivity between 10^{-6} and 10^{-9} cm/sec and a specific storativity between 10^{-4} and 10^{-6} /cm. These values were determined by slug tests alone, since the 0.75 inch ID casing would not accommodate a pump.

Post Retreat Mining

The general effect of pillar extraction mining was to leave the hydraulic conductivity unchanged or to increase it one to two orders of magnitude. In only one case did the hydraulic conductivity appear to decrease and that change was considered insignificant.* The values of specific storativity appear variously to have increased or decreased several orders of magnitude, depending upon the individual sandstone stratum and piezometer installation. No dominant trend is observed.

As shown in Table 8.2, the Lower Connellsville Sandstone (3LC and 5LC) experienced a zero to one order of magnitude increase in hydraulic conductivity; the Saltsburg Sandstone (5S), a zero to two order of magnitude increase; the Buffalo Sandstone (3B), a zero one to order of magnitude increase; and the Mahoning Sandstone (5M), a zero to one order of magnitude increase. The post-retreat value of hydraulic

*The in hydraulic conductivity of the Lower Connellsville Sandstone at 5LC apparently decreased from 4.4×10^{-4} to 2.4×10^{-4} cm/sec.

conductivity for the Mahoning Sandstone must be regarded with caution due to uncertainties in the position of the piezometric level and the integrity of the piezometer casing at the time the test was performed. Even so, all the tests taken together indicate a rather convincing trend toward increased permeability with retreat mining. It is interesting to note, in this regard, that although the slug tests and pump test hydraulic conductivity values for the Saltsburg Sandstone were significantly different, both tests indicated increases of about the same magnitude as a result of retreat mining. Evidence of these changes in permeability are reflected by the shift in the head ratio-log time ratio curves of the slug test (Figure 8.7). Such changes are also reflected in the pump test curves. Those for the Buffalo Sandstone (3B) are shown in Figure 8.8. The two pump tests in the Buffalo Sandstone compare as follows:

1. During the pre-retreat test conducted in July 1982, the piezometric level declined approximately 160 feet in 2.5 hours of pumping at a nominal rate of 3.9 gallons per minute. Recovery took place at a nominal rate of 0.03 feet per minute for the first four hours after the cessation of pumping.
2. During the post retreat test conducted in May 1983, the piezometric level declined approximately 15 feet in 7 hours of pumping at a nominal rate of 6.3 gallons per minute. Recovery took place at a nominal rate of 0.04 feet per minute for the first four hours after the cessation of pumping.

Thus, the effect of retreat mining on the Buffalo Sandstone at Piezometer 3B was such that pumping at a rate 1.5 times faster over a period nearly three times longer only one-tenth the drawdown measured prior to retreat mining and produced a recovery rate 30 percent more rapid than during pre-retreat. In addition, the recovery curve for the post-retreat case is almost a perfect inverse of the drawdown curve, much resembling the ideal drawdown-recovery curves for homogeneous, isotropic aquifers of uniform thickness and infinite areal extent, such as depicted by Todd (1980, p. 133). In contrast, the pre-retreat drawdown-recovery curve is distinctly different--the recovery curve does not resemble the inverse of the drawdown curve. This suggests that because of inherent variations in lithology, jointing, thickness, differences of modulus in loading and unloading, and other factors, the sandstone in its natural (pre-mining) state only roughly approximates a homogeneous, isotropic aquifer but, when subjected to shearing, fissuring and displacements along joints during mining, is, in effect, "homogenized," bringing it into closer conformity with the idealized model.

WATER CHEMISTRY

Background

Although ground water a few hundred feet below major local drainage in the Appalachian basin is often too mineralized to be potable (Ward and Wilmoth, 1968; Gallaher, 1973), the dip of the strata bring the deep lying rock units beneath the C-3 panel to the surface in the eastern portion of the county where local recharge of fresh water is available. Water from these rock units is suitable for household use.

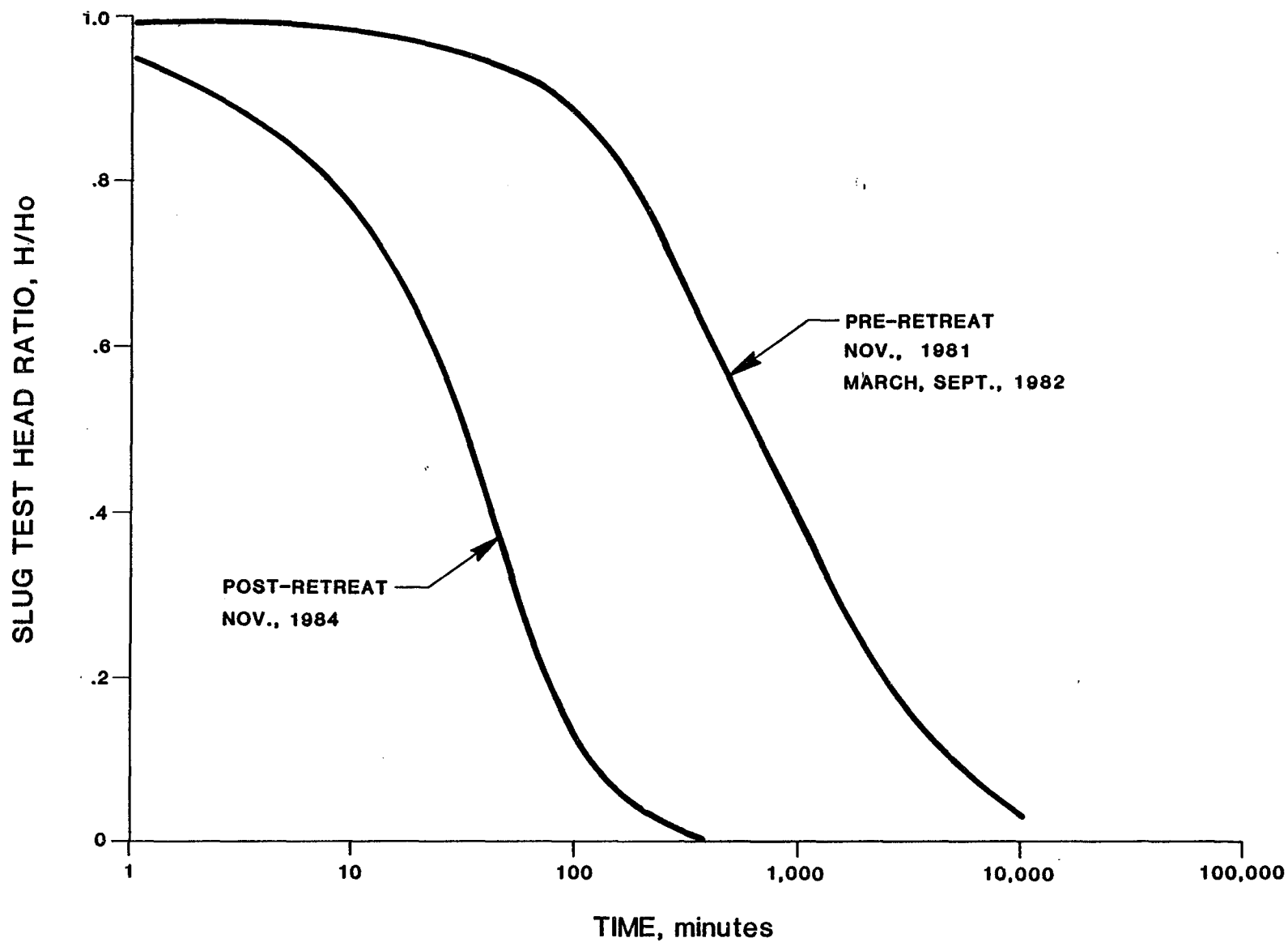


FIGURE 8.7
HEAD RATIO-LOG TIME SLUG TEST CURVES
FOR SALTSBURG SANDSTONE (5S)

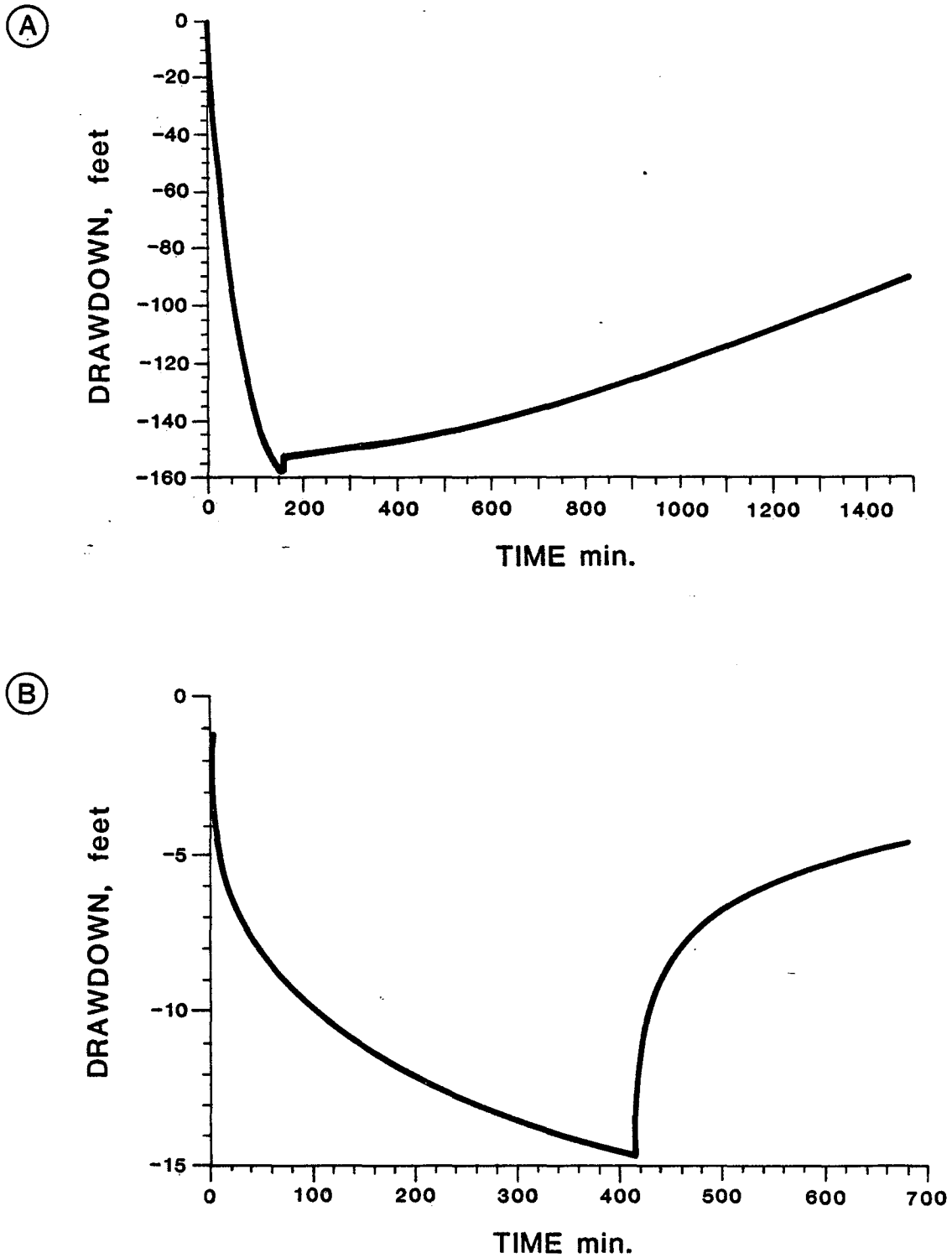


FIGURE 8.8

DRAWDOWN-RECOVERY CURVES, BUFFALO SANDSTONE (3B)
A. PRE-RETREAT, JULY, 1982 B. POST-RETREAT, MAY, 1983

Much of the Kitt Mine property is located on woodland or pasture which, except for perennial grasses cultivated for cattle feed, has not been intensely cultivated in the recent past.

The nearest mining-related surface building is a coal-refuse silo which is located 1600 feet from the ground water monitoring piezometers clustered around instrumentation system D-4. The raw coal storage pile/silo is located 1700 feet east of D-4. A haulage road which has been in its current location at least for several years prior to the beginning of ground water monitoring activities is located 450 feet uphill from the piezometers at D-4. The road was constructed of waste rock from the coal preparation facility, is not paved, and is maintained during periods of snowfall by plowing rather than by salting. Paved State Route 70 is located 550 feet south of the piezometers at D-1. It too is not salted during periods of snowfall. The mine engineering office is 550 feet west of the piezometers at D-1 and the gravel drive to this office passes within 15 feet of the same piezometers. This drive is not heavily used. All facilities described above have been in constant year around use for several years prior to the initiation of the project. No other residential or commercial areas exist within 7000 feet of the project site. During the period of ground water monitoring, site conditions were such that mining would be suspected as a cause of any significant changes in aquifer water quality.

Field Program

Samples of water from Piezometers 5LC, 3LC and 5S were secured for laboratory testing three months prior to the initiation of retreat mining and twenty five months after the completion of mining. The pre-retreat samples were tested for thirty constituents and parameters specified by the U.S. Environmental Protection Agency National Interim Primary Drinking Water Standards. The post-retreat samples were restricted to eight constituents and parameters considered to best characterize water quality changes that may have taken place during retreat mining.

The EPA Interim Drinking Water Standards serve as a basis for assessing the suitability of water for human consumption in terms of concentrations of particular inorganic, organic and bacteriological constituents. Recommended concentrations of certain of the inorganic constituents are based upon considerations of taste and appearance. Drinking water supplies not uncommonly exceed one or more of these limits without harm to consumers. Maximum possible concentrations of inorganic, organic and bacteriological constituents are based upon health considerations. Water exceeding any of these concentrations is unfit for human consumption and cannot be used as a public water supply. Water used for livestock and irrigation is subject to somewhat less stringent criteria.

At selected intermediate times during mining, water samples were drawn from five of the seven piezometers and tested for pH and specific conductivity to identify water chemistry changes while mining was underway. The pH parameter expresses the hydrogen ion concentration in terms of its negative logarithm and ranges from 0 to 14, with 7 being the neutral pH for water. For values of pH less than 7, the hydrogen ion concentration exceeds the hydroxide ion concentration and the water is termed 'acidic'. For values of pH greater than 7, the opposite condition is true and the water is 'basic'. The specific conductance in micromhos per centimeter reflects the ability of a solution to pass electrical current via the inorganic salts in the water and is proportional to the total dissolved solids in milligrams per liter. The total dissolved solids consist primarily of inorganic salts, small amounts of organic matter and dissolved gases.

Samples were drawn after a minimum two piezometer volumes had been discharged by the pump. The pre- and post-retreat mining laboratory test samples were transported to Pittsburgh for testing in sealed containers packed in ice. pH tests were conducted in the field using a Fisher Scientific Model 156 pH meter and conductivity using a Fisher Scientific Model 152 conductivity meter.

Test Findings

A comparison between the pre- and post-retreat mining water chemistry data is presented in Table 8.3. The variation in pH and specific conductivity during mining is presented in Figures 8.9 and 8.10. The findings of the program are as follows:

1. The water from all three installations was near neutral and all contained dissolved salts at concentrations near 300 mg/liter, corresponding to specific conductances between 420 and 460 umhos/cm.

Water from both piezometers in the Lower Connellsville Sandstone (3LC and 5LC) met the EPA Interim Drinking Water Standards except for higher than recommended values of iron and manganese, which would not necessarily preclude use of the water for drinking. Water from the Saltsburg Sandstone (5S) exceeded the recommended concentration for manganese, but also exceeded the maximum possible concentration for coliform bacteria. The latter makes the water from 5S unfit for human consumption.

2. Twenty five months after mining, the water from all three installations remained near neutral--the pH from 5LC dropping slightly from 7.7 to 7.6; 3LC, decreasing from 8.1 to 7.5; and 5S, increasing from 7.8 to 9.0. However, measures of values of specific conductance were noticeably higher than before retreat mining--the specific conductance from 5LC increasing from 460 to 928 umhos/cm; 3LC, from 420 to 636 umhos/cm; and 5S, from 430 to 740 umhos/cm. Corresponding increases were measured in total dissolved solids--the TDS concentration in 5LC increasing from 304 to 584 mg/L; in 3LC, from 298 to 392 mg/L; and in 5S, from 297 to 472 mg/L.

Following mining, water from Piezometers 3LC and 5LC continued to meet the Interim Drinking Water Standard (based on the parameters tested) except for continuing higher than recommended values of iron and manganese. After mining, water from Piezometer 5LC also exhibited a higher than recommended concentration of Total Dissolved Solids. If used for drinking purposes prior to mining, the Lower Connellsville water would probably be considered acceptable for drinking purposes after mining. After mining, water from the Saltsburg Sandstone exhibited a higher than recommended concentration of manganese as it had prior to retreat, along with a higher than recommended concentration of iron. Water from the Saltsburg Sandstone would probably be considered suitable for drinking purposes were the coliform concentration not above maximum permissible levels.

3. The higher concentrations of total dissolved solids (and higher specific conductance) measured after mining reflect changes that had evidently been taking place during retreat mining (Figure 8.10).

Table 8.3
WATER CHEMISTRY DATA
KIT NO. 1 MINE

Constituent/Parameter	Drinking Water Standards	Water Standards for Livestock and Irrigation Crop Usage ^{xx}	Lower Connellsville Sandstone				Saltsburg Sandstone	
			SLC		SLC		SS	
			Pre-Retreat ^x	Post-Retreat ^o	Pre-Retreat ^x	Post-Retreat ^o	Pre-Retreat ^x	Post-Retreat ^o
pH	-		7.7	7.6	8.1	7.5	7.8	9.0
Specific Conductance (umhos/cm)	-		460.0	928	420	636	430	740
Acidity (cold) (mg/L as CaCO ₃)	-		-	10	-	<10	-	<10
	Recommended Concentration Limit (mg/L)*	Recommended Concentration Limit (mg/L)						
Inorganic								
Total Dissolved Solids	500	3000-7000 [§]	304	584	298	392	297	472
Chloride	250		1.6	-	1.0	-	2.0	-
Sulfate	250		77	230	45	57	22	52
Sulfide	0.05		<0.1	-	<0.1	-	<0.1	-
Nitrate-Nitrogen	45	45	<0.1	-	<0.1	-	<0.1	-
Iron	0.3		0.70	1.21	0.33	0.67	0.09	1.07
Manganese	0.05		0.18	0.18	0.08	0.32	0.16	0.27
Copper	1.0		<0.01	-	0.01	-	0.01	-
Zinc	5.0		<0.01	-	<0.01	-	0.07	-
	Maximum Possible Concentration [†]							
Arsenic	0.05	0.20	<0.001	0.013	<0.001	0.016	<0.001	0.012
Barium	1.0		<0.1	-	<0.1	-	<0.1	-
Cadmium	0.01	0.05	<0.005	-	<0.005	-	<0.005	-
Chromium (Hexavalent)	0.05	1.0	<0.01	-	<0.01	-	<0.01	-
Selenium	0.01	0.05	0.006	-	<0.002	-	<0.002	-
Lead	0.05	0.1	<0.03	-	<0.03	-	<0.03	-
Mercury	0.002	0.01	<0.0002	-	<0.0002	-	<0.0002	-
Silver	0.05		<0.01	-	<0.01	-	<0.01	-
Fluoride	1.4-2.4 [§]	2.0	0.33	-	0.52	-	0.72	-
Organic								
Cyanide	0.05		0.006	-	0.006	-	<0.005	-
Endrine	0.0002		<0.01	-	<0.01	-	<0.01	-
Lindane	0.004		<0.005	-	<0.005	-	<0.005	-
Methoxychlor	0.1		<0.05	-	<0.05	-	<0.05	-
Toxaphene	0.005		<0.25	-	<0.25	-	<0.25	-
2,4-D	0.1		<0.5	-	<0.5	-	<0.5	-
2,4,5-TP (silvex)	0.01		<0.05	-	<0.05	-	<0.05	-
Phenols	0.001		<0.01	-	<0.01	-	<0.01	-
MBAS Surfactants [∇]	0.5		<0.01	-	0.06	-	0.08	-
Bacteriological								
Coliform	1 per 100 mL		<3	-	<3	-	12	-

Δ U.S. Environmental Protection Agency, National Interim Primary Drinking Water Regulation, 1975, "Water Programs: National Interim Primary Drinking Water Regulations", Federal Register, 40, No. 248.

xx U.S. Environmental Protection Agency. Water Quality Criteria 1972, EPA R3 73033.

* Recommended concentration limits for these constituents are intended primarily to provide acceptable taste and appearance characteristics.

† Maximum permissible limits are established according to health criteria.

§ Limit depends upon air temperature; fluoride is toxic at concentrations of 5 to 10 mg/L where water is consumed over a long period of time.

x April 1982 (3 months prior to initiation of retreat).

o March 1985 (25 months after completion of retreat).

∇ MBAS = methylene blue active substance.

§ Total Dissolved Solids: small animals, 3000 mg/L; poultry, 5000 mg/L; other animals, 7000 mg/L.

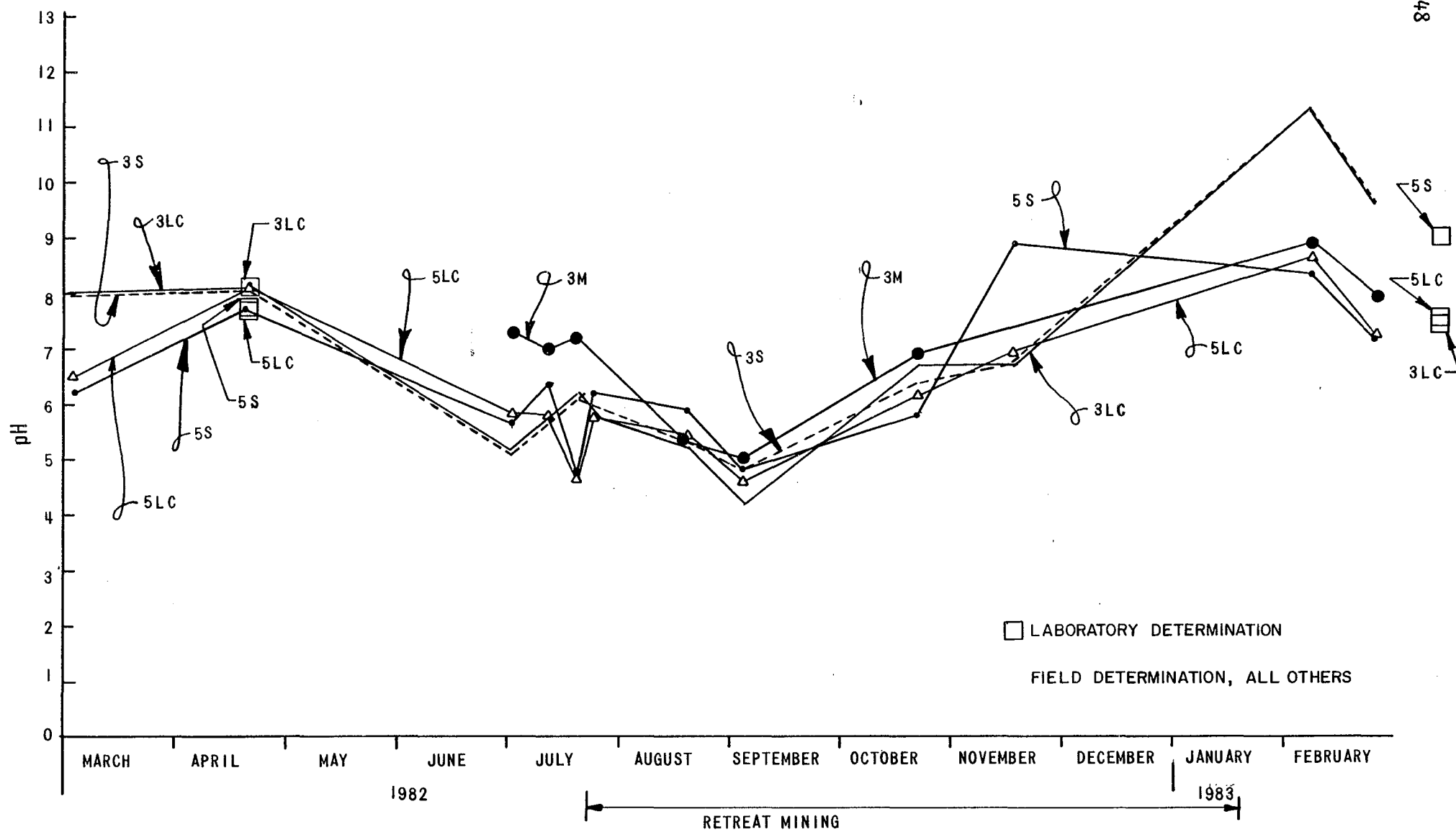


FIGURE 8.9 VARIATION IN pH OF GROUND WATER DURING MINING

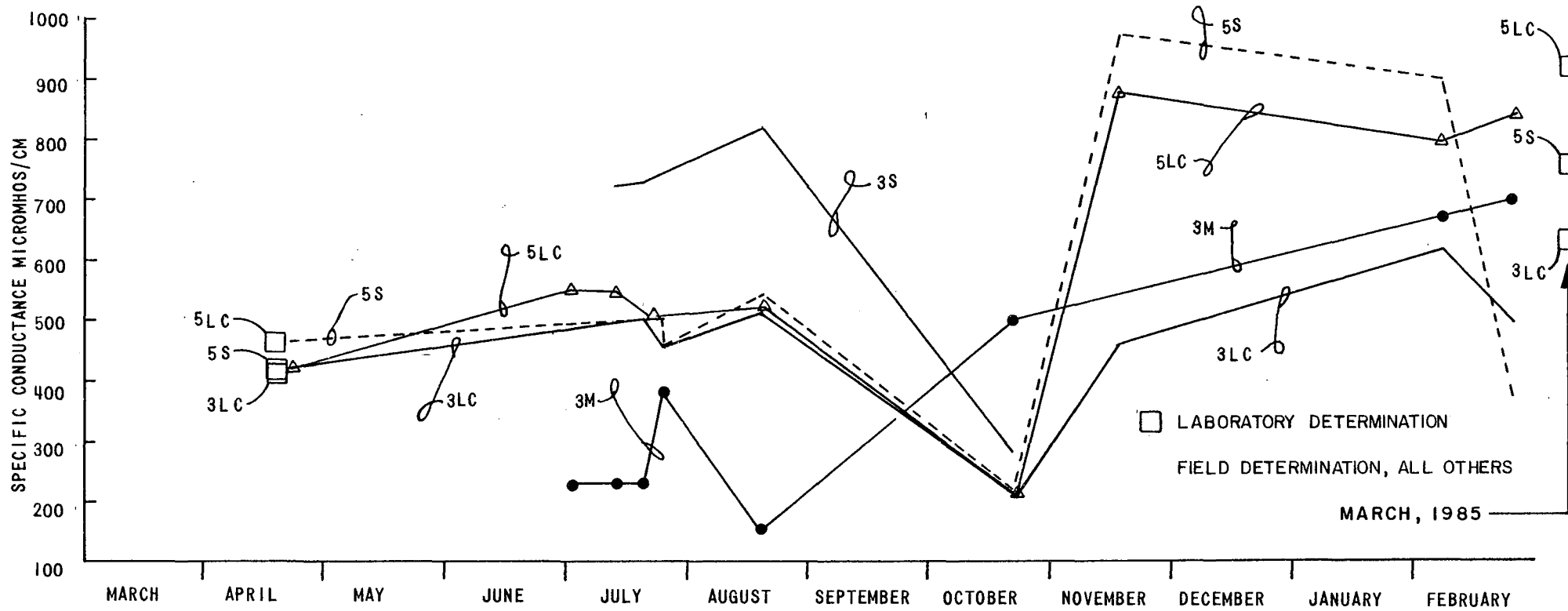


FIGURE 8.10 VARIATION IN SPECIFIC CONDUCTANCE OF GROUND WATER DURING MINING

Values of pH 2 to 3 units lower than the initial values were measured during the first few months of retreat mining and were followed by higher values and a return to near neutral conditions by the completion of mining (Figure 8.9). In recognition that a reduction in pH of 0.5 to 3 units took place in early July before retreat began, it is probable that at least some of the fluctuation in pH is due to seasonal variations or to some unidentified non-mining factor. Specific Conductance fluctuated 300 to 500 umhos/cm above or below the initial value, the amount and direction of the fluctuation depending upon the particular piezometer. The field tests seem generally to bear out the post-mining net increase in Specific Conductance indicated by the laboratory tests. (The data for 5M from August forward must be regarded with caution, since the well casing sheared during retreat mining, presenting the possibility of adulteration. In addition, the casing of 3S sheared in December, removing the opportunity for a post-mining reading.)

Obviously, attempts to explain the fluctuations are speculative. It is conceivable that fracturing of the rock strata and displacements that accompanied retreat mining exposed new rock surfaces to the ground water. This may have resulted in hydrolysis of the exposed salts of heavy metals, such as iron and aluminum, to produce increased acidity and increased concentrations of total dissolved solids. Major ground movements ceased upon the completion of mining so after that time no new rock surfaces were exposed to water. The chemical process possibly slowed and may eventually stop as water continues to flow through the rock.

Based on the data collected, it appears that certain chemical effects on the water may have been produced by mining. These effects were noticeable at the C-3 monitoring site two years after the completion of mining. However, the effects were not necessarily so significant as to render the water unfit for drinking purposes. With time, the effects may or may not more closely approximate pre-mining conditions.

The next section of the report deals with the effects of mining on the ground surface.

APPENDIX 8.1

SLUG TESTS

In discussing the response of a finite diameter piezometer to an instantaneous charge of water, Cooper et al. (1963) present a method for determining the hydraulic transmissivity of a rock stratum by means of a slug test. The slug test entails 1) making systematic observations over time of the water level in a piezometer after a known volume of water has suddenly been injected or withdrawn from the piezometer, and 2) determining the hydraulic properties of the stratum using a graphical technique where the test data are superposed on a family of type curves. Ferris and Knowles (1954) are credited with first having introduced the method.

The physical model on which the slug test is based is a non-flowing piezometer cased from ground surface to the top of a homogeneous isotropic aquifer of uniform thickness and screened through the full thickness of the aquifer. A volume V of water is instantaneously added to (or withdrawn from) the piezometer casing. The water level in the piezometer changes instantaneously by an amount $H_0 = V/A$, where A is the cross-sectional area of the piezometer casing. Initially, the change in head is H_0 inside the piezometer and nil outside the piezometer. Over time, the water in the piezometer restores to its original level according to a time function $H(t)$. Concurrently, the head in the surrounding aquifer varies according to a radial distance time function $h(r,t)$ --the rate of flow of water into (or out of) the aquifer equalling the rate of decrease (or increase) of the volume of water in the piezometer.

A solution for such non-steady flow in a confined aquifer is analogous to one where heat is flowing radially in an infinite region bounded internally by a circular cylinder containing a perfect conductor where no contact resistance exists between the perfect conductor and the surrounding solid. The heat flow solution is given by Jaeger, 1955.

Expressed in hydraulic terms by Cooper et al. (1967), the Jaeger solution indicates the head H inside the piezometer at any moment t , compared to the instantaneous head change H_0 , is given by:

$$H/H_0 = \frac{\beta \alpha}{\pi^2} \int_0^{\infty} e^{-\beta u^2 / \alpha} du / (\Delta(u))$$

$$\text{where } \Delta(u) = [u J_0(u) - 2\alpha J_1(u)]^2$$

$$+ [u Y_0(u) - 2\alpha Y_1(u)]^2,$$

$$\beta \text{ is } Tt/r_c^2,$$

$$\alpha \text{ is } r_s^2 S/r_c^2,$$

r_s is the radius of the well bore at the aquifer, and

r_c is the radius of the well casing.

Computed 'type curves'--families of curves of H/H_0 versus $\log \beta$ for selected values of α --are presented in Figure 8.11.

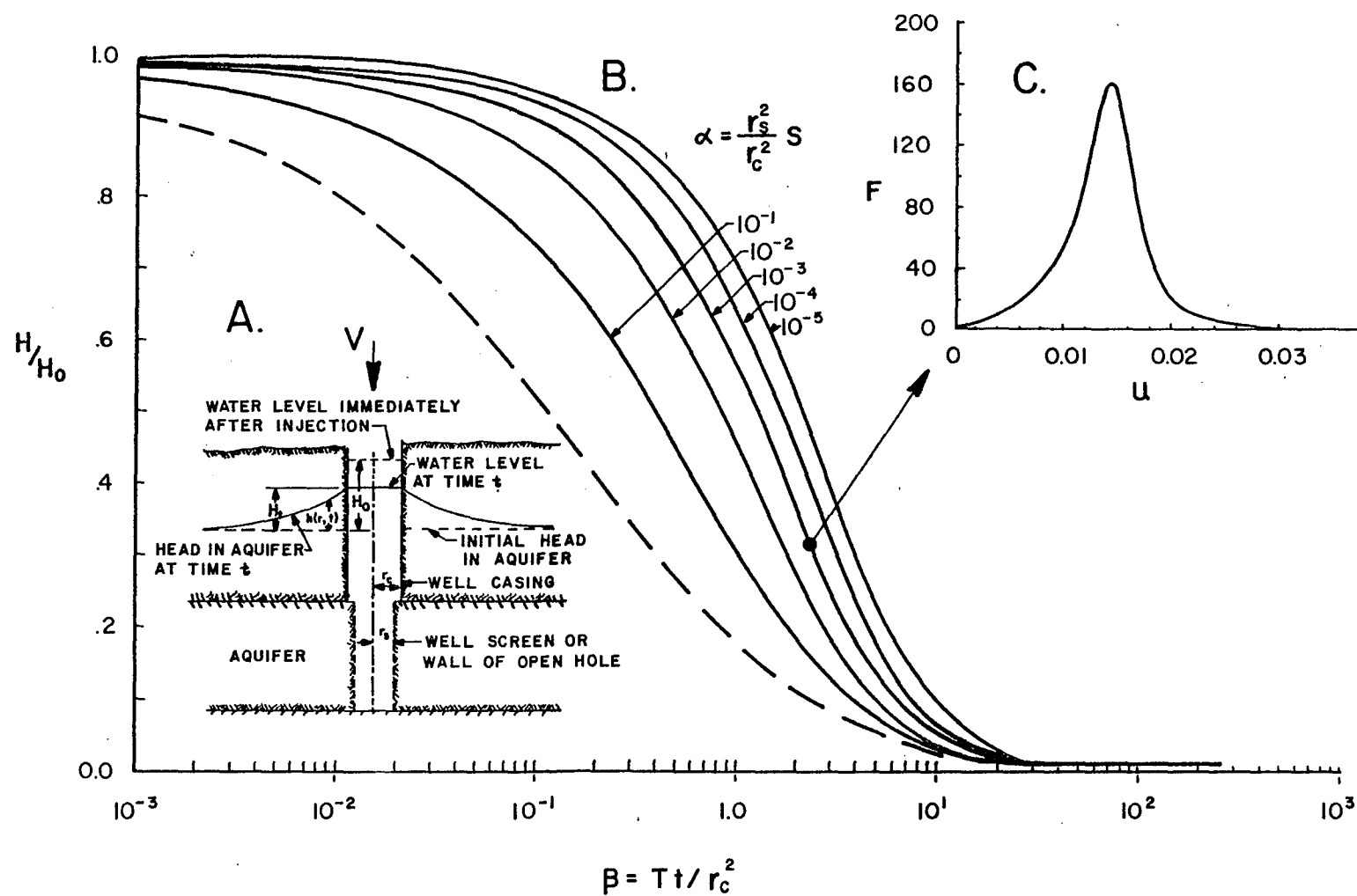


FIGURE 8.11 SLUG TEST SCHEMATIC AND TYPE CURVES

Curves for α between -1 and -10 were taken from Cooper et al. (1967). Curves for α between 1 and 100 were computed by the writers by numerically integrating Equation 8.1 using adaptive Romberg quadrature. Computations were made on a Hewlett Packard 9816 microcomputer.

To determine the hydraulic properties of each aquifer tested, field data were first plotted in an H/H_0 versus log time format at the same scale as the type curves. An example is shown in Figure 8.7. The data were then overlain on the type curves and translated laterally (with the horizontal axes coincident) until the data curve related to a particular value of α . The hydraulic conductivity T was computed from the expression $\beta = Tt/r_c^2$, knowing the value of β from the type curve and the corresponding value of t from the data curve at an arbitrary point selected on the two matched curves. The storage coefficient S was computed from the expression $\alpha = (Rs/Rc) S$.

Cooper et al. (1976) make the following comments concerning the slug test method:

1. The test duration is very short. Consequently, the estimated hydraulic conductivity will be representative only of the rock material close to the piezometer. Furthermore, serious errors could be introduced unless the piezometer is fully developed and completely penetrates the aquifer.
2. Since the vertical permeabilities of most stratified aquifers are only small fractions of the horizontal permeabilities, the induced flow within the small cone that develops during the test is likely to be essentially two-dimensional. The computed value of T would then be expected to represent the rock at the same elevation as the piezometer screen, provided that the aquifer is reasonably homogeneous and isotropic in planes parallel to the bedding and provided the effective radius can be closely estimated.
3. Estimated values of storativity could be in error by perhaps an order of magnitude or more, depending on the assurance with which the data can be matched with a type curve.

In its application at the Kitt Mine, the method has yielded values of hydraulic conductivity consistent with those determined using conventional pump tests. The method has also yielded estimates of storativity (which the single-boring pump tests did not). These estimates of storativity appear reasonable for the rock units tested.

9.0 GROUND SURFACE MOVEMENTS

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INTRODUCTION

Subsidence is defined as settlement of the ground surface in response to underground mining, and is accompanied by heave as well as by lateral movement toward the center of the subsidence trough. The amount of settlement (particularly differential settlement), the ground slope, curvature and strain all relate to potential effects on structures at ground surface. (There were no structures above the C-3 panel).

Ground surface measurements made during retreat mining in the C-3 panel and during the first two years after mining have defined longitudinal and transverse subsidence profiles above the panel, as well as profiles of ground movements in directions parallel and transverse to the direction of mining.

Subsidence along the C-3 panel was detected by survey only after a 360- by 500-foot area (0.6 by 0.8 times the overburden thickness, H) had first been mined out. This was on October 18, 1982 (Survey 9), Figure 3.2. The maximum trough depth at that point was less than an inch.

The trough increased in depth and areal extent as the mined-out area enlarged and eventually occupied the entire mine panel. The maximum trough depth at that point was 1.8 feet. Bounding the mined-out area to a distance of 350 to 400 feet (0.58 to 0.67H) from the margin of the panel was a heave zone whose maximum amplitude was on the order of an inch.

As retreat mining progressed in the C-3 panel, subsidence data from successive monuments along the direction of retreat mining began to approximate a common subsidence curve. This suggested that a limiting condition was being approached at the site relative to the width of the panel.

Time-dependent (creep) movements took place while mining was underway, the probable result of slippage along bedding surfaces, fracturing of the rock and bearing capacity failure of the mine floor along one boundary of the panel. Time-dependent movements continued after the completion of retreat mining, causing residual subsidence. The rate of residual subsidence appeared to diminish appreciably about 4 months after the completion of mining. By that time, maximum subsidence had increased 4.8 inches (about 24 percent) in excess of the 1.75 feet measured at the completion of mining.

At no time was subsidence perceptible with the naked eye. No ground cracks appeared even in zones of known ground extension. Modifications to ground slope or lowering of the ground surface could not be discerned within the mildly hilly topography of this typical Northern Appalachian site.

The following presentation begins with a discussion of survey monument layout and construction, survey equipment and survey schedule. The presentation then turns to ground movements, first, in vertical planes parallel and transverse to the direction of mining and second, in the horizontal plane. Horizontal movements are discussed in terms of components parallel and transverse to the direction of mining. The presentation closes with a discussion of parameters that characterize the subsidence trough and how they relate to predictions made using one of the more widely used methods in the Eastern Coal Fields.

SURVEY MONUMENTS AND SURVEY EQUIPMENT

Monument Network

The survey monument network utilized in the monitoring program is shown in Figure 4.3. The monument lines were laid out in consideration of Kitt Energy's original mine plan, which consisted of two side-by-side panels (C-3 and C-5), Figure 3.3. Two longitudinal lines of monuments were constructed—one along the proposed centerline of each panel. A transverse line of monuments was constructed perpendicular to the panel centerlines so as to bisect the two panels and accommodate their unequal lengths.

After construction of the monuments, Kitt Energy changed the mining plan from a two-panel to a one-panel system, the single panel (now designated C-3) encompassing the two original panels but being two pillar rows narrower than their original combined widths. As a result of this change, the west longitudinal line of monuments came to be located 60 feet ($1/10$ the panel width) from the west lateral boundary of the panel and the east longitudinal line of monuments 180 feet ($3/10$ the panel width) from the east lateral boundary of the panel. The absence of a longitudinal line of monuments along the centerline of the revised panel prompted the installation of five additional outlying monuments along a longitudinal line passing through the transverse monument line offset, effectively creating a longitudinal line of monuments at a distance $4/10$ the panel width from the west lateral boundary of the panel. Funds were not available to construct a continuous series of monuments like those of the east and west longitudinal lines of monuments. However, the data obtained were sufficient to define the general ground movement trends along that alignment.

The east and west longitudinal survey lines, as constructed, extended about 420 feet ($0.7 H$) beyond the vertical projection of the north end of the panel bounding the main entries, in accordance with recommendations presented in the National Coal Board

Subsidence Engineers Handbook, 1975. The transverse survey line extended a similar distance beyond the panel edges. The longitudinal survey lines extended southward to the limits of the company property. The lines were sufficiently long to define all or part of the heave zone bordering the panel.

A monument spacing of 0.05 times the overburden thickness ($H/20=30$ feet) was chosen to achieve satisfactory definition of slope, curvature, extension and compression within the subsidence profile.

In order to interpret ground movements in terms of principal strains, the transverse monument line across the west half of the panel was constructed as a series of equilateral strain triangles, 30 feet on a side. A standard survey tape tensioned with a constant force was used to measure changes in distance between monuments as a supplement to conventional survey measurements. In addition, two individual strain triangles were constructed along each of the east and west longitudinal lines to provide a comparison with movements indicated by the transverse row of monuments. Altogether, 197 monuments were installed above the C-3 panel, 44 along the west leg of the transverse line (numbered 7-51), 33 along the east leg of the transverse line (numbered 57-89), 50 along the east longitudinal line (numbered 90-140), 61 along the west longitudinal line (numbered 141-202) and 9 along the middle longitudinal row. The number of survey monuments in each row is effectively greater insofar as monuments located at the intersections of monument lines can be used twice. Key monument numbers are presented on Figure 4.3 and on ground movement plots discussed below.

Benchmarks

Four permanent benchmarks were established at distances at least 600 feet (1H) beyond the closest edge of the pillar extraction panels in stable, level ground unaffected by prior mining and beyond the influence of present mining. In practice, a benchmark 3860 feet east of the site was used to establish the instrument datum at the beginning and end of each survey day and after monitoring every sixth monument throughout the day. Two other benchmarks, one 700 feet southeast and the other 1000 feet south of the site, served as instrument check points at the beginning and end of each day. The fourth benchmark served as a backup.

Monument Construction

Survey monuments were constructed of 5-foot lengths of 0.75-inch diameter steel reinforcing bars set to a depth of 4 feet below ground surface and anchored in 12 inches of concrete at the bottom of the hole. A stiffer, 2-inch diameter, concrete filled steel pipe was substituted for the reinforcing bar in the strain triangle monuments. A 36-inch long, 4-inch diameter PVC pipe was placed over each reinforcing bar to isolate it from frost heave and other potential movements of the surrounding soil. The space between the PVC pipe and the reinforcing bar was filled with a thick slurry mixture of bentonite and motor oil. This permitted free movement of monument components and sealed off all but the top 10-inch protruding section of the monument from the elements.

Survey Equipment

Field monitoring was conducted using a Keuffel & Esser Vectron electronic theodolite and Auto Ranger electronic distance measuring device. The angular resolution of the Vectron is quoted by the manufacturer as being 3.24 seconds horizontal and

vertical (Keuffel & Esser, 1980). The resolution of computed coordinates is reportedly 1 millimeter (0.0394 inch). The range of the Auto Ranger EDM is 3 feet to 1.25 miles, with a resolution of 1 millimeter and an accuracy of $\pm(5\text{mm}+6\text{ppm})$ in the temperature range 20°F to 105°F (Keuffel & Esser, 1979). The survey instruments were stationed at a point on a hilltop immediately west of the site (Figure 4.3), where 95 percent of the monuments could be viewed. Separate set-ups were required for the eastern extremity of the transverse line and the northern extremity of the east longitudinal line.

Surveys

The monitoring program was designed so that the monuments would be surveyed one month before the initiation of retreat mining, during pillar extraction operations when mining had advanced 1/8, 1/4, 3/8, 1/2, 3/4 and the full panel length, and six months after the completion of mining. Each survey was designed to include all monuments between the south end of the longitudinal monument line (the end from which mining began) and a point 420 feet (0.7H) beyond the position of the pillar retreat line at the time of the survey. All surveys were Second Order.

The writers coordinated with Kitt Energy engineering staff on a continuing basis so that surveys would be conducted at optimal times relative to the mining operation. One of the writers participated for the duration of each survey to ensure the collection of as much data as possible during each outing. With this approach, the monitoring program was conducted essentially as planned, with certain exceptions imposed by field conditions and by field observations that prompted the investigation of certain aspects of the subsidence process in more detail. The net effect was that more surveys were conducted than originally planned.

1. In the six months preceding mining, five surveys were conducted to confidently establish a firm, reproducible ground surface datum, and at the same time identify and resolve potential difficulties in survey procedures before the initiation of retreat mining. One of these surveys was conducted to incorporate supplementary survey monuments installed as a result of Kitt Energy's change in mining plan.
2. In the six months of retreat mining, nine surveys rather than six were conducted. These surveys were aimed towards both documenting the evolution of the trough from its earliest stages and defining the limiting subsidence conditions being approached as the mined-out area became larger.

In order to relate ground surface movements to mining operations, the precise location of mining operations was recorded concurrent with surface survey measurements. These are presented in Figure 3.2 of Section 3, Mining Program.

Several of the surveys were not as complete as planned owing to climatic conditions and certain functional problems that hampered the survey process--ground fog and haze (the lower portion of the site was swampy); high winds (the wind effect was sometimes significant owing to the location of the theodolite station on a hilltop overlooking the site; wind speeds exceeded 100 miles per hour on at least one occasion); and rain, sleet, snow and winter temperatures. Precipitation reduced visibility and when moderate to heavy caused survey shutdowns. Low temperatures reduced theodolite battery life,

necessitating several battery changes per day, each power-up requiring a recalibration of the instrument relative to the offsite benchmarks. Owing to the fact that underground mining continued regardless of weather at ground surface, surveys interrupted on account of weather were sometimes not resumed since ground conditions at the conclusion of the survey would not have matched those at the beginning. Instead, additional surveys were conducted. In any case, the survey data collected during retreat mining, taken together and viewed in the context of families of curves, are sufficiently extensive and precise both in the vertical and horizontal planes to clearly define the stages in development of the subsidence trough.

3. During the post-mining phase, eight surveys rather than one were conducted in order to more clearly define residual subsidence characteristics. Several factors during retreat mining suggested that pronounced residual subsidence might occur: a) bearing capacity failure of the mine floor beneath certain bleeder entry pillars; b) flooding of the gob area as mining progressed; c) the possible existence in the gob of local openings several feet high; d) slippage of overburden strata along bedding surfaces and; e) the potential loads transferred to the C-3 panel due to mining in the D-3 longwall panel on the opposite side of the C-Mains.

The post-mining surveys defined the spatial and temporal characteristics of residual subsidence.

GROUND MOVEMENTS

Ground movements are three-dimensional and are customarily defined in terms of three components -- (1) vertical, (2) horizontal in a direction parallel to overall mining* and (3) horizontal in a direction transverse to overall mining. Each component of subsidence occurring during retreat mining and over the first six months following mining is discussed, first, in relation to the three longitudinal survey lines and, second, in relation to the east and west legs of the transverse survey line.

The nominal position of the retreat line in relation to the respective survey line is identified in each figure. Reference is made to Figure 3.2 for a more detailed representation of the retreat line and configuration of the mined-out area at each stage of mining. Survey data for the end-of-mining (Survey 16) and final post-mining readings (Survey 23) are presented in Appendix 9.1.

VERTICAL GROUND MOVEMENTS

Subsidence Along Longitudinal Survey Lines

Refer to Figures 9.1 (west line) and 9.2 (east line).

*Overall mining refers to the south-to-north movement of the retreat line rather than to the west-to-east movement across the width of the panel that is associated with pillar extraction in a particular row.

Observations are these:

1. Subsidence along the west longitudinal survey line was first perceptible by survey in mid-October (Survey 9) after 36 pillars had been extracted and the mined-out area beneath the line had reached 360 feet in length, and along the east longitudinal survey line in late October (Survey 11) after 44 pillars had been extracted and the mined-out area beneath that line had reached 270 to 360 feet in length. (The mined-out length is 270 feet as measured immediately east of the survey line and 360 feet as measured immediately west due to the stair-step south boundary of the panel.) Along the west line, the initial measured subsidence was less than 0.04 foot (0.5 inch) and along the east line less than 0.08 foot (1 inch).
2. The end-of-mining maximum subsidence (Survey 16) along the west line was 0.7 feet along the middle line, 1.8 feet, and along the east line, 0.95 feet. The lesser subsidence along the west line was probably associated with its lying only one pillar line from the edge of the mined-out area whereas the east line lay four pillar lines from the edge.
3. Subsidence taking place over the first six months following mining (through Survey 23) reached as much as 0.5 near the center of the mined-out area but was progressively less in the direction of the abutments. The measured post-mining (residual) subsidence represented a 28 percent increase in the maximum subsidence above the panel.
4. The profiles were asymmetrical.

The west, middle and east lines exhibited heave zones over the moving abutment (ahead of the retreat line in the direction of mining). The amplitude of the heave zone appeared not to exceed 0.1 feet in any case. The heave zone was less pronounced or absent altogether over the rear abutment. Along the three lines, the end-of-mining ratio of heave to subsidence ranged between 1/6 and 1/15, the lower ratio relating to the middle line along which the subsidence was relatively greater.

Vertical ground movements occurring on lines perpendicular to the direction of mining are considered next.

Subsidence* Along Transverse Survey Lines

Refer to Figures 9.3 (West Leg) and 9.4 (East Leg).

Observations are these:

1. Subsidence along the west leg was first perceptible by survey in late October, 1982 (Survey 11) after pillar extraction had taken place beneath the line, and along the east leg in early December (Survey 13) after the completion of mining in the row immediately preceding and adjacent to the survey row.

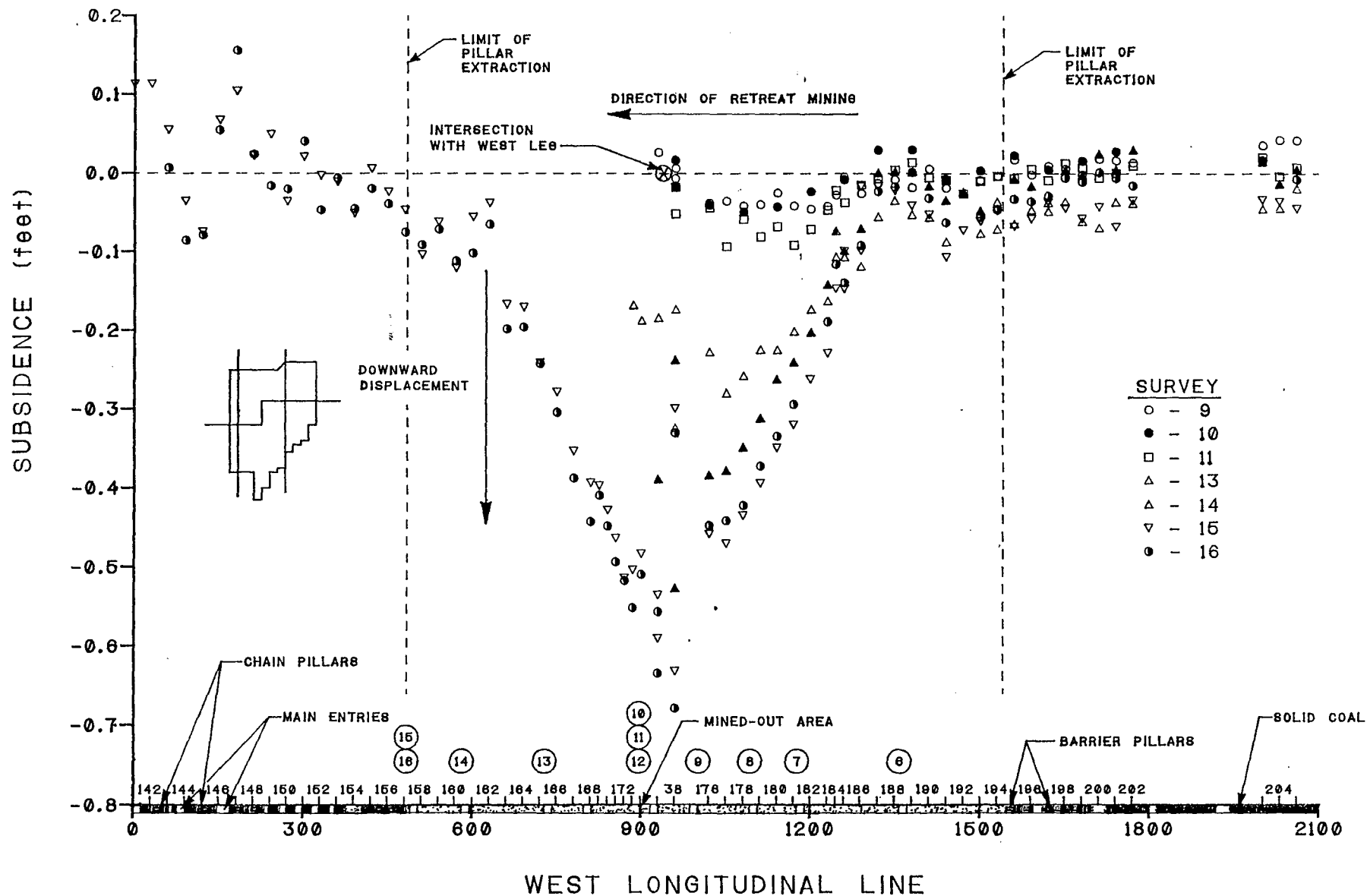


FIGURE 9.1-SUBSIDENCE ALONG WEST LONGITUDINAL SURVEY LINE
A. DURING RETREAT MINING

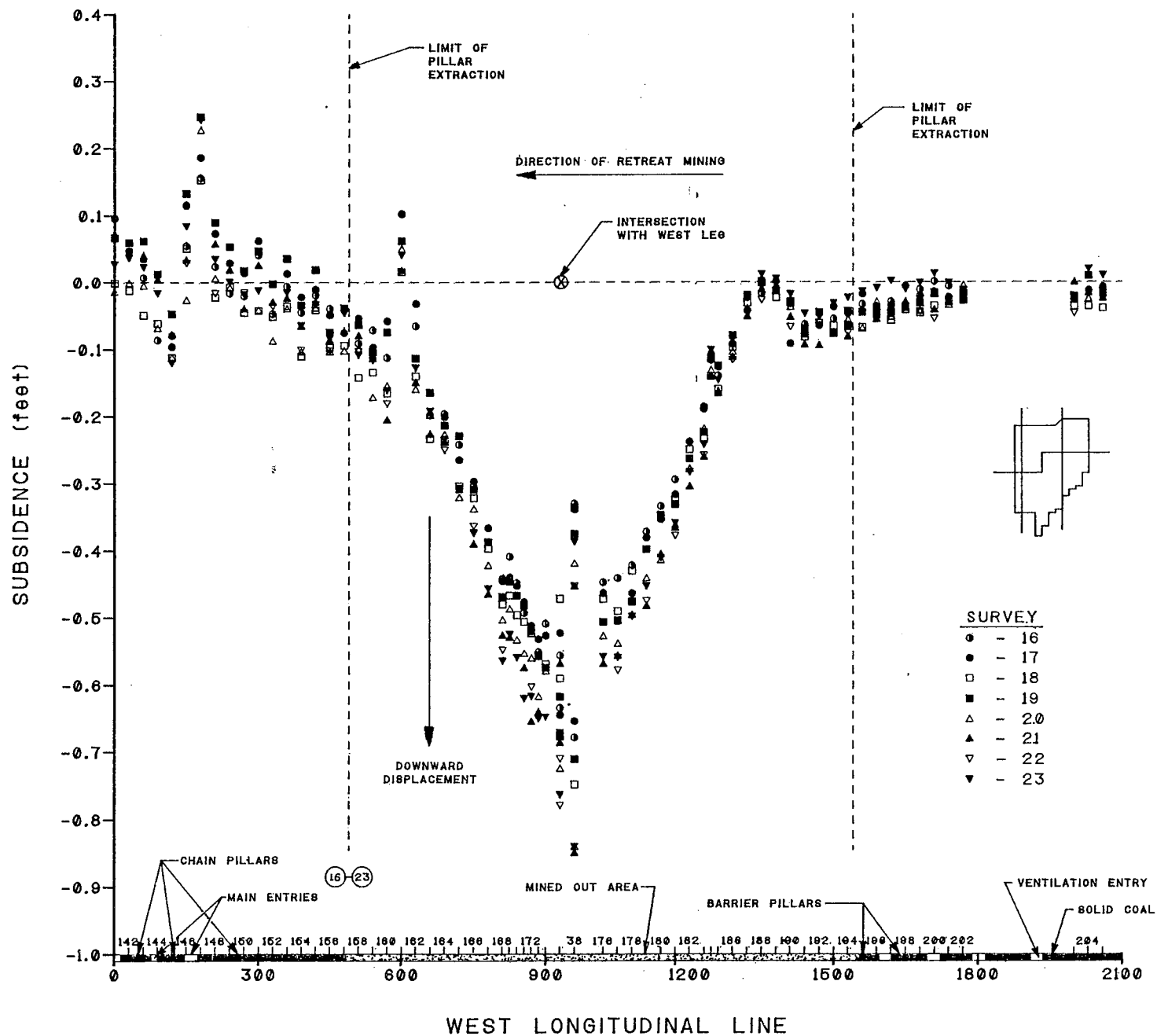


FIGURE 9.1 CONTINUED
B. FOLLOWING RETREAT MINING

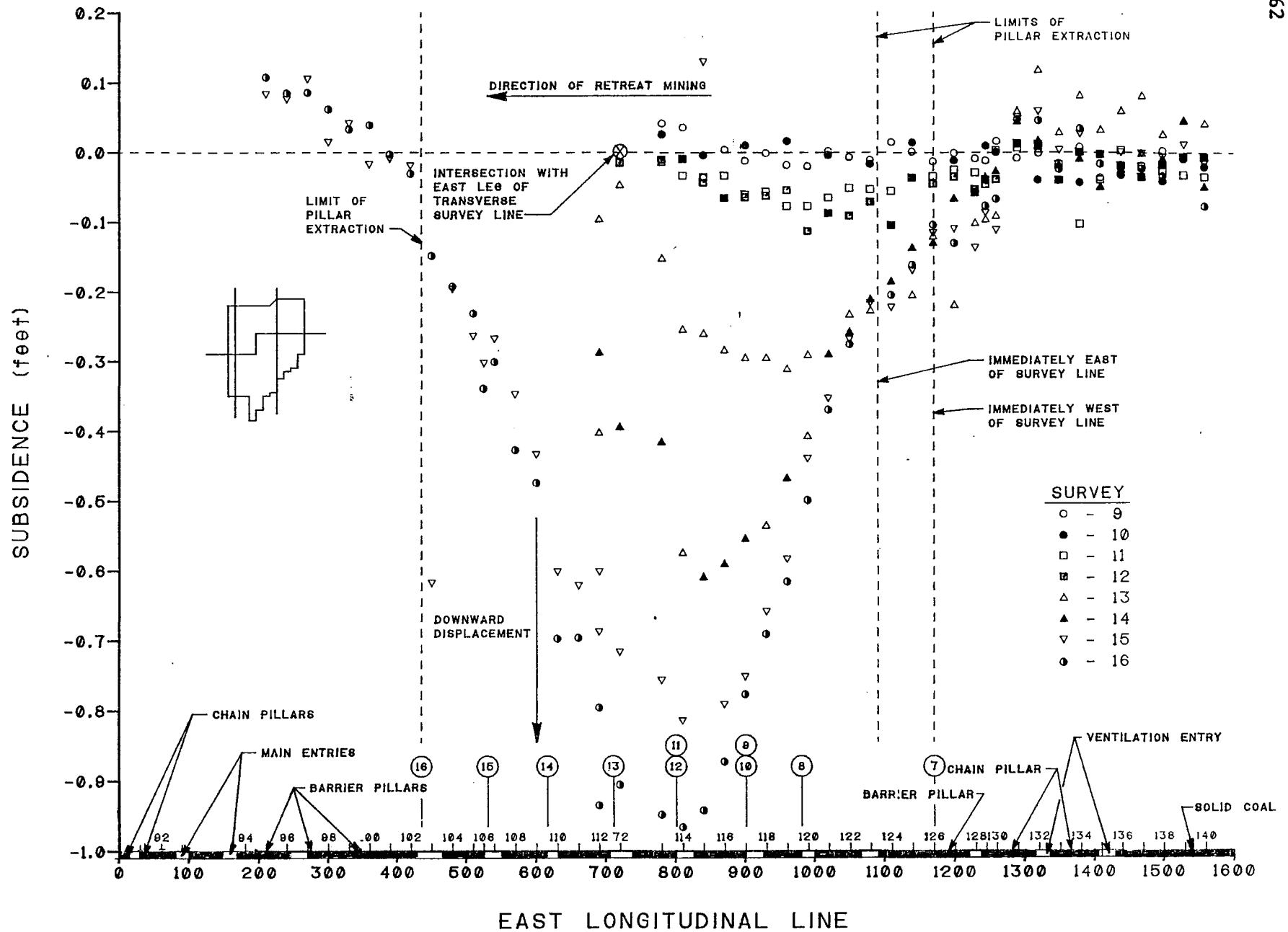


FIGURE 9.2 - SUBSIDENCE ALONG EAST LONGITUDINAL SURVEY LINE
A. DURING RETREAT MINING

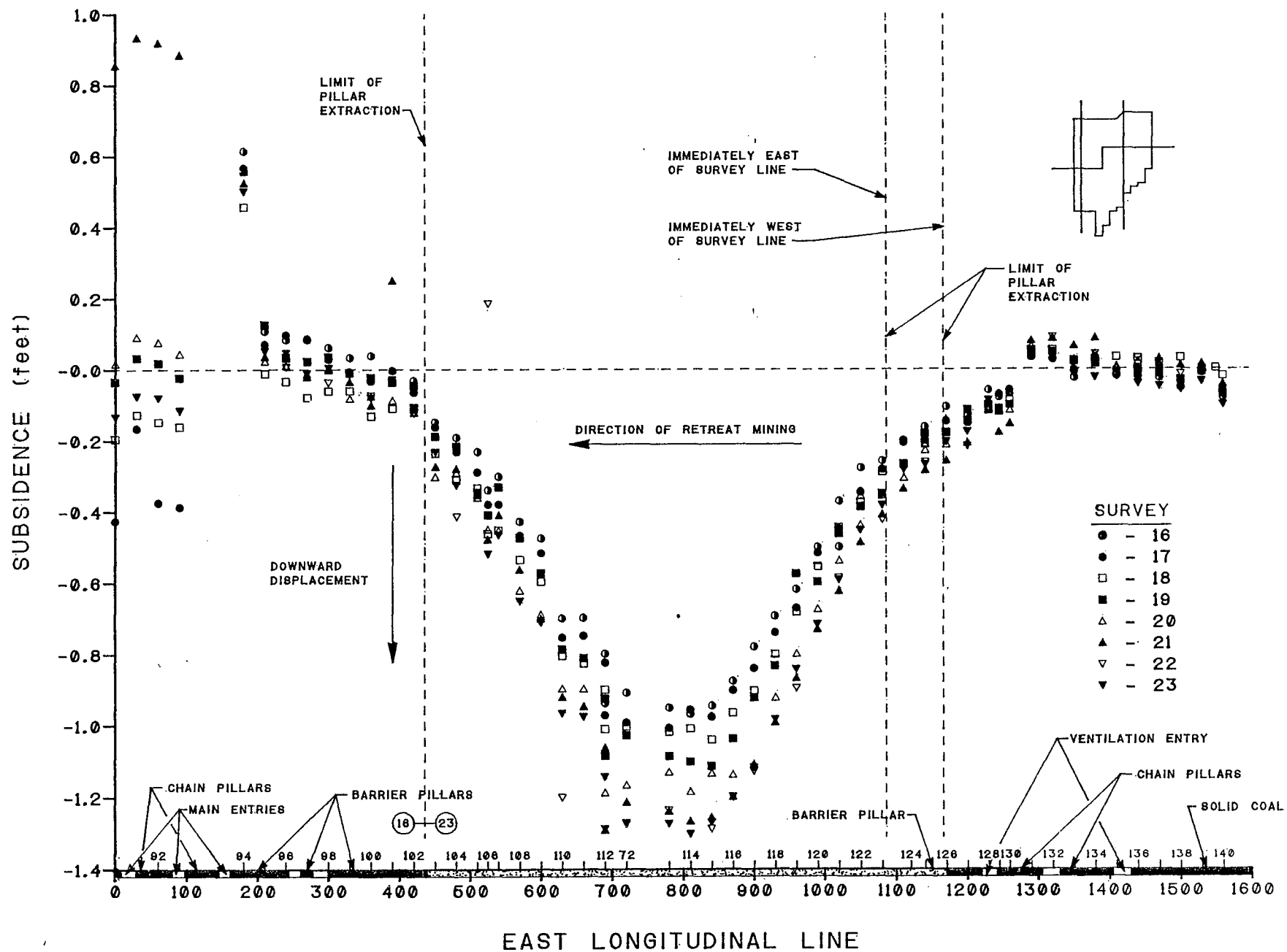
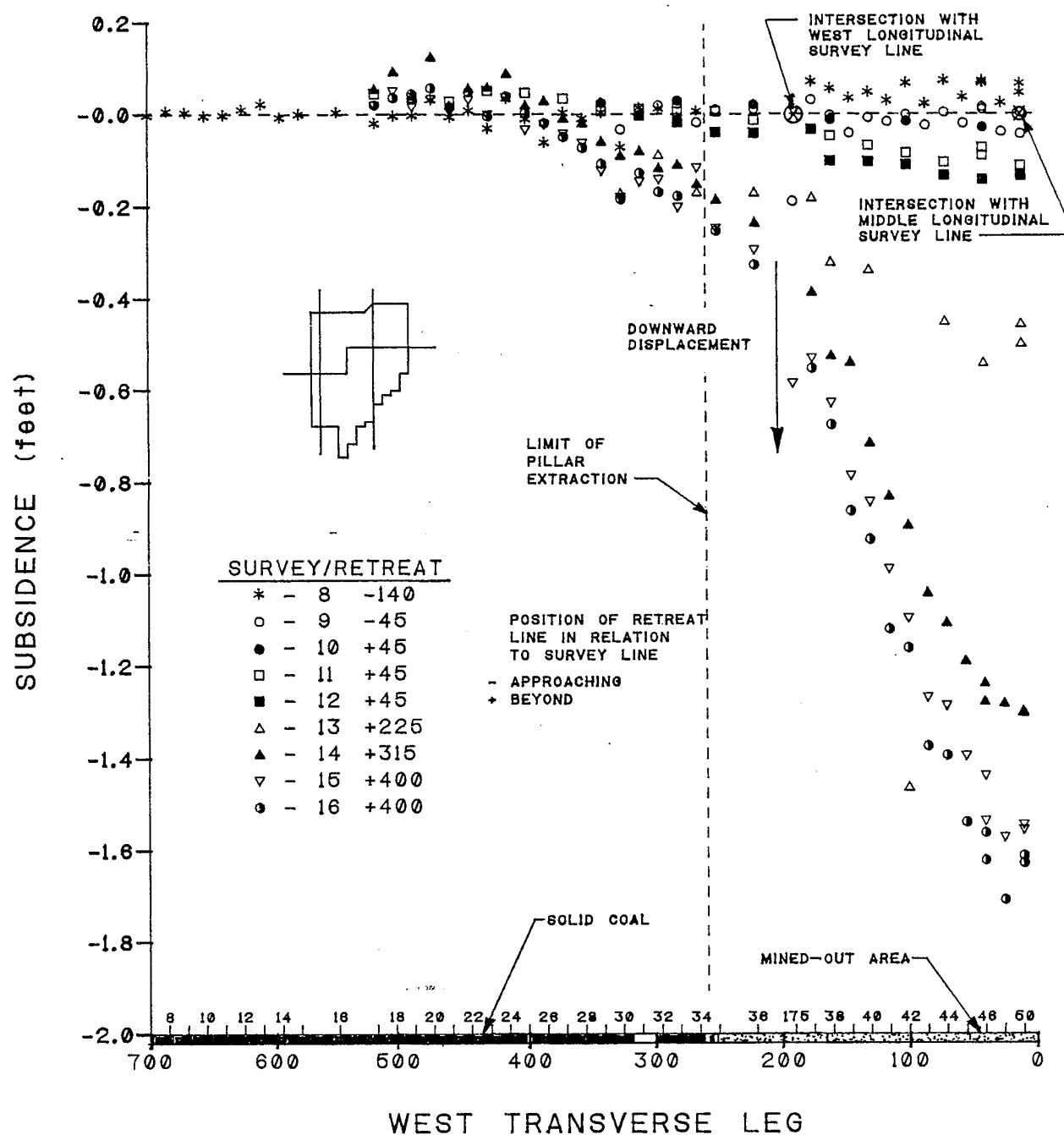


FIGURE 9.2 — CONTINUED B. FOLLOWING RETREAT MINING



BOM.A16

FIGURE 9.3 - SUBSIDENCE ALONG TRANSVERSE SURVEY LINE WEST LEG
A. DURING RETREAT MINING

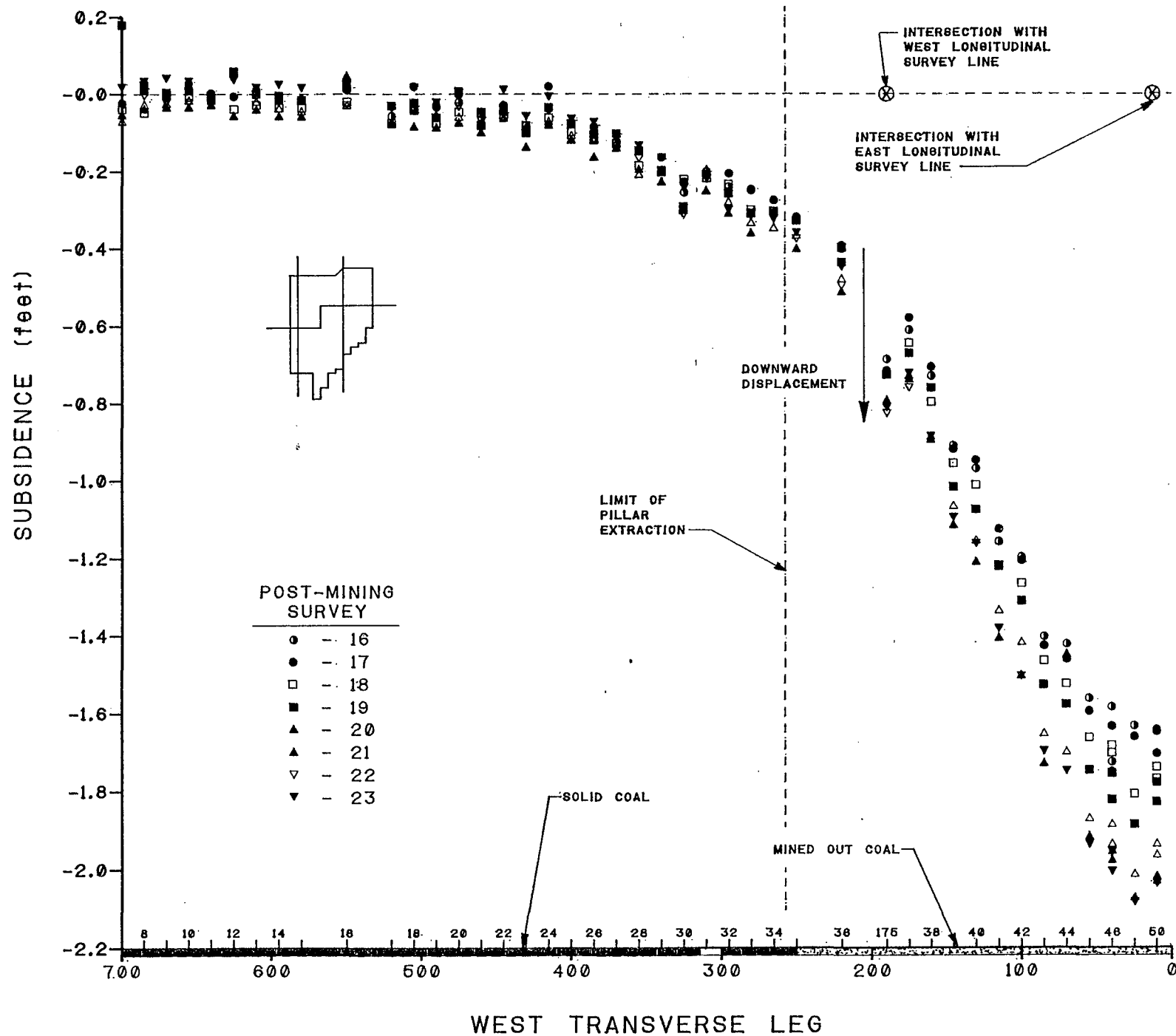


FIGURE 9.3 - CONTINUED
B. FOLLOWING RETREAT MINING

BOM.A23

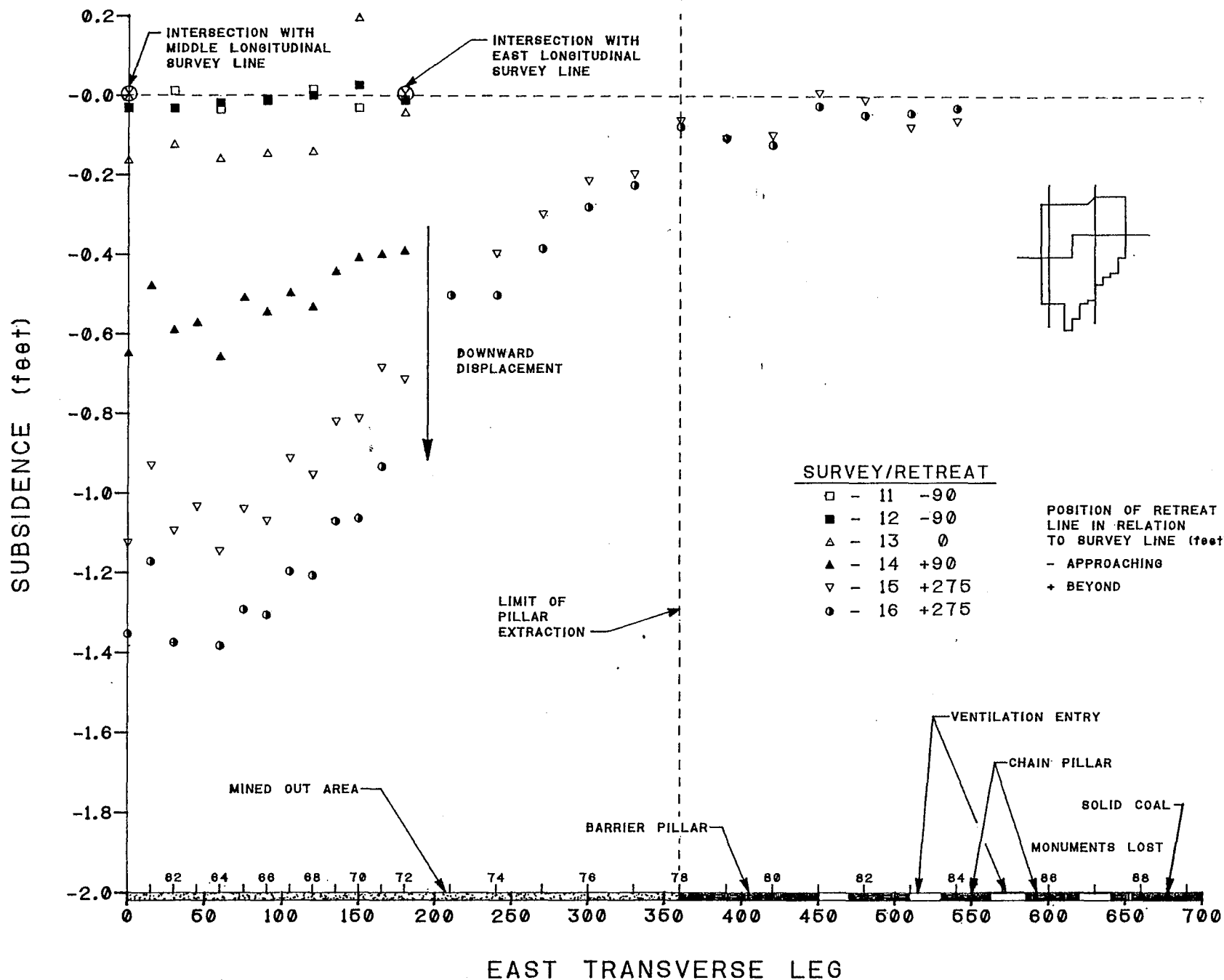


FIGURE 9.4 SUBSIDENCE ALONG TRANSVERSE SURVEY LINE--EAST LEG
A. DURING RETREAT MINING

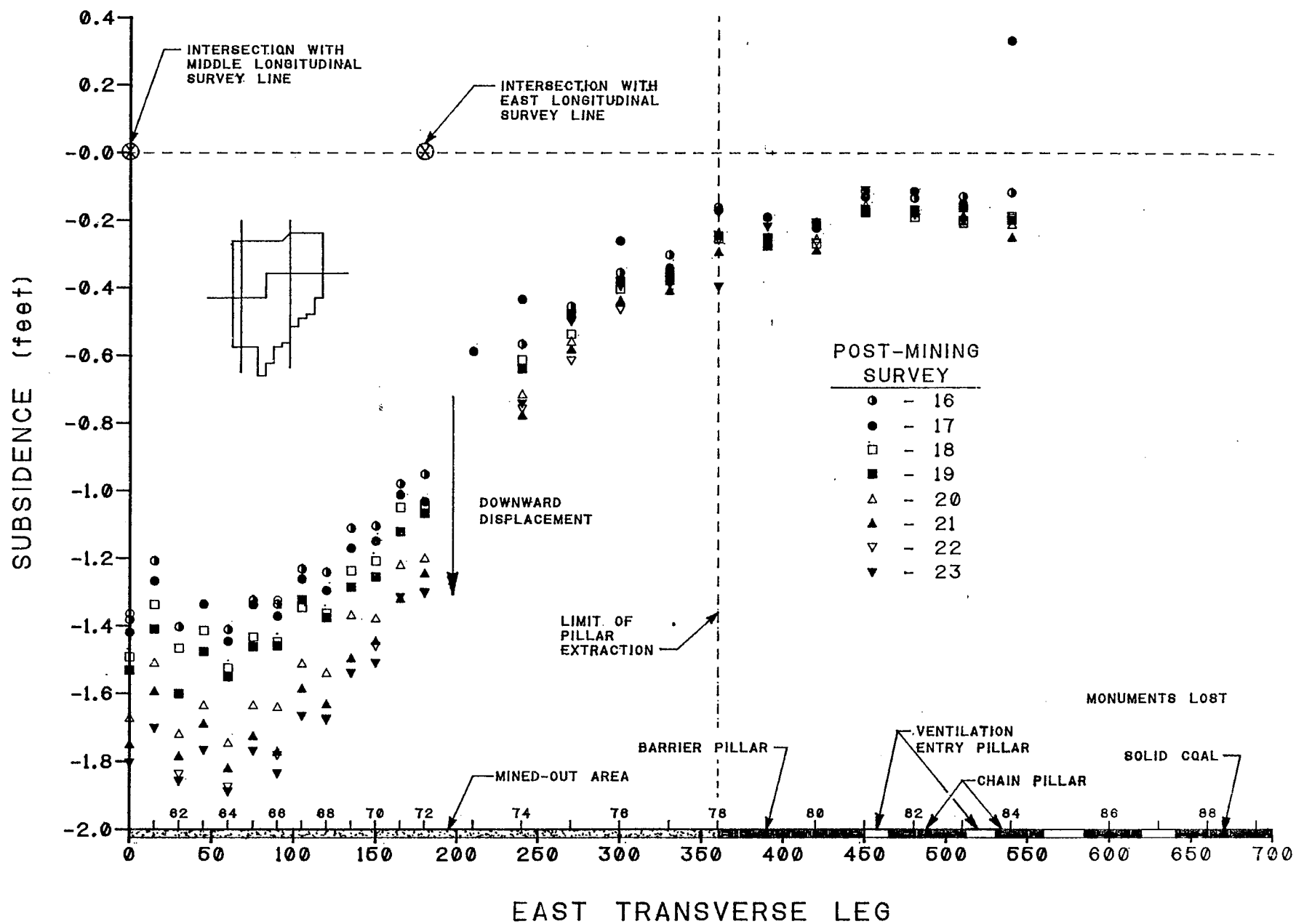


FIGURE 9.4 CONTINUED
B. FOLLOWING RETREAT MINING

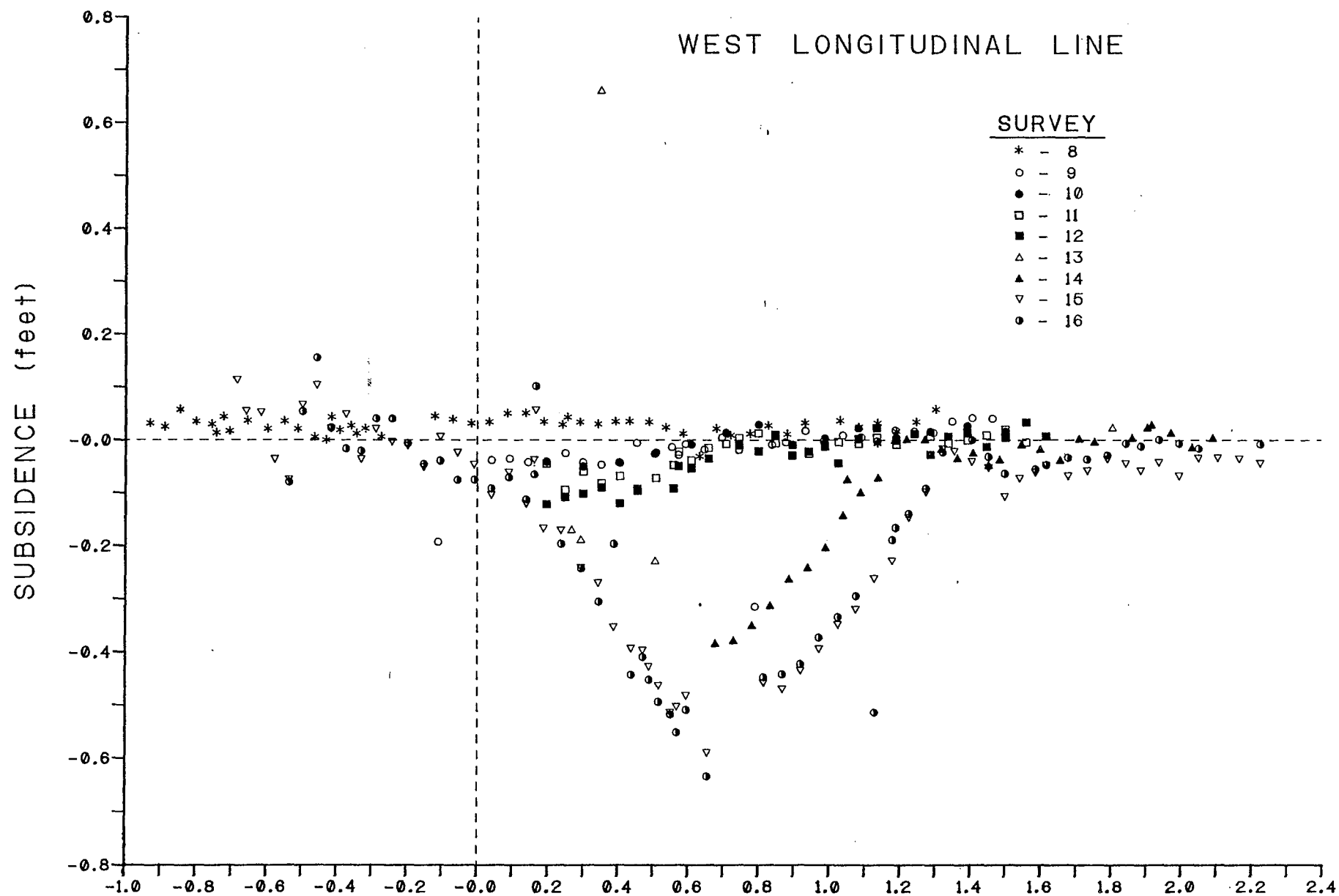
2. As retreat mining progressed, significant subsidence accompanied each move of the retreat line. The end-of-mining maximum subsidence (Survey 16) along the west leg reached 1.7 feet and along the east leg, 1.4 feet.
3. Over the first six months following mining, residual subsidence amounted to as much as 0.5 to 0.6 feet near the center of the mine panel and 0.1 foot over the boundary of the panel.
4. Perhaps the greatest distinction between the two sets of profiles is that the west leg exhibits heave over the abutment whereas the east leg does not. This may relate to the fact that along the east margin of the panel, a 280-foot wide series of barrier and ventilation entry pillars separate the mined-out area from the solid coal, whereas along the west margin only a 60-foot wide ventilation entry and pillar occupy that position. The east boundary of the mined out area may be comparatively less stiff than the west boundary due to the loss of bearing capacity of the mine floor. Some loss of bearing capacity may have taken place along the west boundary as well, but could not be confirmed because of poor roof conditions in that area.

Subsidence in Relation to Position of the Retreating Pillar Line

A subsidence development curve defines the relationship between subsidence of a specified point (survey monument) at ground surface at a particular stage of mining and the corresponding position of the retreating pillar line. The distance between the point and the vertical plane of the retreating pillar line measured in the direction of mining is denoted by X . The family of subsidence development curves serves to summarize the evolution of the subsidence trough during mining.

Several characteristics emerge from these curves (Figure 9.5A, B, C):

1. The initial movement of the ground surface is first recognized when the retreat line has approached to within $0.6H$ to $0.8H$ of the survey monument. At this point, the monument begins to move upward (heave).
2. Upward movement continues until the retreat line has approached to within $0.3H$ to $0.5H$ of the survey monument. The monument has then reached its highest elevation -- an amount that increases with size of the mined-out area but in this program did not exceed 0.1 foot.
3. Downward movement from the crest of the heave zone accompanies further approach of the retreat line. The monument has returned to its original elevation by the time the retreat line has approached to within $0.1H$ to $0.2H$ of the survey monument.
4. Downward movement below the original elevation -- subsidence -- occurs as the retreat line approaches, passes beneath and then beyond the survey of monument. The monument has reached 8 to 12 percent of the end-of-mining maximum subsidence when the retreat line is directly beneath the monument, 50 percent when the retreat line is $0.3H$ to $0.35H$ beyond the monument and end-of-mining maximum subsidence when the retreat line is $0.6H$ to $0.7H$ beyond the monument. Greater maximum subsidence would be expected had the panel been longer.



RETREAT LINE POSITION-TO-OVERBURDEN RATIO, X/H
 FIGURE 9.5 - SUBSIDENCE IN RELATION TO POSITION OF THE RETREATING PILLAR LINE
 A. WEST LONGITUDINAL SURVEY LINE

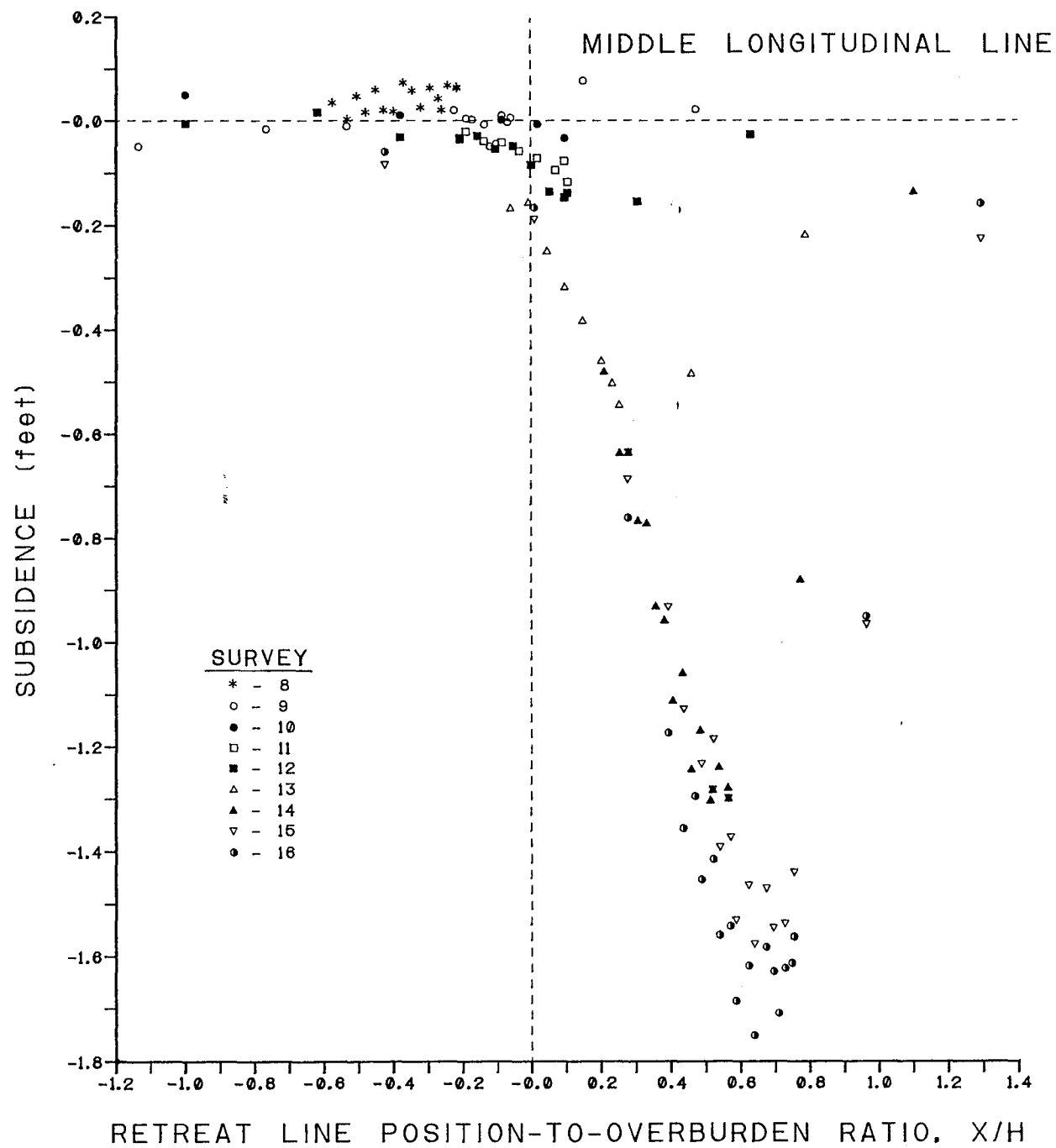


FIGURE 9.5 - CONTINUED B. MIDDLE LONGITUDINAL SURVEY LINE

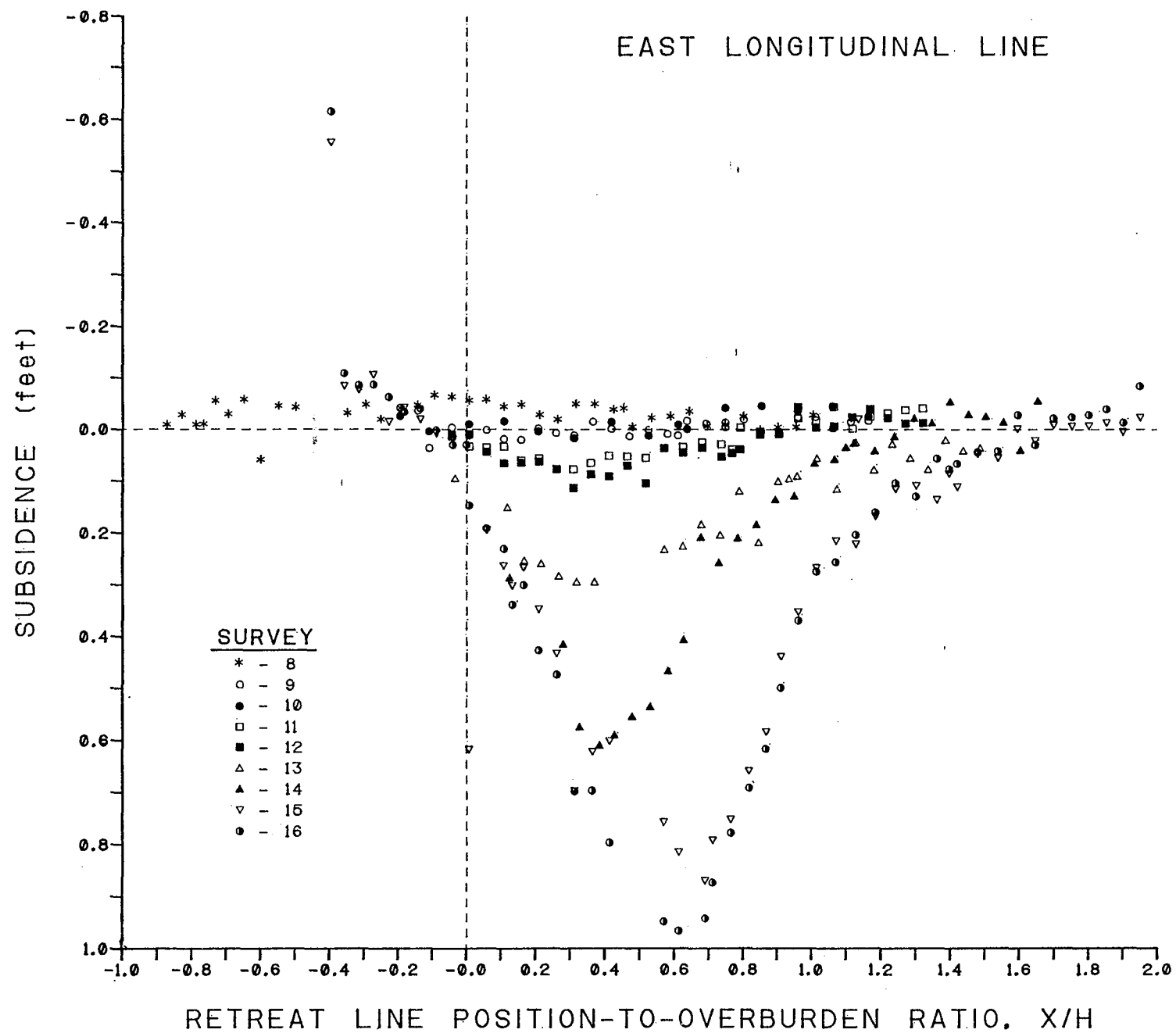


FIGURE 9.5 - CONTINUED C. EAST LONGITUDINAL SURVEY LINE

A few more general observations in relation to the C-3 panel are as follows:

A. For a given longitudinal line of monuments:

1. A family of subsidence development curves is defined, one curve for each monument along the survey line.
2. As illustrated by Figure 9.5 the farther a monument lies in the direction of retreat, the greater is the subsidence the point achieves. This should hold true to a limiting distance beyond which all points along a longitudinal line experience the same amount of subsidence relative to position of the mine face. At the C-3 panel, a limiting subsidence development curve is being approached that provides a common relationship between subsidence and X/H for all points along the survey line lying beyond that point in the direction of retreat. The limiting curve is approximated by the left limb of the family of curves in each figure--the limb into which the subsidence development curve for each monument appears to merge.
3. Each monument behind the limit line (in the direction from which retreat began) defines a unique subsidence development curve -- a subsidence development curve different from that of the monument ahead of or behind it along the same line of monuments.
4. Each monument subsides before the retreat line passes beneath. Thus, the angle of draw is positive.

B. Comparing longitudinal lines of monuments:

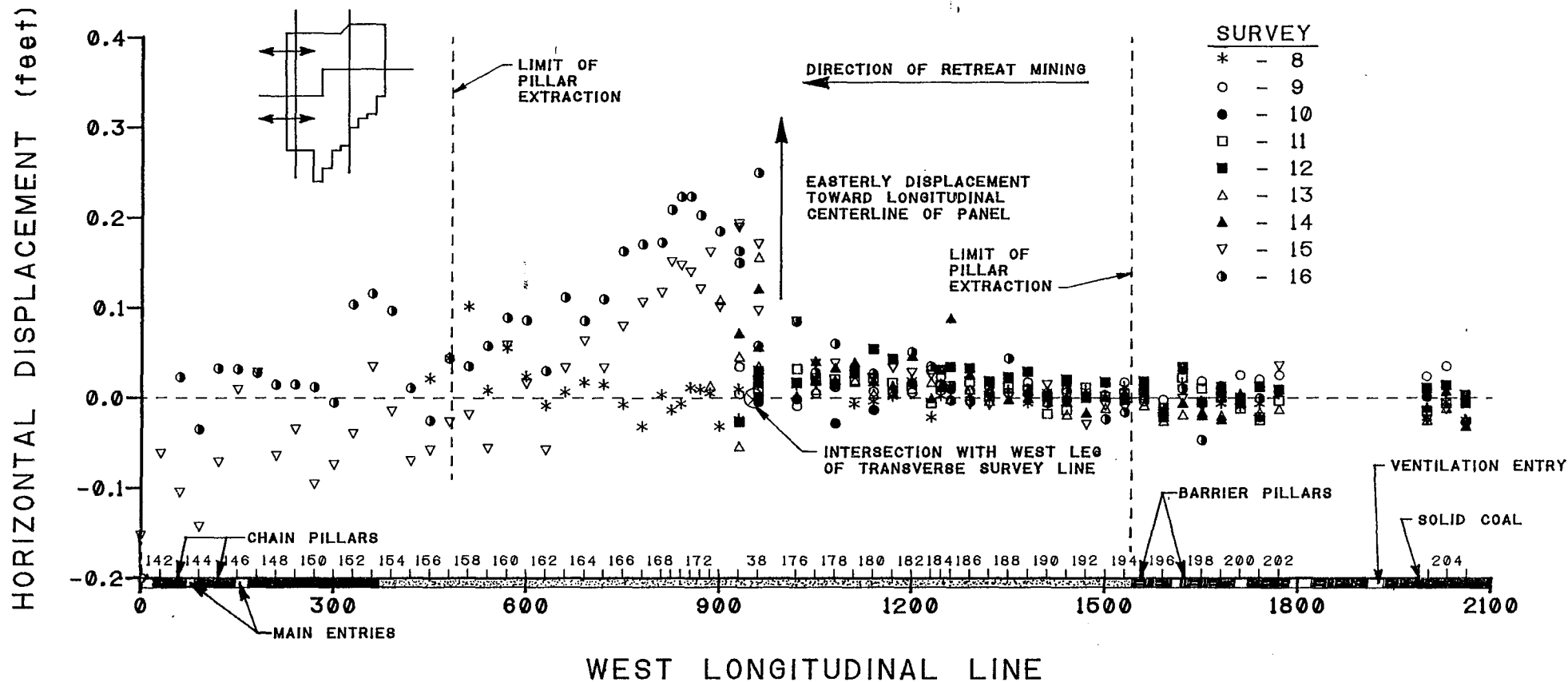
The subsidence development curves are steepest and of greatest amplitude along the middle longitudinal row of monuments. They diminish in steepness and amplitude with increasing distance from the centerline (and closer proximity to the panel edge). The subsidence development curve would be expected to degenerate to a horizontal line outside the panel at the edge of the trough.

HORIZONTAL GROUND MOVEMENTS

Horizontal displacements go hand-in-hand with vertical displacements. With approach of the retreat line, heave (and later subsidence) of a monument was accompanied by lateral migration of the monument toward the center of the mined-out area. Progressive enlargement of the mined-out area and the shift of its center (deepest point) in a northerly direction produced corresponding changes in the direction and amount of movement of points at ground surface.

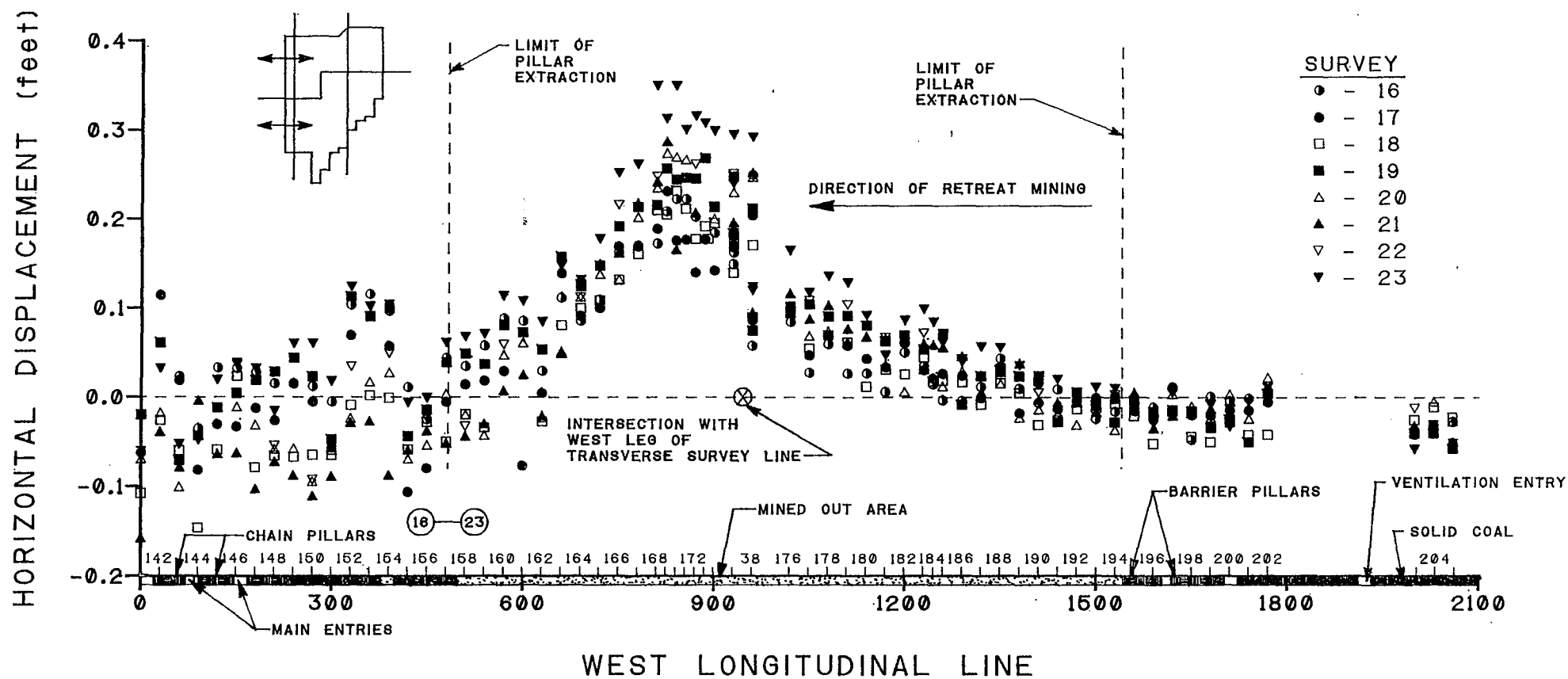
Horizontal Displacements Transverse to the Direction of Mining

Measurements of displacement in an east-west direction transverse to the west, middle and west longitudinal survey lines are presented in Figures 9.6, 9.7 and 9.8, respectively. The principal observations are these:



BOM.A37

FIGURE 9.6 HORIZONTAL DISPLACEMENTS TRANSVERSE TO THE DIRECTION OF MINING WEST LONGITUDINAL SURVEY LINE
A. DURING RETREAT MINING



BOM.A38

FIGURE 9.6 - B. FOLLOWING RETREAT MINING

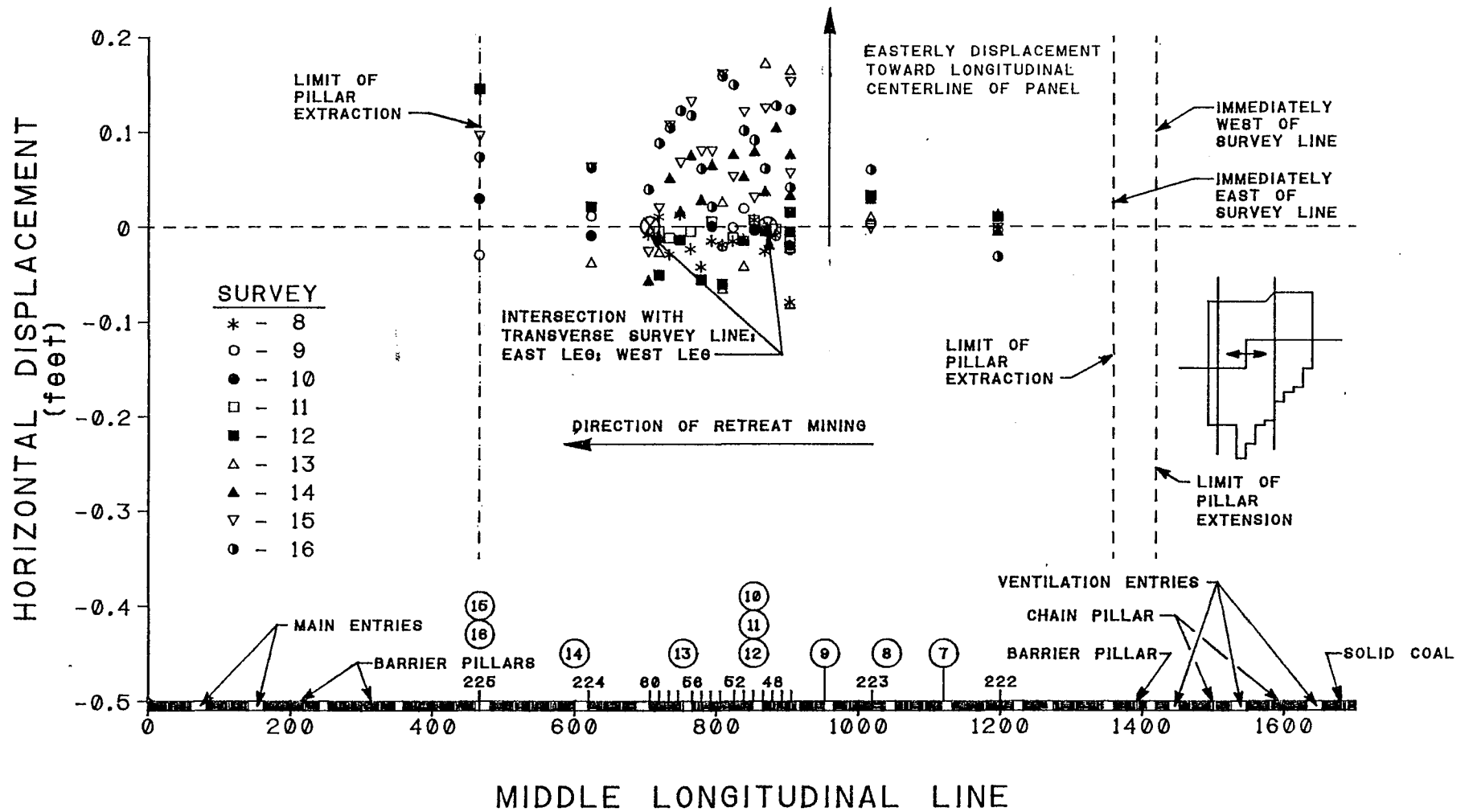
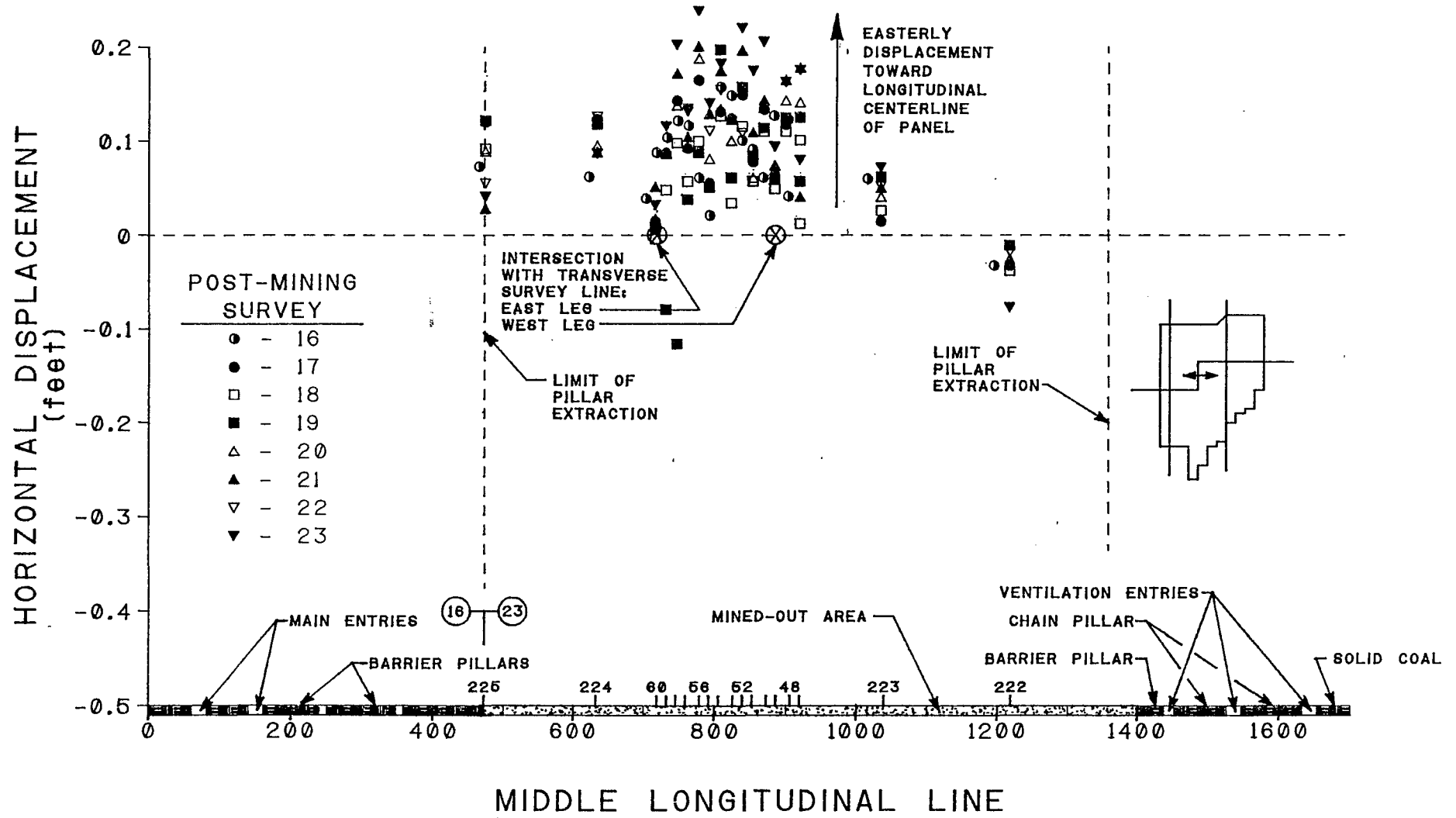


FIGURE 9.7 - HORIZONTAL DISPLACEMENTS TRANSVERSE TO THE DIRECTION OF MINING
A. DURING RETREAT MINING

BOM.A51



BOM.A62

CONTINUED

FIGURE 9.7 - B. FOLLOWING RETREAT MINING

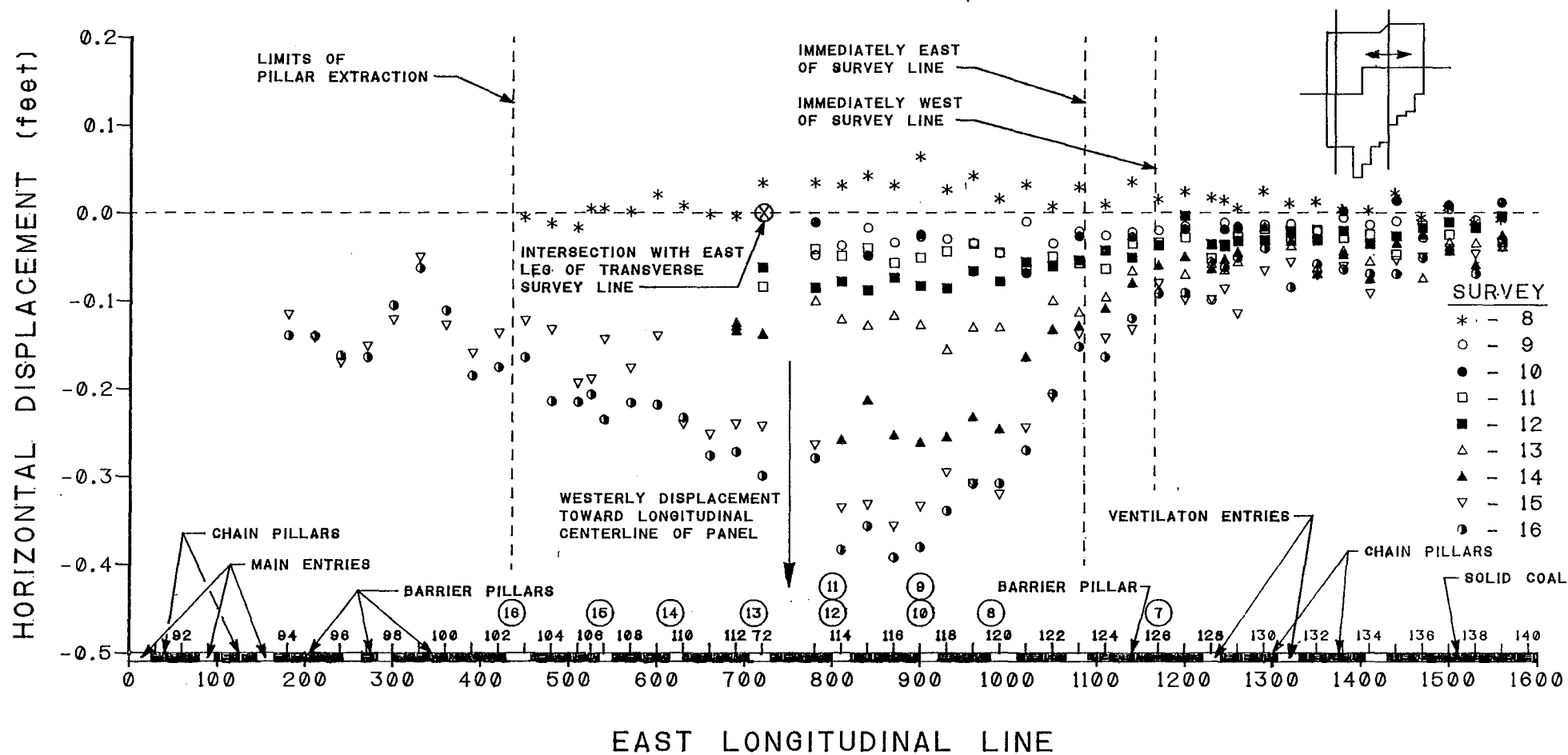


FIGURE 9.8 - HORIZONTAL DISPLACEMENTS TRANSVERSE TO THE DIRECTION OF MINING
A. DURING RETREAT MINING

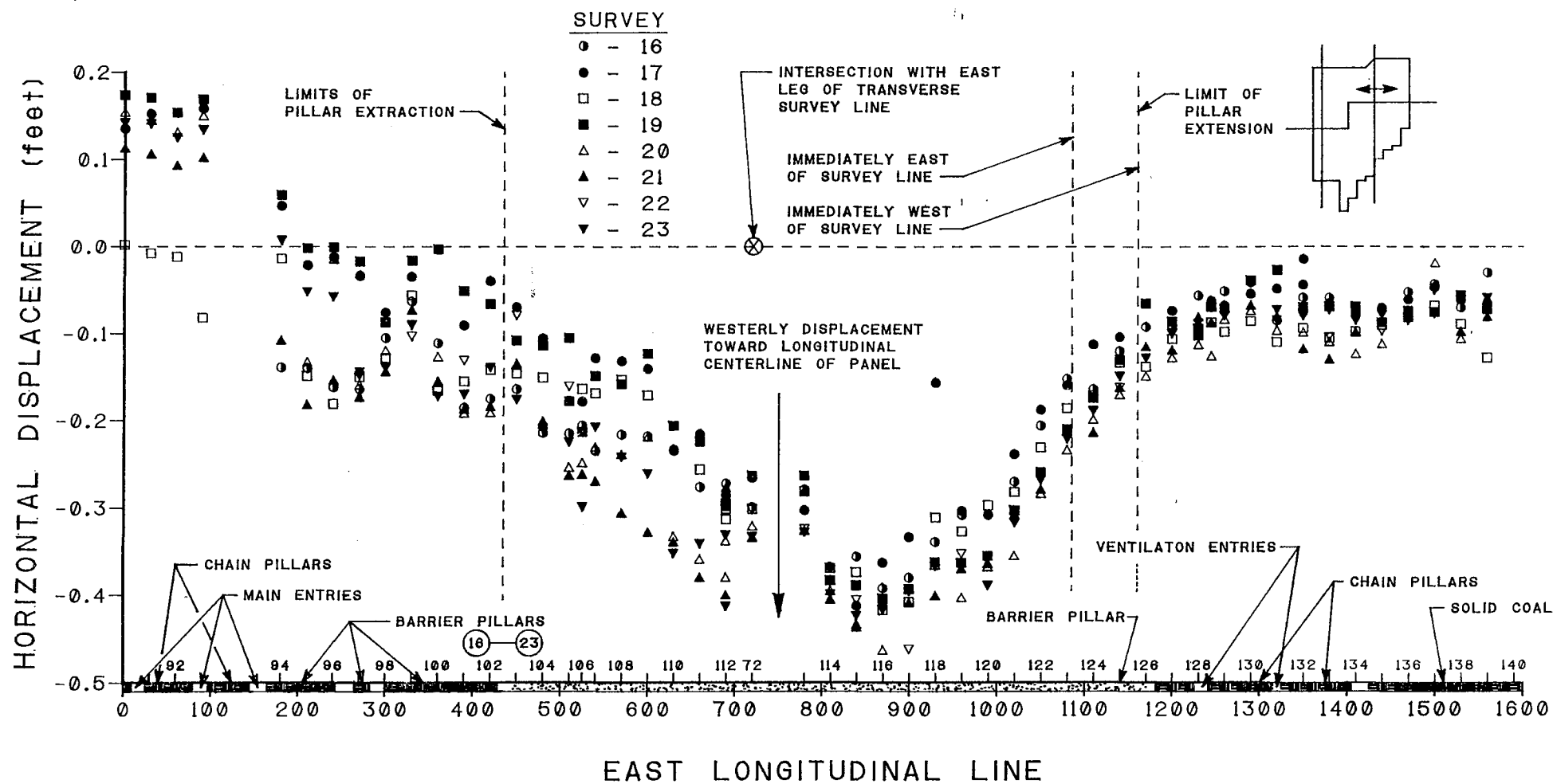


FIGURE 9.8 — CONTINUED

B. FOLLOWING RETREAT MINING

1. Transverse displacements were first recognized on the west longitudinal survey line in late October (Survey 11) after 44 of the 82 pillars had been extracted (54 percent) and the undermined section the that survey line had reached 630 feet in length. The maximum transverse displacement on that line was then about 0.02 feet (0.25 inch).

Transverse displacements were also recognized on the east longitudinal survey line in late-October (Survey 11) after the undermined section of that survey line had reached 180 to 270 feet in length. The maximum displacement was then about 0.03 feet.

2. The maximum transverse displacement increased as the size of the mined-out area increased. The end-of-mining (Survey 16) maximum transverse displacement along the west line was 0.22 foot and occurred approximately 250 feet (3/10 the undermined line length) south of the retreat line and along the east line was 0.38 foot and occurred approximately 420 feet (6/10 the undermined line length) south of the retreat line.

The end-of-mining maximum transverse displacement along the middle line was 0.15 foot and occurred approximately 350 feet (4/10 the undermined line length) south of the retreat line.

Transverse displacements were westerly through early December (Survey 13), but by early January (Survey 14) had become easterly and continued in this manner through the end of mining as well as for the duration of the post-mining monitoring period. By early January, mining was taking place in the second pillar row beyond the mid-panel series of monuments that constituted the largest part of the middle longitudinal survey line. The westerly to easterly shift in direction of transverse displacement appears to reflect a shift in the center (deepest point) of the mined-out area from the west side to the east side of the middle survey line. The fact that transverse displacements occurred at all along the middle survey line demonstrates that the line did not pass precisely through the center of the mined-out area (except for the brief period when the transverse displacement was zero).

3. To the south or north of the point of maximum transverse displacement, the amount of transverse displacement was progressively less the closer the monument lay to an abutment. On the west line, the end-of-mining transverse displacement was zero at or near both the south and north boundaries of the mined-out area. On the east line, the end-of-mining transverse displacement at the south boundary of the mined-out area was about 0.15 foot and approached but did not appear to reach zero in the 400 to 500 feet of survey line lying above the south abutment. The end-of-mining transverse displacement directly at the north boundary of the mined-out area was about 0.18 foot and between 0.1 and 0.18 foot over the first 250 feet of survey line lying above the north abutment.
4. Over the first six months following mining, an increase in maximum transverse displacement of 0.05 to 0.1 foot took place toward the mined longitudinal centerline of the panel. This represented an increase in maximum transverse displacement of as much as 40 percent.

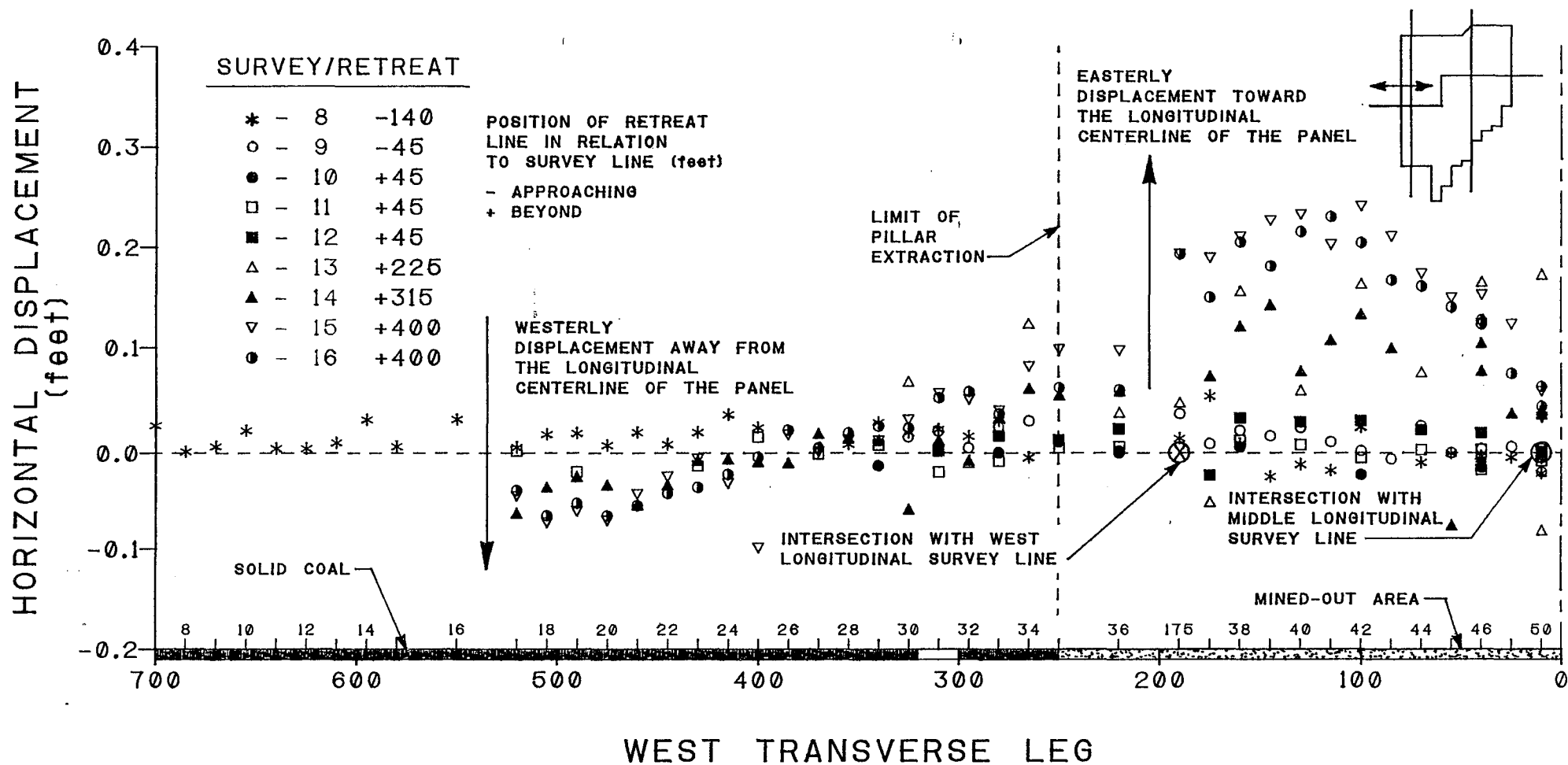
Transverse displacements along the west and east legs of the transverse line of monuments are shown in Figure 9.9 and 9.10, respectively. The principal observations are these:

1. Transverse displacements toward the longitudinal centerline of the panel were first recognized on the west leg in mid-November (Survey 12) after the pillars directly beneath the line had been extracted and the retreat line lay about 45 feet beyond the survey line. Comparable displacements on the east leg were first recognized in later October (Survey 11) when the retreat line had approached to within 90 feet (1 block) of the survey line.

In both instances, mining was nearing completion in the seventh row of pillars. Survey 11 had been performed after the extraction of Pillar 44 (the second from last pillar in the row) and Survey 12 after the extraction of Pillar 45 (the last pillar in Row 7). The transverse displacements that occurred along the west leg during the interval between Surveys 11 and 12 is considered more likely the result of time-dependent deformation (creep) than the result of the extraction of Pillar 45, since the pillar lay no closer than 300 feet to the west leg.

2. The maximum transverse displacement on the west leg occurred at a point 150 feet inward from the edge of the mined-out area (0.24 times the panel width) and along the west leg, at a point 190 feet inward from the edge of the mined-out area (0.31 times the panel width).
3. The maximum transverse displacement increased as the mined-out area enlarged and by the end of mining measured 0.23 foot on the west leg and 0.30 foot on the east leg.
4. In the first six months following mining (through Survey 23), the maximum transverse displacement on both legs had increased approximately 0.05 foot bringing the total transverse displacement to 0.28 foot on the east leg and 0.35 foot on the west leg.
5. In a direction along each leg from the point of maximum transverse displacement toward the middle of the mined-out area, transverse displacements became progressively less and were zero (or nearly so) at the longitudinal centerline of the panel. And in the opposite direction along each leg from the point of maximum transverse displacement toward the margin of the mined-out area, transverse displacements also became progressively less. These displacements would be expected to reach zero over the abutments some distance beyond the edge of the mined-out area. Zero points were not located within the extent of the survey lines. Transverse displacements appear to have taken place over the full length of each leg of the transverse survey line.

The transverse displacements at the ends of both legs were small -- less than 0.2 feet (2.4 inches). Some appearance of displacement may have resulted from survey error. However, the systematic nature of the survey data suggests that the displacements are real--on the west leg 150 to 250 feet from the boundary of the panel, movements away from the mined-out area, and on the east leg zero to 200 feet from the boundary of the panel, move



BOM.A49

FIGURE 9.9- HORIZONTAL DISPLACEMENTS TRANSVERSE TO THE DIRECTION OF MINING--WEST LEG

A. DURING RETREAT MINING

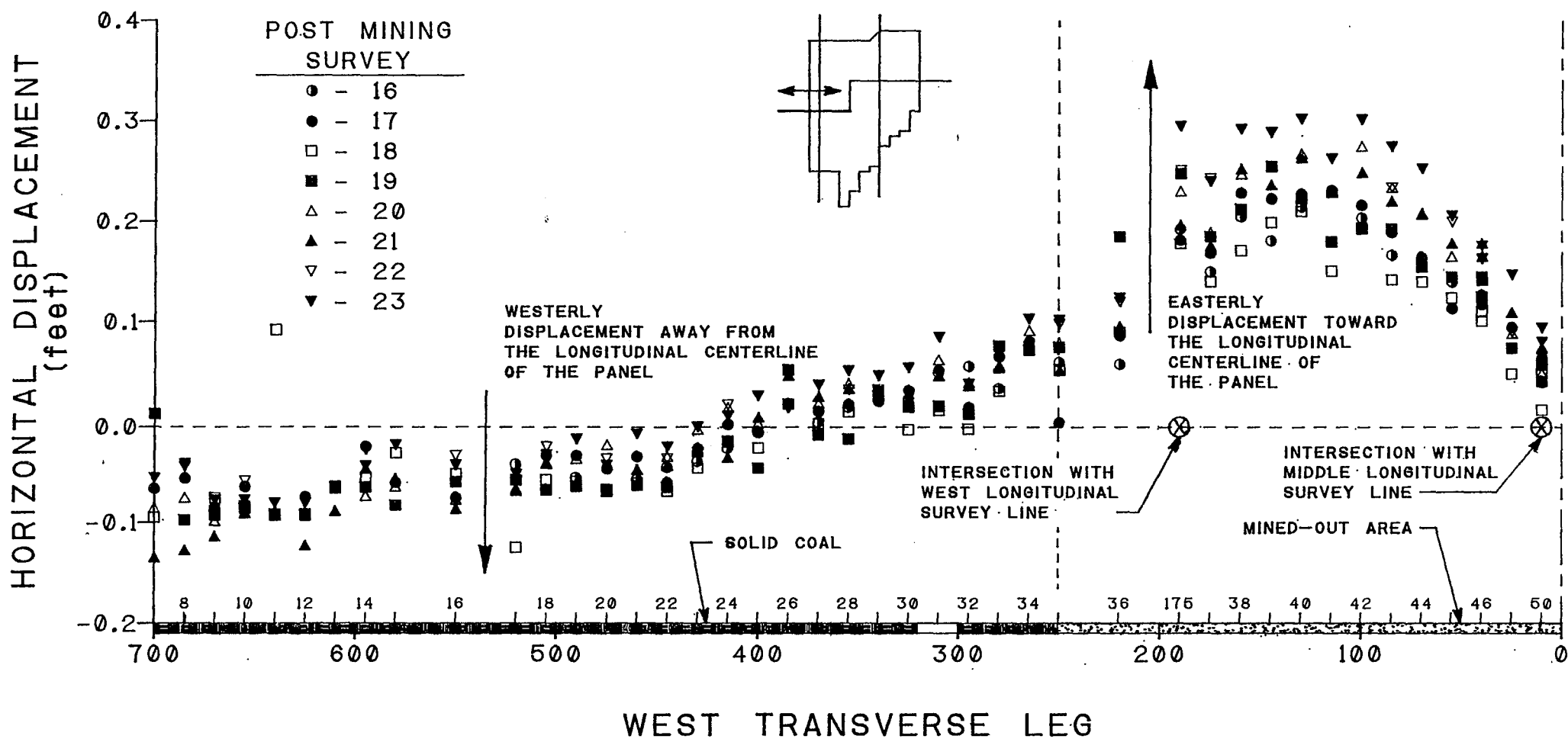


FIGURE 9.9- CONTINUED

B. FOLLOWING RETREAT MINING

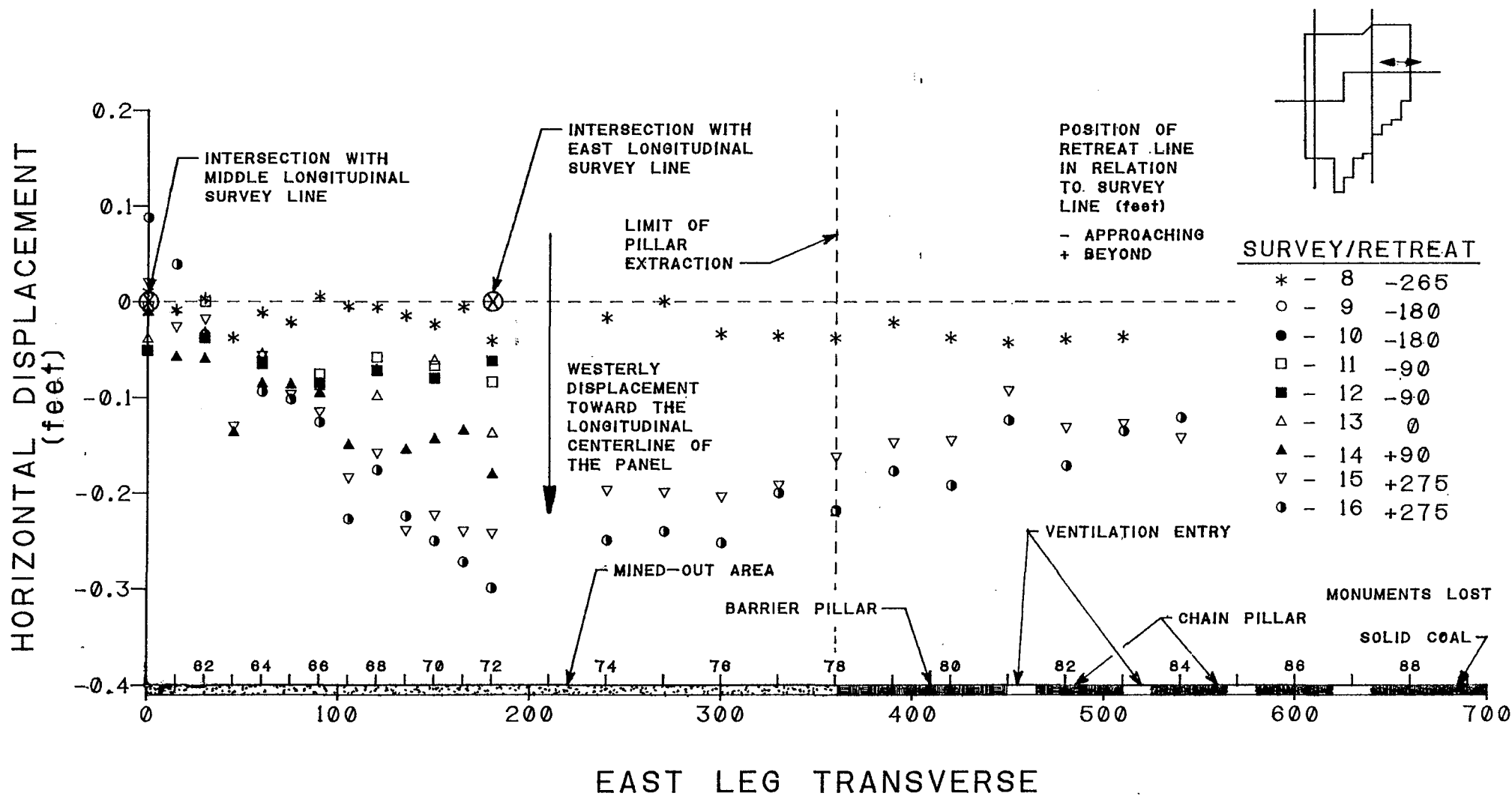


FIGURE 9.10 -- HORIZONTAL DISPLACEMENTS TRANSVERSE TO THE DIRECTION OF MINING

A. DURING RETREAT MINING

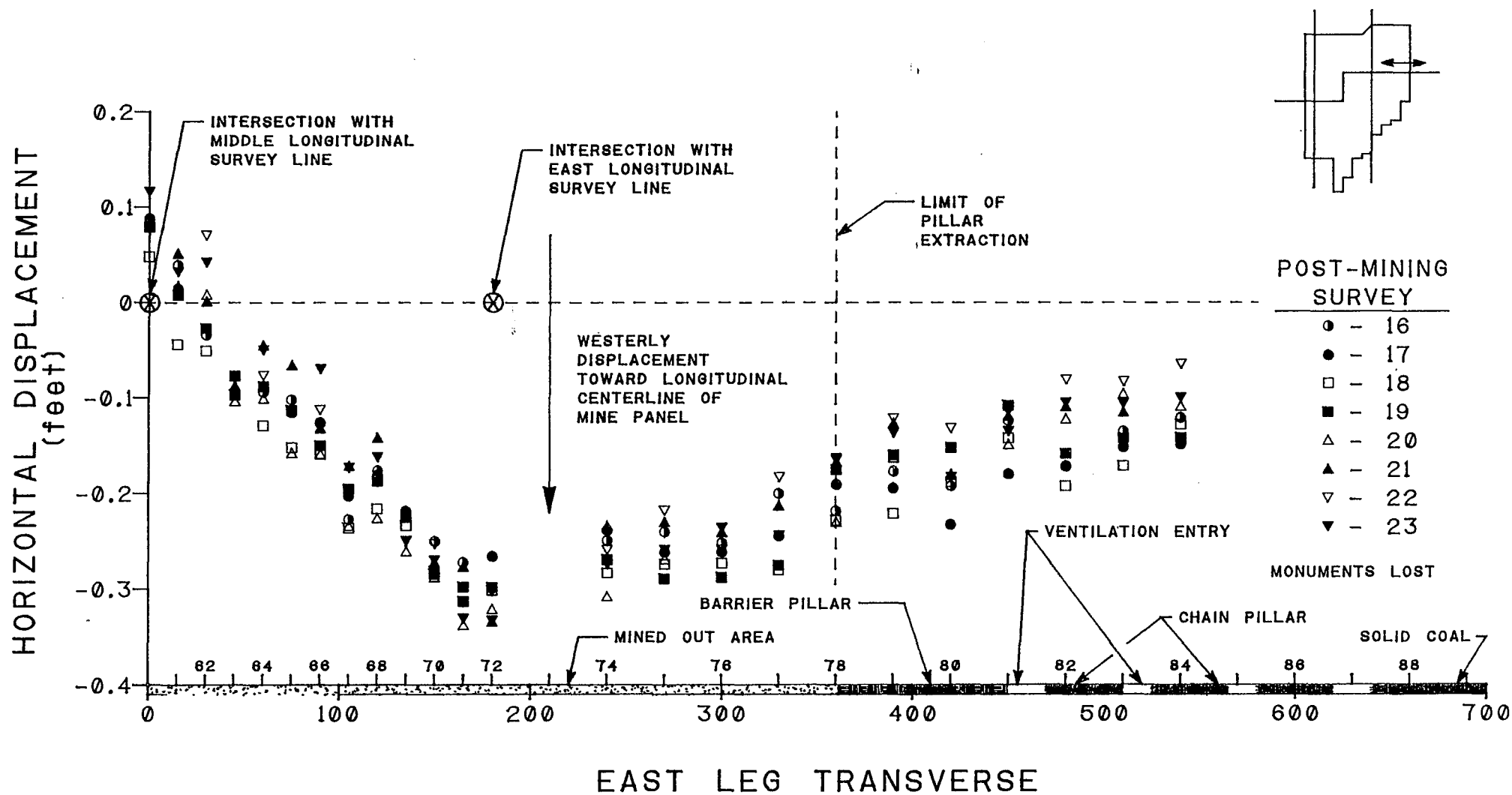


FIGURE 9.10 - CONTINUED

B. FOLLOWING RETREAT MINING

ments toward the center of the mined-out area. Movements away from the mined-out area at the west end are suggestive of separation of the overburden over the mined-out area from the abutment, allowing the abutment to rebound. This is speculation. No ground cracks were observed that might support this possibility. Movements toward the mined-out area at the east end seem consistent with measurements of subsidence over the east ventilation entries.

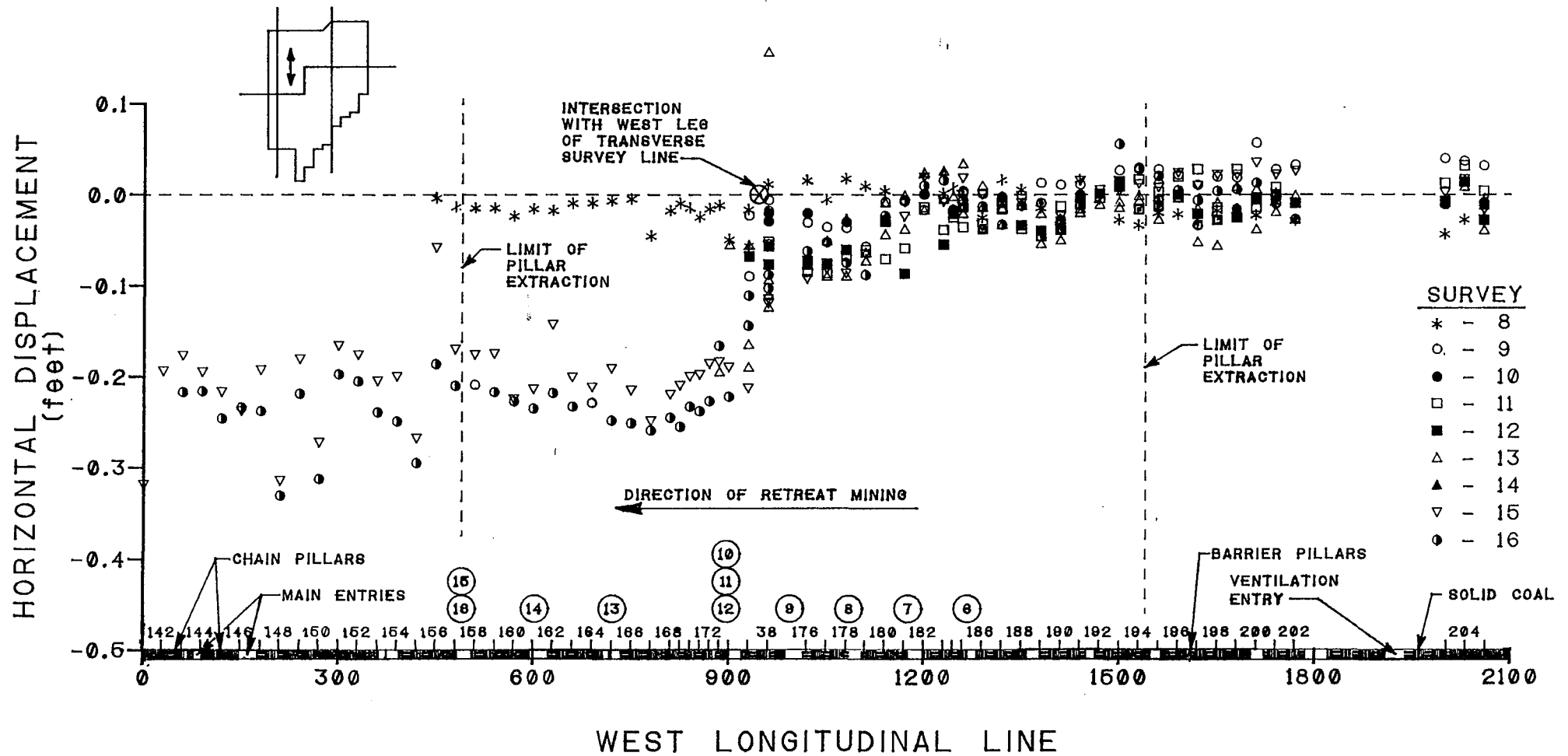
Post-mining parallel displacements on the west leg were, overall, in an easterly direction toward the longitudinal centerline of the panel. This includes the monuments on the west abutment that had moved away from the mined-out area during retreat mining. Post-mining parallel displacements of monuments on the east leg over the mined-out area were westerly toward the longitudinal centerline of the panel and on the abutment were easterly away from the panel centerline. During retreat mining, the displacements over the abutment had been toward the panel center line.

Horizontal Displacements Parallel to the Direction of Mining

Measurements of displacement parallel to the direction of mining on the west, middle and east longitudinal lines of monuments are shown in Figures 9.11, 9.12 and 9.13.

Observations are as follows:

1. Horizontal displacements parallel to mining were first recognized in late October 1982 (Survey 11) when the undermined section of the west line had reached 450 feet in length and the east line 360 feet in length.
2. At each stage of mining, parallel displacements were toward the center of the trough from both the north traveling abutment and the south stationary abutment. Ideally, a plot of such displacements exhibits (1) three zero points--one over each abutment and one at the temporal center of the mined-out area--and (2) two intervening lobes that describe the movements of the monuments intervening between the zero points. The actual curves display these characteristics. The maximum displacement increased as the mined-out area enlarged and along the east monument line was approximately the same for both lobes through early December (Survey 13) after which the lobe nearest retreat line predominated. Along the west line of monuments, the lobe nearest the retreat line predominated throughout the mining program.
3. The largest displacement measured parallel to the direction of mining along these monument lines ranged between 0.2 and 0.3 feet (end-of-mining, (Survey 16).
4. Parallel displacements during the six months following mining were measurements of displacement in a north-south direction along the west and east legs of the transverse row of monuments are shown in Figures 9.14 and 9.15, respectively.



BOM.A36

FIGURE 9.11 – HORIZONTAL DISPLACEMENTS PARALLEL TO THE DIRECTION OF MINING

A. DURING RETREAT MINING

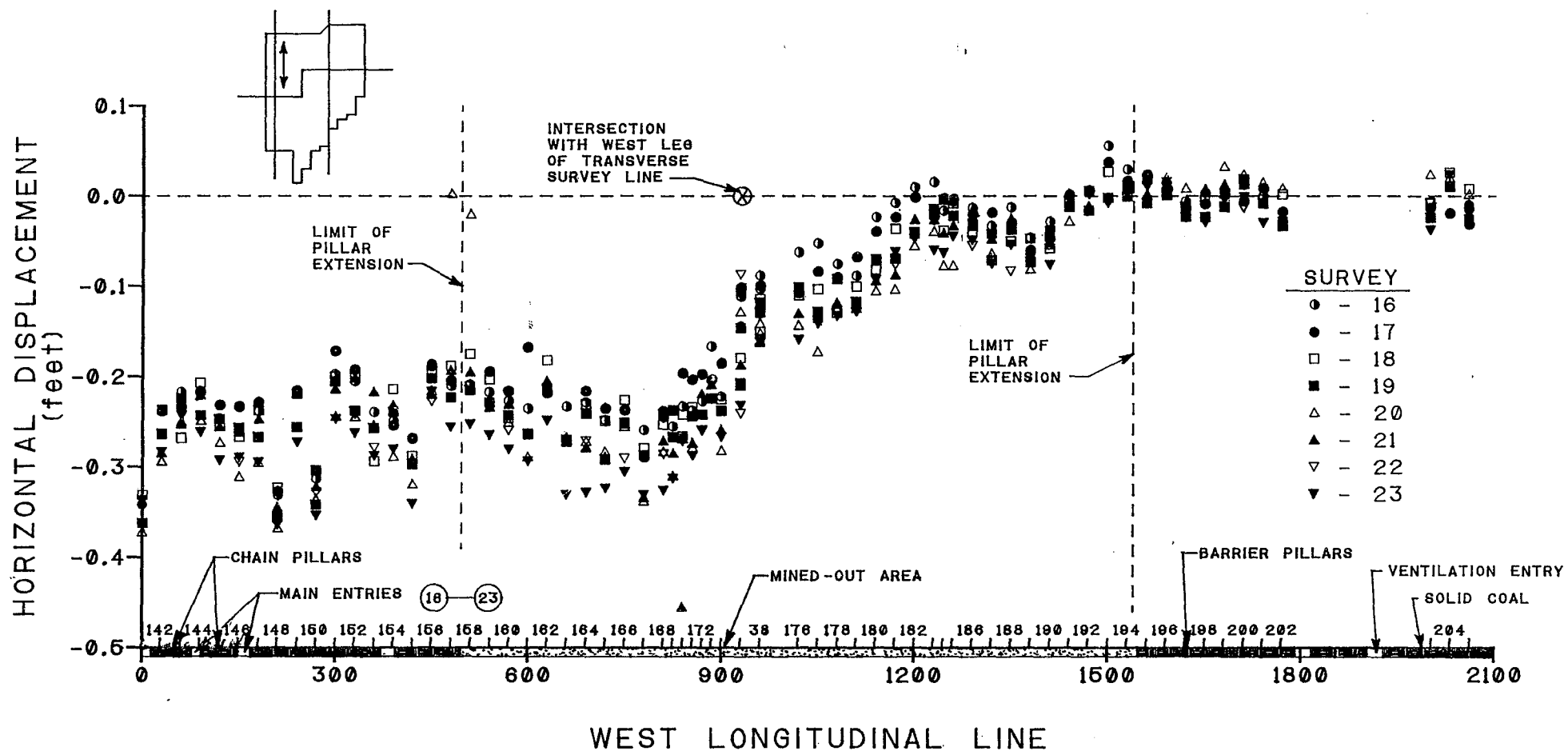
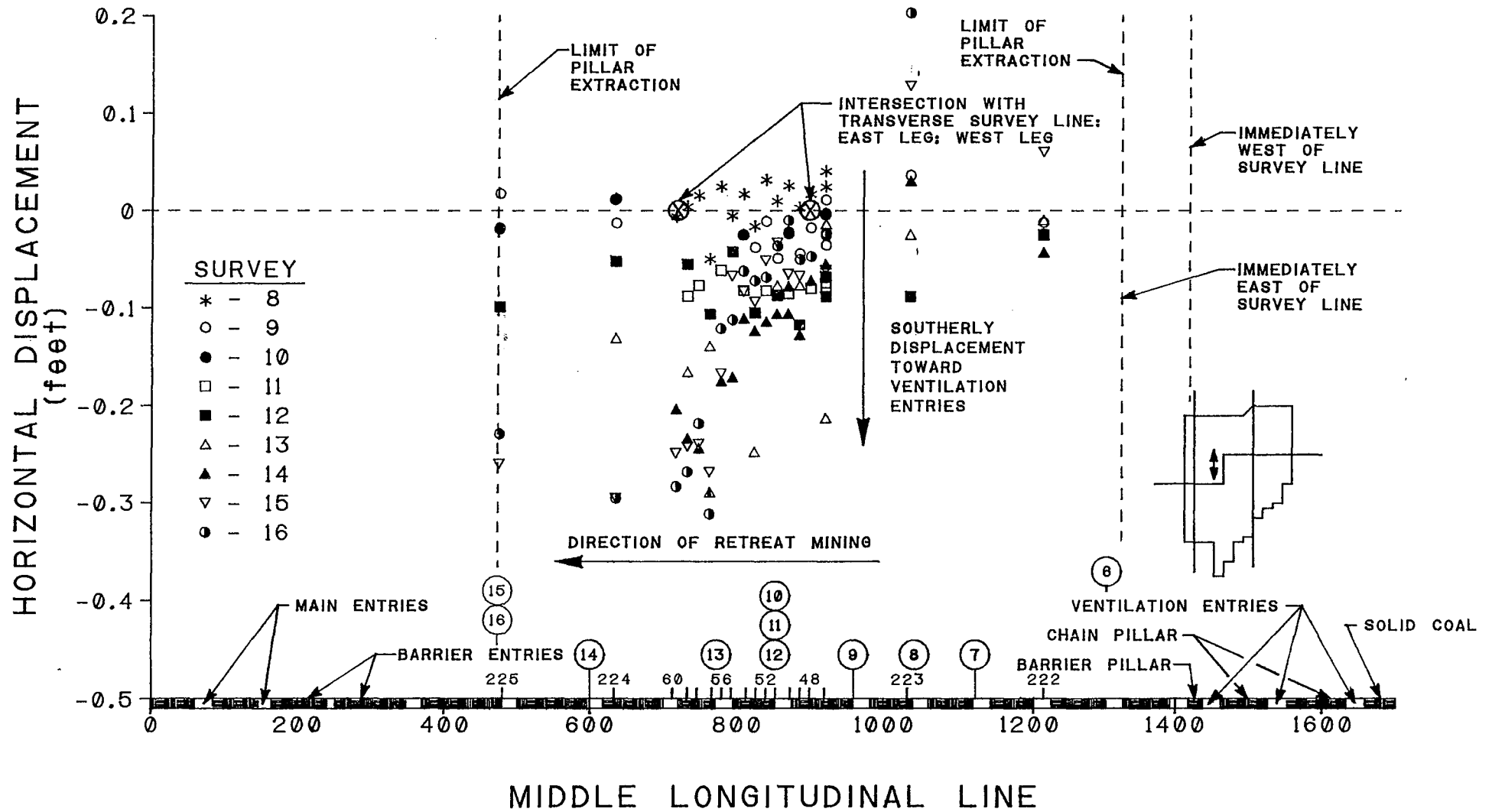


FIGURE 9.11- CONTINUED

B. FOLLOWING RETREAT MINING

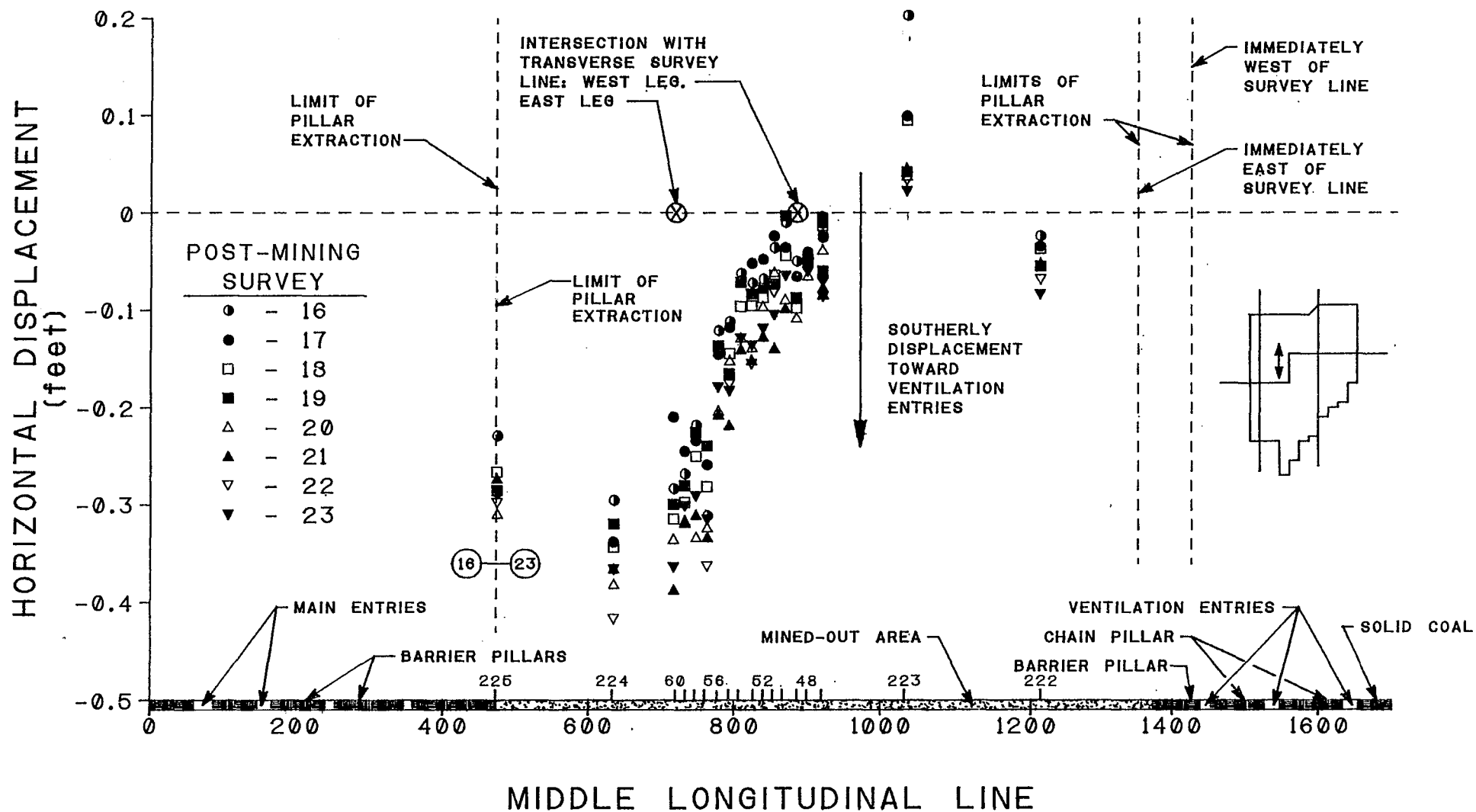
BOM.A38



BOM.A53

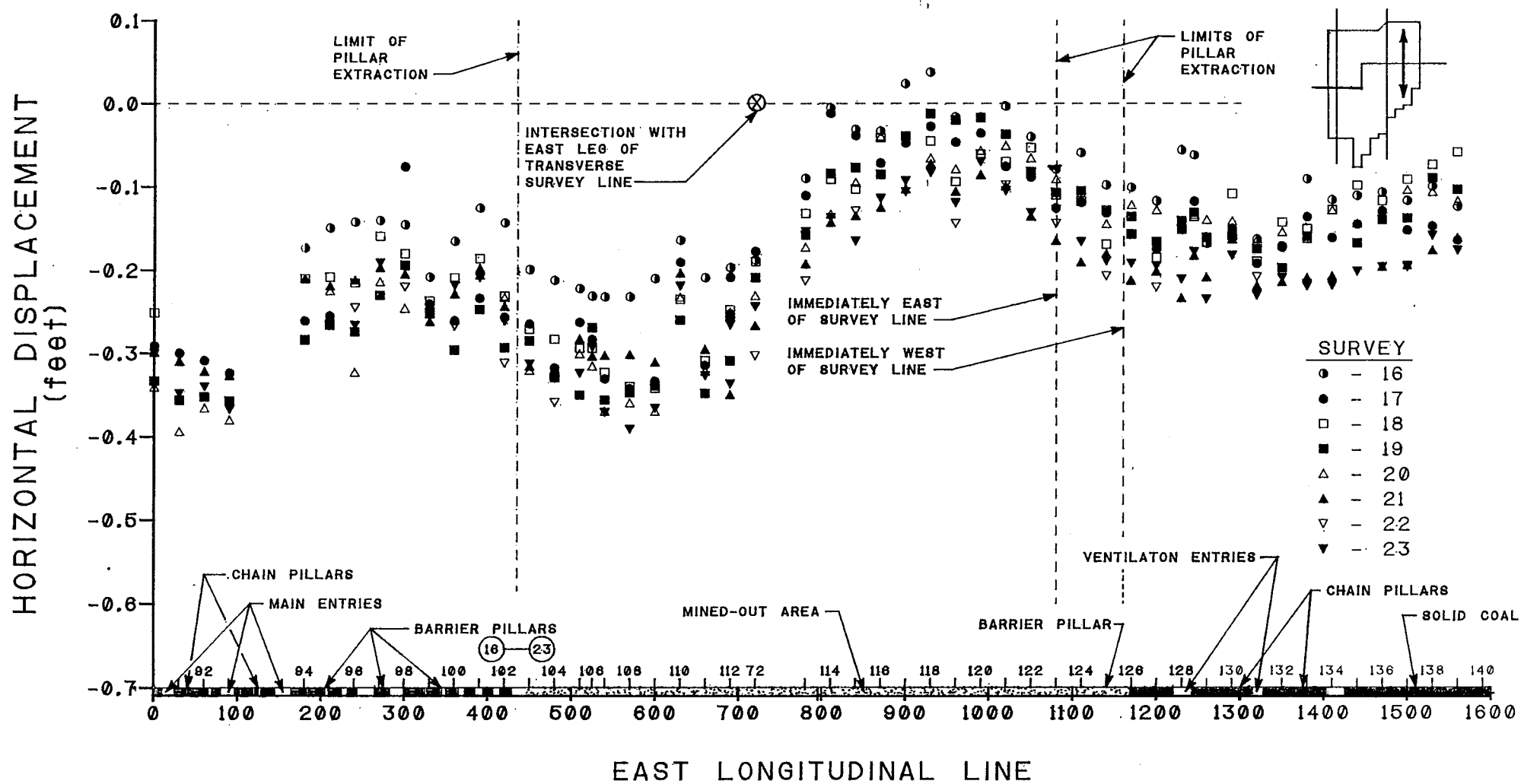
FIGURE 9.12-HORIZONTAL DISPLACEMENTS PARALLEL TO THE DIRECTION OF MINING

A. DURING RETREAT MINING



BOM.A54

FIGURE 9.12- CONTINUED
B. FOLLOWING RETREAT MINING



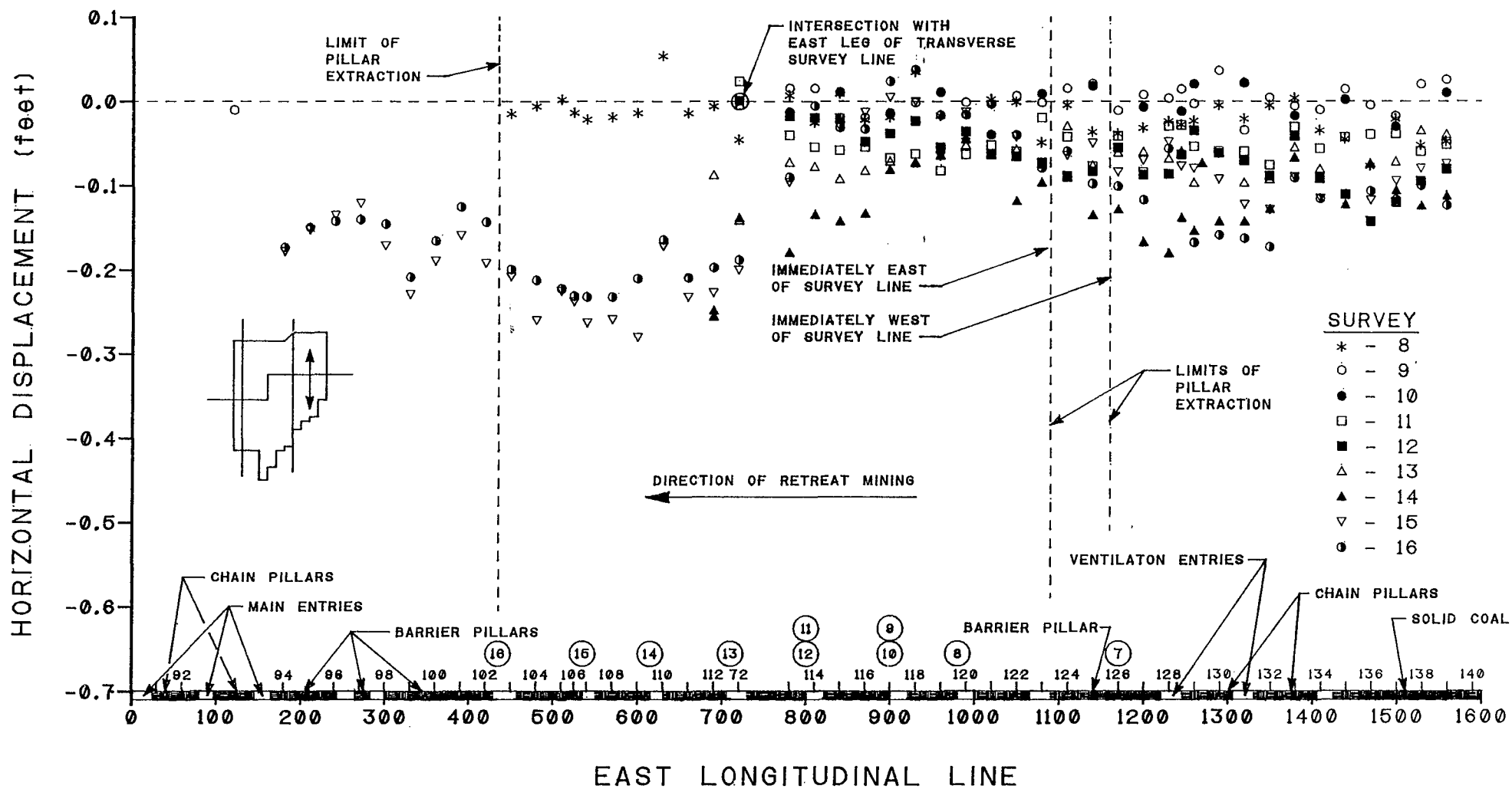


FIGURE 9.13-- CONTINUED
B. DURING RETREAT MINING

BOM.A39

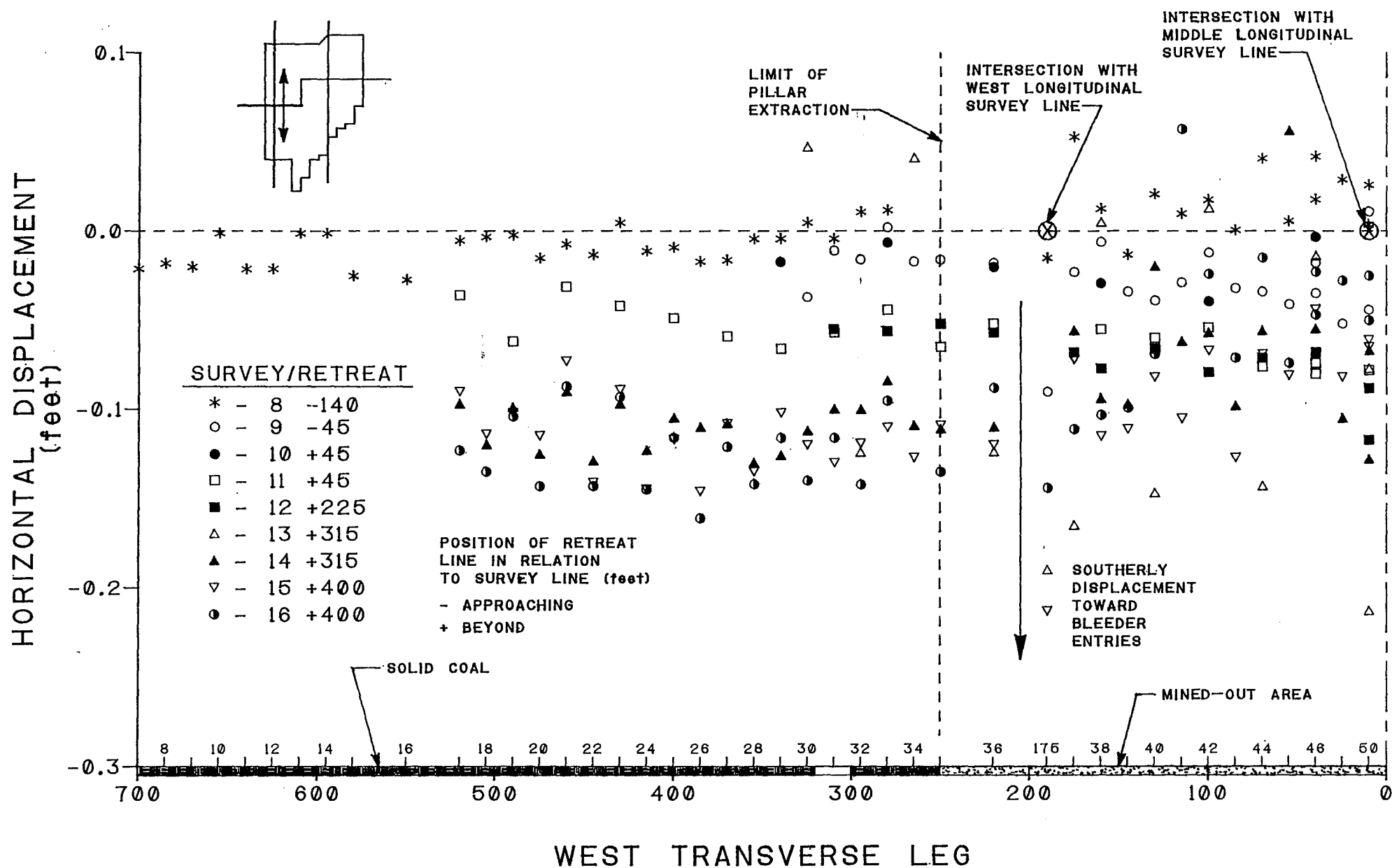


FIGURE 9.14 HORIZONTAL DISPLACEMENTS PARALLEL TO THE DIRECTION OF MINING
A. DURING RETREAT MINING

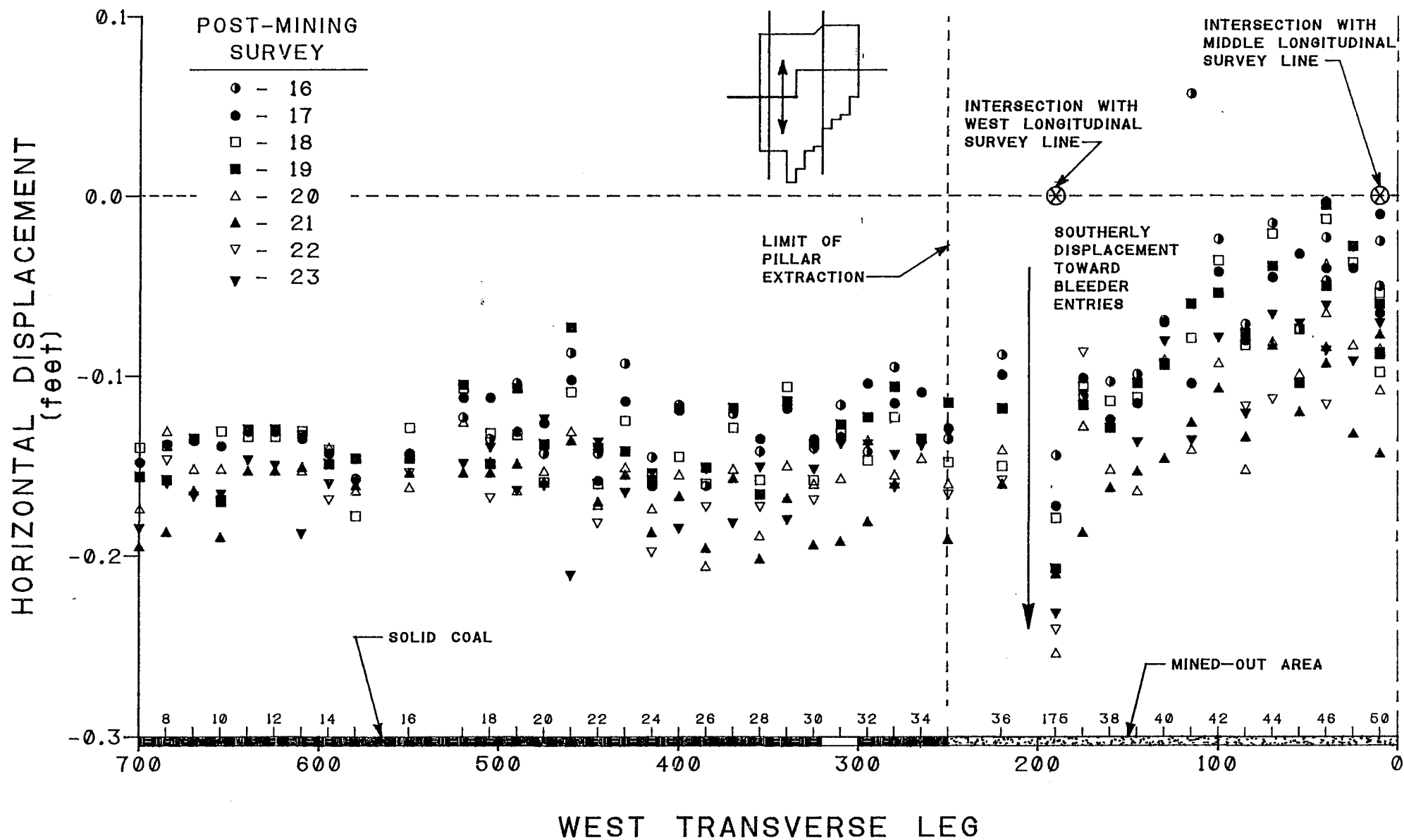


FIGURE 9.14 CONTINUED B. FOLLOWING RETREAT MINING

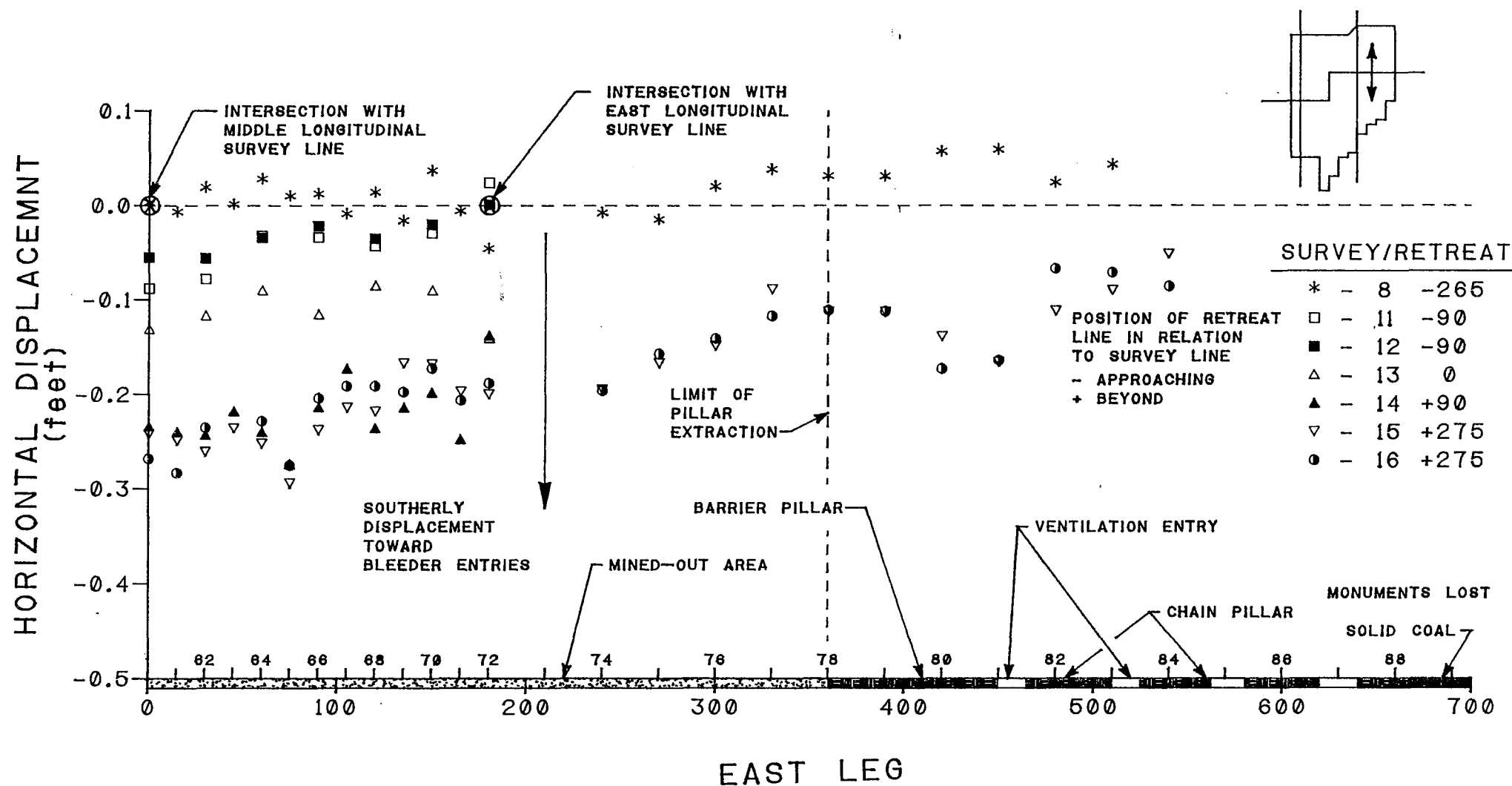


FIGURE 9.15 - CONTINUED
A. DURING RETREAT MINING

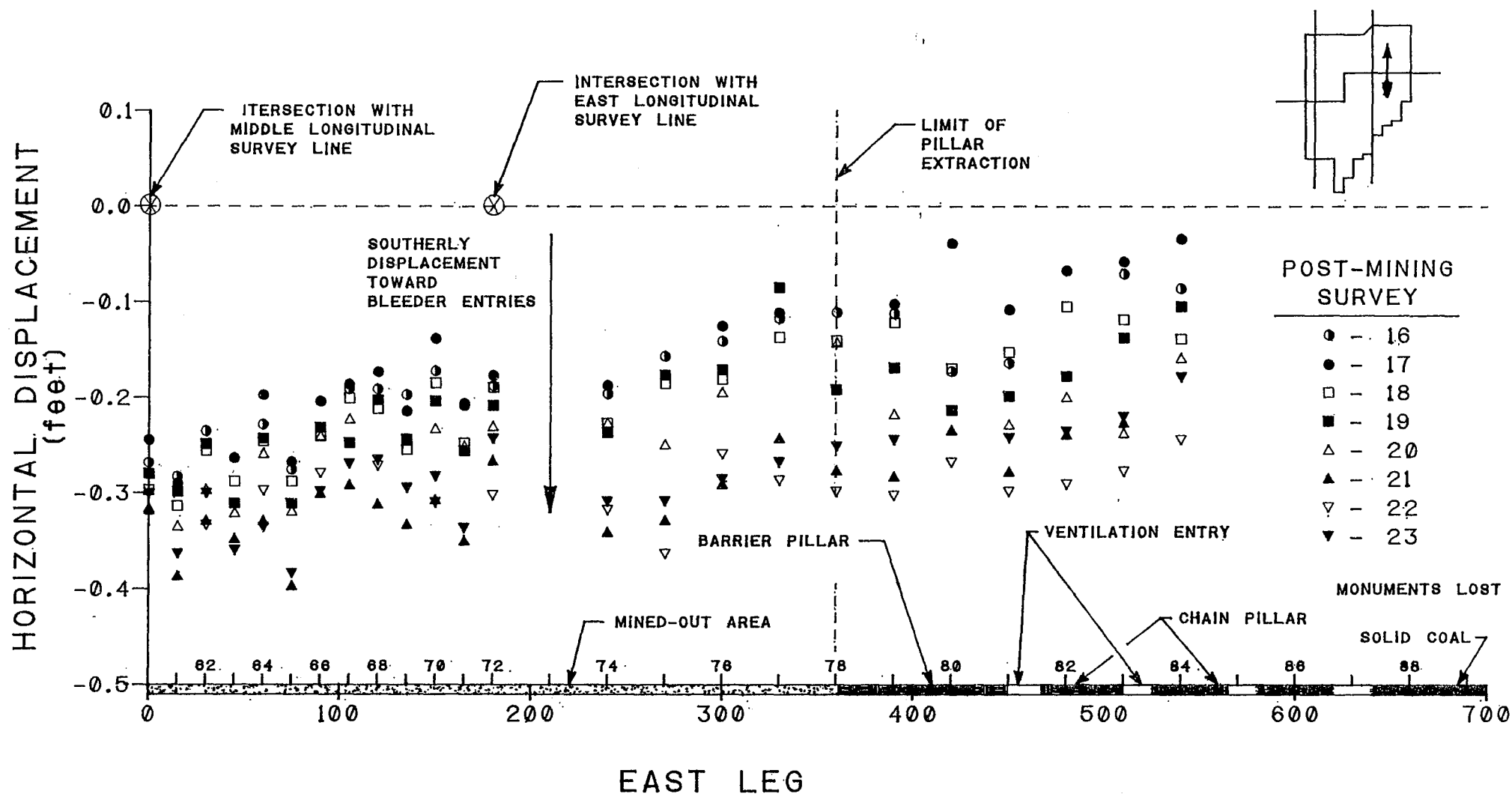


FIGURE 9.15-HORIZONTAL DISPLACEMENT PARALLEL TO THE DIRECTION OF MINING EAST LEG

B. FOLLOWING RETREAT MINING

Observations are as follows:

1. Displacements were first recognized on the west line in mid-October (Survey 9) when the retreat line had approached to within 45 feet (0.5 block) of the survey line, and on the east line one-and-one half weeks later when the retreat line had approached to within 90 feet (1 block) of the survey line (Survey 11).
2. Displacements on each leg were consistently in the direction of the deepest point in the subsidence trough, wherever that point lie at a particular stage of retreat mining. During retreat, displacements on the east leg were southward. Displacements on the west leg were progressively further southward through early December (Survey 13), by which time the first row of pillars when the pillars one row beyond the line had been extracted, as had a few pillars in the second row. At this time, the deepest point in the subsidence trough lay south of the line (toward the bleeders). With further mining, the deepest point of the subsidence trough became located increasingly northward-- directly beneath the survey line so that the monuments over the mined-out area began migrating in a northerly direction back toward their original (pre-mining) positions.

The net parallel displacement at the end of mining (Survey 16) was near zero on the section of survey line that lay over the mined-out area. A similar reversal would have been expected for the east leg had the mine panel been longer and the deepest point of the subsidence trough migrated beneath and beyond that section of survey line.

3. Parallel displacements on the west and east legs reached their largest values at or near the longitudinal centerline of the panel. The displacements diminished in a pronounced manner toward the abutment, but much less so toward the west abutment.
4. The parallel displacements increased with size of the mined-out area, but did not exceed 0.25 foot along either leg.
5. Parallel displacements during the six months following mining were southerly along both the west and east legs.

ROTATION OF PRINCIPAL STRAINS

Progressive changes in the direction and magnitude of principal ground strains that accompanied retreat mining are identified by way of groups of survey monuments arranged in triangular configurations (strain rosettes). A continuous series of such triangles was constructed along the west leg of the transverse survey line and the center section of the middle survey line and at four individual locations above the mine panel.

Data furnished by the strain triangle comprising Survey Monuments 128, 129 and 130 above the bleeder entries near the south end of the east longitudinal row of monuments illustrates the rotation of principal strains that occurred at one particular location during retreat mining. The surveyed locations of these three monumnets at various stages of mining are shown in the lower part of Figure 9.16 and are denoted by the

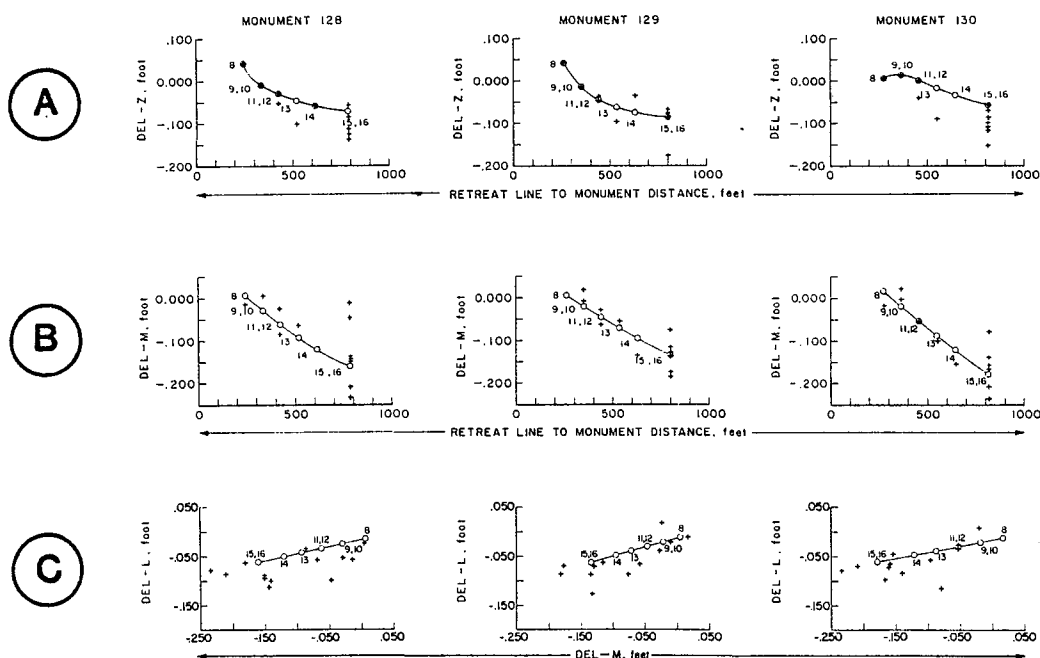
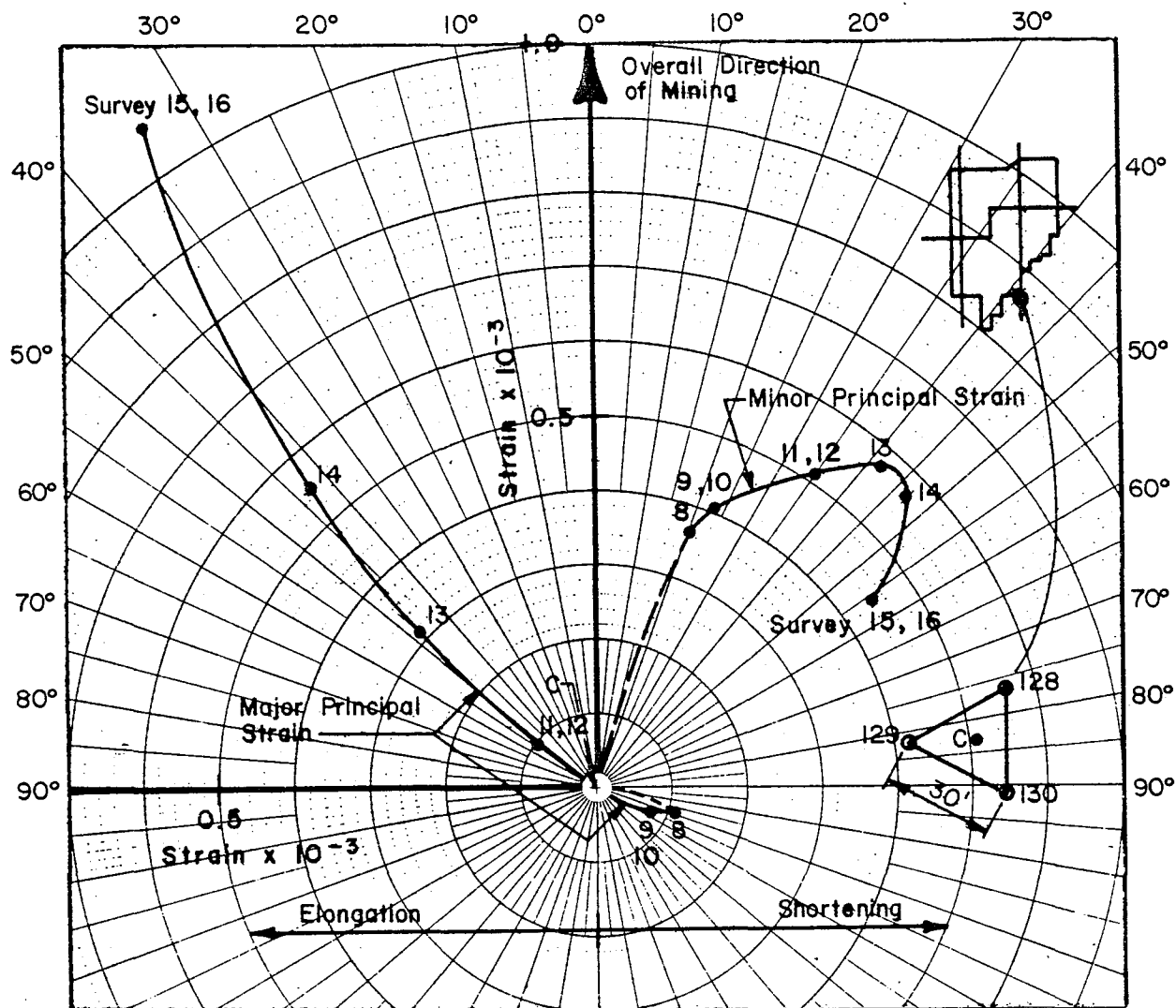


FIGURE 9.16 MINING RELATED ROTATION OF PRINCIPAL STRAINS AT ONE GROUND SURFACE LOCATION

symbol '+'. The solid lines are smoothed representations of the data based on least squares analyses.

In recognition that ground movement components from survey to survey often did not exceed 0.25 inch and were determined from a vantage point 750 feet away, departures of the survey points from the smooth curves almost certainly reflect survey error as well as actual ground motion.

All three monuments exhibited similar trends--each moved downward and horizontally as the retreat line moved away and the mined-out area enlarged. That the monuments moved different amounts is evidence that the ground strained. Given the distance of each monument to the retreat line for each survey, the corresponding subsidence (del-Z) is shown by the respective curve in Figure 9.16A, the horizontal displacement parallel to the direction of mining (del-M) by Figure 9.16B, and the corresponding horizontal displacement transverse to the direction of mining (del-L) from the relationship between del-L and del-M in Figure 9.16 C. Ground strains computed from the smoothed ground survey data are presented in the top part of Figure 9.16, based upon the customary formulas for strain gage rosettes given by Popov (1952), pages 206-209. The monument-to-monument distances for each survey used in the calculation of strain between monuments were made on a three-dimensional basis from the del-M, del-L and del-Z components.

The strain diagram illustrates for this location above the mine panel that in the early stages of mining (through Survey 10), both the major and minor ground strains reflected shortening of the distances between monuments. However, as retreat mining continued (Surveys 11-16), the minor principal strain continued to reflect progressively greater shortening (up to Survey 13 or thereabouts, after which the amount of shortening diminished), whereas major principal strain reflected progressively greater elongation. Accompanying these changes in magnitude was a reorientation of the principal ground strain--the major principal strain shifting to progressively higher angles to the overall direction of mining (and more nearly toward the center of the subsidence trough) and the minor principal strain to progressively lesser angles as retreat mining continued. Corresponding strain relationships at other locations can be utilized to define the overall three-dimensional pattern of ground movements that accompanied mining of the C-3 panel.

PARAMETERS THAT CHARACTERIZE THE SUBSIDENCE TROUGH

The previous discussion has described the evolution of the subsidence trough above the C-3 panel in terms of patterns of movements of survey monuments. The subsidence trough itself will now be characterized in terms of several geometric parameters that permit convenient comparison of the C-3 trough with others formed under similar or different mining and site conditions. These parameters are defined in the following paragraphs and evaluated quantitatively for the end-of-mining C-3 subsidence trough. The data are presented in the context of predictions based on data (primarily longwalls) for the Northern Appalachian Coal Field compiled by Peng and Geng (1983) and Peng and Chiang (1984). Whereas considerable data are available from a variety of sources for comparison to the present data, the syntheses referenced above are the most comprehensive to date and perhaps the most widely used references in the Northern Appalachian Coal Field.

Maximum Subsidence and Critical Panel Dimensions

A mine panel has attained critical dimensions if an increase in its width or length produces no increase in maximum subsidence. The maximum possible subsidence for a panel of critical dimensions is estimated by multiplying the mined thickness of coal m by the Subsidence Factor a' :

$$S_{\max} = a'.m \quad (9.3)$$

The Subsidence Factor depends upon the composition of the overburden and decreases in value with increase in the strength and hardness of the overburden strata. According to Peng and Geng (1983):

$$a = 0.5 (0.9 + P) \quad (9.4)$$

where P is the Combined Strata Coefficient

$$P = \frac{\sum_i h_i Q}{\sum_i h_i} \quad (9.5)$$

Q = a weighting factor for each stratum that reflects the stratum's composition and unconfined compressive strength; and

h = the thickness of the stratum.

As reported in Section 2, the overburden above the C-3 panel is composed of approximately 37 percent sandstone, 37 percent shale-siltstone and 25 percent claystone, with 1 percent coal and limestone. Based on the classification of Peng and Geng, appropriate overburden weighting factors are 0 to 0.1 for sandstone; 0.2 for shale-siltstone; and 0.6 to 0.8 for claystone. Accordingly, the computed Combined Strata Coefficient for the C-3 panel ranges from 0.23 to 0.32 and the estimated Subsidence Factor a' under critical panel dimensions from 0.57 to 0.61. Thus, for a panel equaling or exceeding critical dimensions, the expected maximum subsidence is approximately 3.3 feet.

Critical panel dimensions depend upon the strength and hardness of the overburden strata much as does the Subsidence Factor -- the stronger and harder the strata, the larger is the area required to achieve the critical condition. Peng and Geng (1983) have found that for a Subsidence Factor a' of 0.6, the critical panel dimensions equal 1.8 times the overburden thickness. For the C-3 panel, the estimated critical length and width is therefore 1.8x600 feet or 1080 feet. The C-3 panel, being 615 feet wide and 460 to 1000 feet long is, on this basis, judged to be subcritical both in width and length. If so, the Subsidence Factor for the C-3 panel is less than the critical (maximum) value.

According to Peng and Geng, the subsidence factor for the C-3 panel whose width is 0.57 times the critical dimension is 90% of the Subsidence Factor for critical conditions. The estimated Subsidence Factor a_0 for the C-3 panel is therefore 0.54.

Taking into account the reduced Subsidence Factor a_o and the subcritical dimensions of the C-3 panel in the manner suggested by Peng and Geng, the estimated maximum subsidence above the panel is given by:

$$S_o = a_o m \sqrt{(L_L/L_C) (L_W/L_C)} \quad (9.6)$$

where L_L is the panel length
 L_W is the panel width, and
 L_C is the critical panel dimension

Using a value of 0.54 for a_o , 5.5 feet for m , 615 feet for L_W , 764 feet (the weighted average panel length) for L_L and 1080 feet for L_C , the estimated maximum subsidence for the C-3 panel is 1.9 feet. The maximum subsidence measured above the C-3 panel was 1.8 feet. The maximum subsidence directly at the center of the subsidence trough may have been slightly greater. In any case, good agreement is found between estimated and measured subsidence.

Maximum Horizontal Displacement

The estimated maximum horizontal ground surface displacement is given by:

$$U_o = b S_o \quad (9.7)$$

where b is the Displacement Coefficient

Empirically, Peng and Geng (1983) have found b to equal 0.3 and to be independent of both the composition of the overburden and the size of the mined out area. Based upon the relationship above, the estimated maximum horizontal displacement above the C-3 panel is 0.56 feet. The largest horizontal displacement measured above the C-3 panel during the monitoring program was 0.43 feet. This was along the east leg of the transverse line of monuments. The writers suspect that the C-3 surveys were conducted with as much or greater precision than those from which the value of b was determined by Peng and Geng. The writers therefore suggest that the Displacement Coefficient more nearly equals 0.24 than 0.3 (at least for the C-3 panel).

Angles of Draw and Influence

The angle of draw is the inclination from the vertical of a straight line extending from the edge of the mined out area to the edge of the subsidence trough.

For critical panel dimensions, Peng and Geng (1983) give the angle of draw as

$$\alpha' = 44 - 6 a' - 0.015H \quad (9.8)$$

Using the previously determined value of 0.6 for a' and 600 feet for the overburden thickness H , the angle of draw for a panel of critical dimensions is estimated to be 31.4 degrees.

The angle of draw is generally considered to be smaller for panels of subcritical dimensions. For a panel whose length is critical and whose width is between 0.55 and 0.85 the critical dimension, Peng and Geng give the angle of draw as

$$\alpha_0 = 38 - 6 a' - 0.015H \quad (9.9)$$

Using the same values of a' and H as before, the estimated angle of draw for the condition of critical length but subcritical width is 25.4 degrees. In recognition of the C-3 panel's subcritical length as well as width, an angle of draw less than 25.4 degrees might be expected. How much less is indeterminate.

Survey profiles show that the angle of draw for the C-3 panel at the end of mining ranged between 5 and 40 degrees (+)--14 degrees along the west leg of the transverse survey line; 16 degrees (+) along the east leg of the transverse survey line; 30 to 36 degrees at the south abutment along the east longitudinal survey line; 40 degrees (+) at the south abutment along the west survey line; 10 degrees at the north abutment along the west longitudinal survey line; 7 degrees at the north abutment along the middle longitudinal line; and 5 degrees at the north abutment along the east longitudinal line.

The angle of influence is analogous to the angle of draw but includes the heave zone over the abutment. The angle of influence over the north abutment ranged between 30 and 35 degrees--30 degrees along the west longitudinal survey line; 35 degrees along the middle longitudinal survey line; and 33 degrees along the east longitudinal survey line. The angle of influence along the west leg of the transverse survey line was approximately 30 degrees. Heave zones were absent from the east leg of the transverse survey line and from the south ends of the longitudinal survey lines. Consequently the angle of influence in those locations would equal the angle of draw. The angles of draw and influence are obviously affected by the firmness of the abutment. The angle of draw is much larger over the south stationary abutment that experienced bearing failure than over the north traveling abutment that did not. Similarly, the angle of draw is much larger over the east abutment where four ventilation entries and four pillars separated the mined area from the solid coal than over the west abutment where only one ventilation entry and one pillar separated the mined out area from the solid coal. It is clear that conditions at the C-3 panel make suspect any prediction of angle of draw that is based upon geological factors alone. Meaningful predictions must take into account the boundary conditions of the panel. This is currently beyond the state of practice.

Profile Functions

Profile functions express the geometric characteristics at each point along a transverse section through a subsidence trough.

Given a function $S(x)$ that describes the vertical deflection along the subsidence trough, the slope $i(x)$ at each point is given by the first derivative of $S(x)$ with respect to x ; and the curvature $K(x)$ is given by the second derivative. The horizontal displacement $u(x)$ at each point is related to the slope by a constant B , so that $u(x) = Bi(x)$. The horizontal strain $e(x)$, in turn, is given by the first derivative of the horizontal displacement function, $e(x) = u'(x)$.

Based on an appraisal of more than 20 empirical expressions for representing subsidence profiles from the Northern Appalachian Coal Field, Chen and Peng (1981) conclude that the most appropriate expression is an exponential of the type proposed by Martos:

$$S(X)/S_0 = \exp [-a (x/L)^b] \quad (9.10)$$

where a and b = empirical constants, which Chen and Peng found to be $(a,b) = (-6.67, 1.8)$ based on six longwall profiles from the Northern Appalachian Coal Field;

X = horizontal distance of a point from the origin, which is located at the point of maximum subsidence; and

L = the half width of the subsidence trough

Simplifying the terminology with A denoting Equation 9.10, then

subsidence, $S(X) = S_0 A$

slope, $i(X) = -S_0 A' L^2$

curvature, $K(X) = S_0 A'' L^2$

horizontal displacement $u(X) = -B S_0 A'/L$

horizontal strain $e(X) = B S_0 A''/L^2$

Using these expressions, profiles of estimated subsidence, slope, curvature and strain along the east and west legs of the transverse survey line were computed for the end of mining condition (Survey 16). These curves are presented in Figures 9.16A-D and 9.17A-D. Values of L necessary for the computation were determined from the survey profiles in Figures 9.4A and B. Values of a and b from Chen and Peng (cited above) were assumed to be applicable. Also presented in Figures 9.16 and 9.17 are discrete values of subsidence, slope, curvature and strain determined on a monument-to-monument basis from the Survey 16 data.

The following observations are made:

1. The subsidence data obtained from both the east and west legs of the survey line are reasonably well approximated by the exponential profile function--the east leg better than the west leg. Other values of a and b may improve the approximations, and other functions may fit the data equally well or better. The exponential function does not account for the presence of the heave zone on the west abutment, nor does it account for the irregularities in profile above the east abutment. Neither can be discounted as a potential source of damage to structures at ground surface.
2. The profile functions appear to exhibit the same general trends as the discrete values of slope, curvature and strain computed from the survey data. However, the survey values are widely dispersed above and below the

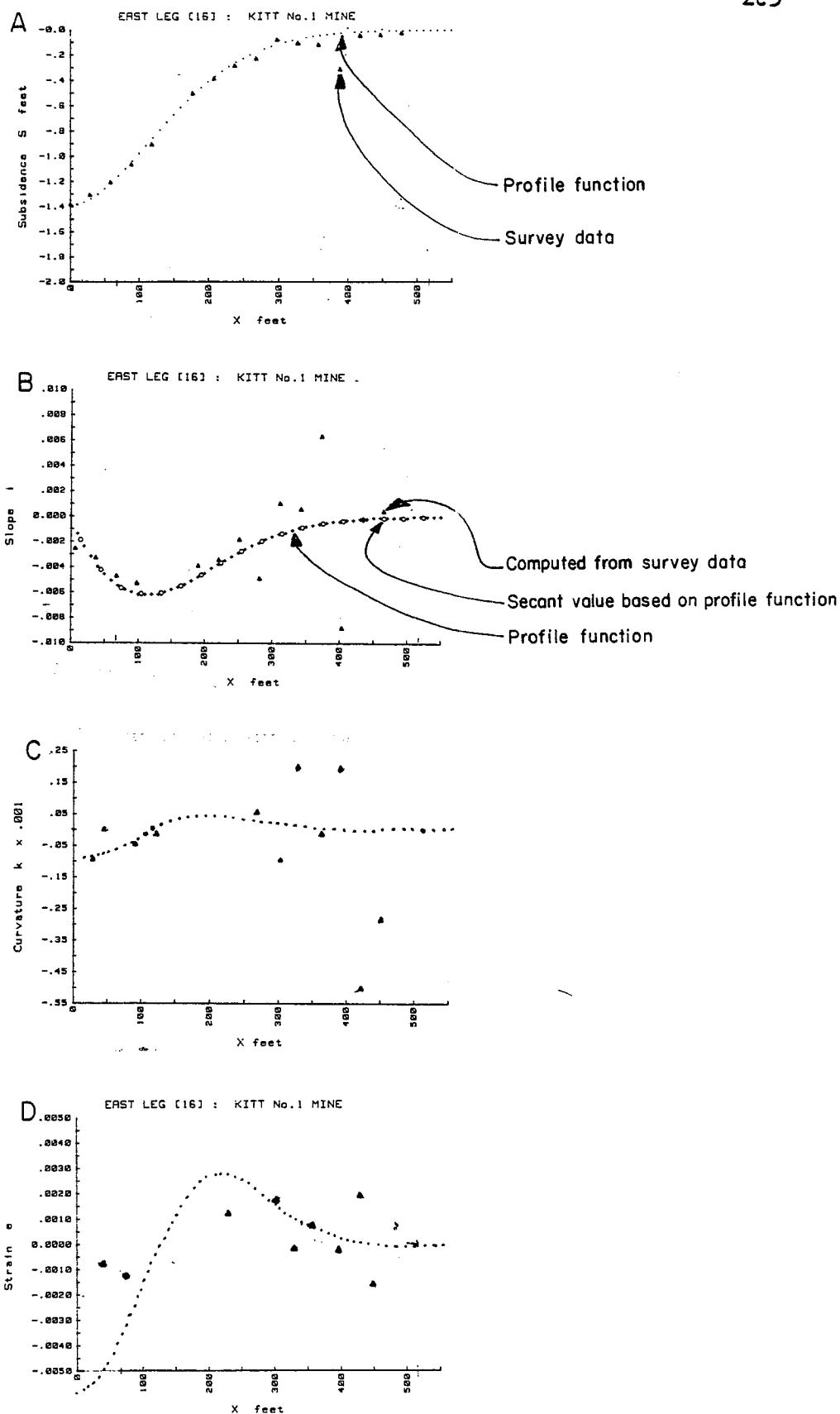


**FIGURE 9.17 COMPARISON BETWEEN MEASURED AND EMPIRICAL
SUBSIDENCE PROFILE AND ASSOCIATED PARAMETERS
EAST LEG, TRANSVERSE SURVEY LINE**

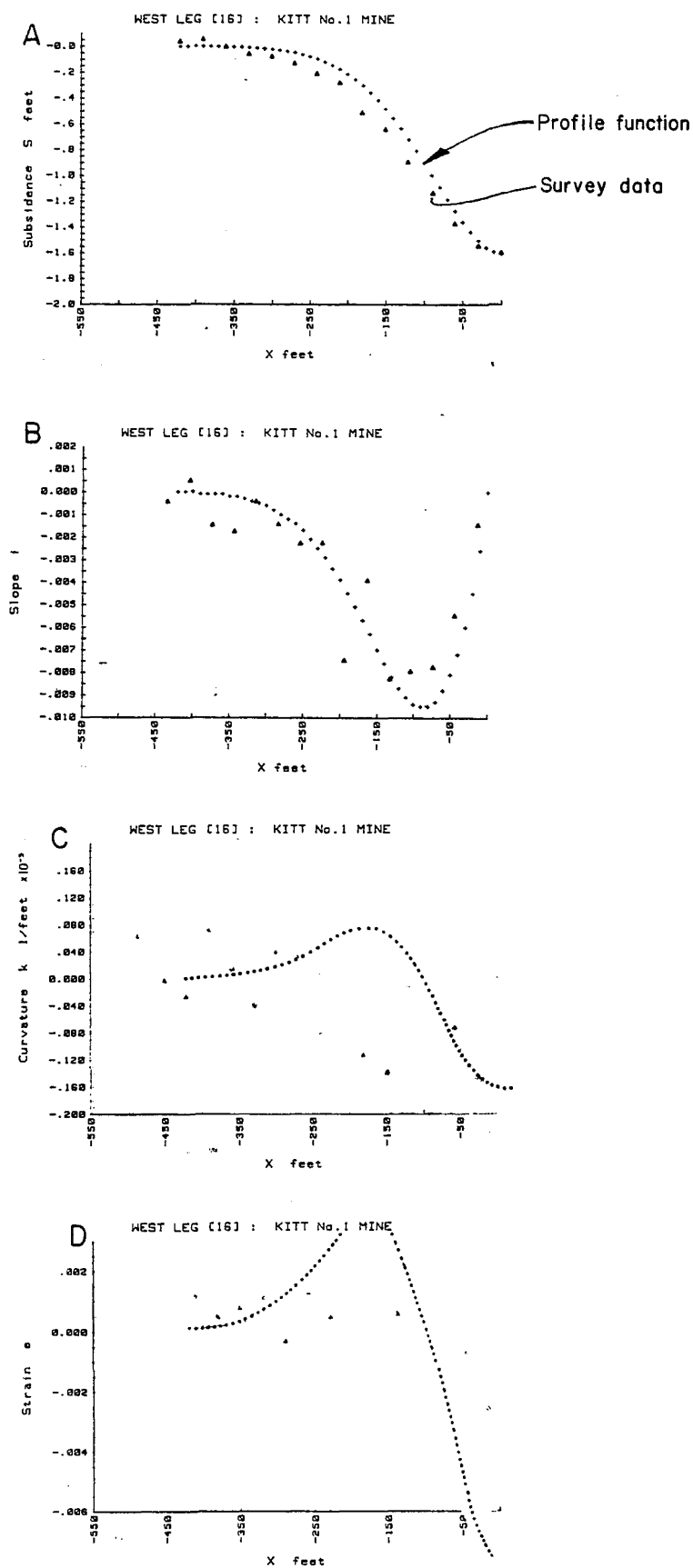


FIGURE 9.18 COMPARISON BETWEEN MEASURED AND EMPIRICAL SUBSIDENCE PROFILE AND ASSOCIATED PARAMETERS WEST LEG, TRANSVERSE SURVEY LINE

respective profile function curves. The dispersion is not due simply to the fact that the parameters based on survey data represent secant values--values derived from the movements of monuments 30 feet apart--whereas the profile curves represent tangent values--exact derivatives of the subsidence profile function. Figure 9.16 shows that secant values of the respective parameters computed at 30 foot intervals from the subsidence profile function lie very close if not directly on the profile function curves. That is, the secant values are close approximations of the tangent values. Part of the dispersion can probably be attributed to survey error. However, the principal reason for the dispersion is probably that the ground movements are actually irregular from one point to the next across the panel.

It is considered appropriate, therefore, when quoting subsidence parameters, to specify a band of uncertainty on either side of the profile function (assuming it to represent the central value) in which the actual value is likely to lie. In the present case, the profile functions appear to yield values of subsidence within 0.15 foot (+/-), of slope within 0.003 (+/-), of curvature within 2×10^{-4} /foot (+/-) and of strain within 0.0015 (+/-).

3. Although the subsidence profile function proved useful for curve-fitting the survey data, the profile function in combination with other empirical relationships presented by Peng and Geng (1983) would not have successfully predicted the subsidence profiles along the east and west legs of the transverse survey line at the Kitt Mine, nor would they have necessarily predicted the associated profile parameters with much accuracy. This is because the two elements required for such a prediction--(1) the maximum subsidence, and (2) the half-width of the subsidence profile cannot always be reliably predicted. The maximum subsidence along the west leg of the transverse survey line, which passed through or very near the deepest part of the trough, was well predicted by Peng and Geng's empirical relationship, as discussed above. However, the maximum subsidence along the east leg could not be predicted from available empirical relationships. The half-width of the two profiles likewise could not be predicted very well. A prediction of half-width depends upon the prediction of angle of draw. Peng and Geng's empirical relationship indicated an angle of draw of 25 degrees (or less). How much less was indeterminate. The actual angle of draw along the west leg was 14 degrees and along the east leg was 16 degrees. Had a prediction of slope, curvature and strain along these two sections of survey line been based on 25 degrees, the values of the derivative parameters would have been too low (unconservative) for both legs. Thus, the principal utility of profile functions at the present time appears to be for fitting survey data rather than for predicting subsidence profiles with available empirical relationships.

CLOSING COMMENTS CONCERNING GROUND SURFACE MOVEMENTS

Developmental mining produced no perceptible movement of the ground surface. Retreat mining produced a dish-shaped depression, or trough, that increased in depth and areal extent as the mined out area enlarged and eventually encompassed the entire mine panel (Figure 9.18). Bounding the mined-out area to a distance of 350 to 400 feet (0.58H to 0.67H) was a heave zone whose amplitude was on the order of an inch (Figure 9.18). The heave zone is consistent with a characterization of the overburden as a broad, thick plate spanning across elastic abutments.

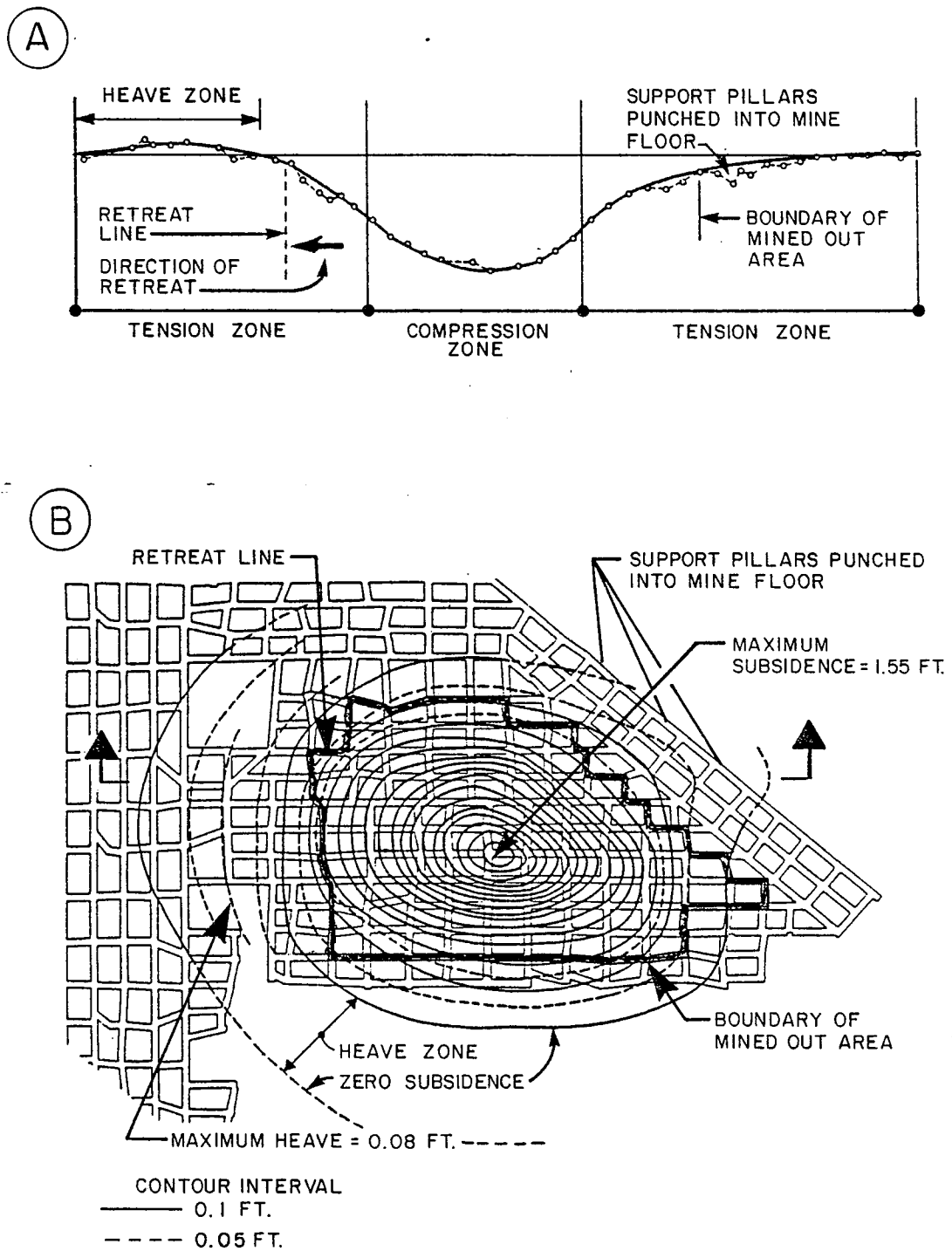


FIGURE 9.19 SUBSIDENCE TROUGH AS MINING NEARS COMPLETION.

- A. PROFILE
B. PLAN VIEW

The mine panel was not of critical dimensions. Consequently, additional subsidence would be expected if the dimensions of the panel were increased.

Subsidence parameters, such as angle of draw, ground strain, etc. depended both on location above the panel and the stage of mining. Tensile and compressive ground strains approached 0.005 locally. At the end of mining, the angle of draw ranged from 5 degrees where the margin of the panel remained firm to as much as 40 degrees (or more) where the margin experienced bearing failure.

Time-dependent ground movements took place while mining was underway, as evidenced by surveys made during lulls in mining. At least some of time-dependent movements were the result of pillars along the margin of the panel punching into the mine floor. The rate of "residual" subsidence first appeared to diminish about four months after the completion of mining (Figure 9.19). By that time, maximum subsidence had increased 4.8 inches (about 24 percent) in excess of the 1.75 feet measured at the completion of mining. Further observations showed subsidence to be continuing.

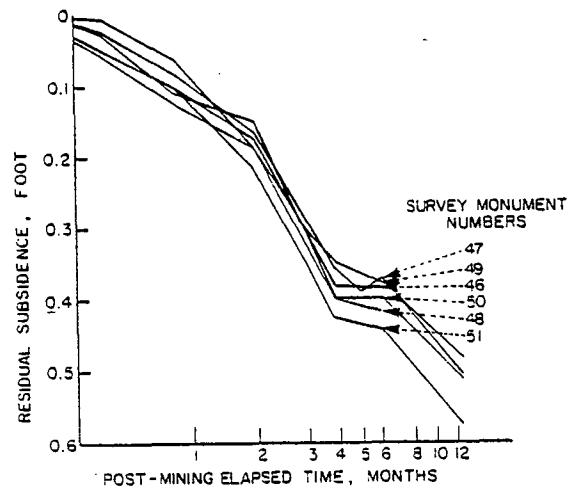


FIGURE 9.20 RESIDUAL SUBSIDENCE AT CENTER OF TROUGH

Appendix 9.1

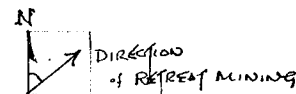
Survey Data:

End of Mining (Survey 16)

Final Post-Mining at Six Months (Survey 23)

COMPARISON OF TWO SURVEYS

INITIAL SURVEY: 5 10/15/1982 Datum
 FINAL SURVEY: 10 1/26/1983 END of REFLECT MINING
 X=NORTH, Y=EAST, Z=ELEVATION



POINT	XI	XF	DELTX	YI	YF	DELTY	ZI	ZF	DELTZ
1	15946.420	15946.420	0.000	18565.830	18565.830	0.000	1479.170	1479.170	-0.000
2	14872.755	14872.785	0.030	22309.311	22309.238	-0.073	1487.579	1487.493	-0.086
3	13735.801	13735.745	-0.057	21011.770	21011.613	-0.158	1363.766	1363.966	0.201
17	16262.139	16262.092	-0.047	18997.385	18997.264	-0.121	1418.551	1418.567	0.016
18	16267.415	16267.379	-0.036	19027.143	19026.997	-0.146	1423.020	1423.053	0.032
19	16239.138	16239.113	-0.025	19016.685	19016.570	-0.115	1417.503	1417.543	0.040
20	16244.477	16244.437	-0.041	19046.091	19045.938	-0.153	1418.989	1419.042	0.053
21	16216.230	16216.217	-0.012	19035.973	19035.869	-0.103	1415.888	1415.899	0.012
22	16221.542	16221.492	-0.050	19065.653	19065.523	-0.130	1412.695	1412.740	0.045
23	16193.256	16193.226	-0.030	19055.210	19055.114	-0.096	1409.475	1409.466	-0.009
24	16198.345	16198.271	-0.074	19084.919	19084.791	-0.128	1412.986	1413.022	0.035
25	16170.427	16170.359	-0.068	19074.415	19074.320	-0.094	1408.008	1408.005	-0.002
26	16175.524	16175.406	-0.117	19104.129	19104.017	-0.112	1413.420	1413.396	-0.024
27	16147.343	16147.265	-0.078	19093.814	19093.722	-0.092	1407.896	1407.843	-0.053
28	16152.714	16152.611	-0.103	19123.496	19123.396	-0.099	1412.704	1412.627	-0.077
29	16124.331	16124.241	-0.090	19113.014	19112.942	-0.073	1409.707	1409.595	-0.112
30	16128.477	16128.372	-0.105	19143.441	19143.347	-0.095	1411.850	1411.662	-0.188
31	16101.429	16101.315	-0.113	19132.418	19132.361	-0.057	1409.405	1409.273	-0.132
32	16073.427	16073.293	-0.134	19122.338	19122.265	-0.073	1405.970	1405.798	-0.173
33	16078.341	16078.253	-0.088	19151.880	19151.829	-0.051	1408.322	1408.140	-0.182
34	16050.629	16055.746	5.117	19141.637	19170.478	28.841	1404.947	1401.013	-3.934
35	16055.554	16055.421	-0.133	19171.081	19171.016	-0.065	1405.523	1405.268	-0.256
36	16032.323	16032.222	-0.101	19190.703	19190.673	-0.030	1400.555	1400.225	-0.330
37	16015.050	16014.864	-0.186	19239.516	19239.528	0.011	1404.408	1403.852	-0.556
38	15986.584	15986.360	-0.223	19228.929	19228.982	0.052	1401.265	1400.587	-0.678
39	15991.648	15991.446	-0.202	19259.101	19259.142	0.041	1401.661	1400.796	-0.865
40	15963.610	15963.401	-0.209	19248.250	19248.335	0.085	1401.108	1400.181	-0.927
41	15968.459	15968.319	-0.140	19278.672	19278.863	0.191	1398.554	1397.432	-1.122
42	15940.579	15940.407	-0.172	19267.537	19267.650	0.113	1399.254	1398.091	-1.163
43	15945.612	15945.438	-0.174	19297.792	19297.845	0.053	1397.457	1396.083	-1.375
44	15917.670	15917.536	-0.133	19286.895	19286.988	0.093	1395.761	1394.366	-1.395
45	15922.490	15922.335	-0.155	19317.369	19317.402	0.034	1395.696	1394.157	-1.539
46	15894.775	15894.666	-0.109	19306.064	19306.126	0.062	1393.552	1391.990	-1.562
47	15899.680	15899.605	-0.074	19336.483	19336.509	0.026	1395.250	1393.542	-1.708
48	15871.497	15871.450	-0.048	19326.226	19326.233	0.007	1392.841	1391.229	-1.612
49	15900.933	15900.805	-0.128	19321.018	19321.063	0.046	1394.300	1392.678	-1.622
50	15891.041	15890.962	-0.079	19349.190	19349.191	0.001	1394.696	1393.068	-1.628
51	15919.988	15919.912	-0.076	19343.365	19343.416	0.051	1396.639	1395.056	-1.582
52	15910.203	15910.103	-0.100	19372.119	19372.156	0.037	1397.503	1395.753	-1.750
53	15939.266	15939.108	-0.158	19366.401	19366.444	0.043	1397.878	1396.262	-1.617
54	15929.701	15929.534	-0.167	19394.879	19394.926	0.047	1398.809	1397.126	-1.684
55	15958.772	15958.716	-0.056	19389.279	19389.245	-0.034	1397.401	1395.859	-1.542
56	15948.674	15948.555	-0.118	19417.688	19417.642	-0.046	1395.403	1393.844	-1.559
57	15978.134	15977.907	-0.167	19411.919	19411.901	-0.018	1396.727	1395.314	-1.414
58	15968.450	15968.158	-0.293	19440.783	19440.624	-0.160	1397.000	1395.547	-1.453
59	15997.641	15997.421	-0.220	19435.021	19434.921	-0.100	1397.833	1396.538	-1.294
60	15987.280	15987.040	-0.240	19463.083	19462.934	-0.149	1397.832	1396.477	-1.355
61	15992.662	15992.450	-0.211	19492.712	19492.520	-0.192	1399.808	1398.636	-1.173

INITIAL SURVEY: 5 10/15/1982
 FINAL SURVEY: 16 1/26/1983
 X=NORTH, Y=EAST, Z=ELEVATION

COMP ON C O S S

POINT	XI	XF	DELTX	YI	YF	DELT Y	ZI	ZF	DELTA Z
62	15964.560	15964.436	-0.125	19482.271	19482.069	-0.202	1399.791	1398.415	-1.376
64	15942.007	15941.932	-0.074	19501.568	19501.333	-0.235	1405.779	1404.396	-1.384
65	15946.740	15946.641	-0.099	19531.128	19530.852	-0.277	1409.887	1408.593	-1.294
66	15919.679	15919.644	-0.035	19521.645	19521.407	-0.237	1406.651	1405.344	-1.307
67	15923.156	15923.207	0.051	19550.224	19549.932	-0.292	1409.733	1408.535	-1.198
68	15895.476	15895.488	0.012	19540.251	19539.992	-0.259	1409.911	1408.703	-1.208
69	15900.629	15900.674	0.045	19569.533	19569.238	-0.295	1415.086	1414.014	-1.072
70	15873.003	15873.084	0.081	19558.853	19558.561	-0.292	1419.366	1418.301	-1.065
71	15877.750	15877.826	0.076	19588.889	19588.556	-0.333	1422.594	1421.658	-0.935
72	15849.294	15849.402	0.108	19578.852	19578.516	-0.336	1424.767	1423.861	-0.906
74	15803.712	15803.777	0.065	19617.441	19617.131	-0.310	1422.125	1421.620	-0.505
75	15780.754	15780.837	0.083	19636.639	19636.364	-0.275	1429.606	1429.216	-0.389
76	15757.426	15757.529	0.103	19655.936	19655.667	-0.270	1432.944	1432.659	-0.285
77	15734.525	15734.602	0.078	19675.166	19674.948	-0.219	1434.509	1434.279	-0.230
78	15711.401	15711.497	0.096	19694.616	19694.391	-0.225	1435.804	1435.722	-0.083
79	15688.522	15688.585	0.063	19713.808	19713.608	-0.199	1436.616	1436.503	-0.113
80	15665.449	15665.485	0.036	19733.162	19732.907	-0.255	1436.739	1436.609	-0.130
81	15642.589	15642.579	-0.010	19752.405	19752.199	-0.206	1435.604	1435.572	-0.032
82	15619.633	15619.721	0.088	19771.625	19771.463	-0.161	1433.196	1433.141	-0.055
83	15596.531	15596.589	0.058	19791.014	19790.872	-0.142	1430.286	1430.236	-0.050
84	15573.508	15573.606	0.097	19810.202	19810.058	-0.144	1425.097	1425.059	-0.038
94	16196.184	16196.180	-0.004	19992.401	19992.179	-0.222	1517.611	1518.226	0.615
95	16177.191	16177.202	0.012	19969.632	19969.428	-0.204	1505.409	1505.516	0.108
96	16157.796	16157.829	0.033	19946.457	19946.244	-0.213	1498.854	1498.940	0.085
97	16138.571	16138.606	0.035	19923.507	19923.294	-0.213	1490.114	1490.200	0.086
98	16119.270	16119.258	-0.012	19900.499	19900.320	-0.179	1481.961	1482.023	0.062
99	16100.052	16099.966	-0.086	19877.519	19877.320	-0.200	1475.849	1475.882	0.033
100	16080.834	16080.813	-0.021	19854.638	19854.440	-0.198	1471.542	1471.580	0.039
101	16061.445	16061.506	0.061	19831.552	19831.336	-0.215	1467.738	1467.735	-0.003
102	16042.065	16042.107	0.042	19808.417	19808.195	-0.222	1461.541	1461.510	-0.031
103	16022.867	16022.864	-0.002	19785.535	19785.276	-0.258	1456.246	1456.098	-0.148
104	16003.734	16003.762	0.028	19762.657	19762.357	-0.300	1450.840	1450.649	-0.192
105	15984.279	15984.301	0.022	19739.474	19739.166	-0.309	1445.170	1444.940	-0.231
106	15994.188	15994.198	0.010	19710.840	19710.531	-0.309	1441.301	1440.962	-0.339
107	15964.996	15965.027	0.031	19716.560	19716.231	-0.328	1441.963	1441.662	-0.301
108	15945.859	15945.882	0.022	19693.631	19693.322	-0.309	1436.609	1436.181	-0.427
109	15926.427	15926.459	0.032	19670.659	19670.358	-0.301	1431.417	1430.943	-0.474
110	15907.460	15907.534	0.074	19647.902	19647.627	-0.275	1427.179	1426.481	-0.697
111	15887.963	15888.040	0.077	19624.741	19624.403	-0.338	1426.996	1426.300	-0.696
112	15868.670	15868.773	0.103	19601.755	19601.411	-0.344	1425.156	1424.361	-0.796
113	15811.090	15811.246	0.156	19533.014	19532.766	-0.248	1417.007	1416.059	-0.948
114	15791.639	15791.930	0.291	19509.861	19509.611	-0.250	1423.553	1422.587	-0.966
115	15772.355	15772.607	0.253	19486.790	19486.538	-0.252	1425.000	1424.058	-0.942
116	15753.041	15753.339	0.298	19463.840	19463.585	-0.255	1423.163	1422.290	-0.873
117	15733.686	15733.992	0.307	19440.742	19440.516	-0.226	1420.747	1419.971	-0.777
118	15714.618	15714.902	0.284	19418.014	19417.825	-0.189	1417.354	1416.663	-0.691
119	15695.244	15695.469	0.225	19394.936	19394.726	-0.210	1416.640	1416.024	-0.616
120	15675.977	15676.180	0.203	19371.926	19371.689	-0.237	1419.382	1418.883	-0.499

COMPARISON OF TWO SURVEYS

INITIAL SURVEY: 5 10/15/1982
 FINAL SURVEY: 16 1/26/1983
 X=NORTH, Y=EAST, Z=ELEVATION
 DELTA FLAGS X,Y,Z: 0.10 0.10 0.10

POINT	XI	XF	DELTA	YI	YF	DELTA	ZI	ZF	DELTA
121	15656.709	15656.913	0.205	19348.914	19348.739	-0.175	1418.676	1418.307	-0.370
122	15637.279	15637.412	0.132	19325.830	19325.607	-0.223	1415.296	1415.020	-0.276
123	15618.030	15618.095	0.066	19302.834	19302.675	-0.159	1411.189	1410.932	-0.257
124	15598.937	15599.024	0.087	19280.026	19279.876	-0.151	1407.184	1406.979	-0.205
125	15579.487	15579.516	0.029	19256.963	19256.811	-0.152	1403.170	1403.009	-0.162
126	15560.292	15560.298	0.005	19234.021	19233.895	-0.126	1399.411	1399.306	-0.105
127	15541.076	15541.070	-0.006	19211.086	19210.938	-0.148	1394.784	1394.654	-0.131
128	15521.722	15521.675	-0.047	19188.222	19188.078	-0.144	1390.431	1390.373	-0.058
129	15531.843	15531.816	-0.028	19160.030	19159.900	-0.129	1386.122	1386.044	-0.078
130	15502.336	15502.267	-0.069	19144.835	19144.674	-0.161	1387.341	1387.273	-0.068
131	15483.108	15483.037	-0.071	19124.064	19124.916	0.852	1383.302	1383.256	-0.046
132	15463.929	15463.890	-0.039	19119.166	19118.987	-0.179	1380.029	1379.984	-0.044
133	15444.638	15444.571	-0.066	19096.320	19096.150	-0.171	1378.036	1378.062	0.026
134	15425.149	15425.141	-0.008	19072.903	19072.792	-0.111	1377.808	1377.776	-0.032
135	15406.067	15406.053	-0.013	19050.247	19050.107	-0.140	1377.231	1377.250	0.019
136	15386.714	15386.696	-0.018	19027.283	19027.153	-0.130	1376.323	1376.343	0.021
137	15367.481	15367.452	-0.029	19004.221	19004.106	-0.115	1376.704	1376.730	0.026
138	15348.235	15348.193	-0.042	18981.252	18981.134	-0.118	1376.284	1376.321	0.037
139	15328.894	15328.884	-0.011	18958.187	18958.065	-0.121	1376.411	1376.423	0.011
140	15309.540	15309.483	-0.057	18935.152	18935.038	-0.114	1376.647	1376.728	0.081
141	15290.497	15290.440	-0.057	18912.883	18912.731	-0.152	1376.253	1376.260	0.007
142	15271.229	15271.117	-0.112	18890.982	18890.794	-0.188	1376.652	1376.656	-0.004
143	15252.067	15252.010	-0.057	18868.174	18868.050	-0.124	1376.987	1376.987	0.000
144	15232.814	15232.784	-0.030	18845.000	18845.000	0.000	1376.911	1376.911	0.000
145	15213.561	15213.531	-0.030	18822.266	18822.266	0.000	1376.841	1376.841	0.000
146	15194.308	15194.278	-0.030	18800.000	18800.000	0.000	1376.771	1376.771	0.000
147	15175.055	15175.025	-0.030	18777.266	18777.266	0.000	1376.701	1376.701	0.000
148	15155.802	15155.772	-0.030	18754.511	18754.511	0.000	1376.631	1376.631	0.000
149	15136.549	15136.519	-0.030	18731.766	18731.766	0.000	1376.561	1376.561	0.000
150	15117.296	15117.266	-0.030	18709.011	18709.011	0.000	1376.491	1376.491	0.000
151	15098.043	15098.013	-0.030	18686.266	18686.266	0.000	1376.421	1376.421	0.000
152	15078.790	15078.760	-0.030	18663.511	18663.511	0.000	1376.351	1376.351	0.000
153	15059.537	15059.507	-0.030	18640.766	18640.766	0.000	1376.281	1376.281	0.000
154	15040.284	15040.254	-0.030	18618.011	18618.011	0.000	1376.211	1376.211	0.000
155	15021.031	15021.001	-0.030	18595.266	18595.266	0.000	1376.141	1376.141	0.000
156	15001.778	15001.748	-0.030	18572.511	18572.511	0.000	1376.071	1376.071	0.000
157	14982.525	14982.495	-0.030	18549.766	18549.766	0.000	1376.001	1376.001	0.000
158	14963.272	14963.242	-0.030	18527.011	18527.011	0.000	1375.931	1375.931	0.000
159	14944.019	14944.019	0.000	18504.266	18504.266	0.000	1375.861	1375.861	0.000
160	14924.766	14924.766	0.000	18481.511	18481.511	0.000	1375.791	1375.791	0.000
161	14905.513	14905.513	0.000	18458.766	18458.766	0.000	1375.721	1375.721	0.000
162	14886.260	14886.260	0.000	18436.011	18436.011	0.000	1375.651	1375.651	0.000
163	14867.007	14867.007	0.000	18413.266	18413.266	0.000	1375.581	1375.581	0.000
164	14847.754	14847.754	0.000	18390.511	18390.511	0.000	1375.511	1375.511	0.000
165	14828.501	14828.501	0.000	18367.766	18367.766	0.000	1375.441	1375.441	0.000
166	14809.248	14809.248	0.000	18345.011	18345.011	0.000	1375.371	1375.371	0.000
167	14790.000	14790.000	0.000	18322.266	18322.266	0.000	1375.301	1375.301	0.000
168	14770.747	14770.747	0.000	18300.011	18300.011	0.000	1375.231	1375.231	0.000
169	14751.494	14751.494	0.000	18277.266	18277.266	0.000	1375.161	1375.161	0.000
170	14732.241	14732.241	0.000	18254.511	18254.511	0.000	1375.091	1375.091	0.000

COMPARISON OF TWO SURVEYS

INITIAL SURVEY: 5 10/15/1982
 FINAL SURVEY: 16 1/26/1983
 X=NORTH, Y=EAST, Z=ELEVATION
 DELTA FLAGS X,Y,Z: 0.10 0.10 0.10

POINT	XI	XF	DELTX	%X	YI	YF	DELT Y	%Y	ZI	ZF	DELT Z
171	16076.920	16076.596	-0.324	-0.0	19290.056	19290.018	-0.039	-0.0	1417.356	1416.863	-0.493
172	16067.311	16067.010	-0.301	-0.0	19278.715	19278.672	-0.043	-0.0	1415.402	1414.884	-0.517
173	16056.487	16056.237	-0.250	-0.0	19268.221	19268.213	-0.008	-0.0	1413.644	1413.093	-0.551
174	16048.000	16047.716	-0.284	-0.0	19255.885	19255.834	-0.051	-0.0	1411.922	1411.414	-0.509
175	16029.115	16028.898	-0.217	-0.0	19232.817	19232.811	-0.006	-0.0	1402.416	1401.782	-0.634
176	15970.962	15970.856	-0.105	-0.0	19163.917	19163.924	0.007	0.0	1394.264	1393.816	-0.447
177	15951.619	15951.565	-0.054	-0.0	19140.842	19140.820	-0.022	-0.0	1392.671	1392.230	-0.441
178	15932.272	15932.177	-0.094	-0.0	19117.796	19117.777	-0.018	-0.0	1391.464	1391.042	-0.422
179	15912.879	15912.801	-0.077	-0.0	19094.746	19094.696	-0.050	-0.0	1390.895	1390.523	-0.372
180	15893.714	15893.680	-0.035	-0.0	19071.770	19071.770	-0.000	-0.0	1389.443	1389.108	-0.334
181	15874.208	15874.199	-0.009	-0.0	19048.762	19048.761	-0.001	-0.0	1389.152	1388.859	-0.294
182	15855.045	15855.012	-0.033	-0.0	19025.842	19025.882	0.040	0.0	1388.852	1388.340	-0.513
183	15835.555	15835.539	-0.016	-0.0	19002.820	19002.854	0.035	0.0	1389.090	1388.901	-0.189
184	15846.181	15846.159	-0.021	-0.0	18974.935	18974.932	-0.003	-0.0	1391.744	1391.627	-0.116
185	15816.719	15816.718	-0.001	-0.0	18980.170	18980.164	-0.006	-0.0	1390.538	1390.399	-0.139
186	15797.265	15797.260	-0.006	-0.0	18957.098	18957.085	-0.013	-0.0	1390.998	1390.906	-0.092
187	15777.940	15777.909	-0.030	-0.0	18934.028	18934.010	-0.018	-0.0	1392.719	1392.696	-0.023
188	15758.682	15758.641	-0.042	-0.0	18911.117	18911.137	0.019	0.0	1396.346	1396.329	-0.017
189	15739.398	15739.361	-0.037	-0.0	18888.107	18888.078	-0.029	-0.0	1399.224	1399.226	0.001
190	15720.165	15720.151	-0.013	-0.0	18865.211	18865.185	-0.026	-0.0	1400.282	1400.250	-0.032
191	15700.885	15700.878	-0.007	-0.0	18842.243	18842.249	0.006	0.0	1401.541	1401.477	-0.063
192	15680.219	15681.521	1.302	0.0	18818.017	18819.300	1.283	0.0	1404.002	1403.659	-0.343
193	15662.295	15662.349	0.055	0.0	18796.396	18796.423	0.027	0.0	1405.743	1405.688	-0.055
194	15642.942	15642.973	0.031	0.0	18773.300	18773.313	0.013	0.0	1407.283	1407.236	-0.047
195	15623.756	15623.771	0.014	0.0	18750.412	18750.428	0.016	0.0	1407.255	1407.222	-0.033
196	15604.333	15604.345	0.012	0.0	18727.297	18727.294	-0.003	-0.0	1405.425	1405.390	-0.036
197	15585.045	15585.034	-0.011	-0.0	18704.312	18704.314	0.002	0.0	1402.301	1402.272	-0.029
198	15565.771	15565.809	0.039	0.0	18681.449	18681.422	-0.028	-0.0	1401.101	1401.094	-0.006
199	15546.605	15546.609	0.003	0.0	18658.553	18658.558	0.005	0.0	1402.919	1402.907	-0.011
200	15527.126	15527.137	0.011	0.0	18635.405	18635.412	0.007	0.0	1401.783	1401.785	0.001
201	15507.982	15507.984	0.001	0.0	18612.573	18612.573	-0.001	-0.0	1399.054	1399.049	-0.006
202	15488.513	15488.489	-0.023	-0.0	18589.348	18589.333	-0.015	-0.0	1396.817	1396.802	-0.016
204	15450.004	15449.233	19.229	0.1	18543.491	18566.374	22.883	0.1	1391.525	1394.833	3.308
205	15430.729	15430.743	0.014	0.0	18520.528	18520.503	-0.025	-0.0	1388.705	1388.697	-0.008
222	15690.267	15690.276	0.009	0.0	19095.543	19095.504	-0.039	-0.0	1383.151	1382.992	-0.159
223	15801.149	15801.233	0.084	0.0	19232.543	19232.737	0.194	0.0	1391.357	1390.407	-0.950
224	16063.001	16062.727	-0.274	-0.0	19520.279	19520.156	-0.123	-0.0	1407.262	1406.502	-0.760
225	16158.037	16157.834	-0.203	-0.0	19655.382	19655.254	-0.128	-0.0	1443.350	1443.184	-0.166
226	16333.300	16333.240	-0.060	-0.0	19866.191	19866.064	-0.127	-0.0	1502.569	1502.510	-0.059

COMPARISON OF TWO SURVEYS

INITIAL SURVEY: 5 10/15/1982 DAFOM
 FINAL SURVEY: 23 7/25/1983 SIX MONTHS AFTER COMPLETION OF REPAIR MINING
 X=NORTH, Y=EAST, Z=ELEVATION

POINT	XI	XF	DELTX	YI	YF	DELTXY	ZI	ZF	DELTZ
1	15946.420	15946.416	-0.004	18565.830	18565.822	-0.008	1479.170	1479.805	0.635
2	14872.755	14872.813	0.058	22309.311	22309.139	-0.171	1487.579	1487.573	-0.005
3	13735.801	13735.804	0.002	21011.770	21011.624	-0.146	1363.766	1363.842	0.076
7	16400.315	16400.239	-0.076	18881.512	18881.335	-0.178	1442.196	1442.290	0.094
8	16405.479	16405.407	-0.071	18911.233	18911.084	-0.150	1447.395	1447.505	0.110
9	16377.290	16377.242	-0.048	18900.876	18900.698	-0.178	1444.362	1444.480	0.118
10	16382.442	16382.395	-0.047	18930.446	18930.270	-0.177	1447.001	1447.111	0.110
11	16354.166	16354.134	-0.032	18920.279	18920.114	-0.165	1443.169	1443.219	0.050
12	16359.409	16359.340	-0.069	18949.772	18949.632	-0.139	1443.831	1443.945	0.114
13	16331.314	16331.266	-0.047	18939.625	18939.469	-0.156	1439.422	1439.515	0.093
14	16336.397	16336.310	-0.087	18969.153	18968.981	-0.172	1440.086	1440.187	0.101
15	16308.312	16308.227	-0.085	18958.820	18958.682	-0.138	1435.579	1435.671	0.092
16	16313.492	16313.422	-0.070	18988.408	18988.258	-0.150	1433.694	1433.799	0.105
17	16262.139	16262.085	-0.054	18997.385	18997.240	-0.145	1418.551	1418.588	0.037
18	16267.415	16267.344	-0.071	19027.143	19027.008	-0.135	1423.020	1423.113	0.093
19	16239.138	16239.061	-0.077	19016.685	19016.567	-0.118	1417.503	1417.556	0.053
20	16244.477	16244.405	-0.073	19046.091	19045.937	-0.154	1418.989	1419.067	0.078
21	16216.230	16216.159	-0.071	19035.973	19035.870	-0.103	1415.888	1415.916	0.028
22	16221.542	16221.425	-0.117	19065.653	19065.475	-0.177	1412.695	1412.783	0.087
23	16193.256	16193.172	-0.084	19055.210	19055.102	-0.108	1409.475	1409.491	0.016
24	16198.345	16198.234	-0.111	19084.919	19084.797	-0.122	1412.986	1413.054	0.068
25	16170.427	16170.308	-0.119	19074.415	19074.313	-0.102	1408.008	1408.017	0.009
26	16175.524	16175.367	-0.157	19104.129	19104.019	-0.110	1413.420	1413.421	0.001
27	16147.343	16147.217	-0.126	19093.814	19093.721	-0.093	1407.896	1407.864	-0.032
28	16152.714	16152.558	-0.156	19123.496	19123.389	-0.107	1412.704	1412.642	-0.062
29	16124.331	16124.198	-0.132	19113.014	19112.929	-0.086	1409.707	1409.613	-0.094
30	16128.477	16128.320	-0.158	19143.441	19143.338	-0.103	1411.850	1411.675	-0.175
31	16101.429	16101.266	-0.162	19132.418	19132.356	-0.062	1409.405	1409.253	-0.152
32	16073.427	16073.309	-0.118	19122.338	19122.256	-0.082	1405.970	1405.735	-0.235
33	16078.341	16078.194	-0.147	19151.880	19151.823	-0.057	1408.322	1408.080	-0.243
34	16050.629	16050.457	-0.171	19141.637	19141.593	-0.044	1404.947	1404.688	-0.259
35	16055.554	16055.386	-0.168	19171.081	19171.040	-0.041	1405.523	1405.228	-0.296
36	16032.323	16032.143	-0.180	19190.703	19190.682	-0.021	1400.555	1400.168	-0.387
37	16015.050	16014.795	-0.255	19239.516	19239.586	0.070	1404.408	1403.737	-0.671
38	15986.584	15986.279	-0.305	19228.929	19229.020	0.091	1401.265	1400.425	-0.840
39	15991.648	15991.339	-0.309	19259.101	19259.181	0.080	1401.661	1400.604	-1.057
40	15963.610	15963.327	-0.283	19248.250	19248.382	0.132	1401.108	1399.982	-1.127
41	15968.459	15968.169	-0.289	19278.672	19278.737	0.065	1398.554	1397.200	-1.354
42	15940.579	15940.297	-0.282	19267.537	19267.671	0.133	1399.254	1397.774	-1.481
43	15945.612	15945.323	-0.289	19297.792	19297.876	0.084	1397.457	1395.778	-1.679
44	15917.670	15917.434	-0.236	19286.895	19287.007	0.112	1395.761	1394.029	-1.732
45	15922.490	15922.287	-0.203	19317.369	19317.447	0.078	1395.696	1393.770	-1.926
46	15894.775	15894.585	-0.190	19306.064	19306.112	0.048	1393.552	1391.606	-1.946
47	15899.680	15899.508	-0.172	19336.483	19336.507	0.024	1395.250	1393.171	-2.079
48	15871.497	15871.390	-0.107	19326.226	19326.223	-0.003	1392.841	1390.810	-2.031
49	15900.933	15900.764	-0.164	19321.018	19321.076	0.058	1394.300	1392.302	-1.998
50	15891.041	15890.914	-0.128	19349.190	19349.184	-0.006	1394.696	1392.667	-2.028
51	15919.988	15919.789	-0.199	19343.365	19343.447	0.082	1396.639	1394.614	-2.024

COMPARISON OF TWO SURVEYS

INITIAL SURVEY: 5 10/15/1982
 FINAL SURVEY: 23 7/25/1983
 X=NORTH, Y=EAST, Z=ELEVATION

POINT	XI	XF	DELTX	YI	YF	DELT Y	ZI	ZF	DELT Z
52	15910.203	15910.002	-0.201	19372.119	19372.150	0.032	1397.503	1395.360	-2.143
53	15939.266	15939.020	-0.246	19366.401	19366.452	0.051	1397.878	1395.877	-2.001
54	15929.701	15929.509	-0.192	19394.879	19394.864	-0.016	1398.809	1396.667	-2.142
55	15958.772	15958.549	-0.224	19389.279	19389.298	0.019	1397.401	1395.440	-1.961
56	15948.674	15948.448	-0.225	19417.688	19417.638	-0.050	1395.403	1393.348	-2.055
57	15978.134	15977.835	-0.299	19411.919	19411.935	0.016	1396.727	1394.891	-1.836
58	15968.450	15968.144	-0.306	19440.783	19440.629	-0.154	1397.000	1395.062	-1.938
59	15997.641	15997.298	-0.343	19435.021	19434.929	-0.092	1397.833	1396.123	-1.709
60	15987.280	15986.998	-0.282	19463.083	19462.928	-0.156	1397.832	1396.036	-1.796
61	15992.662	15992.403	-0.259	19492.712	19492.453	-0.259	1399.808	1398.118	-1.690
62	15964.560	15964.335	-0.225	19482.271	19482.067	-0.203	1399.791	1397.939	-1.852
63	15969.720	15969.549	-0.172	19511.889	19511.564	-0.325	1404.265	1402.508	-1.757
64	15942.007	15941.830	-0.177	19501.568	19501.278	-0.290	1405.779	1403.895	-1.884
65	15946.740	15946.535	-0.205	19531.128	19530.798	-0.330	1409.887	1408.127	-1.760
66	15919.679	15919.540	-0.139	19521.645	19521.371	-0.274	1406.651	1404.823	-1.829
67	15923.156	15923.115	-0.041	19550.224	19549.905	-0.318	1409.733	1408.081	-1.653
68	15895.476	15895.429	-0.047	19540.251	19539.943	-0.308	1409.911	1408.247	-1.664
69	15900.629	15900.631	0.002	19569.533	19569.146	-0.387	1415.086	1413.565	-1.521
70	15873.003	15873.028	0.025	19558.853	19558.463	-0.391	1419.366	1417.876	-1.490
71	15877.750	15877.787	0.037	19588.889	19588.419	-0.470	1422.594	1421.307	-1.287
72	15849.294	15849.393	0.099	19578.852	19578.451	-0.401	1424.767	1423.493	-1.274
74	15803.712	15803.723	0.011	19617.441	19617.028	-0.412	1422.125	1421.436	-0.689
75	15780.754	15780.754	-0.000	19636.639	19636.235	-0.404	1429.606	1429.169	-0.437
76	15757.420	15757.423	-0.003	19655.936	19655.565	-0.371	1432.944	1432.616	-0.328
77	15734.525	15734.540	0.015	19675.166	19674.804	-0.362	1434.509	1434.209	-0.300
78	15711.401	15711.364	-0.037	19694.616	19694.318	-0.298	1435.804	1435.705	-0.099
79	15688.522	15688.470	-0.052	19713.808	19713.532	-0.276	1436.616	1436.472	-0.144
80	15665.449	15665.452	0.003	19733.162	19732.881	-0.282	1436.739	1436.608	-0.131
81	15642.589	15642.536	-0.053	19752.405	19752.132	-0.273	1435.604	1435.573	-0.031
82	15619.633	15619.561	-0.072	19771.625	19771.376	-0.248	1433.196	1433.158	-0.039
83	15596.531	15596.471	-0.060	19791.014	19790.776	-0.238	1430.286	1430.158	-0.127
84	15573.568	15573.530	-0.038	19810.202	19810.000	-0.202	1425.097	1424.980	-0.117
85	15550.613	15550.565	-0.048	19829.525	19829.315	-0.210	1420.057	1420.022	-0.035
86	15527.636	15527.584	-0.053	19848.755	19848.572	-0.182	1416.056	1416.038	-0.017
87	15504.675	15504.625	-0.050	19868.016	19867.828	-0.187	1410.878	1410.871	-0.006
88	15481.718	15481.666	-0.052	19887.258	19887.081	-0.177	1406.053	1405.377	-0.676
89	15458.662	15458.626	-0.036	19906.450	19906.263	-0.188	1401.535	1400.852	-0.683
90	16312.090	16311.794	-0.301	20130.755	20130.616	-0.139	1510.611	1510.477	-0.134
91	16292.973	16292.641	-0.332	20107.684	20107.508	-0.176	1511.944	1511.869	-0.075
92	16273.847	16273.533	-0.314	20084.850	20084.670	-0.180	1519.331	1519.251	-0.080
93	16253.769	16253.430	-0.339	20062.555	20062.360	-0.195	1528.135	1528.020	-0.115
94	16196.184	16195.997	-0.187	19992.401	19992.189	-0.213	1517.611	1518.112	0.501
95	16177.191	16177.061	-0.129	19969.632	19969.396	-0.236	1505.409	1505.460	0.051
96	16157.740	16157.669	-0.071	19946.457	19946.216	-0.241	1498.854	1498.902	0.047
97	16138.571	16138.559	-0.012	19923.507	19923.267	-0.239	1490.114	1490.102	-0.012
98	16119.270	16119.250	-0.020	19900.499	19900.259	-0.240	1481.961	1481.965	0.004
99	16100.052	16099.960	-0.092	19877.519	19877.270	-0.250	1475.849	1475.833	-0.015
100	16080.834	16080.826	-0.008	19854.638	19854.361	-0.277	1471.542	1471.461	-0.080

COMPARISON OF TWO SURVEYS

INITIAL SURVEY: 5 10/15/1982
 FINAL SURVEY: 23 7/25/1983
 X=NORTH, Y=EAST, Z=ELEVATION
 DELTA FLAGS X,Y,Z: 0.50 0.50 0.50

POINT	XI	XF	DELTX	YI	YF	DELTY	ZI	ZF	DELTZ
101	16061.445	16061.441	-0.004	19831.552	19831.282	-0.270	1467.738	1467.709	-0.029
102	16042.065	16042.004	-0.062	19808.417	19808.127	-0.289	1461.541	1461.431	-0.110
103	16022.867	16022.801	-0.066	19785.535	19785.182	-0.353	1456.246	1456.014	-0.232
104	16003.734	16003.683	-0.052	19762.657	19762.269	-0.388	1450.840	1450.514	-0.326
105	15984.279	15984.243	-0.036	19739.474	19739.082	-0.392	1445.170	1444.820	-0.350
106	15964.188	15964.229	0.041	19710.840	19710.423	-0.416	1441.301	1440.782	-0.519
107	15964.996	15964.917	-0.079	19716.560	19716.142	-0.417	1441.963	1441.497	-0.466
108	15945.859	15945.793	-0.066	19693.631	19693.176	-0.455	1436.609	1435.959	-0.650
109	15926.427	15926.392	-0.035	19670.659	19670.211	-0.448	1431.417	1430.707	-0.710
110	15907.460	15907.589	0.129	19647.902	19647.508	-0.394	1427.179	1426.215	-0.964
111	15887.963	15888.014	0.051	19624.741	19624.271	-0.470	1426.996	1426.023	-0.974
112	15868.670	15868.815	0.146	19601.755	19601.286	-0.469	1425.156	1424.014	-1.142
113	15811.090	15811.242	0.152	19533.014	19532.685	-0.329	1417.007	1415.734	-1.273
114	15791.639	15791.857	0.218	19509.861	19509.500	-0.361	1423.553	1422.252	-1.302
115	15772.355	15772.612	0.257	19486.790	19486.438	-0.353	1425.000	1423.731	-1.269
116	15753.041	15753.287	0.246	19463.840	19463.485	-0.355	1423.163	1421.965	-1.198
117	15733.686	15733.929	0.243	19440.742	19440.416	-0.326	1420.747	1419.630	-1.117
118	15714.618	15714.846	0.228	19418.014	19417.715	-0.300	1417.354	1416.373	-0.981
119	15695.244	15695.447	0.203	19394.936	19394.610	-0.326	1416.640	1415.800	-0.840
120	15675.977	15676.231	0.253	19371.926	19371.623	-0.304	1419.382	1418.667	-0.715
121	15656.709	15656.884	0.175	19348.914	19348.630	-0.285	1418.676	1418.085	-0.591
122	15637.279	15637.400	0.121	19325.830	19325.558	-0.272	1415.296	1414.844	-0.452
123	15618.030	15618.118	0.088	19302.834	19302.594	-0.240	1411.189	1410.806	-0.382
124	15598.937	15598.975	0.038	19280.026	19279.777	-0.249	1407.184	1406.902	-0.282
125	15579.487	15579.480	-0.007	19256.963	19256.722	-0.241	1403.170	1402.903	-0.268
126	15560.292	15560.268	-0.025	19234.021	19233.791	-0.229	1399.411	1399.207	-0.204
127	15541.076	15541.026	-0.050	19211.086	19210.873	-0.213	1394.784	1394.608	-0.176
128	15521.722	15521.654	-0.068	19188.222	19188.004	-0.218	1390.431	1390.344	-0.087
129	15531.843	15531.783	-0.061	19160.030	19159.848	-0.181	1386.122	1386.012	-0.110
130	15502.336	15502.245	-0.090	19164.835	19164.605	-0.231	1387.341	1387.273	-0.068
131	15483.108	15483.023	-0.085	19142.064	19141.896	-0.168	1383.302	1383.259	-0.042
132	15463.929	15463.837	-0.093	19119.166	19118.943	-0.223	1380.029	1379.997	-0.032
133	15444.638	15444.564	-0.074	19096.320	19096.108	-0.213	1378.036	1378.054	0.018
134	15425.149	15425.066	-0.083	19072.903	19072.689	-0.214	1377.808	1377.832	0.024
135	15406.067	15405.992	-0.075	19050.247	19050.025	-0.222	1377.231	1377.253	0.022
136	15386.714	15386.644	-0.070	19027.283	19027.078	-0.205	1376.323	1376.365	0.042
137	15367.481	15367.419	-0.062	19004.221	19004.016	-0.205	1376.704	1376.754	0.050
138	15346.235	15348.147	-0.088	18981.252	18981.069	-0.183	1376.284	1376.343	0.059
139	15328.894	15328.839	-0.055	18958.187	18958.026	-0.161	1376.411	1376.448	0.036
140	15309.540	15309.472	-0.068	18935.152	18934.978	-0.174	1376.647	1376.766	0.120
141	16588.240	16588.070	-0.170	19899.054	19898.756	-0.298	1537.133	1537.160	0.027
142	16568.825	16568.618	-0.207	19875.821	19875.625	-0.197	1533.566	1533.603	0.037
143	16549.497	16549.382	-0.115	19852.883	19852.662	-0.220	1532.253	1532.276	0.023
144	16530.229	16530.097	-0.132	19829.982	19829.751	-0.231	1527.652	1527.636	-0.016
145	16510.967	16510.764	-0.203	19807.099	19806.887	-0.212	1522.409	1522.289	-0.120
146	16491.479	16491.264	-0.215	19784.000	19783.802	-0.198	1514.911	1514.995	0.084
147	16472.427	16472.213	-0.214	19761.208	19761.003	-0.206	1506.987	1507.228	0.242
148	16453.298	16453.076	-0.222	19738.266	19737.977	-0.289	1500.145	1500.180	0.035

COMPARISON OF TWO SURVEYS

INITIAL SURVEY: 5 10/15/1982
 FINAL SURVEY: 23 7/25/1983
 X=NORTH, Y=EAST, Z=ELEVATION

POINT	XI	XF	DELTX	YI	YF	DELTY	ZI	ZF	DELTZ
149	16433.789	16433.568	-0.221	19715.052	19714.881	-0.170	1494.317	1494.318	0.001
150	16414.483	16414.210	-0.273	19692.174	19691.941	-0.233	1487.548	1487.530	-0.018
151	16395.233	16395.061	-0.173	19669.134	19668.957	-0.178	1480.154	1480.142	-0.012
152	16376.002	16375.738	-0.264	19646.140	19646.018	-0.122	1476.042	1476.039	-0.002
153	16356.542	16356.284	-0.258	19623.309	19623.160	-0.149	1470.559	1470.544	-0.015
154	16337.568	16337.308	-0.260	19600.354	19600.206	-0.148	1464.754	1464.691	-0.064
155	16318.130	16317.915	-0.215	19577.301	19577.035	-0.265	1459.569	1459.536	-0.033
156	16298.728	16298.589	-0.138	19554.128	19553.961	-0.167	1455.682	1455.599	-0.083
157	16279.556	16279.345	-0.211	19531.320	19531.163	-0.157	1450.956	1450.910	-0.046
158	16260.140	16259.925	-0.215	19508.305	19508.155	-0.151	1446.219	1446.111	-0.108
159	16241.020	16240.795	-0.225	19485.497	19485.340	-0.157	1441.001	1440.885	-0.116
160	16221.761	16221.493	-0.268	19462.284	19462.143	-0.142	1435.862	1435.702	-0.161
161	16193.218	16192.947	-0.271	19467.270	19467.114	-0.156	1427.032	1427.073	0.041
162	16230.905	16230.679	-0.226	19434.250	19434.114	-0.136	1441.168	1441.041	-0.127
163	16202.423	16202.097	-0.326	19439.496	19439.338	-0.158	1434.283	1434.090	-0.192
164	16183.106	16182.794	-0.313	19416.550	19416.382	-0.168	1433.441	1433.206	-0.234
165	16163.680	16163.536	-0.344	19393.546	19393.412	-0.134	1431.936	1431.629	-0.307
166	16144.541	16144.151	-0.390	19370.576	19370.504	-0.072	1429.135	1428.761	-0.374
167	16125.100	16124.686	-0.413	19347.523	19347.439	-0.085	1426.090	1425.633	-0.457
168	16105.811	16105.333	-0.478	19324.534	19324.509	-0.025	1422.757	1422.193	-0.564
169	16096.430	16095.989	-0.441	19313.165	19313.127	-0.038	1421.519	1420.994	-0.525
170	16086.636	16086.193	-0.443	19301.633	19301.649	0.016	1419.409	1418.849	-0.559
171	16076.920	16076.504	-0.416	19290.056	19290.029	-0.028	1417.356	1416.736	-0.620
172	16067.311	16066.903	-0.408	19278.715	19278.719	0.004	1415.402	1414.785	-0.617
173	16056.487	16056.107	-0.380	19268.221	19268.247	0.026	1413.644	1412.994	-0.650
174	16048.000	16047.600	-0.400	19255.885	19255.872	-0.013	1411.922	1411.274	-0.648
175	16029.115	16028.741	-0.375	19232.817	19232.829	0.012	1402.416	1401.654	-0.763
176	15970.962	15970.733	-0.228	19163.917	19163.901	-0.015	1394.264	1393.706	-0.558
177	15951.619	15951.438	-0.181	19140.842	19140.811	-0.032	1392.671	1392.112	-0.559
178	15932.272	15932.082	-0.190	19117.796	19117.781	-0.015	1391.464	1390.966	-0.498
179	15912.879	15912.699	-0.180	19094.746	19094.733	-0.013	1390.895	1390.441	-0.453
180	15893.714	15893.584	-0.130	19071.770	19071.757	-0.013	1389.443	1389.031	-0.411
181	15874.208	15874.132	-0.076	19048.762	19048.745	-0.018	1389.152	1388.793	-0.359
182	15855.045	15854.948	-0.097	19025.842	19025.862	0.021	1388.852	1388.569	-0.283
183	15835.555	15835.441	-0.114	19002.820	19002.837	0.017	1389.090	1388.849	-0.242
184	15846.181	15846.075	-0.105	18974.935	18974.941	0.006	1391.744	1391.643	-0.101
185	15816.719	15816.643	-0.076	18980.170	18980.176	0.006	1390.538	1390.392	-0.146
186	15797.265	15797.203	-0.062	18957.098	18957.086	-0.012	1390.998	1390.913	-0.085
187	15777.940	15777.848	-0.092	18934.028	18934.007	-0.021	1392.719	1392.700	-0.019
188	15758.682	15758.605	-0.077	18911.117	18911.112	-0.005	1396.346	1396.358	0.012
189	15739.398	15739.326	-0.072	18888.107	18888.077	-0.029	1399.224	1399.230	0.005
190	15720.165	15720.098	-0.066	18865.211	18865.167	-0.043	1400.282	1400.264	-0.018
191	15700.885	15700.864	-0.022	18842.243	18842.248	0.004	1401.541	1401.493	-0.047
192	15680.219	15680.216	-0.003	18818.017	18818.021	0.004	1404.002	1403.950	-0.052
193	15662.295	15662.281	-0.013	18796.396	18796.396	0.001	1405.743	1405.712	-0.031
194	15642.942	15642.941	-0.001	18773.300	18773.314	0.014	1407.283	1407.260	-0.023
195	15623.756	15623.772	0.016	18750.412	18750.414	0.002	1407.255	1407.240	-0.014
196	15604.333	15604.366	0.033	18727.297	18727.291	-0.006	1405.425	1405.416	-0.009

COMPARISON OF TWO SURVEYS

INITIAL SURVEY: 5 10/15/1982
 FINAL SURVEY: 23 7/25/1983
 X=NORTH, Y=EAST, Z=ELEVATION

POINT	XI	XF	DELTX	YI	YF	DELT Y	ZI	ZF
197	15585.045	15585.026	-0.019	18704.312	18704.297	-0.015	1402.301	1402.303
198	15565.771	15565.765	-0.005	18681.449	18681.415	-0.034	1401.101	1401.091
199	15546.605	15546.608	0.003	18658.553	18658.545	-0.008	1402.919	1402.918
200	15527.126	15527.151	0.025	18635.405	18635.383	-0.022	1401.783	1401.796
201	15507.982	15507.967	-0.015	18612.573	18612.547	-0.027	1399.054	1399.053
202	15488.513	15488.486	-0.026	18589.348	18589.334	-0.015	1396.817	1396.806
203	15469.220	15469.240	0.019	18566.411	18566.344	-0.066	1394.848	1394.826
204	15450.004	15450.043	0.039	18543.491	18543.489	-0.002	1391.525	1391.544
205	15430.729	15430.755	0.026	18520.528	18520.480	-0.048	1388.705	1388.714
222	15690.267	15690.218	-0.049	19095.543	19095.475	-0.068	1383.151	1382.852
223	15801.149	15801.108	-0.041	19232.543	19232.606	0.063	1391.357	1390.052
224	16063.001	16062.699	-0.302	19520.279	19520.055	-0.224	1407.262	1406.588
225	16158.037	16157.822	-0.215	19655.382	19655.190	-0.192	1443.350	1443.118

10. SUMMARY CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

This report presents the results of a three year subsidence monitoring program conducted at the C-3 panel of Kitt Energy Corporation's Kitt No. 1 Mine near Philippi, West Virginia. The C-3 panel is located in the 5.5 foot thick Pennsylvanian-age Lower Kittanning Coal at 600 foot depth. The panel is of sub-critical dimensions.

Section 2 of the report describes the geologic setting on a local and regional basis and identifies the nature and distribution of rock types composing the overburden. Section 3 describes the method and sequence of mining the C-3 panel, including roof support practices. Section 4 describes the types, locations and methods of installation of devices installed at mine level, in drillholes and at ground surface to monitor the response of the strata and the ground water to underground mining. Section 5 discusses pillar stresses and stresses in individual pillars and across the mine panel as mining progresses. Section 6 describes the convergence of the entries and cross cuts during mining and the relationship between convergence, compression of the coal pillars, and deflection of the mine roof and floor. Section 7 describes the flexure, fracturing and bedding slippage processes that characterize the manner in which the overburden deformed during retreat mining. Section 8 examines the response of the ground water regime to mining, including the changes in piezometric levels, hydraulic properties and water chemistry. Section 9 presents summaries of vertical and horizontal ground surface displacements that took place during retreat mining and draws parallels between the development of the subsidence trough and the deflection of a beam on an elastic foundation. A series of parameters are discussed that characterize the end-of-mining subsidence trough above the C-3 panel. These parameters are compared with values predicted by an available empirical method.

Specific findings of the study are reviewed in the Executive Summary at the beginning of this report.

CONCLUSIONS AND RECOMMENDATIONS

Overall, the writers consider the instrumentation program to have provided a reasonably complete picture of the subsidence process from mine level to ground surface. The data should provide useful input for empirical and analytical subsidence models both because the site conditions are representative of one area of the Northern Appalachian coal field and because similar data have been collected (by others) under a DOE/USBM contract at a longwall panels at similar depth within the Kitt No. 1 mine. The data should prove interesting, as well, because of the trapezoidal shape of the panel and because of the variable support offered by the abutments along the perimeter of the panel and the attendant influences on the subsidence profile.

Visualization of the ground survey data in terms of the deflections of a beam/plate on an elastic foundation helped to clarify the pattern of movements of points at ground surface during mining, particularly those around the perimeter of the mine panel whose movements were about the same order of magnitude as the resolution of the survey equipment. This basis for visualizing the data also helped in identifying areas where inelastic behavior had taken place and how it had influenced the shape of the subsidence trough.

As indicated in previous sections of the report, some instruments failed prematurely or, for other reasons, did not yield as much information as hoped for. The following recommendations are therefore offered for consideration to those who might develop future subsidence instrumentation programs:

1. Use steel casing rather than PVC casing in piezometers or water wells. Doing so should increase the likelihood of the casing remaining intact during mining and thereby limit extraneous water flows into or out of the monitoring installation.
2. Use large diameter boreholes (eg. 8-10 inch) for downhole instrumentation and make allowance for reductions in cross section of several inches that might accompany overburden deformation and subsidence. Avoid packing numerous devices in a single borehole and bring MPBX lead wires to ground surface in an open (non-grouted) hole.
3. Install battery-operated data loggers on stress meters and piezometers, wherever possible, in order to obtain a continuous record of changes. However, avoid long signal cables, which are easily broken by causes natural or otherwise.
4. Use the Time Domain Reflectometry System only in close conjunction with MPBX, inclinometer, or other "proven" instrument systems, until it is shown to provide interpretable, unambiguous data.
5. If possible, conduct a subsurface investigation of the overburden before and after retreat mining in order to confirm the findings of the borehole instrumentation program--the location and height of the caved zone, the fractured zone, the continuous zone, etc. Mining-induced rock breakage could be appraised by logging the fracture frequency of drill core obtained before and after mining and by companion downhole density and sonic logs. The sonic tests would provide a measure of changes in the moduli of the rock strata. A borehole TV investigation after mining would potentially enable the inspection of broken zones below ground surface that cannot be sampled successfully by core drilling and would potentially permit measurement of the size of bedding separations and other breaks in the rock strata produced by mining. Pre- and post-mining profiles of hydraulic conductivity with depth could be defined by a contiguous series of packer tests or drill stem tests. These, in combination with the other facets of the program would potentially lead to an improved understanding of how full extraction mining affects the ground water regime--a subject about which relatively little is known at the present time.

REFERENCES

- Arkle, T. and Brock, S. M. The Geology of construction Sand and Gravel Resources of West Virginia Proc. 19th Annual Highway Geology Symposium, May 16-17, 1968, Morgantown, W.Va., West Virginia Geological and Economic survey, pp. 103-119.
- Barlow, J. A. Coal and Coal Mining in West Virginia. West Virginia Geological and Economic Survey, Coal-Geology Bull. No. 2, Morgantown, W.Va., 1974, 63 pp.
- Bieniawski, Z. T. Improved Design of Room-and-Pillar Coal Mines for U.S. Conditions. Proc. First Conference on Stability in Underground Mining, August 16-18, 1982. SME of the AIME, New York, 1983, pp. 19-51.
- Chen, D.-W. and Peng, S.S. Analysis of Surface Subsidence Parameters Due to Underground Longwall Mining in the Northern Appalachian Coalfield. West Virginia University Research Report TR 81-1, Morgantown, 1981, 22 pp + tables and figures.
- Cooper, H. H., Bredehoeft, J. D and Papadopoulos. Response of a Finite Diameter Well to an Instantaneous Charge of Water. Water Resources Research. Vol. 3, No. 1, 1967, pp. 263-269.
- Hustrulid, W. A. A Review of Coal Pillar Strength Formulas. Rock Mechanics, Springer Verlag, Vienna, 1976, pp. 115-145.
- Jaeger J. C. and Cook N. G. W. Fundamentals of Rock Mechanics. Methuen & Co. Ltd., London, 1969. 513 pp.
- Lambe, T. W. and Whitman, R. V. Soil Mechanics. J. Wiley & Sons, New York, 1969.
- National Coal Board. Subsidence Engineers Handbook. National Coal Board Mining Department. London, 1975, 111 pp.
- Peng, S. S. Fracture and Failure of Chelmsford Granite. Ph.D. Dissertation, Stanford University, 1970, 201 pp.
- Peng, S. S. and Geng, D. Y. The Appalachian Field: General Characteristics of Surface Subsidence and Monitoring Methods in Surface Mining Environmental Monitoring and Reclamation Handbook. L.V.A. Sendlein et al. Elsevier, New York, 1983, pp. 627-646.
- Peng, S. S. and Chiang, H. S. Longwall Mining. John Wiley and Sons, New York, 1984, 708 pp.
- Popov, E. P. Mechanics of Materials. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1952, pp. 206-209.
- Todd, D. K. Groundwater Hydrology. Second Edition. John Wiley and Sons, Inc., New York, 535 pp.

U.S. Environmental Protection Agency. National Interim Primary Drinking Water Regulation. Federal Register, 40, No. 248, 1975.

U.S. Environmental Protection Agency. Water Quality Criteria 1972. EPA R3 73033.

Vesic, A. S. Bearing Capacity of Shallow Foundations. In Foundation Engineering Handbook. H. F. Winterkorn and H-Y Fang, eds. Van Nostrand Reinhold Company, New York, 1975, pp. 121-147.

Wilson, A. H and Ashwin, D. P. Research into the Determination of Pillar Size. The Mining Engineer, No. 141, London, 1972, pp. 409-430.