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DETECTION OF ABANDONED UNDERGROUND COAL MINES BY GEOPHYSICAL METHODS

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DETECTION OF ABANDONED UNDERGROUND COAL MINES BY GEOPHYSICAL METHODS

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and the

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ABSTRACT

Acid drainage produced by abandoned coal mines continues to cause serious water pollution problems. Without knowing the exact location of the concealed openings and the extent of the mine, the application of known, at source abatement techniques is virtually impossible. Drilling is the only known method for accurately determining the location and extent of the mine voids, but this is extremely expensive. This project attacks the problem through field studies of the following geophysical methods: electrical resistivity, self-potential, infrared radiometry, total field and differential magnetometry, seismic refraction and reflection, very low frequency electromagnetic and induced polarization over well documented, drift, coal mines. Airborne infrared radiometry proved to be an excellent tool for detecting and mapping acid mine/fresh water sources, acid mine/fresh water drainage, and fracture traces under selected conditions. Resistivity and magnetics anomalies coincide with some (not all) drift mine entries. Induced polarization data shows some apparent correlations with mine workings. Other methods tested did not yield correlatable information. Conventional geophysical approaches to this problem do not appear adequate for the task. Unconventional approaches including high frequency seismic, shear wave seismic, and induced polarization methods may provide answers pending their further development.

This report was submitted in fulfillment of Project 14010EHN under the partial sponsorship of the Water Quality Office, Environmental Protection Agency.

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SECTION I

CONCLUSIONS

1. Airborne infrared radiometry was successfully used for detecting and mapping acid mine/fresh water sources, acid mine/fresh water drainage, and fracture traces.

2. Electrical resistivity and magnetics data showed anomalies associated with some (not all) of the shallow drift mine entries. This success could not be extended to deeper, more practical depths due to the lack of resolution and sensitivity of the conventional resistivity configurations. In the case of magnetics, the one gamma sensitivity of available magnetometers limits the detection depth to shallow cases. Background noise is a problem with high sensitivity magnetometry.

3. Induced polarization (IP) data, although limited, illustrates apparent correlations with mine workings.

4. Conventional approaches with self-potential, very low frequency (VLF) electromagnetic and seismic refraction and reflection did not yield correlatable information.

5. No conventional geophysical approaches to this problem appear adequate for the task. A given approach may work under very rigid conditions, but will not work when applied to another case or to general conditions. A significant increase in the state-of-the-art in both technique and instrumentation will have to take place before abandoned coal mines can be satisfactorily detected and mapped.

SECTION II

RECOMMENDATIONS

The project was an experimental study of a number of different geophysical tools over selected drift coal mines. Limited successes were achieved with certain tools, as noted in the conclusions. Exploitation of some of these successes should be considered.

Airborne infrared radiometry succeeded as a reconnaissance tool for locating water drainage sources and should be pursued in this regard. Segments of drainage basins that are serious acid mine water problem areas should be overflown. The flights should be made at optimum detection seasons (late fall or early spring). Collateral data (topographic maps, aerial photography) should be used to aid in the discrimination of the acid water from the fresh water sources. Field checking will determine the accuracy of this approach in discerning and mapping the acid water sources relative to the fresh water sources.

The primary conclusion of this program is that conventional geophysical approaches to the problem do not appear adequate for the task. The following developments of an unconventional nature are recommended based on experimental and theoretical considerations.

High frequency seismic (to 1000 hertz) equipment theoretically promises to resolve subsurface features the size of mine workings. Adaptation or development of equipment of high enough sensitivity/power to overcome the high absorption rates expected should be applied in a field testing program.

In that the induced polarization experimental work performed on this project appears to be the only reported shallow earth IP work of this type, basic procedures and techniques were borrowed from mining geophysics. Some success was noted even though these approaches were not optimum. On the basis of the moderate success, it is recommended that field experiments with the IP method at higher power inputs, smaller electrode spacings and unconventional electrode arrays be employed.

Seismic shear waves will not be propagated by voids. This property may be utilized for void detection. Shear wave energy sources and receivers are not generally available. Equipment development for field experiments may be required but should be pursued.

One of the mine sites has been lost to future scientific study due to strip mining. The other sites are not presently in danger, but it would behoove agencies interested in solving some of the problems of abandoned deep mines to consider the utilization of these sites and their data against such an eventuality.

SECTION III

INTRODUCTION

The problem to which this project was addressed was the investigation of techniques for the detection and delineation of subsurface voids. In particular, the voids sought are concealed, abandoned, underground coal mines and associated portals, slump zones, vents and water drainage ways, both natural and man-made. Characteristically, backfill and/or overburden cover the mined areas and all apparent entrances and vents. The cover is variable in age, being related in some cases to subsequent strip mine operations. Slumping, fracture and collapse of portions of the cover of the mine are characteristic. Most of the mine areas of interest possess generally moderate to locally steep topography.

These mined areas are real and potential sources of acid mine water. Rainwater and groundwater percolate through the worked-out rooms and drifts, react with the sulfide minerals present, permeate the cover and eventually find their way to nearby streams.

In order to eliminate this source of water pollution, one of two at-source control measures must be taken; these are: (1) the routes of water movement into the mine workings must be located and sealed or (2) the routes of egress of the acid water from the mine workings must be located and sealed or redirected. In short, the mine workings have to be sealed against water movement. However, in order to seal against water movement, the mined areas and the routes and avenues of water movement must be located.

Drilling is currently the only "tried and true" technique to locate these sources of acid mine water. However, cost effectiveness considerations dictate that drilling is not a practical tool for even a moderate scale attack on the problem. On the other hand, geophysical techniques potentially offer an economical alternative means of detecting and delineating these mined areas and the avenues of water movement.

Geophysical methods have been applied to similar detection problems in recent years. The study of groundwater hydrology, karst terrane characterized by buried caves, solution channels or sinkholes and the location of ore bodies by the detection of zones of mineralization are representative of related problems that have been successfully attacked by geophysical methods.

This project involved the application of selected geophysical sensors and techniques to the problem of detecting and locating concealed, abandoned, underground coal mines and associated water drainage movement.

An extensive field testing program was performed over eight selected mines for which maps were available. The following geophysical methods were tested at these sites: electrical resistivity, self-potential, airborne radiometry, total field magnetometery, differential magnetometry, seismic refraction and reflection, VLF electromagnetic, and induced polarization. (Section XII, Discussion of Methods, introduces some of the basics of these approaches.)

Even though the project was of a feasibility nature, definite objectives (albeit ambitious) were proposed. These seven objectives of the project are listed on the following page, as well as a qualitative breakdown of their relative achievements.

Program objectives were to be accomplished by attacking the problem in five phases, covering a period of eighteen months. These phases were:

1. Selection of Techniques and Site Selection

2. Field Measurements

3. Data Analysis and Technique Evaluation

4. Field Validation

5. Technical Report

The work phases are discussed in detail in the following sections.

OBJECTIVES	FULFILLED	PARTIALLY FULFILLED	UNFULFILLED	REMARKS
1. DETECTION AND LOCATION OF CONCEALED, ABANDONED COAL MINES		X		SOME SUCCESS HAS BEEN NOTED WITH THE RESISTIVITY AND MAGNETICS METHODS IN DETECTING SHALLOW, BURIED DRIFT MINE ENTRIES. INDUCED POARIZATION SHOWED APPARENT PROMISE AT DETECTING MODERATE DEPTH (60') MINE WORKINGS
2. DETECTION AND LOCATION OF PORTALS, FRACTURES, FAULTS, JOINTING PATTERNS, SLUMP ZONES, AND OTHER AVENUES OF WATER MOVEMENT INTO AND OUT OF THE MINES		X		AIRBORNE INFRARED IMAGERY SUCCESSFUL IN DETECTING AND MAPPING ACID MINE/FRESH WATER SOURCES AND DRAINAGE, AS WELL AS, FRACTURE TRACES.
3. DEFINITION OF THE OPTIMUM METHOD OR MORE LIKELY. THE OPTIMUM COMBINATION OF METHODS REQUIRED FOR #1 AND #2			X	MOST OF THE EFFORT WAS DIRECTED AT ESTABLISHING WORKABLE TECHNIQUES.
4. DEVELOPMENT OF THE OPTIMUM FIELD PROCEDURES AND TECHNIQUES REQUIRED TO ACCOMPLISH #1 AND #2			X	MOST OF THE EFFORT WAS DIRECTED AT ESTABLISHING WORKABLE TECHNIQUES.
5. DEFINE THE QUANTITY, DIMENSIONS AND COMPACTION OF THE COVER TO SEAL THE MINE.			X	MOST OF THE EFFORT WAS DIRECTED AT ESTABLISHING WORKABLE TECHNIQUES.
6. DEVELOPMENT OF COMPUTER DATA REDUCTION METHODS TO SATISFY THE REQUIREMENTS OF CERTAIN GEOPHYSICAL METHODS APPLIED TO THIS PROBLEM.	X			THE STAMPEDE PACKAGE AND THE VARIOUS SUBROUTINES THAT HAVE BEEN ADDED FULFILL THIS OBJECTIVE.
7. RECOMMENDATIONS FOR THE DEVELOPMENT OF AN UNCONVENTIONAL METHOD OR MODIFICATION OF AN EXISTING METHOD FOR ITS OPTIMIZATION IN THIS PROBLEM.	X			HIGH FREQUENCY AND SHEAR WAVE SEISMIC, INDUCED POLARIZATION UNCONVENTIONAL ELECTRODE ARRAYS AND HIGH POWER, AIRBORNE INFRARED RADIOMETRY.

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SECTION IV

SELECTION OF TECHNIQUES

The primary objective of the research program was the application of existing geophysical methods and techniques to the detection and delineation of abandoned, underground coal mines and associated water drainage. Prior to initiation of field activities, an intensive literature search was made in order to learn of the latest pertinent experiments in shallow-earth geophysics. Visits and personal communications were extended to government agencies, universities and industrial firms to gain further information on the state-of-the-art in instrumentation and field techniques. From these sources it was concluded that there has been a prominent lack of investigation from bedrock depths to several hundred feet. (The one exception to this statement is in the area of hydrological exploration and studies; however, these investigations were generally confined to alluvial materials.) It was thus apparent that much of the field measurements and analysis oriented toward the project objectives would be pioneer in nature.

The application of geophysics to this problem is based on detection of contrasts in the physical properties between the rock strata surrounding the mined areas and the water avenues and the mined areas and water avenues themselves. These properties include: magnetic susceptibility, elastic properties, electrical resistivity, radiometric parameters, inductive electrical and magnetic properties and spontaneous/natural voltage generation. Measurements are made at the ground surface or certain ones from an airborne platform.

The local variations from normal/background or expected conditions are suspect as related to mining features or water avenues and correlations are sought relative to information on the mine map.

Techniques

Prior to the initiation of field activities the various geophysical techniques were evaluated for their potential application to this problem. In summary, the following criteria were used:

- Portability
- Speed of Data Collection
- Cost
  - Capital Investment
  - Maintenance
- Ease of Data Analysis

Accuracy and Precision
Information on Quantity and Dimensions of Excavation Required to Seal Mine

The evaluation was subjective, but this was expected since a truly quantitative evaluation means did not exist. Consideration was also given to the information available (although limited) in the literature on related studies. Table 1 summarizes the evaluation.

The following techniques were selected for field testing. A brief statement of import related to the problem of shallow earth investigations is included:

Electrical Resistivity

The most widely used geophysical tool for shallow earth investigations. Many math models and theoretical cases are covered in the literature.

Self-Potential

Literature citings of large self-potentials associated with anthracite coal spurred the use of this technique.

Airborne Infrared Radiometry

Manifestations of subsurface features due to surface variations in soil moisture content were sought. Reconnaissance by detection of water sources was practical.

Magnetics

High sensitivity equipment used in low background areas theoretically marginal but worthy of field investigation.

Seismic

Resonance of subsurface cavities reported. Also, delayed returns, amplitude "shadows" and amplitude attenuations feasible.

VLF Electromagnetic

Not ordinarily used for fine detail surveys but recent apparent success at Penn State University for hydrological studies prompted testing.

Induced Polarization

Provides apparent resistivity and self-potential data too. A potentially powerful exploration tool that has been used almost exclusively for deep studies. Advances in understanding the physical phenomena may make this tool the best of the electrical methods.

TABLE 1 SUMMARY OF EVALUATION OF POSSIBLE TECHNIQUES

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				USEFULNESS TO PROGRAM	EVALUATION		
					FIELD TEST	STAND BY	DISCARD
POSSIBLE TECHNIQUES	GEOPHYSICAL	THERMAL	THERMAL*	CORRECTION FACTORS BASED ON TOO MANY UNKNOWNS TO BE OF PRACTICAL VALUE.			X
		RADIOMETRIC	INFRARED	IN CONJUNCTION WITH AERIAL PHOTOGRAPHY TO ESTABLISH REGIONAL PICTURE; E.G., DRAINAGE AND FOR FRACTURE TRACE ANALYSIS	X		
			MICROWAVE	APPLIED USAGE TO SIMILAR PROBLEMS QUESTIONED IN RECENT TECHNICAL LITERATURE.		X	
		ELECTRIC	RESISTIVITY	THEORETICALLY VERY PROMISING.	X		
			SELF-POTENTIAL	MAY BE OF VALUE TO PROBLEM. FIELD TESTING WILL DETERMINE.	X		
			INDUCED POLARIZATION	THEORETICALLY PROMISING.	X		
			INDUCTIVE (ELECTROMAGNETIC)	RECENT SUCCESS IN MINING EXPLORATION INDICATE MERIT IN FIELD TESTING.	X		
		MAGNETIC	SCHMIDT TYPE	OLDER TECHNIQUE -- TOO SLOW.			X
			FLUX GATE	TOO SLOW FOR RECONNAISSANCE. USEFUL FOR BASE STATION.			X
			PRECESSION	RAPID, SIMPLE HIGH SENSITIVITY WORTHY OF FIELD TEST.	X		
		GRAVITY	TORSION BALANCE	TOO SLOW FOR RECONNAISSANCE, LOW SENSITIVITY			X
			GRAVIMETER	EXPECTED ANOMALIES TOO SMALL; LARGE CORRECTIONS		X	
		SEISMIC	REFLECTION	NOT AS PROMISING AS REFRACTION BUT WORTHY OF FIELD EXPERIMENTATION.	X		
			REFRACTION	THEORETICALLY PROMISING	X		
			SEISMI-ACOUSTIC*	POTENTIALLY A SIMPLE TECHNIQUE; NOT ENOUGH KNOWN ABOUT APPLICATIONS.			X
	GEOCHEMICAL	GROUND WATER TRANSPORT	GROUND WATER ANALYSIS	DETERMINATIONS TO BE MADE WHEN PRACTICAL.		X	
			PLANT ANALYSIS	NOT PRACTICAL DUE TO WIDESPREAD SOIL DISRUPTION BY STRIPPING OPERATIONS.			X
			SOIL ANALYSIS	NOT PRACTICAL DUE TO WIDESPREAD SOIL DISRUPTION BY OPERATIONS.			X
		SURFACE WATER TRANSPORT	SURFACE WATER ANALYSIS	LOCATION OF POINTS OF INFLUX AND EGRESS OF MINE WATER	X		
			STREAM SEDIMENT ANALYSIS	ANALYSIS TO FOLLOW STANDARD GEOCHEMICAL RECONNAISSANCE WHERE PRACTICAL.		X	
		TRACERS	CHEMICAL	LOCATION OF SEEPAGE SOURCES THRU GROUND COVER		X	
			DYES	LOCATION OF SEEPAGE SOURCES THRU GROUND COVER		X	
			RADIOACTIVE ISOTOPES	NOT FEASIBLE			X
			SUSPENSIONS	LOCATION OF SEEPAGE SOURCES THRU GROUND COVER		X	
			BACTERIA	NOT FEASIBLE			X

*NEW TECHNIQUE
'TO BE FIELD TESTED IF PRIMARY TECHNIQUES ARE NOT SUCCESSFUL.

Geochemical methods were proposed for use on this problem. Study of the sites selected and the applicability of the geochemical approach led to the conclusion that this effort would be better spent on the geophysical approaches. Section XII, beginning on page 81, includes a discussion of these findings as well as additional discussion of the geophysical techniques used.

SECTION V

SITE SELECTION

This section discusses the eight bituminous coal mine sites that were selected and used. One of the sites, the Bitumen #2 coal mine, has been lost to future scientific study due to strip mining. The other sites are not presently in danger, but it would behoove agencies interested in solving some of the problems of abandoned deep mines to consider the utilization of these sites and their data against such an eventuality.

Prior to any field investigation of geophysical techniques or methods for detection or location of coal mines, consideration had to be given to the desired characteristics of the mines to be tested. It was established that each mine should differ in geology, topography and hydrology as much as practical. This coverage would insure field testing over a wide range of mine environments. The rationale for this approach was based on the fact that each locality could conceivably require a different sensor technique or combination thereof for optimum mine detection.

Prior to establishing all the criteria for specific mine sites, a trip was made to an operating coal mine, the Rushton Mine, near Philipsburg, Pennsylvania. This mine consists of extensive workings in which both conventional and continuous mining equipment are used. By studying the underground workings, a better understanding of the criteria needed to select a mine was established. An appreciation for the geometry and the physical character of the coal mines was also gained which proved invaluable during the data analysis phase.

Criteria for Mine Selection

The Pennsylvania Department of Environmental Resources provided numerous mine maps, personal knowledge and observations against which we were able to weigh our selection criteria. These criteria included:

Depth of Overburden

Shallow mines were most desirable. Less than 100 feet of overburden was preferred. Thin overburden maximizes the probability of detection by geophysical means.

Coal Seam Thickness

The thicker the better, again for purposes of maximizing the probability of detection by geophysical means.

Number of Coal Seams Mined

Preference was given to shallow, single seams for simplicity in data analysis. It was recognized that multiple mined seams closely spaced would generally provide a greater physical parameter contrast for most geophysical measurements but the reduction in ambiguity by studying single seam mines was thought to be more desirable.

Hydrology

Mines discharging large quantities of acid mine water were sought as a first choice in that these types of mines are the primary polluters. Also considered were mines which intermittently discharge acid mine water, as well as mines which discharge no acid mine water.

Topographic Relief

In order to simplify the analysis of the geophysical data and to minimize topographic corrections of the data, sites of gentle relief were sought.

Vegetative Cover

In order that the airborne radiometry techniques might be used most effectively and that field crews have the benefit of true line-of-sight, the mines should be overlain by open fields.

Access to Site

In that variable quantities of equipment for field measurements required transporting to the sites, access roads passable to truck traffic were necessary.

Access to Mine

If the mine had an opening large enough for entry and exit by an exploration party, it was highly rated. The purpose of this requirement was to allow exploration of the mine workings for verification of their nature, i.e., open, dry/wet to completely collapsed, dry/wet. This knowledge was most valuable to the data analysis work.

Absence of Cultural Features

Houses, barns, powerlines, water lines, sewers, roads, cuts and fills, etc., would influence one or more geophysical methods. In order to minimize these sometimes unpredictable "noise" sources, mines were selected on the basis of the absence of these features.

Distance from State College

In order to maximize time spent on field measurements and to minimize travel time, mines that are closer to State College were preferred.

Availability of Complete Maps of Mine Workings

Fundamental to the placement of the traverse lines and the data analysis is the knowledge of the location of the mine workings and their nature.

Each of these criteria was subjectively scaled from 0 to 10 points, with the optimum condition given the value of 10 and sub-optimum conditions given appropriately lower values. Table 2 illustrates the numerical basis and results of this semi-quantative ranking system. The mines listed in Table 2 are those that were considered worthy of field checking and weighing against our selection criteria after discussion and study had reduced a much longer list of mines and their maps as provided by the Pennsylvania Department of Environmental Resources.

Sites Selected

Table 2 shows in gray tone the eight sites that were selected for study. Originally only three sites were to be selected and worked. These were:

Mills #4
Bitumen #1
Bitumen #2

Late in the 1970 field season, after an informal review of project achievements, it was concluded that it would be desirable to perform field measurements along traverses over a number of different mine entries. This conclusion was based on the apparent success of the resistivity techniques in detecting drift mine entries through shallow overburden. In order to exploit this success, the following additional sites were selected:

New Watson (two entries)
Old Watson (two entries)
Big Spring (main entry)
Knowles (main entry)
Hoover (main entry)

The following sections discuss some of the characteristics of these mines.

Mills #4 Coal Mine

Figure 1 is the site location map for the Mills #4 coal mine. This mine is located approximately two miles south of Edendale in Rush Township, Centre County, Pennsylvania. Field activities were initiated at this site.

TABLE 2 MINE SITES INSPECTED AND RATED BY SELECTION CRITERIA

	MINE NAME	LOCATION TWNSP COUNTY	DEPTH OF OVERBURDEN (100 10 PTS)	SEAM THICKNESS (4 10 PTS)	NUMBER OF SEAMS MINED	HYDROLOGY (ABUNDANT ACID MINE WATER 10 PTS)	TOPOGRAPHIC RELIEF (20 1000 10 PTS)	VEGETATION COVER	ACCESS TO SITE	ACCESS TO MINE	ABSENCE OF CULTURAL FEATURES	DISTANCE FROM STATE COLLEGE	COMPLETE MAPS	TOTAL (110 PTS MAX)	MINES CONSIDERED AS POTENTIAL SITE
1	BIG SPRING #1	RUSH-CENTRE	8	8	0	7	7	7	9	0	10	10	8	84	YES
2	RUSHTON (OPERATING)	RUSH-CENTRE	5	8	0	8	5	3	10	10	8	10	10	77	NO (OPERATING)
3	CARTWRIGHT	DECATUR-CLEARFIELD	10	8	10	6	7	8	10	0	8	9	7	83	NO
4	BUCKET LINE	DECATUR-CLEARFIELD	10	10	10	6	5	7	10	0	8	9	7	85	NO (STRIPPED OVER)
5	CUNARD	MORRIS-CLEARFIELD	10	8	10	6	7	8	10	0	5	9	6	79	NO
6	ELLIOT KNOWLES #3	RUSH-CENTRE	10	10	0	8	5	2	8	0	10	10	8	8	YES
7	HARPSTER	RUSH-CENTRE	10	10	10	4	8	5	8	1	10	10	8	84	NO
8	BEAVER #4	RUSH-CENTRE	10	8	10	6	6	3	8	0	10	10	8	79	NO
9	STABCK	RUSH-CENTRE	10	10	10	5	7	6	6	0	10	10	8	82	NO
10	OLD WATSON	RUSH-CENTRE	0	10	10	3	6	8	10	5	5	10	7	84	YES
11	ENGLISH CENTER	WESTPORT-CLINTON	10	10	10	8	8	8	7	0	8	6	8	83	NO
12	BATSCHLET	WESTPORT-CLINTON	10	10	10	8	8	8	7	0	8	8	6	83	NO
13	ELLIOT HILLSIDE	RUSH-CENTRE	10	10	10	6	7	8	5	0	10	8	8	82	NO
14	FLAT RUN #2	GRAHAM-CLEARFIELD	10	10	10	7	8	7	6	0	8	8	8	82	NO
15	SMOOTH HILL #2	RUSH-CENTRE	8	10	10	7	7	2	10	0	8	10	8	80	NO
16	GRANVILLE #5 (OPERATING)	RUSH-CENTRE	10	10	10	8	6	9	9	10	8	10	8	98	NO (OPERATING)
17	ELLIOT, WILBOR #1 (OPERATING)	JORDAN-CLEARFIELD	10	9	10	8	8	7	8	0	6	6	8	80	NO (OPERATING)
18	ELLIOT GINTER #1 (OPERATING)	GULICH-CLEARFIELD	10	9	10	8	8	7	8	0	10	8	8	86	NO (OPERATING)
19	MILLS #4	RUSH-CENTRE	0	10	10	5	8	6	7	0	10	10	10	86	YES
20	SPRUCE RUN #2	WEST KEATING-CLINTON	10	10	10	5	8	6	5	0	9	6	10	79	NO
21	LAUREL RUN	BURNSIDE-CENTRE	9	7	10	5	8	6	10	0	9	8	10	82	NO
22	HOOVER (SANDY RIDGE)	RUSH-CENTRE	10	6	0	8	7	6	6	0	8	10	0	73	YES
23	HERB MORGAN - (2-OPERATORS)	RUSH-CENTRE	10	8	10	7	6	5	6	0	10	10	8	80	NO
24	FLAT RUN #1	GRAHAM-CLEARFIELD	10	9	10	6	8	8	8	0	4	10	8	81	NO
25	GREEN VALLEY	GRAHAM CLEARFIELD	10	8	10	6	8	5	7	0	4	10	8	78	NO
26	BITUMEN #1	WESTPORT-CLINTON	10	10	10	8	10	10	9	0	7	6	8	88	YES
27	BITUMEN #2	WESTPORT CLINTON	10	10	10	3	10	8	9	7	10	6	10	93	YES
28	NEW WATSON	RUSH-CENTRE		10	10	6	6	8	10	0	4	10	10	84	YES
	NUMERIC VALUE EXPLANATION		-1 POINT FOR EACH 10 OVER 100 OVERBURDEN	-1 POINT FOR EACH 6" LESS THAN 4'	0 PTS FOR MULTIPLE SEAM 10 PTS FOR SINGLE SEAM	ABUNDANCE OF ACID MINE WATER 10 PTS NO WATER 0 PTS	1 POINT FOR EACH 20 GREATER THAN 20 1000 I E 20' 1000' 10 PTS, 40 1000' 9 PTS ETC	DENSE WOODS 0 PTS ½ OPEN 5 PTS OPEN 10 PTS	GRADED ON ACCESSABILITY BY VEHICLE	0 TO 10 PTS DEPENDING ON ACCESS TO MINE WORKINGS	HOUSES-POWERLINES GRADED BY HOW FEATURES MAY HINDER FIELD STUDY	30MI 10PTS 40MI 9PTS 50MI 8PTS 60MI 7PTS	DETAILED RECENT MAPS 10 PTS NO MAPS 0 PTS	85PTS AND ABOVE OPTIMUM EXCEPT FOR OPERATING MINES	CP9105

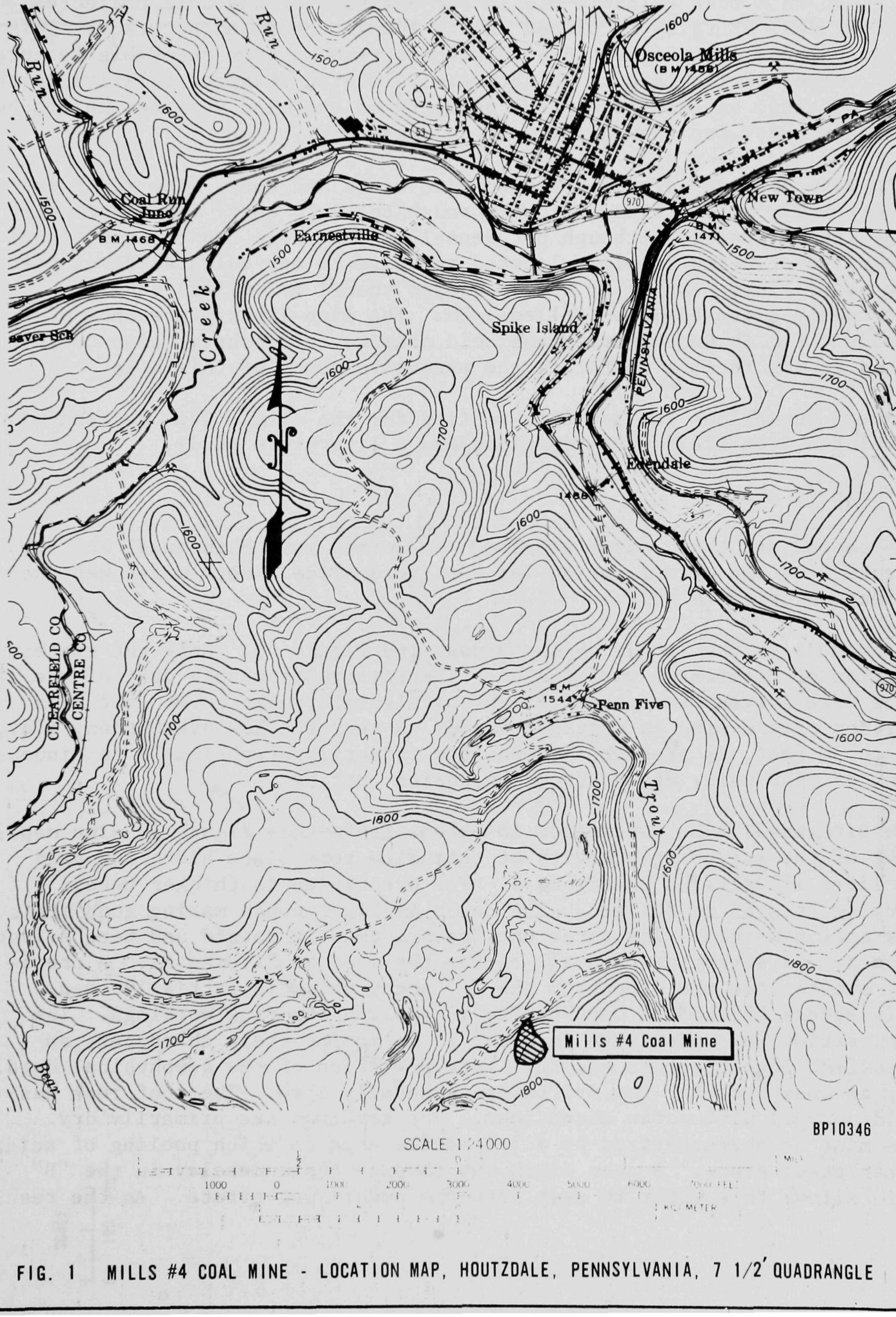

FIG. 1 MILLS #4 COAL MINE - LOCATION MAP, HOUTZDALE, PENNSYLVANIA, 7 1/2' QUADRANGLE

Figure 2 is a copy of the map of the mine workings and related features. This map is a most valuable aid in our analysis of the data collected. A great deal of faith is placed in its completeness and accuracy. This is so because data collected at distances removed from checkable features, i.e., mine entries, has to be accurately located in space relative to the mine workings beneath it and the geometry of the mine workings has to be known in order for the analysis to be meaningful.

Both mine entries have been sealed with earth and rock. The right entry is dry while acid drainage flows through the left entry intermittently. The site is wooded, although not densely. This site has the additional advantage of being remotely located relative to any cultural development (no power lines nearby; no houses closer than 1 1/2 miles) and is reasonably close to State College, Pa. The mine layout, presence of geologic faults and intermittant acid mine water discharge also contributed to the factors dictating the extensive study of this site.

Table 3 summarizes the geologic section for the site. This section was developed from field investigations and a literature study.

Bitumen #1 and #2

The second and third sites selected and worked were Bitumen #1 and #2. Figure 3 is the site location map for these sites. Both mines met the selection criteria well.

Bitumen #1 is the larger of the mines (see Figure 4). Only the eastern portion of Bitumen #1 was studied. The entries from this part of the mine were driven from an old stripping highwall. The cover over this portion of the mine is a grassy field. A very shallow overburden, i.e., 15 to 30 feet, is present and consists primarily of shale. A continuous flow of acid water drains from the buried entries.

The Bitumen #2 mine is smaller in extent (reference Figure 5, mine map). Most of the surveying activity at this site took place along the grid of lines illustrated in Figure 5. The overburden is thicker here, varying from 25 to 60 feet. The cover is light woods making good sight distance possible. The three entries are closely spaced and were driven from an old stripping highwall as was the case at Bitumen #1. A crawlway exists into the mine from the "C" entry which is partially open. This access offered an opportunity to explore the mine workings. The exploration was undertaken in order to determine their character, an important ingredient to any full interpretation of the geophysical data. It was observed that the drifts are generally open. The roof rock has held up well with a few exceptions. The workings are primarily dry. The mine is characterized by a low-saddle area in which pooling of acid water takes place. A deep ditch cut through the underclay in the "B" main allows this water to seep into the underlying strata. As the result,

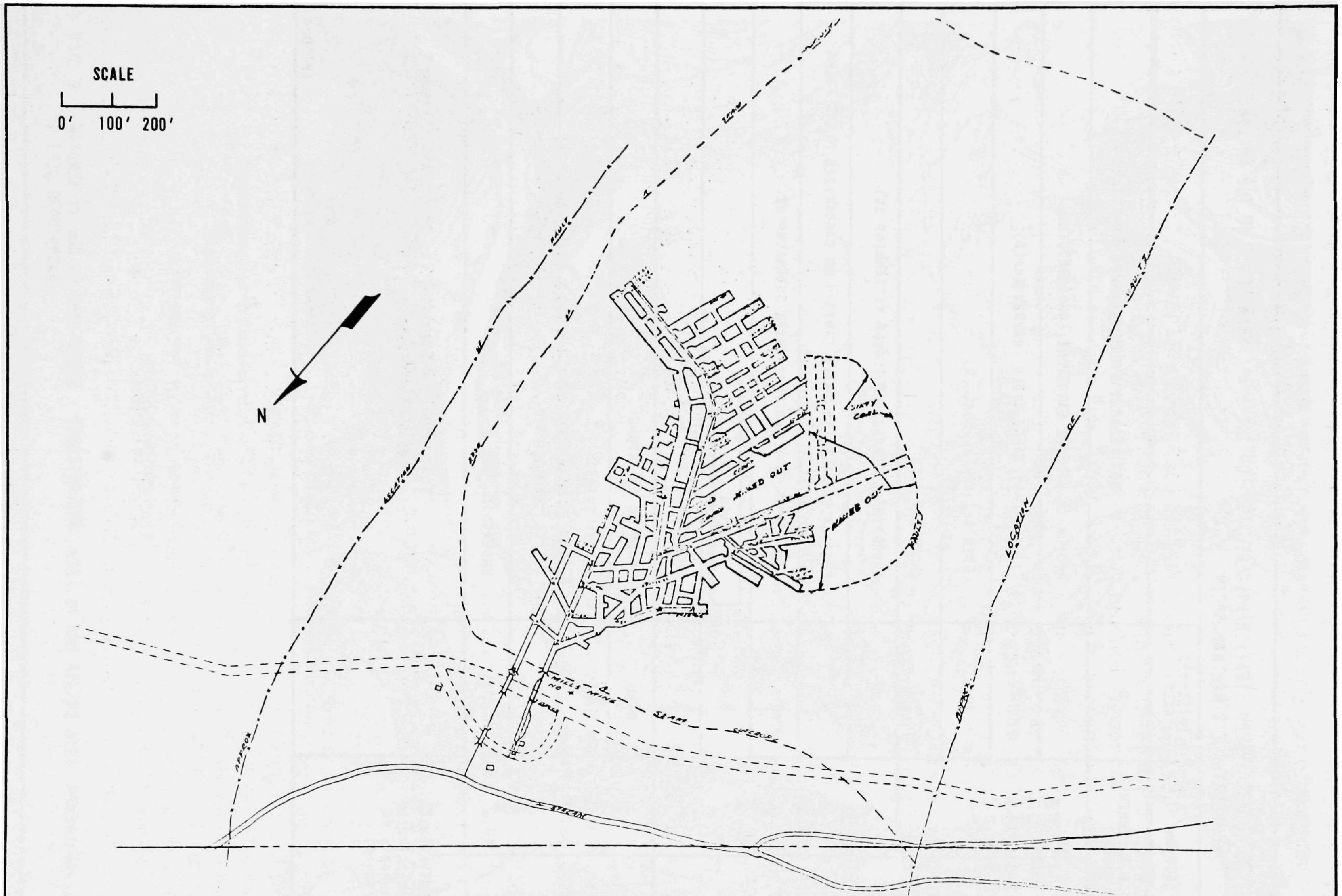

FIG. 2 MAP OF THE MILLS NO. 4 MINE OPERATED BY WALLIN AND CHRISTROFF, RUSH TOWNSHIP, CENTRE COUNTY, PA.
(November 21, 1951, Bernard Lucas -- Engineer)

BP10397

TABLE 3 GENERALIZED STRATIGRAPHIC SECTION FOR THE "A" SEAM COALS OF THE PHILIPSBURG-HOUTZDALE SYNCLINAL BASIN

SECTION		THICKNESS (FEET)	LITHOLOGY
UPPER ALLEGHENY GROUP		0	NOT PRESENT OVER MINE AREA
LOWER ALLEGHENY GROUP	KITTANNING FORMATION	>40	MEDIUM TO MASSIVE SANDSTONE (CROSSBEDDING)
		~15	FISSILE GRAY SILTY SHALE (HAMDEN SHALE)
		4½-5	LOWER KITTANNING COAL (B)
		~6	UNDERCLAY
	CLARION FORMATION	>30	SUBGRAYWACKE SANDSTONE (LOWER KITTANNING SS)
		3-5	FISSILE BLACK SILTY SHALE CONTAINING CARBONIZED PLANT FILMS
		~20	CLARION SS, BUFF AND GRAY-WHITE SUBGRAYWACKE
		3-5	CLARION 1,2,3 (A)
		3-5	UNDERCLAY, SOFT BLUE, IMPURE
POTTSVILLE GROUP	MERCER FORMATION	15-50	HOMEWOOD SANDSTONE
		0-25	MERCER SHALE
		1 3	MERCER COAL (DIRTY)
		5-25	UNDERCLAY
PENNSYLVANIAN / MISSISSIPPIAN (boundary in dispute)		75-100	CONOQUENESSING SANDSTONE (?) GRAY CHANNEL FILLING / POCONO SANDSTONE WHITE

AP10091

FIG. 3 BITUMEN #1 AND #2 COAL MINES - LOCATION MAP, KEATING AND RENOVO WEST, PENNSYLVANIA, 7 1/2' QUADRANGLE

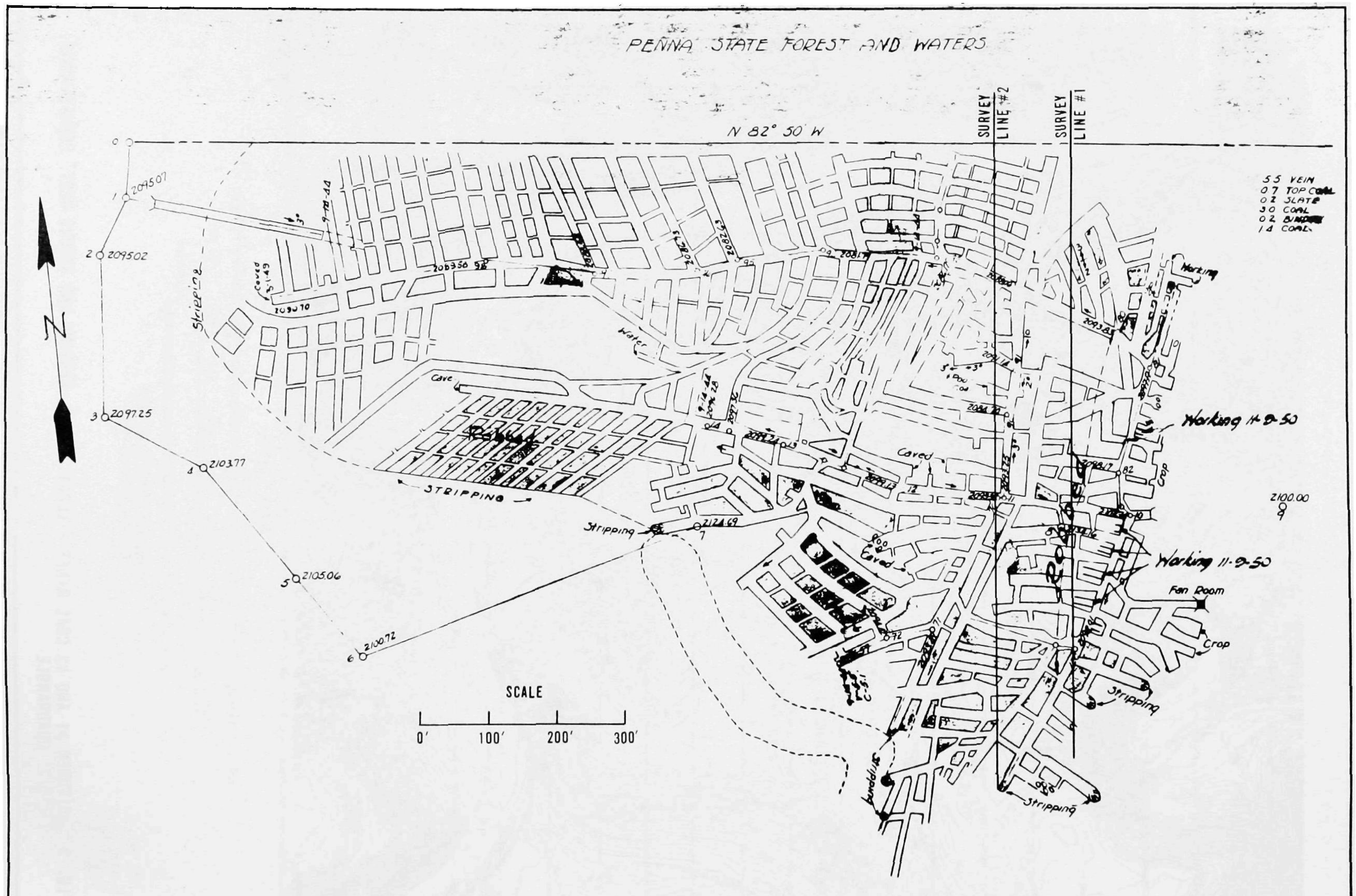

FIG. 4 MAP OF THE BITUMEN #1 COAL MINE OPERATED BY HARRY S. BATSCHELET, CLINTON COUNTY, PENNSYLVANIA (FEBRUARY 1, 1951, F. A. BOBANICK - ENGINEER)

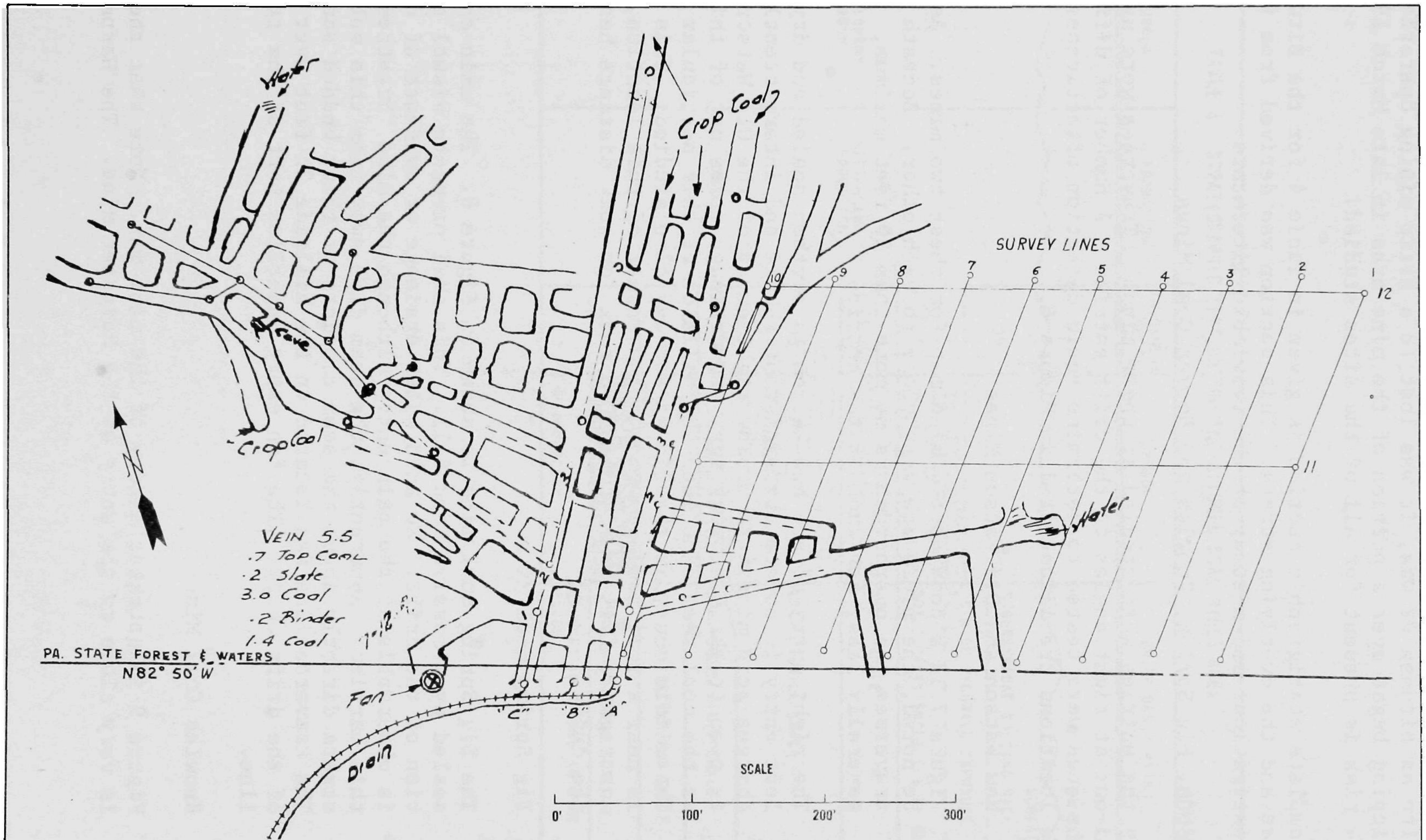

FIG. 5 MAP OF THE BITUMEN #2 COAL MINE OPERATED BY HARRY S. BATSCHELET, CLINTON COUNTY, PENNSYLVANIA (SEPTEMBER 15, 1954, F.A. BOBANICK - ENGINEER)

CP11011

this mine does not have an acid water drainage problem. As excellent a site as Bitumen #2 was, it was lost to a strip mining operation. Stripping began over a portion of the mine area in late March 1971. This risk is present for all of the sites studied.

A complete statigraphic section is given in Table 4 for the Bitumen mines and the overlying strata. This section was derived from field investigations and a study of the available literature.

Watsons, Big Spring, Knowles and Hoover Coal Mines

Only the entries were studied at these mines. Traverses were usually laid-out at right angles to the drift entries. A number of different techniques were tested to determine their detection effectiveness. The mine locations are illustrated in Figure 6.

New Watson and Old Watson Mines

Figure 7 is a copy of the mine map for these two mines. As may be noted, the mines are very close to each other. Beneath the traverses the overburden is no more than 20 feet maximum, generally less, for each of the entries

The right entry of the New Watson is earthen sealed and dry. The left entry is covered by sandstone rubble and intermittently discharges acid mine water. The right entry of the Old Watson mine is open to the mine workings. No drainage comes out of this entry as the coal seam dips into the hillside at this particular point. The middle entry at the Old Watson was also studied. This entry is near a road haulageway. As the result of this location, it was tightly filled with soil and rock for some distance back along the drift.

Big Spring Coal Mine

The Big Spring coal mine is shown in Figure 8. The main entry is sealed by a massive rock fall. This seal prevents visual observation of the drift. No acid water drainage or evidence of drainage is observable at the main entry although the mine "breathes" through this barrier. Apparently, the seam dips away from this entry. The strata directly above the seam consists of thick bedded sandstone. The traverse line was located on the hillside 25 feet over the roof of the drift entry. The fan entry underlies part of the traverse line.

Knowles Coal Mine

Figure 9 illustrates a copy of the mine map. Note that the entry is very close to the entry of the Harpster mine. The Harpster mine

TABLE 4 STRATIGRAPHIC SECTION FOR THE BITUMEN COAL MINES AREA

AP11007

SYSTEM	GROUP	FORMATION	THICKNESS (FEET)	SYMBOL	BRIEF DESCRIPTION
PENNSYLVANIAN SYSTEM	ALLEGHENY GROUP	KITTANNING FORMATION			EROSION SURFACE
			> 30		SUBGRAYWACKE CAPPING HILL
					RIM OF HIGHWALL EXPOSURE
			8		SOIL, SILTY SHALE & S.S. BLOCKS
			4 to 7		SILTY SHALE
			12		GRAY FISSILE SHALE
			2		GRAY/BROWN SILTY SHALE
			6½		BLACK SILTSTONE AND SHALE
			5½		LOWER KITTANNING COAL (B)
			> 3	UNDERCLAY	EXPOSED IN TRENCH IN MINE FLOOR

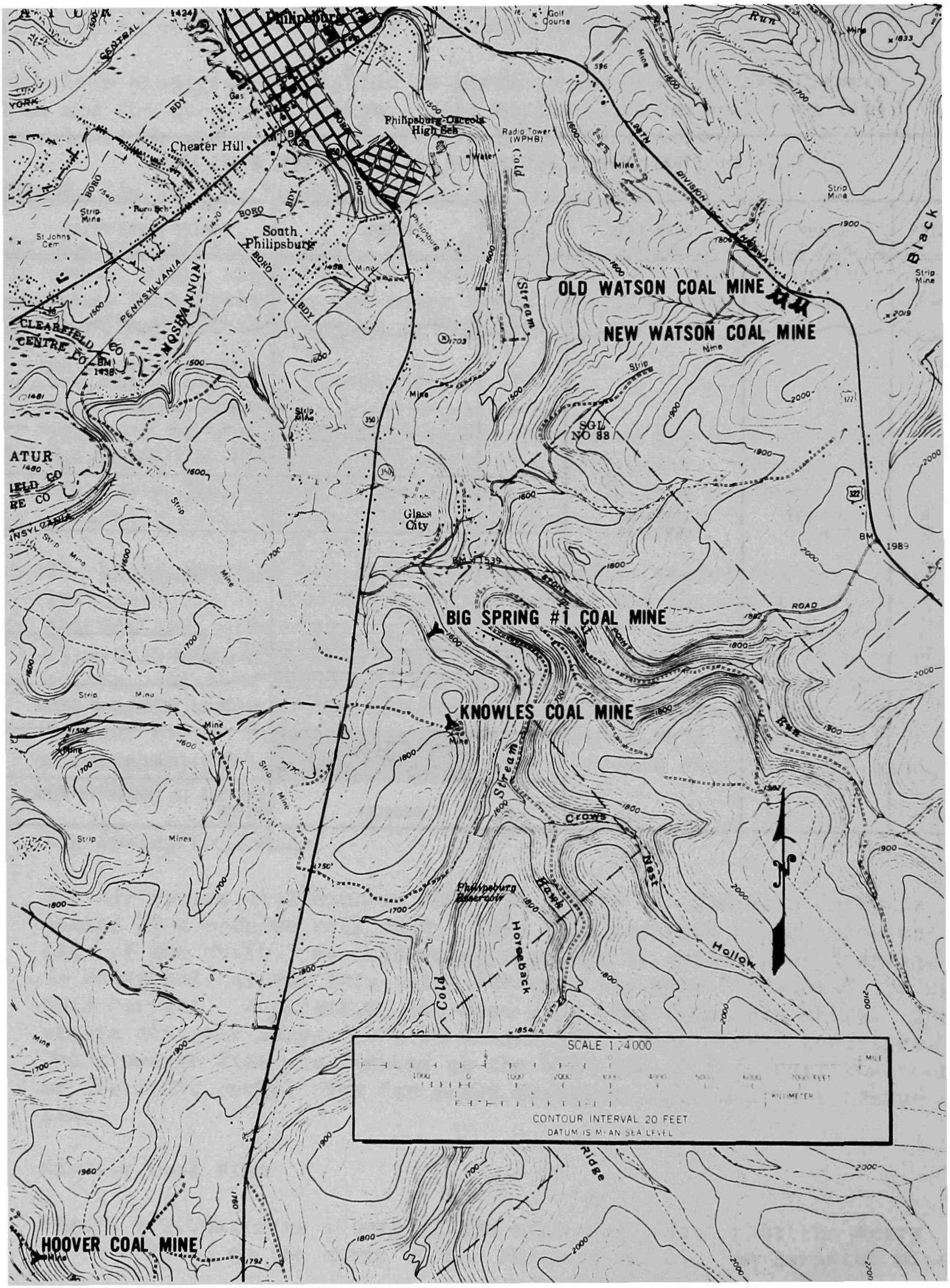

FIG. 6 LOCATION MAP FOR THE NEW WATSON, OLD WATSON, BIG SPRING #1, KNOWLES AND HOOVER COAL MINES -- PHILIPSBURG AND SANDY RIDGE, PENNSYLVANIA, 7-1/2' QUADRANGLES

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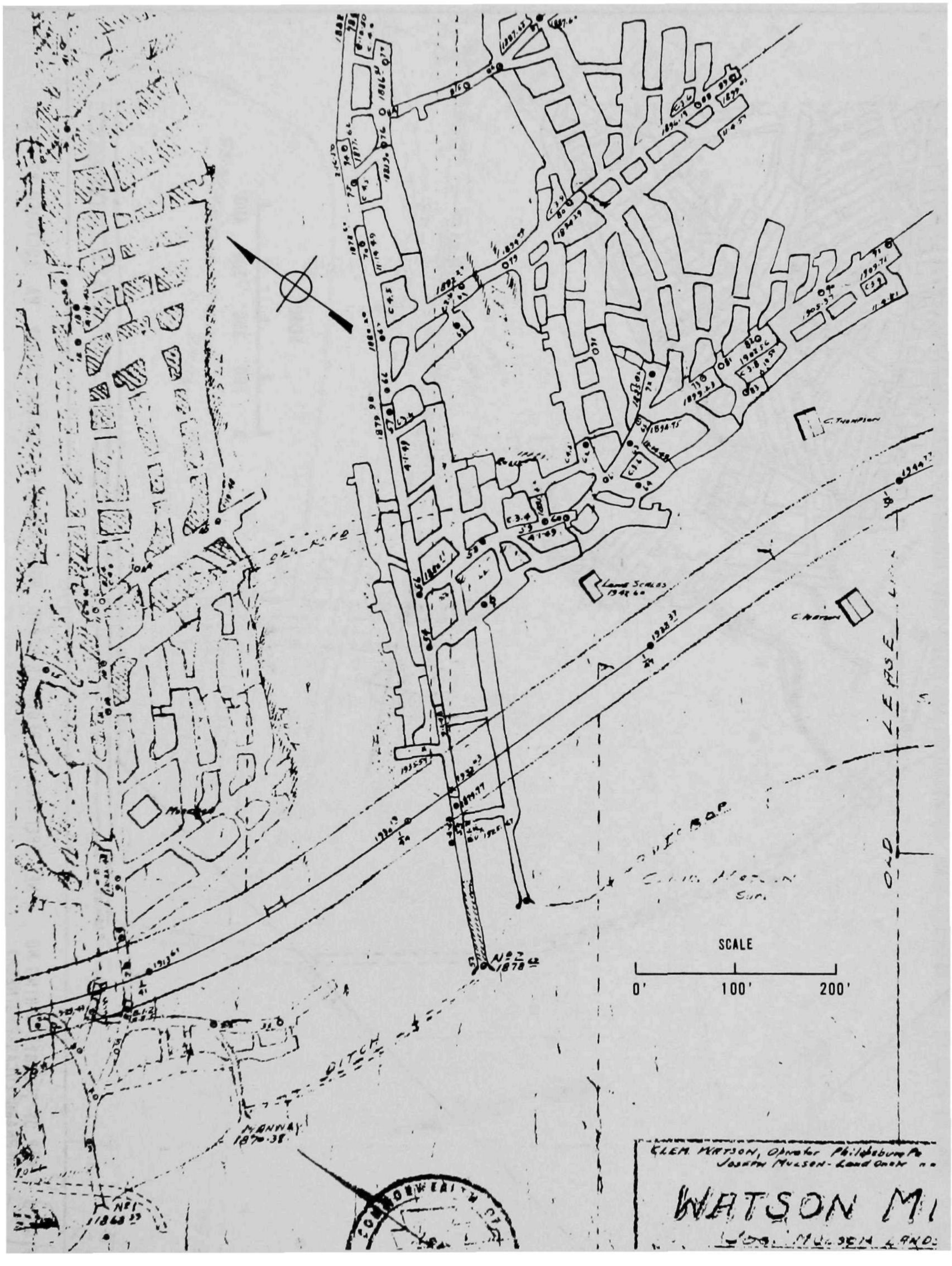

FIG. 7 MAP OF PART OF THE OLD AND NEW WATSON MINES, OPERATED BY CLEM WATSON, PHILIPSBURG, PA. (NOVEMBER 4, 1951, G.E. DUNKLE-ENGINEER)

BP11826

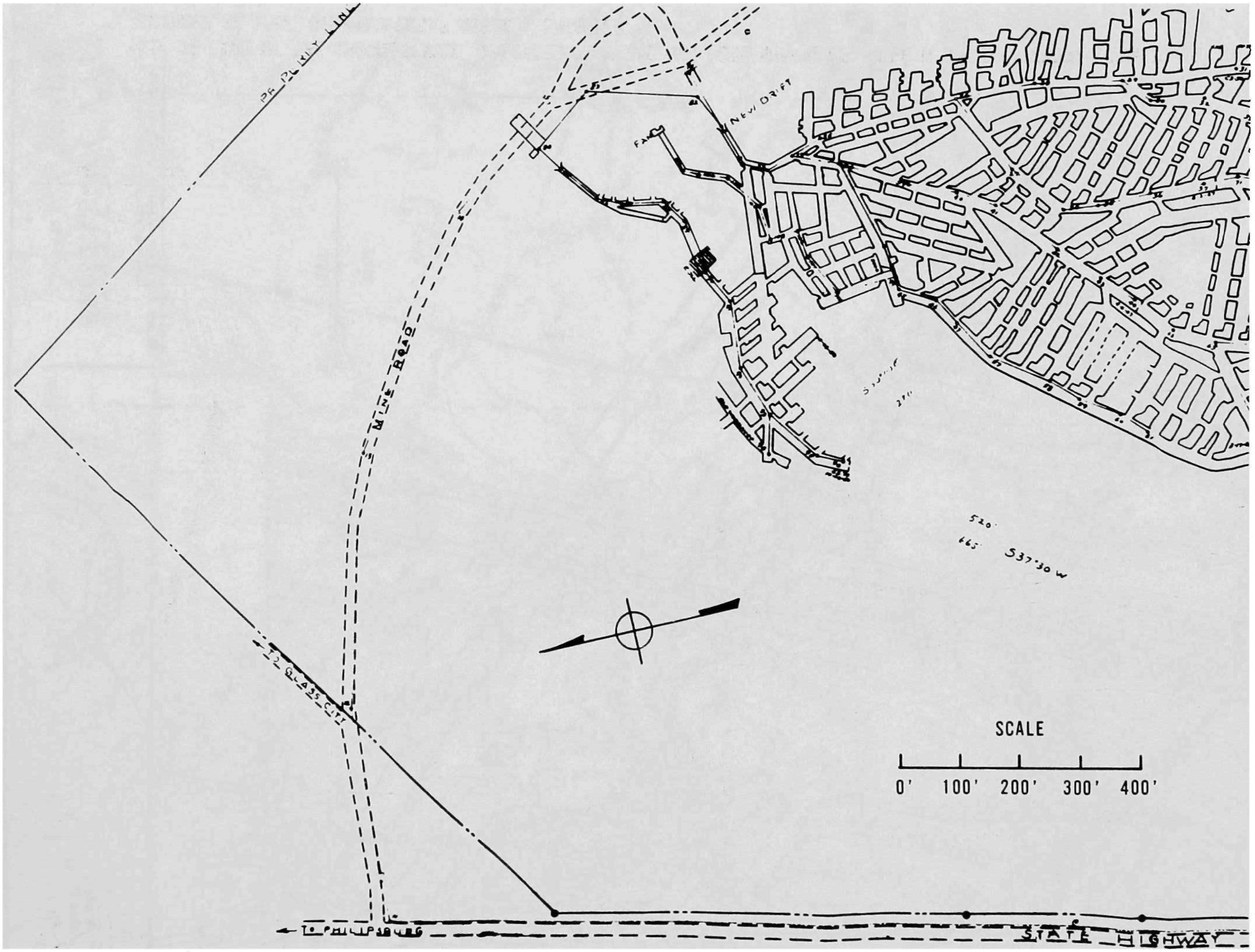

FIG. 8 MAP OF THE BIG SPRING NO. 1 MINE, OPERATED BY REGINALD MEARS, RUSH TOWNSHIP, CENTRE COUNTY, PA. (OCTOBER 27, 1950, BERNARD LUCAS-ENGINEER)

BP11827

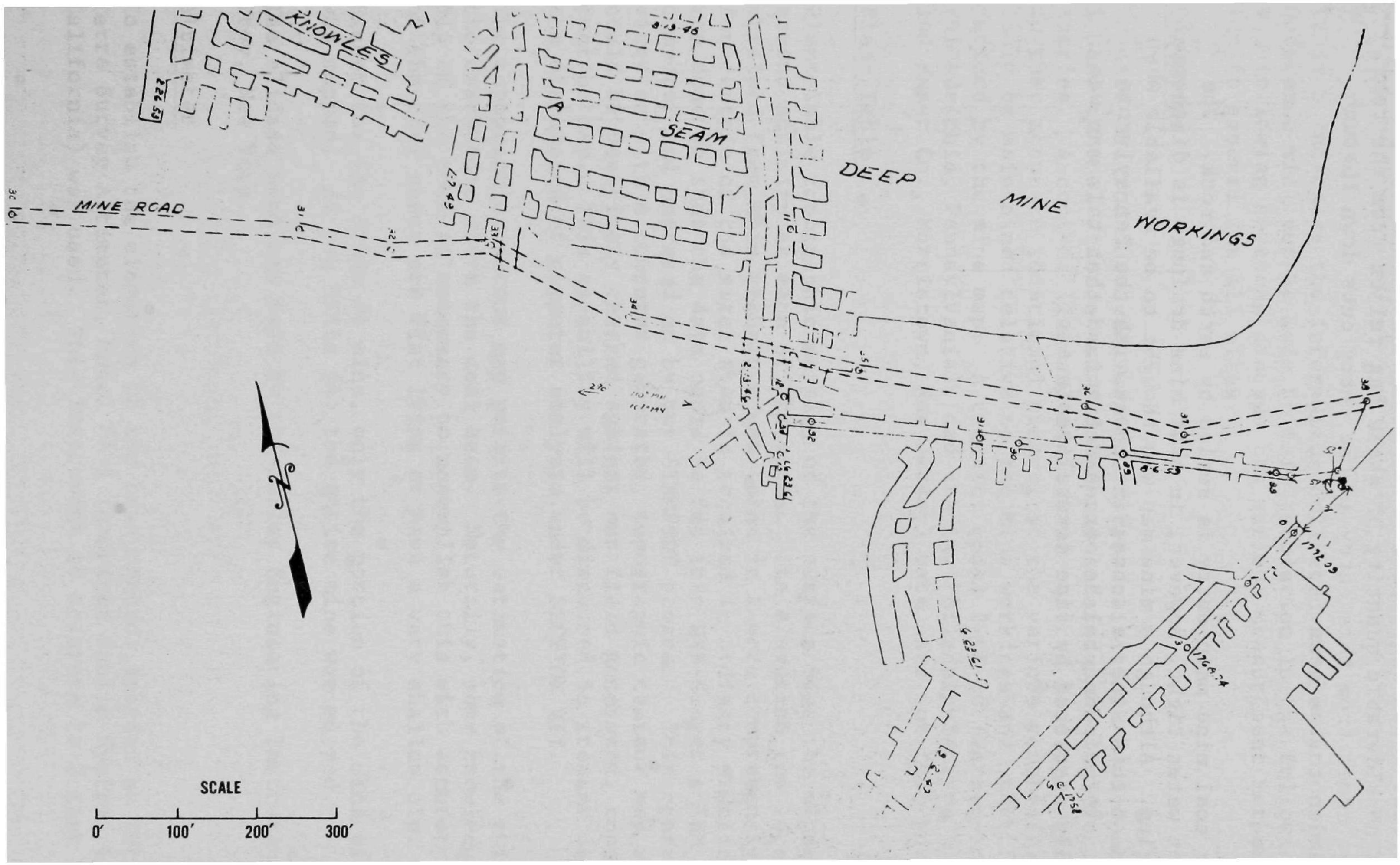

FIG. 9 MAP OF PART OF THE KNOWLES MINE, OPERATED BY THE ELLIOT COAL MINING CO., RUSH TOWNSHIP, CENTRE COUNTY, PA. (OCTOBER 31, 1968, BERNARD LUCAS ASSOC. - ENGINEER)

could make another test site. The overburden beneath the traverse line is 15 feet thick and consists of shale. The entry is open although a considerable quantity of shale has fallen from the roof. No drainage comes from this entry as the entry cuts down through the overburden to the seam.

Hoover Mine

The Hoover coal mine main entry is sealed by earth and rock. The seal is not water tight, however, in that mine drainage is discharged in the spring. Although a mine map was thought to be available when work began on this mine, a subsequent check with the Pennsylvania Department of Environmental Resources determined that this map was accidentally destroyed by fire several years ago.

SECTION VI

FIELD MEASUREMENTS

Table 5 indicates the information collected at the various mine sites. Reference will not be made to this tabulation in the following sections. The following sections discuss the various measurement methods briefly and in general for all sites.

Surveying

Transit and rod surveying was the first activity performed at the sites. A base control station was defined and located near one of the mine entries. A control line and additional control stations were laid-in so that accurate locational control of the various geophysical traverses could be maintained relative to the mine workings and other features as defined by the mine map. A transit, model 2-CF-30 (Warren-Knight Co., Philadelphia, Pennsylvania), and stadia, Philadelphia Type E (Keuffel and Esser Co., Morristown, New Jersey) were used for this work.

Plane Table

Plane-Table topographic mapping of the surface over the mines was the second activity at each of the sites. The elevation and location data obtained from this technique was taken in a more comprehensive manner for certain of the sites than is required in ordinary practice. This was done so that the data could be fed into HRB-Singer's IBM 360-40 computer and operated on by our STAMPEDE program. This operation provided us with a computer generated, topographic contour map which could be positively checked against our field generated, topographic contour map. This capability will be discussed in greater detail in the discussion of computer analysis under SECTION VII.

The topographic contour map permits the estimation of the thickness of the overburden above the coal seam. Naturally, some knowledge of the dip of the coal is necessary to accomplish this with accuracy. Most of the coal seams are flat lying or have a very shallow dip.

Except for the Mills #4 mine, only the portion of the mine of interest was mapped. At the Mills #4, the entire mine was mapped.

The alidade used was made by the Gurley Engineering Instruments Co. of Troy, New York.

Altimeter

To establish the elevation of the base control station at the mines, a Terra Survey Altimeter, Model SA-1 (American Paulin System, Los Angeles, California) was used. This instrument is accurate to 2 feet and is of

TABLE 5 TABULATION OF INFORMATION COLLECTED AT MINE SITES

	COAL MINE SITES AND COVERAGE OBTAINED								REMARKS
	MINES AND ENTRIES STUDIED			ENTRIES STUDIED					
	MILLS #4	BITUMEN #1	BITUMEN #2	NEW WATSON	OLD WATSON	BIG SPRING	KNOWLES	HOOVER	
GEOPHYSICAL AND OTHER METHODS									
TRANSIT & ROD SURVEYING	BASE STATION & SEVEN PRIMARY STATIONS		TEN TRAVERSE(GRID) LINES				TRAVERSE ALIGNMENT CHECKED AGAINST DRIFT ENTRY ALIGN-MENT		BASE STATION ELEVATIONS OBTAINED WITH ANEROID BAROMETRIC ALTIMETER RELATIVE TO LOCAL BENCH MARKS
PLANE-TABLE SURVEYING	SCALE 1 50' 5' CONTOUR INTERVAL	SCALE 1'=100' 5' CONTOUR INTERVAL	SCALE 1"=100' 5' CONTOUR INTERVAL	SCALE 1'=100' 5' CONTOUR INTERVAL	SCALE 1 =100' 5' CONTOUR INTERVAL	SCALE 1"=25' 5' CONTOUR INTERVAL	SCALE 1"=100' 5' CONTOUR INTERVAL	SCALE 1"=50' 5' CONTOUR INTERVAL	PERTINENT PHYSICAL FEATURES SKETCHED ON PLANE TABLE MAPS
ELECTRICAL RESISTIVITY — CONSTANT DEPTH TRAVERSE	16,200'*	1,980'*		1,110'*	1,260'*	1,650'*	2,935'*	2,895'*	WENNER ELECTRODE CONFIGURATION USED CONTINUOUSLY, LEE ELECTRODE CONFIGURATION USED OCCASIONALLY
ELECTRICAL RESISTIVITY — DEPTH PROFILES	5,800'*		3,000'*			450'*	300'*		
SELF-POTENTIAL	25,675'*	1,980'*	3,000'*	370'*	420'*	340'*	600'*	430'*	DIURNAL AND LONGER TERM FLUCTUATIONS MONITORED FOR CORREC-TION PURPOSES.
AIRBORNE INFRARED RADIOMETRY	1000' 2,000' & 3000' ABOVE TERRAIN	200', 500' & 1000' ABOVE TERRAIN	200', 500' & 1000' ABOVE TERRAIN	1000' ABOVE TERRAIN	1000' ABOVE TERRAIN	1000' ABOVE TERRAIN	1000' ABOVE TERRAIN	1000' ABOVE TERRAIN	InSb (3-5 MICRONS), Hg Cd:Te (8-14 MICRONS), & Ge:Hg (8-14 MICRONS), DETECTORS USED AT VAR-IOUS TIMES.
TOTAL FIELD MAGNETICS	10,080'*	1,980'*	3,000'*	370'*	420'*	340'*	600'*	430'*	DIURNAL FLUCTATIONS MONITORED EITHER HOURLY OR CONTINUOUSLY
MAGNETIC GRADIOMETRY	400'*			185'*	150'*		215*		GRADIOMETER ''BUCKS OUT'' NOISE DUE TO FLUCTUATIONS
SEISMIC REFRACTION			1,405'*						ONLY USED WHERE NATURE OF WORKINGS KNOWN DUE TO EXPLORATION.
SEISMIC REFLECTION			1,405'*						DEEP REFLECTION HORIZONS ONLY.
VLF ELECTROMAGNETIC	4,990'*	1,980'*		370'*	300'*		600'*		IN-PHASE AND QUADRATURE COMPONENT MEASURED, STATION NAA, CUTLER, MAINE, 17.8 kHz, 100 kw, PRIMARY FIELD SOURCE
INDUCED POLARIZATION	4,975'*			300'*	240'*		300'*		DIPOLE-DIPOLE ELECTRODE CONFIGURATION USED EXCLUSIVELY.

*SUM OF ALL TRAVERSES

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the aneroid barometric type. Two or three (varied with site) complete altimeter observations were made in as many days in order to establish an average reading for the base stations. Each observation was performed in the following manner while enroute to the mine site: (1) the altimeter was set up and read at a U. S. Geological Survey bench mark (nearest locatable) and at an intermediate check-point, when possible, (2) the altimeter was then moved to the base station at the mine and the reading recorded, (3) the reverse order of these steps was followed while departing the area in the evening. Following two or three complete cycles of altimeter data collection, averages were computed for the base station at the mines.

Electrical Resistivity

The electrical resistivity method was the first measurement technique to be put to use. An earth resistivity meter, model ER-2 (Geophysical Specialties, Minneapolis, Minnesota) was used in these studies. Depth profiling was performed over selected portions of the mines and over selected areas in which there were no mines. These profiles allowed the characterization of the electrical properties of the rock strata. The Wenner (standard) electrode configuration was used as was the Lee partitioning method. The Wenner configuration supplied data that was reduced to standard units, plotted and compared with theoretical curves (Money and Wetzel, 1956).

The Lee partitioning method provided some information on the electrical continuity of the rock strata across the entire electrode spread. This information did not prove to be helpful in the interpretation of the data obtained from the Wenner configuration, and was discarded after work at the Mills #4 mine.

Constant electrode spacing or constant depth traverses were also run. The Wenner electrode configuration was exclusively used for these traverses. The objective of this search procedure was to locate the mined sections and other features (faults, fracture traces, etc.) that provide water avenues into the mines.

Self-Potential

Self-potential surveys were run concurrent with the plane-table surveying at the Mills #4 site. All other sites were surveyed by single-line traverse or by grid coverage. At the Mills mine the reference electrode was maintained beneath the centrally located plane-table while the other electrode was moved in a radial manner about the reference point. The initial equipment used was an earth self-potential potentiometer (McPhar Geophysics, Toronto, Canada) which uses an acoustic null circuit. The electrodes are non-polarizing, porous ceramic pots containing a super-saturated copper sulfate solution which surrounds a copper electrode. The McPhar device developed null problems and was committed to an early retirement. A millivolt-potentiometer, model 8686 (Leeds and Northrup, North Wales, Pennsylvania) was successfully used for the remainder of the self-potential measurements. Control stations were monitored for diurnal and longer term variations.

The objective of these measurements was to measure the natural/spontaneous voltages developed in the vicinity of the mines and to establish if differences appear that may be related to chemical/electrical activity of the mined areas.

Radiometry

Airborne infrared overflights were made at the sites under different operating conditions. The following parameters were varied: date, time of day, altitude, detector and system (RECONOFAX IV, X, XIIIA and AR-2 radiometer made by HRB-Singer, Inc., State College, Pennsylvania).

The objective of varying these parameters was the determination of the optimum conditions for detection of the mine workings or mine related features.

Surface measurements of temperature and soil moisture were made at some of the overflown sites. Supporting weather data was obtained from The Pennsylvania State University weather station for the overflights.

Magnetics

The object of the magnetic measurements was to detect variations in the earth's magnetic field that could be related to the mine workings.

Magnetometer experiments were initiated in July 1970. An HRB-Singer in-house developed, portable, nuclear precession, total field magnetometer was the data collection unit. The instrument has a sensitivity of ± 1 gamma and possesses a direct digital readout in gammas. Cycle rate on the readout is 2 seconds. The sensor is omnidirectional and, hence, requires no orientational setup.

A second nuclear precession magnetometer with a continuous record capability was occasionally used for control station recording. This magnetometer, although built by HRB-Singer, was provided by the Naval Ordnance Systems Command, Code ORD-0534, Washington, D. C.

A third unit, a magnetic gradiometer, was also field tested and evaluated. This unit functions as a differential magnetometer. Two field sensors respond to the earth's field, the signals are electronically subtracted and a difference readout is obtained. The two sensors are capable of being placed any distance apart but for project purposes they were spaced five or ten feet. The sensitivity is rated at ± 0.2

gamma. The cycle rate varies from 3.0 seconds on the coarse scale to 0.3 seconds on the fine scale. This instrument was provided by Mr. Nevin Davis of State College, Pennsylvania.

In order to correct for diurnal drift of the earth's magnetic field, two techniques were used at different times. The first method requires that the survey instrument be removed to a control station and the magnetic field and time recorded approximately once every hour. From a plot of this record, the field drift can be obtained and the survey data corrected accordingly. The second method employs the continuous recording magnetometer which is set up at the control station. The record is studied for drift and the appropriate corrections are made. The gradiometer has the advantage of not requiring drift correction since it merely measures the magnetic field difference.

Initially the control station was located in an area removed from any mine workings. It was determined shortly thereafter that removal was not necessary since the presence of the mine beneath the control station did not cause any time varient field effects.

Seismic

These experiments were directed at (1) determining whether resonance could be induced in coal mines and whether it could be used for detecting them and (2) determining the presence/location of coal mines by (a) delayed returns, (b) "shadow" zones, or (c) amplitude attenuations.

All seismic experimentation was done at the Bitumen #2 coal mine site.

First a few words of introduction with regard to shallow earth seismic field procedures. The arrangement of the detectors may be varied in a multitude of ways. An effective arrangement for a relatively rapid reconnaissance of a potentially mined-out area is the conventional or straight-line spread in which the detectors are arranged in a single straight line from the point of the energy source. In this case, the distance from the point of the energy source and the first detector should be approximately equal to the assumed or measured depth of overburden. The detector spacing should be some smaller distance, i.e., ten feet, depending on the definition sought. This detector spread was primarily used in our studies.

A second arrangement of detectors that is suited for detailed reconnaissance of a given mine site or more specifically, the delineation of a subsurface feature (drift, room, fault, etc.) is the fan-spread. In this arrangement the detectors are spread in a semicircular fashion around the point of the energy source. The point of the energy source being equidistant to each of the detectors. This arrangement was also used.

Four different seismic lines were laid-in over the Bitumen #2 coal mine. The first line was laid-in so that it was parallel to and directly above the "B" entry. The second line started at the high wall point directly over the "B" entry and went 80 feet along a heading of N 23°W. This line would then be over a well-worked section of the mine. The other two lines were established along grid lines #8 and #1, respectively. Line #8 transects a portion of the easterly trending drift. Line #1 should provide a control check against which the other records could be compared. No mining activity is shown on the mine map to have taken place under line #1.

A total of 28 records were obtained along these survey lines. Seventeen records were obtained from the array over the "B" entry including two modified fan shots. This line was heavily investigated since we were attempting to observe the cavity resonance phenomena reported by Watkins, Godson, and Watson (1967). Four records were obtained along the line bearing N 23°W. Four records were obtained along line #8. Three records were obtained along line #1.

A 12-trace, portable, refraction seismigraph, model 506 (Century Geophysical Corporation, Tulsa, Oklahoma), was used as the data collection instrument.

VLF Electromagnetic

VLF (very low frequency) electromagnetic surveys were initiated in May 1971. This instrument, model EM16, is manufactured by Geonics, Ltd., Toronto, Canada and was made available by lease through the Geophysical Instrument and Supply Company, Denver, Colorado. Briefly, this instrument utilizes uniform radio frequency fields generated by a network of U. S. Navy stations that operate in the very low frequency band. Subsurface discontinuities in electrical properties cause inductive field effects which are measured by the receiver instrument at the surface.

The objective for this study was to determine whether these secondary fields are generated or attenuated by mined areas and, if so, whether they are of sufficient magnitude to be measurable.

Traverse lines were run exclusively. Station intervals were either five or ten feet.

Induced Polarization

Induced Polarization (IP) surveys were conducted over selected traverse lines used initially for the resistivity surveys. The equipment used for the IP surveys included a Mark 4 IP Sender and a GEOEX Mark 4C Multiple Frequency IP Receiver (Heinrichs Geoexploration Company, Tucson, Arizona). A portable Briggs and Stratton gasoline engine, coupled to a 120 VAC, 400 cycle generator, supplied the power to the IP Sender. The output current was sent into ground via two 24 inch steel electrodes that were driven into 18 inch deep pits which were previously filled with a brine solution that had soaked into the ground. Two non-polarizing electrodes containing a supersaturated copper sulfate solution were used to receive the signals. A dipole-dipole electrode configuration was used exclusively.

It was hoped that IP effects would be related to mined areas, unmined areas or features related to mining.

Soil Moisture

In order to determine if soil moisture variations can be related to shallow mine features, five soil moisture traverses were run at right angles to the main entry at the Knowles coal mine during the period of airborne infrared overflights of 14 April 1971. The traverses were spaced approximately 50 feet apart along the main entry. Station interval along each traverse line was 5 feet. The instrument used was a nuclear moisture density meter manufactured by Soil Test, Inc., Evanston, Illinois.

Investigation of the Workings of the Bitumen #2 Coal Mine

On 17 November, a detailed exploration of the workings of the Bitumen #2 coal mine was undertaken. The objective of this study was to observe the state of the mine workings (collapsed, open, etc.), the drainage of the mine (Where does the water come from? Where does it go?) and the geology of the roof rock beneath the coal seam.

Dave Milward, Pennsylvania Department of Environmental Resources, led the exploration group. His experience and knowledge of coal mines insured a safe undertaking.

With regard to the state of the mine workings, the mine was observed to be almost completely open and clear. Only two rock falls were observed.

The general condition of the mine was good. The workings are open and the timbering is reasonably good even though the mine has been abandoned for approximately twenty years. Water pools fill low points in the mine. The source of the water is rainfall. Rain water infiltrates the soil and then seeps through the minor joints and fractures in the rock overburden to drip into the mine.

Thin, pencil-like stalactites composed of hydrous iron oxide minerals are found along the intercept of the minor joints and fractures with the roof of the mine. The rain water dissolves minerals as it percolates through the overburden. These minerals are recrystallized at these "drip points" forming the stalactites. An interesting aspect related to the composition of these stalactites is that it brings up the question of the contribution of the iron leached from the overburden to the total iron contribution in acid mine drainage. These stalactites are numerous and lengthy indicating that a considerable amount of iron minerals have been leached from the overburden since this mine was opened. Obviously the composition of the overburden, quantity and character of the sulfide mineralization in the coal, fracturing in the overburden, nature of the mine workings and other factors will affect this contribution.

The Bitumen #2 coal mine has a natural low area due to an undulation in the topography of the coal seam. This low area is apparently large enough to pool all of the mine water accumulated from rain water infiltration. (The mine is not deep enough to intersect the ground water table.) A large ditch running through the low area along the "B" main cuts through the thick (approximately three feet) underclay. This ditch provides access for the water to the permeable rock strata beneath the compact underclay. This provision for getting rid of the water and the good fortune of having a natural pool area insures against this mine having an acid mine water drainage problem.

Geologic Field Work

Geologic field reconnaissance was performed at all of the field sites. Detailed stratigraphic sections were developed for the areas. This work was undertaken in that a fundamental knowledge of the local geology is basic to any geophysical interpretation.

SECTION VII

DATA ANALYSIS AND TECHNIQUE EVALUATION

Electrical Resistivity

Mills #4 Mine

Figure 10 illustrates the location of the resistivity depth profile lines and their respective results. The field data was plotted to a standardized log-log format and compared with Money and Wetzel curves. This comparison analysis yielded a correlation with the theoretical 4-layer case. The apparent resistivities in ohm-feet and the depth of each layer are illustrated in the sections adjacent to each profile line. The estimated top of the coal seam is noted by the black arrow. The coal seam location is estimated from the plane-table topographic map and the projected dip of the coal seam.

The ratio between the electrode spacing used in the Wenner spread and the apparent depth of penetration is dependent on the resistivities of the local rock strata. A generalized ratio can be developed about this site from the data presented in Figure 10. This generalized ratio is: $\frac{1.2 \quad \text{(electrode spacing)}}{1 \quad \text{(apparent depth penetration)}}$. This ratio was of interest when the constant depth traverses were run. Once the topographic data revealed the depth to the mine workings (coal seam) the ratio factor could be applied to establish the electrode spacing required to probe to that depth.

The depth profile lines that are in the southern portion of Figure 10 are exclusively over areas in which there are no mine workings or faults. The results from these profiles provide the basis for comparing and studying the depth profiles over portions of the mine workings and the known faults. It is apparent that there were no well-defined boundaries or breaks in the resistivity 4-layer section that could be correlated with the mine workings.

Constant depth/constant electrode spacing traverses were run along selected lines over the mine area and the control area. These lines included all the lines covered by the depth profiling and some additional ones.

The topographic maps were used to determine the depth of the mine workings along a given line. This depth was multiplied by the scale factor (as determined from the depth profiling) to obtain the electrode spacing required for that particular line. Usually, several different electrode spacings were run along a given line for comparison

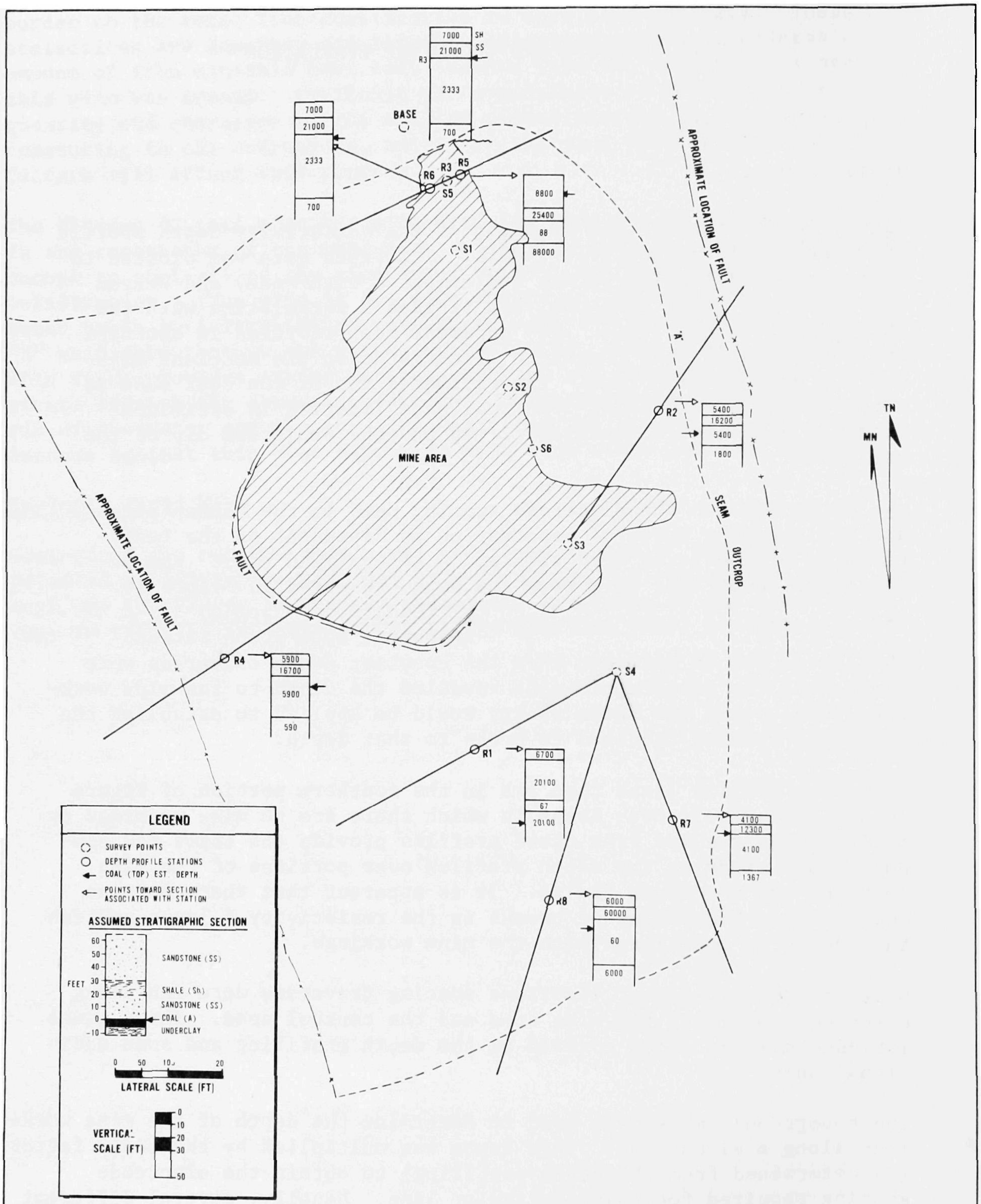

FIG. 10 LOCATION OF THE ELECTRICAL RESISTIVITY DEPTH PROFILE STATIONS, LAYER BOUNDRIES AND APPARENT RESISTIVITY (OHM FEET) OF THE LAYERS AT THE MILLS #4 MINE

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purposes and to bracket the mine workings, lest there be strata above or below the mine (underclay, for example) whose electrical characteristics had been altered by the mining process and, hence, would provide the all important "indicator" horizon.

Figure 11 shows a number of data plots for constant depth traverses over the two mine entries. These traverses show some of our most successful data. Notice the sharp decreases in resistivity over both entries at the 30 and 35 foot spacing traverses. The right entry (sealed, no water flow) also shows sharp decreases for the 20 and 25 foot spacing traverses. The entry with the water flow (left entry), interestingly, shows less of a decrease in resistivity than the entry that is apparently dry.

In Figure 12 three different constant depth traverse lines are plotted relative to the portion of the mine that they overlie. Various electrode spacings were run along each of these lines. Data from several of these different spacings are plotted adjacent to their respective traverse lines.

There is no consistant correlation between the mine workings and the resistivity traverse data. One notable exception is the westernmost traverse line as it crosses the westernmost fault. All of the electrode spacings used along this line revealed a decrease in resistivity near the mine map plot of the fault. This decrease would be expected for a water movement avenue containing a conductive medium (water).

Bitumen #1 Coal Mine

Constant depth traverses were run along each of the survey lines over Bitumen #1. Each of these traverses are underlain by shallow overburden (i.e., 20 to 30 feet). Figures 13 and 14 illustrate apparent resistivity relative to the mine features as indicated by the mine map. No correlation between the resistivity data and the mine workings is apparent. The lack of correlation between the slump zones and the mine workings indicates a number of problems that may include the following factors, wholly or in part: the mine map may not be exact, that there is a lack of correlation between the plane-table survey and the mine map due to tie-in error and/or the plane-table maps are inaccurate. The lack of apparent correlation between the traverse data and the mine is discouraging.

Bitumen #2 Coal Mine

Depth profiles were run along all of the grid lines. Lines 11 and 12 are close to paralleling the topographic contours of the site, hence, their results were expected to differ somewhat from that of grid lines #1 through #10 due to the influence of the additional strata beneath the up-slope side of the electrode configuration for the latter grid

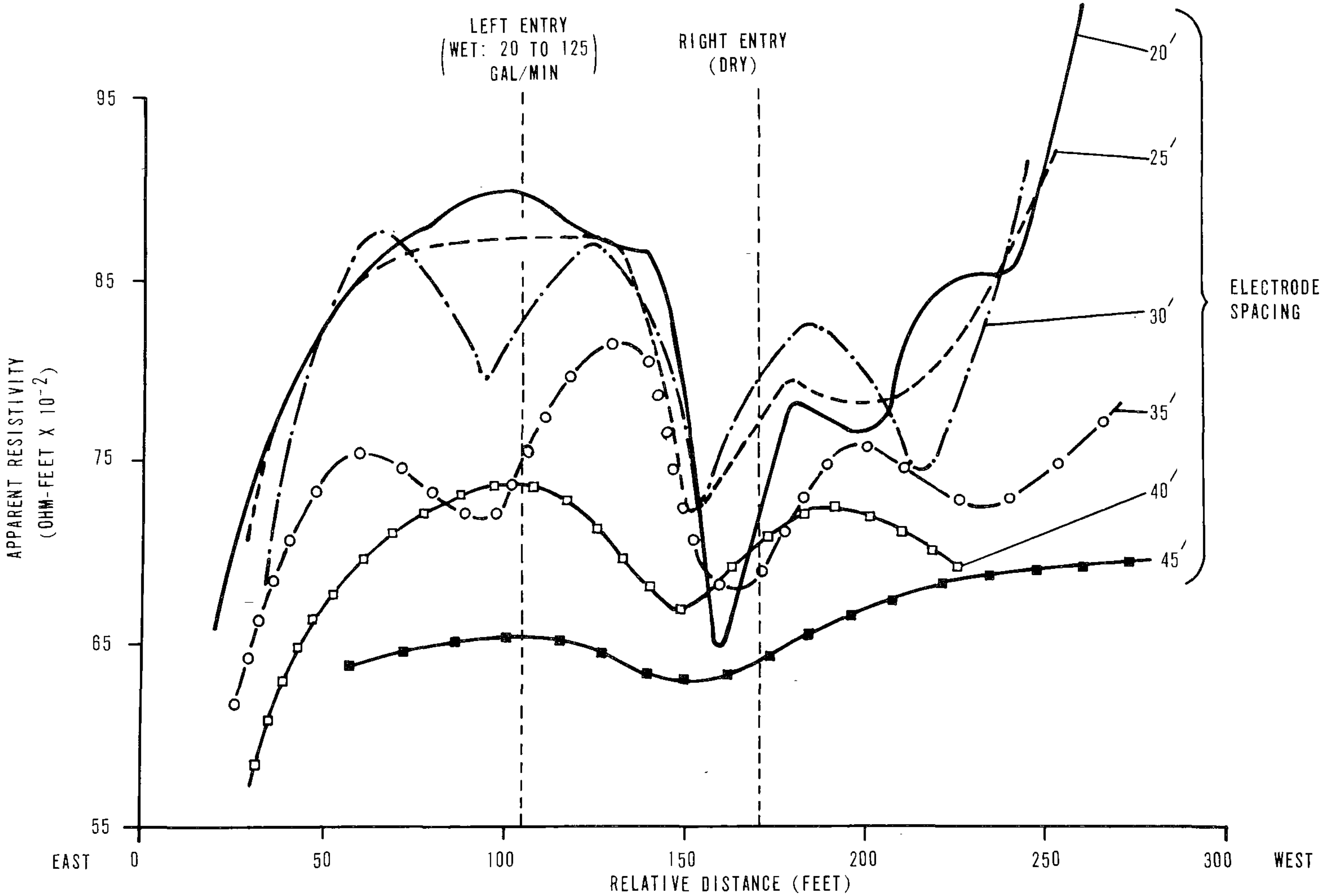


FIG. 11 CONSTANT DEPTH RESISTIVITY PROFILES OVER THE MILLS NO. 4 MINE ENTRIES, DEPTH OF OVERBURDEN = 31 FEET

BP10095

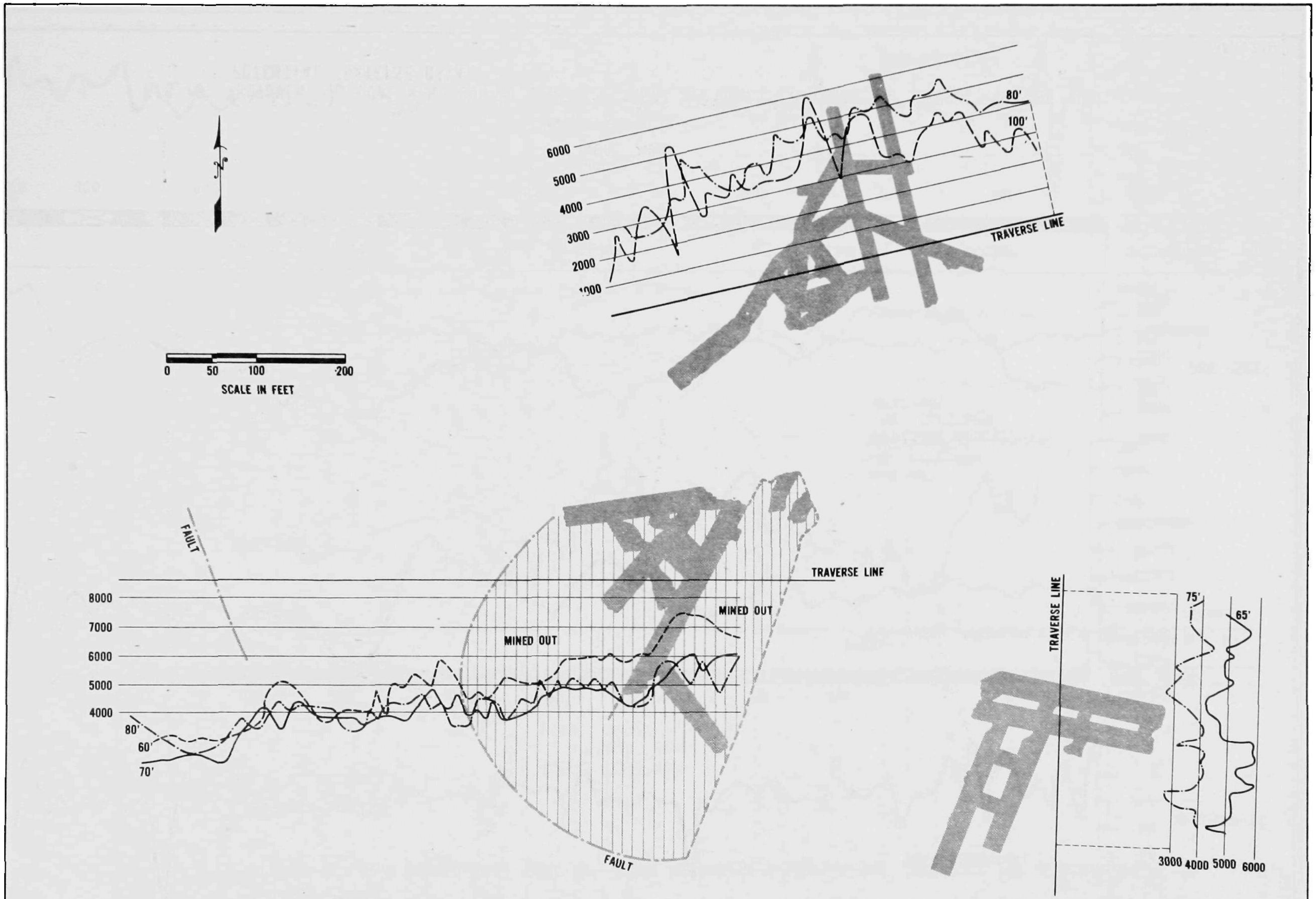


FIG. 12 RESISTIVITY TRAVERSE DATA AT SELECTED 'a' SPACINGS (feet) RELATIVE TO THE MILLS #4 MINE WORKINGS (apparent resistivity units = ohm feet)

JP10396

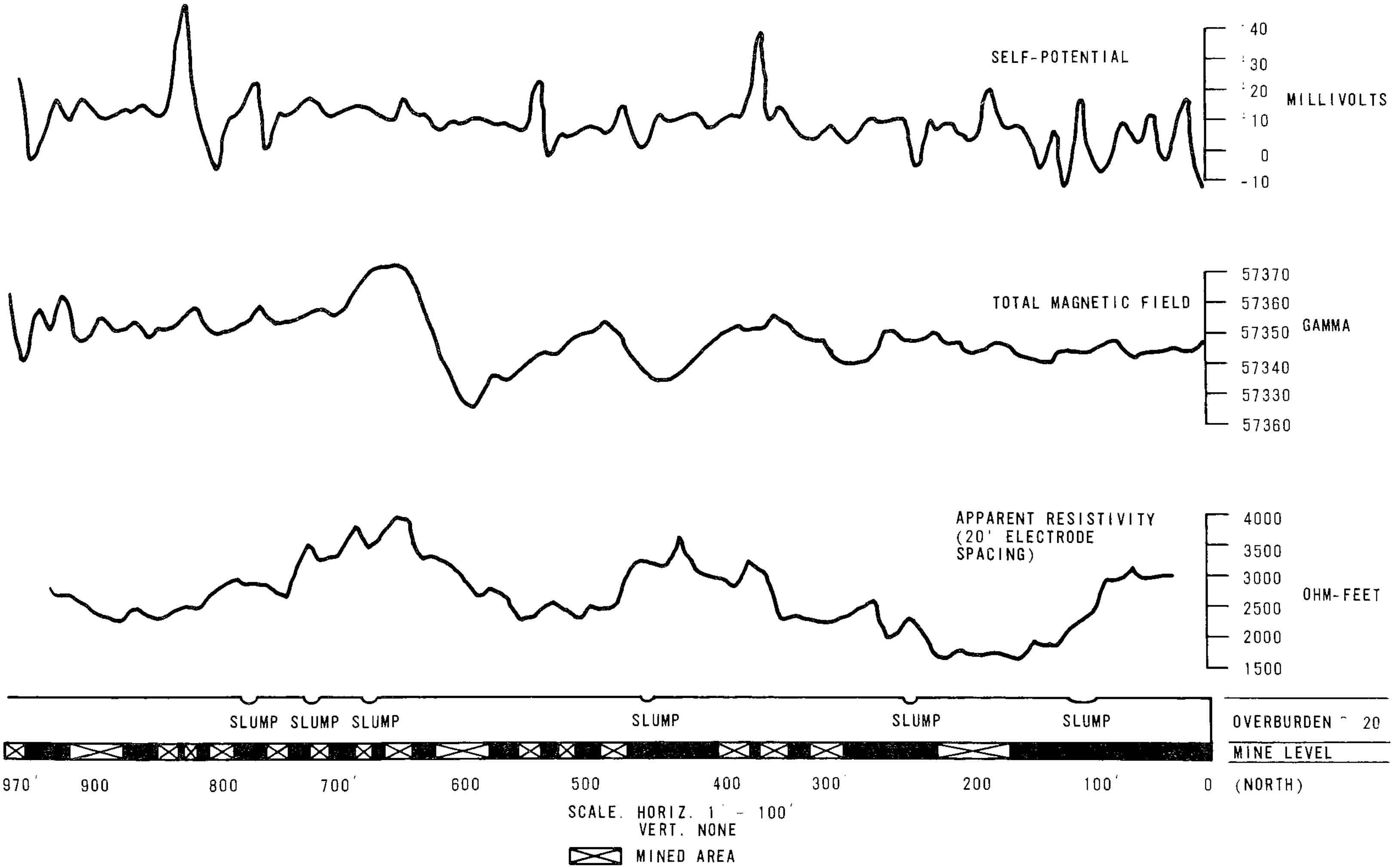


FIG. 13 BITUMEN #1, COAL MINE SURVEY LINE #1, CROSS SECTION WITH RESITIVITY, MAGNETICS AND SELF-POTENTIAL TRAVERSE DATA

AP11259

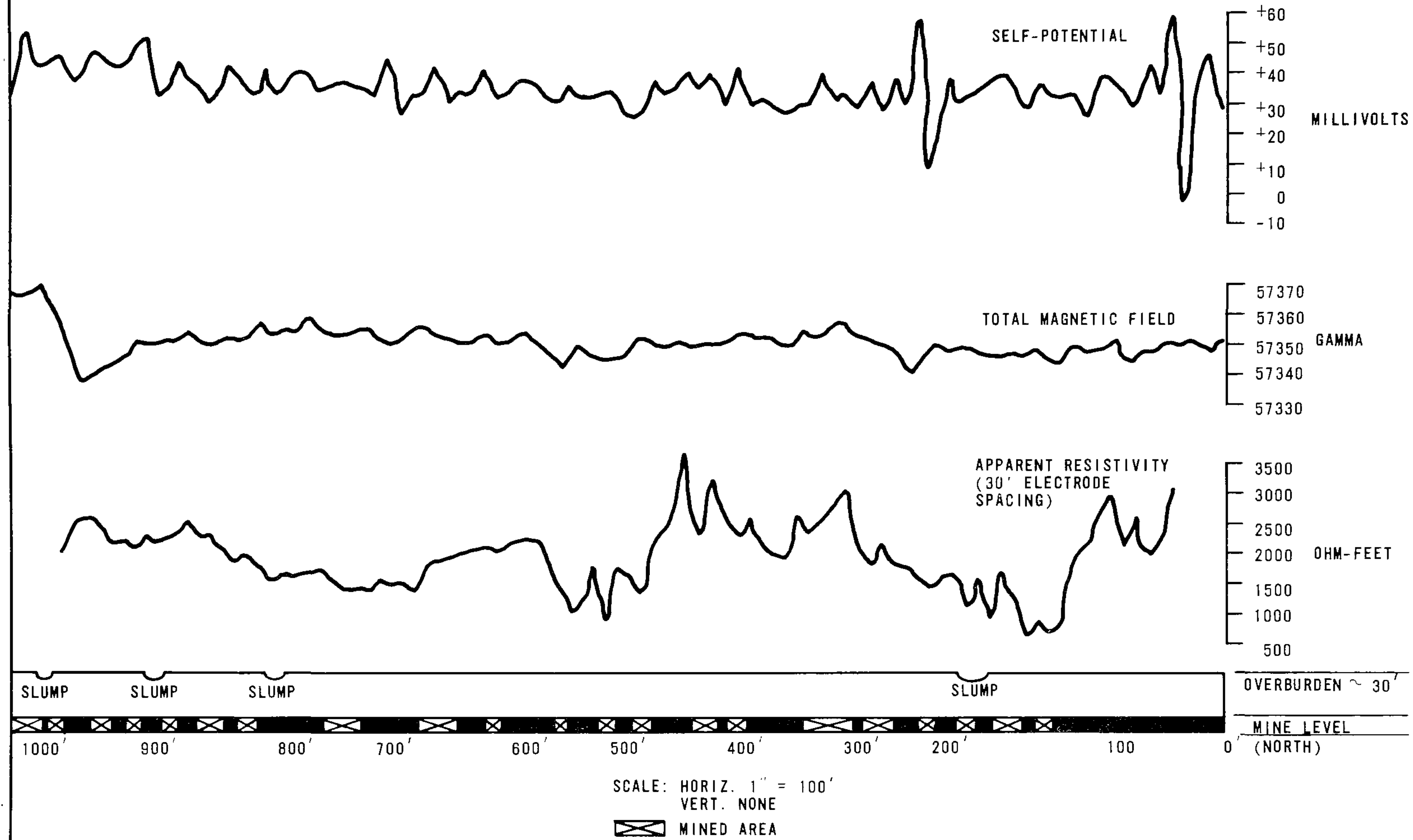


FIG. 14 BITUMEN #1, COAL MINE SURVEY LINE #2, CROSS SECTION WITH RESISTIVITY, MAGNETIC AND SELF-POTENTIAL TRAVERSE DATA

AP11258

lines. The data from lines #11 and #12 indicate that the "topographic effect" need not be considered an influence on the grid lines #1 through #10.

Grid lines #1 through #10 progress from an area free of mining influence (line #1) to an area almost totally undermined (line #10). It was expected that a progressive variation in the character of the curves would be observed. This variation was not observed.

New Watson, Old Watson, and Big Spring #1 Coal Mines

The electrical resistivity data collected over the drift mine entries was plotted and analyzed. Figures 15, 16 and 17 illustrate some of the typical data plots obtained. Figure 15 illustrates the resistivity and magnetics data obtained over the New Watson entries. The resistivity data does not indicate the presence of the entries. The right entry shows generally higher resistivity values than the left; however, the background trend is toward higher resistivity values in this location. Higher resistivity values would be expected for an open, dry non-conductive drift. This does not appear to be the case here as the entrance has a tight earthen seal. However, it should be noted that the traverse line, although at almost right angles to the heading of the entries, is approximately twenty-five feet back from the entry points.

The data illustrated in Figure 16 is more encouraging. Notice the decrease in resistivity for each electrode spacing associated with the location of the drift entry. The overburden thickness is only about fifteen feet here. The peak of the resistivity minima is slightly to the left of the indicated location of the entry. This occurs because the drift bears to the left as it goes into the hillside. The decrease in resistivity is expected for an entry which has a conducting media present, such as acid mine water. However, this entry is open and, although the bottom of the mine is wet, there is no accumulation of water.

Figure 17 illustrates the resistivity plots over the Big Spring #1 coal mine main entry. The overburden is about twenty feet over the main entry nd thirty-five feet over the fan entry. The overburden consists primarily of massive sandstone. The 20, 25, and 30 foot electrode spacing traverses show a fair sized anomaly, whereas, the 35 and 40 foot electrode spacing traverses show small anomalies, all coincident with the main entry. Again, for the latter traverses, it would be difficult to pick out the anomalies if we did not know where to look. No anomalies were observed to be coincident with the fan entry.

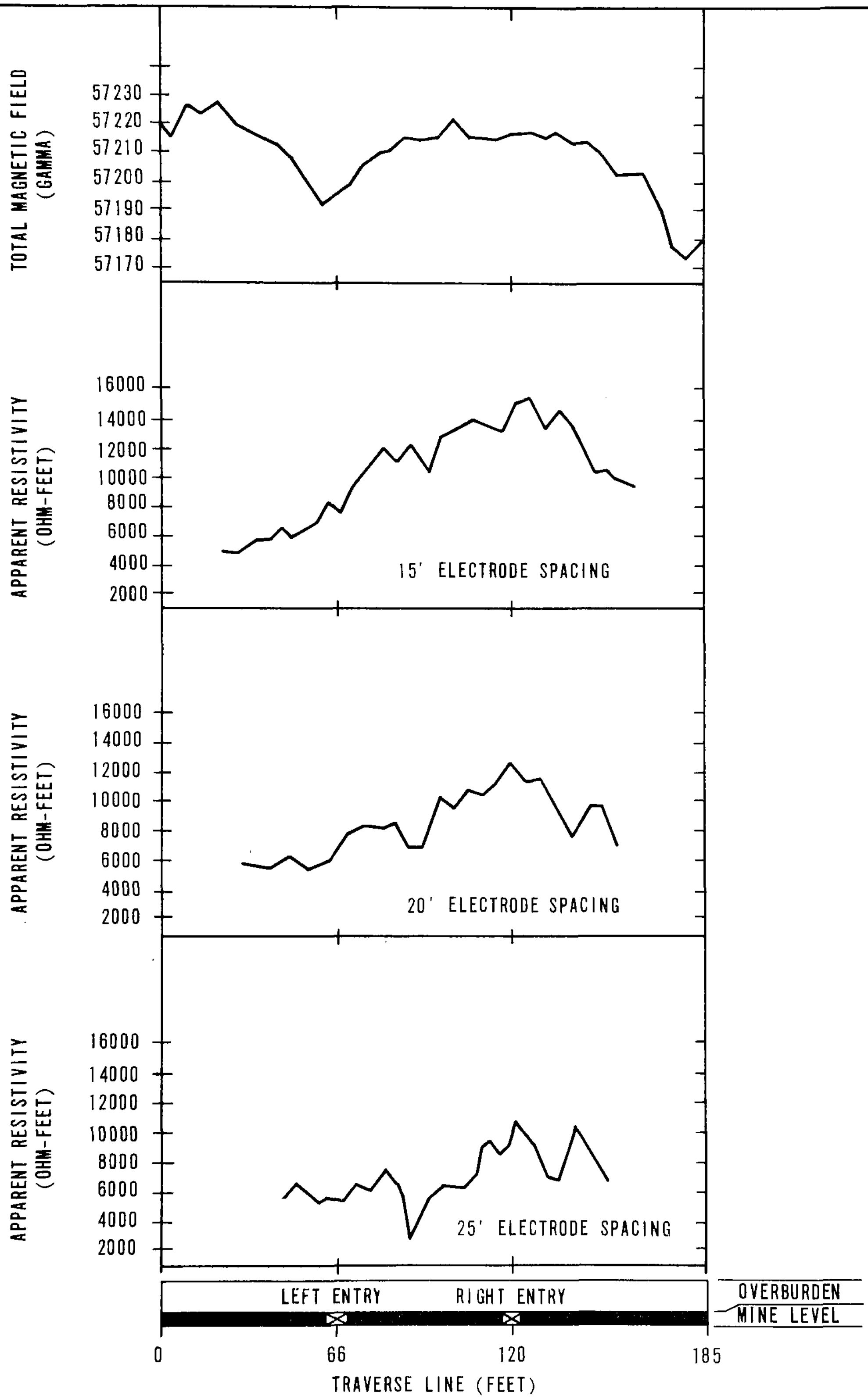


FIG. 15 ELECTRICAL RESISTIVITY AND MAGNETIC FIELD DATA ACROSS THE NEW WATSON COAL MINE DRIFT ENTRIES -- OVERBURDEN THICKNESS - 15 FEET AP11429

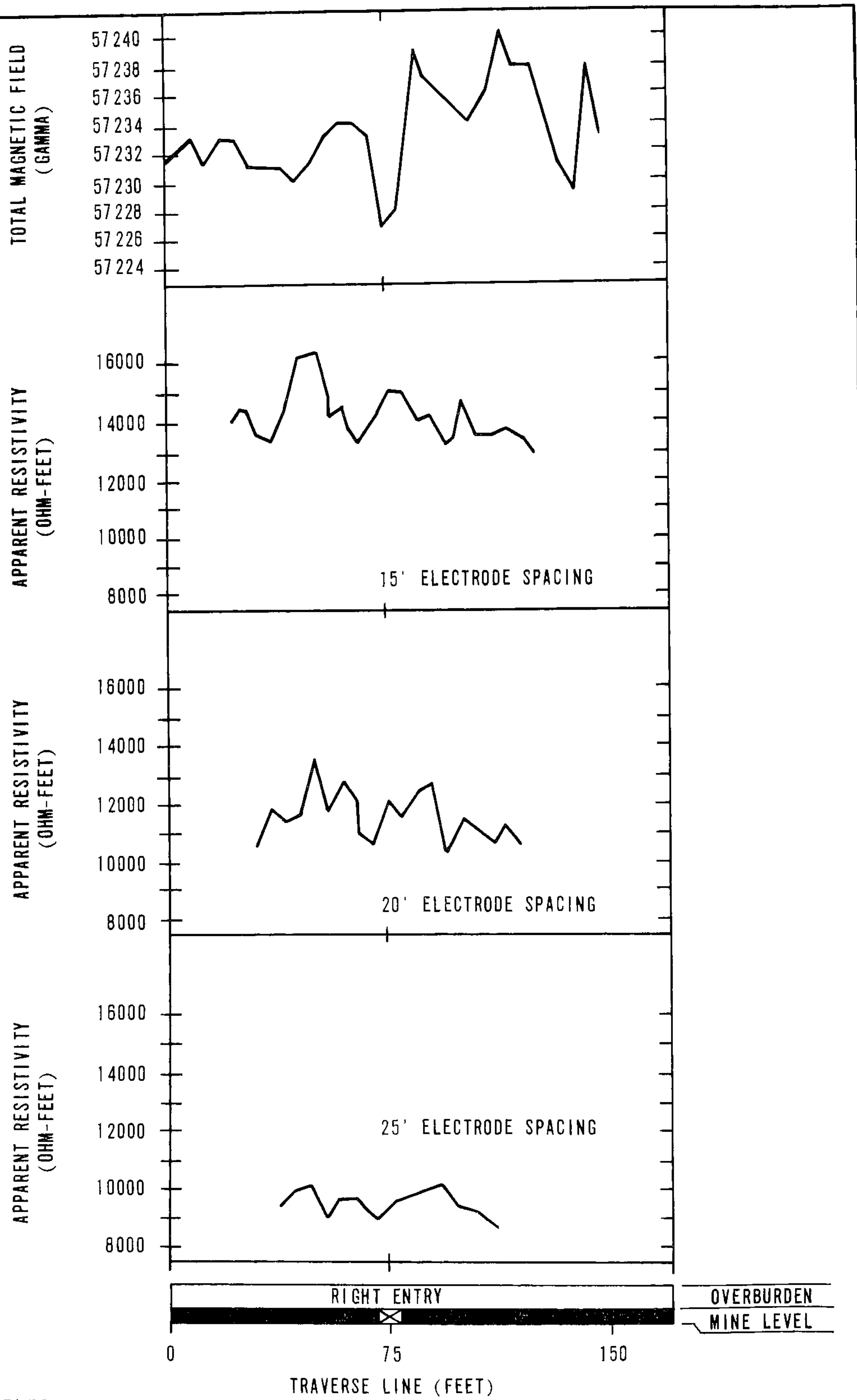


FIG. 16 ELECTRICAL RESISTIVITY AND MAGNETIC FIELD DATA ACROSS THE OLD WATSON COAL MINE RIGHT DRIFT ENTRY -- OVERBURDEN THICKNESS 15 FEET AP11430

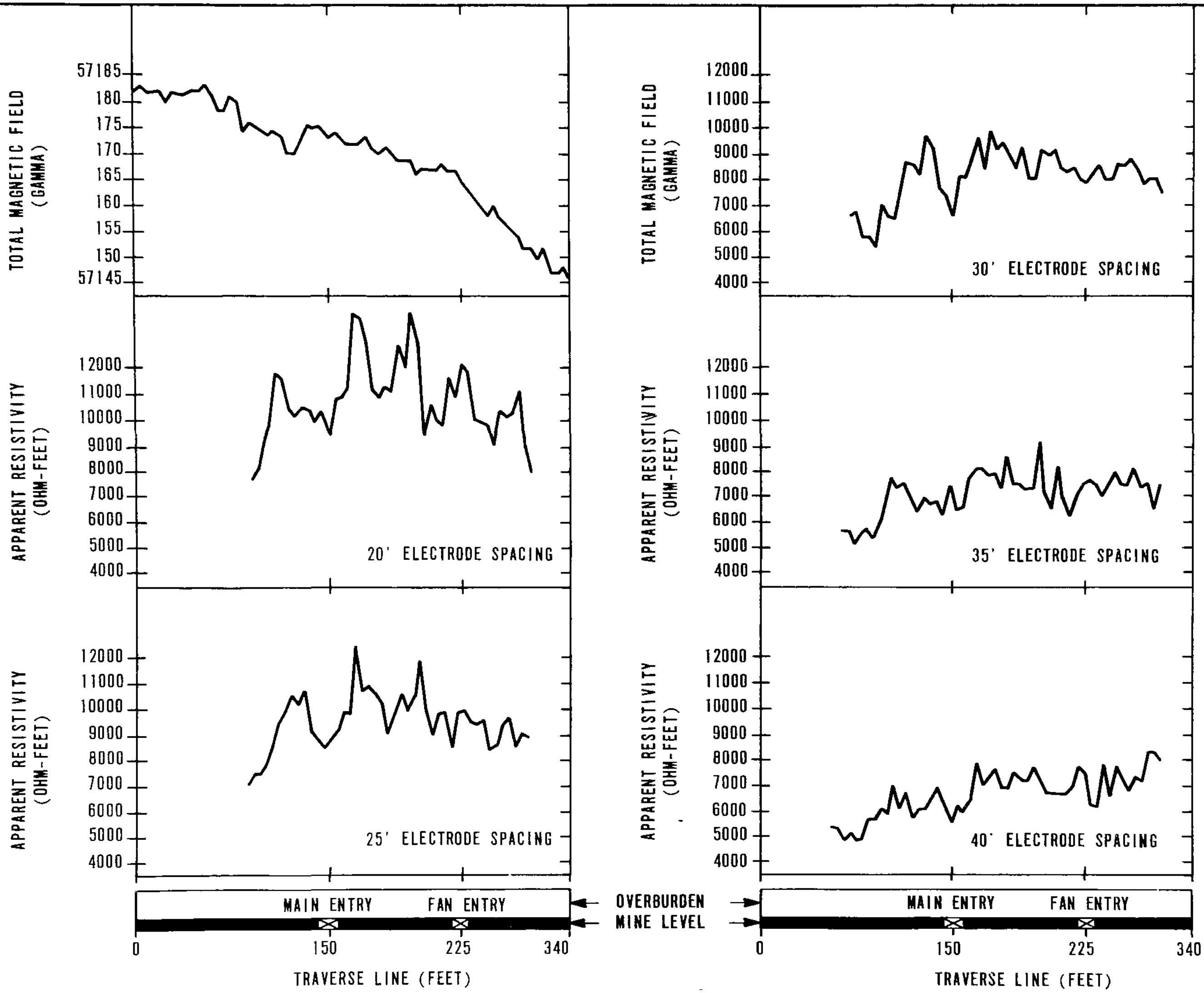


FIG. 17 ELECTRICAL RESISTIVITY AND MAGNETIC FIELD DATA ACROSS THE BIG SPRING #1 COAL MINE DRIFT ENTRY AND FAN ENTRY -- OVERBURDEN THICKNESS 20 FEET AT MAIN ENTRY AND 35 FEET AT FAN ENTRY

BP11312

Although the magnitudes of the anomalies associated with the main entry are not great, they do represent a successful deomonstration under simple conditions.

The following conclusions can be stated about mine entry detection:

> Electrical resistivity apparently permits detection and location of the mine entries in cases of shallow overburden.
>
> Highly mineralized water apparently does not have to be flowing through the entries for it to be detected by this technique.
>
> A fairly wide range of electrode spacings may be possible in the search for mine entries. (See the results for the Mills #4 mine.)

Self-Potential

Mills #4 Coal Mine

The self-potential technique was extensively used on the Mills #4 coal mine area with total coverage obtained on a coarse grid. Tight coverage (10-foot electrode spacings) were obtained along all of the electrical resistivity traverse lines.

The self-potential data collected over the Mills #4 site did not show any correlation with the mine workings or the associated faults.

Computer generated contour maps of the earth potential over the mine were produced. Figure 18 is one such plot. This particular map shows a slight correlation with the mine workings. The low potential values appear associated with no mine workings (the eastern and southern sectors are notable exceptions). Regrettably, this sample proved to be the only one which showed even this much of a correlation. No other computer generated contour maps nor any of the potential plots from the traverse lines showed any definite correlation with either the mine workings or the local faults.

Bitumen #1 Coal Mine

The self-potential traverses across the shallow Bitumen #1 mine did meet some success over the slump zones. Figures 13 and 14 illustrate self-potential minima over or adjacent to the slump zones that were traversed. The field crew observed the correlation in situ. The location of the slumps relative to the geophysical data is exact. The locations were established simultaneous to the surveys.

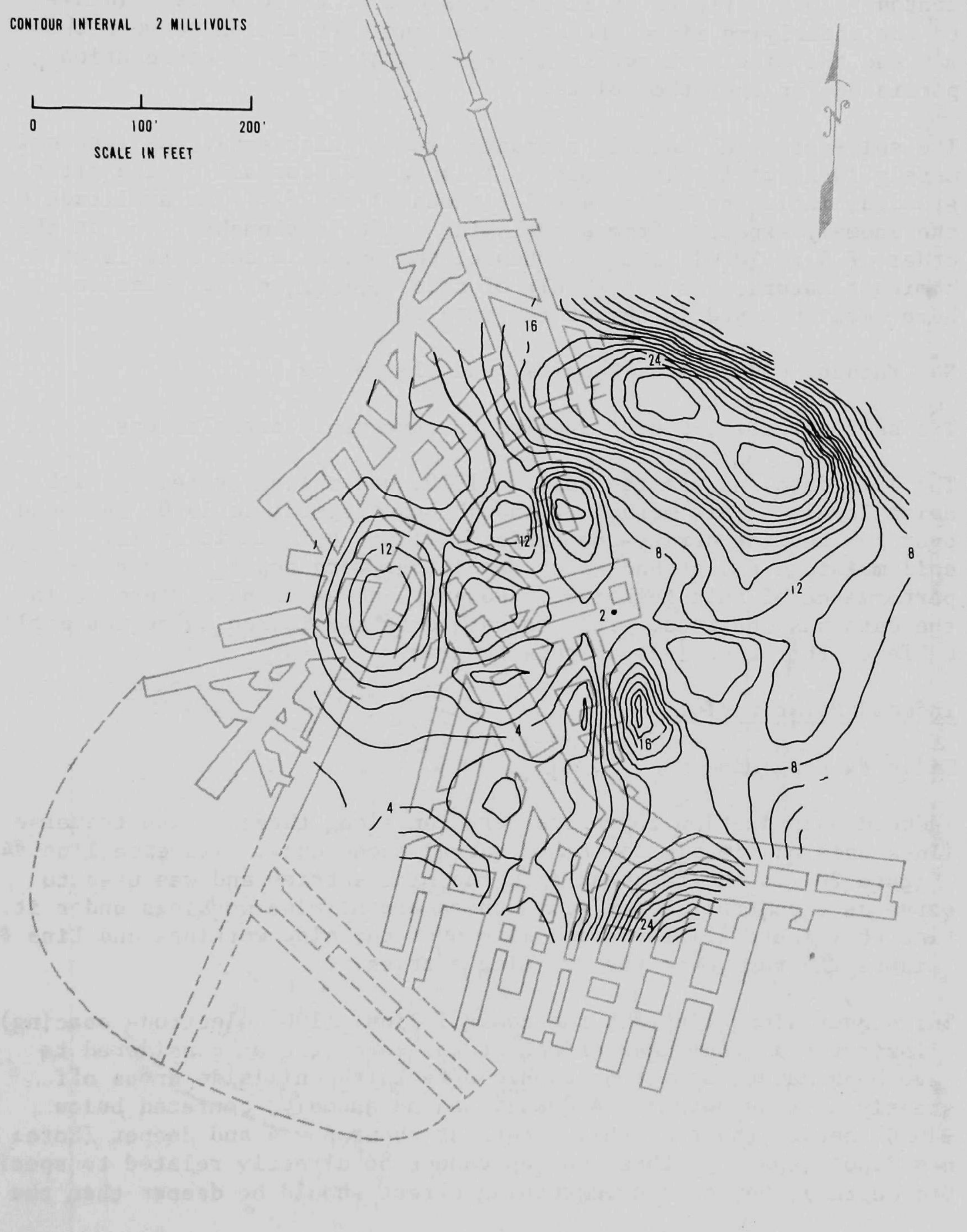


FIG. 18 COMPUTER PLOT OF THE EARTH POTENTIAL AROUND SURVEY STATION #2, MILLS #4 COAL MINE. (positive values only)

CP10395

Bitumen #2 Coal Mine

Self-potential data collected along grid lines 1 through 10 over Bitumen #2 was operated-on by the STAMPEDE program and plotted various ways. Different contour intervals were used and certain apparently incompatible data points were discarded in producing certain of these contour plots. Figure 19 illustrates one of these plots relative to the underlying mined area. No obvious correlation between this map and the mine workings is apparent. This lack of correlation persisted for the other plots.

The self-potential data is characterized by high amplitude (approximately 10-25 millivolts) noise. This is true for all of the sites studied, including Mills #4 and Bitumen #1 and #2. The amplitude of the anomaly expected from a coal mine drift is thought to be on the order of 5 to 10 millivolts. Hence, the noise in our data is of a dominant nature. As the result of this problem, no correlations have been observed in any of the data.

New Watson, Old Watson, Knowles, and Big Spring #1

The self-potential plots revealed no observable correlations.

The 1971 data, as was the case in 1970, was characterized by high noise levels. This method, although unsuccessful in 1970, was held over for testing during the spring 1971 wet hydrologic cycle. High soil moisture and ground water conditions were hoped to improve the performance of this technique. However, no apparent difference in the data was observed. This technique is considered to be not applicable to the objectives of this program.

<u>Induced Polarization</u>

Mills #4 Coal Mine

Induced polarization traverses were run along three of the traverse lines used previously for other survey techniques. Traverse line #4 (Figure 20) is the furthest from the mine entries and was used to serve as a control survey since there are no mine workings under it. Line #6 (Figure 21) is a long line over the mine workings and Line #5 (Figure 22) runs over the two mine entries.

The survey along line #4, the control line, (100' electrode spacing) illustrates a pronounced effect at the zero station considered to have been caused by a topographic effect (the hillside drops off steeply at this point). A deeper seated anomaly, centered below +3000 feet on the traverse, occurs at about n = 4 and deeper (Note: n = dipole spacing, these values cannot be directly related to specific depths); hence, the perturbing effect should be deeper than the

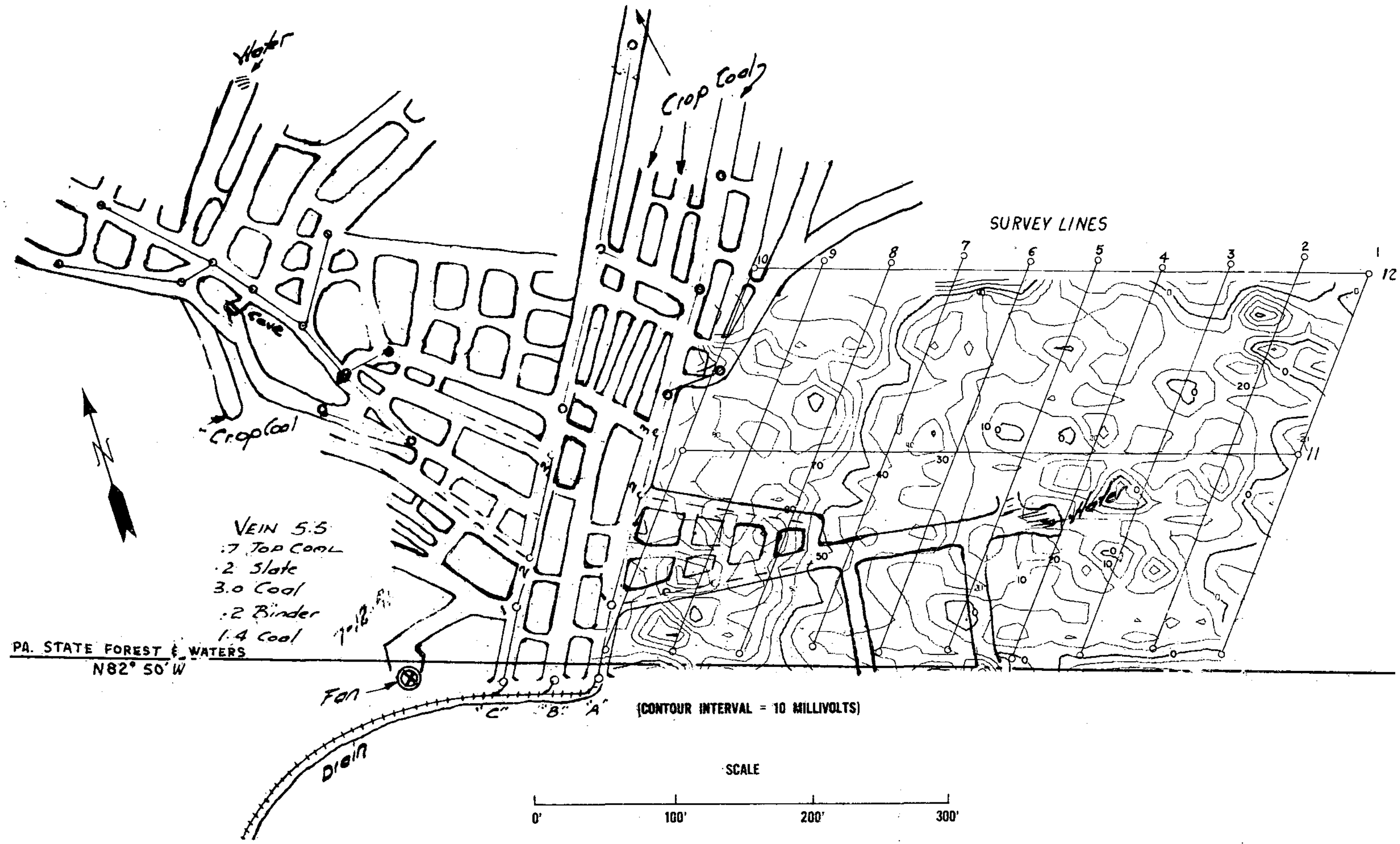


FIG. 19 SELF-POTENTIAL COMPUTER GENERATED CONTOUR MAP OVER A PORTION OF THE BITUMEN #2 COAL MINE, DATA CORRECTED TO BASE POINT (ZERO) ON LINE #1

CP1:011

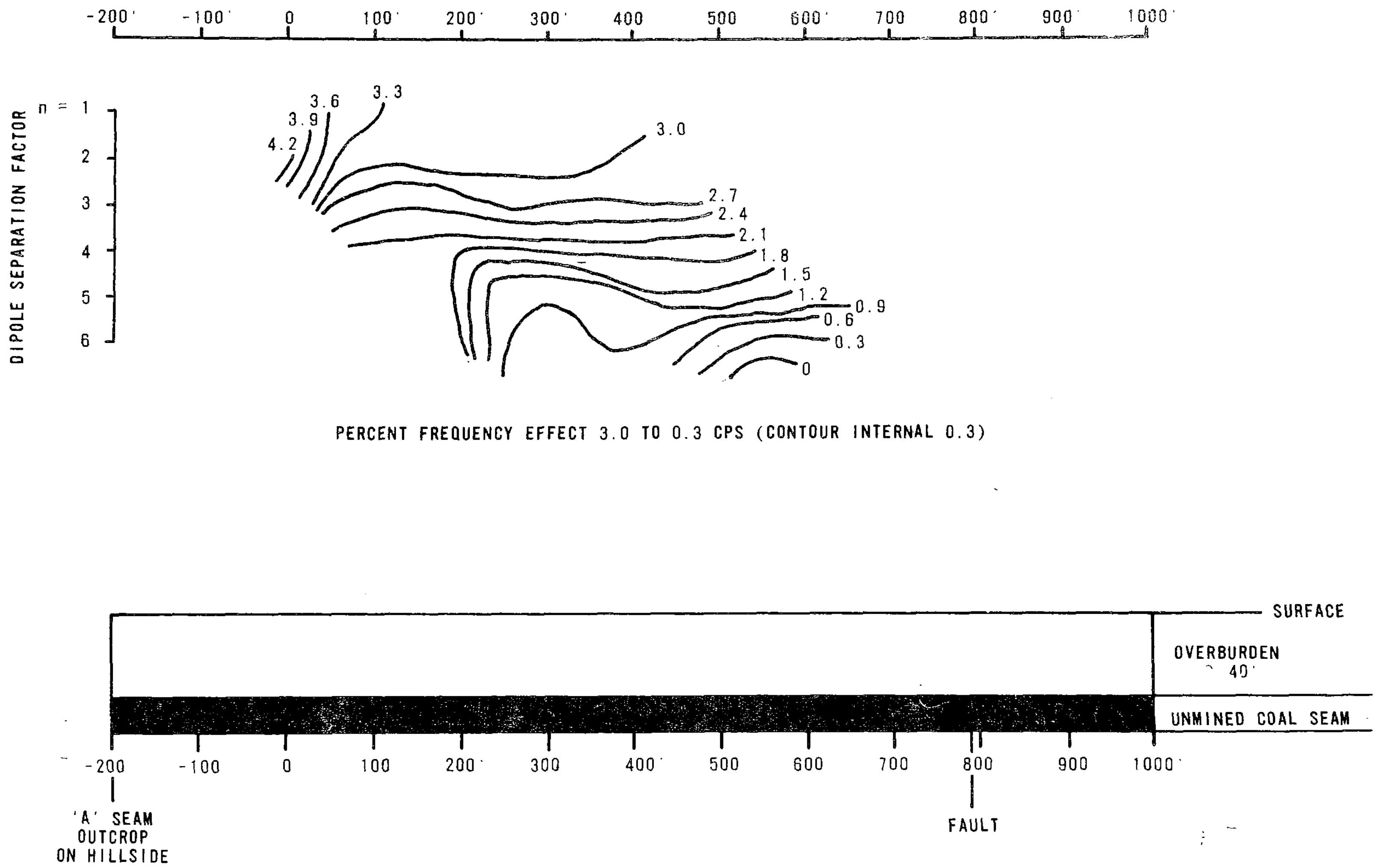


FIG. 20 MILLS #4 COAL MINE, SURVEY LINE #4(CONTROL LINE-NO MINING ACTIVITY), CROSS SECTION WITH INDUCED POLARIZATION DATA (FREQUENCY DOMAIN)

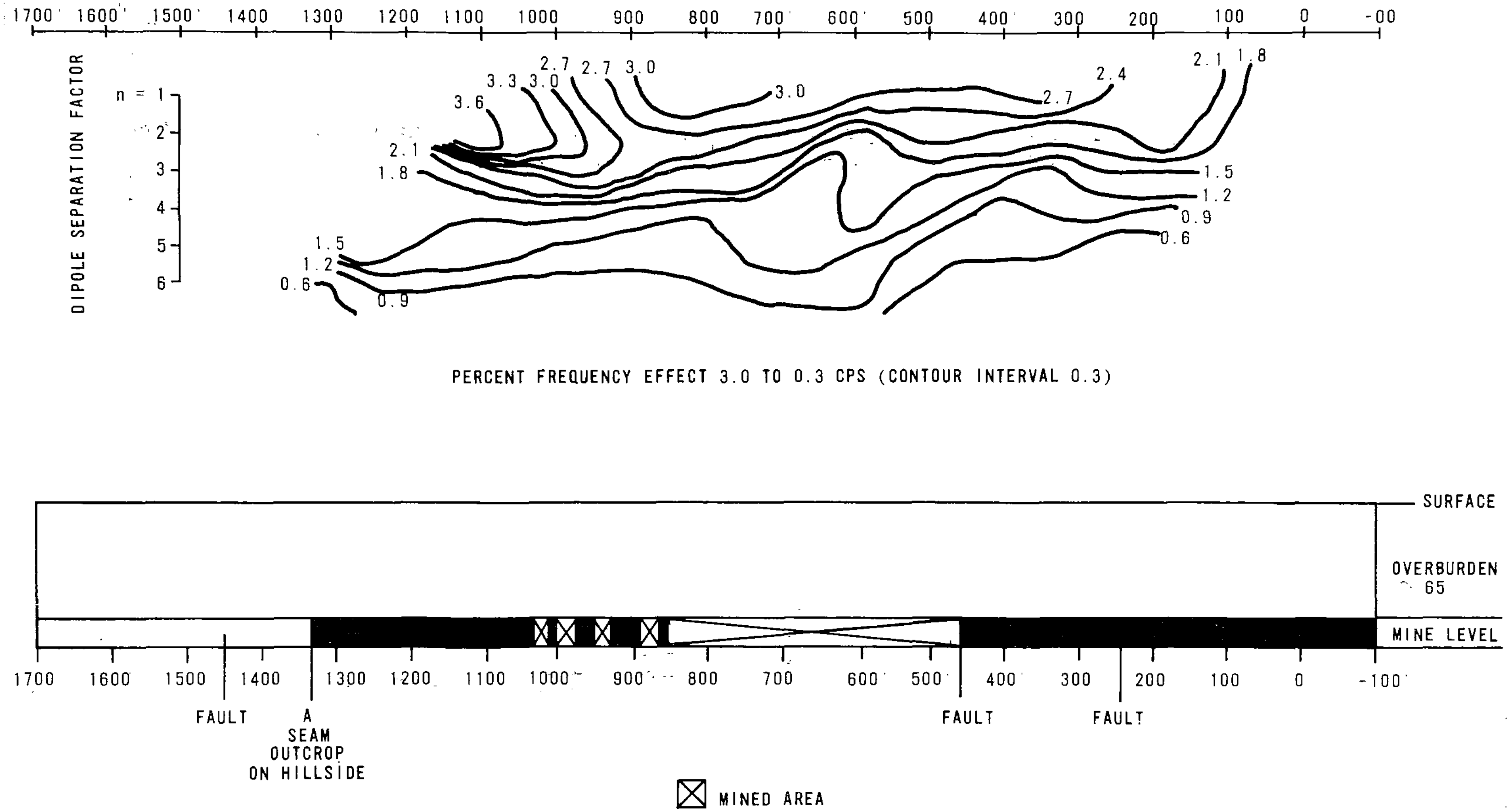


FIG. 21 MILLS #4 COAL MINE, SURVEY LINE #6, CROSS SECTION WITH INDUCED POLARIZATION DATA (FREQUENCY DOMAIN)

AP11796

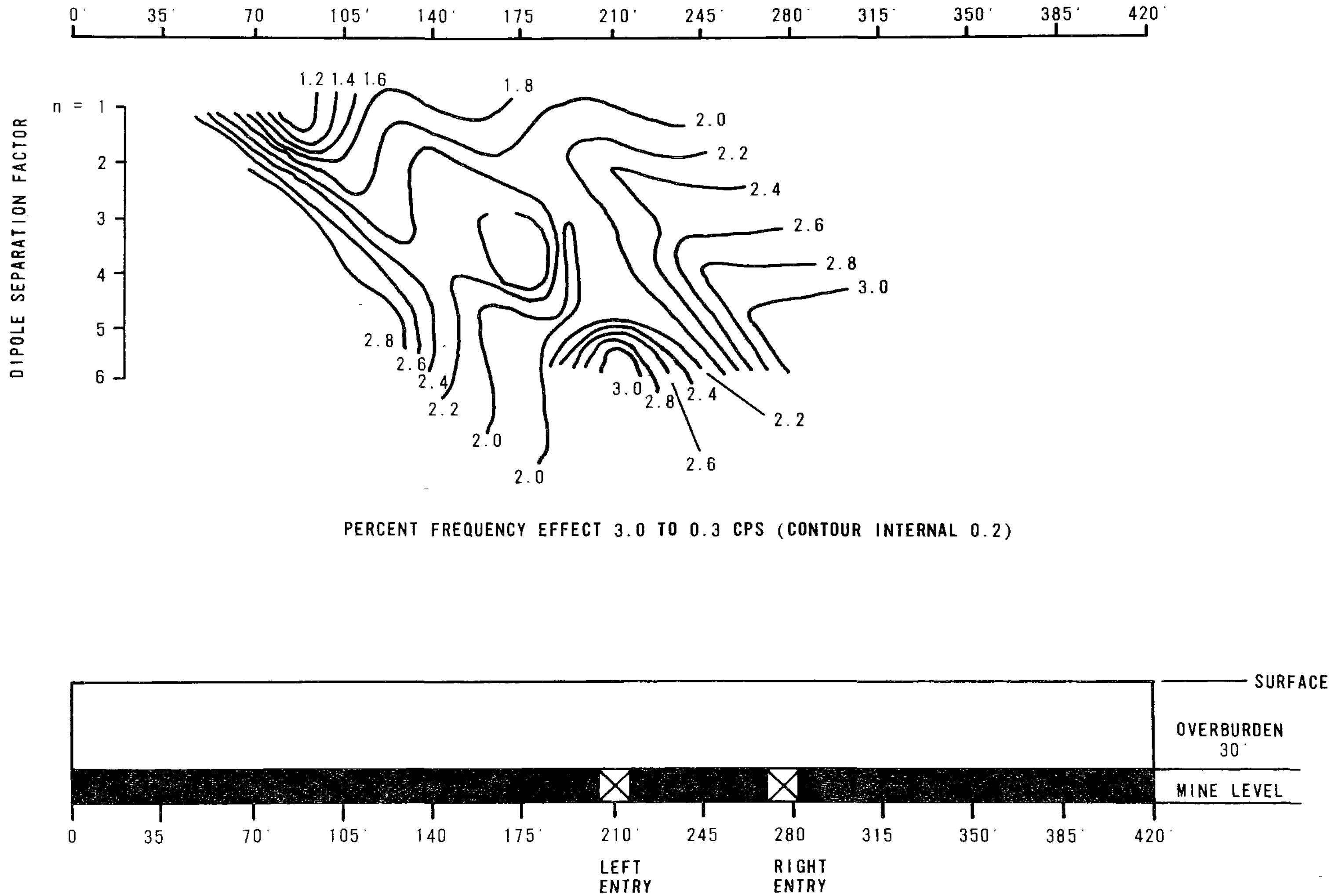


FIG. 22 MILLS #4 COAL MINE, SURVEY LINE #5, CROSS SECTION WITH INDUCED POLARIZATION DATA (FREQUENCY DOMAIN)

the coal seam. The profile along line #6 indicates an anomaly at about +600 feet on the traverse line that is related to the large mined section. The anomalous percent frequency effect data between +900 and 1200 feet is thought due to the same topographic effect mentioned above.

The IP profile along line #5 (Figure 22) over the mine entrances is most encouraging (35' electrode spacing). Although the survey appears to have not been extended far enough to cover the right entry adequately, a distinct anomaly appears over the left entry.

Knowles Mine

The IP survey at the Knowles mine illustrates (Figure 23) an anomaly that is correlatable with the mine tunnel. The anomaly is subtle at small n's, but pronounced at large n's. The pronounced anomaly at large n's is expected to be derived from features beneath the mine. This survey was taken with 30' electrode spacings.

Magnetics

Mills #4 Coal Mine

Magnetometer traverses were run along all of the traverse lines previously occupied by resistivity and self-potential surveys. Generally, the plots of the corrected earth's magnetic field did not show any consistent correlation with the mine workings or the rock faults. Specific traverses did show correlations, however, Figure 24 illustrates the negative anomalies which are coincident with the drift entries.

Bitumen #1 Coal Mine

Magnetics data was corrected and plotted along each of the survey lines (see Figures 13 and 14). No correlation between any of the mine features and the data was observed.

Bitumen #2 Coal Mine

The magnetics data was plotted and studied for each of the survey lines at Bitumen #2. Figure 25 shows in small scale the results of the traverses relative to the mine workings. Again, no consistent correlation is observed. Computer generated contour plots of the same data did not yield any additional correlation.

New Watson, Old Watson, and Big Spring #1 Mines

Magnetic field measurements were made along all of the traverse lines over the coal mine entries. The magnetic plot in Figure 15 illustrates the variation of the earth's magnetic field along the two entries at

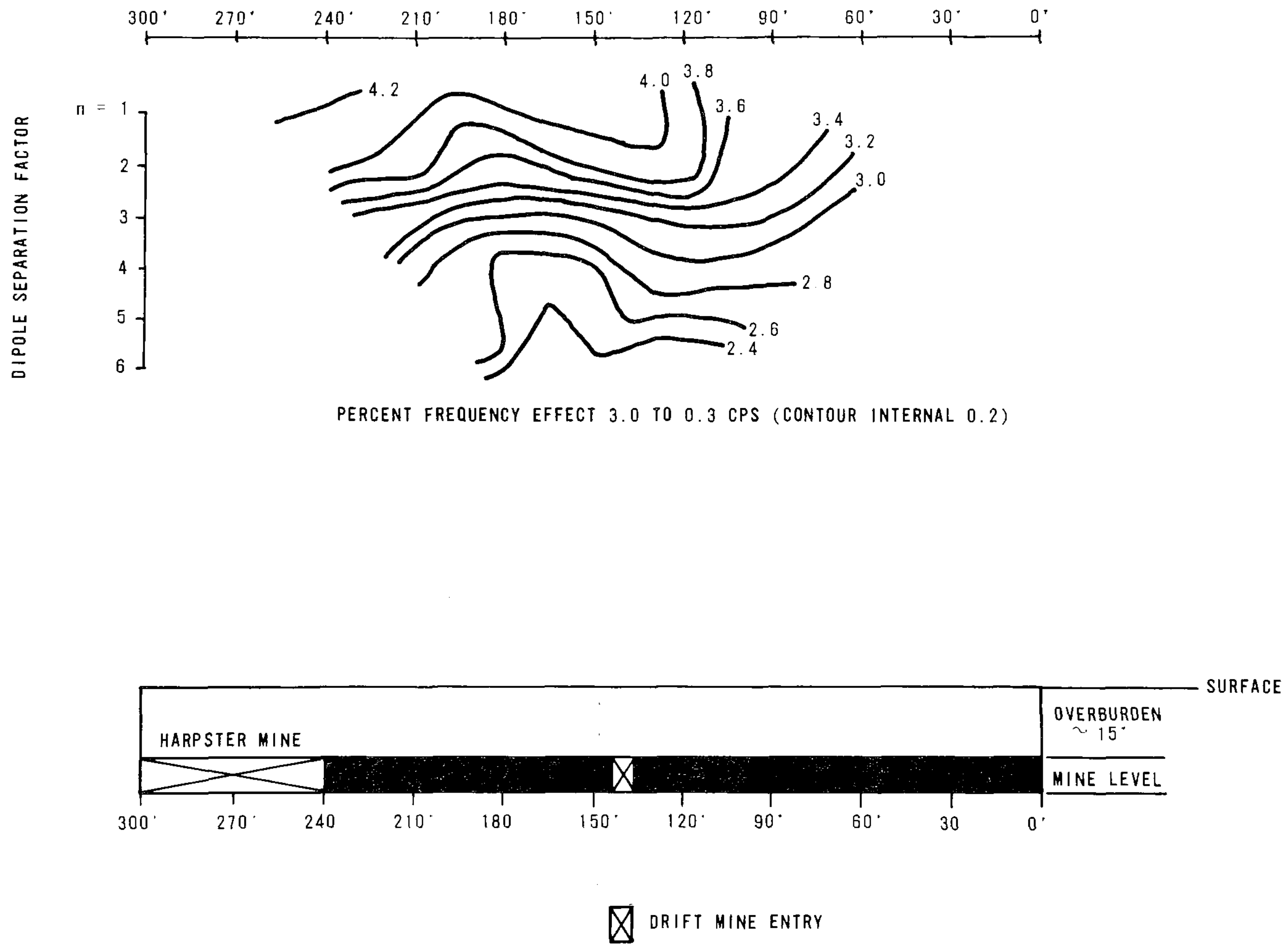


FIG. 23 KNOWLES MINE, MINE ENTRY SURVEY LINE, CROSS SECTION WITH INDUCED POLARIZATION DATA (FREQUENCY DOMAIN)

AP11797

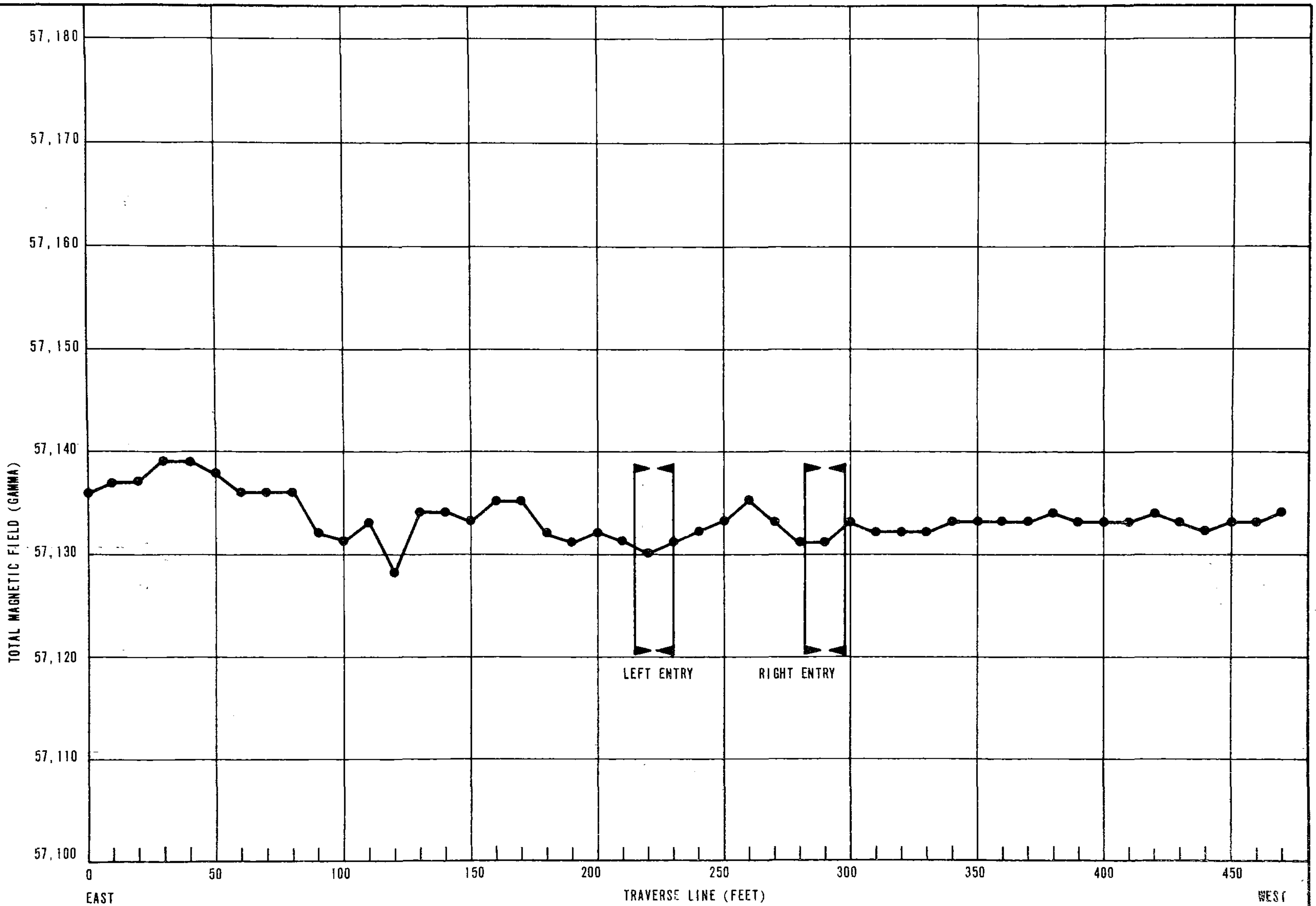


FIG. 24 MAGNETIC FIELD DATA ACROSS THE MILLS #4 COAL MINE ENTRIES

BP11291

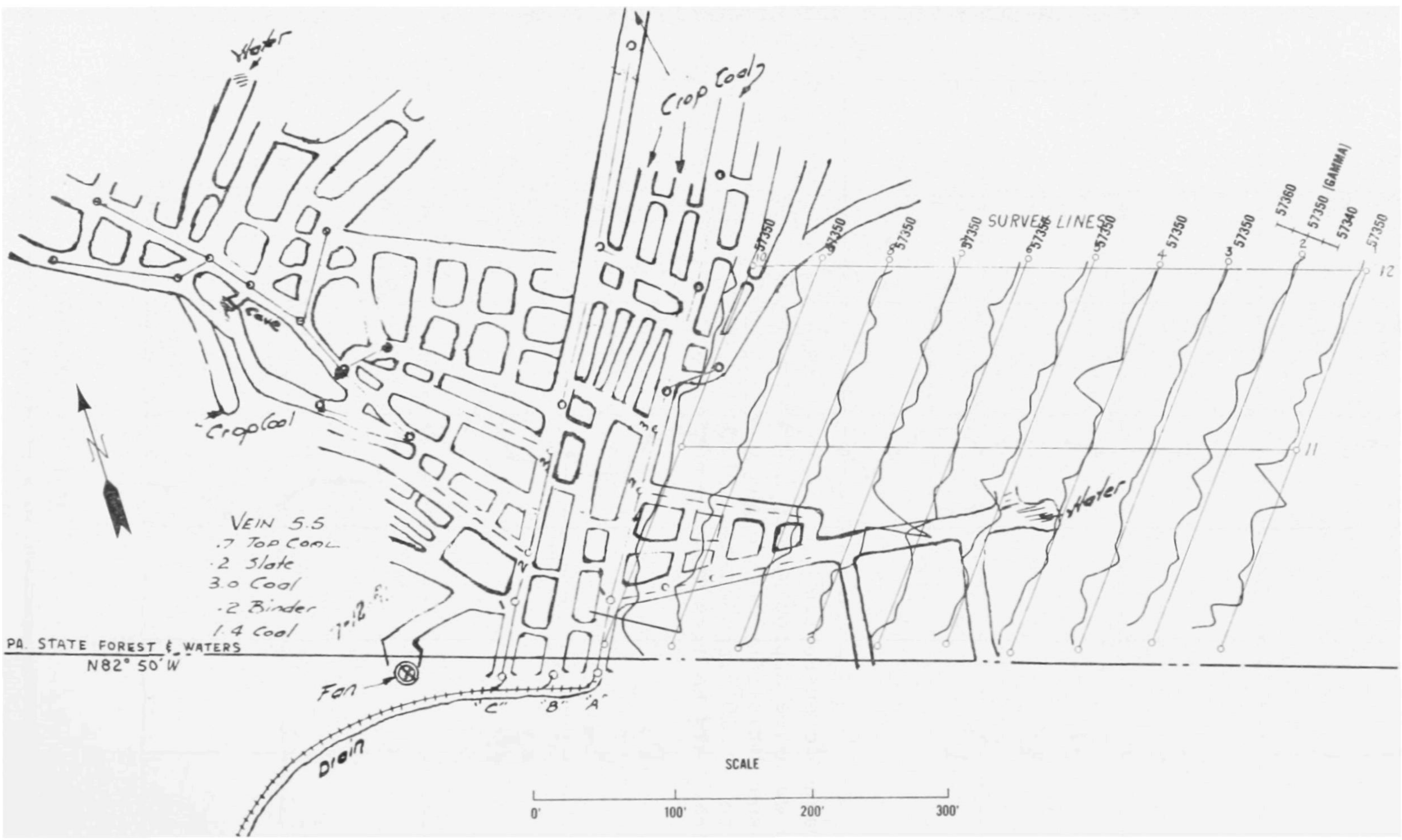


FIG. 25 TOTAL MAGNETIC FIELD TRAVERSE PLOTS FOR SURVEY LINES 1 THROUGH 10, BITUMEN #2 COAL MINE

the New Watson mine. A very large, negative anomaly is coincident with the left entry. This result is most gratifying, but the consistency of these correlations is lacking. (Subsequent field activities at this site noted a powerline close to this portion of the traverse line. The large anomaly may be related to this source.) Notice that the data over the right entry do not show an anomaly. The right entry has a tight, earthern seal. If the seal extends down the drift so that it's beneath the traverse line, then the significance of this data may be greatly enhanced.

The plot of the magnetic field data along the traverse line at the Old Watson mine entry is illustrated at the top of Figure 16. There is a sharp negative anomaly associated with the mine entry. It should be noted that there is a vertical scale exaggeration here relative to that of Figure 15. Although the anomaly appears sharp, it does not possess the amplitude of the anomaly in Figure 15, nor does it stand out from the noise as well.

Figure 17 illustrates the magnetics field data along the traverse line over the Big Spring #1 coal mine entry and fan. There is no correlation between the magnetic field data with the mine entry at Big Spring #1.

The negative anomalies observed are of the direction expected. That is, the magnetic susceptibility of the drift (air), assuming that it's open would be approximately 1×10^{-6} cgs units, whereas, the magnetic susceptibility of the shale and sandstone would be about 5×10^{-6} to 5×10^{-5} cgs units. Since the susceptibility of the drift (air) would be less, the magnetic flux lines would diverge from the drift (air) and crowd into the surrounding rock. The net result would be a lower magnetic field intensity over any drifts or subsurface voids.

The ability to detect these voids is something else and is dependent on equipment sensitivity, background noise and other factors. Background noise appears to be a limiting factor in this application.

VLF Electromagnetic

Mills #4 Mine

The strongest radio signal for the VLF surveys at the Mills #4 mine was received from station NAA, Cutler, Maine on a frequency of 17.8 kHz and a radiated power of 1000 kw. Although the signal was strong for these surveys and could be nulled almost completely, the data obtained and plotted did not show any significant correlation with the entries or subsurface workings. The in-phase and the out-of-phase signal values remained fairly constant for each survey and did not change slope significantly or cross.

Bitumen #1

The plotted data for the two VLF survey lines at the Bitumen #1 mine improved somewhat over the Mills #4 data. However, there appeared to be no consistant correlation with the subsurface workings.

New Watson, Old Watson, and Knowles Mines

The data obtained on the two VLF surveys at the Watson mines were very similar to those obtained at the Mills #4 mine. The in-phase and out-of-phase curves remained relatively constant.

The VLF survey at the Knowles mine improved somewhat again in that the in-phase and out-of-phase lines were not constant and some slope changes occured. This slight variation from the norm was not sufficient to indicate the location of the mine entry.

Seismic Refraction at the Bitumen #2 Mine

Seismic refraction investigations were confined to the Bitumen #2 coal mine. Detection of the mine workings was the objective. Three seismic phenomena were used to gain this objective. These phenomena included: anomalous delays in arrival times, anomalous attenuations of the seismic waves and cavity resonance. In that Godson and Watkins (1968) had considerable success in observing cavity resonance due to the radial oscillations of the underground voids triggered by seismic waves, the greater part of our effort was directed at attempting to observe this phenomena as a prelude to using it for detection pruposes. It should be noted that Godson and Watkin's experimental work is based on Biot's (1952) theoretical relationship between the dimensions of a cylindrical bore in an infinite solid and the resonant frequency. The agreement between the experimental and theoretical being within a factor of three. Biot's relation being:

$$D = \frac{Vs}{1.55f}$$

where

D = diameter of the bore
Vs = shear wave velocity
f = resonant frequency

We were at a loss to identify resonance on the early records. (Resonance is identifiable as a time-independent wave train persisting for as short as one second or as long as four seconds.) An experiment was designed to show whether resonance could be generated in the mine workings or not. The experiment consisted of placing a dynamite charge in one of the mains of the coal mine, detonating it and observing the seismic activity with a string of surface geophones overlying the main.

A copy of one of the records obtained from this experiment is shown in Figure 26. Readily apparent from this record is evidence of some resonance (unshaded area) extending for about one and a half seconds after the usual wave arrivals have concluded. The resonance is not strong nor is it persistent when one considers that the energy source was internal to the mine. The energy was provided by one-half pound of 40 percent strength dynamite which was placed on the mine bottom. No stemming was used, thereby, providing air coupling of the energy to the two walls and the roof of the main.

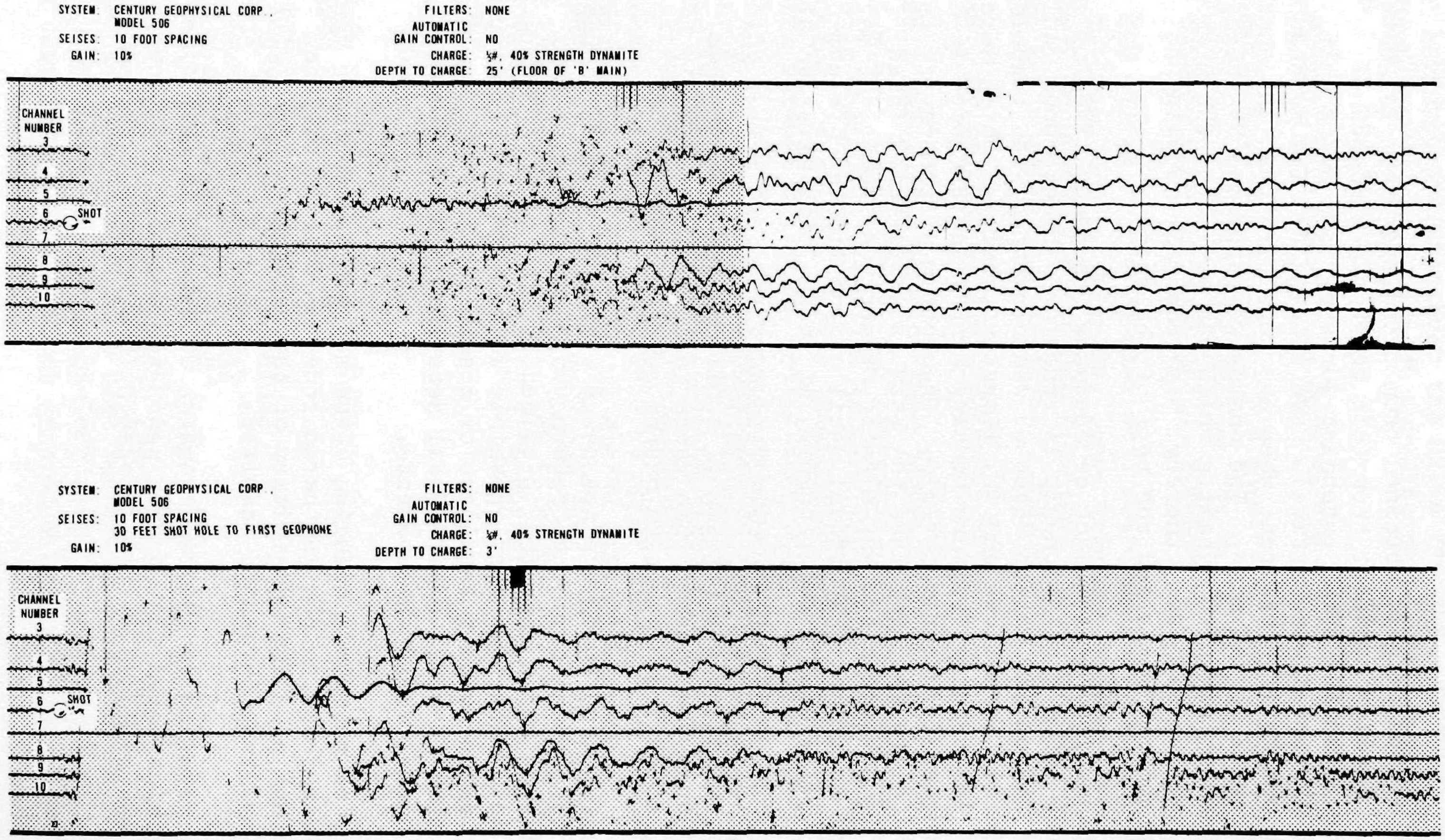
By way of explanation for the lack of adequate resonance, the following is offered. Biot's relationship is true for a homogeneous media. The work that Godson and Watson reported was concerned with tunnels or cavities in (1) lava flows and (2) limestone, both of which were homogeneous. In our case, we were working with a cavity which is composed of three different materials. The bottom of the cavity is underclay, the sides are coal, and the roof is siltstone. These three materials possess different elastic properties, hence, it may be impractical to assume that radial oscillations from such a composite would follow Biot's relationship, if indeed they exist at all.

Another approach to the problem of resonance inducement and detection would be to define the frequency, amplitude and type of wave required to induce resonance. Once these factors are reasonably well defined, an optimum detection system could be built.

The frequency required to induce resonance would, of course, be the frequency of the resonance. The frequency of resonance will have to be more closely known than that provided by Biot's relationship. Experimental determinations where possible would more closely define the frequency and provide a catalogue of possibilities which could be used for cases in which experimental determination is impractical prior to the actual field measurements.

The amplitudes of resonance inducing waves may not be important yet attenuation losses due to the weathered zone, as well as the rock strata overburden plus the sensitivity of the receiver system, will dictate the amplitude threshold required.

The wave type required to induce resonance is unknown at this time. Godson and Watkins noted that better resonance was obtained from dynamite charges exploded at shallow-depth (approximately three feet)



NOTES:

TOP RECORD ILLUSTRATES POSSIBLE CAVITY RESONANCE (UNSHADED PORTION).

BOTTOM RECORD ILLUSTRATES A STRAIGHT-LINE SHOT FROM THE SAME LOCATION FOR COMPARISON.

CHANNELS 5 AND 7 ARE "DEAD"

TIMING INTERVAL = 0.1 SECONDS BETWEEN MAJOR DIVISIONS.

FIG. 26 PARTS OF TWO SEISMOGRAMS RECORDED OVER 'B' MAIN, BITUMEN #2 COAL MINE

CP11431

as opposed to larger charges exploded at deeper depths (or approximately 50 feet). They suspect that since the shallower shots generate larger Rayleigh waves (on the order of several order of magnitude larger than normal compressional or shear waves), that the Rayleigh waves may be the triggering mechanism for the resonance. Although beyond the scope of this project, this possibility needs to be proven and the implications for field procedure studied.

Radiometry at the Mills #4 Coal Mine

Airborne infrared scanner imagery obtained on 10 and 11 June 1970 and 14 April 1971 were studied for the following features:

- Local active water drainage
- Fracture traces and fracture trace intersections
- Faults
- Jointing and jointing patterns
- Slump zones

Vegetation cover prevented complete analysis for these features on the June imagery. However, in some cases, full vegetation assisted in the analysis since there is a correlation between vegetation health and vigor and some of the above features. Figure 27 illustrates the result of an analysis of the April 1971 imagery in terms of detection of local active water drainage. The light tones represent exiting water from seeps and springs, pools of water and stream courses. Comparison of this imagery with that taken on 10 and 11 June 1970 readily indicates that the optimum time for infrared imaging is at a time of year when the drainage is at or near a maximum, when water temperature exceeds ground temperature, and when there is no screening due to leaf cover. This optimum time is early spring.

It should be noted that while this technique allows great accuracy in locating drainage sources, it cannot be used to distinguish between acid and fresh water seeps except by association with visible mine features. A ground survey was made with a portable pH meter at most of the seepage sources and in Trout Run. This survey revealed pH levels between 2.5 and 6.9. All of the seeps and streams checked drain into Trout Run, a tributary of Moshannon Creek. There has been considerable strip mining in the area and most of the drainage is related to this activity. The Mills #4 coal mine contribution is almost negligible by comparison.

Soil Moisture Determinations at the Knowles Mine

The soil moisture profiles did not illustrate any correlatable variation with the location of the mine entry. Although surface soil moisture was being measured, it was hoped that due to the shallow

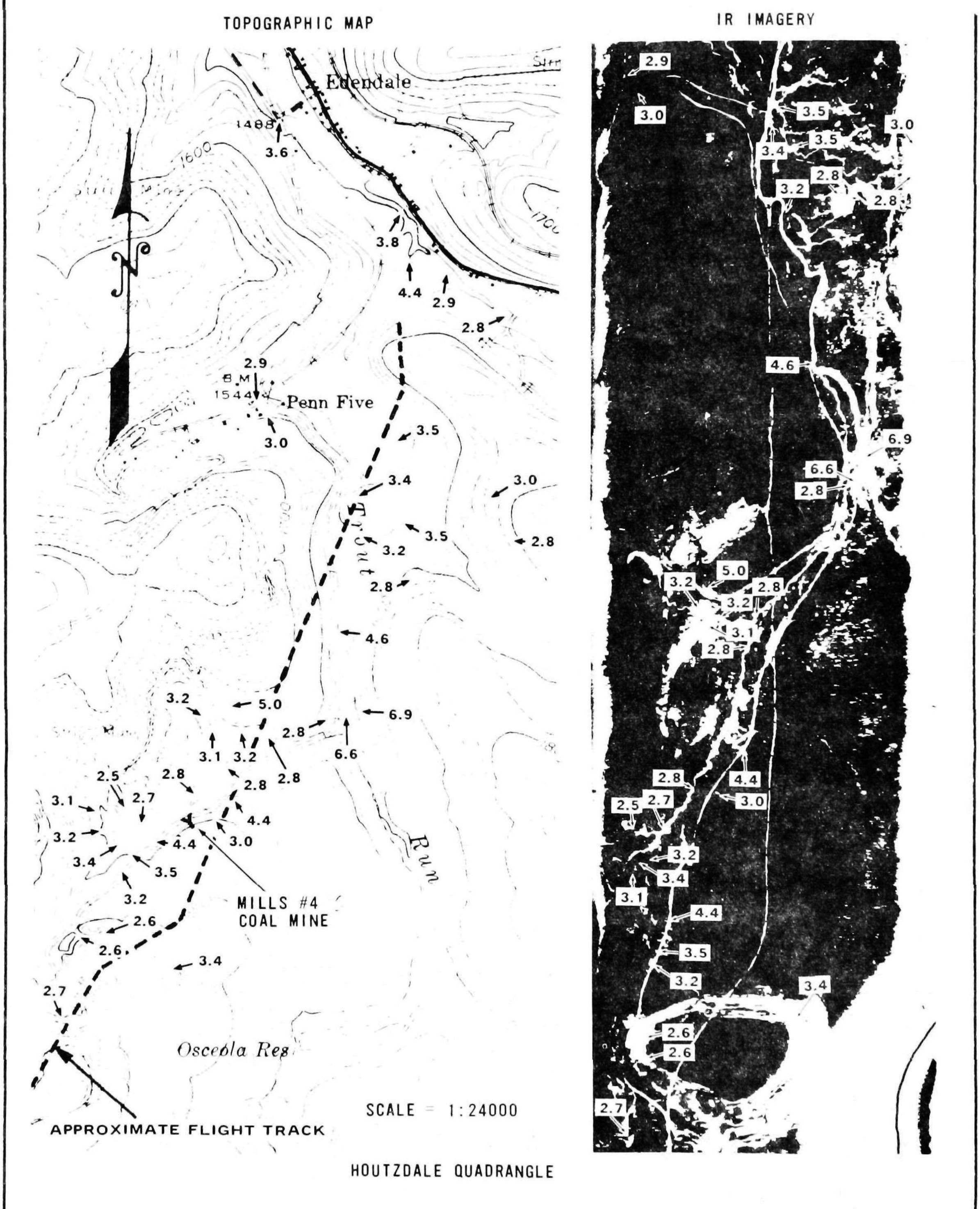


FIG. 27 UTILITY OF AIRBORNE INFRARED IMAGERY FOR DETECTION OF ACID MINE/FRESH WATER SOURCES; pH VALUES OF WATER SOURCES INDICATED; 14 APRIL 1971

AP11825

depth to the mine entry (approximately 20 feet) that a moisture profile variation would be visible as a manifestation of the mine. There is some precedent for this assumption in that soil moisture varys significantly in soils overlying carbonate bedrock topography (the deeper soils have the higher moisture content). In the mine case, however, the shale and sandstone strata comprising the overburden have quite different water permeability than the soils over limestone; therefore, the phenomena is nonexistent.

Computer Data Reduction Methods

A computer program developed by the IBM Canada Laboratory in 1968 called Surface Techniques, Annotation and Mapping Programs for Exploration, Development and Engineering (STAMPEDE) was selected to aid in reducing the field data. This program is adaptable to application areas which require the quantitative description of surfaces. Programs are included for making numerical and analytical approximations to a set of three coordinate values defining a surface, for manipulating one or more of these surfaces, and for preparing a display of surface geometry in the form of printed or annotated contour maps. In addition, this program is capable of determining volume, net volume, and area within the entire area of interest or within a specific contour.

Once the program was received, it was made compatible with the IBM 360-40 computer at HRB-Singer, Inc. The program was verified by comparing a computer plotted topographic map with that drawn in the field from the same plane-table data. After debugging, the program was used to contour the field data as required.

The next few paragraphs discuss an in-house research effort directed at the calibration, digitizing and computer processing of geophysical data.

We initially felt that existing equipments had the sensitivity and accuracy required for the geophysical tasks to which they are applied, i.e., detecting and locating abandoned coal mines. We felt that the principle limiting factor in accomplishing this task was the ability to discriminate between the signal and the noise. We felt that the application of signal enhancement and other analytical techniques could overcome this limiting factor.

The first step that we took in this effort was to develop the ability to quickly and efficiently convert the analog data, as recorded in the field, to digital form for the purpose of computer software processing. Fortunately, the hardware required for this effort existed. It required some interface engineering and the cooperation of several groups within the company, including our Signal Processing and Analysis Facility.

A number of signal processing and enhancement possibilities are incorporated into this overall capability. The STAMPEDE program package provides a basis for the addition of other analytical tools. Some of the programs that are included or are planned are: amplitude analysis, amplitude moment analysis, Fourier analysis, autocorrelation, residual determination, downward continuation and model fitting. Limited time and resources precluded the full benefit of this in-house effort on this program.

Subsequent field experimentation with the various techniques led us to re-evaluate the sensitivity and accuracy requirements of the instruments for this task. Our conclusion being that the current state-of-the-art of conventional geophysical techniques are not adequate to the task. Although computer assisted analysis was benificial and will continue to compliment this type of geophysical work, the basic problem of mine detection will have to be solved first. When this is achieved, the true utility of computer-aided analysis can be demonstrated.

Geology

Philipsburg-Houtzdale Synclinal Basin

The study of the general geology and the specific lithology of this area included both field and literature investigations. Table 3 (see page 19) illustrates the generalized stratigraphic section for the mines in this region. The following sections discuss the regional geologic features, the Mills #4 mine area, fracture trace analysis of the region, and other "A" seam coal mines.

The regional strike follows the axial trace of the Philipsburg-Houtzdale syncline which runs diagonally (NE-SW) through the west central, north central, and northeast sectors of the Houtzdale quadrangle. The strike varies from N59°E in the southwest to N40°E in the northeast.

The regional dip varies from horizontal strata at the synclinal axis to 4°-5°NW at the Mills #4 mine. This gentle rise to the SE carries the Lower Kittaning Coal (B seam) from an elevation of approximately 1600 feet at Penn Five (Figure 1) to 1860 feet at the Mills #4 mine. The B seam is the main coal unit to be locally strip mined although stripping operations were later carried out in younger units (C, D, and E seams). The section overlying the B seam is well exposed along stripping highwalls 1/2 mile NW and 1/2 mile SW of the Mills #4 entries. At these highwalls, 14 to 16 feet of gray thin bedded fissile shale is observed to directly overlay the coal. The shale is followed by a thick sequence (25') of medium bedded to massive cross-bedded sandstone. A similar sequence was studied along a highwall 1/2 mile SW of Penn Five. Near Penn Five, an old mine entry into the B seam reveals the shale/coal contact. The steep hillside immediately south of this old mine has been strip mined. The hillside exposes the complete post-Lower Kittanning, Allegheny section and is capped by Conemaugh strata above 1800 feet (elevation).

Mills #4 Coal Mine Area

The Clarion Coal (A seam) was mined at Mills #4 and a sandstone roof is present at the entry. The A seam has also been strip mined along the hillside northwest of the Mills #4 mine and a stratigraphic section exposed in the highwall has provided exposure of the post-Clarion and pre-Lower Kittanning section.

The eastern entry to the Mills #4 mine is at an elevation of approximately 1661 feet and sustains an intermittent flow of water. The A seam rises (SE) under the hillside containing the mine and outcrops (covered) on the back slope overlooking the Osceola Reservoir at an elevation of approximately 1800 feet. The dip of the coal in the mine approximates 4°31'NW. Within the area of geophysical surveying, the section is all pre-Lower Kittanning. Surveys run east of the base survey line carry onto Pottsville strata and, therefore, onto strata below the mine level. The overburden above the mine is shallow. The cover reaches a maximum of approximately 55 feet between survey stations 1 and 3.

Fracture Trace Analysis

Jointing is prominant in the Allegheny rocks. Measured joint directions in the sandstone sequence above the A seam correspond closely to the joint directions reported by Nickelsen and Hough (1967) for the Houtzdale Quadrangle (Figure 28). They demonstrated that systematic joints (designated A) strike approximately perpendicular to fold axes. The fundamental joint system forms the basic unit of jointing in the region. It consists of systematic and nonsystematic joint sets intersecting at approximately 90°.

Systematic jointing is of significance in an aerial study of fractures since systematic joints cut completely through structural lithic units and may cross the boundaries of successive rock units with some change in orientation, surface character, and frequency. Where mineralization along systematic joint planes is lacking, leakage of meteoric water into and out of mines occur.

Faulting is present in the Mills #4 area and is confined in strike direction to the arc extending from N20°W to N85°W (Figure 28). The fault known to border the mine on the SW has an observed strike that corresponds to the systematic joint direction of N37°W.

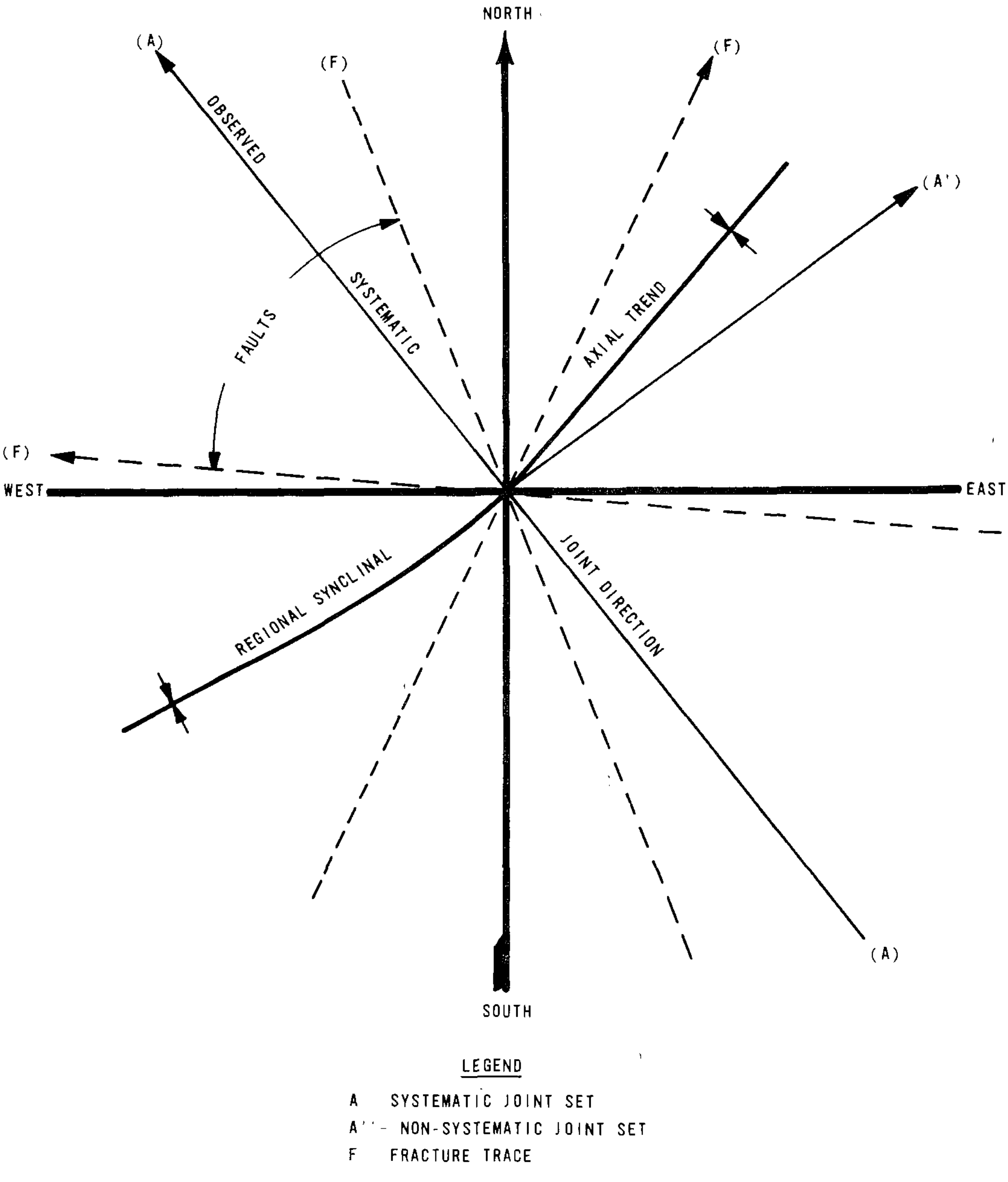


FIG. 28 GENERALIZED GEOLOGIC STRUCTURAL TRENDS FOR THE HOUTZDALE 7½' QUADRANGLE

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Fractures not corresponding to regional joint or fault directions are grouped under the general term of fracture traces. Fracture traces are defined by Lattman (1958) as natural linear features detectable on aerial photographs which are less than one mile long and which are surface expressions of joints and small faults. Fracture traces are considered to represent vertical fractures or zones of vertical fractures because they are straight, regardless of topography.

The dip of the strata is believed by Trainer and Ellison (1967) to control the abundance of fracture traces because both vertical joints and fracture traces appear to be more numerous in gently dipping strata than those which dip more steeply.

Stero examination of 1969 photography (GS VBYX-12 U.S. Geological Survey) of the Mills #4 coal mine area reveal fractures present in the mine overburden. A systematic joint set (A) runs across the center of the mine approximately parallel to the surveyed control line. Several fracture trace intersections are noted over the mine. The fracture traces may be grouped into two sets approximating strike directions of N35°E and N85°W.

Other "A" Seam Coal Mines

This section includes the geology of the New Watson, Old Watson, Big Spring #1, Knowles and Hoover coal mine areas. All of these mines are in the lowest mineable coal unit of the Allegheny Group. Koppe (1967) and Edmunds (1968) review the stratigraphy in the Houtzdale Quadrangle and report on recent changes in stratigraphic terminology of the Allegheny Group. Within the Houtzdale quadrangle, the mineable coal belongs to the Clarion, Lower Kittanning, Lower and Upper Freeport formations. East of the Philipsburg-Houtzdale synclinal axis (east of Moshannon Creek) the upper beds of the Allegheny Group are absent and the majority of the "deep" mines are in the lowermost or Clarion Coal. The Clarion is a single unit in this eastern area and is the equivalent of the Brookville, A, A', and three-foot terminologies. The Clarion splits into 3 units -- the Clarion 1, 2 and 3 coals northwest of this area. The single unit (A coal) varies from four to six feet thick, is dirty, and generally carries a top bony bench. Roof rock is variable throughout the area. A sandstone roof is present at the Big Spring and Watson mines, whereas, a shaly-siltstone roof rock is present at the Knowles and Hoover coal mines.

Clearfield Synclinal Basin - The Bitumen Coal Mines

The Bitumen coal mines are located in the west central portion of the Renovo West, Pennsylvania 7 1/2' quadrangle. The mines lie within 1/2 mile (SE) of the synclinal axis of the northeastward extension of the Clearfield Synclinal Basin. The regional strike of this synclinal axis is N53°E as reported in Nickelsen and Hough (1967). Because of the virtually horizontal attitude of the strata at the mine site, dip and strike measurements were unobtainable in the field. Systematic joint measurements in the field (N33°W) are consistent with those reported by the authors cited above (N34°W).

The Bitumen mines are in the Lower Kittanning coal ("B" seams) of the Allegheny series. The Lower Kittanning coal at the Bitumen mines lies wholly within an area of transitional environment of deposition between marine and continental sedimentation for the roof beds (Williams and Keith, 1963).

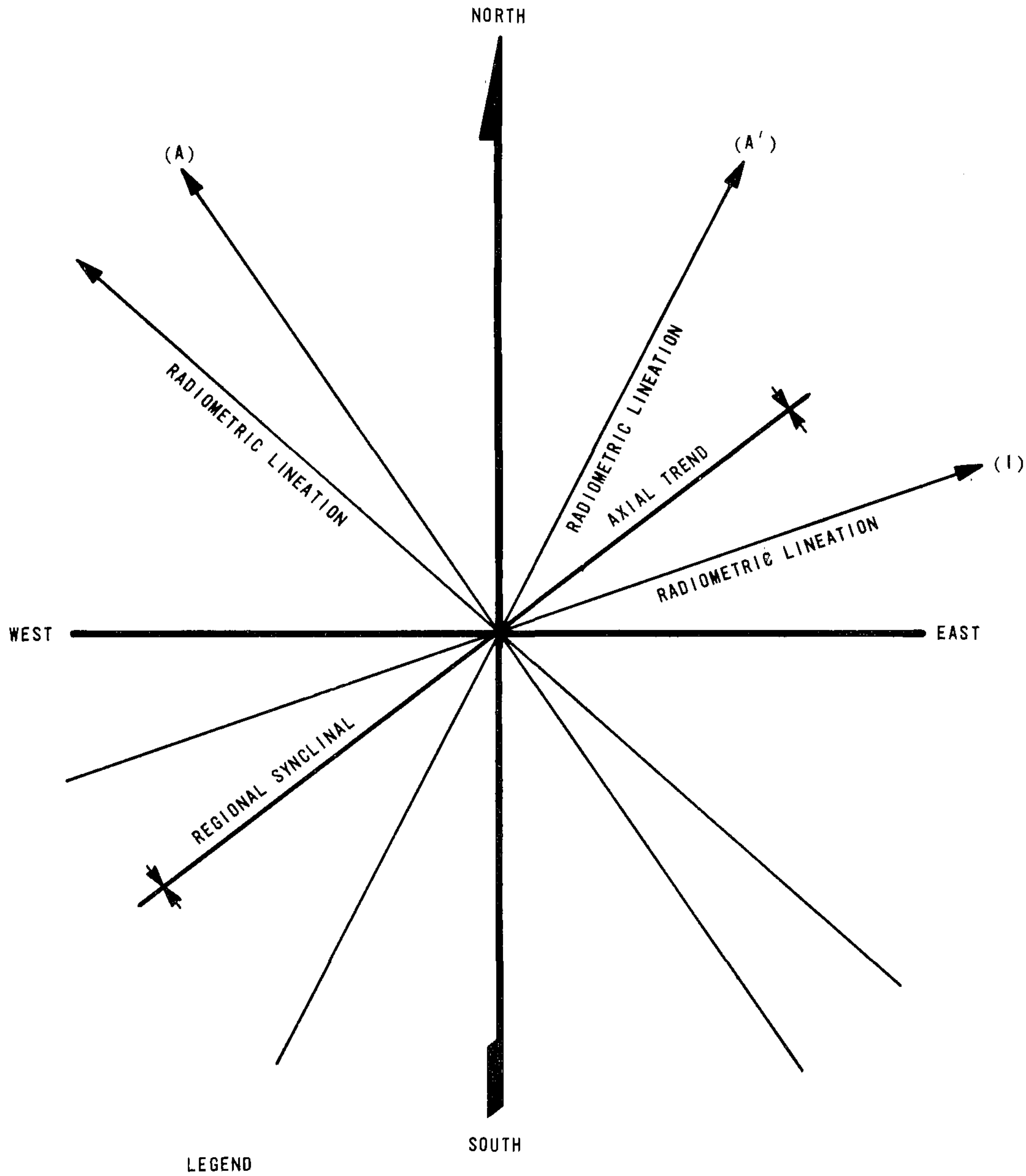
A stratigraphic section compiled from field measurements was presented in Table 4 (see page 24). The B seam is 5.5 feet thick at this location and has a black siltstone roof that evidently has held up well at Bitumen #2. This mine is clear in most drifts and relatively dry. The mine map apparently is accurate. Entrance to the mine is effected through a crawlway at portal 'C'.

The shallow overburden at portions of Bitumen #1 has collapsed into the mine. Slump zones are apparent on the surface and were mapped during the plane-table survey. No access to the mine was possible as the entries are well covered (although not water sealed). A lithologic facies change apparently took place between the mines as the roof rock at the eastern portion of Bitumen #1 consists of fissile shale rather than sandstone. This change in roof rock and its weaker supporting strength is responsible for the large number of collapse zones over Bitumen #1.

Fracture Trace Analysis - Bitumen Coal Mines

Airborne infrared imagery and aerial photographs were studied for fracture traces and joint sets. The aerial photos used were U. S. Geological Survey, 9 inch, GS-VTH, dated 2 March 1944. The general area of the Bitumen #1 and #2 coal mines was emphasized in this study.

Sterographic analysis of the aerial photographs and study of the infrared imagery revealed three different strike directions of existing fractures (see Figure 29). The three directions correspond to the systematic joint sets (A, A' and I) mapped by Nickelsen and Hough (1967). The (A) direction corresponds to systematic jointing in the shale and sandstone while the (I) direction refers to systematic jointing in the coal. Direction (A') approximates the non-systematic joint direction expected in the shale and sandstones.



LEGEND

(A) SYSTEMATIC SHALE JOINT MEASURED IN FIELD

(I) SYSTEMATIC COAL JOINT (NICKELSEN & HOUGH 1967)

(A') PROBABLE NONSYSTEMATIC JOINT

FIG. 29 LINEAR GEOLOGIC TRENDS FOR THE BITUMEN MINES AREA

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Rather intense study was required to detect the subtle expression of the fracture traces in the Bitumen mines area. This was not surprising since the absence of unique fracture trace directions is to be expected in horizontal strata where fracture traces represent zones of joint and small fault concentration that are parallel to the major joint sets.

Bitumen #1 is actually transected by two fracture traces in the (A) direction, two fracture traces in the (A') direction and is bounded along the northwest portion of the mine workings by a fracture trace in the (I) direction. The relatively large number of fracture traces associated with this mine may account, at least in part, for the acid water drainage emanating from the mine. The gently sloping terrain over the mine contributes in this regard, as rain run-off is generally inhibited. Rain water infiltrates to the mine workings much more readily through the fracture trace zones, as they are zones of high permeability. Topographic lows are associated with the fracture traces (usually the case) which when combined with the gentle slope contributes significantly to the infiltration rate of rain water into the mine.

Bitumen #2 is transected by one short fracture trace in the (A) direction. This mine is of relatively small extent and the overlying topography is relatively steeply sloping; hence, rain water is well drained and does not infiltrate in the quantity necessary to contribute to an acid water problem.

SECTION VIII

FIELD VALIDATION

This phase was deleted in favor of applying the so designated effort to Phase II, Field Measurements, and Phase III, Data Analysis and Technique Evaluation. Phase IV had been included in the project in order to gain experience and costing data pertinent to the applied usage of the successful techniques. In that no technique or group of techniques tested have been successful to the point at which validation tests would be meaningful, it was in the best interest of the project to continue with the field effort over well known mine sites.

SECTION IX

PROBLEMS AND CORRECTIVE ACTION

A number of problem areas were encountered during the course of this project. The following sections summarize these problems and the corrective actions taken to overcome the problems.

Accuracy of the Mine Maps

The first problem, that of the accuracy of the mine maps, was of prime concern. All of the analyses performed are dependent on this factor. Plotting errors, north arrow mislocated or incorrectly read from compass, incomplete maps and differential shrinkage of the map paper could all contribute to locational error and, hence, error in the analyses. Specifically, locational errors of points on the surface of the ground relative to the mine features as indicated on the mine map will be minimal near a visually checkable feature, i.e., mine entry. Conversely, the error will be greater as the distance from such features increases. In order to overcome this problem, emphasis was given to the collection of data near the main entries.

Data Collection During the Dry and Wet Hydrological Cycles

Data collection during the "wet" hydrological cycle was never fully achieved. The 1970 field season was relatively dry and the expected wet conditions in the spring and early summer of 1971 never materialized. Theoretically, the electrical techniques should work better during the wet cycle. It is to the detriment of the project that conditions were not favorable for field experiment during this time.

Lack of Physical Property Information

Although we have a good knowledge of the geology of the rock strata in the vicinity of the various mines, exacting knowledge of the electrical, magnetic and other physical properties of the strata is not available. Information of this type is desirable for an in-depth analysis of the geophysical data. It should be noted that although this information is desirable, it was not practical within the course of this contract to pursue physical property determinations in that at least as great an effort would be required as was allowed for this entire project.

Nature and Conditions of Mine Workings

A great deal of speculation on the nature of the worked out mine areas is necessary. These areas may range from totally open, dry workings to completely collapsed water saturated rubble. Additional direct information on the workings is necessary in order to answer these questions that are so important to the data analysis. Two ways of obtaining answers to this problem exist. The first approach is to drill. The drillers log may be studied for information on the nature of the workings and also their locations relative to that shown on the mine maps. It was not possible to provide drilling information during this project. The second and more descriptive approach is to explore the underground workings, provided access can be had to the mine. This was possible at the Bitumen #2 coal mine.

Loss of the Bitumen #2 Coal Mine Site

It came to our attention during the October-December 1970 quarter that we may be faced with the loss of two of our coal mine sites prior to the completion of our data collection activities. Strip mining was planned for the Bitumen #1 and #2 coal mine areas. Efforts to defer the stripping until our field activities were completed were unsuccessful. An airborne overflight of the Bitumen coal mines in March 1971 revealed stripping well underway. Bitumen #2 was completely stripped except for the fan and the "C" entry. At Bitumen #1 approximately 210 feet of each original survey line was obliterated due to a road cut.

SECTION X

ACKNOWLEDGEMENTS

Thanks are extended to Mr. David Milward and Mr. Perry Gaddis for their invaluable assistance in the selection of abandoned coal mines as field sites and in providing mine maps. Both men were with the Pennsylvania Department of Environmental Resources (Mr. Milward is now retired). Special thanks are extended to Dr. David Maneval and Mr. John Buscavage of this same department for their help in the execution of this project.

The Philipsburg Coal and Land Company is thanked for permission to operate over the Mills #4 mine. The Kettle Creek Mining Corporation is thanked for permission to operate over the Bitumen mines. Special thanks is given Mr. William Lindberg for his assistance with the Bitumen mines. The Pennsylvania Department of Forest and Waters is thanked for permission to operate in State Forest Lands over the Bitumen #2 mine.

The Pennsylvania State University, Department of Geology and Geophysics, is thanked for the loan of geophysical equipment. Special thanks are due Dr. Robert Alexander and Dr. Peter Lavin for their assistance in this regard.

The Naval Ordnance Systems Command, Washington, D. C. is thanked for permission to use a continuous recording magnetometer developed under naval contract at HRB-Singer, Inc.

* * * * *

The objective of this project was to demonstrate the feasibility of geophysical methods in the detection of underground mines, and mine openings. Such research projects, intended to assist in the prevention of pollution of water by industry, are required by Section 6b of the Water Pollution Control Act, as amended. This project of EPA was conducted under the direction of the Pollution Control Analysis Section, Ernst P. Hall, Chief, Ronald D. Hill, Chief, Mine Drainage Pollution Control Activities, Donald J. O'Bryan, Project Manager, and Henry R. Thacker, Project Officer.

SECTION XI

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SECTION XII

APPENDIX - DISCUSSION OF METHODS

A brief discussion of the geophysical methods that were field-tested follows. It should be noted that the mathematical basis for these methods are well covered in the classical texts by Jakosky (1960) and Heiland (1963) and the theoretical Volume (II) of Mining Geophysics by the Society of Exploration Geophysicists (1967) and are not treated in this report.

Resistivity is probably one of the most powerful geophysical tools for this problem. It is widely used for shallow earth investigations.

Conventionally, electric currents of external origin are needed to locate targets having anomalous electrical properties. When these currents are applied to a material, the amount of current that flows is related to the resistivity of the material, and the distribution of the current is determined by the relative resistivity of the inhomogeneities of the medium.

The basic procedure is to measure the potential gradient on the surface associated with a known direct current or low-frequency alternating current which flows in the earth. Irregularities in the conductivity below the surface affect the relation between the current and the potential drop at the surface.

While the range of resistivities in rocks and rock material may extend from 10^{-3} to 10^{6} ohm-meters, most common rocks have no consistent difference in resistivity. Except for certain rock materials such as the metallic sulfide minerals, the resistivity of a rock depends primarily upon the electrolyte concentration of the liquid filling the interstices of the rock formation itself. A mined-out area can be expected to have a resistivity somewhat different from that of the surrounding country rock. It will be either higher or lower depending upon whether or not the void has collapsed and upon the quantity of acid mine water present.

The following brief summary is representative of pertinent work by researchers that helped to shed light on the use of resistivity to this project.

Dutta, et. al. (1970), reported detection of solution channels in limestone. They noted that the anomalies were higher resistivities. A fault was also detected at depths of 141 and 76 feet and confirmed by drilling. It is significant to note that the presence of other than a thin shale section over portions of the limestone (due to local faulting) precluded the detection of cavities in the limestone. Hence, the three-layer case (soil, shale, limestone) became too complex for detection purposes. The Schlumberger electrode configuration and the one current electrode far configuration were used exclusively.

Self-potential methods are based on the measurement of potential differences due to currents generated by electrochemical actions such as salt-concentration gradients; filtering action of certain materials, particularly clays; flow of fluids through porous rocks; and chemical reactions between minerals and pore-filling fluids. The degree to which such potentials are produced or modified by mining operations is unknown.

Airborne Radiometry. Airborne infrared imaging has been successfully applied to the detection and mapping of faults, fracture traces and geologic formation boundaries, among other features. These features possess contrasting infrared radiation characteristics relative to their background. The contrast is due to higher soil moisture associated with faults and fracture traces and to emissivity and thermal inertia contrasts between geologic rock types, respectively.

Detection and mapping of surface water drainage associated with mines is easily accomplished as was reported. However, the optimum conditions for this task require that the overflights be made in early spring. This time frame assures: (1) peak water flow, (2) no tree cover, and (3) maximum temperature contrast between water and terrain.

The detection of infrared radiation variations at the surface that are manifestations of underlying mine workings is a much more complex task. Making the task complex are factors such as: (1) intensity of the radiant energy from the sun, (2) absorption of the solar energy by the terrestial cover, (3) emissivity of the terrestual cover, (4) subsurface thermal conductivity, and (5) conductivity of the thermal energy to air. Theoretically, the "signal" from/due to mine workings would be buried in the noise contributed to the above factors.

Magnetic Method. For the purpose of detecting mine voids, it is necessary that the concentration of magnetic minerals in the rock strata surrounding the void be high enough to produce a measurable change in the total magnetic field as measured at the surface. That is, the magnetic susceptibility of the surrounding materials must be high enough to produce a contrast in the geomagnetic field that is within the sensitivity of the magnetometer. (The magnetic susceptibility is the ratio of the intensity of magnetization of the material to the magnetic field intensity which established the magnetization.) Sedimentary rocks may have a susceptibility as low as 1 x 10^{-6} cgs units and some coastal sands may be as high as 1 x 10^{-1} cgs units. The magnetic susceptibility of soil materials may vary greatly.

Iron litter within the void as well as water pipes, power lines, etc., in close proximity to the area of measurement, in many cases will produce anomalies much greater than the void. However, the magnetic effect of the iron will produce positive anomalies while the voids will appear negative.

The fact that the void is an extended feature will aid in the discrimination of non-mine anomalies. Some of the local effects can be greatly reduced by using a gradiometer.

Seismic. Conventional seismic methods utilize pulses generated in the earth by explosive or mechanical means, and the detection of the seismic waves by an array of detectors distributed on the surface or in drill holes. From the character and the relative arrival times of the detected pulses, one can generally obtain information on the depths, slopes, and thickness of strata. From seismic velocity measurements, the type of rock in a given strata can sometimes be identified. Although these techniques are straightforward and effective in areas of simple stratification with small dips, in areas where the strata are severly folded, or extensively faulted, or where fill occupies much of the region, the seismic waves are scattered in such a complex way that the structure often cannot be resolved.

Several seismic methods have been considered for the detection of underground cavities or voids. If the area has good reflecting horizons below the void, reflection "shooting" above the cavity may show the strata below the cavity, with a time and/or energy level anomaly or "shadow zone" directly above the cavity. The distance to which a shadow zone will extend from an obstacle before being eliminated by diffraction around the obstacle is the critical factor.

Refraction seismic methods over relatively short distances may be useful for detecting low velocity zones near the surface. If either the explosive or the geophone is located close to the void and the other at the surface on the other side of the void, it is possible that the effect of the void should be detectable.

Because of the sharp discontinuity in the graphic result when using seismic refraction, this method is generally preferred over resistivity for finding depth to bedrock. For purposes of void detection, the resulting velocity plot would consist of three velocity lines (assuming the tunnel is in a homogeneous medium); an initial segment representing the velocity of the surrounding material, a middle segment with a different slope, and the third line segment having the same slope as the initial segment. In at least one instance where underground cavities were being located, this three-segmented line was produced. The object of the search was an underground tomb in Italy and a refraction seismograph with a one-meter spread between geophones was used. The line of geophones was directly on top of and on either side of the underground tomb. The resulting seismic profile had very sharp discontinuities, allowing the cavity to be readily detected. In some instances, the refraction seismograph failed to detect underground cavities. For example, Humble Oil Company's refraction seismology team failed to detect Mannoth Cave in Kentucky; several investigators failed to locate small limestone caves. Therefore, it appears that although the seismic refraction method will, in some cases, detect underground tunnel-like structures, it may not have a very high detection reliability.

Very Low Frequency (VLF) Electromagnetic. Electromagnetic methods utilize the measurement of secondary electromagnetic fields generated by induction in subsurface conductors. For the VLF electromagnetic case, the primary energy sources are electromagnetic fields generated by U. S. Navy VLF-transmitting stations. That is, the transmitted waves induce currents in subsurface conductors as the waves pass through them. The currents are formed in accordance with the laws of electromagnetic induction. The currents are then sources of new waves which radiate from the conductors and are detected at the surface. Inhomogeneities in the electromagnetic field observed at the surface indicate variations in conductivity of subsurface features.

Again, the mine itself may exhibit either limit of conductivity, that is, highly conductive (rubble filled cavity full of highly mineralized water) or insulative (noncollapsed void with no water). Most likely, the mine will exhibit electrical characteristics intermediate to these limits. As is the case with resistivity, induced polarization and self-potential, to be successful in this application, the induction method relies upon a discontinuity in electrical characteristics between the mine and its surroundings and/or presence of an "indicator" such as a clay sublayer whose characteristics are markedly different due to the presence of the mine/absence of the coal.

Induced polarization techniques utilize a strong primary current which polarizes the subsurface strata and produces a potential field which persists after the current circuit is interrupted. The intensity of this potential field and its decay time are the parameters usually measured. Field and laboratory experiments show that buried metallic conductors such as sulfide ore bodies will produce substantial induced polarization effects measurable on the surface if the conductors are not too deeply buried. Other experiments have shown that ionic exchange in clays and similar phenomena in water-saturated sediments will also produce sizable induced polarization effects.

The induced polarization methods can produce unique responses from buried metallic conductors and water-saturated rocks. They do not inherently have any better depth penetration or resolution than resistivity or electromagnetic methods. The method may be most valuable in detecting clays and other highly conductive layers associated with the coal seam, rather than by direct detection of underground cavities. The best equipment used in the application of the method is at least one order of magnitude more sensitive than the equipment used in resistivity surveys. This increased sensitivity is useful because the techniques used minimize the response of extraneous features.

Geochemical Methods. In that geochemical methods were initially proposed, it became apparent that they would not be used to any large extent. The following section discusses why.

The application of geochemical exploration techniques to the problem was predicated on the basis of the detection and measurement of a chemical "indicator" or "tracer". The indicator has to be relatable to the mining activity or the mining activity has to have caused the indicator to change or cease to be detectable relative to normal concentrations (background). The indicator generally is one that is related to the mining activity and is mobile, detectable in low concentrations and non-reactive. The obvious indicators are pH and total iron. In fact, these two indicators proved to be the best for the task, in that (1) they are the physical components that make mine drainage a pollutant, (2) the establishment of threshold norms would be the same as that for pollution detection and (3) simple, well-defined equipment and procedures have been established for their analysis.

Once the site selection phase had been completed, it became apparent that most of the mines visited were either non- or intermittent acid water generators. The mines that did produce acid water continuously were easily traceable right to their entries by pH measurements. Hence, the utility of the geochemical approach as an area or regional reconnaissance tool was reiterated.

The applicability of this tool for detecting covered, hard-to-visually-locate mines was questionable. Study of the literature [Ault (1959), Barnes (1964), Baines, et. al. (1964), Caruccio (1967), Corbett & Douglas (1967), Hawkes (1969), Holland (1970), Mason (1960), Morrison (1965), Rozell (1968), Scott & Carroll (1970), Smith (1963), Thatcher (1961), Ward, et. al. (1963), Wedepohl (1969)] yielded no clues toward a soil indicator that would allow the mapping of a superimposed halo which was relatable to mining activities or just entries (if, indeed, the entries were ever buried to the extent that this approach would be required). Similarily, stream sediment analysis and ground water analysis, both of which appeared to be reasonable areas of investigation, proved to be unimportant for further consideration when the actual mine sites were studied. This was due to the ease and utility of simple pH measurements which provided the same basic information; and the tracer analysis of water input sources lost its importance when it was established, by observation of the mines, that primary water sources are rain and snow melt due to percolation through the overburden. Hence, the geochemical approach was fundamentally abandoned (except for pH studies related to airborne IR detection of water sources) in favor of a greater emphasis on the geophysical approach.

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27 *Abstract*

Acid drainage produced by abandoned coal mines continues to cause serious water pollution problems. Without knowing the exact location of the concealed openings and the extent of the mine, the application of known, at source abatement techniques is virtually impossible. Drilling is the only known method for accurately determining the location and extent of the mine voids, but this is extremely expensive. This project attacks the problem through field studies of the following geophysical methods: electrical resistivity, self-potential, infrared radiometry, total field and differential magnetometry, seismic refraction and reflection, very low frequency electromagnetic and induced polarization over well documented, drift, coal mines. Airborne infrared radiometry proved to be an excellent tool for detecting and mapping acid mine/fresh water sources, acid mine/fresh water drainage, and fracture traces under selected conditions. Resistivity and magnetics anomalies coincide with some (not all) drift mine entries. Induced polarization data shows some apparent correlations with mine workings. Other methods tested did not yield correlatable information. Conventional geophysical approaches to this problem do not appear adequate for the task. Unconventional approaches including high frequency seismic, shear wave seismic, and induced polarization methods may provide answers pending their further development.

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