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IMPROVED RESOURCE CHARACTERIZATION FOR COAL MINING (GEOPHYSICS AND DRILLING TECHNOLOGY)

Final Report

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IMPROVED RESOURCE CHARACTERIZATION FOR COAL MINING (GEOPHYSICS AND DRILLING TECHNOLOGY)

FINAL TECHNICAL REPORT

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16. Abstracts Improvements in drilling and geophysical technology have developed to the point where the most cost-effective programs for coal exploration/characterization can best be accomplished through a combination of techniques. The high resolution seismic reflection technique offers the potential for significantly extending the knowledge of deep coal beyond what can be obtained from borings alone and other surface techniques have limited, but significant applications for shallow coal, such as magnetic measurements to map clinker. Borehole applications, particularly the use of natural gamma and density sondes, are sufficiently effective so as to greatly reduce the need for cored boreholes. A great potential exists for applying geophysical technology underground, but the seam wave seismic method has not been developed in the U.S. and the range of radar is limited. Existing geophysical technology is still underutilized in the coal industry. Specific equipment and data processing improvements can be recommended, but this need is overshadowed by the greater need for more interaction between the geophysical and coal mining industries.

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FOREWORD

This report was prepared by D'Appolonia Consulting Engineers, Inc., 10 Duff Road, Pittsburgh, Pennsylvania 15235 under Contract No. DE-AC22-80PC-30114. The contract was administered under the technical direction of the Pittsburgh Energy Technology Center with Mr. Richard Fowkes succeeded by Mr. Robert W. Stephan acting as the Contract Monitors.

The basic study for this contract was completed during the period September 1980 through February 1982. This final report was submitted by the authors in June 1982.

EXECUTIVE SUMMARY

The amount of coal mined in the United States is likely to increase over the next decade. A significant percentage of this production is expected to come from underground mines in deeper seams using increasingly more sophisticated mechanical mining systems. The mining of deeper seams with mechanized systems will require an increased knowledge of the characteristics of the coal seam, if mining is to proceed with the maximum efficiency. An increased and more efficient use of geophysical and drilling techniques can be cost-beneficial components in the overall effort to achieve increased production goals and minimize production costs.

Drilling technology has improved for the coal industry through the development of efficient, smaller, slimline rigs that can be used more effectively in the rough terrain of the Appalachian coal fields. In particular, increased use of compressed air with rotary rock bit drilling and improved wire line core drilling techniques has allowed for more efficient production for most drilling purposes. Two of the most important recent developments are the plug-bit, which allows for continuous diamond drilling to a point where rock core can be recovered with a wire line system, and in-hole bit replacement, a device not yet commercially available which will eliminate the need for pulling the rods to change or inspect a bit. The use of a destructive drilling technique, such as rotary-air, assumes that core sampling is not required. This implies that an alternative method exists for characterizing the coal seam without the need for taking a core sample, which is geophysical borehole logging.

One of the most important technological advances for the characterization of a coal seam has been the development of geophysical borehole logging sondes for use in a slimhole environment. A wide variety of tools are now available which, taken together, can nearly replace coring for all general information requirements except those relating to coal quality. The most important logging techniques are the gamma gamma density and natural gamma logs, which, when used with a caliper log, can usually resolve seam thicknesses to within one or two inches, detect shale partings, and be used to calculate the ash content of the coal. Future developments of geophysical logging, with the use of a neutron-gamma spectra device, promise to include in situ quantitative chemical analyses of the coal.

A wide variety of geophysical techniques can be applied from the surface to assist in the mapping and characterization of coal, but only one technique has the potential for providing detailed information for a deep seam, high resolution seismic reflection. This method has seen its greatest development and application in Europe, where it is used to detect faults, sand channels, pinchouts, abandoned workings, and other hazards that affect seam minability. High resolution seismic reflection is also used in the United States, but not as frequently as elsewhere

EXECUTIVE SUMMARY
(Continued)

and published information on the suitability and limitations of the technique is negligible. Nevertheless, there is evidence that its usage is increasing, particularly to resolve production problems as they are encountered during mining operations.

Other surface geophysical techniques have limited applicability for characterizing surface or near-surface coal, but under certain circumstances can be highly effective. In particular, the magnetic method offers excellent potential for delineating clinker zones. Other methods, such as gravity, electromagnetics, and resistivity all offer varying degrees of ability to map surficial coal and to detect abandoned workings.

Seam wave seismics and radar offer the ability to detect coal discontinuities in advance of the working face. Commercially available pulse radar systems have an effective range of about 50 feet (15 meters), but current research may extend this range several-fold. Seam wave seismics can detect discontinuities up to several hundred meters in front of the working face and the technique receives widespread application in Europe. Applications in the United States, however, are negligible and mine-suitable equipment and processing software have not been developed, or at least are not commercially available.

The main conclusion is that the potential power of geophysics is not as well recognized as it could or should be and presently existing technology is underutilized. Additional research and development for specific hardware, such as for seam wave seismics, a better source for surface seismic reflection, a refined neutron-gamma spectra sonde, or a better automated surface resistivity measurement system would be beneficial, but not as important as promoting the increased appliation of existing technology. A strong need exists for developing confidence in geophysical interpretations, which can only come from a more active dialogue between the geophysical and coal industries and the increased availability of site-specific geophysical case histories. Particularly important is the development of a climate whereby geophysics is considered for use from the very beginning of a coal exploration/mining project.

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1.0 INTRODUCTION

1.1 PURPOSE OF STUDY

Coal is one of the more abundant sources of energy (and chemical feedstock) in the United States. Various projections suggest that the mining of coal is likely to increase over the next decade. Of this present and future production, a significant part is expected to come from underground coal mines, with an attendant increase in the greater use of more sophisticated mechanical systems. An increased and more efficient use of geophysical and drilling techniques can be cost-beneficial components in the overall effort to achieve increased production goals and minimize production costs.

The U.S. Department of Energy has embarked on a multifaceted program designed to improve the productivity of underground coal mining. As part of that effort, D'Appolonia Consulting Engineers, Inc. (D'Appolonia), was contracted to evaluate the state of the art of geophysics as it pertains to exploration and production objectives. The U.S. Bureau of Mines also actively develops general mining techniques, with one program emphasizing geophysics as it applies to improving safety.

This study examines the applications of geophysics and drilling, assesses the present and potential future state of the art of these technologies, evaluates the cost benefits of their application, and recommends future courses of action.

1.2 SCOPE

The scope of the project includes two principal technologies: geophysics and drilling. Geophysics includes all technologies which detect in situ characteristics of the coal, the surrounding rocks, and the physical features of the site. It includes remote sensing, traditional geophysical surveys (e.g., seismic, magnetic, gravity, electrical), and borehole logging. Remote sensing could be classified as a geophysical technique; however, for this study the more conventional definitions have been followed and remote sensing has been excluded. Also specifically excluded herein are the techniques that use or depend on geotechnical/geomechanical/rock mechanics tools (e.g., extensometers, inclinometers, etc.). Drilling is considered as a technology to obtain core for laboratory investigation or to make a hole to support geophysics, not for operational purposes such as methane drainage. Geophysics receives the greater emphasis and includes techniques applicable from the surface, from boreholes, and within the mine. The focus is on underground coal mine operations. The desired output is systems or technologies to improve productivity, although safety is recognized to be of vital concern. Applications of this study by others, as well as other research programs, address the safety aspects. A slight geographic emphasis is placed on "Eastern U.S." type coal deposits relative to "Western U.S." types.

A comprehensive literature review, telephone and letter canvass, and limited site visits were conducted as the primary means to acquire input data. During the study, it became apparent that ways to improve the confidence of coal mine owner/operators in geophysically derived data was more important than an enumeration of specific improvements in hardware, technique, or analysis. This conclusion was reached after numerous discussions with industry (mine owner/operators, service companies, and equipment vendors) and government personnel. It was generally recognized that hardware generally was not the factor limiting more widespread and more confident use of geophysics. Accordingly, this report is structured so as to emphasize the role that geophysics does and could play. Where present deficiencies in hardware are limiting application, appropriate note is made.

1.3 DATA NEEDS AND EXPECTED BENEFITS OF THE TECHNOLOGY

This study documents the status of the applications and applicability of geophysics and advanced drilling technology in terms of:

- Present status,
- Current research and expected future status,
- Applications of the technologies, and
- Costs and benefits of the technologies.

According to Vaninetti (1978), geophysical and drilling technology is applied for three fundamental major end-member goals:

- Academic knowledge,
- Economic evaluation, and
- Development of mining plans.

To this list may be added:

- Mining operation and control.

Table 1-1 summarizes pertinent general attributes of these goals.

Academic investigations are not of major concern here although, through them, data bases are improved and an understanding of the interrelationships of variables and the ability to predict conditions are improved. Certainly, improvements in our understanding of the coal formation process will lead to a more effective interpretation of site data. For example, an understanding of how and why sand channels form can be used to limit the exploration effort (hence, expense) necessary to adequately map them.

The three principal applications of concern in this study are the development of data for economic evaluation, for mine planning, and mine operation and control.

Geophysical techniques have played a minor role in mine planning and development of past coal and prospect characterizations. Historically, most coal production has come from the thickest, most consistent, and best quality coal seams. However, in many areas, these seams have been nearly mined out. Future production must come from seams in which there is very little information available because of limited outcrop exposure. Also, with modern coal processing technology, the known, more marginal quality seams can be considered. Conversely, but with the same impact on the need for information, the environmental aspects of coal consumption, or its use in synfuel plants, require a greater understanding of the distribution of minor mineral components.

The following discussion outlines the industry trends and specific major reasons why a more detailed characterization of a mine site is becoming more important in the overall effort to achieve increased production and minimize production costs. The increased size of properties requires the investment of large amounts of capital. Owners are demanding a better understanding of risks.

Coal supply contracts are trending towards larger yearly deliveries and longer terms. Because transport and utilization facilities are uniquely designed to these production rates and defined coal quality characteristics, there is a need on the part of the supplier and buyer to be assured that such production is achievable. Regulatory action and economics have forced coal consumers to match the characteristics of the coal fed into the boilers with the boiler design and to assure that a sufficient supply of the most appropriate coal is available. Coal consumers are specifying cleaned coal (washed coal) to assure a uniform boiler feedstock. In order for processing engineers to produce a uniform product, they must continually be aware of the incoming raw coal quality to make in-plant adjustments. Also, as cleaning plant investments are significant, they should be backed by a substantial proven reserve base. Coal conversion, the development and utilization of chemical processes which convert coal to gaseous and liquid fuels, will require substantial production. Generally, the DOE synthetic fuels plan calls for plants requiring on the order of 10 million tons of coal per year. These plants will require substantial proven reserves of known quality and chemical composition properties.

Recent industry trends appear to be toward large company-owned underground mines. For example, in 1979, 21 companies in Kentucky mined 44 percent of the state's production and 900 companies produced only 16 percent of the state's output. The new large underground mines require large investments in sophisticated mechanical mining systems. To make these equipment investments cost-effective over the long term, the mechanized high production mines should be situated on large reserve tracts. In most cases, these tracts have been obtained through large capital outlays. The magnitude of these capital outlays demands that there be a comprehensive understanding of the reserve quality, quantity, and minability.

As there is a trend toward having greater proportions of the total production of a mine become more dependent on fewer, larger machines, knowledge of general mine site characteristics becomes more important. The temporary loss of a major mining unit, due to an unforeseen condition, can have significant impact on production and mining costs. Geophysics and drilling can identify such issues as roof strength, ground water, faults, sand channels and rolls and horsebacks beyond the working face, and minimize unplanned production sags.

The benefits of a well-planned program of geophysics and drilling are to accrue from having a more detailed knowledge of the mine site characteristics at a higher level of confidence than would be otherwise available. Mining conditions would be more predictable so that improvements in the following should ensue:

- Reserve evaluation/valuation,
- Mine planning/construction, and
- Mine operation/production.

The perceived benefits of the greater use of refined geophysical and drilling techniques are the improvement in resource characterization to support capital outlays and sales, mine planning, and the optimization of production. The improvement of the techniques and the exposition and demonstration of their capabilities and value should advance their use and possible further development.

1.4 REPORT ORGANIZATION

The main body of text presents:

- A general description of the integrated mine planning process to develop the information requirements (Chapter 2.0),
- A description of technologies (Chapter 3.0),
- An analysis of selected applications with an evaluation of their costs relative to perceived benefits (Chapter 4.0), and
- Recommendations for future activities (Chapter 5.0).

The appendices provide a bibliography which also serves as a reference list for the main body of the text; and detailed descriptions of the most important geophysical techniques and applications.

TABLE
CHAPTER 1.0

TABLE 1-1

GENERAL ATTRIBUTES OF
MINE-RELATED INFORMATION GOALS

MAJOR GOAL	TIME DEPENDENCE	EMPHASIS ON ACCURACY	AREAL AND DEPTH COVERAGE	COST	TECHNICAL EMPHASIS
Academic Knowledge	Independent	Variable	Generally limited	Generally Low	• Interpretation of depositional environments, stratigraphy, and correlation of beds. • Development and verification of geologic and structural models.
Economic Evaluation	Dependent	Moderate	Emphasis on full geometric definition	Moderate	• Coal extent, thicknesses, volumes. • Coal quality. • Some emphasis on mining conditions and hazard/risk analysis (Text Chapter 2.0).
Development of Mining Plans	Dependent	Moderate to High	Detailed in specific areas	High	• Details of coal geometry and quality. • Conditions pertinent to mining (Text Chapter 2.0). • Hazard and risk analyses (Text Chapter 2.0).
Mining Operation and Control	Generally "Immediate"	High	Limited extent, often close to the present workings	Variable	• Potential hazards on "local scale." • Monitoring stability (e.g., roof fall potential, etc.). • Plan specific operations (e.g., pillar robbing and longwall cut heights). • Control equipment (e.g., shearers, etc.).

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2.0 INFORMATION REQUIRED FOR INTEGRATED MINE PLANNING

The exploration staff is responsible for gathering the information that will be used by the mine owner, accountants, management, and marketing personnel, along with engineers and scientists in the fields of mining, geology, coal preparation, geotechnics and the environment. Since the needs of these experts are sometimes specific and overlooked, this entire group should meet with the exploration staff to arrange a timely and economical exploration program. The program should specify the quality and quantity along with the time and form in which information is needed by each specialist. Meetings between the specialists and exploration staff should be carried out several times during the exploration program to assure that the program moves along the right path and to direct the exploration staff to gather additional needed information. A conclusion of this study is that geophysical technology should be fully considered in the program from the start for its benefits to be fully realized.

During the operational phases of mining, the need for geophysics is related to operational problems and control. Problems may include the encountering of a major anomaly, such as a fault, which has to be defined as to extent. Control issues, not treated here, would be sensors which help to regulate and guide mining equipment, such as part of a system to optimize cutting heights. The operational characterization phase does not differ much from that in exploration except that the target or problem is usually well defined and techniques requiring mine access can be used.

Sections 2.1 through 2.3 outline a generalized exploration program for a hypothetical prospect area for which little or no previous knowledge is assumed to exist. Section 2.4 discusses the geology of six United States coal regions (Figure 2-1) with an emphasis on region-specific parameters which the exploration staff must consider.

2.1 THE INITIAL STAGES

The type of information to be gathered by the exploration staff depends on the stage of development of the reserves. In areas not familiar to the exploration staff, a literature search must be started. This search must start with the knowledge of the quality and quantity of coal needed by the company and should include published and unpublished geologic literature, available drillers logs, geophysical logs, geophysical surveys, strength data, etc. Information gathered should include details such as:

- General geology
- Linear, joint and fault locations
- Types and thickness of overburden
- Number of coal seams
- Continuity of the coal seam

- Thickness of seams
- Coal quality data

Some geophysical work can be completed at this point such as regional gravimetric and aerial magnetic (aeromagnetic) surveys. These surveys can help in estimating basin or area reserves. For example, regional gravimetric surveys have been used to delineate gross basin structures in Australia (Neumann, 1965), western Canada (Ball 1976) and India (Verma, et al., 1976). Aeromagnetic surveys have recently been used for a rapid reconnaissance of an area of Kane County, Utah to distinguish coal from clinker in near surface seams (Friedberg and Crosby, 1981; Figure E-3 in Appendix E).

After the basin is defined, specific areas must be located to satisfy the company's needs. An exploration program should be conducted consisting of:

- Review of published and unpublished geologic literature and related documents.
- Study of available satellite imagery and aerial photography as well as available geophysical data.
- Site and areal analysis for ground confirmation by fly-over and drive-through reconnaissance.
- Evaluation of mining experience within the region and correlation of that experience with the general conditions of the site.

2.1.1 Review of Published and Unpublished Geologic Literature and Related Documents

Valuable information that can be gained from a literature search includes:

- General to specific information on the regional and local geologic conditions, including the origin and types of overburden rocks and soils as well as the nature, type and quality of coals in the area.
- Identification of major geologic anomalies.
- General to specific information on the regional and local groundwater conditions.
- General geologic conditions as exposed by mining or major construction activities in the area.

- Specific geologic information from nearby operations that may be pertinent to the specific site.

- General knowledge of actual or potential conditions in the mineral body and adjacent strata that should be considered when planning a detailed geotechnical investigation.

- Geologically related environmental reports that may be important to the development of a mine at the site.

- Seismic data.

- Speculation or other available geophysical information from data brokers. It should be noted that much of the information from brokers will be from oil exploration surveys and may not have sufficient resolution to be useful for coal investigation.

The most complete compilations of well log data are usually available from the state geological surveys.

In addition to publicly available information, important private sources of information can include:

- University sources - data from university research projects obtained from libraries and knowledge from interviewing individual professors.

- Files of the owner of nearby projects or consultants when arrangements for cooperative exchange of information can be established.

2.1.2 Study of Available Satellite Imagery and Aerial Photography

Photogeologic investigations can be done very quickly and economically when publicly available material is utilized. For the United States (in fact, for many parts of the world), several types of imagery and photography are available from government agencies for conducting initial geotechnical evaluations.

The importance of expert interpretation of imagery and photographs to identify site characteristics cannot be overemphasized. Although obvious geologic features can be recognized by most geotechnical professionals, a great deal of experience is required to complete an accurate and full geologic analysis. Despite this requirement for specialization, economy over geologic ground surveys is significant for the following reasons:

- Photointerpretation provides the only practical means to assure locating many significant anomalies that otherwise could go undetected throughout an entire geotechnical investigation.

- The identification of particular geologic features by photointerpretation can be valuable for planning the most efficient and effective site-specific investigative program, including geophysical surveys. Stereo pairs of aerial photographs are especially valuable in this regard.

In addition to conventional interpretation of surficial geology, aerial photographs, and satellite imagery can also be used to detect linears. Linears are any alignment of geologic/topographic/cultural features visible from the aerial photographs or satellite imagery. Researches such as Ealy, et al., (1979) Rinkenberger (1978, 1979), Simpson and Wielchowsky (1975), and Sullivan (1978) have demonstrated that linears are often indicative of fault zones or fracture concentrations, where areas of unstable roof and floor conditions are likely to be enountered in the mine. Faults with large displacement may completely truncate the coal. Linears are easy to find, but determining their effects (if any) on mining can be difficult. Nevertheless, the identification of linears early in the exploration program alerts the planner to possible structural geologic problems which may be resolved by additional investigations.

2.1.3 Ground Confirmation by Fly-Over and Drive-Through Reconnaissance

The general site evaluation study should include sufficient site-specific observations by investigators to assure realistic general analyses of field conditions and to verify the adequacy and applicability of information obtained.

2.1.4 Correlation of Regional Mining Experience with General Site Conditions

The goal of a general site evaluation study is to identify geologic conditions which may influence mine design at a particular site. When available, information gained by evaluating experiences at nearby mines is particularly valuable in this regard. Care must be taken during such evaluations to assure that the geologic conditions are similar, or if different, that the differences are fully considered.

Two primary sources of industry experience pertinent to the general site evaluation study are:

- Publicly available mine plans--particularly those portions directly influenced by geotechnical conditions such as roof support safety measures--available in state and federal (MESA) inspection offices. Consideration should be made of the manner in which procedures changed with time as technical innovations were realized, regulations were implemented, general operating conditions were improved, or different geologic conditions were encountered.

- Observation in operating mines when procedures for cooperative data transfer between owners have been established. The greatest value from an in-mine inspection normally results when conditions are examined and discussed by a team of geotechnical experts.

At this stage, it would be prudent to acquire existing geophysical logs of coal seams to initiate the basin data file, for both seam correlation purposes and to evaluate the response of the logs to variations of coal quality.

2.2 BLOCK EXPLORATION

After a desirable area of the basin is chosen, a geophysical and drilling exploration program should start. The exploration staff must work closely with the reserve-acquisition and mine design staffs to assure that an acceptable mine block is being explored. This stage of exploration includes the following:

- Continue to catalogue and analyze all acquired geophysical and drilling data;
- Start geostatistical work so that it may aid in guiding future drilling programs;
- All drilling programs should follow the outline presented in Section 3.2 and be accompanied by a geophysical borehole logging program; and
- Discussion between specialists should continue so that all necessary data are obtained during the exploration program.

Information gathering should place an emphasis on identification of limiting factors and reserve size. Examples of limiting factors which must be looked for are:

- Thickness variations or discontinuities which will affect production, restrict equipment or require special techniques and/or equipment;

- Quality data and preparation requirements that will affect marketability;
- Mine roof or floor conditions that will restrict the use of any types of equipment or support systems;
- Water inflow quantities that will be reduced or better controlled by specifying special arrangements for advance and retreat operations;
- Overburden conditions that dictate the location and type of entries and surface facilities;
- Important aquifers that will dictate special handling of the overburden materials or subsidence control;
- Other geological features, such as highly fractured zones or conditions that will dictate the mining methods or arrangements.

The combination of limiting factors from each discipline often clearly defines unfeasible mining systems and provides the basis for planning investigations to quickly determine the suitability of other possible systems.

Geophysics can supply much of the information needed at this point. Geophysical borehole logs can generate information in the areas of quality and thickness of coal, type of floor and roof strength of rock, groundwater levels, and location, permeability, porosity, and salinity of aquifers. High resolution seismic reflection profiles can supply information on continuity of the coal seam, geologic structure such as faults and folds and possibly abandoned mine workings. For shallow coal within about 50 meters of the surface, other geophysical techniques such as resistivity, gravity, and magnetics can generate information on faults, linears, and possibly abandoned mine workings. These ideas are expanded in Section 3.1.

2.3 MINE PLAN

After the block is secured, exploration should be directed to specific problems such as determining linear patterns and butt and cleat direction. Geophysics should be used to improve visibility of washouts, pinchouts and faults and better define roof rock changes.

Before mine design is finalized, the slopes, shafts, and important in-mine intersections should be drilled and geophysical survey lines should be run over mains to locate any geologic hazards.

Once production has started, geophysics can be used to solve specific problems that occur within the mine; an example would be searching for faults, no coal areas, and abandoned workings or wells in front of the headings or within a longwall panel.

2.4 BASIN-SPECIFIC EXPLORATION REQUIREMENTS: EXAMPLES FROM FIVE U.S. COAL BASINS

The generalized exploration program presented is meant to be a complete outline of needed exploration data. The outline must be modified in different basins to take into account already established data and specific needs of the basin. Some of the important characteristics of major coal fields of the United States are briefly discussed below to point out areas where geophysics could be used in designing exploration programs in these fields. The U.S. coal regions covered (Figure 2-1) include:

- Northern Appalachian Basin
- Southern Appalachian Basin
- Illinois Basin
- Powder River Basin
- Uinta Region

An attempt has been made to select basins which represent the greatest amount of coal production, but it is recognized that western U.S. coal, in particular, is not readily categorized. The coal fields of the western United States are divided into three major provinces: Pacific Coast, Rocky Mountain, and Northern Great Plains. The vegetation, topography, coal quality, structural, geology, etc., are extremely variable between and within each province. To simplify the discussion, two coal regions with large coal reserves have been selected to represent these provinces, the Powder River Basin, located in the Northern Great Plains Province and the Uinta Region, located in the Rocky Mountain Province. In both areas, mines tend to be large operations.

2.4.1 The Northern Appalachian Basin

The Northern Appalachian Basin known as the Northern Coal Fields consists of several basins located in western Pennsylvania, southeastern Ohio, and northwestern West Virginia. The boundaries of the Northern Coal Fields are marked by outcrops, except towards the southeast where a hinge line forms the boundary. This hinge line, which runs from Kentucky through the counties of Wayne, Kanawha, Braxton, and Tusher, in West Virginia, separates the relatively thin section and coal seams of a stable shelf deposition, representative of the northern fields, from the thick section and increased number of coal beds characteristic of a rapidly subsiding trough, representative of the southern fields. The northern fields are represented by more than 20 economically minable seams of Pennsylvanian and Permian age.

This basin has some significant problems which must be understood by the exploration staff. They are:

- Limited areal extent and thickness of seams
- Sulfur content
- Washouts and pinchouts
- Interfingering of rock types in the roof

2.4.1.1 Areal Extent of Seams

Except for the Pittsburgh seam, all other seams are limited in extent to a few thousand square miles or less. The seams or multiple splits which have the same name such as Lower Kittanning or Upper Freeport throughout the northern fields represent coals occurring at about the same stratigraphic location, but are not continuous seams.

2.4.1.2 Sulfur Content

High sulfur content in the northern fields often makes the coal uneconomical. Since most of the coal is cokable, this sulfur content is important. The sulfur content generally ranges from low values averaging around 1.5 percent sulfur near the hinge line and low values in Somerset County, Pennsylvania, to higher values to the west and northwest (over 3 percent). Locally, sulfur content is known to increase as the coals increase in age (depth).

2.4.1.3 Washouts and Interfingering

Upper Paleozoic rivers and streams have cut many of the coals of the northern field. Although some of the larger washouts are well studied, the smaller washouts must be located because of their effects on mine design. Interfingering or facies changes which occur during sedimentation can lead to differential compaction between two rock types and cause slickensides and breakage of the more brittle members, sometimes causing severe roof conditions.

2.4.1.4 Other Characteristics

Other characteristics of the northern fields are:

- The coal rank which ranges from high volatile in the north and west changing to low-volatile coal in Cambria and Somerset counties, Pennsylvania.

- Variation of Btu content - Cambria and Somerset counties generally contain coal with a high Btu content, averaging around 15,800 Btu/lb to lower than 12,000 Btu/lb in western West Virginia and Ohio.

- Coking properties which vary from 5 to 9 free-swelling index and 6.5 to 11.0 agglutinating.

- Coal has minimum ash values near 4 percent with values increasing from under 6 percent near the hinge line to 12 or more percent in Ohio. Ash content is usually higher for seams below the Lower Kittanning.

- Dips which are typically about 1 to 3 degrees but may be as high as 8 degrees. Dips of 30 degrees are common in the Broad Top Field.

- Faulting, which is significant in Cambria, Clearfield, Clinton and Centre counties, Pennsylvania.

The basins of northern Appalachia are fairly well understood. Information about the general geology, sedimentology and hydrology, and aerial photography are readily available. This reduces the task of exploration, and often there is borehole data already available to start a geostatistical analysis. Local details, however, are likely to be missing and geophysical techniques have important possible applications, particularly from boreholes to measure seam thickness and to estimate quality, but also from the surface to identify washouts, faults, and other structural problems.

2.4.2 Southern Appalachian Basin

The Southern Appalachian Basin is located in West Virginia below the hinge line, and in southwestern Virginia, eastern Kentucky, and eastern Tennessee. The area is often referred to as the Southern Field or low-sulfur field.

The Southern Appalachian Basin has marked differences from the northern fields which must be considered in exploration. Such problems are:

- Faulting
- Areal extent
- Correlation of seams
- Washouts
- Possible Mesozoic intrusives

2.4.2.1 Faulting

The Pine Mountain Thrust is the predominant fault and its effects must be understood in reserve calculation. This fault is in southeastern Kentucky, northern Tennessee, and Virginia. The southeastern edge of the coal field is bounded by a series of thrust faults, and faulting in Tennessee often will determine the size of the mine block.

2.4.2.2 Correlation

Seams are not as continuous as in the northern fields. About 60 economical seams are known to exist and there are many more uneconomical and unnamed seams. This large number of seams, in the presence of faults and numerous small washouts and variations in thickness, makes correlation a monumental task, sometimes solvable only by seismic reflection surveys and geophysical logging.

2.4.2.3 Other Characteristics

Mesozoic igneous intrusions exist in the extreme eastern part of the field and could be good targets for magnetic surveys. Other noted characteristics of the southern fields are:

- Steeper slopes and more rugged topography than in the north.

- Low sulfur, usually below 1.5 percent.

- Low ash, usually below 8 percent.

- High Btu, usually above 13,500 Btu/lb.

- Low to medium volatile, with the low volatile coals concentrated in the extreme southwest region of West Virginia.

Although much information exists for the southern fields because of the greater geological complexity, there is a need to generate more data to obtain the same confidence as in the northern fields. Much of the needed data can be obtained through the application of geophysical techniques.

2.4.3 Illinois Basin

The Illinois Basin is located in Illinois, western Kentucky, and southeastern Indiana. The economically produceable coal is located in ten seams, but most production comes from the Herrin and Harrisburg-Springfield seam. Exploration in this basin is simplified because of the persistence and the consistent thickness of this seam.

The structural geology is also relatively simple with few faults and folds. Most folds are gentle and the seams are normally considered flat, rarely exceeding two percent grade. On the eastern and southern ends of the basins, dips can exceed 15 percent grade through the La Salle anticlinal belt on the east and the DuQuain monocline and the Cottage Grene fault system on the south.

Other faults having effects on mining are concentrated in the southern parts of the basin and include Rought Creek fault system, Flourspar Are fault complex, Shawneetown fault, and the Wabash Valley fault system.

Most coals outcrop at basin boundaries with the coal dipping to the basin center while near Wayne and Clay counties the Herrin coal is over 1300 feet (400 meters) deep.

Coal thickness is fairly constant with the thickest coals in an area referred to as "Quality Circle." The "Quality Circle" is located in and around Franklin and Williamson Counties, Illinois, and displays Herrin coal thickness to be near 14 feet (4.3 meters).

Quality, especially as determined by sulfur content, plays a major role in marketability and thus exploration. The coal of this basin is not generally the quality of the coals of the Appalachian basins. The Illinois Basin contains a high volatile coal with high volatile A located in the southern parts of the field, grading to high volatile C in the northern, northeastern, and western parts of the basin. There is some proof that with increased depth of the coals there is increased rank.

Sulfur content, mostly pyritic, ranges from less than 1 to 2 percent in the "Quality Circle" to a basin average between 3 and 5 percent. It has been noted that sulfur content is correlated to roof strata. If these strata are nonmarine and thick (20 feet), the coal will have a low sulfur content (<1.5 percent), while coal will have a relatively high sulfur content (3 to 5 percent) if marine sediments make up the roof rock. The "Quality Circle" has nonmarine strata as its roof rock.

Large channels cut the coal resulting in substantial areas of no coal. However, most of these channels have been defined in the Herrin and other seams. Knowledge of the location of these channels is important to mine planning and production as channel-related problems such as poor mine roof conditions and loss of reserves can be anticipated and accounted for in planning the mine layout.

Btu values follow the same pattern as rank with high values in the southeast (near 15,000 Btu/lb) to low values in the northwest (near 11,000 Btu/lb) and also appear to increase with depth.

2.4.4 Powder River Basin

The Powder River Basin covers 20,000 square miles (50,000 square kilometers) of Wyoming and southeastern Montana and is a north-northwest trending, broad, asymmetric syncline. The basin is separated from the Williston Basin by the Miles City Arch, although this division is often placed at the Cedar Ridge Anticline. Coal covers over 10,000 square miles (25,000 square kilometers) of the basin in Upper Cretaceous and Tertiary Age strata. Coal varies in dip from zero to three degrees except for the very western parts of the basin where dips are up to 25 degrees. Faulting is concentrated in the western end of the basin, mostly in Johnson County, Wyoming. Faults are rare in the rest of the basin and when they do occur, they usually show vertical displacement and generally strike northeast-southwest. Up to 400 feet (120 meters) of displacement has been noted on some faults.

Coal thickness varies from zero to over 100 feet (30 meters) with the thickest coal sequence in the Wyodok-Anderson coal region in Sheriden County, Wyoming where seam thicknesses over 50 feet (15 meters) are common.

Seam correlation, burn areas, and coal quality will offer major problems to the exploration staff. Correlation over 50 miles (80 kilometers) is uncommon and is seldom well documented and any correlation across the basin or between fields is an educated guess and should be looked on as such. Burns, mostly located at outcrops, have destroyed some reserves, especially on the eastern side of the basin. These burns must be defined for accurate reserve estimate and optimal mine design. Aerial photographic mapping of reddish soil associated with clinker along with aeromagnetic surveys offer a rapid methodology for regional mapping of burn zones. Magnetic mapping has been shown to provide better resolution of the margins of the burn facies than conventional aerial photographic interpretation and surficial mapping. Rank varies from lignite in the northeast corner to subbituminous through the rest of the reserve. Rank increases towards the basin center and increases with the depth and age of the coal.

Estimates of sulfur content are aided because sulfur content can be correlated with marine, nonmarine depositional history. The sulfur content is mostly organic and highest in the Cretaceous coals, but still low by national standards (usually below one percent). Ash also is dependent on depositional history, depending on the influx of inorganic debris into the basin.

2.4.5 Uinta Region

The Uinta Region covers west-central Colorado and east-central Utah. Generalization about this region on matters such as rank, topography, quality, and tectonic setting cannot normally be made since the coal region is complicated and poorly explored. Tectonically, the region covers the following units: Uinta Uplift, Uinta Basin, Wasatach Plateau, Douglas Arch and the Piceance Basin. This complicated tectonic setting results in areas of steeply dipping seams, some of which are vertical. Mining regularly takes place on dips up to 30 degrees.

The coal seams in this region are lenticular in shape and there may be 20 or more minable seams in one field. Coal varies in thickness with some seams exceeding 20 feet (6 meters) in thickness (Rio Blanco County, Colorado). Although most of the economical coals are from the Mesaverde Group, the seams have not been adequately correlated and correlation is considered to be extremely difficult in the region.

Volcanics and igneous intrusives also present problems, especially in the southeastern parts of the region where Tertiary age sills, dikes, and laccoliths along with associated faults and folds have been identified. The Tertiary West Elk volcanic fields cover the very southeastern end of the region. Faults are common but are fairly well spaced for mine operations. The east side of the region is associated with the Overthrust Belt and normal faulting.

Overburden also presents problems of exploration costs and determinations of reserve size. The dip around the basin is such that coal fields may be limited to only a few miles around the basin edges. Significant coal reserves are known to exist below 3000 feet of overburden.

Quality is also not clearly associated with any pattern in the fields and rank varies from subbituminous A and B, associated with some of the edges of the basins, to anthracite, associated with intrusives in the southern end of the region. Large bituminous, high-volatile A, B and C bituminous, semianthracite and natural coke also exist and are being produced. High resin (6 to 8 percent) coals are also present on the Wasatch Plateau area of Utah, which are suitable for the binder industry. Large burn areas at many outcrops have eliminated large reserves in the region.

The lack of exploration, rugged terrain, high altitude (much of the field is over 10,000 feet in elevation) and remoteness offers additional challenges to the exploration staff.

There is no typical mine in this region and many of the mines are one of a kind. Innovative mining techniques have to be developed to survive in these differing geologic environments. As a result, the exploration staff must put an extra effort in communicating with the mine design staff so that necessary additional and nonconventional data will be gathered. One such example of nonconventional data would be water inflow, which has proven to be a problem in the region.

FIGURE

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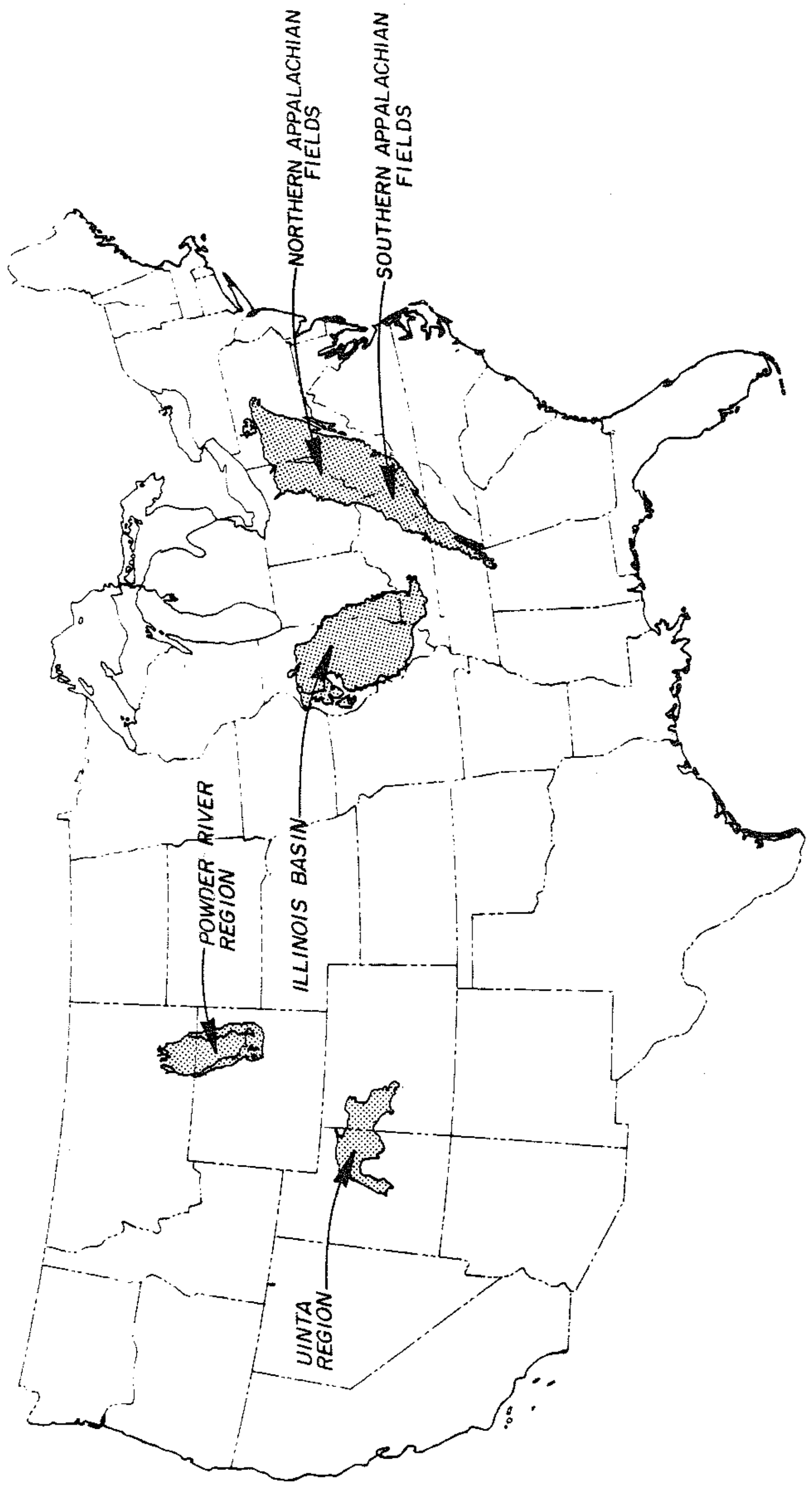

FIGURE 2-1

COAL BASINS CITED AS EXAMPLES IN TEXT

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3.0 INTRODUCTION TO GEOPHYSICAL AND DRILLING TECHNOLOGY

This chapter reviews the basic principles and procedures used in applying geophysical and drilling technology to coal. Appendices B through H describe specific geophysical techniques in greater detail.

3.1 GEOPHYSICAL TECHNOLOGY

Geophysical technology is simply a means to observe physical characteristics of the earth. As opposed to more conventional measurement or observational techniques, most geophysical techniques do not require direct physical access to the feature being characterized. The principal alternative requires drilling or excavating to the zone of interest to either remove a physical sample (e.g., a core) for surface laboratory analysis, or to gain access for personal inspection and measurement (e.g., via a drift). The ability to characterize features without direct access forms the substance of the advantages that geophysics can have over direct observation methods.

Direct observation is costly due to the expense of either retrieving the sample or gaining personal access. Additionally, the cored or excavated volume defines the limits of the extent of observation. In compensation, one normally feels confident in the observations due in part to the normal human emotion "If you can see it, you can believe it." Geophysics generally "samples" or characterizes a volume or plane in the subsurface. The observation can be direct, but more commonly the geophysicist observes anomalies or relative changes in response. Techniques are normally set up so that a continuum of measurements results which presents a profile of data which heightens perception of overall conditions and increases the ability to recognize anomalous conditions. This advantage is offset by the general decrease in resolution (or accuracy) with distance and uncertainty in interpretation. This latter characteristic is essential to the understanding of geophysical intepretation.

Geophysics can be applied in the direct sense that one uses a ruler to measure distance or a thermometer to measure temperature. This type of application, while very useful, is only a small part of the essence of geophysics. Chapter 2.0 purposefully outlined data required for the exploration and planning of a coal mine. This chapter will show on a generic basis how basic geophysical principles can be manipulated to acquire the needed data. The key word is manipulated because rarely can geophysics measure directly the exact property needed. For example, there are no geophysical "Btu Meters" or "Ashmeters" or "Geologic Fault Detectors." There exists, however, an impressive array of properties of the subsurface which, if characterized appropriately, can be interpreted into the desired information.

3.1.1 Fundamental Concepts

The generic principals of geophysics can be described by using examples of phenomena that form the physical bases for a geophysical technology. These bases include:

- Seismic wave propagation
- Electrical resistivity
- Magnetic attraction
- Electromagnetic propagation
- Gravimetric attraction

For these purposes, seismic propagation and specifically the seismic reflection technique have been used to illustrate the generic aspects of geophysical technology. For a more complete discussion of seismic reflection technology, refer to Appendix B.

A seismic or vibratory disturbance initiated in the earth propagates by several means. The geophysicist can measure attributes of that propagation at one or more locations. Because, among other factors, the propagation is affected by the characteristics of the earth, it is possible to have some conceptual inference regarding properties distributed along the propagation path. One can wait for the earth itself to initiate seismic waves; however, this is inconvenient so a source of seismic energy is developed that can be located and used to best suit the problem to be investigated. Armed with a source and a means of detecting seismic waves, the geophysicist has a system which can introduce energy into the ground at one point and receive it at another. The development of a mature technology involves several generic steps which are highly interrelated. These include:

- Develop the understanding of the physics of the system.
- Develop the analytical ("mathematical") ability to translate measurements into data.
- Develop the understanding which relates geophysical data to appropriate mining data.
- Develop confidence in the data.

The principal impetus to development comes from the mining industry and the authors suspect that the greater the awareness of geophysical capability there is, the greater will be the communication of encouragement to be inventive or undertake research and development. If there is a need or a potential market, someone will fill it. Active and effective communication between the geophysicist and the remainder of the mining team can focus on capabilities and needs. Over time, this process has led to the present state of the art.

In the discussions between geophysicists and the remainder of the mining team, four of the more frequent important questions or concepts which repeatedly appear involve: Can you measure it; what is the interpretation certainty; coverage; and resolution? Each will be briefly discussed in turn.

Can you measure it? - Most often, geophysics cannot directly measure the data required. Measurement of such properties as pressure, temperature, and similar conditions are straightforward. The determination of properties such as seismic velocity or density requires calculations involving assumptions or measurement of multiple parameters. To answer the question - Can you determine the depth of a coal seam? - requires several steps. Seismic reflection measures it by the following (somewhat simplified) method:

- When an elastic wave is induced in the ground, its propagation through the subsurface is governed by the distribution of subsurface properties.
- Two properties of a coal seam which exert major control on elastic wave propagation normally differ greatly from the surrounding rock. The density and seismic velocity of coal are less than that of the other rock, leading to a phenomenon called reflection. Some of the energy incident on the coal-rock interface (that which is sought) is reflected. Thus, by manipulating the geometric arrangement of a suitable source and receiver network, this interface can be detected. The time taken for the seismic energy to complete the path from source to receiver via reflection of the coal is recorded. At this point in the simplified discussion, the geophysicist could reply--yes, we can say there is probably coal beneath our feet.
- The geometry of the application of this technique, which is under the control of the geophysicist, can be manipulated to determine one more piece of information--the distribution of rock velocities. Multiplying velocity by time yields distance (in this case, depth); so at this stage, the response to the opening question becomes--yes, we can identify the presence of and measure the depth to a coal seam.

The foregoing has been a purposefully drawn-out description of a well known and developed technology to emphasize that the measurement is far from direct. Prudence would suggest that when several sequential steps involving multiple phenomna are required, there is a question of certainty.

Interpretation Certainty - The above discussion on the determination of depth of coal presumed that one could uniquely distinguish the coal seam reflection from the other reflections recorded. The geophysicist interprets the presence of coal by one or a combination of characteristics. Although not absolute, the diagnosis of a particular reflection as coal is relatively certain. There are other geologic situations, however, which could lead to a reflection that looks like coal. The more lines of evidence available, especially if they are independent, the greater the certainty in interpretation. If the seismic determination was made at the location of a borehole where core or a geophysical log was available, then not only would the identification of the seam be confirmed, but, additionally, the depth would be "calibrated." One may logically inquire--If I need the borehole to confirm the geophysics, why do the geophysics? The answer lies in the increased coverage that the geophysics can provide.

Coverage - A borehole can precisely identify and determine the depth to a coal seam. The data are certain, but strictly limited to that specific location. A particular strength of geophysics is that, depending on the particular type (e.g., gravity, seismic, etc.) and form of measurement, data can be obtained over a line, plane, or volume. A more complete discussion may be found in Section 3.0 of the UCG Reactor Definition Instrumentation Manual (Salotti, et al., 1980). As will be illustrated later, if more lateral information is desired, seismic reflection may be highly appropriate and cost effective. Because the basic seismic reflection method can provide 2-D or 3-D representations of the subsurface, the true power of seismic reflection method emerges. Figure 3-1 illustrates in cartoon form typical exploration problems. One-dimensional well data could be a very inefficient means of mapping sand channels (as shown in Figure 3-2) or faults (as shown in Figure 3-3). The seismic section essentially gives you a "borehole equivalent" at every CDP point with a spacing between 20 and 200 feet depending on the survey. Thus far, the ability of geophysics to provide some answers has been discussed, but a new question arises--how well?

Resolution - Resolution is the ability to discriminate a specific target from surrounding material. For example, if the top and bottom of a coal seam can be detected seismically and a depth calculated for each, the thickness can be determined. Resolution is a measure of how well this can be done. As a general rule, the farther removed from the sensor the feature to be resolved lies, the less it can be resolved. There is no physical basis which makes this statement an absolute certainty, but as the limit is one of practicality, resolution can be increased by improvements in technique, hardware, and analysis/software. A substantial portion of geophysical R&D is undertaken to make increased resolution more practical. Because it is such a central topic to this effort, the following paragraphs will expand on the topic of resolution using an example.

An example of the problems of gaining greater resolution is routinely faced in the seismic reflection technique. Farr and Peace (1979)

discuss resolvable bed thickness in terms of the predominant seismic wavelength in the coal, which is derived from the coal velocity and the predominant reflection frequency. These authors note that coal beds as thin as one-twelfth wavelength can be detected, but resolution of the top and bottom of the seam requires that the seam be at least one-eighth or in the worst case one-fourth of the predominant wavelength thick. For a typical coal, one meter thick, a predominant seismic wavelength responding to a predominant wavelet frequency in excess of 200 Hertz would be required to resolve the thickness of the coal (Figure B-2 in Appendix B).

From the above discussion, it is apparent that higher frequencies and signal-to-noise ratios (S/N) both tend to improve resolution. Several components of the seismic reflection technique directly bear on resolution: the source, the receiver, the geometry, and the processing. Higher frequencies are attenuated more severely than lower frequencies (Figure B-3 in Appendix B.) If this attenuation lowers the S/N to uninterpretable levels, the frequency must be lowered and/or the source energy increased.[1]

With regard to sources, if dynamite for example is selected, there are subsequent choices to be made regarding placement number and the size of charge(s). To illustrate the conflicts, it is sufficient to regard the size alone. The following characteristics of the explosive pulse depend on the mass, M, of the charge (Ziolkowski and Lerwill, 1979) as indicated below:

- Duration is proportional to $M^{1/2}$
- Amplitude is proportional to $M^{1/2}$
- Absolute spectral bandwidth is inversely proportional to $M^{1/3}$
- Amplitude of the spectrum is proportional to $M^{2/3}$

Use of small charge sizes shifts the spectrum of seismic energy towards higher frequencies but preserves the signal bandwidth (in octaves). The lowering of amplitudes decreases the depth to which usable signals can be recorded because the decreased amplitude diminishes the S/N. The geophysicist must carefully examine exploration objectives to tailor the field technique, using available technology to achieve the best possible resolution, given constraints of budget and the earth. The restrictions

(1) Note that this discussion is somewhat simplified. The interested reader is referred to Anstey, 1980; Ziolkowski and Lerwill, 1979; and Farr and Peace, 1979, for excellent detailed technical discussions.

of these limits can be eased by a tailored design of the survey to fit the objectives and earth conditions. Presurvey testing is an extremely important part of that effort.

The R&D effort normally addresses either or both of two aspects:

- Improving technical performance.
- Making existing technical performance easier, faster, cheaper, or more dependable.

To this list, confidence-building may be added. In a seismic survey, literally billions of digital data bits are recorded, processed, and presented graphically for display, but the confirmation or refutation of the interpretation may be years away, resulting in little positive feedback into the interpretation process.

3.1.2 Geophysical Techniques

This section provides descriptions and applications of the main geophysical techniques which can be used from the surface or underground for coal exploration/characterization. Geophysical techniques as applied from boreholes are discussed in Section 3.2. The methods can be categorized as follows in terms of the physical property which they measure:

- Velocity (seismic, acoustic)
  - high resolution seismic reflection
  - seam wave seismics (transmission and reflection)
  - seismic refraction
- Electromagnetic
  - radar
  - active and passive EM
- Potential Field
  - gravity
  - magnetics
- Electrical
  - resistivity
  - spontaneous potential
  - induced polarization

The theory, implementation, interpretation, and current research for the most important techniques are presented in Appendices B though G. The following sections summarize the basic concepts and applications of the methods. The main applications and limitations of the geophysical techniques are tabulated in Figure 3-4.

3.1.2.1 High Resolution Seismic Reflection

The fundamental concepts of the high resolution seismic reflection technique are discussed in Section 3.1.1 and in greater detail in Appendix B. In essence, the method consists of measuring the travel time required for a compressional wave generated by an explosive or vibratory source in the earth to travel to and from a subsurface reflector. Coal is usually an excellent seismic reflector due to the large difference in acoustic properties in comparison with the strata that normally bound the coal.

The seismic reflection technique as applied to coal is referred to as "high resolution" because the traditional use of this method for oil and gas exploration is to identify deep geologic structure, at depths of thousands of feet, whereas coal applications require information usually from the first few hundred feet. The low frequency records obtained for oil and gas exploration often do not resolve the strata within the first few hundred feet, so the identification of shallow strata requires variations in shooting and recording procedures to provide a high resolution.

Provided that physical conditions (coal thickness, reflection coefficient of seam and depth, discussed further in Appendix B) allow for the coal to be a measurable reflector, a number of important characteristics can be identified from a high resolution survey:

- Gross coal structure and number of seams
- Local disturbances to the reflection that can be interpreted to affect the coal (faults, pinch-outs, sand channels)
- Relative variations in seam thickness--presence of roof rolls and horsebacks
- Abandoned workings--particularly if they are air filled

Highly detailed profiles have been able to detect other parameters, including:

- Coal seam thickness
- Variations in lithology of roof rock
- Lithologic variations within the coal, e.g., shale partings

The last three characteristics have been determined in only a few instances under the most favorable conditions and where a major effort was made to achieve the highest possible resolution.

A number of factors can inhibit or prevent the mapping of a coal seam with the high resolution technique. These include:

- High dip angle of reflecting surfaces
- Presence of low velocity surficial material of variable depth
- Presence of strong reflectors above the coal, including other coal seams
- Presence of abandoned workings above the coal

In most cases, careful planning and modifications of recording procedures and/or processing can reduce the impact of any adverse conditions, but in some areas conditions may be so severe so as to make it impractical to obtain useful results.

The use of the high resolution seismic reflection technique is routine in countries such as the United Kingdom and the Federal Republic of Germany and it is in these countries where much of the research and development of the technique for coal has been conducted. Experience at the British National Coal Board (NCB) with seismic profiles (two-dimensional surveys) has demonstrated several modifications to the conventional oil and gas exploration type of seismic reflection profiling to achieve the high resolution necessary for coal work (Ziolkowski and Lerwill, 1979):

- Scaling down of the explosive charge size and using single geophones instead of groups
- Scaling down the sampling interval in time and space
- Use of deep shot holes and, where possible, deep transducers to reduce the effect of near surface layers

The use of these procedures in the U.K. has allowed for the obtaining of useful results in all but a few cases. The goal of British surveys typically is to characterize coal seams at a depth of about 2,000 feet (600 meters), where the natural filtering effects of the earth preclude the need for following data acquisition procedures to obtain the highest possible resolution. As U.S. coals are typically mined at shallower depths than in the U.K., increased resolution can be obtained, but at a higher cost.

The complex tectonic setting of coal in the Federal Republic of Germany has forced the development of more sophisticated recording and processing techniques to unravel the structural setting of the coal. The technique of three-dimensional or areal surveying now constitutes more than

70 percent of the surface seismic surveys in that country. An example of the results of this type of surveying (Figure B-9 in Appendix B) illustrates the power of this method to resolve complex tectonic structure. A drawback to the three-dimensional method is that the redundant coverage inherent in the technique tends to reduce resolution and this must be weighed against the advantages of obtaining improved structural information.

In the U.S., the trend is towards an increased use of two-dimensional profiles, but the technique is not yet a standard operating procedure. A three-dimensional survey over a coal prospect in the U.S. has been completed under the direction of the USBM Denver Research Center. This experiment was designed to delineate abandoned workings and the results are promising. Another example is provided by Dobecki (1981) for the detection of shallow sand channels in a shale host rock in Utah for the purpose of identifying tight gas sands. Although the example is not directly related to coal, the width and depth of the sand channels (400 feet and 300 to 700 feet, respectively) is comparable to a coal exploration target. A ten-foot-thick coal seam was observable beneath the sand channels. Although unconfirmable, some proprietary 3-D surveys for coal have been performed in the U.S.

Based on interviews with different seismic contractors, a total of 14 firms were found to have experience performing high resolution surveys for coal in the U.S., representing a combined total experience of roughly 100 surveys. The number of published case histories is negligible because of the proprietary nature of the surveys. Nearly all of the surveys were conducted for oil companies that also have coal mining interests.

U.S. contractors report using a wide range of specifications for coal surveys. Some indicate that their surveys were run with enough resolution to detect and determine the continuity of the coal seam, but that no effort was made to obtain the highest possible resolution. Other contractors indicate that their surveys have been conducted with the goal of determining the highest possible resolution and that it has been possible to have records with a predominant wave frequency in excess of 500 Hertz where coal thickness could be determined adequately for seams a few hundred feet deep.

The wide variations in procedures followed in the U.S. naturally result in a significant variation of costs per mile and rate of production. The highest resolution obtainable could cost as much as $20,000 per mile with production rates as low as 1/4 mile per day (ten-foot transducer spacing). For surveys where the highest possible resolution was not a requirement, contractors have claimed as little as $2,000 per mile with a production rate of 2-1/2 miles per day. The range of prices and production rates clearly indicates that the coal operator must have a clear idea of what resolution he requires and how to specify recording and processing parameters to achieve that resolution. It is not sufficient to specify that a high resolution seismic survey be performed because different contractors will have widely different criteria to fit their definition of high resolution. The NCB in the United Kingdom faced the problem of widely varying quality of their seismic lines when such surveys were first performed because contractors did not adhere to a common set of specifications. Useful results were obtained only when the NCB hired their own geophysicists to make detailed specifications consistent with what information was required at each mine site (Ziolkowski, 1981).

3.1.2.2 Seam Wave Seismics (Transmission and Reflection)

Seam waves, also known as channel or guided waves, are seismic waves which are "trapped" within a coal seam and can thus propagate over relatively large distances with little attenuation. They are a phenomenon most commonly associated with coal, because it is the relatively low velocity and density of the coal with respect to adjacent strata which allows the seam wave to be generated. Accordingly, seam wave technology has been developed strictly for coal characterization and is not a technique borrowed or adapted from the oil or mineral exploration industry. The theory of seam wave generation is complex and is treated in greater detail in Appendix C.

Seam wave measurements are normally conducted along the working face of a mine in order to identify discontinuities such as faults, pinchouts, sand channels, or abandoned workings within the coal seam to be mined. The method can also be deployed between boreholes to determine coal continuity. When used between two boreholes, the seam wave seismic technique is one of analyzing the transmission of a seam wave and if conditions are favorable, the interpretation could be simply that of determining whether a seam wave has been transmitted and received. If a seam wave has been transmitted from one point to another, then the coal is continuous between the two points. Assuming that conditions are such that a seam wave can be generated, the absence of a seam wave indicates that a discontinuity is present. Transmission between two points does not allow for determining the location of a discontinuity, but transmission between many points can allow for a certain degree of resolution. The range of transmission surveys is several kilometers (Arnetzl, 1971), but borehole-to-borehole transmissions have been successful only to a range of a few hundred meters.

In-mine transmission studies can allow for the spatial resolution of discontinuities, if the mine openings are favorably located so that numerous transmission and receiver points can be established. Such conditions commonly exist where mines are developed using an advancing longwall technique, as is typical in the United Kingdom or other areas of Europe. The plotting of raypaths and noting which paths permit wave transmission and which ones do not, is a simple way to spatially define discontinuities with little or no processing of the data (Figure C-7 in Appendix C). Sophisticated processing methods have also been applied to seam wave transmission data to determine the seam wave velocity field which can be shown to be related to stresses within the coal (Figure C-8 in Appendix C).

A favorable location of mine openings for transmission studies is less likely to occur if retreat rather than advancing longwall mining is followed, and would be very unlikely to occur in the case of room-and-pillar mining. In such cases, discontinuities can be identified by analysis of seam wave reflections. The seam wave reflection technique allows for a greater resolution of discontinuities than can be achieved with the transmission method and offers the advantage that the shot point and receiver can be located along a single mine face.

The seam wave reflection technique can be considered as analogous to surface seismic reflection measurements, but where the seam waves are confined essentially to two dimensions. However, certain characteristics of seam waves and seam wave reflectors complicate their interpretation, such as:

- Seam waves are dispersive, i.e., different frequency components travel at different velocities. Because the seam wave is spread out in time, it is difficult to obtain an accurate estimate of wave arrival time.
- There are two basic types of seam waves and each possesses a family of modes of different predominant frequencies. These different waves are dispersed and it is difficult to separate them.
- The reflection off of a discontinuity may not be of the same mode as the incident wave, i.e., may be of a different predominant frequency and return with a different velocity than the incident wave. In the case where a discontinuity does not cut the coal seam, some frequencies may pass the discontinuity, while others are reflected.
- Reflectors may occur at any angle to the strike of the geophone array.
- The amount of data available for processing is usually very limited in comparison to surface data, as ideal shot and geophone placements are not always possible.

The difficulties of seam wave reflection analysis have been handled in the United Kingdom and Federal Republic of Germany through the development of sophisticated processing techniques specifically for seam waves, as discussed in Appendix C. The interpretation of seam wave reflections has proved to be successful. The NCB in the United Kingdom reports that seam wave reflections have successfully defined fault structures at distances ranging from 60 to 500 meters from the mine face (Buchanan, et al., 1980), similar to results reported from the Federal Republic.

of Germany (Millahn and Marschall, 1980). An example of the results of a seam wave reflection survey is provided in Figure C-9 in Appendix C).

The use of the seam wave seismic technique in the U.S. is negligible, with most of the work experimental and conducted from boreholes. Studies have shown that U.S. coal seams can serve as good guides for seam waves, but the technology is not being exploited. Part of the reason is that the mechanized mining systems in use in Europe require more detailed information with regard to coal discontinuities than in the U.S., where the tendency has long been to "mine around" any problems encountered. This attitude will likely change as increased use is made of mechanized mining systems in the U.S. At the present time, mine-certified instruments and sources still need to be developed. In addition, data processing techniques to interpret seam wave reflections have not been developed, or at least are not commercially available in the U.S.

3.1.2.3 Seismic Refraction

The seismic refraction method consists of measuring the travel times of compressional waves between an impulsive source at or near the surface and a surface receiver for several different source/receiver spacings. The raw data consists of travel times and distances which are processed to determine subsurface velocity distribution.

The seismic wave of interest in a refraction survey is the first arrival which may be of two different types:

- The direct wave
- The critically refracted wave

The direct wave travels through the near-surface layer along the shortest path between the source and receiver, while the critically refracted wave travels along layer boundaries where the lower layer has an appreciably higher velocity than the upper layer. The type of wave which arrives first is determined by the subsurface velocity distribution and the source-receiver spacing.

For subsurface configurations that can be represented by a sequence of horizontal layers whose velocity increases appreciably with depth, the first arrival for small source-receiver spacings will be a direct wave through the uppermost layer. As the source-receiver spacing is increased, the first arrival will be a critically refracted wave from the boundary of the first and second layer with an observed velocity equal to the velocity of the second layer. For greater spacings, the first arrival will be a critically refracted wave from deeper layer boundaries and the observed velocity will be that of the lower, high-velocity layer. The systematic change of travel time with source-receiver offset is characteristic of subsurface velocity distribution within the limitations of the seismic refraction technique.

A low velocity layer, such as coal, cannot be detected by the refraction technique because the incident wave is refracted downward instead of toward the surface. Because such a layer cannot be detected by the refraction technique, its thickness will not be accounted for, resulting in erroneous depths for all layers beneath it. Consequently, this method has a very low potential for coal exploration/characterization and is not discussed in greater detail in an appendix.

Where the seismic refraction technique has application, however, is in determining the thickness and velocity of surficial soil. This is very important in the static correction for the high resolution seismic reflection technique. Also, knowledge of overburden thickness and velocity is important in surface mining, as the results can be interpreted in terms of the rippability of the overburden.

Although the detection of a coal seam by means of seismic refraction requires that the overlying material be of a lower velocity than the coal, there are a few areas, such as in the Powder River Basin, where this is the case and refraction measurements have successfully traced the top of the coal. Also, where near-surface coal seams are very thick (about 20 meters or more) a second refraction has been observed from the bottom of the coal (J. Cooksley, Cooksley Geophysics, Inc., personal communication, July, 1981).

3.1.2.4 Radar

The radar technique, in the traditional sense, is the location of an object by means of transmitting electromagnetic radio waves and spatially locating reflections of the waves. As applied to coal mining problems, the technique can be extended to three fundamental variations:

- Pulse radar reflection--this technique is closest to the traditional definition of radar, in that the method consists of measuring the travel time for a high frequency electromagnetic wave (15 to 200 megahertz), generated by a pulser and antenna unit to return to the antenna after reflection from an interface between materials with different electromagnetic properties. Radar reflections can be interpreted in a manner similar to seismic reflections, except that travel times are measured in terms of nanoseconds, rather than tenths of a second.

- Frequency modulated-continuous wave (FM-CW) technique--this technique also detects and determines the distance to electromagnetic interfaces, but measures the phase shift between the transmitted and reflected signal to determine the distance to the interface.

- High frequency electromagnetic (HFEM) technique--with this method the transmitter and receiver antennas are located in different positions within a mine or in different boreholes. The travel time, amplitude, and phase of the received signal are analyzed to determine the electromagnetic properties of the material in between.

The HFEM technique has limited usefulness for coal exploration/characterization, except for providing velocity data which can be useful in the interpretation of pulse radar reflection records. Accordingly, the main applications and limitations of the radar technique refer to pulse radar reflection and FM-CW systems.

The main applications of the radar technique include the detection of voids (abandoned workings), abandoned wells, channel sands, faults, seam pinchouts, clay veins, and pyrite and sulfur balls within the seam. The resolution of reflections within a coal seam is limited to about 50 feet (15 meters) with present-day technology, but this limit is expanding as new equipment is being developed. Most of the radar reflection work is done with pulse radar systems. From a theoretical standpoint, FM-CW systems are equivalent in terms of resolution, but FM-CW hardware has been directed primarily to short penetrations with high resolution, usually with the goal of determining the thickness of coal in the roof after the passing of a continuous miner.

The theory of electromagnetic wave propagation is complex and is discussed in Appendix D, but in simple terms, anything which has an electrical conductivity or dialectric constant which differs significantly from the surrounding materials can reflect radar waves. Fractures and other strata discontinuities will generally be seen as reflectors. The main limitation of identifying radar reflections is signal attenuation. In highly resistive homogeneous rock, such as salt, radar penetrations of thousands of meters can be achieved. Dry, igneous rock is also highly transparent to radar waves. Low resistivity material, however, severely attenuates radar signals with only a few meters of penetration possible in a wet clay. Pulse frequency is also important as lower frequency signals are attenuated less than high frequency pulses, but resolution is less. The source frequency is then a compromise between resolution and depth of penetration, with most work in earth done in the frequency range of 50 to 500 MHz.

As coal generally has a higher electrical resistivity than other rocks in a coal sequence, radar penetration is generally fairly good, but decreases rapidly as moisture content increases. The presence of relatively conductive materials such as pyrite or sulfur balls can also greatly increase attenuation. The effective range of a pulse radar system is about 50 feet (15 meters), but recently transmissions over distances of 200 feet (61 meters) have been recorded with a new prototype radar unit known as the synthetic pulse system (Fowler and Hale, 1980). This implies that reflections could be obtained at a range of

100 feet (30 meters) and Fowler and Hale indicate their belief that eventually the range could be double this distance.

Most of the research and development of radar systems has taken place in the United States and European countries are only just beginning development of radar equipment for coal. Research under the auspices of the U.S. Bureau of Mines is being conducted by Xadar Corporation of Springfield, Virginia for the continued improvement of the pulse radar reflection technique including the development of the prototype synthetic pulse system. A pulse radar system designed for use in a coal mine is available from Xadar. As this equipment records digitially, reflections can be recorded and processed in a manner similar to seismic reflection data, allowing for increased resolution of discontinuities (Figure D-2 in Appendix D).

Another recent development has been the manufacture of a prototype borehole radar probe at Southwest Research Institute, which has an effective range of about 50 feet (15 meters) and an angular resolution of about 30 degrees azimuth. This directional probe offers great potential for void detection, but its short range may limit its usefulness in coal mine work. FM-CW equipment has been developed at both the National Bureau of Standards and Southwest Research Institute for use in determining the thickness of roof coal. While the technique usually did determine roof coal thickness, problems of interpetation occurred due to the presence of sulfur, shale lenses, and other dialectric discontinuities.

The most powerful application of the radar technique is the use of a pulse radar system to "see" in advance of the working face. Although commercial equipment is available, the overall level of use of the method is low. The main difficulty is that current equipment does not penetrate more than at most a few working days ahead of the mine face and its application has been primarily to resolve specific problems which were known to exist or were encountered during mining, such as the location of abandoned wells. As instrumentation and effective range improve, it is likely that future applications will increase.

3.1.2.5 Other Electromagnetic Techniques

A number of deep probing electromagnetic techiques have been developed for the mineral industry which use the measurement of spatial and temporal variations in the electric field (E-field) and magnetic field (H-field) at the surface to infer the subsurface distribution of resistivity. The main methods are the following:

- Telluric
- MT (magnetotelluric)
- AFMAG (audio frequency magnetic)
- EM (electromagnetic)
- TDEM (time domain electromagnetic)

Naturally occurring variations in the E- and H-fields, due to causes such as lightning, are used by the telluric, MT, and AFMAG techniques, which thus use passive measurements. The EM and TDEM techniques utilize active sources.

All of the techniques are designed to detect variations in earth electrical resistivity and are particularly sensitive to chemical changes and changes in pore (ground) water distribution and chemistry. Their main application is the search for conductive bodies which may indicate the presence of metallic ore and for this reason all equipment for surface arrays exists in commercial form. Processing, although complex, can be automated to give quasi-real time data displays.

None of these EM techniques has had any significant application to problems of coal exploration/characterization, although in theory they should be able to perform the functions of a direct current electrical resistivity survey, discussed in Section 3.1.2.7. However, these electromagnetic techniques are usually used for regional reconnaissance and do not have the resolution required for coal work. Accordingly, the methods are not detailed in an appendix. An electromagnetic system which has potential for detecting voids has been developed by Southwest Research Institute, but it does not appear to have the resolution of a direct current system also developed by that organization and discussed in Section 3.1.2.7.

3.1.2.6 Potential Field Methods (Magnetics and Gravity)

Potential field measurements are those of naturally occurring fields which decrease in intensity with increasing distance from the source. The earth's magnetic and gravity fields fit within this definition. Measurements of both magnetics and gravity respond to the overall fields of the earth itself, along with local variations due to near-surface inhomogeneities. The measurement of these local changes is the goal of both types of measurement. In the case of magnetics, the local variations of magnetic intensity can be modeled as subsurface changes in the magnetic susceptibility of the rock. Similarly, variations in the earth's gravity field can be interpreted in terms of near-surface rock density. Appendix E provides a more detailed discussion of the magnetic method, while additional information about the gravity technique is presented in Appendix F.

Both the magnetic and gravity methods have limited application to the exploration and characterization of coal deposits, but can be highly effective for specific problems. Specifically, magnetic methods are widely used to map clinker zones in shallow coal deposits. Another application is the delineation of igneous dikes which intrude coal seams at some localities. As coal has a low density compared with most other rocks, the gravity method can be effective in delineating coal cutoffs in thick, shallow seams. The gravity method has also been used successfully to map buried stream valleys which may cut near-surface coal or lignite deposits. Another possible use for both methods, applied

frequently in the United Kingdom, is the delineation of abandoned mine workings, especially vertical shafts.

The main application of the magnetic method is in the mapping of clinker deposits. The magnetization of rocks is strongly affected by temperatures associated with the burning of coal. Laboratory tests indicate that the baking and then cooling of sedimentary rock causes as much as a 6,000-fold increase in magnetization and that temperatures as low as 200°C. will cause the increase (Hasbrouck and Hadsell, 1976). Accordingly, burn zones are a good target for a magnetic survey and numerous case histories are available to demonstrate that magnetic surveys can offer a greater resolution of the extent of a burn zone than can be obtained by surface geological mapping. Examples are provided in Figures E-1 and E-2 of Appendix E. Aeromagnetic surveys (magnetic surveys conducted from an airplane) have been a standard reconnaissance tool for the mineral exploration industry since the 1940's, but it has been only recently that such surveys have been used in coal exploration. Friedberg and Crosby (1981) demonstrate that an aeromagnetic survey can quickly give an accurate regional picture of the distribution of clinker deposits. Their example from Kane County, Utah is provided in Figure E-3 in Appendix E.

While sedimentary rocks are not normally magnetic unless they are baked, igneous rocks, particularly basic igneous rocks such as basalt or lamprophyre dikes, typically contain significant amounts of ferromagnesian minerals, which also makes them a good target for a magnetic survey. The use of the magnetic method to map dikes in the western U.S. is discussed by Hasbrouck, et al. (1980). Current mapping of igneous dikes by the magnetic method is also being conducted in the southern Illinois Basin.

The use of the gravity method for mapping cutoffs in thick coal seams in the western U.S. and detection of buried stream channels is documented by Hasbrouck and Hadsell (1976, 1978) and examples are provided in Figures F-2 and F-3 in Appendix F. One of the most important recent advances, allowed by the development of highly sensitive gravimeters, is the use of high-precision gravity (microgravimetric) measurements for engineering applications, in particular the detection of voids. Butler (1980) provides a comprehensive discussion of the microgravimetric technique for numerous geotechnical applications and provides several case histories.

Gravity and magnetic measurements have long been used by the mineral industry as tools for regional geologic reconnaissance. The use of these methods together allows for the definition of the gross geologic structure of a coal basin in terms of areal extent, depth and fault control. Examples of such use are provided by Ball (1976) for western Canadian coal exploration and by Verma, et al. (1976) for a coal field in India.

Both gravity and magnetic measurements are limited by the ambiguity of modeling the subsurface to fit the observed data. While a given subsurface configuration will produce a unique data set, the converse is not true. Many models can be developed which will produce the same anomaly pattern and the validity of any interpretation must be evaluated in terms of consistency with other available information, as well as the observed anomalies. The gravity method is particularly sensitive to local density inhomogeneities which may obscure the true target, topographic effects which may not be adequately accounted for and elevation errors. The main difference between gravity and magnetic field measurements is the requirement of the gravity technique for precise leveling, as an error in elevation of a few centimeters could completely mask an anomaly in a microgravimetric survey. Magnetic surface detritus, such as iron objects, magnetite boulders in areas of glacial till, and nearby electrical transmission lines can limit the validity of magnetic measurements.

The gravity and magnetic techniques have been standard exploration tools for over 50 years and represent a mature technology. Their application to coal is limited, but for specific problems for shallow coal they can be highly effective. Both methods are fast and relatively inexpensive in comparison with borings or other geophysical techniques, the magnetic method being the least expensive of the two. Costs of the gravity technique are primarily tied up in the requirement for precise elevation control. A recent significant advance is the use of aeromagnetic measurements for the regional reconnaissance of clinker deposits. Airborne gravity surveys have recently become available, but probably not yet with the precision required for coal work.

3.1.2.7 Electrical Techniques

Three electrical measurement systems have been developed and used extensively in the mineral exploration industry, and include:

- Resistivity,
- Spontaneous potential, and
- Induced polarization.

The spontaneous potential method measures naturally occurring voltage differences from a fixed electrode in the ground to other positions. The technique is particularly sensitive to areas of weathering metallic ore which tends to produce a natural "battery" in the earth. Such conditions are not associated with coal deposits and the suitability of this technique for coal exploration/characterization is negligible and is not further discussed. The induced polarization method measures voltage decay in the ground after an applied current source has been cut off. The method is particularly sensitive to disseminated conductors and has been used extensively in the search for metallic sulfide deposits. A variation of this technique known as the Differential Induced Polarization (DIP) method has been used with limited success in the mapping of coal seams (Labounsky, 1973, 1974), but it appears probable

that similar results could have been obtained from surface resistivity methods and the induced polarization method is not further discussed.

The resistivity technique, discussed in greater detail in Appendix G, has been used from the surface to detect geological features since the beginning of this century. Successful applications to coal exploration have been documented as early as 1934 (Ewing, et al., 1936), but since that time it has been used infrequently. The technique has the ability to resolve the stratigraphy and structure of near-surface coal and is now being developed as a powerful tool for detecting voids.

The resistivity method consists basically of inducing a DC or a low-frequency AC voltage in the ground through two electrodes and measuring voltage in the ground through another pair of electrodes. Examples of the most commonly used electrode configurations are provided in Figure G-1 in Appendix G. The results of a resistivity survey are interpreted in terms of resistivity, measured in ohm-meters or ohm-feet, versus depth and/or horizontal position. The resistivity of coal and coal measure rocks is highly variable, but coal usually has a higher resistivity than surrounding rocks. In terms of coal exploration/characterization, the method has the potential for mapping shallow coal seams and identifying discontinuities which may affect the coal, such as cutoffs, seam splits, faults, washouts, etc. Verma and Bhuin (1979) and Verma, et al. (1980), provide a good case history of the use of the resistivity method to map coal and detect seam discontinuities in the Jharia coal field, India. Another potential application is the detection of near-surface voids.

The use of the surface resistivity method to detect voids is widely discussed in the literature. The possibility of using the resistivity method to detect near-surface voids has been recently enhanced by the development of an automated system by Southwest Research Institute for use in U.S. Bureau of Mines research. This system automatically samples and records measurements between electrodes and uses a computer to obtain the best fit of a void model to the data set. Research is still continuing to adapt this system to the detection of abandoned workings in coal.

The main limitation of the electrical resistivity method is that subsurface inhomogeneities can greatly decrease the probability of success of an electrical survey. The technique is capable of defining vertical resistivity variations up to only about five layers of different electrical properties. Interpretation is impeded if too many layers are present or abrupt laterial variations exist. Layers of very high or very low resistivity impede current pentetration. Man-made constraints include buried culverts or other pipelines, metallic fences, transmission lines, or other sources of EM disturbances.

In spite of the limitations, the electrical resistivity method offers good potential for characterizing near-surface coal. The method is one of the least expensive of the geophysical techniques and is rapidly deployed in the field. Resistivity measurements have been conducted for as long as geophysics has been a science, but computerized data gathering and processing still being developed represent a significant improvement in the technique, particularly as applied to void detection.

3.2 DRILLING TECHNOLOGY AND BOREHOLE LOGGING

3.2.1 Coal Exploration Drilling Methods

Generally exploratory drilling is done by two methods; percussion drilling and rotary drilling. As percussion drilling is not normally used for exploring deep coal deposits it will not be addressed in detail in this discussion.

In the coal industry, percussion drilling using compressed air as the circulating fluid is used for blasthole drilling and shallow exploratory drilling (generally 60 to 100 feet) in advance of surface mining operations. Beyond these depths, the inertia of the drill steel lowers the energy delivered to the bit and lowers the drilling speed. Also, the expulsion of cuttings (chip samples) becomes difficult. The downhole hammer type percussion drill can penetrate to deeper depths; however, this type of drilling is associated with heavy high pressure rigs, with limited mobility. This technique is usually used in hard rock blasthole exploratory and water well drilling. Other types of percussion drilling include churn drilling (cable-tool drilling) and jet drilling which are generally used for drilling oil and water wells.

Rotary drilling can be divided into two categories; destructive drilling and core drilling. Destructive drilling recovers chip samples a quarter of an inch or less in diameter. The chip samples are brought to the surface in the circulating fluid which can be air, water, mud or foam. Core drilling recovers rock core samples, ranging from about 1 to 6 inches in diameter brought to the surface in tubes extracted from core barrels positioned at the end of the drill pipe. Drilling techniques that recover only chip samples (destructive drilling) are as follows:

- Rotary Rock Bit Drilling.
- Rotary Rock Bit Reverse Circulation Drilling.

Drilling techniques that recover core samples are as follows:

- Combination Rotary Rock Bit/Conventional Diamond Core Drilling.
- Conventional Diamond Core Drilling.
- Wire Line Diamond Core Drilling.

Figure 3-5, Drilling Method Comparison, and Figure 3-6, Drilling Costs, compare the advantages and disadvantages, and the drilling costs of the mentioned drilling techniques.

Geophysical logging is more extensively used in rotary rock bit drilling (destructive drilling); however, it can also be a valuable tool in the analysis of cored drill holes (i.e., detect areas of core loss, aid in seam correlation, back up depth check, and in applications where large volumes need to be assayed or fine detail is required). Geophysical logging is discussed in detail in Section 3.2.3.

3.2.2 Destructive Drilling

Rotary Rock Bit Drilling

Rotary rock bit drilling is used with air, water, drilling mud, foam or air/water combination as the circulating fluid. Air or air/water is most frequently used in eastern United States coal exploration. This permits use of a fairly mobile unit (in gentle to moderate terrain) that is virtually self-contained, with capabilities of drilling four- to eight-inch holes to 1,500 feet. Generally, rotary water or mud rigs with enough reaction weight to penetrate coal bearing strata in the eastern United States with any speed are too large to move in rugged terrain. However, as much of the development in the west has been in the weaker (semiconsolidated) Tertiary and Cretaceous rocks, rotary drilling with drilling mud predominates. Also, beyond 1,500 feet air rotary rigs are limited by the pressure and capacity of the air compressor. Auxiliary air compressors or larger, less mobile rigs or large rotary water or mud rigs are generally required beyond this depth.

The equipment is generally truck mounted and has a mast capable of at least a 20- to 30-foot drill rod length. Figure 3-9 is a sketch of a medium weight rotary (destructive type) drilling. Average hourly drilling penetration rates for rotary drilling using tricone bits is as follows (Church, 1981):

Class of Rock	Average Drilling Penetration Rate (feet/hour)
Soft	70 - 100
Medium	40 - 70
Hard	0 - 40

Rotary drilling is very effective in coal-bearing areas, as the overburden is seldom hard and is usually composed of clays, soft shales, and limestone. In harder foundations, the life of a rock bit is shortened, often due to the lack of adequate bearing capacity from small bits. Larger bits need larger drill rigs and tools which result in higher costs. In hard formations, diamond core drilling techniques are generally used.

As previously indicated, rock bit drilling is most always used in conjunction with geophysical logging. This is because only chip samples or cuttings are obtained by rock bit drilling. Chip samples become contaminated with other strata while moving up in the annular space between the drill rod and the drill hole side wall. This makes it difficult to determine coal quality and structure. Also, if water and/or mud are used as the circulating fluid the handling and packaging of large volumes of sludge type material is necessary, probably requiring additional personnel. In most cases, the cuttings are not collected and rotary rock bit holes are used strictly for geophysical logging. Where rock bit drilling is used for prospecting in shallow surface mining operations (less than 100 feet of overburden) the observation of coal cuttings and the action of the drill confirm the presence of coal. The drill advancement is stopped when coal cuttings are observed, the rod is marked, and the remainder of the seam is penetrated.

Recent developments in rotary rock bit drilling include replacement of mechanical hoist components (i.e., chains, sprockets, bearings, and springs) with a piston type hoist, reducing maintenance. Also, surface instrumentation on rigs recording penetration rate, torque, rotation speed, weight on the bit and pressure and quantity of drilling fluid can be used to predict performance of machinery such as continuous miners, longwall systems, tunnel boring machines, blasting characteristics, and rippability.

Rotary Rock Bit Reverse Circulation Drilling

A recent development in rotary rock-bit drilling is the reverse circulation or center return method. A double-walled drill pipe is used. It is called reverse circulation because fluid circulation is down the annular space between the inner and outer pipe with the return of fluid and cuttings up the center. Air is generally used as the circulating fluid, with some water added to prevent caking of materials such as damp clay. The cutting samples returned to the surface are collected and separated from the drilling fluid in a centrifugal separator. Collection of the samples from the separator can be done with long plastic bags, sized to match the hole diameter, allowing the bagged sample to display the vertical progression of the strata drilled. The improvements over ordinary rotary rock bit methods are the reduction in contamination of the samples and the preservation of stratigraphic succession. This comes at very little increase in operational cost, however, the drill pipe capital cost is substantially higher. Also, in ordinary rotary rock bit drilling where a considerable thickness of soil overburden is encountered, pulling the drill rod for a tool change prior to penetrating the coal will probably result in the hole caving, preventing reentering. No bit or tool change is required with reverse circulation drilling prior to entering the coal.

Continuous coring is a drilling technique that also uses the reverse circulation system. Cylindrical pieces of core rise up the inner pipe in a drilling fluid. The advantage of this technique is that a large

sample is obtained during a continuous drilling operation. The system is not extensively used in the coal industry because the rig is very heavy, the drill pipe is expensive and the system is expensive to operate.

3.2.3 Core Sample Recovery Drilling

Combination Rotary Rock-Bit/Conventional Diamond Core Drilling

To take advantage of high production, low cost per foot rotary rock bit drilling and obtain adequate roof rock samples, coal seam and floor observations and coal samples, a combination rotary rock bit/conventional diamond core drilling technique is used. Air is the most frequently used circulating fluid. Rock bit techniques are used to a point, about 30 to 50 feet above the coal seam of interest (distance would depend on prior knowledge of structure), and conventional coring techniques are used to extend the boring down through the coal into the floor rock. Generally, about 10 to 20 feet of floor rock is desired.

Combination rotary rock bit/conventional core drilling necessitates pulling the drill rod and rock bit at the desired coring depth, attaching the core barrel and reentering the hole. Once the rock core has been cut and the core barrel is full, the rods must be pulled and the core recovered. Generally, 10-, 15-, 20-, or 30-foot long core barrels are used. Using core barrels of this length and obtaining sufficient overburden and floor rock will necessitate several rod "pulls" and reentries.

This is not a good method for "pioneering" exploration work in areas where there is no information available. The elevation of the seam or seams of interest should be obtained from a review of available geologic publications, previous drilling in the area, outcrops, or if necessary, the drilling of an adjacent pilot hole. This hole is drilled using rotary rock bit techniques and the seam elevations are recorded during its progress. Unless the structure is very complex, the "two-hole" technique should only have to be used for a few initial holes or until the structure is established. As rotary air drilling is about 25 percent of the cost of diamond core drilling (on a per-foot basis), "two-hole" rotary air drilling should be competitive with diamond core drilling to depths of about 1,500 feet, or where larger rotary equipment is needed.

Conventional Diamond Core Drilling

With the development of rotary air/logging and wire line core drilling techniques, conventional diamond core drilling is being used less frequently in exploration for coal. Historically, conventional core drilling has been performed by small truck or skid mounted rigs utilizing water or drilling mud as the circulating fluid. Hole diameters generally range up to four inches with core diameters ranging to about three inches. Depending on the rod size and rig size, drilling depth capacities for conventional core drilling rigs used in coal exploration is about 800 to 2,000 feet. The large design core barrels (core diameters to about six inches) are generally used with the larger rotary rigs previously discussed. Most of the conventional diamond core drilling taking place today is with the large rotary rigs in hard rock mining, oil exploration, and coal exploration used in combination with rotary rock bit drilling, especially in the western United States.

As indicated in the discussion of combination rotary rock bit/conventional core drilling, in conventional core drilling, once the core has been cut and the core barrel is full, the rods are pulled, core is recovered, and the hole is reentered. Core barrel lengths are usually 10, 15, or 20 feet.

Conventional core drilling with water or mud is probably only used in the coal industry in shallow overburden holes (200 feet or less) for surface mine evaluation. Figure 3-10 shows a typical drill rig used for conventional core drilling in coal fields. This rig can also be set up for wire line drilling; however, it does not have an automatic chuck and rod has to be added after each stroke. Enough water for circulation while drilling shallow holes can be carried on the rig or drillers pickup. A reliable water source is required for deep diamond core drilling. It is usually scarce in relation to most drilling sites and is transported from source to drill site by water trucks or a series of pumps and water lines.

Wire Line Diamond Core Drilling

The difference between wire line and conventional diamond core drilling equipment is in the in-hole tools (i.e., rod and core barrel). Wire line drill rods are thin-wall hollow tubes. The core barrel is designed so that an inner core barrel containing the cored rock can be raised on a wire line up through the drill rods without removing the entire string of rods. An overshot assembly is lowered down the rods on the end of a wire line. The overshot grasps the inner barrel and a wire line hoist brings the inner barrel to the surface and the core is removed. The inner barrel is then lowered back down the string of rods and drilling is resumed (Figure 3-11). The drill rods are not pulled until the bit needs replacing. For wire line drilling, all of the other equipment (i.e., rig, fluid circulation system, mast, and surface tools) required for conventional drilling is the same. Figure 3-12 shows a typical rig used for wire line drilling in the coal fields.

Wire line drilling has resulted in greatly improved drilling production over conventional coring systems in which approximatley 70 percent of the rig time is spent in pulling and lowering rods, compared to approximately 30 percent of the rig time spent in pulling and lowering the inner tube or barrel when using the wire line system (Svendsen, 1976).

In the past few years, there has been a trend toward larger-diameter cores and longer core barrels. Larger rigs equipped with wire line

systems can obtain cores up to about 3.5 inches in diameter. The British National Coal Board has had success with 60-foot core barrels, but in general, 30 feet is more commonly used (Shaw, 1976).

Most of the recent developments and research being conducted in drilling technology are in the area of wire line core drilling. Some of the developments and research are as follows:

- Plug-Bit--The plug-bit is inserted in the end of a wire line core barrel. The bit allows continuous diamond drilling to a point where rock core recovery is desired. The bit is removed by pulling the drill string. This product can currently be purchased.
- In-Hole Bit Replacement--This product is currently in the development stages and marketable product may be four to five years away. In continuous wire line core drilling, the rods have to be pulled in order to change or inspect a bit. This development will allow a bit to be removed by inserting an unlocking and retrieving device down the hollow rods to extract and replace a bit.
- Wire Line Packer--This packer can be inserted down through the core barrel upon removal of the inner tube so that continuous permeability testing can be performed as the hole is "descended."
- Automatic Pre-Torque and Break Out Equipment--This is a rig attachment that automatically locks and unthreads the rods as they are inserted or extracted from the borehole. This development will eliminate the continuous knuckle scarring incurred by drill crews working with break out wrenches (Figure 3-13).
- Deflection or Multiple Borehole Technique--To avoid redrilling for additional sample in thick overburden situations, wedges are placed above the zone of interest to deflect the drill bit a few degrees from the parent hole in order to sample several other places.
- Uniform Diamond Exposure Impregnated Bits--The bits have an even diamond distribution throughout the matrix to ensure even exposure of new diamonds over the life of the bit.

- Core Barrels for Soft and Hard Formations--The barrel is equipped with an adjustable water shut-off valve for manometer indication when the inner tube is full or core blockage occurs to lessen the risk of burnt bits. Also, the annular space between the outer and inner tube is large enough to allow high viscosity mud flushings.

3.2.4 Horizontal In-Seam Boreholes

Most of the work done with in-seam boreholes of significant distance for exploratory work has been in conjunction with degasifying coal seams and the locating of old workings. Technology is now available to drill three-inch horizontal degasification boreholes in an active mine, ahead of mine entry development, to distances greater than 3,000 feet. Transferring this technology to exploration, horizontal boreholes could be used in conjunction with in-seam geophysical techniques (Section 3.1). Logging tools are usually advanced by air or water and retrieved by wire line in directional or horizontally drilled holes. This technique could be used in areas where deep seams result in high cost boreholes from the surface and where it may be necessary to detect small throw faults in advance of a longwall system. Accurate surveying of underground horizontal boreholes is necessary to accurately locate any anomalies. Photographic techniques, recording deviations on film, have been used in surveying degasification holes. The most important information needed in the survey of an in-seam borehole is its position in the vertical plane during drilling in relation to the trends of the seam. The ideal in-seam borehole would follow the contours of the seam in the vertical plane while maintaining a straight line in the horizontal plane.

Horizontal wells have been successfully drilled form the surface in the oil industry. Reservoir depths of about 2,000 feet have been penetrated horizontally from a surface initiated well, for distances greater than 1,000 feet. With improved horizontal directional control, it may be possible to penetrate coal seams in this manner during preliminary exploration stages. Accurate borehole direction (azimuth) and inclination (drift) can be determined from downhole measurements made by tri-axial magnetometers and accelerometers, however, technology is not available that will keep a nearly horizontal inclination angle from deviating a coal seam height of less than 10 feet for any distance.

3.2.5 Borehole Geophysical Logging

The basic premise behind borehole geophysical logging is simple: lower an instrument (the sonde) on a wireline down a hole, and measure parameters of interest. Essentially it is a technology of bringing the instrument to the sample instead of bringing the sample to the instrument, as is done in core analysis. The history of logging is one of increasing hardware and analytical development, largely in response to needs for increased knowledge of the subsurface. The information normally required from a drilling and logging program includes:

- Thickness of coal
- Coal quality
- Data for preparation planning
- Data for interpreting structure
- Unusual conditions, in seam (e.g., faults, cut-outs, splits, and others)
- Overburden, roof rock, interburden, and floor rock properties; general hydrogeologic, environmental, and engineering data.

Clearly, there is a trend to rely more heavily on logging to supplement and possibly selectively replace coring and core analyses to provide much of this data. There is comfort in the perception of certainty that coring provides. The coal or rock can be visually examined and tested as desired. However, if logging is performed with calibrated instruments and interpreted by experienced people (especially those who have the benefit of correlating their log signatures to some core analyses within the coal field of interest), a good measure of confidence can be obtained.

Modern logging technology has a vast array of probes and analytical tools at its disposal. A more detailed discussion of the different logging techniques is presented in Appendix H. This equipment has been developed to exploit the generic potential advantages of logging, vis-a-vis coring including:

- Elimination of higher cost coring
- In situ measurements
- Rapid data acquisition
- Vertical detail
- Greater sensed volume than core

Each of these generic advantages is discussed in turn.

Eliminate Coring - As described earlier, coring adds a great premium to the cost of a borehole. To develop data requires core description, boxing and shipping, and laboratory analyses, all expenses. Unless rock conditions are favorable and the drilling crew is expert, parts of the section may not be recovered. Short of substantial additional expense, they can not be replaced. Logging has the potential to offset these disadvantages.

In Situ Measurements - Logging can be used to measure unique in situ properties such as temperature which can not be measured in the laboratory. More importantly, properties which are sensitive to temperature and stress can be measured directly under in situ conditions so that the data is truly representative.

Rapid Data Acquisition - With the use of a competent data analyst/interpreter, a modern digital recording system, and the power of computers, complete interpretations are possible within hours after the hole is drilled. The complete data can be sent over commercial phone lines to the home office; thus it is not necessary to have highly experienced people in the field. The alternative, coring and laboratory analyses, would require days.

Vertical Detail - Geophysical logs are continuous records over the entire hole whether cored or not. Any "missing" segment can be relogged easily. Zones of interest can be logged to provide any level of detail desired, limited only by instrumental and analytical factors. To make point-to-point measurements on cores would require an excessive number of tests.

Sensed Volume - A core sample is likely to be at most a cylinder only a few inches in diameter. Depending on the type of logging probe, the sensed diameter may be substantially larger, permitting a more representative measurement. Some techniques enable the radius of investigation to be changed.

As presented in Appendix H, there are a number of discrete logging technologies under development. A listing of these techniques, along with their applications and limitations is presented in tabular form in Figure 3-7. Probably foremost is the use of the computer to reduce the data, display it as desired, and perform analytical computations. The final result must be evaluated in terms of how effectively has logging provided the information sought in comparison to the alternatives. It is important to recognize, however, that for some issues, one logging tool may not provide the complete answer, but that several different logs may be required to derive the piece of information.

- Thickness of Coal. Coal is an ideal target for geophysical logs. It has a high contrast with respect to normal bounding rocks in physical properties such as density or sonic velocity. The response of logs to coal is summarized in Table H-1 in Appendix H. Measurements of the thickness of coal or partings is possible to an accuracy of within two inches. If the hole is not badly caved and the coal is bounded by shale or sandstone, the gamma ray, density log, or a resistivity log are useful. If bounded by limestone, a combination of tools including the density log is often necessary. If bounded by clay, the coal thickness may be overestimated due to washout of some clay. In this case, the caliper record is a useful aid in interpretation. The

density tools are more reliable than the neutron tools if wet clays abut the coal.

- Coal Quality. The quality of the coal is determined in the laboratory from core samples using standard test methods. The rank of coal normally would be known; however, it is possible to grossly rank coal by logs alone. The three principal components are: carbon, ash, and moisture. There are no logs which are uniquely diagnostic of any of these factors. Edwards and Banks (1978) have shown, however, that specific relationships could be developed so that log responses could be used to determine coal quality. Earlier work had demonstrated that the response of the density tool correlated well with ash content. When resistivity was included in the analysis, the correlation improved. These methods, using three equations so that the three unknowns can be determined, yield "in situ" values by weight or volume. The laboratory proximate analysis reports fixed carbon and ash from air-dried samples. For the log data to correlate with the standard way to report lab data, the coal water and the ash water must be determined and subtracted. To account for the volatile fraction, another correction is required.

  When all these corrections are made, correlations between the log interpretation method and core analyses typically agree to better than ± 2 percentage points. One must consider that not all of the imperfection in correlation is due to errors in the logging.

  The particular value of the above is the ability to do these analyses rapidly, relatively inexpensively, and one would hope that following experience in a coal field, very accurately. Another potential advantage is one of detail. The analyses could be automated and a continuous record over the entire coal interval determined. The vertical measurement density would greatly exceed what would be practical by core analyses. This detail may be especially useful in designing heights of cuts, in correlation work, or selecting parts of thick seams having the highest sale value.

- Data for Preparation Planning. As noted above, logging can provide data on ash content in great detail. Presently, logging tools are under development that have the potential to log elemental abundances, including iron, sulfur, silicon, and other elements whose presence may influence the use and value of the coal.

- Data for Interpreting Structure. A very common use of logs is stratigraphic correlation. A suite of logs reveal, in easily used form, very fine details or signatures of formations and contacts. These data, coupled with lithologic information (derivable from logs), fracture spacing (derivable from logs), and interpreted information from specialty logs such as the strata dip logs, all as functions of depth, are powerful tools for the structural analyst.

- Unusual Conditions. The good vertical resolution, the ability to portray detail, and the relatively large sensed volume (compared to a core) can be useful in detecting unusual conditions.

- Rock and Environmental Properties. As noted, logs can be run from the surface to total depth, thus information over the whole depth can be obtained. This information can include geomechanical properties useful for mine planning or subsidence prediction, water-bearing properties, and similar information.

Logging can be performed in boreholes of nearly any size. Instruments as small as 1-1/4 inches in diameter have been developed and at least one logging instrument has been developed to log 12-foot-diameter shafts. While logging is most easily done in vertical holes, holes of any orientation can be logged. Logging horizontal boreholes can be with air, water, drill string, or hydraulic pressure. Some instruments require an uncased hole in order to function, others a dry hole (Figure 3-7).

The development of small diameter (slimline) logging tools capable of being used in coal exploration core holes has made it possible for smaller, more mobile rotary rock bit drill rigs to be used in coal exploration and together are the main reasons for the increasing use of geophysical logging. Also, core loss, incomplete analysis from cuttings observations, and the high cost of diamond core drilling (Section 3.2.3) created a market need for the development of coal logging technology. Some of the logging techniques used in the coal industry have been in use in the oil and gas industry for many years. The "technology transfer" has resulted because coal mined in the future, especially in Appalachia, will be thinner, more discontinuous and deeper, creating the need for less expensive, yet accurate exploration techniques. The

skepticism or lack of confidence in "black box" techniques expressed by coal company managers in the past may be lessened as more and more coal companies are being acquired by oil and gas companies.

3.2.5.1 Primary Coal Logging Technique

As indicated in Appendix H, logging techniques can be categorized into mechanical, electrical, nuclear, acoustic, thermal, gravimetric, and video. Borehole logs can be interpreted to determine resistance, lithology, structure, bulk density, porosity, permeability, and chemical and physical characteristics. The most important of these interpretations or characterizations in coal deposits to date are based on nuclear (radiation) and electrical measurements. These measurements are generally combined in one tool, often called the "combination coal tool," which combines the density and natural gamma techniques, along with a caliper log. In some cases a resistivity measurement is substituted for one of the density tools. Besides the savings in time because of the reduced number of logging runs, combination tools simplify the correlation between different logs as the information is recorded and presented on the same run and display log, respectively. The following discussion briefly defines the main applications and limitations of the different logging techniques.

Density Logging

Density logging or gamma-gamma logging is the most important tool normally used for logging coal. The technique responds to the large density difference which exists between coal deposits and surrounding rocks. Two density logs are generally recorded which have different spacings between the gamma ray source and detector. The spacing between scource and detector determines the depth of penetration, the minimum bed thickness a tool may detect, and the accuracy to which a bed boundary may be read. The longer spaced tool is used to give the best approximation of overall bulk density of the coal, while the shorter spaced tool is used to resolve the boundaries of the coal.

As the tool approaches a boundary between two rocks of contrasting densities, the count rate will start to change from that for one type to that for the other. The distance required for the complete transition depends on the source-detector distance and it will be large for large spacings. If a bed exists whose width is equal to or less than this spacing, the count rate will not reach the true value for that rock before it starts to change again as the next boundary approaches (Jackson, 1981). Thus, for smaller spacings, bed boundaries may be located on the analogue trace from the trace of the transition curve; however, the readings will give no indication of true density, as the smaller the source-detector spacing the smaller the penetration of radiation from the tool.

Increased spacing will increase the penetration and decrease the effect of irregularities in the borehole wall. The deeper penetration will provide more accurate bulk density information and combined with computer applications, can be used with other logs to generate quantitative information on coal quality and geomechanical parameters. A summary of the types and resolution of different density probes is presented in Section H.1.1 of Appendix H. A comparison of two different types of density logs is presented in Figure H-3 in Appendix H.

Bulk density is affected to a large degree by porosity so bulk density changes can be caused by variations in porosity as well as lithology. With both gamma-gamma and neutron logs from the same borehole, grain density can be determined independently from porosity using cross-plotting techniques. The grain density, however, does not indicate lithology uniquely, since a given grain density may represent a single lithology or a combination of lithologies. Independent information and experience in the area of interest can provide important guidelines in this situation.

Gamma Ray Logging

The natural radioactivity or gamma rays emitted from radioactive elements (e.g., potassium, uranium, and thorium) are measured by a scintillation or geiger counter. The gamma ray log (NGR) can identify suspected coal horizons, as the natural radioactivity in coal is low, being of organic origin, as opposed to the rocks above and below the coal which are often potassium-rich shale beds. The gamma ray log can be useful for denoting the distribution of shale and sandsone for correlation or roof condition purposes or for that matter, provide a lithologic log. Clay-bearing sediments have higher natural gamma activity than siltstones and much higher than coarse-grained sandstones. Also, marine bands or limestone not readily observable in rock core can be detected by gamma ray logs because of potassium enrichment. Figures H-1, H-14, and H-17 in Appendix H indicate the responses of gamma ray and density logs in coal and surrounding rocks. Care must be exercised in that some coals may have associated uranium bearing minerals.

The gamma ray log can be very useful for determining paleo-depositional energy levels and subsequent depositional environment modeling (Miller and Moore, 1980). Recent work in this area has indicated that important coal seam characteristics are determined by the environment in which the coal and the surrounding strata were deposited. The topographic surface on which a coal swamp developed controlled the extent and thickness of the seam and the environments of deposition of the overlying sediments greatly influenced roof conditions and coal quality.

Caliper Logging

Caliper logs are always run simultaneously with density logs to correct for caved hole conditions essential for true density measurements. Beyond this, however, caliper logs can indicate considerable detail allowing more accurate seam and parting thickness measurements. Also, rock strength or incompetent strata and squeezing due to horizontal

stress can be measured by successive runs. Evaporites, for instance, are characterized by borehole enlargement due to solutioning and bentonite clays are characterized by borehole restriction due to swelling. Measurement accuracies of less than 2.5 mm are now being achieved.

Electrical Logging (Resistance or Resistivity)

As indicated, sometimes an electrical resistance or resistivity tool is substituted for one of the density tools in the combination coal tool. Such logs measure the flow of electrical current between electrodes within the sonde. Coal generally has a high resistivity, but its resistivity can also vary somewhat depending on the mineral composition of the seam and the degree of metamorphism. As clean sandstones also have high resistivity, it may be difficult to delineate coal seams surrounded by massive sandstones. Shales on the other hand display low resistivity and electrical methods can usually define a coal/shale contact with high accuracy.

Drawbacks to the use of resistivity logs are that uncased holes and conductive fluids (e.g., drilling mud or fresh water) are required and variations in the electrical properties of coal and adjacent strata may inhibit a straightforward interpretation. Normally, resistivity logs are run as an initial log to check the condition of the hole and possible caving.

Focused-beam resistivity tools have been developed that can measure true resistivity with improved resolution. In focused-beam resistivity, the current is focused from an electrode directly into the formation with only a minimal current allowed to flow in a vertical direction. As the current lines spread out away from the sonde, most of the voltage is dropped in the part of the formation near the sonde. Focused-beam resistivity logs may show features (i.e., moisture or pyrite) not visible on other logs (Jackson, 1981).

Combination Coal Tool Log Analysis

The combination coal tool coupled with a computer can produce lithology, seam thickness, and coal quality (ash content) logs. Improved calibration of density logs has allowed true rock densities to be displayed on logs rather than relative density. The use of these logs to derive lithology is discussed in Appendix H and an example is provided in Figure H-17.

3.2.5.2 Additional Geophysical Borehole Logging Techniques

Most of the chemical analyses performed from log data are obtained from combining the combination coal tool logs in a matrix of simultaneous equations with neutron and sonic logs. Also, neutron and sonic logs provide valuable geomechanical information.

Neutron Logging

Neutron logs measure the hydrogen concentration in the formation and are, therefore, very sensitive to water and hydrocarbons present in coal. In most rocks other than coal, hydrogen nuclei exist mainly as pore water in rocks. Formations are bombarded with neutrons, and if the rock has a high hydrogen content, the neutrons are slowed down and captured by the hydrogen nuclei, whereas if the hydrogen content is low, the neutrons travel relatively large distances and fewer neutrons reach the detector.

The neutron log is mainly recognized as a tool for indicating the porosity of rocks other than coal. A porosity index can be created by scaling the log in water filled porosity units and treating all rocks logged as some assumed matrix composition, the two most common being calcite and quartz. Charts are available for converting neutron values from one matrix composition to another.

In sandstone the neutron response is generally logarithmic with porosity, such that at low porosities (a few percent) it is sensitive, but at high porosities (40 to 60 percent) it is less sensitive. Coal gives a high response (approximately 60 percent effective porosity) caused by its high hydrocarbon content. The result is an erroneously high porosity for coal. Also, methane in coal influences the neutron log due to its hydrogen content. When used to delineate coal boundaries, the high moisture content of overlying, underlying, or contained clay seams may result in unuclear boundaries when crossing into coal. For these reasons, density logs are generally favored over neutron logs for coal seam delineation. Higher resolution neutron logs are being achieved as are improved log responses in the higher porosity range, which will make accurate moisture content determination available (Reeves, 1978).

Spectral neutron devices, a variation of the conventional tool, determines the gamma ray spectra from certain elements generated from neutron bombardment and can assess the concentrations of these elements. Silicon, aluminum, iron, titanium, and chlorine concentrations in coal have been determined. Identification of the ash composition with some accuracy has led to more accurate total ash content and calorific value estimates. The Metalog system developed by Scintrex, Ltd. in Canada measures gamma emission from sulfur in the coal matrix. Sulfur content can be measured to an accuracy of one percent with this tool. This tool also measures emission from silicon and carbon at different energy levels enabling seam boundaries to be delineated accurately as the probe passes the seam boundary (Jackson, 1981). Except for the Metalog system, most neutron gamma spectra tools are still in the experimental stage.

Sonic Logging (Acoustic)

The sonic log records interval transit time for an acoustic compressional wave to travel a fixed length through the formation. Transit times

or sonic velocity measurements are useful as indicators of coal rank, chemical properties, rock strength, and porosity, as further discussed in Appendix H.

Sonic tools were originally developed for the oil industry and are large diameter. However, BPB Instruments, Inc., has developed a two-inch-diameter sonic tool approximatley six feet in length. Perfection of small diameter sonic tools will greatly enhance premining geomechanical studies of roof and floor rock conditions.

The logs discussed to this point are the most frequently used logs and are logs that are generally, and in some cases necessarily, run as combinations in order to develop a coal or geomechanical characteristic. The following logs are not used as frequently; however, they are sometimes used to characterize unusual occurances (e.g., strata dip) or enhance or verify findings (e.g., temperature logs) of the more popular suite of logs.

Spontaneous Potential (SP) Logging

The SP log measures the natural potential differences between two points in the ground or, as used in the coal industry, between borehole fluids and surrounding rock materials. The borehole must be full of water or drilling mud. The log generally produces two extremes--shale line and the sand line. The greatest positive spontaneous potential (SP) readings are expected in shales and the greatest negative readings can be expected in sands. Assuming that the ionic concentration of the borehole fluid and the aquifer water (if any) are constant throughout the depth of the borehole, then the shale-sand ratio can be determined by the position of the associated SP readings with regard to the shale and sand lines.

Coal being a poor conductor of electricity does not usually produce an anomalous measurement unless the seam has been fractured and filled with dirt or clay interfaces. The log is not generally used in the coal industry, and when used, it is generally only used for initial borehole safety checks.

Strata Dip Logging

The strata dip or dipmeter log uses the electrical resistivity of rocks to measure strike and dip of rock layers. The probe consists of instrumentation for measuring borehole azimuth and tilt and strata dip and azimuth of the dip. The dipmeter, previously only available to the oil industry has been developed in slimline (down to two-inch diameter). This makes it possible for coal industry geologists to determine the true thickness of coal seams penetrated. This is especially important in the western United States coal exploration where thick steeply deeping seams are encountered. Apparent thickness measurements can be very misleading in these situations.

The ability to determine the true penetration of a borehole allows for sampling points and possible areas of poor roof to be accurately located. Also, the dips of interbedded sandstones and shales in immediate roof rock and the slope of a channel sand cut out can be determined. This ability to detail bedding characteristics will also aid in refining depositional environment studies and give more confidence to predictions of coal quality and continuity.

Typical results are presented in a "tadpole plot" (Figure H-9 in Appendix H). The dot or body designating the angle of dip and the tail indicating the direction of dip (Reeves, 1978). The results from borehole azimuth and verticality are generally presented as a continuous analogue recording.

Temperature Logging

Temperature logs are used for locating fluid flows (i.e., gas, water, or oil) and in areas where ventilation studies are necessary (e.g., deep, large area mines). As coal has a lower thermal conductivity than surrounding rock, it is also sometimes used to verify a coal occurrence.

Gravimetric Logging

The borehole gravimeter is a unique logging tool in that it can yield information from distances of several hundred feet around a borehole. Gravity is measured in microgals, approximately one billionth of earth's gravity field and accuracies of about 5 microgals can be achieved under ideal conditions. The general purpose of the log is to sense porosity not normally detectable by conventional logs. Intergranular porosity, vugs, fractures, and voids can be sensed. This allows for the calculation of very accurate bulk densities.

The gravimeter can be used in cased holes. The log is very expensive to run and its application in the coal industry is generally special problem identification such as the location of abandoned works and weak roof conditions.

Fluid Movement Logging

As most of the current and past underground coal mining has been drift mining in seams above drainage, groundwater flow analysis has not been necessary. However, as above drainage seams are mined out deeper seams will be mined and groundwater inflow will become a major problem in underground mining. Aquifer permeability, hydraulic gradient cross-sectional area, and lateral extent are primary parameters related to groundwater flow that will have to be determined. Borehole logging (i.e., fluid movement logging) is an extremely useful tool in analysis of groundwater flow, as it provides some quantification of these parameters.

Video Logging (Borehole TV)

Borehole TV is expecially useful in abandoned mine inspection for safety checks prior to entry or subsidence potential. Mine roof and timber conditions and the effectiveness of underground mine slurry backfill operations can be observed. Other uses include observation of the point of groundwater inflow in a borehole, joint or fracture patterns and groundwater movement.

3.3 DECISION PROCESSES

The use of geophysical and drilling techniques to explore for and characterize coal involves several decisions. The mine planner first needs to know what information is required and have an understanding of the quantity and quality of information that may already be available. Usually the mine planner has some general knowledge of the problems which the mine may face during development. The decisions made should also consider the depth of the coal to be investigated, as investigation programs may be completely different for coal at strippable depths than for deep coal to be mined underground. The planner can assume that a certain number of cored boreholes will be required. Beyond that, the following questions arise:

- Do I need geophysics?
- What geophysical technique should I use and to what level of effort?
- What geophysical logs should I run, if any?
- Can I do the work myself, or do I need to contract the services?
- What drilling technique should be used?
- How many holes should be drilled?

Once mining has begun, the use of geophysical technology assumes a different role. The first two questions are still valid, as is the fourth, but the mine operator has usually encountered a specific problem that has affected his operation. In such cases, the use of a geophysical technique could become the critical path to the reaching of full production and the costs of the technique are not as significant as in the planning stage.

Do I need geophysics?

Geophysical technology is, with reference to surface and underground deployments, applicable if it can provide information about mining conditions that would otherwise be unknown, and which could adversely affect the profitability of the mine to a dollar value greater than the cost of the geophysics. Not all mine development plans require geophysics, but many could profit well from it. Critical factors determining the need for geophysics include:

- Extent and Quality of Available Information - The nature of the coal seam to be mined and previous experience in mining it might be sufficiently well known so that the planner has adequate knowledge of potential problems to accommodate them in a program not requiring geophysics.

- Depth of the Coal Seam - The depth of the coal is a critical factor in determining the need for geophysics from a cost benefit standpoint. For example, drilling costs per foot decrease while the high resolution seismic reflection technique becomes more expensive as coal depths decrease. For this example, the critical depth beyond which the seismic reflection technique becomes beneficial is probably somewhere between 60 and 120 meters (200 and 400 feet), but this is highly dependent on variable contractor costs and the degree of resolution desired. Most of the other techniques have the opposite limitation, i.e., they are valid only for shallow coal or have short penetrations into the rock. Their need is dependent on whether favorable conditions for their use are known or suspected, such as clinker (magnetics), cutoffs (gravity; resistivity), abandoned workings (resistivity, gravity), etc.

- Type of mining method employed - Mechanized mining systems are much more susceptible to problems affecting profitability than nonmechanized systems. Room-and-pillar mining techniques offer the greated flexibility in "mining around" problems that may be encountered. The costs of adjustments to the mining system should be considered when determining the need for geophysics. For example, it might be less expensive to encounter unexpectedly and mine through a 40-foot-wide sand channel (and accept production lag and costs) than to detect it with prior comprehensive geophysics. The economics would clearly favor the advance detection of a 200-foot-wide channel.

The need for geophysics after mining operations have begun is somewhat dependent on the degree of coal characterization that has been achieved during the mine planning phase. Where problems are anticipated, the use of geophysics is usually dependent on whether horizontal borings are

more or less cost effective. Problems not amenable to location by means of borings, such as the detection of an abandoned oil well, are usually best accomplished by geophysics, particularly radar. The detection of abandoned workings, however, might be risky if detection was limited to borings if there is a flooding potential. Faults with small displacements are difficult to characterize by borings and a surface geophysical survey could be more effective, depending on other factors such as depth discussed above.

What geophysical technique should I use and to what level of effort?

The selection of a geophysical technique must be based on the applications and limitations of each technique as presented in Figure 3-4. For deep coal, at least beneath strippable depths, the only effective technique is high resolution seismic reflection and the decision to use this technique depends on the factors discussed above. If the high resolution seismic reflection technique is used, the number of line miles required should be dependent on a geostatistical evaluation of what amount of data is significant to the mine planner and is dependent on property size and size of target (sand channel width, number of faults to be detected, extent of abandoned workings, etc.).

For shallow coal, the technique to be selected depends on the target to be identified. Typical applications are as follows:

- Definition of burn zones (clinker) - magnetics
- Identification of coal cutoffs - gravity, resistivity
- Geotechnical properties and groundwater conditions of overburden - seismic refraction, resistivity
- Faults - gravity, magnetics, resistivity, seismic refraction
- Igneous intrusions - magnetics, gravity
- Buried stream valleys - gravity, resistivity
- Abandoned workings - gravity, resistivity, radar, magnetics
- Abandoned wells - resistivity, magnetics, radar

The selection of one technique versus another depends on the cost benefit comparison. For example, a magnetic survey might have limited application for detecting abandoned workings or a fault, but is so inexpensive that it might be worth the attempt before using another technique. In other cases, resolution can control the decision. Where none of the techniques by themselves offer sufficient resolution, the use of more than one technique should be considered to increase resolution.

In an underground environment, the selection of a technique is most greatly restricted by the availability of mine-suitable equipment. The technique most effective in detecting coal discontinuities in advance of the working face is the seam wave seismic method. In the U.S., this technology is still experimental and mine suitable equipment is not available. The only technique with commercially available equipment is pulse radar. If a problem exists where a system that has a range of 50 feet (15 meters) is acceptable, then the radar method is suitable.

What geophysical log should I run, if any?

In this case, the question is not whether geophysical logs should be run, but which ones. Even in the case where all boreholes are cored, geophysical logs run at a relatively modest increase in cost over the cost of drilling can offer capabilities of seam thickness determination and correlation that surpass the core samples. Figure 3-7 defines the applications and suitability of the different geophysical logs.

Logging with a coal combination sonde capable of measuring density, natural gamma count, and borehole diameter (caliper log) are sufficient for most applications. Resistance or resistivity logs are usually only necessary when there is some doubt about the interpretation from the density and natural gamma logs, such as can occur when there is an unusual concentration of uranium or other radioactive minerals.

Acoustics (sonic) logs are beneficial and should be a requirement if a high resolution seismic reflection survey is also being performed. This log should also be considered if the planner desires in situ information about rock strength.

The neutron logs are more expensive than the other types and are applicable mainly when other techniques have left some doubt with regard to interpretation. The neutron gamma spectra log offers good potential for defining the concentrations of different elements, but is costs are high and availability extremely limited. At the present time, it is probably more cost effective to core and perform laboratory tests than to use this tool.

Other logs, such as the temperatures or fluid flow techniques are useful when groundwater is a problem. The application of the borehole TV camera is best for investigations of abandoned mines, and can be very effective in this regard.

Can I do the work myself or do I need to contract the services?

In nearly all cases, the application of a geophysical technique requires that a geophysicist be on the mine planning staff. Oil companies normally employ geophysicists and have equipment so these companies with

mining interests are capable of doing their geophysical work in-house. Coal operators who do not have a geophysicist on their staff must usually rely on a contractor. Possible exceptions to this would be the performance of magnetic or electrical resistivity surveys. For these techniques, equipment costs or rentals are not high and the field procedures and interpretation relatively straightforward.

With regard to borehole logging, the standard coal logs can be interpreted with a moderate educational effort and if a coal company does a large amount of drilling may wish to consider purchasing their own logging equipment. Truck mounted slim line (less than two-inch diameter) tools capable of measuring and recording the combination coal tool suite of logs can be purchased for prices ranging from $20,000 to $30,000. The equipment should be mounted in a cross-country (4x4) vehicle. These units cost about $12,000 to $15,000. Coal companies that are exclusively core drilling should probably not consider purchasing a logging unit unless they are running more than two rigs continuously. On the other hand, coal companies that are drilling with rotary rock bit techniques should consider purchasing a logging unit. Companies drilling mor than 50,000 feet per year can nearly pay for a unit in two years.

What Drilling Technique Should be Used?

When deciding on drilling technique best-suited for a specific property or drilling program, numerous factors must be considered. Obviously, if certain types of drilling equipment are owned, variation of drilling technique is limited. When consideration is being given to purchasing or contracting drilling equipment for coal exploration, the first consideration is the type or types of sampling and the size of samples needed. If only chip samples and logging are required, then a rotary rig would be adequate. If core samples are required, then a core drill or a rig capable of doing both rotary rock bit and diamond core drilling is needed. The next consideration is the mobility of the rig and the topography that will be explored. Generally, rotary rigs are large and not as mobile as core drill rigs. If rotary rigs are selected, should the circulating fluid be air or water? Detailed site geology is another important consideration. Some of the factors to be considered are:

- Overburden lithology
- Overburden thickness
- Structure
- Rock and coal hardness
- Seam thickness
- Seam partings
- Groundwater

Initial investment and owning and operating costs probably dictate the type of drilling equipment purchased in most cases. New rotary equipment initial costs and annual operating costs for one unit both range from $250,000 to $400,000 (Figure 3-8). However, because of the high production of rotary equipment, unit costs range from about $3.00 to

$7.00 per foot. New diamond core drilling equipment will generally cost between $100,000 and $200,000. Annual operating costs range from $150,000 to $200,000, with unit costs ranging from about $13.50 to $20.00 per foot.

There are so many variables to consider when purchasing a drill rig that no "perfect" rig is available. Ideally, each area to be investigated should be examined and drilling equipment selected on the basis of the circumstances associated with each area. It follows then that exploration groups should have both rotary and core drilling equipment available, giving them mobility, high production with logging capabilities, and core hole capabilities.

If budget limitations prevent owning both rotary and diamond core drilling equipment, consideration should be given to contracting all or a portion of the drilling work on a particular property. On most properties, a mix of rotary and diamond core drilling is used. As contract drilling is expensive, the importance of (1) expert preplanning by experienced professionals, and (2) use of boreholes for multiple purposes, should be emphasized.

Figure 3-6, Suitability and Economic Factors for Various Types of Coal Exploration Drilling, summarizes and compares various performance criteria, geotechnical testing suitability and economics factors for the previously discussed drilling techniques. Coupled with mobilization costs, the costs per foot indicated in Figure 3-8, should approximate contract driller fees. If any adjustments could be made to these unit costs with respect to contract driller fees, rotary drilling costs may be slightly higher due to the high cost of mobilization, and core drilling costs may be slightly less due to contract drillers operating with fully depreciated equipment and possible lower labor rates.

How Many Holes Should be Drilled?

In eastern United States coal mining areas, outcrops and previous exploration usually indicate the presence or absence of coal. However, because of variation in thickness, erosional features (i.e., sand channels) and variations in quality, exploration programs should go to a point of detail where additional study would not provide a significant increase in the level of reliability. Generally, a "rule-of-thumb" for coal exploration in the Eastern United States has been to continue drilling or obtaining points of observation in a coal seam until the "measured coal" reserves do not change by more than 10 to 20 percent with an additional observation. Measured coal, as standardized by the U.S. Bureau of Mines and the U.S. Geological Survey, is defined as follows:

> Measured Coal - Measured coal is coal for which tonnage is computed from dimensions revealed in outcrops, mine workings, and drill holes. The points of observation and measurement are so closely spaced and the thickness and extent of the coal are so well defined that the computed tonnage is judged to be within 20 percent or less of the true tonnage. Although the spacing of the points of observation necessary to demonstrate continuity of coal will vary in different regions according to the habit of the coal beds, the points of observation are, in general, about 1/2 mile apart. The outer limit of a block of measured coal, therefore, shall be about 1/4 mile from the last point of positive information (that is, half the distance between points of observation).

Another rule has been to drill a property until one equipment life has been proven. This would be about three to five years of mining. The total tonnage would depend on the type of equipment used, number of mining sections, and the number of shifts per day.

Some of the conventional "rules" can be broken if the borings are supplemented with geophysical information from the surface. In particular, the high resolution seismic reflection technique can provide information that can allow for a significant reduction in the number of borings. For shallow coal where specific problems are present, such as clinker, cutoffs, buried stream valleys, igneous intrusions, etc., the use of a variety of geophysical techniques can greatly reduce the number of borings required to resolve the specific situation. Examples of the use of geophysics with borings as opposed to the use of borings alone is discussed in terms of a cost-benefit analysis in Chapter 4.0.

In order to obtain an array of observations that would best achieve the above levels of measured coal, some uniform grid sampling system is necessary so that an optimal coverage is obtained. In actual practice, however, especially in Appalachia, access problems due to terrain and surface rights generally result in a grid that is a compromise between what is desired and what is physically possible or economical.

As indicated, in coal exploration, especially in the eastern United States, some prior information is usually available on the seam or seams targeted for exploration. This is not always true in the west, where much coal exploration work is "blind." An exploration program should be set up in stages, with the decision to proceed from one stage to the next based on a thorough evaluation of the previous stage results. A drill hole pattern for the initial stage should be selected to insure that the observations obtained will provide an answer to the question to "proceed" or to "not proceed" at the lowest cost in the shortest possible time period. Based on existing geologic information, the location of the main entries can usually be approximated. The initial holes should be put down in a profile line along this assumed main entry. For this initial line, the holes should not be more than 1/2 mile apart. Also, during this first stage, a profile line should be drilled at a right angle to the initial line. These holes should not be more than one mile apart. If these initial observations are favorable, additional holes are drilled, expanding the grid from the initial profile lines.

Historically, the primary value of a coal property has been based on "measured" and "indicated" reserves as defined by the U.S. Bureau of Mines and U.S. Geological Survey. At a minimum, properties should be at least drilled to the "indicated" level. If a project is in the actual mine planning and quality evaluation stage, a grid obtaining the measured coal or even tighter control should be achieved. Indicated coal is defined as follows:

> Indicated Coal - Indicated coal is coal for which tonnage is computed partly from specific measurements and partly from projection of visible data for a reasonable distance on geologic evidence. In general, the points of observation are about one mile apart but may be as much as 1-1/2 miles for beds of known geologic continuity. For example, if drilling on 1/2-mile centers has proved a block of measured coal of fairly uniform thickness and extent, the area of measured coal, according to the judgment of the estimator, is larger than the actual area of drilling by as much as 1/4 mile on all sides. If, from geologic evidence, the bed is believed to have greater continuity, the area of measured coal is surrounded by a belt of indicated coal, which, according to the judgment of the appraiser, may be as much as 1-1/2 miles wide.

Generally, borings put down at closer intervals than required for "measured" coal are put down for three reasons; geological, geotechnical, and geostatistical. The geologic borings are needed to solve specific problems such as sandstone extent, washouts, and hard streak correlation. Geotechnical borings are needed for testing such factors as in situ strength, geomechanical moduli, and blasting vibration. A nonbiased geostatistical study will recommend additional borings to better define needed parameters, such as thickness and percent sulfur. The number of borings finally selected will naturally be site specific and depend on the understanding of the property by the geologists, geotechnical engineers, and mine designers.

The results of the individual analyses (i.e., geological, geotechnical, and mine design) can be discussed in a round table group to see if additional borings designated are in close proximity and if one boring can satisfy all their needs. This procedure often results in fewer recommended borings than the "rule-of-thumb" methods now employed.

Geostatistics has advantages over classical statistics because it takes into account location of the sample and points out not only the needed number of additional borings, but their locations. This prediction starts by calculating variograms for the existing data. These

variograms relate the parameters under study to the areas of influence and are used in a Kriging equation. Kriging is a map generating geostatistical technique that not only produces isopach maps, but also generates a second map of the associated error. Since this second map is presented in standard deviation or variance, it will then be easy to select additional borings which will reduce this associated error to acceptable levels.

The geologist can be aided in his predictions by the use of geostatistics, in particular, the Kriging equation. Geostatistics has its advantage over standard methods of generating isopach and isoquality maps because of an accompanying estimation of the error so there can be a stated confidence in the maps.

The information obtained during the initial data gathering and drilling phase of the reserve evaluation can be used in a "higher level" round table group consisting of the mine owner, geologist, geotechnical engineer, designer, preparation specialists, environmental specialists, operations personnel, and marketing specialists. Discussions within this group will concern the importance of the conditions on the property and the coal quality extraction sequencing and mining methods that will recover the coal most profitably.

FIGURES
CHAPTER 3.0

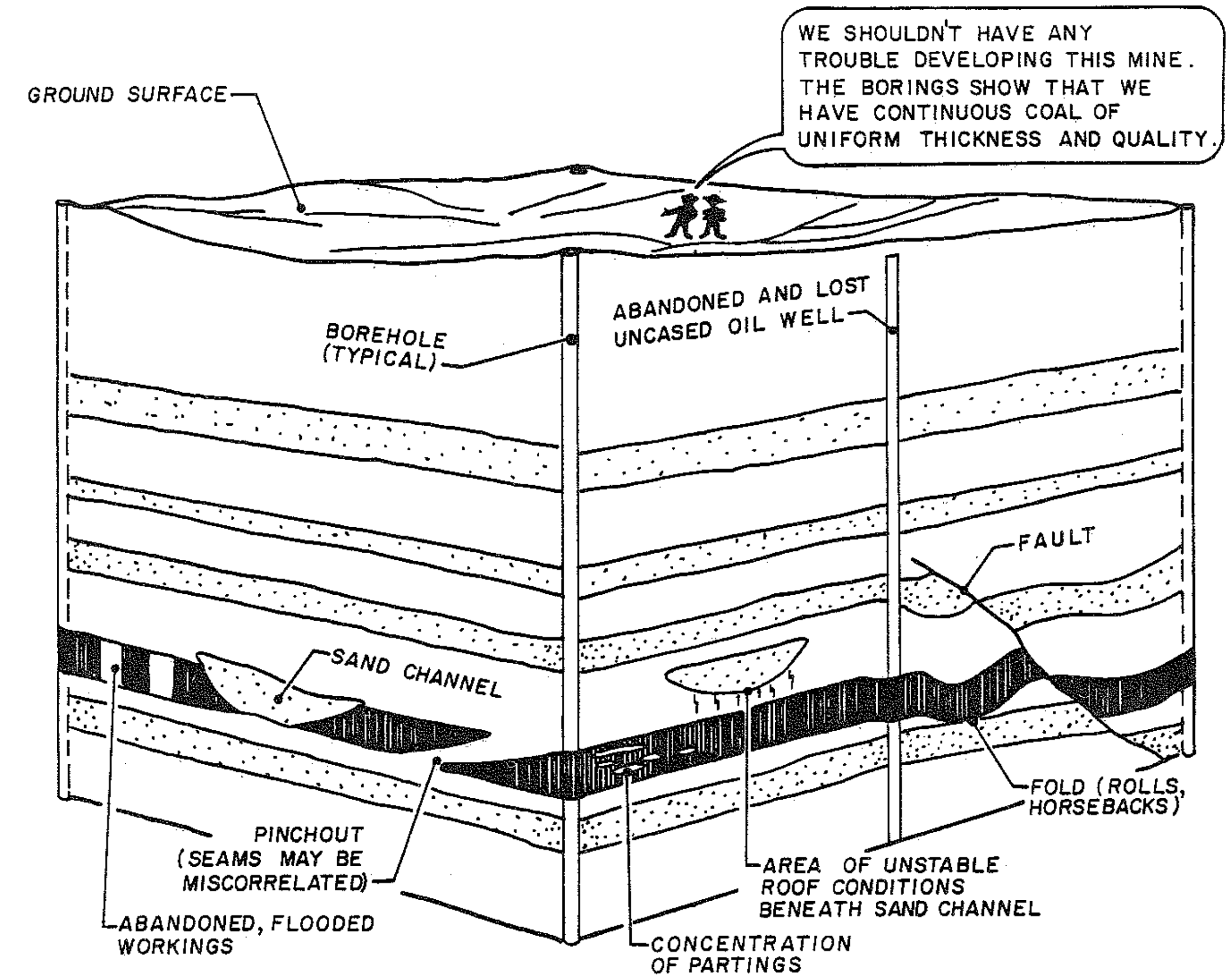


FIGURE 3-1

LIMITATIONS OF INTERPRETATION FROM BOREHOLE DATA

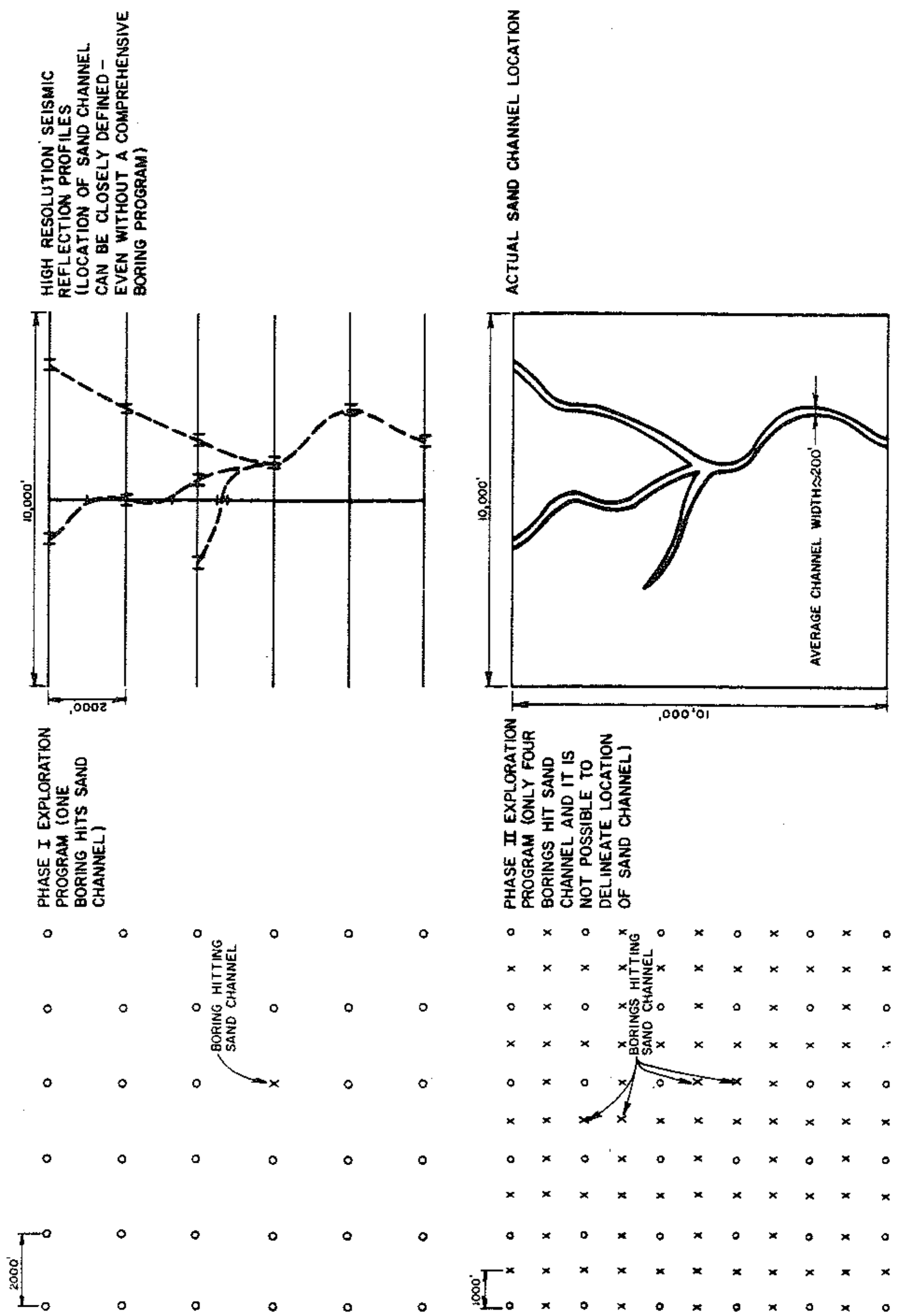


FIGURE 3-2

ILLUSTRATION OF THE ADVANTAGES IN DEFINING THE LOCATION OF A 200 FOOT WIDE SAND CHANNEL USING GEOPHYSICAL RATHER THAN CONVENTIONAL TECHNOLOGY

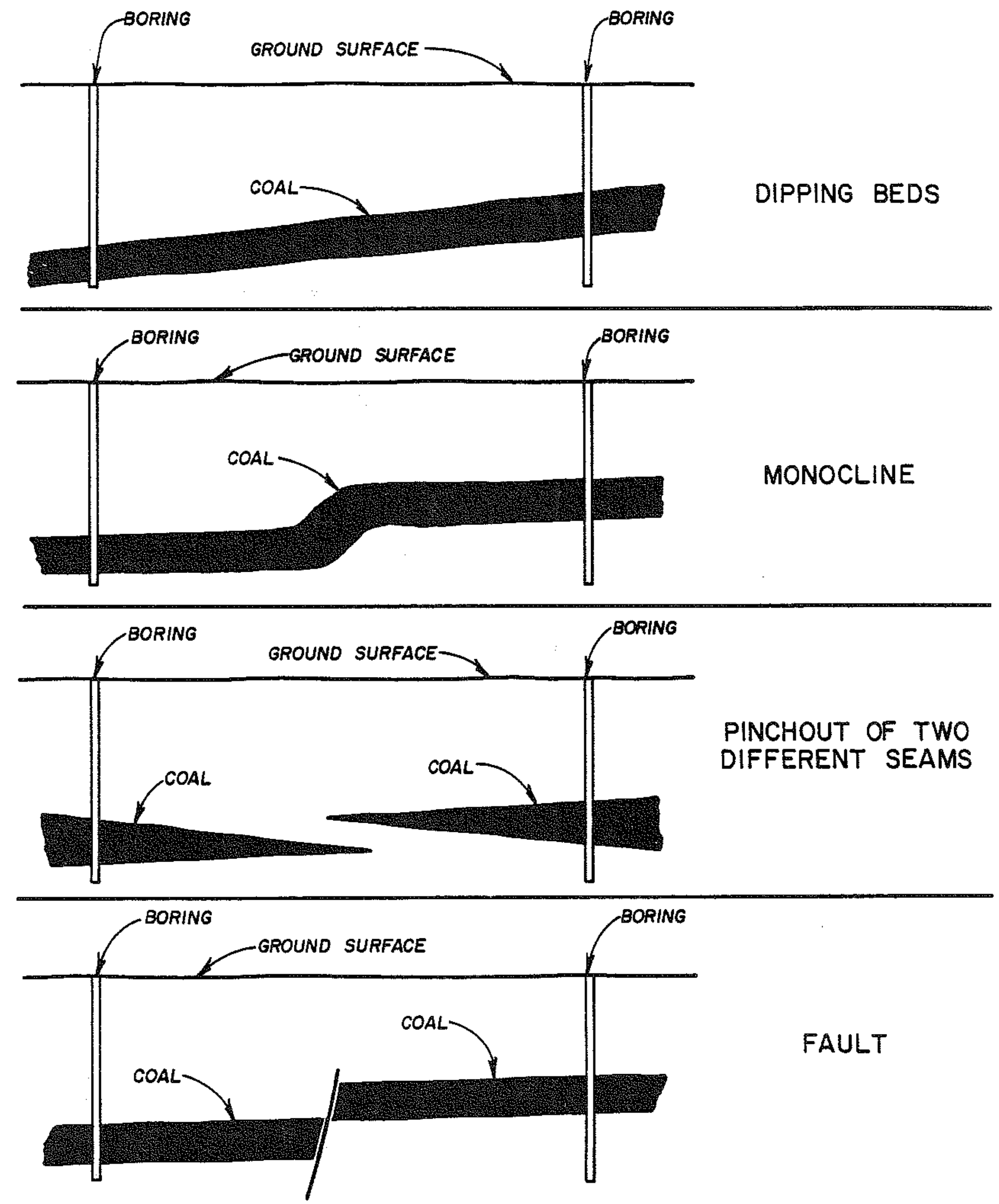


FIGURE 3-3

POSSIBLE INTERPRETATIONS OF AN APPARENT OFFSET OF A COAL SEAM AS DETECTED BY TWO BOREHOLES

TECHNIQUE		DEPLOYMENT	DEPTH TO SEAM	SEAM THICKNESS	SEAM DISCONTINUITY DETECTION	STRUCTURE	COAL QUALITY	LITHOLOGY	LITHOLOGIC CORRELATION	GROUND WATER CONDITIONS	VOID DETECTION	ABANDONED WELL DETECTION	FLOOR AND ROOF CONDITIONS	CLINKER DETECTION	RIPPABILITY OF OVERBURDEN	TARGET DEPTH/PENETRATION	DIP	TECTONIC COMPLEXITY	GROUND WATER	LITHOLOGY	SURFACE CONDITIONS	AVAILABILITY	GENERAL USE IN ALL MINERAL EXPLORATION	RELATIVE TO COAL IN U.S.	RELATIVE TO COAL OUTSIDE U.S.
	CHARACTERISTICS		APPLICABILITY														LIMITATIONS						STATE OF THE ART		
ACOUSTIC	HIGH RESOLUTION SEISMIC REFLECTION	S	(1)	2	1	1	–	2	1	3	1	–	2	–	–	1	2	2	4	4	2	C	1	2	1
	SEAM WAVE TRANSMISSION	U	–	3	1	2	3	–	1	–	1	–	3	3	–	6	4	4	4	4	–	E	4	3	1
	SEAM WAVE REFLECTION	U	–	3	1	2	3	–	3	–	1	–	3	2	–	5	4	4	4	4	–	E	4	3	1
	SEISMIC REFRACTION	S	3	3	3	3	–	2	3	2	2	–	2	2	1	2	2	2	3	4	2	C	1	2	2
ELECTROMAGNETIC	PULSE RADAR	U/S	2	2	1	1	3	2	3	2	1	1	2	3	–	3	4	4	1	2	2	C	2	2	3
	FM-CW	U	–	2	3	3	3	2	–	2	3	3	1	–	–	3	4	4	1	2	–	E	4	3	4
	HFEM	U	–	–	–	3	3	2	3	2	3	3	3	–	–	4	4	4	1	2	–	E	4	3	4
POTENTIAL FIELD	MAGNETICS	S	3	3	2	2	–	2	3	–	2	2	3	1	–	2	4	4	4	4	3	C	1	2	2
	GRAVITY	S	3	2	2	2	3	2	3	–	(1)	3	3	3	–	2	4	4	4	4	3	C	1	2	2
ELECTRICAL	RESISTIVITY	S	(1)	2	2	2	3	(1)	2	2	1	2	2	2	–	2	2	2	2	2	2	C	1	2	2

DEPLOYMENT LEGEND
S NORMALLY SURFACE
U NORMALLY UNDERGROUND

APPLICABILITY LEGEND
1 VERY APPLICABLE IN MOST CASES
(1) VERY APPLICABLE IN CONJUNCTION WITH OTHER TECHNIQUES
2 APPLICABLE SOMETIMES IN CONJUNCTION WITH OTHER TECHNIQUES
3 INDIRECTLY APPLICABLE IN SOME CASES

TARGET DEPTH/PENETRATION LEGEND
1 TARGET DEPTH >30 METERS
2 VALID FOR TARGETS ≤STRIPPABLE DEPTH
3 PENETRATION ≤15 METERS
4 PENETRATION ≤100 METERS
5 PENETRATION ≤500 METERS
6 PENETRATION >500 METERS

LIMITATIONS LEGEND
1 OFTEN A SEVERE LIMITATION
2 SOMETIMES A SEVERE LIMITATION
3 SELDOM A LIMITATION
4 NOT AN IMPORTANT CONSIDERATION

AVAILABILITY LEGEND
C COMMERCIALLY AVAILABLE IN U.S.
E EXPERIMENTAL IN U.S.

STATE OF THE ART
1 MATURE TECHNOLOGY/WIDESPREAD USE
2 DEVELOPING TECHNOLOGY/LIMITED USE
3 STRICTLY EXPERIMENTAL/HIGHLY LIMITED USE
4 NOT USED

FIGURE 3-4

APPLICATION AND SUITABILITY OF SURFACE AND UNDERGROUND GEOPHYSICAL TECHNIQUES

TYPE OF SAMPLE	DRILLING METHOD	SELF CONTAINED	MOBILE RIG	FAST SET-UP	HIGH PENETRATION RATE	LOW COST PER FOOT	CONTINUOUS DRILLING	LARGE SAMPLES	STRATIFIED SAMPLE RECOVERY	REDUCED SAMPLE CONTAMINATION	UNCONTAMINATED SAMPLES	PERIODIC BIT OBSERVATION	LOW CAPITAL COST	GOOD PENETRATION IN HARD FORMATIONS	LARGE DIAMETER HOLES	NEED RELIABLE WATER SOURCE	LARGE IMMOBILE RIG	SLOW SET-UP	LOW PENETRATION RATE	LOW CORING SPEED	HIGH COST PER FOOT	REPEATED PULLING AND REENTERING	SMALL DIAMETER HOLE AND SAMPLE	SAMPLE CONTAMINATED	BIT CHANGE FOR SAMPLING	SMALL PARTINGS NOT OBSERVABLE	NO PERIODIC BIT OBSERVATION	HIGH BIT WEAR IN HARD FORMATIONS	DIFFICULT SAMPLE HANDLING	DIFFICULTY WITH HIGH WATER INFLOW	HIGH CAPITAL COST
		METHOD ADVANTAGES														METHOD DISADVANTAGES															
CHIP SAMPLE	ROTARY ROCK BIT - AIR	●	–	●	●	●	●	–	–	–	–	–		–	●	–	●	–	–	–	–	–	–	●	–	●	●	●	●	●	●
	ROTARY ROCK BIT - WATER OR MUD	–	–	–	●	●	●	–	–	–	–	–	●	–	●	●	●	●	–	–	–	–	–	●	–	●	●	●	●	–	–
	ROTARY ROCK BIT - REVERSE CIRCULATION - AIR	●	–	●	●	●	●	●	●	●	–	–	–	–	●	–	●	–	–	–	–	–	–	–	–	●	●	●	●	●	●
	ROTARY ROCK BIT - REVERSE CIRCULATION - WATER	–	–	–	●	●	●	●	●	●	–	–	–	–	●	●	●	●	–	–	–	–	–	–	–	●	●	●	●	●	●
CORE SAMPLE	COMBINATION ROTARY ROCK BIT CONVENTIONAL DIAMOND CORE DRILLING - AIR	●	–	●	●	●	–	●	●	–	●	●	–	–	●	–	●	–	–	●	–	●	–	–	●	–	–	●	–	●	●
	COMBINATION ROTARY ROCK BIT CONVENTIONAL DIAMOND CORE DRILLING - WATER OR MUD	–	–	–	–	●	–	●	●	–	●	●	●	●	●	●	●	●	–	–	–	●	–	–	●	–	–	●	–	–	–
	CONVENTIONAL DIAMOND CORE DRILLING - WATER OR MUD	–	●	–	–	–	–	–	●	–	●	●	●	●	–	●	–	●	●	●	●	●	●	–	–	–	–	–	–	–	–
	WIRE LINE DIAMOND CORE DRILLING - WATER OR MUD	–	●	–	–	–	●	–	●	–	●	–	●	●	–	●	–	●	●	–	●	–	●	–	–	–	●	–	–	–	–

FIGURE 3-5

DRILLING METHOD COMPARISON

Type of Sample	Drilling Method \ Selection Factors	Project Suitability: Performance Criteria: Mobility	Self Contained	Loose Overburden	Hard Rock	Soft Rock	Drill Log	Coal Thickness	Coal Partings	Coal Samples	Sample Handling	Bit Observation	Ground Water Inflow	Lost Circulation (Fractured Rock)	Testing: In Situ Strength	Blasting Vibrations	Pumping	Permeability	Geophysical Log	Economic Factors: Equipment Cost	Set-Up Time	Approximate Penetration Rate (Feet per Hour)	Drilling Cost	Approximate Cost-1981/Ft.$
CHIP SAMPLE RECOVERY	ROTARY ROCK BIT-AIR	3	1	2	2	1	3	3	3	3	3	3	2	1	1	1	1	1	1	c	a	50	a	3.11
	ROTARY ROCK BIT-WATER OR MUD	2	3	1	3	1	3	3	3	3	3	3	1	1	2	1	2 OR 3	2 OR 3	1	b	b	30	a	3.72
	ROTARY ROCK BIT-REVERSE CIRCULATION-AIR	3	1	1-2	2	1	1-2	2	2	2	2	3	3	1	1	1	1	1	1	c	b	40	a	4.59
	ROTARY ROCK-BIT-REVERSE CIRCULATION-WATER	2	3	1-2	3	1	1-2	2	2	2	3	3	3	1	1	1	2	2	1	c-b	c	20	b	7.16
CORE SAMPLE RECOVERY	COMBINATION ROTARY ROCK BIT/CONVENTIONAL DIAMOND CORE DRILLING-AIR	3	1	3	2/2	1/3	3/1	1	1	1	1	2/1	2	2	1	1	2	2	1	c	b	18	b	6.24
	COMBINATION ROTARY ROCK BIT/CONVENTIONAL DIAMOND CORE DRILLING-WATER OR MUD	2	2	2	3/1	1/3	3/1	1	1	1	1	2/1	1	2	2	1	2 OR 3	2 OR 3	1	c-b	c	14	b	6.60
	CONVENTIONAL DIAMOND CORE DRILLING—WATER OR MUD	1	3	2	1	2-3	1	1	1	1	1	1	1	3	1	1	2	2	2	a	c	3	c	19.76
	WIRE LINE DIAMOND CORE DRILLING—WATER OR MUD	1	3	2	1	2-3	1	1	1	1	1	3	1	3	1	1	2	2	2	b	c	5	c	13.66

PROJECT SUITABILITY LEGEND
1. = EXCELLENT SUITABILITY
2. = FAIR SUITABILITY
3. = POOR SUITABILITY

ECONOMIC FACTOR LEGEND
a. = RELATIVELY LOW COST
b. = MODERATE COST
c. = RELATIVELY HIGH COST

FIGURE 3-6

SUITABILITY AND ECONOMIC FACTORS FOR VARIOUS TYPES OF COAL EXPLORATION DRILLING

GEOPHYSICAL LOGGING APPLICATIONS AND SUITABILITY

Log Type \ Application and Data Requirements	Instrument Limitations: Minimum Hole Diameter (inches)	Cased (C) Uncased (U)	Wet (W) Dry (D)	Lateral Penetration	Vertical Resolving Power	Seam Section Factors: Coal Seam Indicator	Seam Thickness	Clay or Shale Partings	Coal Quality Factors: Ash Content	Carbon Content	Moisture Content	Rank	Volatile Matter	Sulfur	Calorific Value	Elemental Analysis	Geology Factors: Lithology	Lithologic Correlation	Geomechanical Factors: Bulk Density	Modulus of Deformation	Fractured Zones	Voids	Structure	Aquifer Properties: Porosity	Ground Water	Flow Direction and Rate	Source of Water Inflow	Water Chemistry
NATURAL GAMMA	3	C/U	W/D	30cm	≥5cm	1	2	2	1	(1)	(1)	—	—	—	(1)	—	(1)	1	3	3	—	—	1	(1)	3	—	—	3
GAMMA-GAMMA (Density)	3	C/U	D/W	9–16 cm	≥2 cm	1	1	1	1	(1)	(1)	(1)	(1)	—	(1)	—	(1)	1	1	(1)	3	3	1	(1)	3	3	—	—
NEUTRON-NEUTRON	3	C/U	D/W	VARIABLE	≥5cm	2	3	3	(1)	(1)	(1)	(1)	(1)	—	(1)	—	2	2	2	3	3	3	—	(1)	1	3	—	—
NEUTRON—GAMMA (Spectral)	3	C/U	W/D	VARIABLE	POOR	2	3	3	1	1	1	1	1	1	1	1	2	2	2	3	—	—	—	—	3	3	—	1
CALIPER	3	U	W/D	0	2.5mm	2	2	2	—	—	—	—	—	—	—	—	2	3	2	2	2	2	2	2	2	—	2	—
FLUID MOVEMENT	5-6	U	W	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	3	3	2	3	2	1	1	3
RESISTANCE	3	U	W	VARIABLE	≥5cm	1	2	3	—	—	—	—	—	—	—	—	(1)	1	3	3	3	—	1	3	3	3	3	3
RESISTIVITY	3	U	W	VARIABLE	≥5cm	1	3	1	(1)	—	3	(1)	(1)	3	(1)	—	(1)	1	3	3	3	—	1	2	2	2	2	3
SPONTANEOUS POTENTIAL	3	U	W	VARIABLE	≥5cm	2	2	3	—	—	—	—	—	3	—	—	(1)	1	3	—	—	—	—	2	2	2	2	3
ACOUSTIC (SONIC)	3	U	W/D	30-60 cm	≥20cm	2	3	—	(1)	(1)	(1)	(1)	(1)	—	(1)	—	2	2	2	(1)	1	1	2	(1)	2	3	2	—
THERMAL	3	U	D/W	0	POOR	3	—	—	—	—	—	—	—	—	—	—	2	—	—	—	—	—	—	—	1	3	1	3
GRAVIMETRIC	5-6	C/U	W/D	10's-100's ft	POOR	2	3	—	2	—	—	3	—	—	—	—	2	3	1	2	3	1	—	(1)	3	3	3	—
INDUCED POLARIZATION	5-6	U	W/D	VARIABLE	≥10cm	2	3	—	—	—	—	—	—	1	—	—	2	3	3	—	—	—	—	—	—	—	—	3
BOREHOLE TV	2-3	U	W/D	0	1mm	1	3	1	—	—	—	—	—	3	—	—	2	3	—	—	1	1	3	3	1	1	1	—
DIPMETER	3	U	W/D	<5cm	~1°	—	2	—	—	—	—	—	—	—	—	—	2	2	—	—	3	3	1	—	—	2	—	—

APPLICABILITY LEGEND
1 VERY APPLICABLE IN MOST CASES
(1) VERY APPLICABLE IN CONJUNCTION WITH OTHER LOGS
2 APPLICABLE SOMETIMES IN CONJUNCTION WITH OTHER TESTS
3 INDIRECTLY APPLICABLE IN SOME CASES

FIGURE 3-7

GEOPHYSICAL LOGGING APPLICATIONS AND SUITABILITY

DRILLING COSTS(1)

		COST ITEM	COST($) PER DAY	COST($) PER FOOT	PERCENT OF COST	COST($) PER MONTH	COST($) PER YEAR
CHIP SAMPLE RECOVERY	ROTARY ROCK BIT DRILLING-AIR (500 ft./day)	CAPITAL	448	0.90	29	9408	112,896
		SUPPLY	856	1.71	55	17,976	215,712
		LABOR	248	0.50	16	5208	62,496
		TOTAL	**1552**	**3.11**	**100**	**32,592**	**391,104**
	ROTARY ROCK BIT DRILLING-WATER OR MUD (300 ft./day)	CAPITAL	274	0.91	25	5754	69,048
		SUPPLY	594	1.98	53	12,474	149,688
		LABOR	248	0.83	22	5208	62,496
		TOTAL	**1116**	**3.72**	**100**	**23,436**	**281,232**
	ROTARY ROCK BIT REVERSE CIRCULATION DRILLING-AIR (400 ft./day)	CAPITAL	858	2.15	47	18,018	216,216
		SUPPLY	727	1.82	40	15,267	183,204
		LABOR	248	0.62	13	5208	62,496
		TOTAL	**1833**	**4.59**	**100**	**38,493**	**461,916**
	ROTARY ROCK BIT REVERSE CIRCULATION DRILLING-WATER (200 ft./day)	CAPITAL	723	3.62	51	15,183	182,196
		SUPPLY	460	2.30	32	9,660	115,920
		LABOR	248	1.24	17	5208	62,496
		TOTAL	**1431**	**7.16**	**100**	**30,051**	**360,612**
CORE SAMPLE RECOVERY	COMBINATION ROTARY ROCK BIT/CONVENT. DIAMOND CORE DRILLING-AIR (183 ft./day)	CAPITAL	452	2.47	39	9492	113,904
		SUPPLY	443	2.42	39	10,164	121,968
		LABOR	248	1.35	22	5208	62,496
		TOTAL	**1143**	**6.24**	**100**	**24,864**	**298,368**
	COMBINATION ROTARY ROCK BIT/CONVENT. DIAMOND CORE DRILLING-WATER OR MUD (138 ft./day)	CAPITAL	278	2.02	31	5838	70,056
		SUPPLY	383	2.78	42	8043	96,516
		LABOR	248	1.80	27	5208	62,496
		TOTAL	**909**	**6.60**	**100**	**19,089**	**229,068**
	CONVENTIONAL DIAMOND CORE DRILLING-WATER OR MUD (30 ft./day)	CAPITAL	201	6.70	34	4221	50,652
		SUPPLY	144	4.80	24	3024	36,288
		LABOR	248	8.26	42	5208	62,496
		TOTAL	**593**	**19.76**	**100**	**12,453**	**149,436**
	WIRE LINE DIAMOND CORE DRILLING-WATER OR MUD (50 ft./day)	CAPITAL	211	4.22	31	4431	53,172
		SUPPLY	224	4.48	33	4704	56,448
		LABOR	248	4.96	36	5208	62,496
		TOTAL	**683**	**13.66**	**100**	**14,343**	**172,116**

(1) A. Costs reflect 1981 dollars.
B. Costs do not include return on investment, taxes, insurance, professional supervision, and dozer work.
C. Costs are based on one rig operating a 10-hour work day (21 days per month) with 3-man crews
D. Capital equipment is one year old and drill tools have a life of one year.
E. Costs reflect drilling to depths of 500 to 1000 feet.
F. Supply items are bits, fuel, tires and other miscellaneous costs.
G. The estimated production per day is based on D'Appolonia's experience with the techniques and discussions with users and manufacturers.
H. Drilling production rates can vary greatly with the experience of the crew and the material penetrated.

FIGURE 3-8

COMPARISON OF TYPICAL COSTS FOR DIFFERENT DRILLING TECHNIQUES

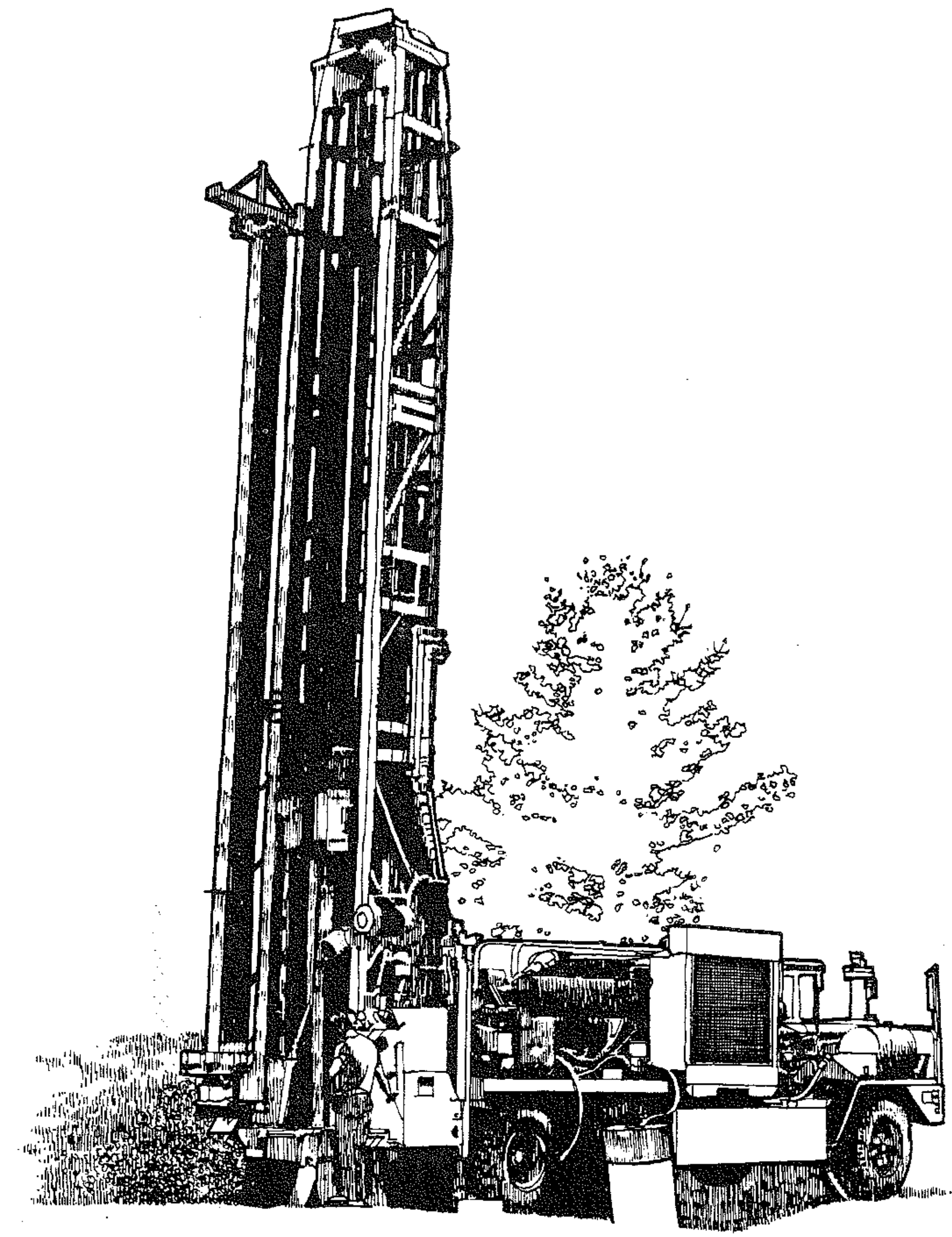


FIGURE 3-9

MEDIUM WEIGHT ROTARY (DESTRUCTIVE TYPE) DRILL RIG

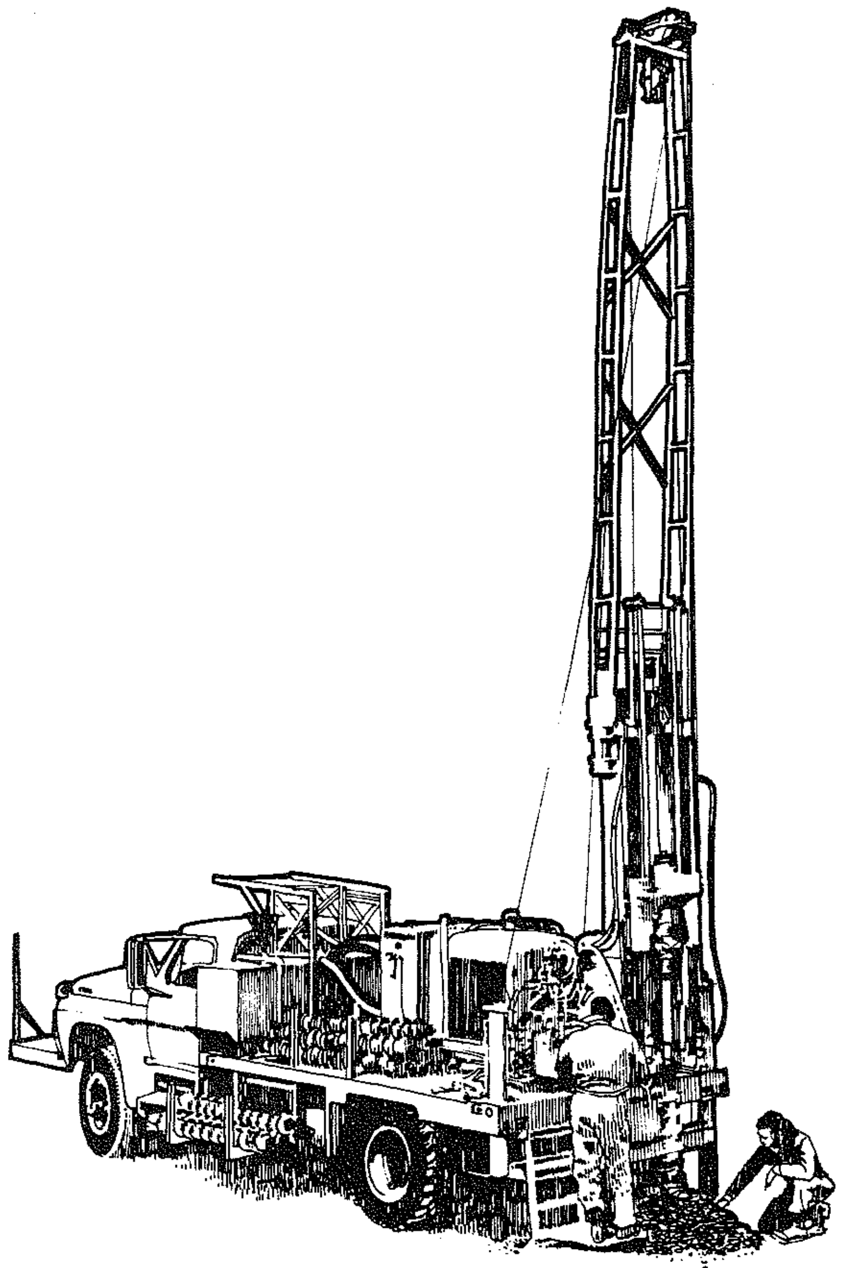
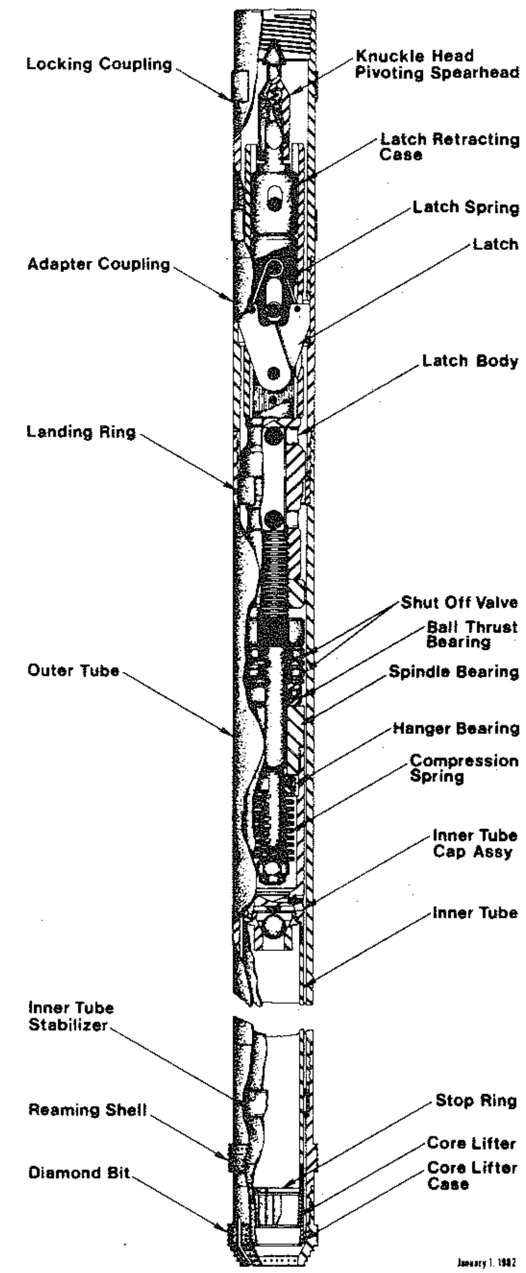


FIGURE 3-10

TYPICAL DRILL RIG USED FOR
CONVENTIONAL CORE DRILLING
IN COAL FIELDS

Longyear Q/CHD Wireline Core Barrel



Longyear Q/CHD Wireline Overshot

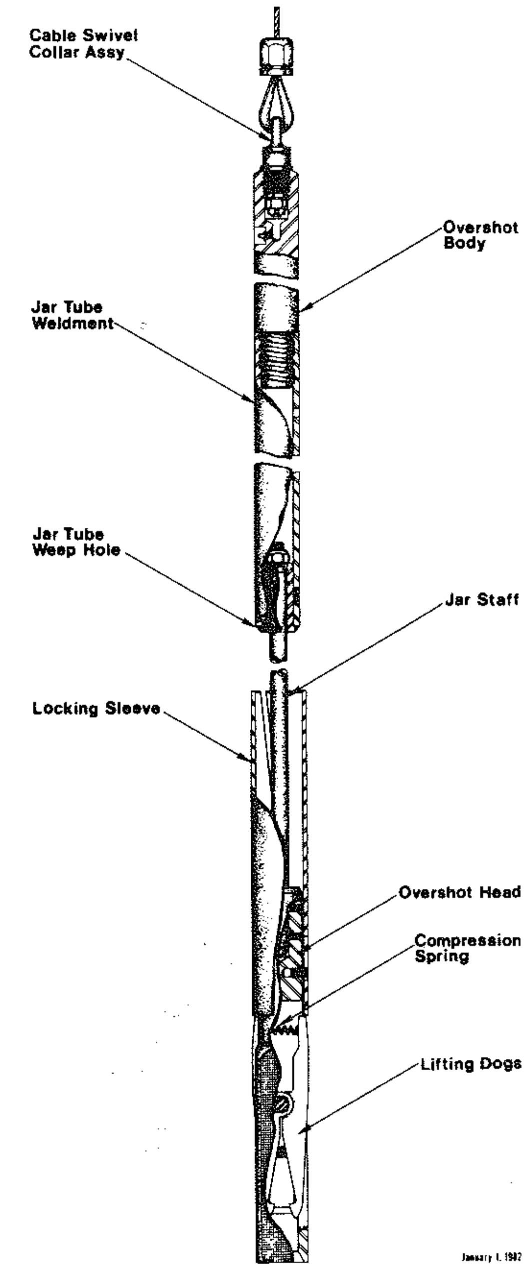


FIGURE 3-11

WIRELINE CORE BARREL
AND OVERSHOT ASSEMBLY

REFERENCE:
PROVIDED THROUGH THE COURTESY
OF THE LONGYEAR CO.

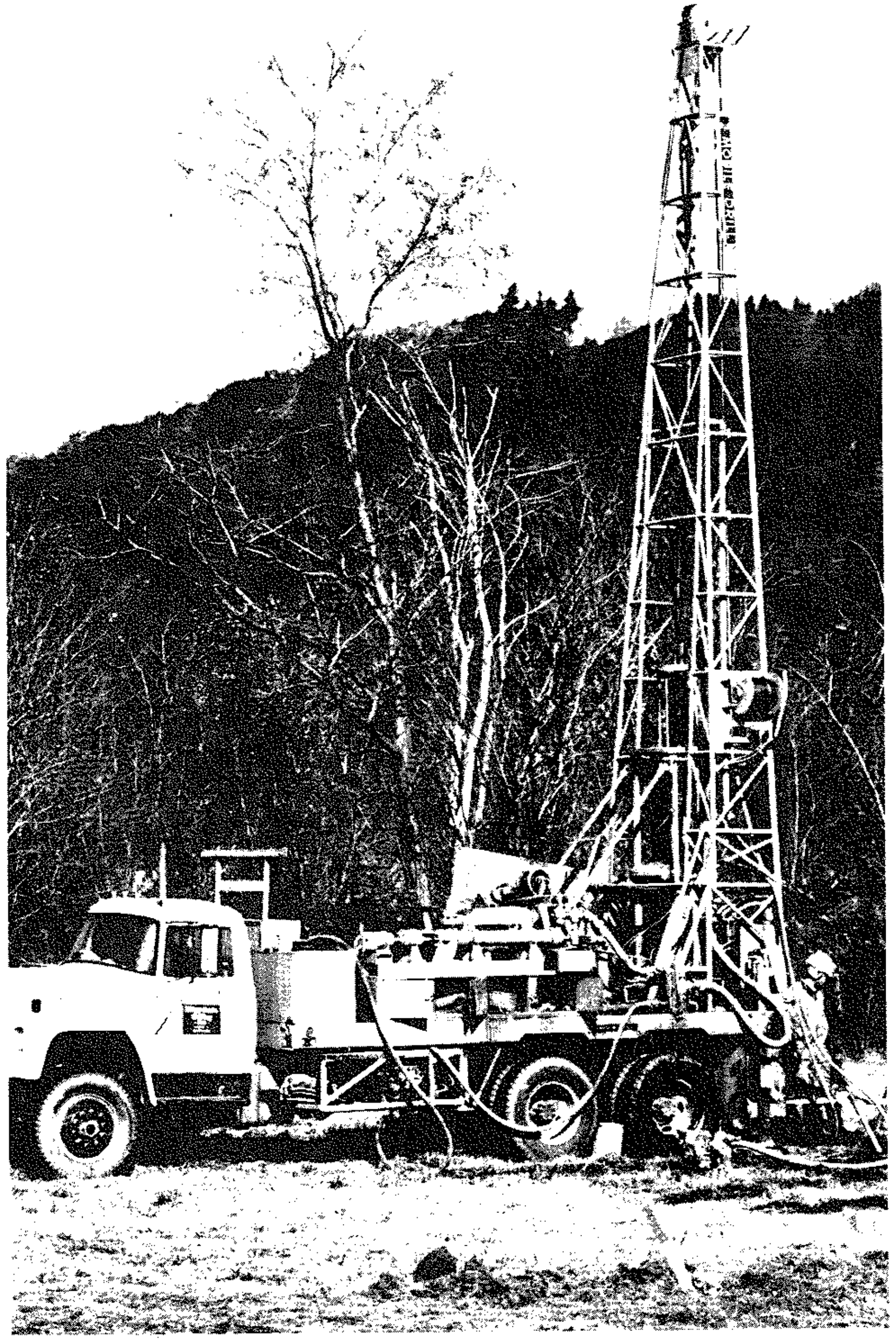


FIGURE 3-12

TYPICAL DRILL RIG USED FOR WIRELINE CORE DRILLING IN COAL FIELD

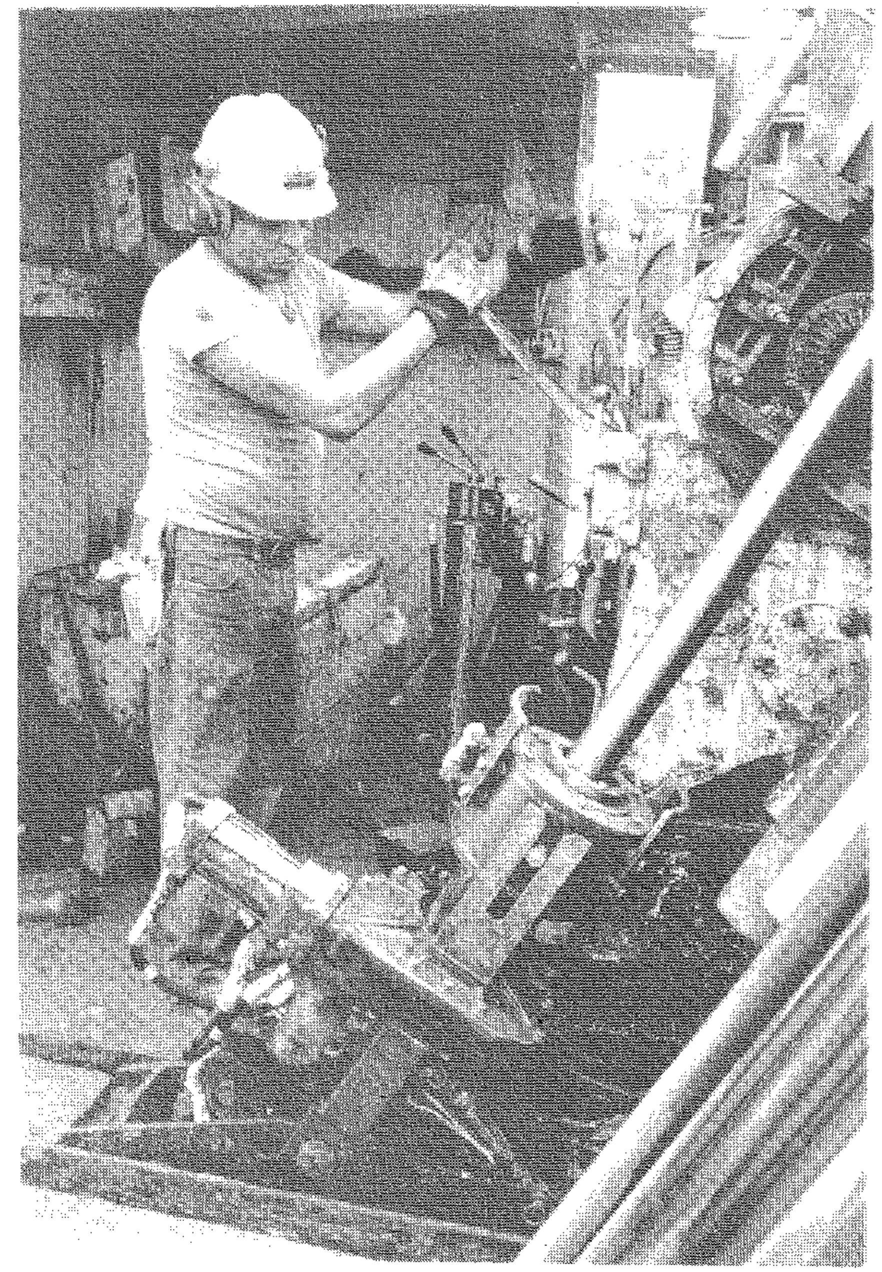


FIGURE 3-13

AUTOMATIC PRE-TORQUE AND BREAKOUT TOOL

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4.0 COST-BENEFIT ANALYSIS

4.1 INTRODUCTION

Geophysical methods will be used because of a number of factors:

- They have been shown (i.e., experience demonstrates them) to be a cost-effective means to acquire needed information.
- They are mandated by regulations.
- They are customary.

The latter two are insignificant at present. We know of no regulations in existence or pending which require the use of geophysics. The use of geophysics, as applied to coal, clearly has not advanced to the status of customary use, such as the routine use of electrical or EM methods for sulfide mineral exploration. This chapter focuses on the first factor, cost-benefit.

Implicit in the concept of cost-benefit is a comparison of alternatives, thus this chapter discusses a general situation where the use of geophysics is compared with its nonuse and also where it is used in conjunction with other technologies, primarily drilling.

The costs and the benefits of the use of geophysical techniques are sensitive to a number of factors, none of which are explicitly quantifiable. An attempt has been made to use some typical coal mining scenarios developed in Chapter 2.0 (to define what is needed) along with the information regarding the predictable performance and cost components of the geophysical technology developed in Chapter 3.0. The following paragraphs discuss costs and benefits in general terms.

The cost of any information program is composed of many components and accounting methods. The examples selected assume that for any survey the capital costs for equipment and training of personnel are included on an amortized basis--that is to say these costs are distributed over several such projects. Costs are also variable based upon experience, both of the field crew and the geophysical interpreters and the general use of the technique in the coal mining industry. The surveys are assumed not to be pioneering efforts, but still have some degree of customization required so that they are still not classifiable as "routine production-oriented projects." Cost variability is also introduced by site conditions (e.g., terrain, structural complexity, coal depth, number of seams, etc.) and detail and precision required. An attempt has been made to exemplify those aspects that are most typical of a major coal mining project. Costs have been considered in the aggregate, although it is recognized that in industrial practice, costs for various specific aspects of premining investigations may be allocated among

several cost centers. One particular advantage of geophysical methods is that the survey results can be used for multiple purposes, resource evaluation, engineering and mine planning, and for environmental consideration. This is another argument considering the use of geophysics from the start of a program.

Benefit is not easily definable in quantitative terms. An attempt has been made to define situations where the applied geophysical technique has a reasonable chance to provide the data of interest. Instances where the differences in data types, amounts, or quality are important will be identified.

4.2 COMPARISON: BORINGS VS. HIGH RESOLUTION SEISMIC REFLECTION

4.2.1 Introduction

Generally, reflection surveys are performed to achieve either or both of the following:

- Gain a comprehensive overview of a coal prospect, including potentially usable data on:
  - Number, thickness, and gross structures of seams
  - Structural or other discontinuities
  - Mapping of abandoned workings
  - Roof and floor rock characteristics
- Resolution of operational problems, such as how far does a fault encountered in mining run and where does the sand channel go?

As stated earlier, the ability or success of achieving any of these objectives depends upon circumstances. These have been discussed in the preceding section and in detail in Appendix B. It is reiterated that the success, and hence the benefit, of any geophysical endeavor can only be judged by the quality of the data, as site conditions and technique will permit, in terms of the data needs as site conditions and mine planning require. Cost-benefit can be assessed by comparing the alternatives:

- Drilling/coring operations only, or
- An integrated program of geophysics and borings.

4.2.2 Integrated Exploration Program

The integration of the high resolution seismic reflection technique into a drilling exploration program is a very rational consideration. Given an adequate technical basis, a cost-benefit question could be expressed as: how many miles of reflection equals how many boreholes. The underlying premise is that the two techniques complement the other's weakness; as generalized below:

Technique	Strength	Weakness
Borehole (core/log)	Point Detail	Areal Coverage
Seismic Reflection	Areal Coverage	Point Detail

It must be recognized that the relative difference between these factors depends upon site conditions and how important is the resolution of an issue.

For example, the presence of sand channels, besides reducing the reserves of coal, may adversely impact the minability of the coal and the mining costs. It is recognized that given the documented or suspected presence of sand channels, a program to define their extent and impact is a prudent action. One component of that is geologic analysis; the other coupled component is field data acquisition. Figure 3-2 illustrates a sample sand channel system. The illustrations within Figure 3-2 represent a progressively denser patterned drilling program which is simply used to illustrate the ineffectiveness of blind drilling. A sand channel network probably would occupy less than three percent of the land area, but be so distributed as to far more significantly impact the mine plan and costs than its low percent may suggest. The probability of any drill hole, sunk at a random location such as on a grid pattern, of striking sand instead of coal is equal to the proportion of sand to coal. Faced with this situation, the prudent explorer calls upon the geologist to push his interpretations of structural patterns, aerial imagery and the like, to guide the drilling locations. Stepouts from known intercepts of the channel are made.

The seismic reflection technique cited above could be, in effect, an adjunct which not only delineates the sand channels (at possibly lower cost in a more detailed way), but which also can provide additional information as well.

4.2.3 Cost-Effective Comparison

An integrated exploration program using a combination of drilling (rotary rock bit and diamond core drilling), geophysics (surface and downhole), and geostatistics probably results in the most cost-effective coal exploration program. The primary advantages to using this combination are cost and time savings, as slower, expensive core drilling is replaced by higher production, less expensive rotary rock bit drilling and the effectiveness of downhole geophysical logging, and borehole spacing is increased with the use of surface seismic reflection between boreholes.

If a targeted coal seam is not exposed or defined by previous mining, it is general practice to initially drill several well-spaced diamond core

holes on a property. Besides providing necessary calibration and control information for downhole and surface geophysics, coal core extracted from these holes confirm the coal and its quality and thickness for mine owners, coal buyers, and marketing specialists who may not be comfortable with geophysical methods and their lack of "hands on" exposure.

Unless numerous exposures and previous drill holes are available, the density of coal observation points is probably not adequate for geostatistical analysis after these initial diamond core holes are put down. A pattern is then developed during the second phase of the exploration program, usually around the initial holes, using rotary rock bit drilling and downhole logging. In Section 3.2.5 it was suggested that the initial holes be put down in a profile line along an assumed main entry at 1/2 mile centers and in a profile at a right angle to the main entry one mile apart. Also, depending on access, if an underground property is taken to the mine planning phase, a grid with data points at 1/2 mile centers should be approximated. Integrating surface geophysics and geostatistics into this second phase of drilling may permit a substantially increased borehole spacing to be used, say to one mile centers. Additional borings would be put down where needed based on:

- Estimation of variance information from geostatistics for thickness and quality parameters (i.e., sulfur, ash, and Btu)
- Detection of faults and channel sand washouts by high resolution seismic reflection.

Review of the seismic reflection data and the variance information will determine where additional borings and/or seismic sections (phase three exploration) may be required. The additional drilling could be core drilling or rock bit rotary with logging depending on if the reduction of the confidence interval is for quality, thickness, or geotechnical parameters.

Using a medium-sized property in Appalachia, an example can be made of how the use of an integrated exploration approach can have a distinct cost benefit over an attempt to core drill to a tight grid. All coal properties in the east each uniquely present different problems to an exploration project and there probably is no "typical" coal property. However, the property described for this example exhibits some of the more common problems.

The property contains about 11,000 acres of steep, forested hillsides. The vertical relief is about 750 feet; with elevations ranging from about 780 to 1,530 feet above sea level. The property is somewhat elongated in a north-south direction with the eastern border consisting of a ridge line and the western border consisting partially of a major stream, a ridge line, and a random boundary configuration caused by the acquisition of several adjacent smaller tracts.

The coal seam targeted for exploration outcrops at about Elevation 800 feet at the south edge of the property and just west of the west property boundary. The general dip of the structure is toward the east at about two percent.

To confirm the areal extent of minable thickness of the seam on the property and its quality, ten preliminary diamond core holes are put down. Six of these borings are put down at locations with easy access, generally in a north-south line (assumed main entry) through the center of the property. The other four borings are put down at right angles to the main entry (two on each side) to check the dip of the seam. The borings are cored for the entire length and analyses of the coal cores are performed. If the results of the initial borings indicate that the property has potential for development, the second phase of exploration is initiated.

As the initial borings will probably not reveal any significant information concerning trends on the property, the drilling pattern for Phase Two should approximate a systematic grid. As previously indicated, it has been the practice, within access constraints, to obtain data points at 1/2 mile centers. A rectangular grid system, with coordinates at 1/2 mile spacing superimposed on the property designates 76 boring locations. The average depth to the coal from these locations is about 300 feet. The approximate cost of diamond core drilling with wire line techniques at 1/2 mile centers is as follows:

Item		Cost ($)
Drilling $13.50/ft x 300 ft x 76 holes	=	$307,800
Dozer (access) $400.00/day x 76 holes	=	30,400
Field supervision of drilling (three rigs) $300.00/day x 152 days	=	45,600
Total cost for Phase Two diamond core drilling program		$383,800

For an integrated exploration program, the Phase Two drilling is located on a rectangular grid coordinate system having a wider spacing, say one mile. Twenty-two boring locations are identified at one mile spacings. Most of these borings are put down using rotary rock bit drilling with air and they are logged with geophysical techniques. However, as most of the initial diamond core holes were put down in a north-south line through the center of the property, five additional core holes are designated east and west of this line for better quality coverage and additional observations of roof and floor rock conditions.

High resolution surface reflection seismic is performed on all grid lines except those bordering the edge of the property or only traversing a small segment of the property. About 20 miles of reflection seismic

are identified. Note that in this example quite a bit of seismic reflection is used to see the impact on cost and data coverage. This presumes that the principal concern of this property is mining conditions and other factors which seismic reflection delineates very well, as opposed to concern for major coal quality variations, for example.

The approximate cost of the rotary drilling, logging, and seismic reflection is as follows:

Item		Cost ($)
Drilling and Logging (rotary air) $5.00/ft x 300 ft x 17 holes	=	$ 25,500
Drilling (diamond core and logging) $14.50/ft x 300 ft x 5 holes	=	21,750
Field Supervision of Drilling $300.00/day x 30 days	=	9,000
Reflection Seismic Survey 20 miles x $15,000/mile	=	300,000
Total cost of Phase Two integrated exploration program.		$356,250

As indicated, the integrated approach does not necessarily result in big, or for that matter, any cost savings when high resolution seismic reflection is used. However, the combining of surface seismic techniques with boreholes provides both point-specific data and general information resulting in a more cost-effective exploration program. In areas where sand channels, faults, and abandoned works (which have a low probability of being detected by borings) are of concern, this example program using high resolution seismic reflection would result in a far better definition of conditions than a straight drilling program alone.

Using geostatistics in the analysis of the phase two data improves the current drilling operations and determines where additional borings should be placed to improve the reserve estimate and obtain quality data where information is lacking. The use of geostatistics will more than likely result in the identification of a few needed additional borings, (Phase Three drilling program), however, the borings will probably be fewer and more cost-effective than additional borings selected by more traditional methods.

For our example property, five borings are designated to obtain information on thickness variability and five for quality or geotechnical variability. Also, two additional miles of reflection seismic survey are required to define the extent of sand channeling. The cost of this Phase Three exploration work is as follows:

Item		Cost ($)
Drilling and Logging (rotary air) $5.00/ft x 300 ft x 5 holes	=	$ 7,500
Drilling (diamond core and logging) $14.50/ft x 300 ft x 5 holes	=	21,750
Field Supervision of Drilling $300.00/day x 30 days	=	9,000
Reflection Seismic Survey 2 miles x $15,000	=	30,000
Total cost of Phase Three integrated exploration program.		$68,250

Only 16 diamond core holes could be put down for the equivalent cost of the example Phase Three integrated exploration approach. If ten borings are used to evaluate quality and thickness parameters, only six borings would be available for defining a sand channel for the same dollar. If only one or two of these holes encounter the sand channel it would be very difficult to predict the direction of the washout.

The level of sampling and testing employed to determine the quality characteristics of the coal will depend on the intended use of the coal, preparation required, and to a lesser degree, the mining method employed. Typically, all cores extracted are analyzed or tested to provide the following:

- Proximate Analysis
  - Moisture
  - Ash
  - Volatile Matter
  - Fixed Carbon
  - Sulfur and Btu content (on individual basis)

  Some laboratories include ash-fusion temperature in the proximate analysis. The short proximate analysis used for quick assessment of steam coals consists of moisture, ash, sulfur, and Btu.

- Ultimate Analysis
  - Carbon
  - Hydrogen
  - Sulfur
  - Nitrogen
  - Ash
  - Oxygen

Recently, chlorine has been included in the ultimate analysis, however, generally there is an extra charge.

- Ash Fusibility
  - Initial Deformation Temperature
  - Softening Temperature
  - Hemispherical Temperature
  - Fluid Temperature
- Mineral Analysis of Ash
- Grindability
- Free-Swelling Index (FSI) - a cokability analysis
- Equilibrium Moisture
- Ash Viscosity
- Water Soluble Alkalies
- Sulfur Forms

Prior to submitting coal core to a laboratory, a detailed log of each core should be made, giving a description and measurement of each horizon or zone of the seam. It is often recommended to have laboratories log the coal core again, prior to preparation for testing, to insure that the designated core is being tested. Also, detail logs should be made of about 50 feet of the roof rock and 20 feet of the floor rock. This core should be logged for structural information, using rock-quality designation (RQD).

In order to meet environmental requirements and to assure a uniform boiler feedstock, coal consumers are specifying clean coal (washed coal). It is, therefore, necessary to submit representative samples to washability testing or float-sink analysis. The specifics of the test and the number of cores subjected to float-sink analysis will depend on the consumers' specifications of washed coal quality and the total number of cores obtained. Generally, 20 to 50 percent of the cores should be subjected to float-sink analysis; however, if selected coring is used, a greater proportion must be tested.

The remaining cores are tested as per the previous list, testing the composite seam for the majority of the cores and each horizon separately for some.

Costs for performing the suggested analyses are shown in Table 4-1, Cost of Coal Analysis. The costs were obtained from laboratories at various locations in Appalachia and Colorado. It can be noted, especially in the east, that a considerable range of prices for specific tests were quoted. Washability testing is always quoted on an individual project basis.

The cost of coal quality analysis for the total diamond core drilling program on the hypothetical eastern coal property would probably range from about $60,000 to $100,000. This includes performing the tests indicated on Table 4-1, on the ten preliminary cores and about half of the 76 phase two cores, washability tests on 10 to 15 cores and proximate analyses on the remaining cores.

Coal testing costs using the integrated exploration approach for the eastern coal property previously described would probably range from about $20,000 to $35,000. This includes performing the tests indicated on Table 4-1, on the ten preliminary cores and the five cores extracted during Phase Three drilling and washability tests on the five cores obtained during phase two exploration. Based on a similar testing program performed by one of the responding laboratories, the washability testing for these five cores would probably range from $13,000 to $22,000. As all drill holes are geophysically logged, additional quality information can be obtained by computer analysis of digital data obtained from the suite of logs from the rotary rock bit holes. Also, for the core recovery holes, preliminary computer analysis of seam quality and structure can be used to identify sample and testing intervals within a seam, resulting in a reduction of sample intervals and therefore, laboratory costs and improved correlation of seam units from core to core.

As in the east, western United States coal exploration shows a trend toward fewer drill holes and the increased use of geophysics (both downhole and surface). This trend is probably stronger in the west because of specific problems related to the occurrence of western coal and the lack of basic geologic information due to minimum development and available geologic investigations. The specific problems related to the occurrence of western coal are as follows:

- Occur in isolated structural basins.
- Discontinuous seams.
- Few outcrops.
- Burned and eroded outcrops.
- Complex structure.

The phases of exploration for both eastern and western coal exploration are basically the same, however, in western exploration more time and effort is directed toward the earlier, predrilling phases. The lack of existing and previous mining and geologic publications on western coal areas requires more intensive field reconnaissance and mapping phases. The narrow basin configurations and scarcity or lack of outcrops necessitate detailed field mapping and depositional environment interpretation prior to drilling so that drill holes yield maximum information and do not miss targeted seams. High mobilization and water transport costs to remote areas make drilling very expensive. Magnetic surveys are

often performed to locate burned outcrop areas during the mapping phase of exploration.

Contrary to what one would think, considering the scarcity of water in many remote western areas, rotary rock bit drilling with water, utilizing downhole geophysical logging is most frequently used in the west. Frequent soft formations and highly fractured zones make rotary air and diamond core drilling difficult. Obviously, some core drilling must be done to ascertain coal quality and geotechnical parameters. Vaninetti, 1978, outlines a coal exploration project for an underground reserve (approximately 25,000 acres) in the Wasatch Plateau, Utah. During phase two exploration, 18 holes were drilled and geophysically logged, three of which were core drilled for coal quality analysis and rock mechanics testing. Some outcrop and previous mining quality information were available.

Difficult terrain and a limited exploration season due to severe weather conditions make drilling virtually impossible in some areas. It has been common practice in some western areas (deep mine reserves) to make adit entries into seams for bulk samples for analysis and testing. This is sometimes necessary to obtain samples beyond burned or oxidized zones. For the most part, exploration for western deep mining coals is similar to exploring for its eastern counterpart, however, the trend toward rotary rock bit drilling and downhole geophysical appears stronger.

4.3 SUMMARY

This chapter has indicated that the benefits of alternative means of coal exploration are not strictly quantifiable. An example of an integrated exploration program which employs geophysics as a vital part has been offered. A comparison was made for an "actual" site case with the costs for a program relying solely on coring (and geological analyses) alone. The costs of the two programs were very comparable; the reader can judge the relative benefits. In the drill-only program, "high-confidence" detail is known at a large number of points. The integrated program yields a lesser number of "high-confidence" detail points but compensates by providing extensive lateral description and projection of the characteristics of the coal seam and bounding rocks. If knowledge of mining conditions, as may be related to structures, etc., was more important than say washability, then the integrated program (as presented) would be favored. However, if a washability was paramount, and it was highly variable over the site, less geophysics and more core holes would be recommended.

TABLE
CHAPTER 4.0

TABLE 4-1
COST OF COAL ANALYSIS[1]

TEST ITEM	EASTERN U.S. ($)	WESTERN U.S. ($)
Proximate Analysis[2]	36.00 - 56.00[3]	33.00 - 37.00
Short Proximate Analysis	19.00 - 33.50	22.00 - 29.00
Ultimate Analysis	65.00 - 141.00[4]	66.00 - 89.00[4]
Ash Fusibility	18.00 - 56.00	23.00[5]
Mineral Analysis of Ash	115.00 - 155.00	130.80 - 150.00
Grindability	30.00 - 41.00	28.00 - 41.00
Free-Swelling Index	5.50 - 23.00	7.00 - 11.00
Equilibrium Moisture	40.00 - 48.00	32.00 - 49.00
Ash Viscosity	70.00 - 95.00	-
Water Soluble Alkalies	35.00 - 50.00	27.00 - 44.00
Sulfur Forms	30.00 - 69.00	36.00 - 43.00
Washability Studies	quoted	quoted

(1)1981 dollars.
(2)Includes sulfur and Btu.
(3)Includes ash-fusion.
(4)Includes chlorine.
(5)Only one response.

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CHAPTER 5.0

5.0 RECOMMENDATIONS AND CONCLUSIONS

This report identifies the information planners require in order to locate, evaluate, plan, or operate a successful coal mine. In the past, the principal information users were the staff of (or contractors to) a coal production organization. The consumers of coal, primarily utilities or the metallurgical industry today, but likely to include synthetic fuel producers in the future, are rapidly evolving into sophisticated purchasers, demanding a well-defined coal product. The definition includes quality, cost, and delivery schedule. A recent conference entitled "Workshop on Applied Coal Geoscience and the Electric Utilities" (November 2 to 4, 1981 - Austin, Texas; sponsored by the Electric Power Research Institute, the Texas Energy and Natural Resources Advisory Council, and the Texas Bureau of Economic Geology) emphasized this perspective. The proceedings of this conference are recommended reading for those wishing to capture the essence of this very important trend.

Price (1981) made the point in the workshop that when considering long-range planning, facility siting, and development/operations phases, geoscience techniques will increase the confidence in reserve description and that the ensuing knowledge of mining hazards will reduce risks of users and producers. In this workshop was a near total absence of mention or disussion of geophysics as a potentially powerful tool although a detailed discussion of drilling programs, geostatistics, and depositional analysis was presented. Although these observations form only a small part of the basis for our conclusions, they do form an apt preface to our major conclusion: the potential power of geophysics is not as well recognized as it could or should be. Accordingly, our principal recommendations are those which have as objectives education, demonstration, and confidence building rather than discrete hardware or analytic improvements.

5.1 CONCLUSIONS

The overall state of the art of coal geophysics on a technical basis is near mature for techniques that have uses other than coal exploration/characterization. The geophysical techniques that have developed strictly in association with the coal industry, i.e., seam wave seismics (transmission and reflection) are not yet mature, particularly in the United States. These techniques, however, are well developed in Europe.

Applications and degree of refinement of coal geophysics do not appear to be as well advanced as the geophysical technology applied to the oil and gas and mineral (e.g., sulfide or uranium deposits) exploration industries, but this is a relative judgment. Research and development activities are ongoing at a number of government and private facilities. This study did not compare the percentage of coal industry revenue dedicated to geophysical research with that of the oil and gas industry, but it is clear that the percentage is very small. Nevertheless, much of the technology developed for the oil and gas industry can be modified for coal applications.

With regard to the overall state of the art of coal geophysics, the main conclusion is that presently existing technology is underutilized. Research and development is still required for specific examples of equipment and data processing software, but this need is overshadowed by the greater need of the coal industry to understand the application and limitations of the different techniques in providing information that can be adapted and integrated into existing programs of exploration, characterization, and problem solving. An important aspect of this understanding is the need to develop confidence in geophysical interpretations. As emphasized in this report, the coal industry is not accustomed to utilizing the results of a geophysical survey. The geophysical data must be interpreted and presented in a form which the non-geophysicist, the mine planner, can utilize the information. Where the geophysical results are ambiguous, the mine planner should have an understanding of the alternative explanations which will be consistent with the data.

In addition to these main conclusions, some observations have been made regarding specific techniques. The level of development and application varies among the methods, in particular as they are used in the United States and Europe. The following sections provide technique-specific conclusions.

5.1.1 High Resolution Seismic Reflection

High resolution seismic reflection profiles provide the only means of detecting the detailed structure of a deep coal seam from the surface. The technique appears to be applied with the greatest success and frequency in the United Kingdom and in the Federal Republic of Germany, at least as represented from the open literature. In the United States, there appears to be insufficient general industry recognition of the field and geologic conditions under which the technique can be expected to produce meaningful results, and, conversely, when problems can be anticipated. It is encouraging to hear (from proprietary sources) that the local operators of some mines have successfully applied high resolution seismic reflection surveys to resolve production problems, but it would be more encouraging to hear that the problems were avoided because the surveys were conducted before the beginning of mining operations.

The number of published case histories of the use of the seismic reflection method to map United States coal is negligible. Accordingly, unless a coal operator has access to proprietary material, there is no available basis for assessing the usefulness of the method, let alone whether there is information about the results and problems that may be specific to a particular coal field. The opposite situation exists, for example, in the United Kingdom, where the National Coal Board can draw upon the experience of thousands of kilometers of previous work to design new surveys with the greatest probability of success. One can presume that if United States case histories were more public and subject to more widespread reappraisal, the application of these surveys would increase and their technical performance improved.

Currently, available field hardware and processing systems appear to be adequate. A wide variety of sources are commercially available and under development, although it is recognized that the development of the "perfect" high resolution source, one which is inexpensive, highly portable, and can be repeatable over a broad frequency spectrum at a high energy level, is a worthwhile R&D goal. Additional research to optimize the field procedures used in a high-resolution survey could also be beneficial. Field costs are closely tied to how efficiently field crews can lay cable and place receivers and shots. Studies indicate that the best technical results are obtained when the source and receivers are placed in shallow boreholes and this procedure can be time consuming and expensive.

5.1.2 Seam Wave Seismics

The seam wave seismic methods are well developed in Europe and used on a routine basis to detect discontinuities in a coal seam hundreds of meters in advance of the working face of the mine. The technique is still experimental in the United States and a major limiting factor to its use is that mine-suitable equipment has not been developed. In addition, as was apparent in a seam wave workshop held at the 1981 Annual Meeting of the Society of Exploration Geophysicists in Dallas, Texas, the physics-mathematics involved in the processing and integration of seam wave data is highly complex. The short history of its use (relative to surface seismic reflection), the complexity of the physics-mathematics, the lack of mine-suitable equipment, and the general uncertainties in interpretation appear to preclude the widespread use of this technique in the United States within the next few years.

5.1.3 Borehole Logging

Borehole logging is a mature technology. Presently, there exists a wide range of tools and interpretive techniques which taken together can nearly replace coring for all general information requirements except those relating to coal quality. Basic lithologic and geotechnical information can be routine in most cases. The identification of coal and the resultant calculations of thickness have certainties and precisions adequate for most applications. Resolution of coal bed thicknesses to within one or two inches can commonly be achieved. Likewise, splits or ash stringers of one to two inches in thickness can be recognized. Success has been achieved in using multilogs and cross-plotting or computer data analysis to calculate moisture-carbon-ash values rivaling core analyses in accuracy. Neutron-gamma spectra logs offer the potential for in situ quantitative chemical analyses. These logs are still experimental and are not yet cost-effective, but additional R&D may allow for their eventual routine use. The possibility exists that log data may entirely supplant core data for routine information, and that coal be "bought and sold" on that basis.

5.1.4 Electrical/Electromagnetic/Radar

The electrical resistivity method has received limited use over a long period of time in the evaluation of shallow coal reserves. A major limitation has always been uncertainties in interpretation when the earth exhibits too many vertical and horizontal variations in resistivity as is commonly the case. This difficulty is being overcome by recent developments in computer processing and modeling. Computerized data gathering, processing, and modeling have been developed specifically for void detection. The development of this equipment for better resolution of abandoned workings in coal and in developing a general electrical model of the subsurface is a worthy R&D goal.

Radar has demonstrated its usefulness in detecting hazards such as abandoned wells and discontinuities in the coal up to a distance of about 50 feet (15 meters) from the working face of the mine. Commercial equipment is available with this capability. More widespread utilization of this technique will probably occur as current R&D efforts extend the effective range of radar reflection measurements.

5.1.5 Magnetics and Gravity

Magnetic and gravimetric methods are based on mature technologies. Although they have limited application to coal exploration/characterization, they can be highly effective for resolving specific targets in shallow coal, such as burn zones, coal cutoffs, buried stream channels, and shallow voids. Borehole gravimetry, a relatively recent advance, is available as a commercial service, although its cost benefit for coal is probably not favorable. It's not likely that airborne gravimetry, an area receiving some attention in the geophysics industry, will have the accuracy and precision necessary for most coal projects, but aeromagnetic surveys are showing good promise for rapid regional reconnaissance of burn zones in shallow coal. Probably the single-most important advance in the field of gravity and magnetics has been the introduction of interactive graphics. The most effective have been those where magnetic and gravity data can be used simultaneously.

5.2 RECOMMENDATIONS

In the following sections, recommendations are presented and discussed, but are not addressed towards any particular group for possible action.

5.2.1 General Recommendations

General recommendations cover the spectrum of geophysics and drilling technology. In response to the major conclusion, most of the following recommendations could serve to:

- More clearly formulate when, where, and how might geophysics be used effectively;

- Better define the confidence that can be placed in geophysics, and
- Dispel residual "bad feelings" arising from prior less-than-successful experiences.

Recommendation 1: Coal Geophysics Applications Guidelines

"Develop a guidelines manual which relates various geophysical techniques to data needs and coal mining problem areas as functions of:

- How the survey is conducted, and
- Existing conditions (terrain, coal depth, coal altitude, etc.)

so that a better appreciation of the probability of success can be estimated by the individuals concerned with developing exploration and characterization programs."

Additionally, it is important that the guidelines be tailored to the peculiarities of the various coal regions, basins, fields, or even major seams. Important preparatory work for these guidelines would be Recommendation 2, the development of a rationale for when and where to consider geophysics and Recommendation 3, the development of technical case histories and summaries of geophysical successes and failures as functions of the important recording and data processing variables.

Recommendation 2: Geophysics in the Exploration, Mine Planning, and Operations Phases

"Develop a systematic basis which defines the overall process of subsurface information gathering and its analysis with a major emphasis on describing the potential role of geophysics and how it relates to and supports (or supplants) alternative methodologies."

A number of excellent guidelines are available for the integration of all appropriate technologies into a rational program of support mining (e.g., Ellison and Thurman, 1976; Ellison and Scovazzo, 1981). A more quantitative and technically detailed exposition of the pertinent characteristics of geophysical technology within such a framework is expected to be highly useful. It would indicate at what stages in the overall process geophysics should be considered, and specific technical guidance for implementation of the techniques.

Recommendation 3: Case Histories

"Develop a body of technical performance case histories and analyze them for strengths and weakness of the geophysical techniques."

One of the most important limitations to the application of geophysical technology to United States coal is the scarcity of good or publicly available case histories from which a mine planner can have at least some indication of how well a geophysical technique can be expected to work. This situation is particularly acute with regard to the high resolution seismic reflection technique.

This report notes the importance of testing techniques, in particular in new geographic areas, to determine the best field procedures for optimizing data gathering (e.g., seismic receiver placement and source characteristics). For analysis of data from geophysical logs, particularly for coal quality parameters (e.g., moisture, ash, carbon), it may prove highly useful to correlate log-derived and laboratory results, particularly on a seam or field basis to improve the certainty of fundamental relationships between "geophysical wiggles" and the data customarily seen by the coal industry. Analyses could be achieved preserving the proprietary nature of input data. This expansion of the data base would permit more refined analyses to define the conditions under which certain "empirical" relationships work or do not work, and of course, more data tend to improve empirical relationships.

5.2.2 Specific Technical Recommendations

Specific recommendations include:

- Support development of improved high resolution seismic sources;
- Support demonstrations of several seismic sources and field array techniques over the same objective and analyze results. This should be done in several key coal basins over "typical" conditions. Ideally, short-term followup (mining or extensive drilling) should be contemplated to verify results;
- Support development of improved methods (i.e., more efficient and productive) of placing shot and/or receiver points below the surface zone of poor coupling and large inhomogeneity;
- Support programs which can lead to routine and productive use of transmission and/or reflection in mine seam wave seismic work and radar. The former should be encouraged for the characterization of large coal blocks (e.g., a longwall panel) where discontinuities affecting production may be present. The latter appears best suited towards development as an operational tool tied to routine short-term production planning;

- Support the continued development of the neutron-gamma spectra logs to enable cost-effective in situ chemical analysis of coal;
- Support the continued development of automated surface resistivity measurement systems to detect voids and derive an electrical model of the shallow subsurface;
- Support conferences, workshops, and open data exchanges on the successes and failures of geophysics. The latter, the failures, are important to future success;
- Support digital recording and processing wherever possible.

It is firmly believed that if the general recommendations were successfully carried out, if an active dialogue were to take place between the geophysical and the coal industries, and if site-specific technical data would be made more generally available, geophysics would be used more often, and more effectively. Particularly important is the development of a climate whereby geophysics is considered for use from the very beginning of a coal exploration/mining project.

APPENDIX A

BIBLIOGRAPHY

APPENDIX A

BIBLIOGRAPHY

This bibliography includes the general literature relative to the geophysical and drilling technology associated with coal exploration/characterization and includes the references cited in the report. References marked with a dot (•) are those which are cited in the text or appendices. References marked with an asterisk (*) are those which are considered to be particularly relevant to a particular technology and represent current state of the art.

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APPENDIX B
HIGH RESOLUTION SEISMIC REFLECTION

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B.1.0 GENERAL DESCRIPTION

The seismic reflection technique can be one of the more complex and expensive geophysical methods in use today. This method principally consists of measuring the travel time required for a compressional wave generated in the earth to return to the surface or near surface detectors after reflection from acoustic interfaces between subsurface materials. Although not new, interest in the characteristics of the pulse in addition to the arrival time has recently been rekindled. The reflections are detected by receivers which are located on the ground surface or in shallow boreholes at distances from the source which are generally small compared to the depth of the reflector.

Variations in the reflection arrival times can be used to map structural features in the subsurface. Depths to reflecting interfaces can be determined from the travel times using velocity information that can be obtained from the reflected signals or from borehole surveys. Figure B-1 shows a schematic diagram of reflected seismic signals. Coal is an excellent seismic reflector due to the large difference in its acoustic properties as compared with those of the strata that normally bound it.

B.2.0 PHYSICAL PRINCIPLES AND CONSTRAINTS

B.2.1 Background Theory

The underlying principle of the reflection technique is acoustic impedance. This is the criteria which determines whether an interface is reflecting or not. The acoustic impedance for a material is equal to the product of wave velocity and density. The reflection coefficient, R, across an interface is the ratio of the amplitude of the displacement of a reflected wave to that of the incident wave and is given by (Dobrin, 1960):

$$R = \frac{\delta_2 V_2 - \delta_1 V_1}{\delta_2 V_2 + \delta_1 V_1}$$

where

R = Reflection coefficient

$\delta 1$, $\delta 2$ = Density of materials on sides 1 and 2 of interface

V_1, V_2 = Compressional wave velocities on sides 1 and 2 of interface

The sign of R determines the polarity of the reflected wave. If R is negative, the polarity of the reflected wave is opposite to that of the incident wave.

Coal generally has a lower density and velocity than other sedimentary rocks such as sandstone and shale commonly found in a coal deposit. The density of coal typically ranges between 1.2 and 1.8 g/cm^3 (Schlumberger, 1972), whereas other sedimentary rocks typically have densities ranging between 2.0 and 2.7 g/cm^3 (Dobrin, 1960). Reflection coefficients between coal and surrounding sediments typically range between 0.15 and 0.50 (with reversed polarity), values that represent the fraction of incident energy that is reflected back towards the surface. Abandoned workings are also especially favorable targets as the reflection coefficients between rock and air are nearly 100 percent. Walker (1979) calculates that the reflection coefficient of a flooded mine with a shale roof would be about 0.40.

The ability of the seismic reflection method to detect a coal seam is not only a function of the acoustic impedance of the coal/country rock contact, but also depends on local noise, the seam thickness, and the predominant reflection frequency. A coal bed cannot be clearly depicted if the amplitude of the reflected wave is less than the ambient noise, although the problem of noise can be mitigated with special recording and processing techniques discused further in Chapter B.4.0. Assuming that a vertical incidence reflection signal is just detectable above the noise, the dimension of the thinnest coal seam that can be detected at this amplitude of the reflected wave is the resolution of the technique in terms of the minimum resolvable coal bed thickness (Farr and Peace, 1979).

Widess (1973) has developed an approximation for determining the resolvable bed thickness based on reflection amplitude, the velocity of the coal, and the predominant reflection frequency. Using Widess' formula, the detectable coal bed thickness is the predominant seismic wave length in the coal divided by 12.6 (Farr and Peace, 1979). If both the top and bottom of the bed are to be resolved, then the seam should be no thinner than about one-fourth to one-eighth of the signal wave length. Assuming a typical coal velocity of 2,300 meters/second, a conventional oil exploration type of seismic survey with a predominant frequency of 20 Hertz will only be able to resolve beds in excess of about ten meters. A one-meter resolution implies a predominant frequency of at least about 200 Hertz (Figure B-2). The need for high predominant frequencies of the seismic waves clearly distinguishes the requirements of a coal survey from those of conventional oil exploration.

The ability to propagate high frequency seismic waves suitable for the detection and mapping of coal seams is a function of a number of factors, including source characteristics, depth and earth material characteristics, receiver geometry and characteristics, and processing. The source should have a wide band width which will yield a satisfactory signal-to-noise ratio. The earth itself acts as a low pass filter.

Because high frequencies attenuate faster with propagation distance than lower frequencies, resolution decreases with depth (Figure B-3). The thickness and homogeneity of low velocity surficial deposits are particularly critical in whether or not high frequency waves can be propogated. The surface transducers must have the ability to record high frequency ground motion and the type of transducer used (geophone, hydrophone, or accelerometer) will affect the results of the survey. The physical characteristics of the transducer emplacement (at the surface, in boreholes, submersed in water, etc.) determine the degree to which the transducer is coupled to the ground (preserving signal strength) and also affect the degree to which high frequency motion can be recorded. The spacing of the transducers is also critical. Closer spacing allows for the resolution of higher frequency waves and, the signal-to-noise ratio permitting, single transducers rather than transducer groups may allow for the recording of higher frequency motion. Conventional processing techniques may cause the loss of the higher frequency component of the record and alternative techniques must be used to prevent this loss. The requirements for sources, transducers, spread geometries, and processing are further discussed in Chapter B.4.0.

The above discussion focuses on vertical resolution, i.e., what is the minimum detectable thickness of a coal seam under particular physical conditions. Horizontal resolution is also important in cases where coal discontinuities have been encountered. As the reflected signals bounce off the various interfaces (assumed horizontal here) at a point one-half of the horizontal distance between the source and receiver, the theoretical lateral resolution due to path geometry is one-half the geophone spacing. Actual horizontal resolution is also a function of the processing techniques used to spatially locate a reflector (migration) and is typically less precise than the vertical resolution.

B.2.2 Information Derived From Measurements

Provided that physical conditions (coal thickness, reflection coefficient of seam, depth) allow for the coal to be a measurable reflector, the first major information obtained is the gross coal structure and the number of seams. Local disturbances that affect a coal reflection can be interpreted to affect the coal. A displacement in the reflector could represent a fault, while the disappearance or degradation of a reflector likely represents a seam pinch-out or a stream channel cutoff. Variations in the dip of a reflector or a general "fuzziness" can represent those changes in the coal seam, including roof rolls and horsebacks. The main potential usefulness of the high resolution seismic reflection technique is mapping the continuity of a coal seam and determining the location and nature of discontinuities which could represent a hazard to the miner. Highly detailed profiles have been used to detect variations in lithology of roof rock and to detect lithologic variations within the coal itself, e.g., shale stringers.

Detailed interpretation of lithologic variations are often assisted by the use of synthetic seismograms and vertical seismic profiles (VSP's). Variations in seismic velocity derived from borehole measurements can be used to generate synthetic seismograms which can be used to interpret actual surface records. Alternatively, the VSP method consists of measurement of the total seismic signal from borehole transducers to derive the characteristics of true reflectors which can then be correlated with lithology. The analysis of velocity has four major applications:

- Interpretation of lithology.
- Interpretation of lateral variations.
- Provide fundamental data for migration routines.
- Provide data for calculating true depth sections.

Such procedures are common in oil exploration (Anderson and Lennett, 1981), but are not widely applied to high resolution surveys for coal in the U.S. Another application of the high resolution seismic reflection technique is in the detection of voids, such as abandoned mine workings.

B.2.3 Site Constraints

The physical and mechanical properties of the strata which affect the reflection survey results include the acoustic impedance contrasts between the layers, the acoustic attenuation versus frequency for each layer, and the dip angle of the strata. The first two effects are described above. A high dip angle of the reflecting surfaces causes the reflection to appear in a different position in space. A processing technique known as migration is used to move the reflector back to its "true" position (for practical purposes, migration is limited to corrections of less than 45 degrees dip). For dip angles above 45 degrees, surveys should be conducted along the strike to minimize analysis problems. The gathering and processing of data in three dimensions enable a much greater refinement of the migration corrections and eliminate the need for orienting profile lines along an assumed strike.

Ground water has the effect of changing the density and acoustic velocity of porous materials, hence their transmission and reflective properties. Ground water is not normally a significant concern in identifying reflectors in an undisturbed coal sequence, but is significant when the target is abandoned workings. As noted in Section B.2.1, flooded workings are much less reflective than those filled with air.

Two of the most important constraints are the nature of surficial deposits and the presence of strong reflectors above the target horizon. Low velocity surficial deposits of variable thickness can cause localized delays in wave arrival times that can seriously interfere with the ability to identify reflectors. Such problems are often encountered in areas of steep relief where these problems are particularly acute because of the need to assume a velocity of surficial sediments when making an elevation datum correction. This effect can be mitigated by carefully determining the variations in depth and velocity of the surficial material by means of a refraction survey, or, if possible, locating the shot points and transducers in boreholes below the low velocity layer. A data processing technique known as a statics correction also helps reduce the effect of surficial variations, but must be used carefully to avoid the smoothing out of real discontinuities in the subsurface. Strong reflectors above the target seam such as evaporites (salt/gypsum/anhydrite) or other coal seams may reduce the amount of energy that can penetrate to the reflector of interest. A particularly serious problem can be the presence of abandoned workings, which may reflect and/or distort the transmission of seismic energy to the point where seams beneath the workings are effectively masked. This has proved a serious problem in a few examples from the U.K. (Ziolkowski, 1981).

Generally speaking, some site constraints can be defined prior to the survey, while others may not be known until some results have been obtained. In most cases, problems can be accounted for through modification of recording procedures and/or processing. However, in some cases, site conditions may be so severe so as to make it impractical to obtain useful results. As demonstrated in the U.K. (Ziolkowski, 1981), careful planning can avoid most problems, but the technique is not necessarily effective in all areas.

B.3.0 SURVEY TEST PREPARATION

One of the most important aspects of a successful high resolution seismic reflection survey is the initial planning. It is not sufficient to contract services for the performance of a certain number of miles of survey lines of high resolution survey without carefully specifying the way the survey is to be performed. The mine planner should have a clear idea of the objectives of the survey, which could be:

- Establish the continuity and extent of a coal seam/establish correlation of coal between borings.
- Detect and trace offsets or discontinuities in the coal (faults, sand channels).
- Delineate areas of old abandoned workings.
- Map lithologic variations in the roof rock.
- Estimate amount and minability of coal.

These different objectives require varying degrees of resolution and levels of interpretive effort. For example, the mapping of lithologic variations or estimating amounts and minability of coal would require

that the survey be of the highest possible resolution, with resolution of both the top and bottom of the coal seam and distinction of lithologic variations above and within the coal. Such resolution may not be achievable, but survey specifiations for such objecives would be significantly different from one simply to establish coal seam continuity.

Critical factors that require planning and/or field decision include:

- Type of survey to be conducted--2D or 3D. Three-dimensional surveys may be preferable if coal is in a structurally complex environment. Line coverage (2D) is sufficient in most areas.
- Number of line miles required (2D) or aerial coverage (3D).
- Type of source.
- Type of transducer (geophone/hydrophone/accelerometer).
- Transducer layout and spacing.
- Sampling rate of digital recorder (generally between 1/4 and 1 msec).
- Depth of transducer and shot.
- Shooting procedures (Common Depth Point - CDP - coverage required).
- Processing techniques to be used.

The preparation of specifications for a high resolution seismic survey to define the above parameters implies that the planner should be very familiar with how parameter variations can affect the survey results. In the case of the National Coal Board in the U.K., highly variable results were obtained from their early surveys because contractors were allowed to work out much of the details of the surveys by themselves. Better and more consistent results have been obtained since geophysicists were hired to work with the Coal Board to assist in survey planning (Ziolkowski, 1981).

The importance of field decisions should not be minimized, however. When surveys are being performed in a new area, considerable field experimentation may be required to determine the system layout that will yield the optimum results with respect to what the mine planner wants to obtain. In particular, the choice of source, transducer, spread geometry, and depth of shot/detector are best determined in the field.

Once a survey plan has been established, minimum survey test preparation includes the surveying of shot and receiver locations for both horizontal and vertical control. In addition, borings for the shot and/or transducers are normally required.

B.4.0 DEPLOYMENT OPTIONS

The seismic reflection technique can be deployed following several options, including:

- Land surface
- Marine or from any body of water
- In-mine
- Borehole

As applied to coal mining, the technique is generally applied from the surface. The type of survey used for coal applications would be a high resolution survey, in either two or three dimensions.

B.4.1 Land Surface Technique

The standard field technique for seismic reflection surveys is common depth point (CDP) profiling. This form of profiling consists of advancing shotpoints and equally spaced receivers along a line so that multiple coverage (redundancy) of the subsurface is obtained (Figure B-4). Redundant coverage provides a statistically improved reflection signal plus information on subsurface velocities.

Conventional surface seismic reflection surveys (i.e., petroleum exploration) usually involve up to 96 channels or more of recording with geophone groups spaced 30 to 90 meters apart. Shallow engineering or high-resolution surveys can use 12 to 48 channels of recording with geophones spaced 5 to 10 meters apart. Surface high-resolution surveys normally use smaller energy sources and higher frequency transducers than conventional surveys. In addition, high-resolution surveys usually use a smaller number of transducers per receiver location than the large arrays commonly used in oil exploration. Where the highest resolution is required, single transducers are often used and the transducers are placed in boreholes to increase acoustic coupling, decrease statics effects, and reduce the effect of groundroll. Arrays reduce groundroll by summing the signals from several transducers into one channel; but while this summing may reduce the groundroll effects, much of the high frequency component of the signal may also be lost.

Areal or three-dimensional surveys are an extension of two-dimensional surface profiling. Transducers are arranged in a rectangular grid instead of a line. The resulting subsurface coverage is also in the form of a grid and profiles can be produced along any azimuth. Areal surveys are preferable in areas of complex structure or excessive cross dip. Such techniques have been used extensively to map coal seams in the Ruhr Valley of Germany.

The overall level of development of the surface seismic reflection technique is high. Low resolution surveys for oil and gas have been routinely conducted for tens of years, while high resolution surveys have been performed for over about the past five years. The most recent development of the high resolution technique is the areal or three-dimensional survey, for which the level of technology generally meets or exceeds the needs of coal problems.

B.4.1.1 Equipment

The equipment required for a reflection survey must have the ability to record the shape of the acoustic pulse as a function of travel time and includes a source, transducers, spread cable, a roll-along switch, and a recorder.

Energy Source

Common energy sources for seismic reflection surveys include explosives, projectile impact devices, oxy-propane exploders, air guns, hydraulic hammers, piezoelectric sources, and mechanical vibrators. No one source is best for all areas and each has been used in high resolution work.

Explosive sources are still among the most commonly used for high resolution seismic reflection work. When detonated in a borehole at a suitable depth, explosives liberate seismic energy across a wide frequency band. Disadvantages are the need to drill shot holes in which to place the explosive and cultural and/or legal restrictions on its use in certain areas. A wide variety of explosive types are available. Conventional dynamite is still the most commonly used explosive. Variations such as Primacord (a trademark of Primacord Seismic Services) are also used.

The size of charge used is critical in high resolution work, as the predominant frequency of the pulse is dependent on the charge size (Ziolkowski and Lerwill, 1979). Small charges produce higher predominant frequencies than large charges, but the peak amplitude is reduced and the most efficient charge size is then the smallest that can be used that still sends out enough energy to be reflected and recorded from the coal seam of interest. For the highest resolution work for very shallow depths, charges as small as the blasting caps themselves have been used. Surveys in the U.K. by the National Coal Board are typically conducted using small charges (0.3 to 1.5 kg) placed below the surficial soils (Jackson, 1981).

Projectile impact devices, such as the "Betsy," (trademark Seisgun Source) utilize modified rifles to shoot slugs into the ground. The "Betsy" uses a special 21 mm percussion or electric ammunition which shoots a three-ounce slug at a velocity of 1,750 feet/second and with a muzzle energy of 9,000 foot/lbs. This source enables a high production rate to be obtained and reduces or eliminates permitting requirements normally associated with explosives. The electric detonation option allows one gun to be fired singly or several guns to be fired simultaneously in a pattern.

Oxy-propane exploders, such as the "Dinoseis," (trademark of the Atlantic Richfield Oil Company) generate acoustic pulses by exploding an oxygen-propane mixture inside a surface-coupled chamber. This type of source can be exploded rapidly to facilitate high production rates. The method is quiet and is suitable for use in an urban environment.

An air gun contains a chamber which is filled with air under high pressure. Energy is released when the chamber is depressurized upon an electrical signal from the recorder. Air guns have been successfully used in shallow boreholes where they are equivalent in energy release to very small charges (less than 200 grams) of dynamite.

Hydraulic hammers are a type of vibrator source which have been used in densely populated areas of the Ruhr Valley in Germany (Keppner, 1978). This source consists of a 485-kilogram hammer mounted on a truck. During operation, the hammer strike plate rests on the ground and the back wheels of the truck are raised in the air. A hydraulic valve triggers the blows, which can be made at a rate of up to six to eight blows per second.

Another type of source is a discrete frequency generator based on the piezoelectric principle. A stack of crystals are axially loaded in compression and the piezoelectric effect is used to generate a sharp impulse which is discharged with a very narrow frequency band. Southwest Research Institute has developed a 500 Hertz source of this type for testing by the U.S. Bureau of Mines.

The mini-SOSIE system (trademark of Societe Nationale Elf Aquitaine-Production) is a vibrator source described by Serres and Wiles (1978). The vibrator used is a conventional earth tamper used to compact soil at construction sites. It produces a long duration, pseudo-random pulse of several seconds duration. The pulses are fed to a recorder processor which crosscorrelates the pulse with the recorded signal to produce the record. The method has been used for high resolution work to a depth of about 600 m. Its success in Australian coal fields is described by King (1978). The method is most effective when there is little variation in surface soil stiffness.

The Vibroseis (trademark of CONOCO) is a different type of vibrator source because it imparts a several second continuous variable frequency wavetrain into the earth rather than a distinct pulse. The Vibroseis consists of a truck-mounted hydraulic vibrator which can be coupled to the earth by jacking the truck up onto a base plate. The frequency of the vibrator is increased (upsweep) or decreased (downsweep) smoothly during generation of the wavetrain. The resulting seismic record is specially processed on a computer to compress the wavetrain into a discrete pulse. The Vibroseis source can be synchronized to the recorder by radio or by hard wire links. Models are available to generate

shear waves, and various manufacturers have reported designs for P-wave generators with top end frequencies of 400 Hertz and possibly as high as 600 Hertz. The U.S. Bureau of Mines has developed an electromechanical source similar to the Vibroseis with a frequency range of 100-10,000 Hertz and a depth of penetration of about 300 meters (Condon, 1979).

Transducers

Transducers for seismic reflection surveys include acceleration sensors (accelerometers), velocity sensors (geophones), and pressure sensors (hydrophones). Accelerometers and hydrophones are generally used for high-resolution, shallow penetration surveys where their superior high-frequency response is required. Physically, all of these transducers are similar in appearance.

Geophones are the most widely used transducers for reflection surveys and are available with natural resonant frequencies from 4 to 100 Hertz. Geophones are commonly wired together in groups to form a single receiving array or channel. These arrays can be physically configured on the ground to discriminate between vertically-traveling signals and undesirable horizontal-traveling noise (groundroll). These geophone groups in turn are arranged to form the receiving spread.

Geophones are most commonly used on the land surface. Where it is possible to place the transducer under water, research by Western Geophysical Company (Farr and Peace, 1979; Peace, 1979) indicates that hydrophones are preferable due to their superior coupling wih the ground. However, these studies indicate that different transducers, even with apparently similar characteristics, can have significant differences in response. By making a comparison of different transducer types prior to conducting the actual seismic survey, better results can be produced. The depth of burial of the transducer also appears to be a factor at least as significant as the type of transducer used. Research conducted in Mexico for very shallow oil and gas using GeoSpace geophones indicates that 100 Hertz geophones give the best results (GeoSpace, 1980).

Accelerometers are sometimes used in high resolution work because of their generally good response to the higher frequencies. Their main disadvantage is that they are more expensive than geophones or hydrophones.

Spread Cable

The spread cable provides an electrical path for signals between the transducers and recorder. The cable typically contains from 12 to 96 or more conductor pairs. Take-outs or connectors are provided at intervals along the cable for plugging in the transducers. Additional connectors are provided at the ends for plugging the cable into a recorder and for connecting several cables end to end. It is common practice for the cables to be constructed in short segments to facilitate handling. A truck is usually required to transport the spread cables and transducers. Several manufacturers market "cableless" systems which are of two basic types. One uses radio signals to transmit transducer signals to a central recording station, while the other employs cassette recorders spaced along the line.

Roll-Along Switch

The roll-along switch provides an electrical means of positioning the recorder channels along the spread cables. The roll-along switch may have inputs for up to 240 conductor pairs with outputs to 12, 24, 48, or 96 recording channels. The roll-along switch is located with the recorder.

Recorder

Seismic reflection recorders are sophisticated devices. They must be capable of recording signals over a wide range of amplitudes with frequencies ranging from 10 to 1,000 Hertz depending on local conditions and survey design. Modern reflection recorders are digital devices which measure signal amplitude and polarity at discrete times rather than continuously as in analog systems. Rates at which the recorder must measure signal amplitudes are as high as 4,000 samples/second (e.g., 1/4 msec sampling). Normally, the capacity of a recorder is such that the product of the number of channels and the sample rate is a constant, thus shifting from 1 msec to 1/4 msec sampling reduces the number of available channels by a factor of four. Recorders are normally truck mounted, although the trend over the past few years has been to develop smaller units with increased capacity.

The aforementioned equipment is supplied by a variety of suppliers. Further information can be obtained from The Geophysical Directory, Houston, Texas.

B.4.1.2 Operation

The general setup is illustrated in Figure B-5. Personnel consists of an observer (one man) to run the recording equipment; a cable crew of four or five persons to move cable and geophones; a survey crew of two or three persons; an optional drilling crew depending on source used and transducer placement of two or three persons; and a blaster or source operator.

The first step in a field operation is for the surveyors to mark the locations of the transducers and shot points. After the surveyors have positioned the spreads, drill rigs are used to make borings if required for the shot holes and possibly the transducers. Survey requirements may dictate the need for locating transducers in borings. Peace (1979) demonstrates that the best results are obtained when both the shot and transducers are placed beneath the surficial low velocity material or at least below the water table. Such procedures are not always followed

and many surveys have been conducted without burying the transducers, particularly with 3-D surveys where a very large number of transducers are placed in a spread.

Regardless of whether or not the geophones are buried, the normal procedure followed after drilling is the loading of the shot, detonation of the explosive or other source, and finally recording the data. The first recordings are normally of an experimental nature to determine the ambient noise level and optimum recording parameters. When profiles are run where both the source and geophone are to be located in borings, a "rollalong" procedure can be followed (Farr and Peace, 1979). With this procedure, the transducer nearest the source is removed after the fist shot and another added at the end of the line. The vacated hole is then made the next source and the procedure continues until the traverse is complete.

Production rates are highly variable and depend on terrain conditions, weather, ambient noise, crew experience, and the technical specifications of the survey. The technical factors which determine production rates are the same as those which control the resolution that can be achieved. Factors such as transducer spacing, number of transducers per array, use of boreholes to bury transducers, and number of shots per spread are particularly critical. Rates between about 400 and 4,000 meters per day are claimed by different U.S. contractors, but these rates reflect procedures that will produce results of very different degrees of resolution.

B.4.1.3 Analysis

The analysis of seismic reflection data is accomplished in two steps. Once the data have been gathered in digital form on magnetic tape, the tapes are sent to a processing center where final profiles will be produced. Field monitor records, which involve little processing, are highly useful checks on field performance and allow for assurance that the magnetic tapes contain acceptable data. The final step is for a geologist and/or geophysicist to interpret the profiles to make a geological model of the coal prospect.

Data Processing

Processing of reflection data almost always requires the use of a specialized, large memory computer called an array transform processor. This device is able to perform operations (Fourier transforms, digital filtering) on very large amounts of data (typically, 4,000 samples in one record for every detector location). A seismic crew can acquire 10^8 to 10^9 data bits a day. For this reason, processing is normally accomplished at processing centers with the necessary specialized computer facilties. Depending on processing requirements, the turn around time from field work to time section can range up to three to four weeks.

The objectives of computer processing of field data are to improve the signal-to-noise ratio of the records and to enhance the signals reflected from the coal seam of interest. Noise on a seismic record is not just the ambient ground noise, but includes the effects of ground roll (surface waves propagated away from the shot point) and any unwanted signal originating from velocity variations within the rock mass or complex geometric raypaths (multiples, diffractions, etc.). Processing techniques to accomplish these objectives include a wide variety of routines of varying names due to the fact that software may be written differently by different processing firms. A few of the more important, generic types in a possible sequence of application are as follows:

- DEMUX - Data recorded on field tapes must be demultiplexed (DEMUX) in order to be worked on by the computer. Following the DEMUX, data are sorted into records.
- Datum Statics - Usually the elevation along a profile varies so the data are corrected to a common elevation datum using an assumed velocity.
- Band Pass Filtering - Both low- and high-frequency noise is eliminated by designing a filter to pass only the desired frequencies.
- Statics Corrections - Not all the topographic effects can be removed by datum statics. Additional corrections are made by examining the various energy paths available from CDP coverage. These data are used to refine the near surface corrections more precisely.
- CDP Gather & NMO - All traces reflecting off of a common depth point (CDP) are found and gathered together. Traces tend to curve parabolically due to increasing source/receiver distance and this curvature (Normal Move Out:NMO) is removed by applying the proper velocity to the CDP gathers.
- Deconvolution - A technique to remove multiples from the data. It is typically used before and/or after CDP stack.
- Migration - Dipping beds cause the reflections to move away from their actual reflection point. Migration is a process to move, or migrate, the data back into its proper place on the seismic profile. In addition, the technique is used to remove diffraction patterns caused by faulting. Several types of migration are possible, but

common forms are wave equation and FK, or frequency domain, migration.

The end product of all of the processing steps is to generate a seismic record or seismogram in terms of a time section and depth section which can be interpreted by the geologist and/or geophysicist.

Interpretation

The seismic interpreter must attempt to relate all available geologic data from the surface and boreholes to relate the seismic reflections to lithology. Intepretation is greatly benefited if a deep boring exists somewhere along the seismic line and an acoustic (sonic) log has been run so that the velocities of discrete sedimentary layers can be defined. The interpreter can then identify with some certainty which sedimentary units correspond to which reflection.

An acoustic (sonic) log can be used to generate a synthetic seismogram which can be compared with the actual record. A second technique to assist interpretation is the vertical seismic profile (VSP). The fundamental principle of the VSP is that transmitted and reflected energy propagate past each borehole transducer as a complex superposition of upgoing and downgoing wavefields. The analysis of the total seismic signal as a function of depth in the borehole allows for the resolution of reflectors in an environment that enhances the signal-to-noise ratio and the bandwidth of the seismic signal (Wuenschel, 1976).

Once the reflectors have been related to specific geologic horizons, the interpreter can then concentrate on structural and stratigraphic interpretation. Faults, folds, sand channels, pinchouts, splays, and other features of interest to a coal deposit can be identified. The overall layering of the sedimentary system can be used to determine the depositional environment of the coal. Knowledge of the depositional environment allows for inferences to be made with regard to roof and floor rock, sulfur and trace element content, and ash (Horne, et al., 1978).

B.4.1.4 Case Histories

Examples of the use of the high resolution seismic reflection technique for coal exploration and characterization are available in the literature. Ziolkowski and Lerwill, 1979; Ziolkowski, 1981; Peace, 1979; and Farr and Peace, 1979, are particularly valuable in that they present the results of extensive experimentation to determine the optimum procedures for gathering and processing data from coal seams. Experimentation with 3D seismics to assess coal reserves has been conducted to the greatest extent in Germany. Publications by Arnetzl, 1980; Bading, 1978; Krey, 1978; Houba, 1979; and Lemke, 1980, are particularly useful in understanding the potential applications of gathering, possessing, and interpreting data in three dimensions.

One of the world leaders in the application of the high resolution seismic reflection technique to coal characterization problems is the British National Coal Board (NCB). Since 1976, seismic surveys have been used in every active British coalfield (Ziolkowski, 1981). The experience gained by the NCB has allowed the technique to be developed to the point where useful results have been obtained in all but a very few cases. The main modifications to conventional oil exploration type of seismic reflection profiling have been the following (Ziolkowski and Lerwill, 1979):

- Scaling down the explosive charge size and using single geophones instead of groups.
- Scaling down the sampling interval in time and space.
- Use of deep shot holes and, where possible, deep transducers, to reduce the groundroll, statics correction, and low pass filtering effect of near surface layers.

The results of experimentation by Western Geophysical Company (Peace, 1979; Farr and Peace, 1979) confirm the experience of the NCB. High resolution surveys are required for coal work and the NCB techniques are those required to gain the highest resolution. However, the degree of resolution attainable is highly dependent on the amount of money invested in the survey.

Greater vertical and horizontal resolution can be achieved by decreasing the spacing between transducers and increasing the sampling rate, but this increased resolution must be balanced with the greatly increased costs for data gathering, processing and interpretation. Figure B-6 provides a comparison between the resolution obtainable from a record taken with a 0.5 msec sampling rate and a 10-meter transducer spacing and the resolution obtained along the same line using a 0.25 msec sampling rate and a 5-meter spacing. A higher resolution is achieved with the closer spacing, but the cost of achieving this increased resolution would be about twice that required for the example shown with the 10 meter spacing.

The high resolution surveying in the U.K. typically is achieved with a 0.5 to 1.0 msec sampling rate with geophones separated about 10-12 meters. The goal of surveys in the U.K. is to determine structure at a typical depth of about 600 meters, while in the U.S., coal is normally mined at shallower depths. The definition of structure at depths shallower than that typically considered in the U.K. requires an increase in resolution, i.e., increased costs.

Under favorable conditions, the high resolution seismic reflection technique can yield information that is highly significant to the characterization of a coal deposit. Figure B-7 illustrates a seismic

reflection profile and its geologic interpretation as presented by Farr and Peace (1979). This line shows a fault, pinchouts, and sand channels and illustrates that conventional borings could have completely missed the geological hazards and mining constraints identified from this profile. Areas in the U.K. where the seismic reflection technique has had serious difficulties have been where an irregular low velocity layer exists at the surface, where the coal seams of interest are underneath seams already mined out or under limestone/anhydrite layers which reflect most of the energy upward (Ziolkowski and Lerwill, 1979).

The technique of three-dimensional or areal surveying was first applied to resolving structure in coal beds in the Federal Republic of Germany in 1975. Developed by Prakla-Seismos GmbH with Ruhrkohle AG and Westfaelische Berggewerkschaftkasse, the method is now used in more than 70 percent of the surface seismic surveys in Germany. This type of surveying is preferred in Germany because of the increased potential for resolving the complex tectonic structure of German coal fields. In such areas of complex structure, where the coal measures are buried under a thick overburden, conventional two-dimensional surveys were unable to detect faults with throws as high as 25 meters (Arnetzl, 1980), while such structure could be resolved with a 3-D survey.

A typical field layout for an areal survey in Germany is shown in Figure B-8. The exploration area is divided into several parallel strips, each strip consisting of overlapping blocks, with each block typically consisting of 120 transducer stations. The shotpoints belonging to each block are located along traverses perpendicular to the geophone lines. Apart from the edges of the strip, each subsurface data point (usually 12.5 to 20 meters apart) reflects waves from six combinations of shotpoint and groups of transducers, three in the "x" direction and two in the "y" direction. An example of the results of 3-D surveying from a tectonically complex coal sequence in the Federal Republic of Germany is presented in Figure B-9. These results illustrate how the technique allows for the depiction of structure in plan view, in addition to along profiles.

Current research at the USBM Denver Research Center is directed at using 3-D surveying to obtain plan views (time slices) over abandoned coal workings to assess the technique in delineating areas already mined out. Preliminary results of these 3-D experiments are promising (Frank Ruskey, USBM, personal communication, April 1981). A significant drawback of the 3D method is that the redundant coverage inherent in the technique tends to reduce the high frequency content of the signal, reducing resolution. This decrease in resolution must be weighed against the advantages of obtaining improved information with regard to structural geometry (Krey, 1978).

In the U.S., there is evidence of increasing use of the high resolution seismic reflection technique, nearly always as 2D profiles. Based on interviews with different seismic contractors, a total of 14 firms were found to have experience performing seismic surveys for coal, representing a combined total experience of roughly 100 surveys. The number of published case histories is negligible, primarily because most of the surveys are proprietary. The work for coal operators not related to the oil industry is probably no more than about five percent of the total work performed.

Geophysical contractors in the U.S. appear to express two different philosophies about the performance of high resolution surveys. Some firms believe that the attempt to achieve the highest possible resolution is overrated and indicated that they feel that it is more in the interest of the coal operator to lower the cost per mile and decrease resolution, but still provide enough resolution to detect the coal horizon. Other contractors emphasize the need to obtain the highest possible resolution with whatever means necessary. Clearly, some of this difference is due to differences in survey objectives. The former would be amenable for general exploration, the latter for resolving specific problems where the detail is necessary. Several firms report that they have obtained records with a predominant frequency in excess of 500 Hertz where it was possible to "see" the top and bottom of coal seams at a depth of a few hundred feet. These records also provided sufficient information to map lithologic variations in the roof rock in some cases. It is interesting to note that many of the high resolution surveys have been run to attempt to resolve specific problems encountered during mining operations, rather than just as an exploration tool.

The wide variations in procedures followed in the U.S. naturally result in a significant variation of reported costs per mile and rate of production. The highest resolution obtainable could cost in excess of $20,000 per mile with production rates as slow as 1/4 mile per day (10-foot spacing). The contractors not as concerned with achieving the highest possible resolution have claimed as little as $2,000 per mile with a production rate of 2 1/2 miles per day. It is clear that the coal operator, when specifying a survey to be contracted, must have an understanding of the variations in recording parameters as they affect data quality.

B.4.2 Surveys Over Water

Seismic reflection surveys conducted over water follow the same physical principles as conventional land surveys, but can be performed with much greater resolution than can be normally achieved on land. Applications to coal characterization and mine planning occur when coal seams extend under a lake or the ocean. In such cases, exploratory borings can be exceedingly expensive and the seismic reflection technique is one of the only feasible methods for obtaining the necessary information about the coal seam to allow for mine planning.

The overall level of development of the seismic reflection technique over water is high. Low to high resolution marine surveys have been conducted for many years for oil and gas exploration. The presence of

water enables both the source and the hydrophone transducers to have a uniformly high degree of coupling with the earth, allowing for the transmission and reception of high frequency signals and the obtaining of a high resolution record. Line locations are established by positioning systems which establish locations at much lower costs than can be achieved on land.

B.4.2.1 Equipment

Aside from the need for a vessel and a positioning system, the main difference between land and marine surveys is the type of source used. Marine surveys do not normally employ explosives, but mechanical or electromechanical devices which produce signals of either a broad or narrow frequency band. A wide variety of options exist so that a source can be selected which will optimize the resolution for the depth of penetration required. Suppliers of sources and positioning systems are provided in "The Geophysical Directory."

B.4.2.2 Operation

In a marine survey the source and hydrophones trail behind a vessel which typically moves at a speed of between three and five knots (3.2 - 6 miles) per hour. At this speed, a typical marine survey can accomplish between 30 and 60 miles of line per day, considerably in excess of what can be achieved on land. A typical marine seismic crew will consist of a geophysicist and four or five technicians to operate the source, recorder and to maintain the hydrophone string, in addition to the regular crew of the vessel.

Because of the specialized nature of marine seismic work and the limited demand for marine work in the coal industry, it is probable that a coal operator would contract out this type of work to a specialist. Numerous contracting firms are available to perform marine surveys throughout the world. For a relatively small project such as a survey over an offshore extension of a coal prospect, the costs will be mainly dependent on the extent of mobilization required for a boat to arrive at the survey location. Nevertheless, the line costs will be considerably less than for a land survey.

B.4.2.3 Analysis

The analysis and interpretation of marine data is essentially the same as for land surveying. Generally speaking, however, marine data tends to be of higher quality than land data because of the water allowing a greater coupling of the source and transducers to the earth. An exception to this general rule occurs when the water is very shallow and "ringing" occurs between the bottom and surface of the water. Careful processing is required to reduce the interference produced by the ringing.

B.4.2.4 Case Histories

Good examples of the use of marine high resolution seismic reflection surveys for coal exploration/mine planning are available from the National Coal Board of the U.K. A recent survey (1979) off the coast of Dunham, U.K. was able to resolve the disposition of coal beds in an area where the geological structure is complicated and could not be resolved on the basis of borings alone (Ziolkowski, 1981). In the U.S., the USBM Denver Research Center is conducting experiments in inland lakes to determine the usefulness of overwater seismic surveys to characterize a coal deposit. Difficulties to be overcome include the mobilization of equipment normally operating on oceanic vessels and recording and processing difficulties due to the relative shallowness of the water in an inland lake.

B.4.3 In-Mine Applications

The seismic reflection technique has been attempted from within a mine in only a few instances. As the equipment, operations, and analysis are not conventional, some available case histories are presented to illustrate potential applications of in-mine seismic reflection.

The Institut fur Geophysik at the Westfaeliche Berggewerkschaftkasse in Germany has conducted experiments for the past several years to obtain seismic reflections from both the floor and roof of a coal mine (Ruter, 1979). The downward directed seismic profiling has been to prove deeper coal reserves at depths from 20 meters to 500 meters below the mined seam. The results of the studies indicate that in-mine conditions are more favorable than at the surface (static corrections reduced; noise levels are lower) and that it should be possible to identify faults with throws of one meter. Seismic reflection shot upwards from the roof has been conducted to determine the distance to the overburden.

The one obvious problem of in-mine seismic reflection is the distinguishing of wave arrivals from both above and below the transducer. In Germany, this has been accomplished by the use of a vertical array technique (Schepers, 1977) where several transducers record simultaneously from different elevations within a borehole. By comparing wave arrival times from the different transducers, it is possible to distinguish whether a wave is arriving from above or below the transducers and the unwanted arrivals can be processed out.

In the United States, an underground seismic reflection survey supported by the USBM was conducted by Southwest Research Institute (SWRI, 1980) in a coal mine having water invasion problems from an abandoned mine at an elevation of about 15 meters above the active mine. Seismic reflection studies were conducted from the roof of the active mine to delineate the low points of a section of the abandoned mine so that appropriate dewatering holes could be drilled. The seismic source utilized in this instance was unusual in that transverse polarized shear waves were generated within a 1 to 3 kHz frequency range. Preliminary

analysis of the field survey data indicates that it is possible to use this technique to detect and delineate an overlying seam and its abandoned mine entries.

B.4.4 Borehole Applications

A borehole seismic reflection probe operating in the frequency range of 1 - 10 kHz (very high resolution) has been developed by Southwest Research Institute. The probe was developed to evaluate fracture conditions in natural gas wells. The probe could conceivably be used to detect underground voids (abandoned workings) from a borehole, but has the disadvantage that it is omni-directional. The range of the device is about 10 meters, which is consistent with what could be obtained from a downhole radar probe. However, directional radar probes are being developed.

B.5.0 STATE OF THE ART

Future developments in the high resolution seismic reflection technique will likely be in terms of more effective and efficient processing, where most or all of the required processing can be accomplished in the field in real time. Some contractors already offer preliminary processing in the field.

With regard to the coal industry in the U.S., future developments will likely be to arrive to the state of the art that has already been achieved in other countries, such as the U.K. and Germany. The present state of the art is to perform three dimensional surveys. Existing 3D processing techniques lose much of the high frequency content of the record, sacrificing resolution to gain an increased perspective of the geometry of a coal deposit. Future developments in 3D surveys could be in the development of processing techniques which will retain high resolution.

APPENDIX B

REFERENCES

APPENDIX B

LIST OF REFERENCES

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APPENDIX B
FIGURES

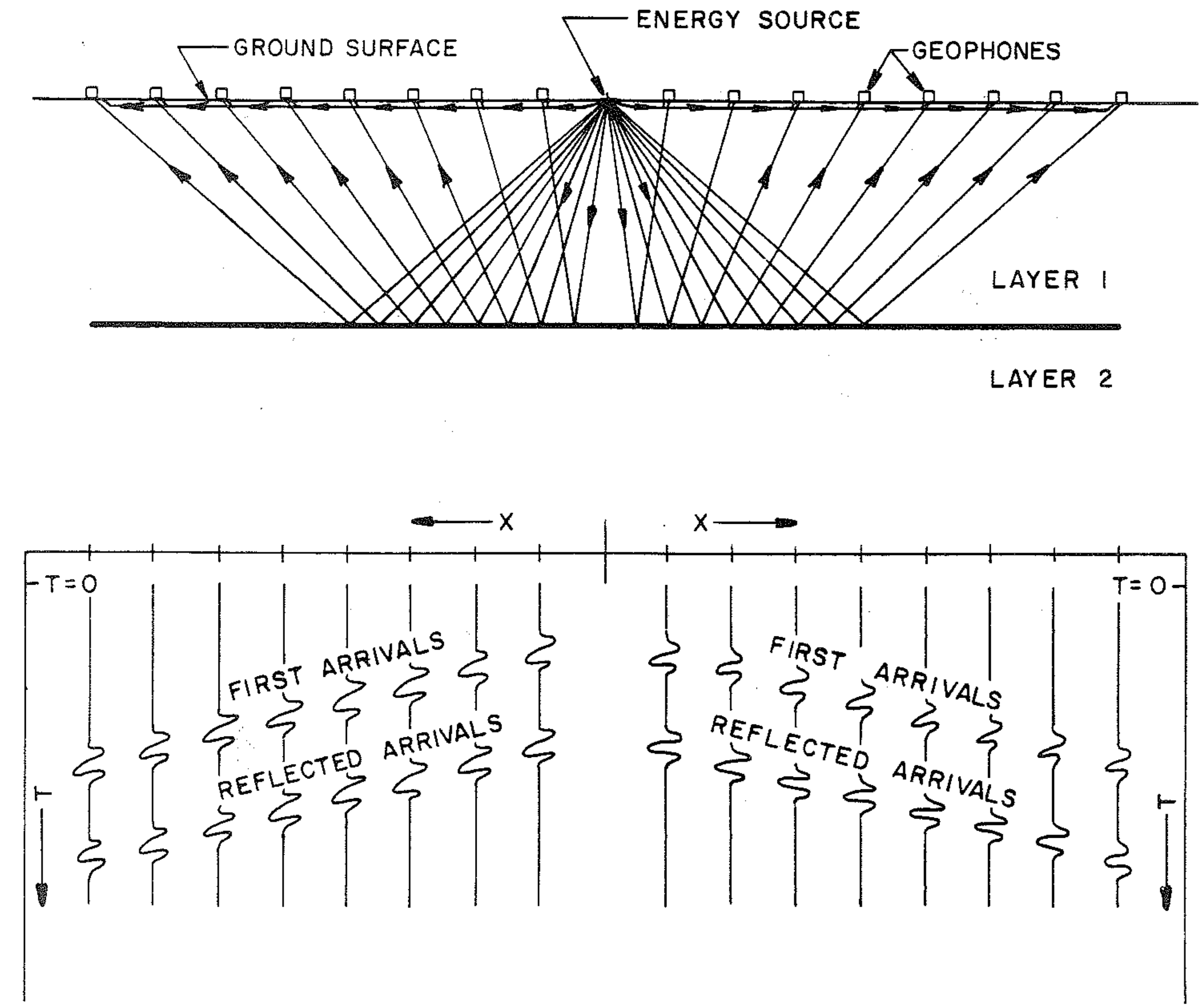


FIGURE B-I

SEISMIC REFLECTION PRINCIPLE
AND SCHEMATIC OF
REFLECTION DATA RECORD

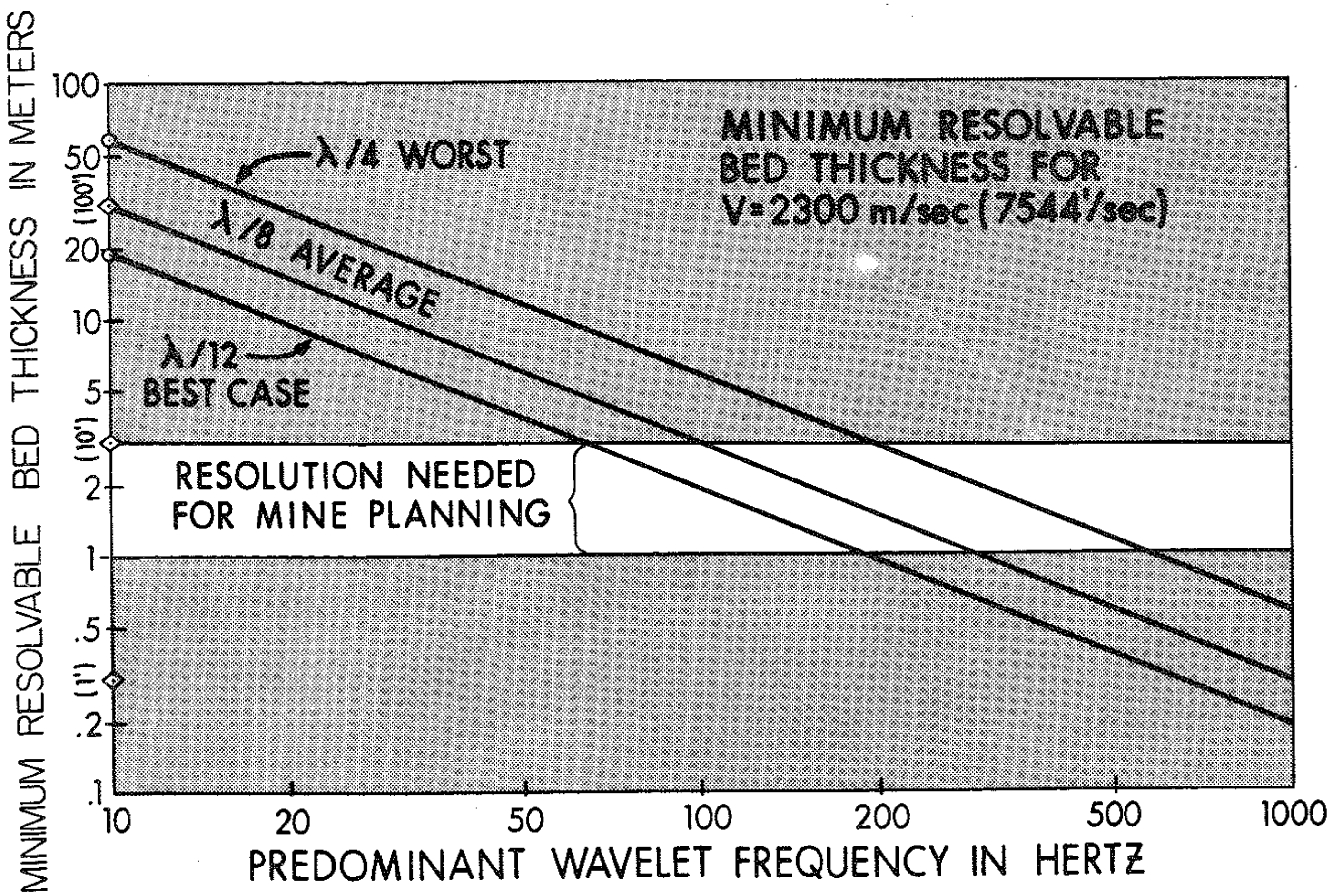
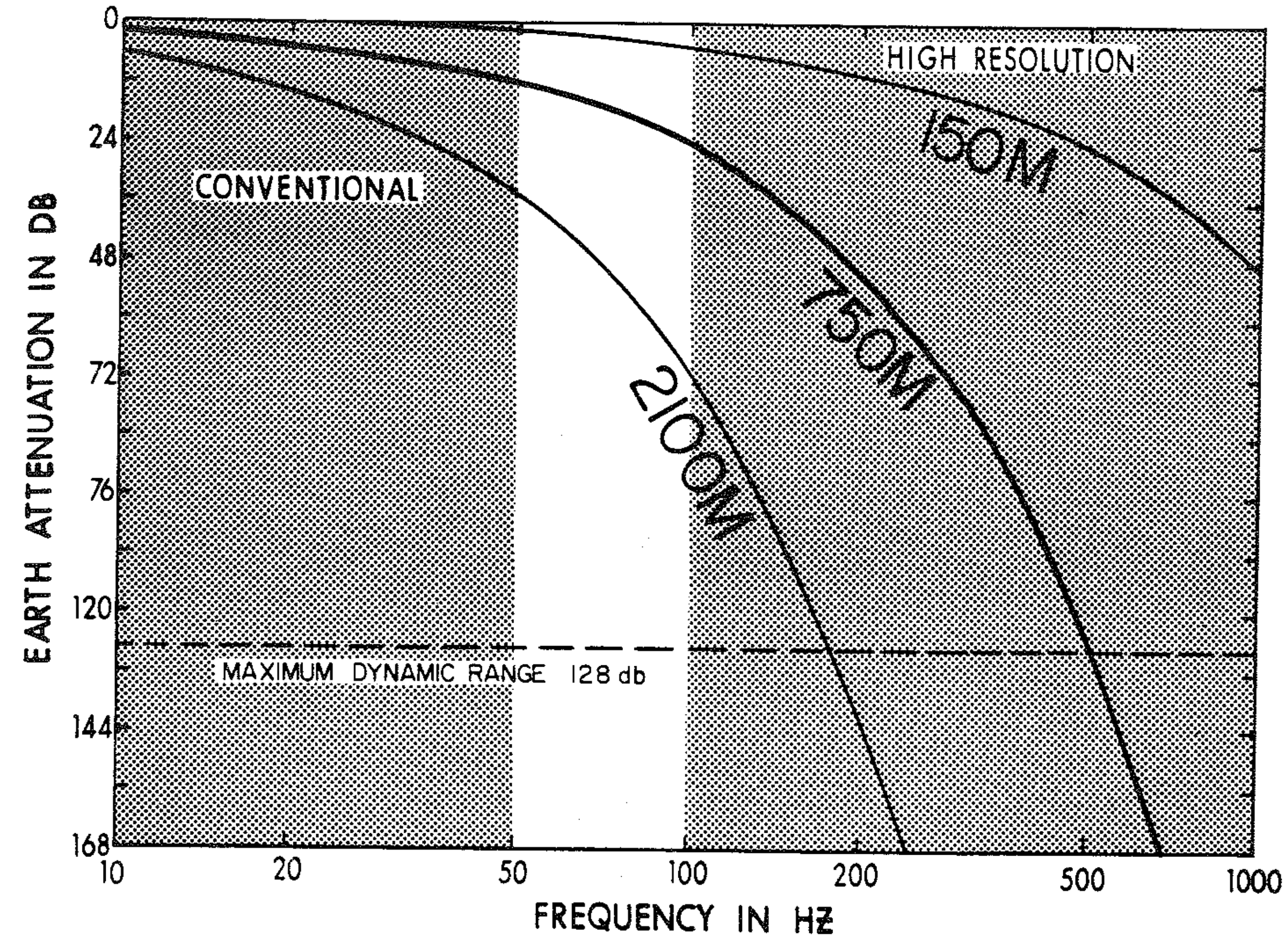


FIGURE B-2

MINIMUM RESOLVABLE COAL BED THICKNESS AS A FUNCTION OF PREDOMINANT REFLECTION FREQUENCY

REFERENCE:
FARR AND PEACE (1979)
REPRODUCED THROUGH THE COURTESY OF WESTERN GEOPHYSICAL COMPANY

ATTENUATION vs. FREQUENCY FOR V=3050 M/sec AND α = 0.5 db/λ



NOTE:
150 M, 750 M AND 2100 M ARE DEPTHS IN METERS.

FIGURE B-3

EARTH ATTENUATION AS A FUNCTION OF FREQUENCY FOR AN AVERAGE GEOLOGICAL SECTION

REFERENCE:
FARR AND PEACE (1979)
REPRODUCED THROUGH THE COURTESY OF WESTERN GEOPHYSICAL COMPANY

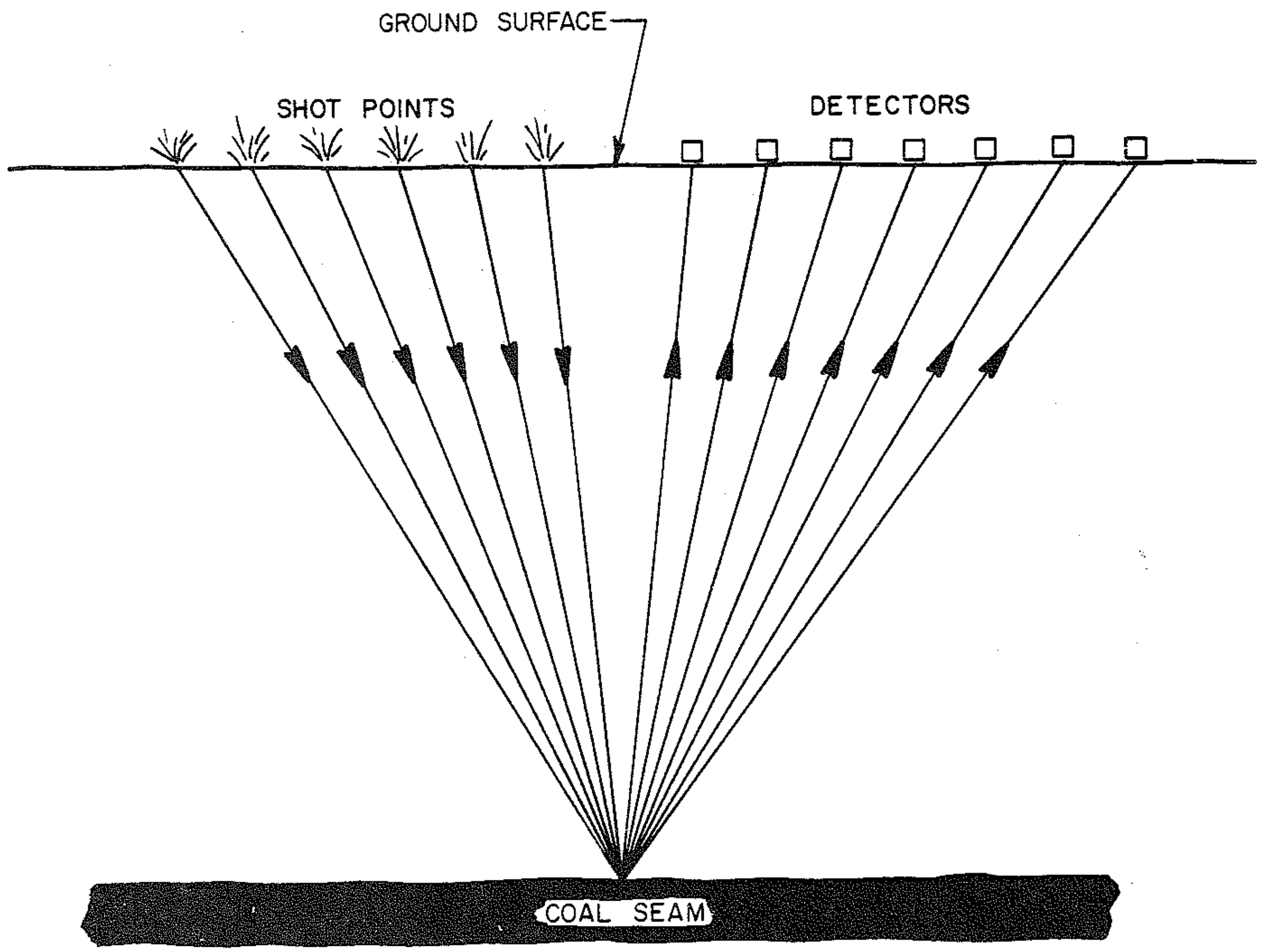


FIGURE B-4

EXAMPLE OF SIX-FOLD (600%)
COMMON DEPTH POINT (CDP) COVERAGE

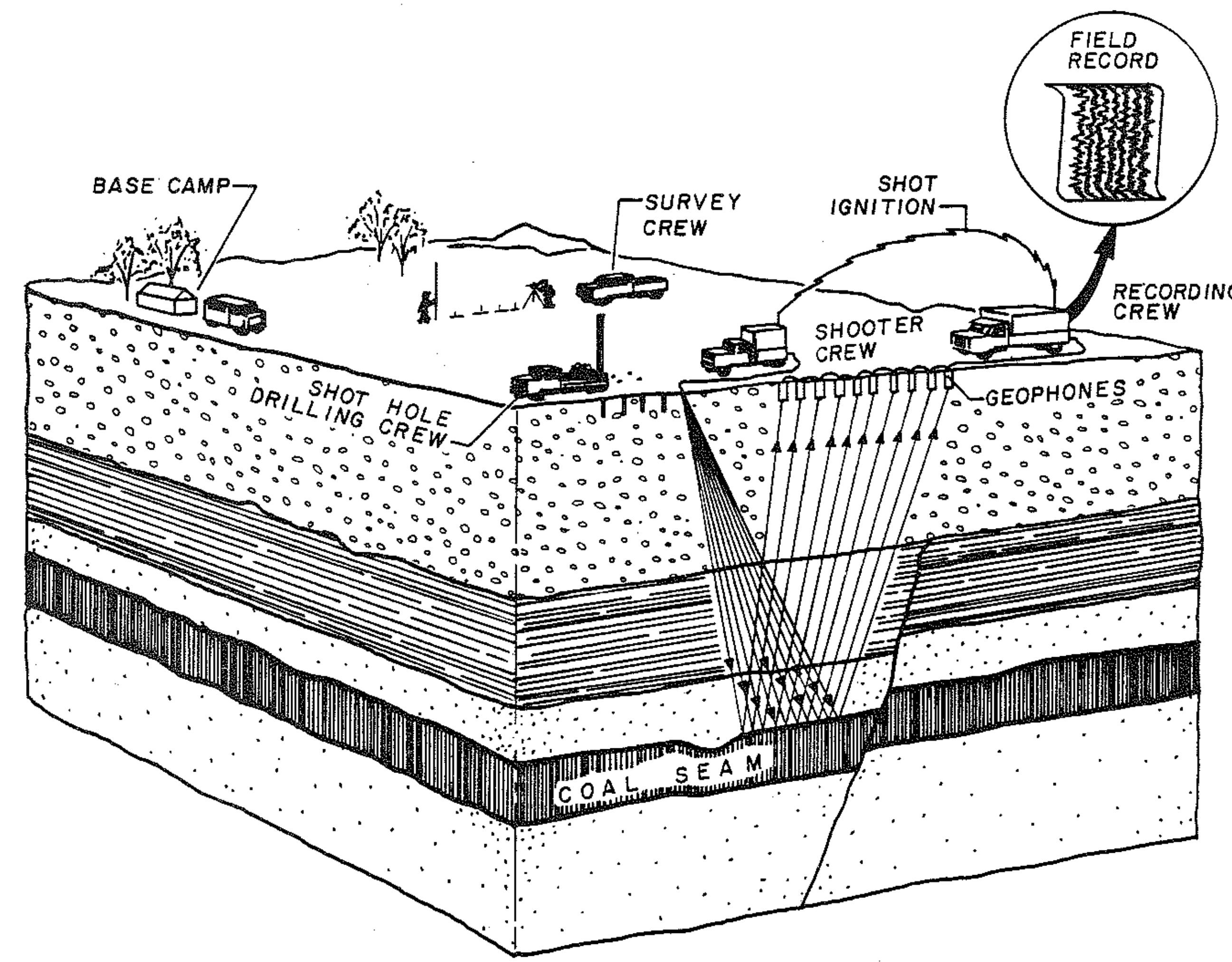


FIGURE B-5

SCHEMATIC OF FIELD OPERATIONS
FOR A SEISMIC REFLECTION SURVEY

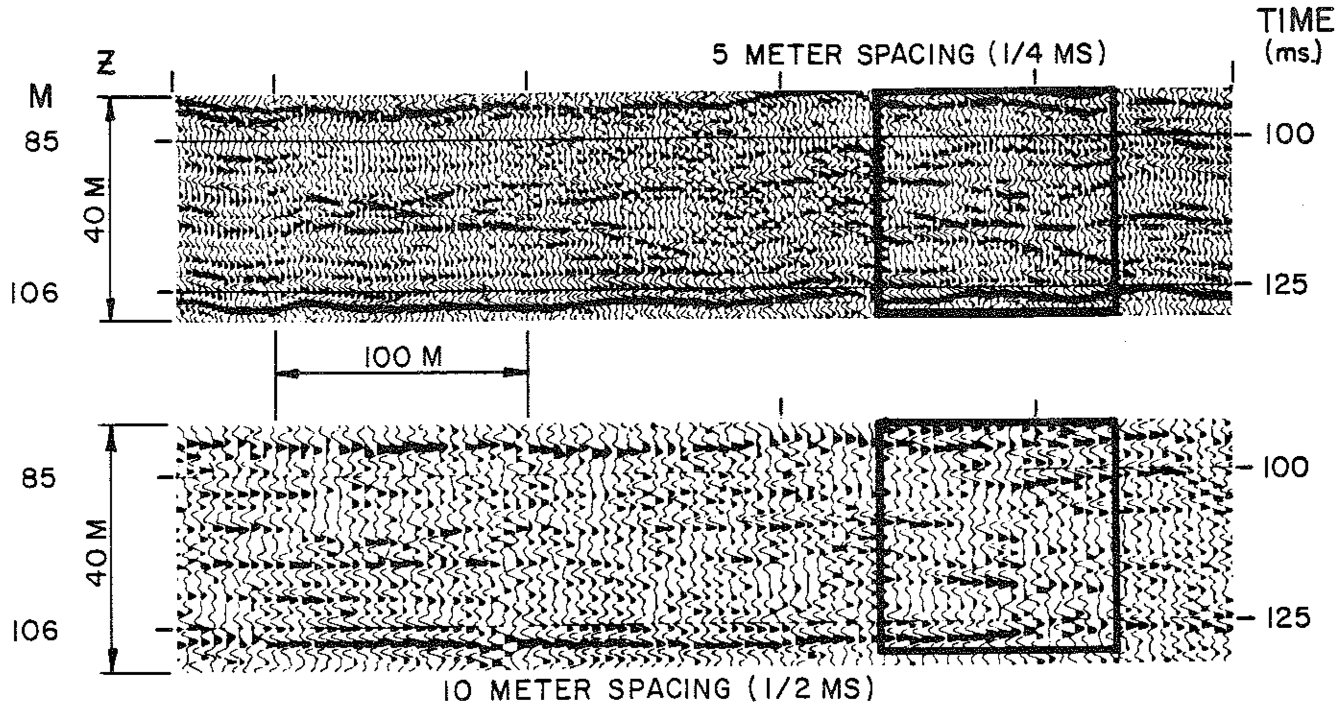
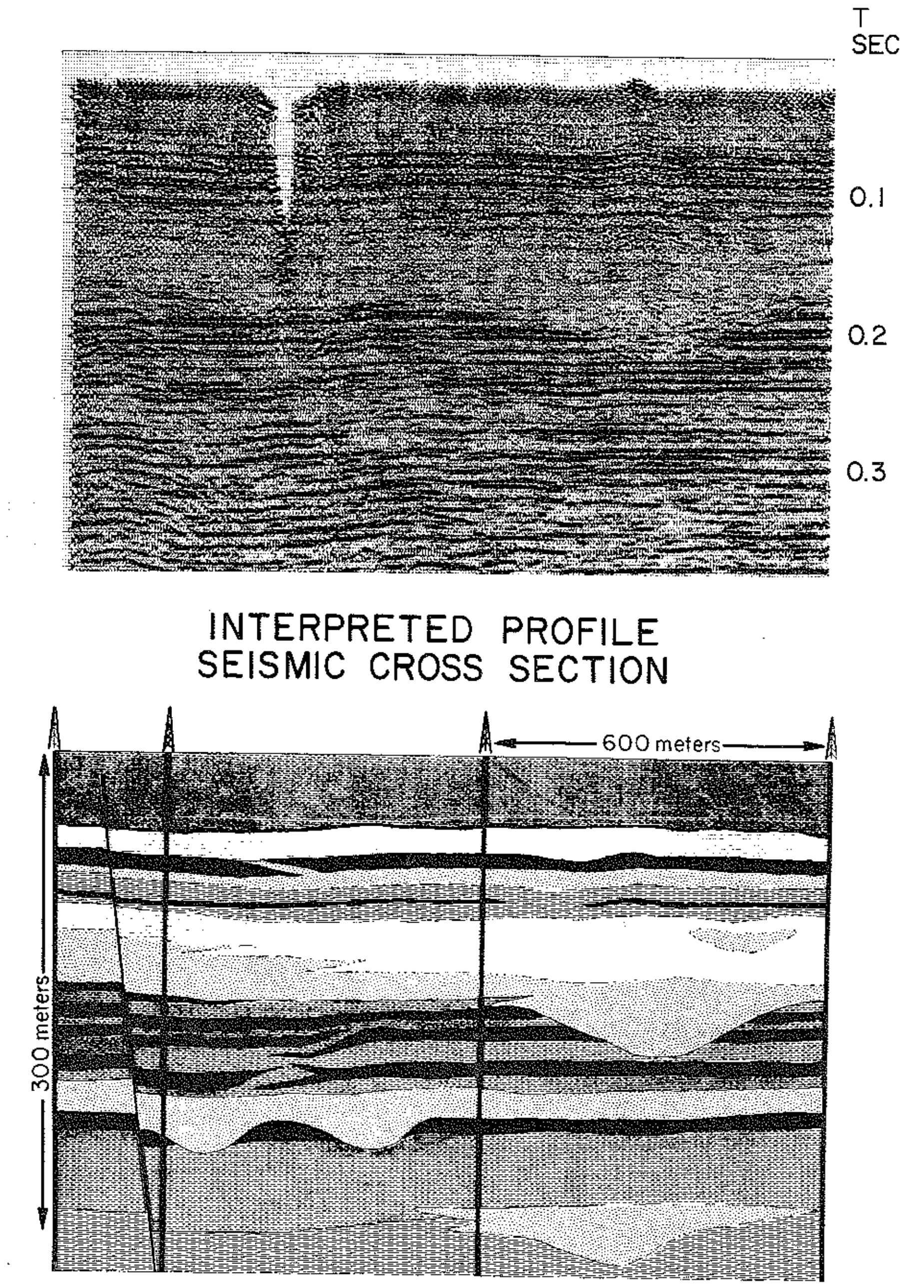


FIGURE B-6

COMPARISON OF RESOLUTION OBTAINED ALONG A PROFILE USING DIFFERENT TRANSDUCER SPACING AND SAMPLING RATES

REFERENCE:
FARR AND PEACE (1979)
REPRODUCED THROUGH THE COURTESY OF WESTERN GEOPHYSICAL COMPANY

HIGH RESOLUTION
SEISMIC REFLECTION PROFILE



NOTE:
AN INTERPRETATION BASED ONLY ON THE HYPOTHETICAL BORINGS WOULD HAVE MISSED ALL OF THE SAND CHANNELS, PINCHOUTS, AND THE FAULT.

FIGURE B-7

EXAMPLE OF HIGH RESOLUTION SEISMIC REFLECTION PROFILE WITH INTERPRETATION

REFERENCE:
FARR AND PEACE (1979)
REPRODUCED THROUGH THE COURTESY OF WESTERN GEOPHYSICAL COMPANY

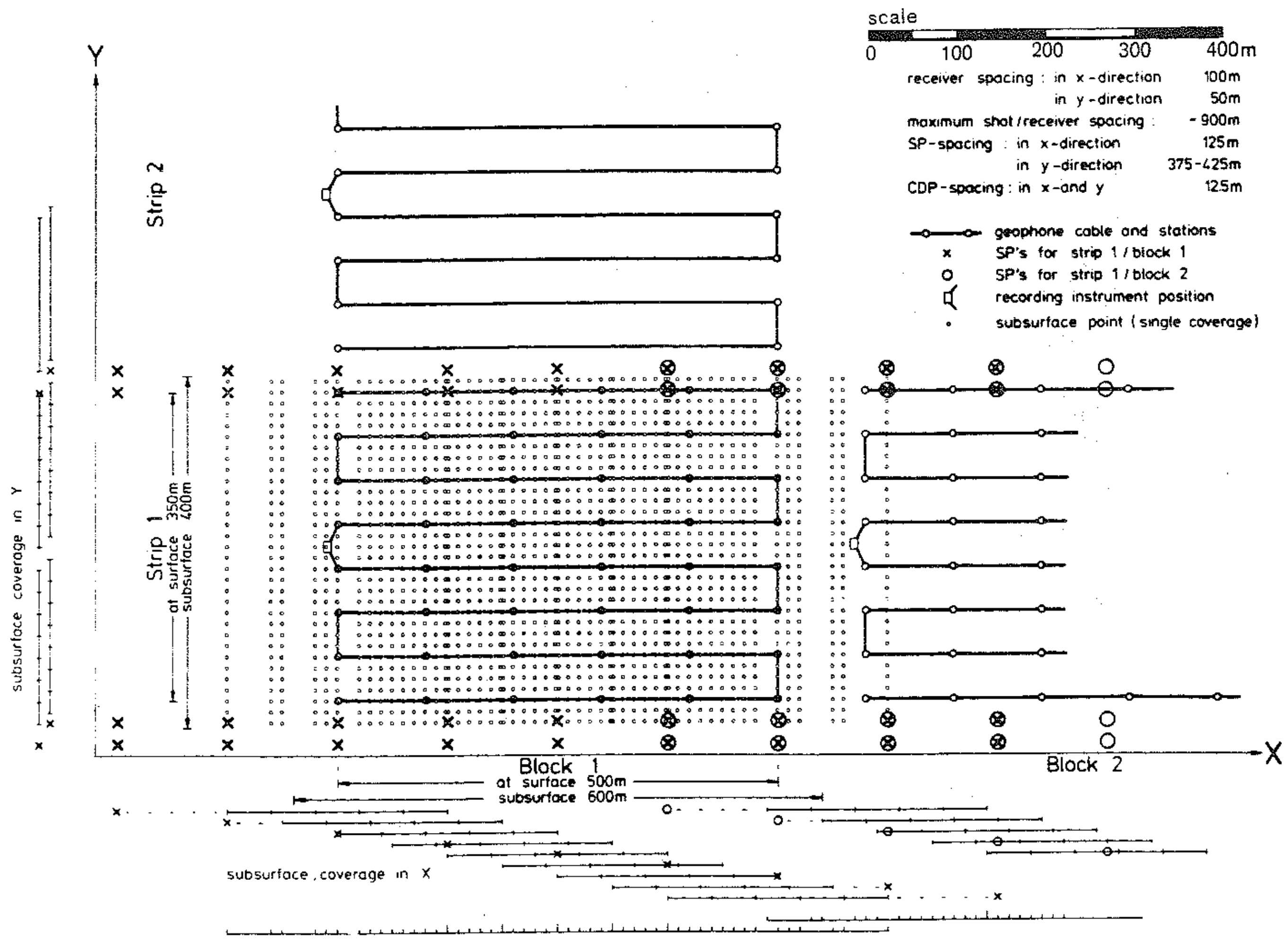
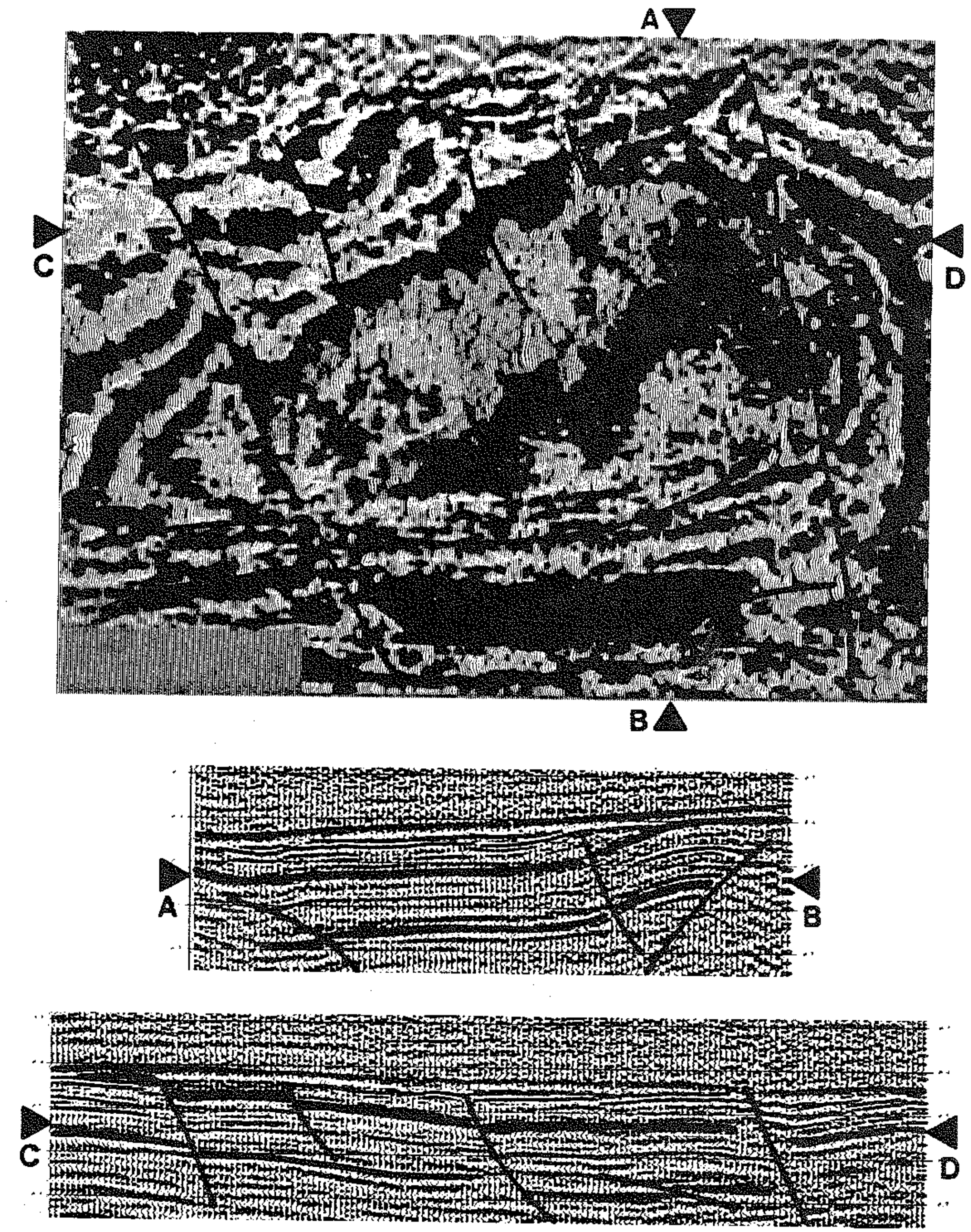


FIGURE B-8

FIELD LAYOUT FOR A 3-D SEISMIC REFLECTION SURVEY

REFERENCE:

PRAKLA SEISMOS, 1977
(REPRODUCED THROUGH THE COURTESY OF PRAKLA-SEISMOS GMBH)



NOTE:

TIME SLICE CORRESPONDS TO A DEPTH OF 530 METERS.

FIGURE B-9

EXAMPLE OF 3-D TIME SLICE AND PROFILES OVER COAL MEASURES IN THE FEDERAL REPUBLIC OF GERMANY

REFERENCE:

TRAPPE, 1981 (REPRODUCED THROUGH THE COURTESY OF PRAKLA-SEISMOS GMBH).

APPENDIX C

SEAM WAVE REFLECTION/TRANSMISSION TECHNIQUES

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SEAM WAVE REFLECTION/TRANSMISSION TECHNIQUES

C.1.0 GENERAL DESCRIPTION

A coal seam may act as a seismic wave guide when its density and acoustic/seismic velocity are lower than the corresponding values in the material above and below the coal. Where this situation occurs, the body waves generated by a seismic source within the coal seam will be reflected and refracted from the top and bottom of the seam and will interfere constructively to form seam (also known as channel or guided) waves that will propagate in two dimensions along the seam. Discontinuities within the coal seam, such as faults, pinchouts, sand channels or abandoned mine workings will interfere with or completely disrupt the propagation of a seam wave. An analysis of seam waves can therefore be used to identify discontinuities that could represent potential mine hazards and production losses (Krey, 1963).

Two techniques are used to analyze seam waves, transmission and reflection. Transmission techniques are followed to determine whether a seam wave can be transmitted between two points. Given a successful transmission of a seam wave, the nature of discontinuities present can be inferred from analysis of the data. This technique may provide for the rapid reconnaissance of areas to be mined (Freystatter, 1974; Guu, 1975; Krey, 1976 and 1978). The technique is well suited to determine coal seam continuity between boreholes (Bahavar, 1980; Regueiro and Major, 1980). The transmission method cannot spatially locate a discontinuity unless information can be obtained between a large number of points. The reflection technique allows for the spatial determination of a discontinuity in a manner similar to identifying reflectors from the surface. Figure C-1 conceptually illustrates the transmission and reflection techniques.

C.2.0 PHYSICAL PRINCIPLES AND CONSTRAINTS

C.2.1 Background Theory

Certain types of coal act as waveguides because their density and seismic velocities are lower than the roof and floor rock. Where this situation occurs, certain types of seismic energy may become "trapped" and will propagate along the coal seam, normally with little radiation to adjacent beds. Certain geologic conditions (e.g., nearby coal seams) or poor instrument location may lead to significant energy transmission in energy leakage pathways. Seam waves can be divided into two categories:

- SH (generalized Love) waves - These seam waves can be considered to result from the interference of multiply reflected, horizontally polarized shear waves (SH). The particle motion is perpendicular to the direction of propagation and parallel to the coal seam.

- P-SV (generalized Rayleigh) waves - These seam waves can be considered to result from the interference of many multiply reflected vertically polarized shear waves (SV) and compressional waves (P). Particle motion exhibits both vertical and radial components.

A third type of trapped wave phenomenon important in in-seam seismic methods occurs along the boundary of the coal and the mine opening and is confined above and below by high seismic velocity rock. Such waves are known as roadway modes and rapidly decay away from the coal/mine opening interface (Reeves, 1979). Roadway modes induce problems comparable to groundroll when performing seismic reflection from the surface.

Each type of seam wave possesses a family of modes. In some of the modes energy is lost from the coal seam (leaky modes), while other modes remain trapped in the seam (normal modes). The fundamental mode is the simplest and most predominant mode and has the lowest frequency, as well as being symmetrical to the coal seam for both types of seam waves. In the case of the Rayleigh wave, the fundamental mode of propagation is a flexure of the seam with a maximum particle motion at the center of the seam and decreasing exponentially outside of the seam. Particle motion is also at a maximum at the center of the seam and decreases exponentially outside of the seam in the case of the fundamental mode of the Love wave. All modes higher than the fundamental mode exhibit cutoff periods beyond which energy of that mode is attenuated or will not propagate (Peterson, 1979).

An underlying principle of seam wave transmission is based on the phenomenon known as dispersion. That is, the speed of propagation of seismic waves is directly related to their frequency. In general, an impulsive seismic source (explosion or hammer blow) generates a range of frequencies that propagate in all directions. As distance from the source increases, the frequencies become dispersed with the lower frequency energy traveling faster than the higher frequency energy (hence the term dispersion) and thus arriving at a given reference point at different times. An example of a non-dispersed and dispersed wavelet is shown in Figure C-2, taken from Peterson (1979).

Dispersion curves describe the relationship between velocity and frequency content of the wave. It has long been recognized (Krey, 1963) that the thickness of the coal affects the frequency content of the seam waves. For that reason, the periods of the dispersion curves are commonly normalized to the seam thickness H. An example of this is provided in Figure C-3, which presents the dispersion curves for Love waves in deep coal seams with a 2:1 velocity contrast of the adjacent rock

units with the coal (Peterson, 1979). Waves with frequencies corresponding to the minimum of the group velocity curve constitute the Airy phase and tend to have the largest amplitudes and propagate the greatest distance within a seam, although this is not always the case (Dresen and Freystatter, 1978; Buchanan, 1978).

The dispersive nature of seam waves is one of the major obstacles to overcome in the interpretation of seam waves to detect geological hazards. The dispersion presents three main difficulties (Buchanan, 1979):

- Because the seam wave is spread out in time, it is difficult to obtain an accurate estimate of the time at which it arrives.
- Different dispersed waves may overlap and it is difficult to separate them.
- Dispersion reduces the amplitudes of the waves, sometimes to the level of noise.

The difficulties caused by wave dispersion require expert interpretation.

C.2.2 Information Derived From Measurements

The general objective of the analysis of seam waves is the identification of discontinuities in a coal seam in advance of mining. Discontinuities include faults, clay veins, sand channels, and pinchouts. The response of seam waves to these discontinuities is illustrated in Figure C-4, taken from Suhler (1978). Where measurements are made between boreholes, the only practical goal is to determine whether a specific seam is continuous. In-mine monitoring is designed for locating discontinuities within the coal by means of the analysis of transmitted and/or reflected seam waves. The method is complementary to the surface seismic reflection technique in that it is capable of detecting faults and other continuities that are beyond the resolution that can be achieved from the surface. The method is capable of delineating discontinuities on the order of a few hundred meters from the working face, considerably greater than can be achieved by radar, but with much less resolution.

C.2.3 Site Constraints

The velocity contrast between the coal seam and the material above and below the coal is the primary factor in determining whether it is possible to generate a seam wave. Coal/rock velocity contrasts of 1:2 are conducive for development. Velocity contrasts of 1:1.4 do not preclude seam wave development, but ratios any closer to 1:1 probably will not allow for wave development (Prof. Major, CSM, personal communication, April 1981). Waves are best developed when the upper and lower seam contacts are abrupt. Gradational contacts are less likely to be conducive to seam wave development. The thickness of the coal also has an effect on the ability of the seam wave to be transmitted and the characteristics of the seam wave (frequency, phase, wave type, i.e., Love or Rayleigh). The presence of groundwater is not an important factor. The seam wave technique is not limited by depth or dip of beds for deeply buried beds (where the depth is greater than about 10 x the seam width). For shallow depths it is possible that the seam wave will be affected by the overburden (Peterson, 1979).

C.3.0 SURVEY TEST PREPARATION

Shot and receiving locations should be surveyed for both vertical and horizontal control. With regard to shot size (if an explosive source is used) and geophone type and spacing, considerable field experimentation may be required to optimize results. In the case of in-seam reflection surveys, considerable data processing may be required before the success of any individual field configuration can be determined.

C.4.0 DEPLOYMENT OPTIONS

The in-seam seismic technique can be deployed following three basic options:

- Borehole transmission
- In-mine transmission
- In-mine reflection

Borehole reflection is theoretically possible, but the difficulties of identifying the reflected wave from a single receiver and the inability to spatially locate any reflector identified effectively preclude this deployment. The method is uniquely applicable to coal and is generally conducted within a mine. As these three deployment options are closely related, case histories of actual applications are discussed together in Section C.5.0.

C.4.1 Borehole Transmission

The goal of measuring seam waves from boreholes is simply to determine whether a seam wave can be transmitted from a coal seam intersected by one boring to the same seam intersected by another boring. It is beneficial to locate transducers in at least two locations at varying distances from the source within the coal seam to be tested. Transducers in current use normally require at least a 4.5-inch-diameter borehole.

C.4.1.1 Equipment

A system to generate and record seam waves between boreholes within a coal seam includes a source, transducers, and a recorder.

- Source: This application requires reoccupation of the same space in the borehole, so a nondestructive repeatable source is necessary. A mechanical shear wave generator is desirable, but compression wave generators such as sparkers and small explosives within cased holes have been used successfully.

- Transducer: Three component geophones, measuring two horizontal components and the vertical component are required in order to be able to distinguish the arrival of the Love and/or the Rayleigh wave.

- Recorder: Two types of recording the wave form - analog and digital. An analog recording is typically a photograph of an oscilloscope trace or a chart paper record. A digital record is usually stored on magnetic tape, and the display is usually chart paper. Both types of recorder typically have the amplifier and delay circuitry built in. A digital device is preferred as enhancement techniques can be used. Such a device should have a 50 ms sample rate, which implies a Nyquist frequency of 10 KHz and an alias filter setting of 5 KHz.

C.4.1.2 Operator

Two people are normally required to conduct the survey, one to operate the source and the other to operate the recorders, assuming borings have been drilled and cased, and the source and transducers have been locked into the borehole at the center of the coal seam to be tested. Testing is normally accomplished in less than a few hours per setup.

C.4.1.3 Analysis

Analysis of seam wave data from boreholes deals primarily with recognition of the seam wave and determining the dispersion characteristics of the wave once it is recognized. This requires a computer to apply various digital filters to the data and to display vector combinations of two components versus time to recognize the arrival of either a Love or a Rayleigh wave. Where a seam wave is observed, the results should be compared with a theoretical model of a seam wave through the coal, in order to determine whether the seam wave is influenced by, or could actually be guided by seams other than the coal. The thesis by Bahavar (1980) documents how a nearby low velocity clay layer can also act as a wave guide and influence the results.

C.4.2 In-Mine Transmission

The transmission technique is applicable only when it is possible to locate the shot and recorders within different parts of a mine and the area to be investigated lies between them. Such a condition commonly exists in where mines are developed using an advancing longwall technique, as is typical in Great Britain or other areas of Europe. This situation is less likely to occur when retreat longwall mining is followed or would be very unlikely to occur in the case of room-and-pillar mining. Accordingly, the method has been developed primarily in Great Britain and West Germany and has received little attention in the U.S.

C.4.2.1 Equipment

Commercial equipment certified for in-mine use has not been developed in the U.S. In-mine seam wave experiments to date in the U.S. have been conducted in nonrestricted entryways or by trailing long cables into the mine. In such cases, equipment as described in Section C.4.1.1 has proved suitable.

Equipment certified for use in West German mines has been developed by Prakla Seismos. This equipment is basically a 24-channel Texas Instruments DFS V digital recorder encapsulated to operate in a nitrogen atmosphere. A detailed description of this equipment is provided by Ruter and Schepers (1979). While it seems reasonable that this equipment could be certified for use in the U.S., the unit may be too bulky for convenient use.

The Sercel SN 338 digital recorder with 12 or 24 channels has been modified for use in mines in the U.K. The modifications for underground use are not as substantial as done by Prakla Seismos in Germany and are used in U.K. mines only with special permission from the authorities and cannot be used where methane concentrations exceed 0.25 percent (Buchanan, 1979).

Explosive sources, generally 0.1 to 0.2 Kg, are used in the U.K. and the Federal Republic of Germany to generate seam waves. Although explosive sources are approved for use in mines in these countries, regulations could make the use of explosives in mines more difficult in the U.S. A piezoelectric source to generate shear waves has been developed by the Southwest Research Institute. This source has the advantage of being able to produce Love-type waves better than an explosive (Suhler, et al., 1978).

C.4.2.2 Operation

Where conducted in Europe, the in-mine seam wave transmission technique typically requires the drilling of shallow horizontal borings of one to three meters depth for shot and transducer placements. Once the equipment has been set up, one person to operate or detonate the source and another to monitor the recorder is normally required.

C.4.2.3 Analysis

The analysis of transmitted seam wave can include several steps:

- Filter out background noise as well as possible.
- Identify whether seam waves are present.
- Locate any discontinuities by means of geometric plotting of raypaths where seam waves are not observed or are modified.
- Derive the two-dimensional seam wave velocity field of the coal seam.
- Determine the dispersion relationship for the Love and/or the Raleigh waves.
- Compare actual dispersion characteristics with theoretical models.

Filtering of the data to reduce background noise is fairly conventional and it is usually possible to determine visually whether or not a seam wave is present (Figure C-5). The presence or absence of seam waves can be an important criterion for defining coal discontinuities.

The identification of seam waves has been used for many years as a basis for identifying areas of potential problems across longwall panels in both the U.K. and Germany. As depicted in Figure C-6, the transmission technique offers the possibility of quickly verifying the suitability of a proposed area and when a third panel can be used for shot/receiver locations, some resolution can be made regarding the location of potential problem areas. In such cases, little or no processing of the records is required for interpretation.

Another application of seam wave transmission analysis is the determination of a two-dimensional velocity model of the coal seam. Mason (1981) presents procedures for identifying apparent static error (differences in theoretical wave arrival times) to detect variations of velocity within the coal panel to be investigated. Algebraic reconstruction techniques were used to reduce the first break arrival times for the seam wave into a profile of velocity inhomogeneity. This method is somewhat analogous to seismic refraction fan shooting used years ago in the U.S. to locate salt domes (McGee and Palmer, 1967). The results of the study by Mason (1981) indicate that the velocity of seam waves in coal is dependent on the stress existing within the coal and that the stress field can effectively be mapped by an analysis of transmitted seam waves. Additional details of this study are presented in Section C.4.2.4.

Most of the sophisticated processing techniques for analysis of seam waves are applied to the interpretation of seam wave reflections, as presented in Section C.4.3.3. Nevertheless, the first step of most processing techniques, the definition of the dispersion characteristics of seam waves, is readily applicable to the interpretation of transmitted seam waves.

One method of extracting the dispersion relationship of the seam wave of interest (dispersion relationships of the Love and Raleigh wave are different) is by use of a multiple filter technique (Dziewonski, et al., 1969; Chilcoat, 1977; Buchanan, 1978). This method consists essentially of filtering out all but a narrow band of frequencies from the original record and determining the arrival time of that particular frequency group. When this procedure is followed for several frequency groups, a dispersion curve can be derived. An alternative method would be to choose a dispersion function which is described by a number of unknown coefficients and then use the recorded data to find the best fit for the coefficients (Buchanan, 1978). Mason, et al. (1980), describe this process of dispersion characterization in terms of examining the spatial and temporal periodicity of the seismic waves using a two-dimensional Fourier analysis consistent with that described by Embree, et al. (1963).

Once the dispersion curves for the seam wave have been defined, it is possible to compare the actual curves with theoretical curves (Peterson, 1979) to confirm if the transmission of the recorded seam wave is consistent with transmission by the coal seam. In a study conducted by D'Appolonia, seam waves from a low velocity clay layer about eight meters above the coal seam also transmitted a seam wave which contributed to the record obtained from the coal (Bahavar, 1980). The results of this study confirm the need to understand the stratigraphy above and below the coal seam when interpreting a seam wave transmission survey and indicate that it may not be sufficient simply to identify the presence of a seam wave.

C.4.3 In-Mine Reflection

The seam wave reflection technique is used primarily in Great Britain and Europe to provide greater spatial resolution to seam discontinuities than can be achieved by the analysis of seam wave transmissions. The method has the additional advantage that the tests can be conducted from a single mine face, although it is still most common to place the shots and transducers in different panels to reduce the interference from the roadway modes.

C.4.3.1 Equipment

Equipment suitable for seam wave reflection studies is the same as that used for transmission. Commercial equipment certified for in-mine use has not been developed in the U.S.

C.4.3.2 Operation

The operation of equipment for a seam wave reflection survey is the same as for transmission study. In Europe, seam wave reflection and transmission surveys are commonly performed simultaneously. In such cases, one additional man could be required to monitor the extra transducer set.

C.4.3.3 Analysis

The analysis of seam wave reflections includes some of the steps applicable to seam wave transmission studies, such as the filtering out of the background noise to the maximum extent possible and the determination of the seam wave dispersion relationships. In addition, seam wave reflection analyses are subject to many of the processing requirements of surface reflection studies, but with important differences, as follows:

- Deconvolution - This procedure is a filtering technique that may be applied at several stages during data processing and has the ability of compressing the source wavelet into a spike. Pulse compression is required for surface reflection studies where vibrator sources are used. In the field of seam wave seismics, pulse compression is referred to as "recompression," because the waves were originally emitted in a compressed form prior to dispersion. Wave recompression, then, is an operation to eliminate dispersion.

- Common Depth Point (CDP) Stacking - This is comparable to CDP stacking from the surface, but the stacking velocity is frequency dependent due to the effects of dispersion. A modification of the CDP method applicable to seam wave studies known as Dynamic Trace Gathering (DTG) has been developed in the U.K. by Buchanan, et al. (1979).

- Migration - As performed from the surface, migration techniques are designed to obtain the correct spatial geometry of the reflector by accounting for the velocity of material between the surface transducers and the reflector. Migration techniques for seam wave reflections have the same goal, but are more complex due to wave dispersion, possible mode (and velocity) variations of the reflected wave as opposed to the incident wave, local inhomogeneities, and the increased range of possibilities of the angle between the fault and spread line strikes. In the U.K., high resolution image reconstruction techniques have been developed based on the use of lag-sum processors, also known as Huygens-Kirchoff diffraction stack migration operators (Mason, et al., 1980; Buchanan, et al., 1979). A different method of migration based on a polarization analysis using two components has been developed in the Federal Republic of Germany (Millahan and Marschall, 1980).

- Static Corrections - As applied to surface seismic reflection surveys, these corrections are designed to eliminate slight differences in wave arrival time due to variations in near surface weathering and/or topograpic variations. This situation normally does not exist underground because coal faces are relatively flat and the coal should be fresh. Where apparent static corrections are required, the situation could be related to inhomogeneities in the coal or a variable stress field applied to the coal (Mason, 1981).

In general, the analytical techniques used to process and intepret seam wave reflections have the same goals as for surface reflections, but are different because of the difference in waveform types.

Deconvolution - Pulse Recompression

The problem of pulse compression is not unique to seam wave surveys. Surface seismic reflection surveys using a swept-frequency vibrator require that the pulse be compressed so that the individual reflections can be distinguished. This pulse compression requires the identification of a filter with an impulse response that resembles the time inverse of the signal emitted by the swept-frequency vibrator. In a seam wave survey, the waveform at the source is not the waveform received at the transducer due to the wave dispersion, so the problem of wave compression is more complex.

Mason, et al. (1980), describe the problem of time varying pulse compression by using a one-dimensional spectral warping operation in the frequency domain originally described by Booer, et al. (1977). Spectral warping is capable of simultaneously recompressing both direct and reflected arrivals in a time domain output trace. Millahn and Marschall (1980) describe two alternatives for the recompression of seam waves recorded by transducers with two horizontal components, consistent with Marschall (1979). The first technique involves the formulation of the compression operator as a recursive filter (Marschall, 1977). In the second, the method for wave recompression explicitly accounts for the dispersion characteristics of the seam. Having determined the group delay from the actual dispersion curves, the integration of the phase

spectrum of the desired compression operator is derived and applied to recompress the seam wave.

CDP Stacking

Common depth point (CDP) stacking is a process for summing recordings from the same reflection point in order to reduce noise and enhance the seismic reflection. By applying normal-moveout corrections to account for the different raypath lengths when reflecting from a single point from different positions, several traces can be added together or stacked. The stacked traces should reduce noise and enhance the signal.

The British and German seam wave seismic reflection work generally uses six-fold stacking (Buchanan, et al., 1980; Prakla Seismos GmbH, 1980).

The stack of seam wave reflections involves several technical difficulties beyond what is normally experienced in surface reflection seismics:

- Reflections may be of variable mode and velocity, depending on the nature of the reflecting surface. In cases where a discontinuity does not completely cut the coal seam, some frequencies may pass the discontinuity, while others are reflected.

- The reflectors may occur at any angle to the strike of the geophone array.

- The amount of data available for processing is usually very limited in comparison to surface data, as ideal shot and geophone placements are not always possible.

In the U.K., a technique known as Dynamic Trace Gathering (DTG) has been developed (Buchanan, et al., 1979) which accounts for the above differences with regard to CDP stacking of surface reflection data. In Germany, similar procedures have also been developed. A method for CDP stacking of Love-type seam waves in Germany is presented by Klinge, et al. (1979).

Migration

The ultimate goal of a seam wave seismic reflection is to spatially locate discontinuities (the reflectors) within the coal seam. Migration techniques have the potential for accomplishing this goal. The physical means for migrating a reflector have evolved somewhat differently in the U.K. and Germany. Jackson (1981) provides a comprehensive summary of migration techniques.

In the U.K., migration techniques are known as diffraction migration or broadband holographic mapping. The mathematical operators are called lag-sum processors, also referred to as Huygens-Kirchoff diffraction stack migration operators (Mason, et al., 1980; Buchanan, et al., 1979).

In order to correctly locate faults, the data are migrated based on calculations of real and virtual sources. A reflected wave is "seen" as a virtual source by the transducers, just as we observe a virtual image of ourselves when looking in a mirror. Even after a wave is recompressed, there is still some variation in wave velocity depending on what part of the wave is picked. Calculations of the location of real and virtual sources based on travel times to different transducers are also uncertain. The definition of the most probable locations of sources is the underlying principle of the lag-sum processor. Four different types of lag-sum processors have been developed (Mason, et al., 1980; Buchanan, et al., 1979).

- Radical Lag Sum (RLS) or Time Delay Sum - This method enables the contouring of both real and virtual sources in terms of their most probable location. This method has the disadvantage that it does not distinguish between real and virtual sources and does not actually plot the location of any discontinuities. Nonlinear hazards, such as abandoned shafts, wells, or curving sand channels or faults, etc., may not be identified. In addition, data from only one shot can be analyzed to produce the map and the possibility of mode conversion during reflection is ignored.

- Elliptical Lag Sum (ELS) - This technique has the advantage of distinguishing virtual from real sources and plots a contour map of the probable location of the reflector, rather than the source. However, the technique still has all of the remaining disadvantages of RLS mapping.

- Mode Conversion Lag Sum (MCLS) - This mapping technique works on the same principle as RLS and ELS, but is capable of accounting for possible mode conversions.

- Adaptive Lag Sum (ALS) - This technique, developed by Buchanan, et al. (1979), possesses the advantages of the other techniques, but is capable of summing together several shots, taking into account targets at different angles to the transducer spread and also considering mode conversions. Along with DTG processing, this technique is that currently employed in the U.K. for the analysis of seam wave reflection records (Buchanan, et al., 1980).

Work in the Federal Republic of Germany has closely paralleled the work in the U.K., but using slightly different procedures. RLS and ELS migration techniques have been used, as well as a different method based on a polarization analysis of two-component records (Ruter and Schepers, 1979; Millahn and Arnetzl, 1979; Millahn and Marschall, 1980; Millahn, 1980). Graphs of particle velocity (hodographs) are obtained by plotting on an X-Y coordinate system the consecutive values of two seismogram traces within a specific time window. These graphs form the basis for a polarization analysis, a measure of the degree of linear polarization of the recorded motion (rectalinearity) and determination of the direction of incidence of the seismic waves. The polarization analysis forms the basis for a migration technique that compares favorably with ELS mapping. The technique places emphasis on the analysis of the Airy phase of the SH Love seam wave.

Static Correction

The final processing technique that is normally performed in the analysis of surface seismic reflection profiles is the static correction. This correction is required to account for variations in arrival time of reflected waves due to the presence of low velocity material at the surface. As the seam reflection work is conducted from fresh coal faces, this correction is not necessary. However, variations in arrival time can sometimes be detected in transmitted waves as discussed in Section C.4.2.3. These arrival differences can imply velocity anomalies that could be due to significant variations in stress concentration (Mason, 1981) further discussed in Section C.5.0.

C.5.0 CASE HISTORIES

The majority of case histories for the application of seam wave seismics are from Europe, particularly the U.K. and the Federal Republic of Germany. The National Coal Board of the U.K. is conducting just under forty in-mine surveys per year (Buchanan, et al., 1980) and the technique has developed to the point of being an accepted method for mine planning. The situation in Germany is similar. In the U.S., with few exceptions (Suhler, et al., 1978; Reeves, 1979), in seam seismics has been applied only from boreholes. U.S. examples are all experimental and the technique has not been used for mine planning purposes, except where borehole to borehole surveys have been conducted to determine seam continuity, as has been done by Exxon (H. Gluskoter, July 1981, personal communication).

Surveys from boreholes are normally transmission surveys as it is difficult to identify reflectors from a single point and reflectors cannot be located spatially from a single borehole. An early example of a borehole survey is provided by Brentrup (1971) who describes a case history from the Saar area of Germany where seam waves generated in a borehole were clearly detected in a mine roadway 1,200 meters away. Hasbrouck and Hadsell (1976) provide examples of early work in the U.S.

The best documented examples of borehole surveys are recent theses from the Colorado School of Mines. Regueiro (1980) and Regueiro and Major (1980) demonstrate the feasibility of generating seam waves between boreholes in a coal seam in the Zulia coal basin of Venezuela. In this example, it was possible to transmit a seam wave a distance of 240 meters, even though the country rock/coal velocity contrast was only 1.33:1. Another example is the thesis of Bahavar (1980) where a seam wave could be transmitted up to a distance of about 130 meters in coal seam about 1.5 meters thick. This study demonstrated that other low velocity layers near the coal seam, in this case a soft clay about eight meters above the coal seam, could also provide a path for the transmission of a seam wave that could contribute to the transmission record through the coal.

In-mine seam wave transmission studies are routinely conducted in Europe, including the U.K., where longwall mining techniques are prevalent. The original work by Krey (1963) and other early case histories by Arnetzl (1971) and Krey (1976) provide numerous case histories of the use of transmission records to locate coal discontinuities. A good example of a successful transmission survey is provided by Arnetzl (1971), where unusual types of washouts known as "puit naturels," could be detected (Figure C-7).

An example of the "state of the art" in the interpretation of transmission surveys is provided by Mason (1981). Mason (1981) used an algebraic reconstruction technique to reduce the first break arrival times through a 425 x 950 meter rectangular block of coal into a profile of velocity inhomogeneity at the Thoresby Colliery, U.K. (Figure C-8). This velocity profile map was constructed in a High Hazels seam located 60 meters above another seam previously mined known as the Hart Top seam. Pillars of unmined coal left in place in the Hart Top seam are directly underneath the high velocity anomalies detected in the High Hazels seam (Figure C-8). The shape of the velocity field is consistent with the probable in-seam pressure pattern and the study concludes that coal velocity is pressure sensitive and that subsidence into old workings can be mapped using transmitted seam waves.

Numerous examples of recent successful in-mine seam wave reflection surveys are available in the literature (Buchanan, et al., 1980; Mason, et al., 1980; Millahn and Marschall, 1980; Prakla Seismos, 1980). In most cases, reflection surveys are conducted together with tranmission surveys and the analysis of transmitted waves contribute to an interpretation of the reflections.

Buchanan, et al. (1980), present an example of a seam wave reflection survey southeast of the G20 retreat longwall panel, South Kirkby Colliery, U.K. The example is interesting in that it offers an opportunity to compare the surface and in-seam reflection techniques for the location of a fault. Transmission data was obtained shooting across G20, while the roadway AB (Figure C-9) was used as the base for the seam wave reflection survey. The trend of reflectors in the DGT stack of the

reflection data adjacent and parallel to the roadway is interpreted to be the roadway mode, while the seismic anomaly near the center of the figure is interpreted to be a fault. A comparison of the projected fault location as determined by both the seam wave and surface seismic reflection methods is provided in Figure C-9. The fault identified by the seam wave survey is somewhat closer than the position predicted by the surface reflection survey. It is conceivable that the fault detected by the in-seam reflection method is a branch to a more important fault in the position defined from the surface. The immediate importance of the results was that it proved possible for the mine manager to plan a particular width of panel adjacent to G20. Work in the Federal Republic of Germany has also continued with a high level of technology and numerous examples can be cited where seam wave reflection surveys have successfully delineated faults and other discontinuities prior to their being mined.

The seam wave reflection technique has proved effective in delineating structure sufficiently far in advance of mining so that the mine planners can consider how to cope with discontinuities to the seam. The National Coal Board of the U.K. has successfully defined fault structures at distances ranging from 60 to 500 meters from the seismic survey line (Buchanan, et al., 1980). Similarly, in Germany, seam wave reflection surveys have reliably mapped faults up to distances corresponding to 200 to 300 seam thicknesses (Millahn and Marschall, 1980).

C.6.0 STATE OF THE ART

The state of the art in seam wave surveys in the U.S. is behind that of the U.K. and Germany. Studies in the U.S. have demonstrated that seam waves can be generated in U.S. coals, but considerable work needs to be performed to obtain results as good as being obtained in Europe. Mine certified instruments and sources still need to be developed. In addition, data processing techniques to interpret seam wave reflections have not been developed, or at least are not available commercially.

The state of the art in Europe is being advanced primarily in the area of processing software. Mine certified equipment still needs to be developed in the U.K., but the National Coal Board has been able to make extensive use of noncertified equipment by operating in low methane environments. Prakla Seismos has already developed mine certified equipment in the Federal Republic of Germany. Additional refinement to the seam wave seismic technique will undoubtedly come when areas previously surveyed are mined out and interpretations can be "ground-truthed." Direct verification of actual conditions should provide insight into areas of previously questionable interpretation.

APPENDIX C

REFERENCES

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LIST OF REFERENCES

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APPENDIX C
FIGURES

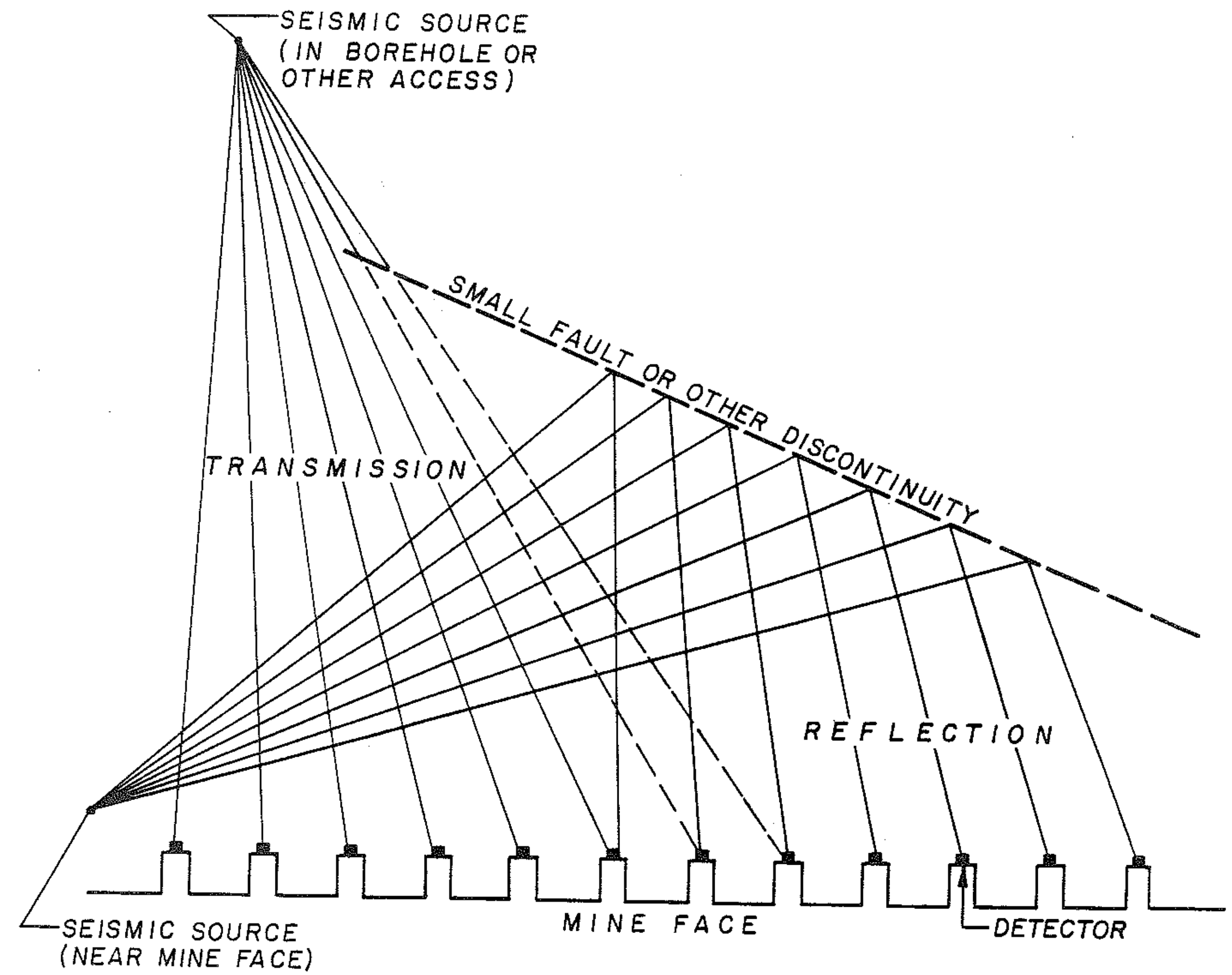


FIGURE C-1

CONCEPTUAL ILLUSTRATION OF TRANSMISSION AND REFLECTION SEAM WAVE TECHNIQUES

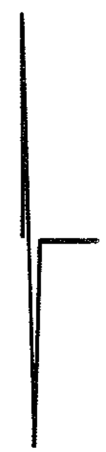


FIG. 2a NON-DISPERSED WAVELET

FIG. 2b DISPERSED WAVELET

NOTE:

THE NON-DISPERSED WAVEFORM (FIG. 2a) APPEARS TO BE AN IMPULSE NEAR THE ENERGY SOURCE BUT CHANGES CHARACTERISTICS AS IT PROPAGATES AWAY FROM THE SOURCE (FIG. 2b)

FIGURE C-2

GRAPHIC REPRESENTATION OF DISPERSED AND NON-DISPERSED WAVELETS

REFERENCE:
PETERSON, 1979

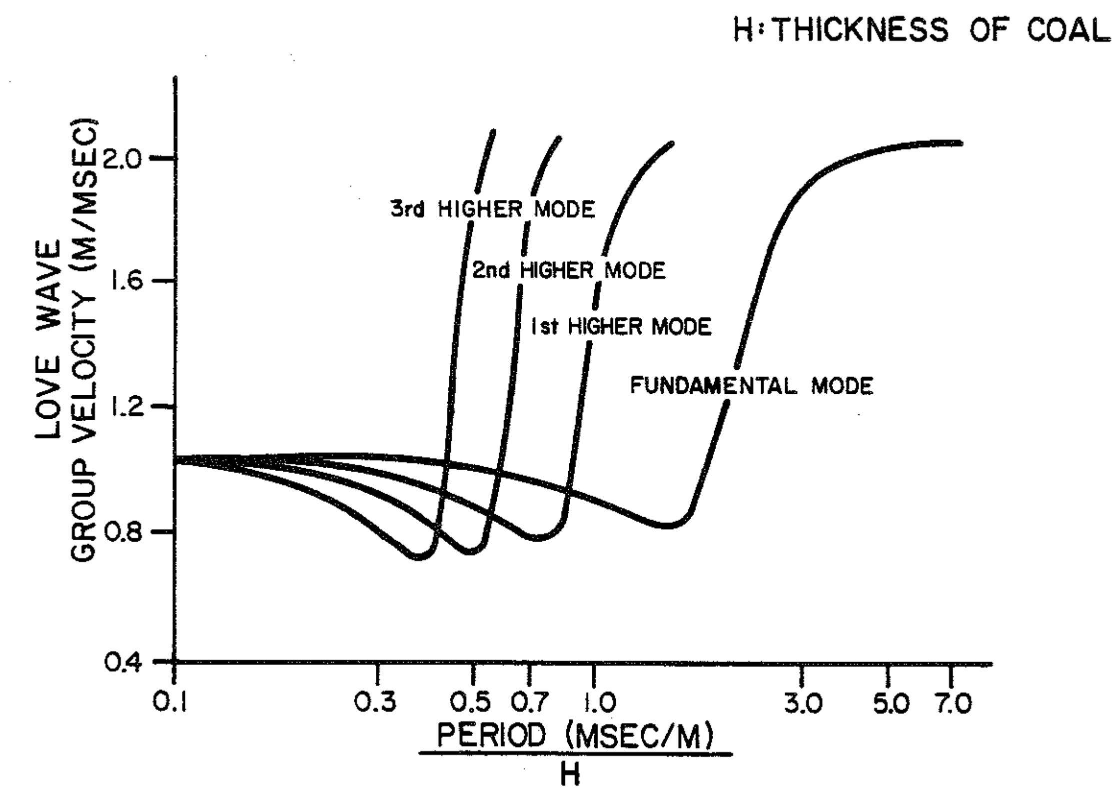


FIGURE C-3

EXAMPLE OF LOVE WAVE DISPERSION CURVES FOR A DEEP COAL WITH A ROCK/COAL VELOCITY CONTRAST OF 2:1

REFERENCE:
PETERSON, 1979

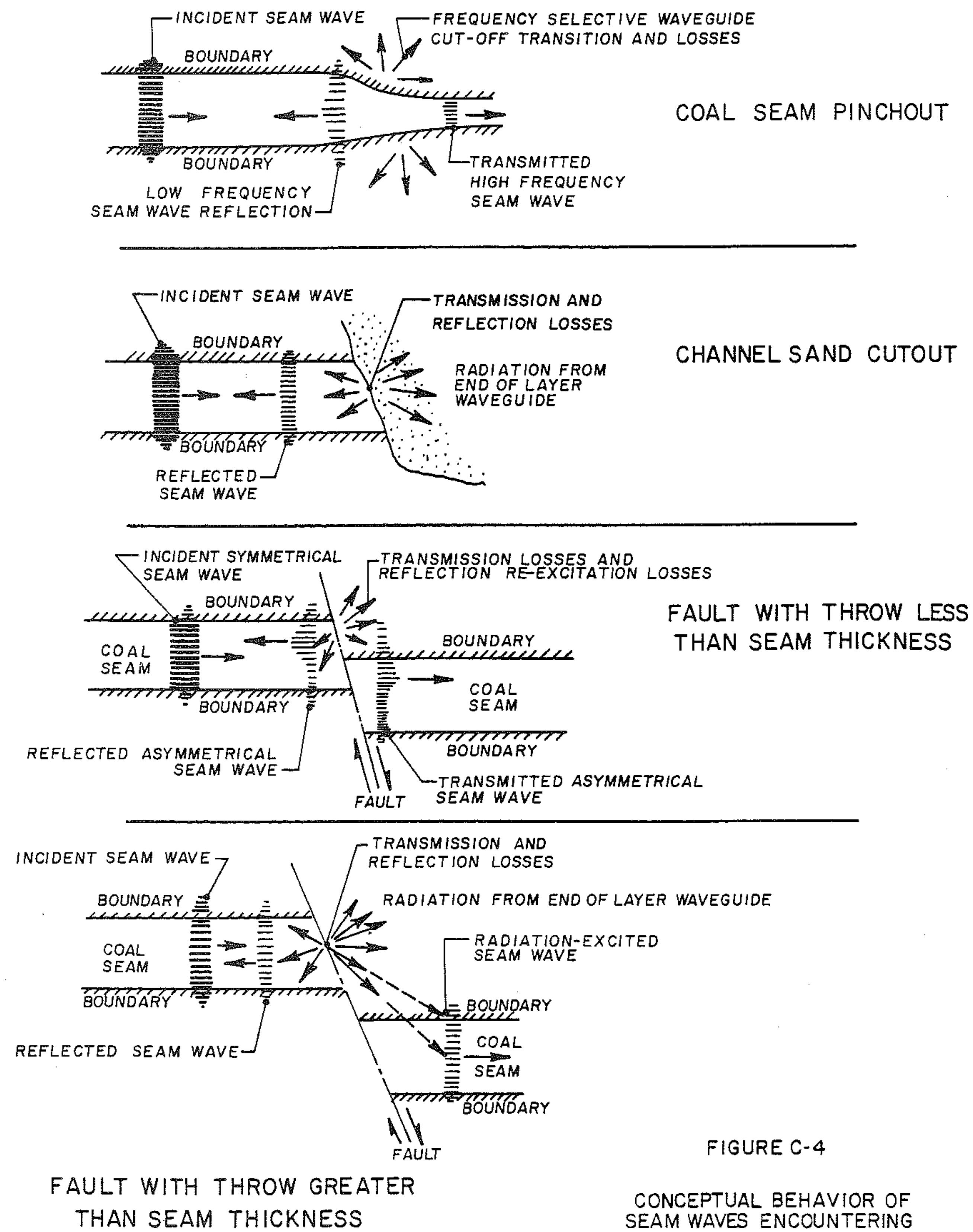


FIGURE C-4

CONCEPTUAL BEHAVIOR OF SEAM WAVES ENCOUNTERING VARIOUS DISCONTINUITIES

REFERENCE:
SUHLER ET AL, 1978.

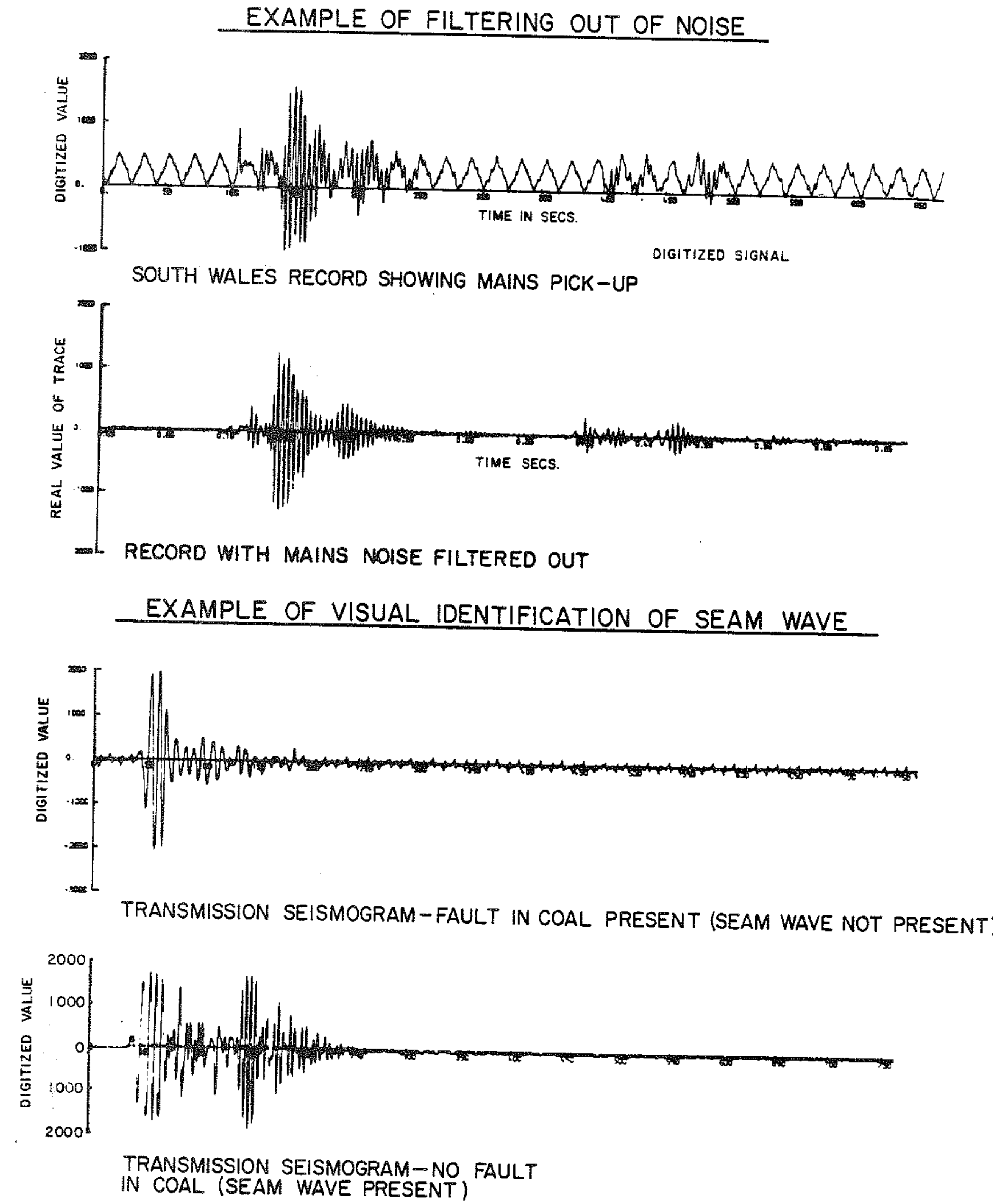


FIGURE C-5

EXAMPLES OF FILTERING AND VISUAL IDENTIFICATION OF SEAM WAVE

REFERENCE:
BUCHANAN (1978)
REPRODUCED THROUGH THE COURTESY OF THE NATIONAL COAL BOARD

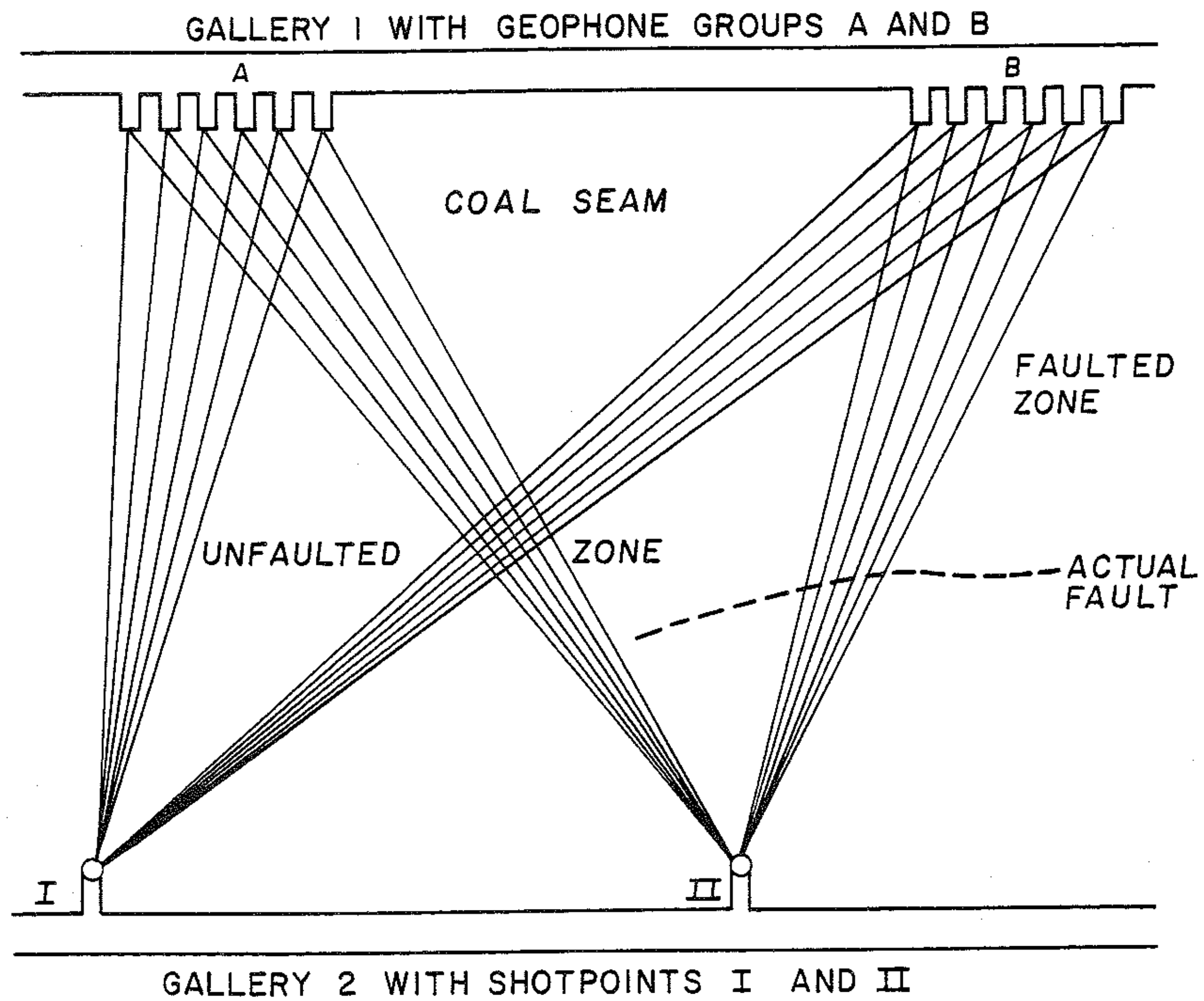


FIGURE C-6

ILLUSTRATION OF SEAM WAVE TRANSMISSION TECHNIQUE FOR RAPID APPROXIMATE DELINEATION OF FAULT ZONE

REFERENCE:
KREY (1976)

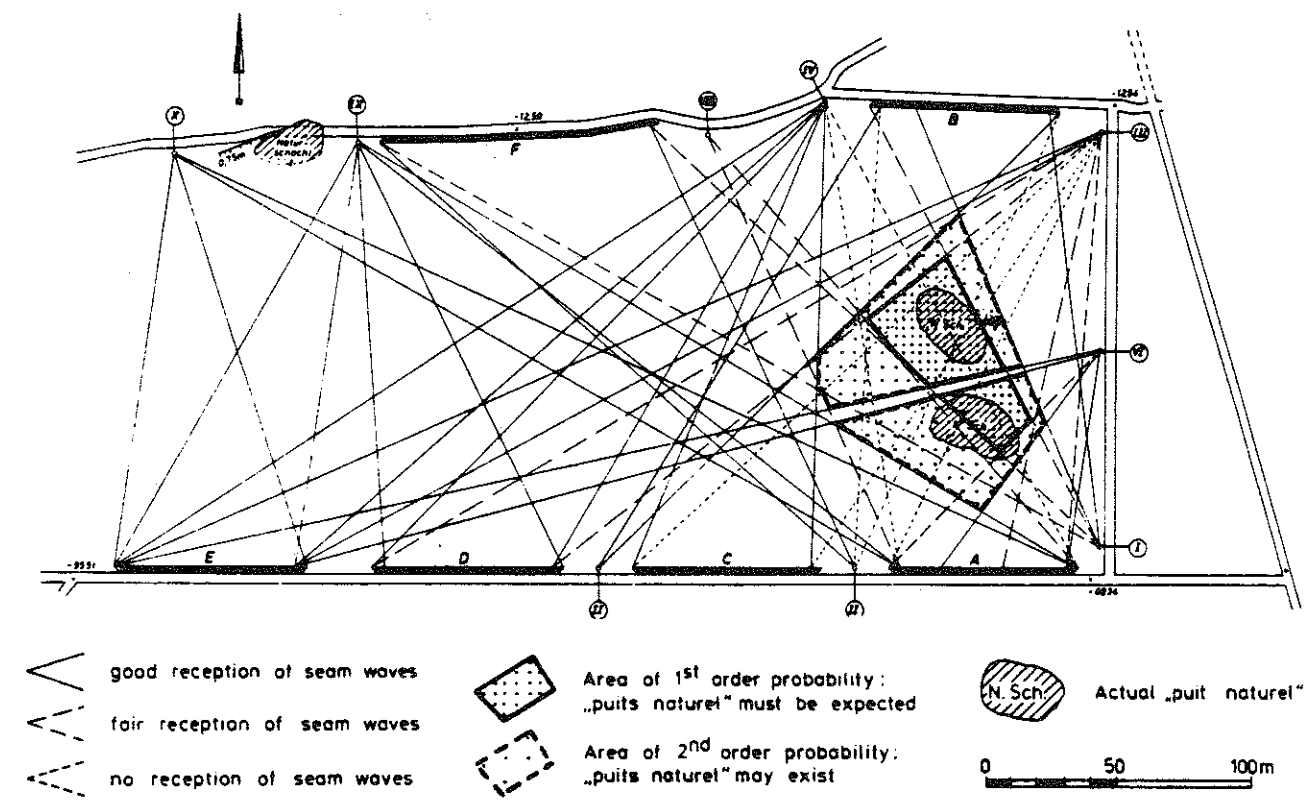
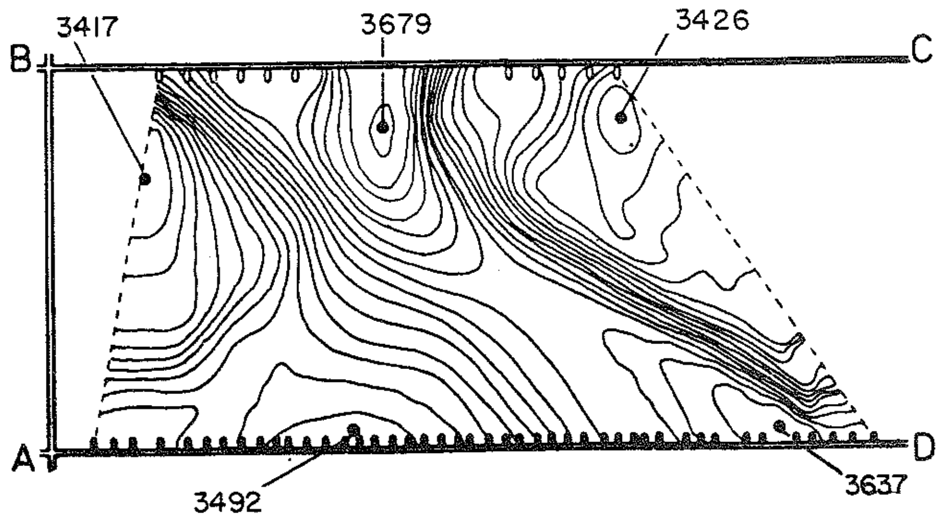


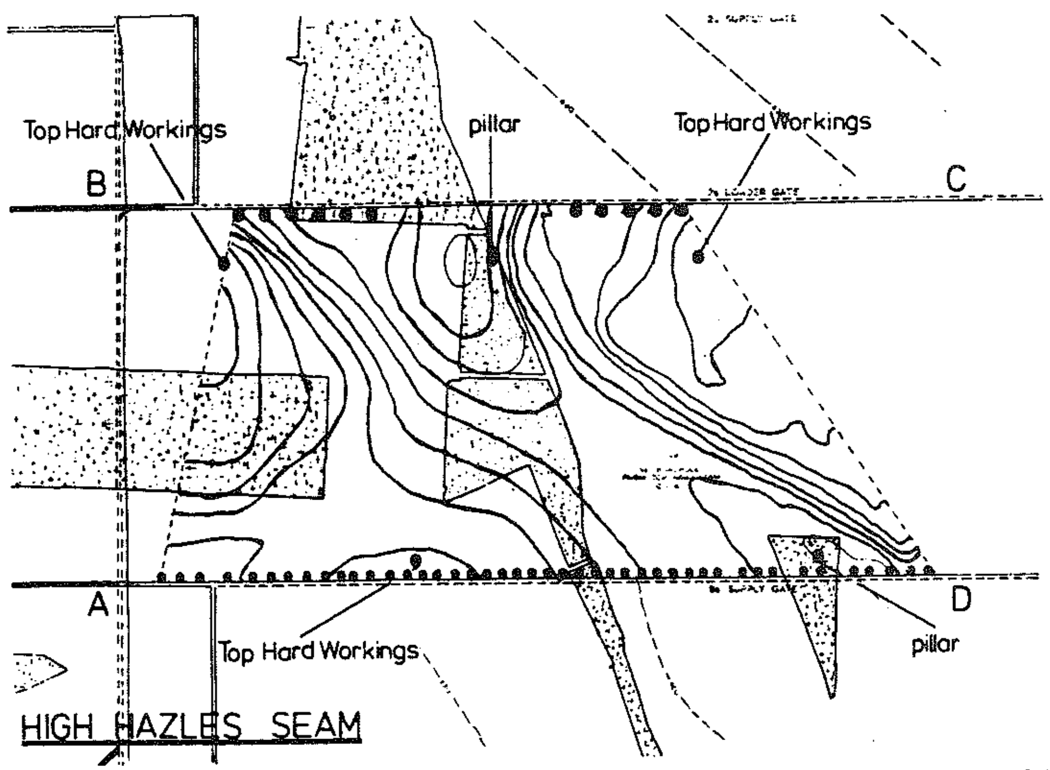
FIGURE C-7

EXAMPLE OF THE RESULTS OF SEAM WAVE TRANSMISSION SURVEY

REFERENCE:
ARNETZL (1971)



ALGEBRAIC RECONSTRUCTION OF A CHANNEL WAVE VELOCITY FIELD WITHIN THE HIGH HAZLES SEAM OF THORESBY COLLIERY. SPOT VALUES ARE GIVEN IN m/sec. THE FIELD CONSISTS BASICALLY OF A DIAGONAL HIGH-VELOCITY RIDGE, WITH A SPUR CUTTING OFF TOWARD A.



SURVEYORS MAP OF THE HIGH HAZLES PANEL. THE SHADED AREAS INDICATE THE POSITIONS OF PILLARS LEFT IN PLACE AFTER EXCAVATIONS IN AN UNDERLYING SEAM. SELECTED VELOCITY CONTOURS ARE SHOWN TO PROVIDE REGISTRATION BETWEEN THE SURVEYORS MAP AND THE ALGEBRAIC RECONSTRUCTION OF VELOCITY SHOWN ABOVE.

SCALE

200 0 200 400 METERS

FIGURE C-8

EXAMPLE OF INTERPRETATION OF VELOCITY FIELD WITHIN HIGH HAZELS SEAM, THORESBY COLLIERY AND COMPARISON TO UNMINED AREAS REMAINING IN A LOWER SEAM

REFERENCE:
MASON (1981)

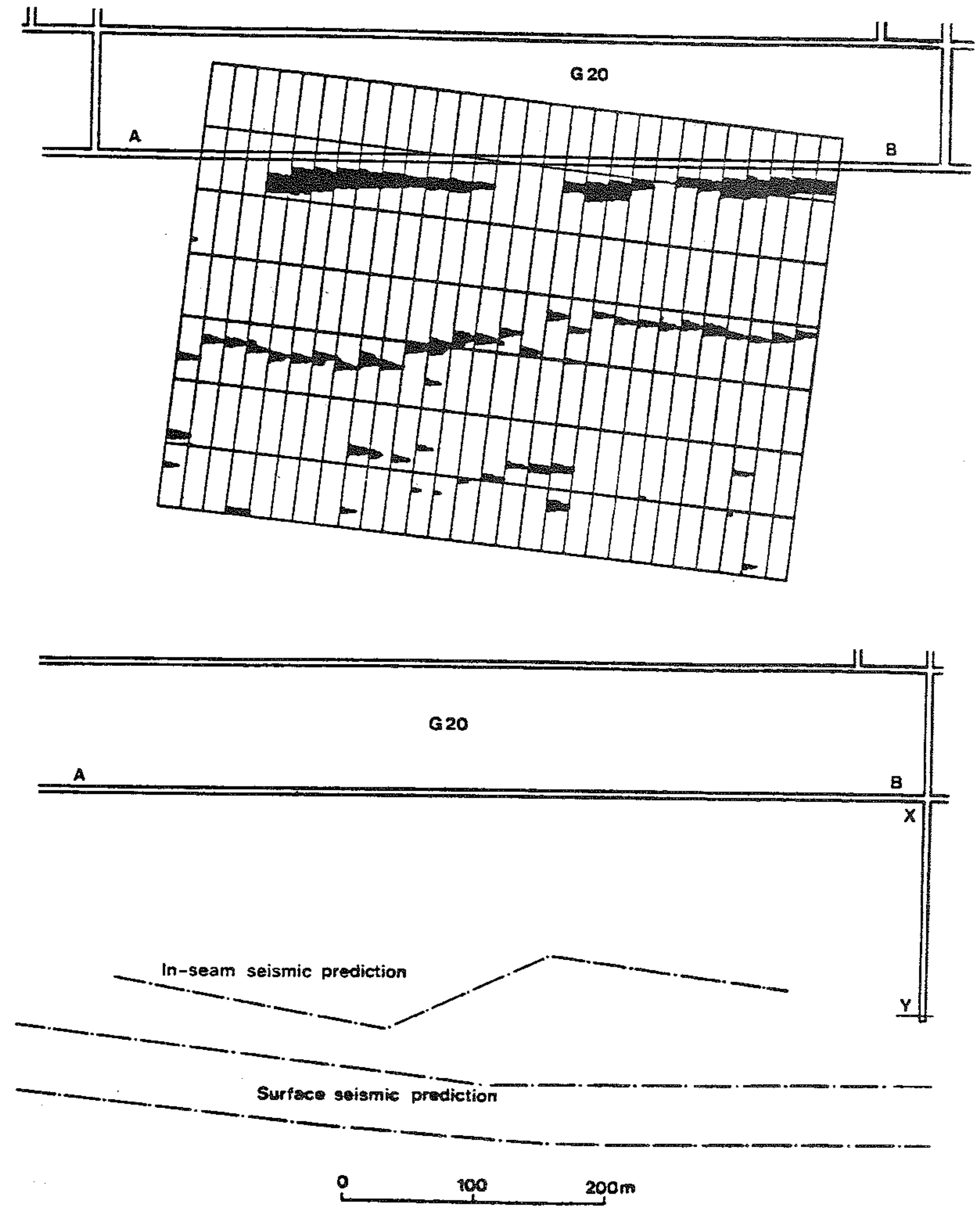


FIGURE C-9

DGT STACK AND INTERPRETATION OF SEAM WAVE REFLECTION SURVEY SOUTH KIRKBY COLLIERY, U.K.

REFERENCE:
BUCHANAN ET AL, 1980
(REPRODUCED THROUGH THE COURTESY OF THE NATIONAL COAL BOARD)

APPENDIX D

RADAR

APPENDIX D

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RADAR

D.1.0 GENERAL DESCRIPTION

Radar, which is short for ra(dio) d(etecting) a(nd) r(anging), is defined in the usual sense as a system to determine the presence and location of an object by measuring the time for the echo of a radio wave to return from it and the direction from which it returns. When applied to coal mining problems, the technique can be extended to include the transmission and reception of electromagnetic waves between two points known as the high frequency electromagnetic technique (HFEM). Another variation of the radar technique is the use of frequency modulated continuous waves (FM-CW), where reflections are recorded by noting phase shifts between transmitted and reflected signals. All of these technqiues are closely related and have been considered together under the title of radar.

The radar reflection method consists of measuring the travel time for a high frequency electromagnetic wave (15 to 500 megahertz), generated by a pulser and antenna unit to return to the antenna after reflection from an interface between materials with different electromagnetic properties. Radar reflections can be interpreted in a manner similar to seismic reflections, except that travel times are measured in terms of nanoseconds rather than tenths of a second. Reflections may be detected by the same antenna which generated the signal; in such a case, a special switch switches the antenna from transmit to receive just after the signal has been transmitted. The technique is normally applied from the surface or in a mine, but is being developed for use from a borehole. Alternatively, with the FM-CW method, the radar pulse can be sent continuously with a varying frequency and a phase shift between transmitted and received signals noted which can be related to distance to the reflector.

The HFEM technique can be used in a cross hole type setup where a transmitter is placed in one borehole and a receiver is placed in another borehole. This technique can also be used within a mine to transmit across pillars or panels. The travel time, amplitude, and phase of the received signal are analyzed to determine the characteristics of the materials between the boreholes. As the HFEM technique has a limited applicability to conventional coal investigations, discussions of physical principles and constraints and survey test preparation relate to the radar reflection technique.

The main applications of the radar technique are the detection of voids, abandoned wells, channel sands, faults, seam pinchouts, clay veins, and pyrite and sulfur balls within the seam. The resolution of reflections within a coal seam is limited to about 50 feet (15 meters) with present-day technology, but this limit is expanding. With this range of penetration, the most important application of the technique is to identify hazards in front of the working face, giving the mine operator about a one-day warning of conditions before they are encountered. An additional application in an underground environment has been to measure the thickness of the coal layer remaining in the roof after passage of a continuous mining machine. Knowledge of the thickness of roof coal is important from the standpoint of controlling the cutting horizon of the continuous mining machine, as well as for safety reasons.

D.2.0 PHYSICAL PRINCIPLES AND CONSTRAINTS

D.2.1 Background Theory

The criteria which determines whether an electromagnetic interface will reflect or not is the electromagnetic impedance (similar to acoustic impedance in the seismic reflection technique). The coefficient of reflection across a given electromagnetic interface is determined by the difference in impedances of the two materials divided by the sum:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

where

R = reflection coefficient

Z_1, Z_2 = electromagnetic impedance of materials 1 and 2, respectively.

The electromagnetic impedance is defined by the relationship $Z = \frac{\mu^*}{\varepsilon^*}$ where μ^* and ε^* are the complex magnetic permeability and complex permittivity, respectively.

These terms are defined as follows:

$$\varepsilon^* = \varepsilon' + j\,\varepsilon''$$
$$\mu^* = \mu' + j\,\mu''$$

where

$j^2 = -1$

ε' = dielectric constant

ε'' = loss factor = $\frac{\sigma}{\omega}$ where σ is the conductivity of the material and ω is the angular frequency ($2\pi f$)

μ' = magnetic permeability

μ'' = magnetic loss factor

From the equations above, it can be seen that the electromagnetic impedance of a material is a function of its magnetic permeability, dielectric constant, and the resistive and magnetic loss factors. This makes the definition of an electromagnetic interface somewhat more complex than the definition of an acoustic interface.

The effectiveness of ground probing radar is limited by its maximum effective range in the medium of interest. The propagation loss of an EM wave may be described as follows (Cook, 1975):

$$E = E_o\, e^{-\alpha x}$$

where

E = E field intensity

E_o = E field intensity at point of origin

α = EM plane wave absorbtion coefficient

x = distance from origin

The absorbtion coefficient is defined by the following relationship:

$$\alpha = \omega \left\{\frac{\mu\varepsilon}{2}\left[\left(1 + \frac{1}{\omega\rho^2\varepsilon^2}\right)^{1/2} - 1\right]\right\}^{1/2}$$

where

μ = magnetic permeability

ε = dielectric constant

ω = angular frequency

ρ = r.f. loss resistivity

Loss, A, is typically expressed in terms of db/foot and is roughly given by a $\frac{db}{ft} = 2.65\alpha$. As seen by the above equations, the loss over distance is much greater for higher frequencies. Besides a dependence on frequency, the loss factor also depends on the conductivity of the material. In general, the loss factor increases with an increase in conductivity. Radar transducers typically have a dynamic range of 100-130 db. In general, a radar signal cannot be detected if it has been attenuated by a factor which is greater than the dynamic range. For example, a transducer with a dynamic range of 100 db, in a medium with a loss factor of 1.0 db/m, could detect a reflector at maximum distance of 50 m, half of the total distance necessary to attenuate the signal 100 db.

The ability of radar to penetrate rock is highly dependent on rock type, moisture content, and the predominant frequency of the radar pulse. Radar has been used for many years to probe homogeneous rocks, such as salt, with penetrations of thousands of meters (Unterberger, 1977). Dry igneous rock is also highly transparent to EM waves. Low resistivity material, however, is highly resistant to radar with only a few meters of penetration possible in a wet clay. Water has a high dielectric constant, but a low resistivity. This low resistivity means that attenuation is severe for water-saturated material. Coal has a higher resistivity than most other rocks in a coal sequence and is a fairly good transmitter of EM waves. For dry samples of coal, the distance of propagation of a one MHz signal with a 100 db attenuation was up to about 500 meters. With a 100 MHz signal, penetrations up to about 50 meters could be achieved (Cook, 1975). In an actual mine environment, penetrations of about 30 meters have been recorded with the radar energy in the frequency range of 40 to 500 MHz.

The ability of the radar method to resolve discontinuities in the coal is highly dependent on the frequency of the pulse. Resolution is directly proportional to source frequency; i.e., resolution increases as frequency increases. Unfortunately, depth of penetration is inversely proportional to the frequency, which means that as the depth of penetration increases, the resolution decreases. In general, a reflective material must be 1/8 of a wavelength (wavelength = wave velocity divided by frequency) thick to be detected. This corresponds to a thickness of 30 m for a 1 MHz signal and a thickness of 0.3 m for a 200 MHz signal. The source frequency is then a compromise between resolution and depth of penetration. Most work in earth is done in the frequency range of 50 to 500 MHz.

Field studies (Coon, et al., 1981) have shown that the polarization of the radar pulse is also significant in determining the effective depth of penetration within a coal seam. EM energy polarized perpendicular to the bedding plane of the seam is attenuated less (propagates a greater distance) than energy polarized parallel to the bedding plane.

D.2.2 Information Derived from Measurements

The general objective of the analysis of EM waves is the identification of discontinuities present within the coal. In advance of the working face, the radar reflection technique can identify discontinuities such as voids, abandoned wells, channel sands, seam pinchouts, clay veins, and clay and pyrite balls within the coal. The technique has been used to detect coal thickness and discontinuities within the mine roof. The method can also be used in a transmission mode to determine variations in electromagnetic properties across a mine pillar or between boreholes to locate discontinuities in a manner similar to the seam wave transmission technique. The transmission distance for radar (up to about 30 meters) limits the usefulness of the method in a transmission mode. The radar reflection technique can locate discontinuities about 15 meters in advance of the working face, which is a considerably smaller range than from the seam wave technique, but resolution is much higher.

D.2.3 Site Constraints

Anything which has a magnetic permeability, electrical conductivity, or dielectric constant which differs significantly from the surrounding materials can reflect EM energy of radar frequencies. Consequently, the presence of groundwater, fractures, and strata discontinuities will have an effect on the radar transparency of a material. Fractures and strata discontinuities are of primary significance since they will be seen as reflectors. The effect of groundwater will be to change the conductivity and dielectric constant of a material, which may alter the attenuation characteristics of that material, generally to increase attenuation. The presence of highly conductive material within a coal seam, such as pyrite or sulfur balls, also increases attenuation.

Although a coal seam is a very good EM reflector, the depth of burial normally places it out of range for surface radar. In addition, the presence of water-saturated soil near the surface usually limits radar penetration to a few meters. Under the very best of conditions, radar has penetrated less than 200 m below the surface through hard, dry, highly resistive rock. The use of the surface radar technique is therefore greatly constrained by the depth of penetration and is useful only when targets are near surface, such as abandoned shafts or wells.

Although the presence of competent, dry rocks in an underground environment makes radar more effective than from the surface, the factors which determine the attenuation characteristics (coal conductivity, moisture content, presence of discontinuities) will affect the quality of the results.

D.3.0 PRETEST REQUIREMENTS

Pretest requirements for surface or underground use of a radar system are negligible. When conducted from a borehole or boreholes, the boreholes should be cased with material of high resistivity, such as PVC or fiberglass. Dry holes are preferable, but not absolutely necessary. Interpretation is best served by field measurements of dielectric constant and conductivity of the coal. By transmitting across a working face or between borings, these parameters can be derived by measuring arrival time and the power and phase changes of the source signal.

D.4.0 DEPLOYMENT OPTIONS

The radar technique can be deployed in reflection and/or transmission modes from the surface, underground, or from boreholes. These deployment options are presented in terms of the three main radar techniques, pulse radar, HFEM, and FM-CW.

D.4.1 Pulse Radar Systems

Pulse radar systems can be deployed from either the surface, underground, or from boreholes with basically the same equipment and required analysis.

D.4.1.1 Equipment

A pulse radar system consists of antennas, a control unit, recorder, power supply, and optional ancillary units to the control unit which control repetition rates and can perform signal enhancement. A block diagram and photograph of the short pulse radar system developed by Xadar Corporation is provided in Figure D-1. The receiver/recorder unit contains a high-speed sample and hold circuit which "stretches" the signal by a factor of several million so that a radio frequency sequence can be presented on ordinary radio frequency recorders, either analog or digital. Commercial suppliers of surface and underground radar systems include Xadar Corporation (Springfield, Virginia) and Geophysical Survey Systems, Inc. (Hudson, New Hampshire). Borehole radar systems are still in the experimental stage. A directional borehole pulse radar unit for use in a single borehole has recently been developed by Southwest Research Institute.

D.4.1.2 Operation

From the surface, a continuous profile is generated by towing the transducer at low speeds (2 to 3 mph). The reflected signals are presented graphically on a graphic recorder and are recorded on a magnetic recorder for subsequent processing (if required) and playback. The graphic recorder is identical to those used for marine subbottom profiling.

Underground operations are not as simple as surface surveys in that transmitter and receiver antennae must be placed directly against the coal and moved in discrete intervals for either reflection or transmission modes. Underground operations are affected by the usual problems of access due to the presence of mine equipment, narrow openings, moisture, and dust. Part of these problems have been alleviated by the development of a portable, environmentally safe unit specifically for underground use by the Xadar Corporation. Borehole reflection operation is similar to surface operation except that the borehole antennas are moved along the borehole axis.

D.4.1.3 Analysis

Analysis of profiled data consists of measuring the travel time to a reflector and converting the travel time to distance. Computer processing techniques analogous to seismic reflection processing, such as common depth point (CDP) stacking, bandpass filtering, source signature deconvolution, and event correlation, may be applied if the tapes are played back and digitized. The velocity, dielectric constant, and conductivity of the region of interest must be known as these will directly affect the accuracy of the results obtained.

Real time capabilities depend on the type of analysis performed. If it is necessary to use some of the sophisticated processing techniques mentioned above, then there will be a considerable lag time between data acquisition and interpretation. If the region of interest is relatively

free of perturbations in dielectric constant and conductivity between the transducer and the target, simple interpretive techniques can be applied. This would result in a short lag time (less than one day) between data acquisition and interpretation.

D.4.2 High Frequency Electromagnetic (HFEM) Technique

D.4.2.1 Equipment

Equipment for HFEM transmission is not commercially available, but has been developed by Lawrence Livermore Laboratories as described below. The transmitter provides a continuous wave and can operate in the range of 1 to 100 MHz. For coal propagation 10 to 25 MHz is normally used. Designed for use in a borehole, the transmitter antenna has a 1-inch-diameter and is approximately 1/8 of a wavelength long (18 to 20 inches). The receiver antenna is two inches wide and the same length as the transmitter. All transmitter and receiver electronics are on the surface and only the antennas are lowered in the boreholes which should be cased with a nonmetallic material, such as PVC or fiberglass.

D.4.2.2 Operation

In an HFEM survey, where transmitter and receiver antennas are located in separate boreholes, the probes are moved in discrete intervals. When the target is the identification of a specific anomaly between two boreholes, such as a void, the intervals selected may be designed to maximize the number of possible raypaths between the two borings as discussed by Lager and Lytle (1977).

D.4.2.3 Analysis

Analysis of transmitted HFEM data, generally taken between two boreholes, is discussed by Lager and Lytle (1977). In order to identify anomalous zones between the boreholes, which could correspond to voids or other geologic or man-made discontinuities, different types of image reconstruction algorithms have been used. These algorithms, developed originally by medical researchers working in the field of tomography, are known as the Algebraic Reconstruction Technique (ART) and the Back Reflection Technique (BRT). These methods are based on modeling the electromagnetic equations describing the signal behavior between the transmitter and receiver as linear equations assuming ray-optics approximations. By dividing the area between boreholes into rectangular cells, electrical properties are derived for each cell which will best fit the observed transmitted data, taking into account the amplitude and phase of the transmitted and received signal, cable losses, and the transmitted power and gain of the antennas. Cells will be assigned similar electromagnetic properties if material between the boreholes is homogenous; if not, the anomalies will stand out.

D.4.3 Frequency Modulated-Continuous Wave (FM-CW) Technique

D.4.3.1 Equipment

Frequency Modulated-Continuous Wave (FM-CW) equipment is normally used in an underground environment. The equipment is still experimental and under development by the National Bureau of Standards (Ellerbruch and Belsher, 1978). The transmitter sends out sweep EM waves in the 1 to 2 GHz range. A similar system is under development by the Southwest Research Institute and operates in the 2 to 6 GHz range to guide the head of a continuous mining machine. The receiver does not record the arrival time of the reflections, but the reference (transmitted) signal and reflected signal are fed into a mixer which is then passed through a spectrum analyzer to yield an output of amplitude versus phase difference, usually recorded in KHz. This system requires less power than a pulse system, but the electronic circuitry and display is more complex.

D.4.3.2 Operation

The operation of a FM-CW system is similar to a pulse radar system. The system is also subject to the usual problems of access, moisture, dust, etc.

D.4.3.3 Analysis

The interpretation of FM-CW results are done in the field by developing empirical correlations of the amplitude peaks recorded at different phase shifts to reflecting horizons within the mine roof. Minor variations in roof stratigraphy, especially the presence of pyrite or sulfur, cause large changes to the nature of the reflectors, so checks are necessary to verify the origin of the reflectors identified.

D.5.0 CASE HISTORIES

Most of the research and literature documenting the radar techniques is from the U.S. In this country, coal deposits often contain abandoned oil or gas wells and tunnels which represent risks of flooding by water and/or gas if encountered. The most important radar technique in use is pulse radar, which is used to detect the reflections of hazards in advance of the working face, or to pinpoint known hazards with greater precision so that mining efforts can be optimized. For example, an abandoned well may be known to exist in a certain area. Unless the location can be determined precisely, it may be necessary to leave unmined or thicker pillars of coal than would be left if the location could be determined.

The main organizations conducting radar research in the U.S. are the Southwest Research Institute (San Antonio, Texas); Xadar Corporation, a division of ENSCO, Inc. (Springfield, Virginia); the Lawrence Livermore Laboratory (Livermore, California); and the National Bureau of Standards (Boulder, Colorado). Another pioneer in radar research and development

is John C. Cook of Teledyne-Geotech (Dallas, Texas). Much of the research has been channeled through the U.S. Bureau of Mines (Denver, Colorado), who also perform their own research. Key publications from individuals in these and other organizations include Suhler, et al. (to be published shortly by the USBM), Coon, et al. (1981), Fowler (1981), Fowler and Hale (1980), Cook (1970, 1972, 1973, 1975, 1977), and Ellerbruch and Belsher (1978).

Until recently, little interest has been shown in radar technology in Europe as wells and abandoned workings are not as serious a problem as in the U.S., and the longwall technique of mining normally employed relies on seam wave techniques to locate possible geological hazards. Nevertheless, research is now being conducted, particularly in Germany, and experiments consistent with those already performed by the U.S. Bureau of Mines are showing some success (Jackson, 1981).

Experimental tests of commercially available short pulse radar for both reflection and transmission modes of operation are presented by Coon, et al. (1981). This study presents three different tests including determination of penetration distances, velocity of propagation, and attenuation versus frequency in a large coal pillar. Velocity propagation was approximately half the velocity in air, i.e., half the speed of light. Tests showed that it was possible to transmit EM enegy in the range of 20 to 500 MHz through 50 feet (15 meters) of coal. Using a source with a center frequency of 100 MHz, it proved possible to resolve reflections at distances greater than 50 feet (15 meters) using a tenfold CDP data stack to improve the signal-to-noise ratio. An example of the detection of clay veins within a coal pillar is provided in Figure D-2. The final series of tests demonstrate the ability of the radar reflection method to locate a six-inch uncased borehole that had been drilled in the coal seam from the surface (Figure D-3). The studies also showed that EM energy polarized parallel to the bedding planes.

Fowler and Hale (1980) note that the short-pulse system is inefficient in that the antennas must be purposely detuned to obtain the bandwidth necessary for sharp pulses, making the system inefficient from a power standpoint. They also note that because of the relatively wide bandwidth of the receiver, the gain of the electronics must be limited in order to minimize oscillation problems.

Research is continuing by Xadar Corporation under contract to the U.S. Bureau of Mines to increase the range of the radar reflection technique (Fowler and Hale, 1980). In particular, an increase in range to 200 to 300 feet (61 to 91 meters) would be more practical for a mine operator. For example, it is usually necessary to leave a barrier pillar of 200 feet (61 meters) of coal between an active and abandoned mine. Knowledge of the precise distance to the abandoned workings could prevent unnecessary leaving of minable coal or, conversely, advise the mine operator if he is too close to the abandoned workings. A possible increase in radar range is represented by the synthetic pulse system still in the prototype stage.

The synthetic pulse system differs from the short-pulse system in that, instead of transmitting a single broadband pulse, it transmits a frequency spectrum of that pulse by radiating one frequency at a time and measuring the amplitude and phase at the receiver. The reflection sequence is then generated by performing an inverse Fourier transform on the data. A prototype of this system has been developed and transmission has been achieved throuh 200 feet (61 meters) of coal. With better designed antennas and better source/receiver decoupling, reflections from 200 feet (61 meters) appear feasible (Fowler and Hale, 1980).

The development of a borehole radar system is continuing at the Southwest Research Institute under contract to the U.S. Bureau of Mines. An onmidirectional borehole radar unit has already been developed which uses a pulse transient signal in the 30 to 300 MHz frequency range. The effective range is about 50 feet, dependent on earth characteristics, particularly moisture content. A prototype of a directional borehole probe has recently been completed and tested. This new system has an angular resolution of about 30 degrees azimuth and improved range over the omnidirectional system. This system is best at locating voids or coal seam discontinuities and would also be useful in locating abandoned wells. In order to accurately resolve distance from the borehole probe, it is necessary to measure the velocity of the radar waves in the earth material penetrated. This requires measurements between borings (cross hole) or across pillars or the mine face within the mine. Borehole probes are not yet commercially available.

Cross hole measurements using the HFEM technique have been developed in association with underground coal gasification projects to delineate the advance of the burn front within the coal. By transmitting in the 10 to 100 MHz frequency range between nine wells separated typically by roughly 40 feet (12 meters), it was possible for Lawrence Livermore Laboratory to monitor the progress of the Hoe Creek, Wyoming burn in 1977 (Davis, et al., 1979). The HFEM technique has also been used to detect tunnels. In one experiment, a tunnel at a depth of 24 meters in granite, at a site near Gold Hill, Colorado, was successfully detected by lowering receiver and transmitting antennae in unison down two boreholes. A minimum signal was recorded when passing the tunnel between depths of 23 and 26 meters. The Back Projection Technique described in Section D.4.3 was used successfully to resolve the horizontal location of the tunnel (Lytle, et al., 1979; Lawrence Livermore Laboratory, 1977).

The FM-CW technqiue has been developed at the National Bureau of Standards and the Southwest Research Institute primarily to measure the thickness of coal in the roof to optimize mining operations and improve mine safety. A number of case histories are presented by Ellerbruch and Belsher (1978) for experiments conducted in the Bruceton, Loveridge, and Hillsboro mines. Extremely high resolution was obtained, and it was usually possible to determine the thickness of the roof coal. Problems of interpretation occurred because of the presence of sulfur balls, shale lenses, and other dialectric discontinuities. Wide variations in

the dialectric constant of the coal were also found, attributed to variations in moisture content of the coal. Other problems have been reported by the Southwest Research Institute because coal/roof rock contacts are not always abrupt, but may be graded, and the high absorption of the EM waves by the coal, especially at right angles to the bedding plane. Owen and Tranbarger (1977) also report difficulties with a prototype system developed for a steerable auger in tests in coal mines near Hazard, Kentucky.

D.6.0 STATE OF THE ART

The most significant advances in radar systems still under development are the synthetic pulse system and the directional borehole radar. If the goal of the synthetic pulse system for in-mine use to be able to resolve reflections from a distance of 200 feet (61 meters) can be achieved, the mine operator will have a powerful tool which will allow for more efficient mine planning. The successful development of a directional borehole probe offers great potential for void detection, but its short range may limit its usefulness in coal mine work. Greater application may be found in geotechnical investigations for structures over old mine workings or natural caves.

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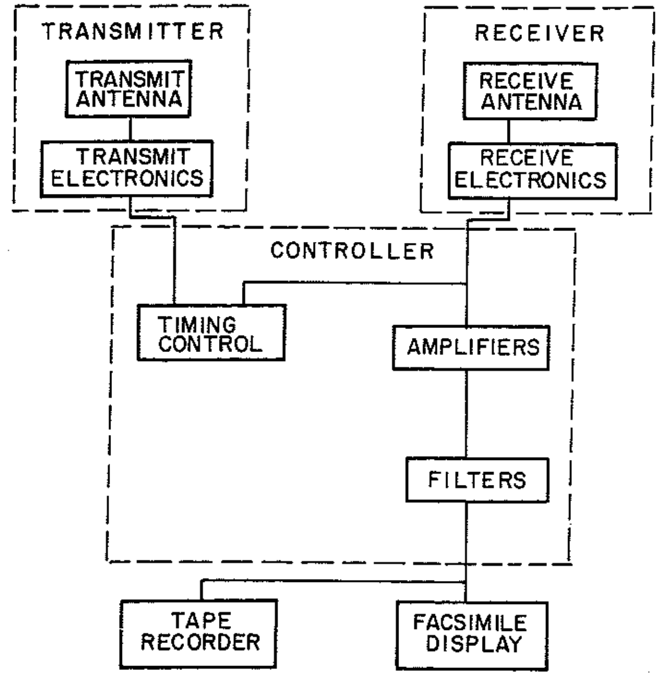
APPENDIX D
FIGURES



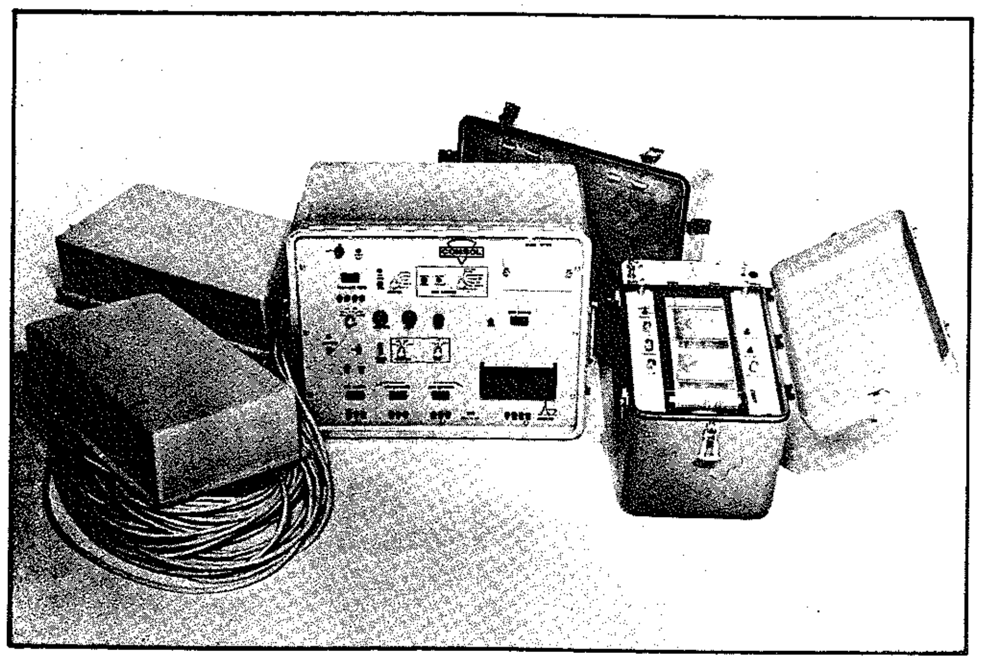
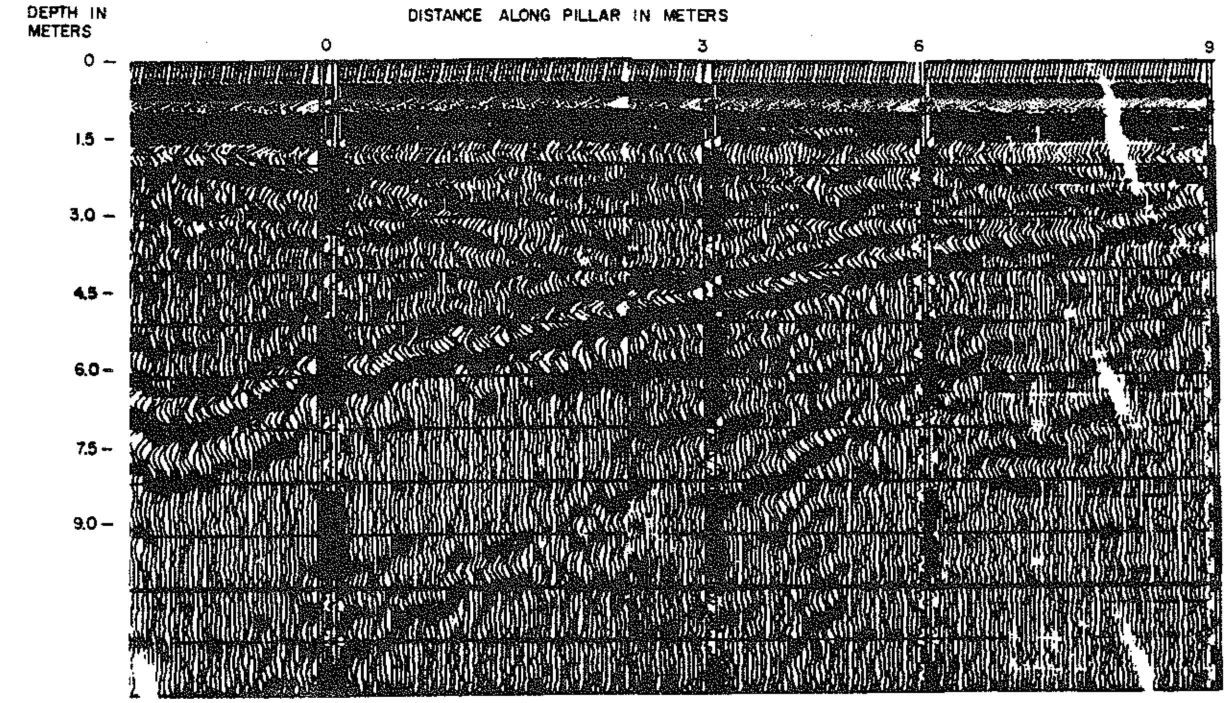


FIGURE D-1

BLOCK DIAGRAM AND PHOTOGRAPH
OF PULSE RADAR SYSTEM

REFERENCE:
FOWLER, 1981 REPRODUCED THROUGH
THE COURTESY OF XADAR CORPORATION.



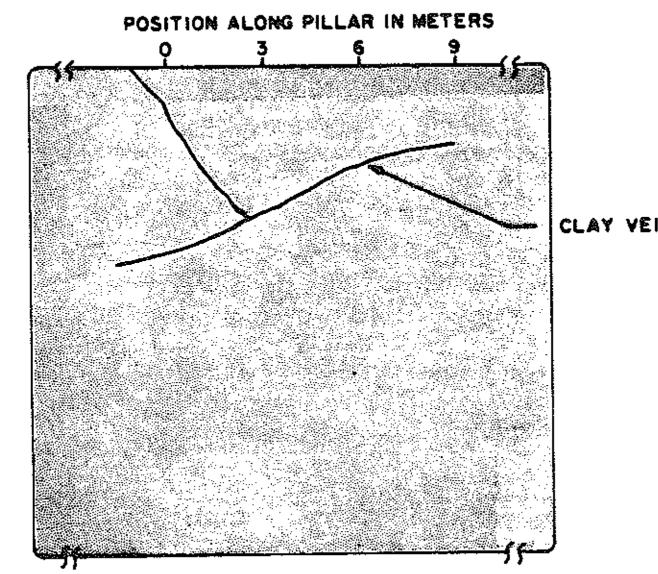
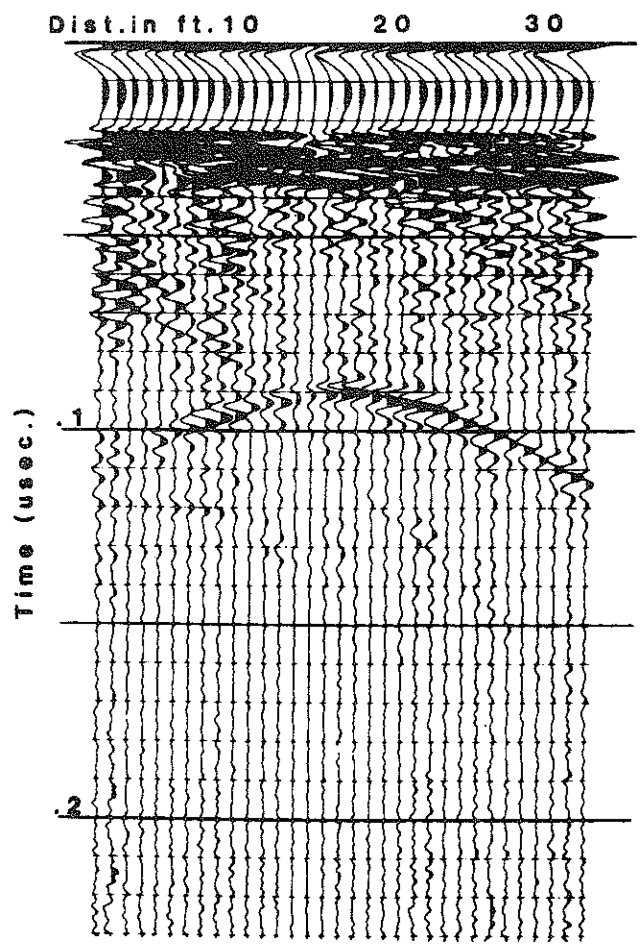


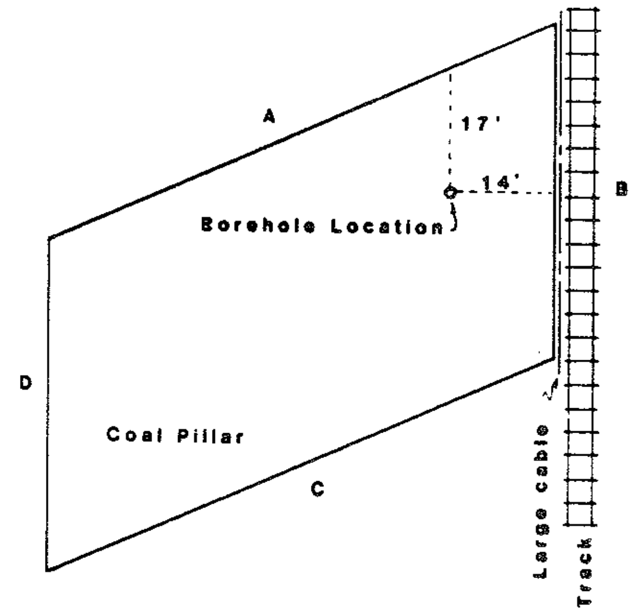
FIGURE D-2

RADAR PROFILE AND ACTUAL
LOCATION OF CLAY VEINS
WITHIN A COAL PILLAR

REFERENCE:
FOWLER, 1981 REPRODUCED THROUGH THE
COURTESY OF XADAR CORPORATION.



REFLECTION PROFILE ALONG SIDE B. THE TRANSMITTER-RECEIVER OFFSET IS 5 FT. THE CURVED REFLECTOR IS FROM THE UNCASED BOREHOLE.



MINE LAYOUT FOR TEST TO LOCATE AN UNCASED BOREHOLE

FIGURE D-3

EXAMPLE OF USE OF PULSE RADAR TECHNIQUE TO DETECT AN UNCASED BOREHOLE

REFERENCE:
COON ET AL, 1981.

APPENDIX E
MAGNETIC METHODS

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MAGNETIC METHODS

E.1.0 GENERAL DESCRIPTION

A magnetic field intensity sensor is placed at various positions in the area of interest and measurements of magnetic field intensity are obtained. After the removal of diurnal variations, a map showing equipotential lines of field intensity is constructed. Anomalous regions on this map are then used to infer the location of magnetic materials in the subsurface. The gradient of magnetic field intensity can easily be measured and used as well.

Magnetic methods have limited application to the characterization of coal deposits, but can be highly effective for specific problems. Specifically, magnetic methods are widely used to map clinker zones in shallow coal deposits. Another application is the delineation of igneous dikes which intrude coal seams in some localities such as in the western U.S. and in the southern Illinois Basin. Another possible use, applied frequently in the United Kingdom, is the delineation of abandoned mine workings, especially vertical shafts.

E.2.0 PHYSICAL PRINCIPLES AND CONSTRAINTS

E.2.1 Background Theory

The presence of any ferromagnetic material in a magnetic field will disturb both the total intensity and the orientation of the field. With the exception of diurnal variations, the earth's magnetic field remains fairly constant in any given area in terms of both intensity and direction. By mapping the intensity (normally measured in units of 10^{-5} oersteds called gammas) and/or the direction of the natural magnetic field, zones of anomalous intensity (and direction) can be found which can be attributed to magnetic materials in the subsurface. By analyzing the shape and amplitude of a magnetic anomaly, and with a knowledge of the general magnetic properties of the subsurface, it is possible to approximate the position of the magnetic materials causing the anomaly.

Magnetic sources always appear in nature with two opposite poles. This configuration, called a dipole, exhibits a field strength that decreases as the inverse cube of distance. If the poles of a single source are separated by a distance much greater than the observation distance from one of the poles, then the field strength at the observation point decreases as the inverse square of distance. This later case is an example of an apparent monopole. Geologic structures are typically modeled as combinations of monopoles and dipoles.

The magnetization of rocks is strongly affected by temperatures associated with the burning of coal. Laboratory tests indicate that the

baking and then cooling of sedimentary rock causes as much as a 6,000 fold increase in magnetization. These studies also indicate that it is not necessary to heat the rocks above the Curie temperature of the magnetic minerals (the Curie temperature of magnetite is 580°C) for the rocks to be magnetized, but a temperature of 200°C is sufficient (Hasbrouck and Hadsell, 1976). Given that coal may burn for a century or more, the 200°C isotherm may cover a wide area around a burned coal seam and this area becomes a good target for a magnetic survey.

While sedimentary rocks are not normally magnetic unless they are baked, igneous rocks, particularly basic igneous rocks such as basalt or lamprophyre dikes, typically contain significant amounts of ferromagnesian minerals, which makes them also a good target for a magnetic survey.

E.2.2 Information Derived From Measurements

Measurements of the intensity and direction of the earth's magnetic field (or of gradients), either from profiles or gathered across an area, can be interpreted to spatially define the source of magnetic anomalies. The pattern of earth magnetism can then be related to geologic conditions, which may be igneous intrusions or burn zones within a coal seam. The magnetic contour maps or profiles can then provide a basis for mapping of the geologic features, even if they are not exposed at the surface.

E.2.3 Site Constraints

The magnetic method has adequate resolution for spatially defining changes in the magnetic properties of the subsurface. This method is not affected by fractures or groundwater, but is sensitive to major local electrical surges and nearby radio transmissions in some cases. Variations in the strata such as ash stringers in the coal seam or changes in strata thickness (assuming the strata contain magnetic materials) will cause perturbations in the measured field. This method is not limited by depth or dip angle; however, resolution decreases with depth.

E.3.0 SURVEY TEST PREPARATION

The only survey support requirement for preparation for the magnetic technique is surveying station locations where magnetic readings are taken. Airborne surveys usually require that radio transmitters be located on the ground to be used in positioning the aircraft.

E.4.0 DEPLOYMENT OPTIONS

The required equipment can be deployed on the surface, from aircraft and in boreholes. All options will be treated as one in the following sections, as the only difference is in the sensor. A borehole sensor requires a borehole cased with a four-inch ID nonmagnetic casing.

E.4.1 Equipment

The equipment required for a magnetic survey includes a base station magnetometer (with sensor) to record diurnal variations and a field magnetometer (with either surface or borehole sensors). A wide variety of magnetometer types are commercially available. The most commonly used instrument is the proton precession magnetometer which provides a digital readout in gammas. This type of magnetometer is also the type used from aircraft. This instrument is convenient because it is highly portable and does nct require leveling. Another commonly used type is the flux-gate magnetometer which is also field portable.

E.4.2 Operation

A recording base station magnetometer is placed in a permanent location to record the daily (diurnal) variations in the magnetic field. This magnetometer should be located in an area where it is posible to avoid perturbations caused by cars, trucks, and other mobile metallic objects, and sources of electromagnetic emission.

When deployed from the surface or boreholes, a portable magnetometer is then used to measure the field intensity at various locations. Only one person is required to operate and maintain the system, although it is usually convenient to have one person take the readings and another to record them. Measurements with the portable magnetometer can be taken at the desired time interval at the specified station locations.

The spacing between magnetometer readings is dependent upon the survey target. Hasbrouck, et al. (1980), indicate that station separation in areas of burnt rock in the western U.S. is usually in the range of 10-30 meters, with data plotted as profiles separated by the station spacing. Dearman, et al. (1977), report using a two-meter grid in the search for abandoned mine shafts. Magnetic surveys can be conducted more rapidly than most other geophysical methods. Hasbrouck, et al. report that a 300-meter traverse can be conducted in less than an hour. Dearman, et al. (1977), note that it takes about one hour to survey 1,000 square meters on a two-meter grid using a flux-gate magnetometer and three hours to perform the same with a proton precession instrument, but with more detail.

Airborne (aeromagnetic) surveys are different from those from the surface or boreholes in that magnetic data is gathered continuously along profiles. Data can obviously be gathered much more rapidly from an aircraft, but the ability of the aircraft to fly a close pattern restricts its use for detailed surveys. Airborne surveys are suitable for a rapid reconnaissance of wide areas.

E.4.3 Analysis

To interpret shallow magnetic anomalies, the data are corrected for diurnal variation and other magnetic fluctuations as measured at the

base station. Regional deep-rooted anomalies are removed from the data set, leaving the shallow magnetic patterns which can then be interpreted in terms of the local conditions. The interpretation of aeromagnetic data is similar to that gathered on the ground, except that the plane elevation must be accounted for.

Model support for interpretation consists of estimates of magnetic susceptibility (these can be measured with a susceptibility log) of the strata. The actual analysis consists of modeling the subsurface as a collection of prisms and plates. Using these simple geometric objects, a model magnetic map is constructed. The shapes and susceptibilities of the prisms or plates are altered until the magnetic field calculated from the model agrees with the magnetic field as measured on the site. Mathematical expressions for the interpretation of magnetic profile data are provided by Dobrin (1960), Battacharyya (1964), and several other general texts of applied geophysics.

E.5.0 CASE HISTORIES

The best examples of the use of magnetic surveys to delineate burn facies (clinker deposits) are presented by Hasbrouck and Hadsell (1976; 1978). An example of a profile from Gillette, Wyoming is presented in Figure E-1, which clearly shows the discrepancy in locating the edge of the clinker from surficial soil color, the usual mapping criteria, and the magnetic results. Hasbrouck and Hadsell estimate that this discrepancy along an outcrop distance of 300 meters represents an underestimation of reserves by about 300 million tons. In another example, from Decker, Montana (Figure E-2), the validity of the magnetic interpretation is confirmed by boreholes and, again, an interpretation based on surficial color changes would have been misleading.

The identification of deep coal burns, when overlying beds have also been burned, remains a difficult task. It would be expected that deep coal burns would produce low frequency anomalies that could be distinguished from higher frequency anomalies at the surface, but clinker magnetization is so irregular that deeper anomalies are likely to be masked.

Friedberg and Crosby (1981) report the results of aeromagnetic surveying to delineate clinker beds in Kane County, Utah. By flying at a height of about 100 meters above the land surface with a line separation of 400 meters, it was possible to contour the magnetic data with two gamma contours. The resulting contour map (Figure E-3) showed good definition of clinker zones, as well as areas that had no high frequency anomalies and could be interpreted to have unburned coal present. Some of the clinker anomalies were as high as 100 gammas, but others were less than two gammas, indicating that for an airborne survey to be successful it appears important to fiy as close to the ground as possible, with a magnetometer of the highest possible sensitivity.

Hasbrouck, et al. (1980), report the results of magnetic surveys over igneous dikes in Colorado. It is usually possible to trace the dikes geologically at the surface on the basis of their outcrop pattern, but their subsurface configurations is not generally known. In many cases the intrusions may have entered the coal seams as sills which have no surficial expression. These authors report that the dikes could be qualitatively located, but a quantitative assessment was precluded by surface noise from a variety of sources, including eroded material from surface outcroppings of the dikes. The magnetic method, however, is capable of successfully locating igneous intrusions and magnetic mapping of dikes is also taking place at certain localities in eastern U.S. coalfields.

The detection of mined openings, particularly vertical shafts, is widely reported in the literature (Maxwell, 1975 and 1976; Higgenbottom, 1976; and Dearman, et al., 1977). Some success is reported, particularly where the shafts are lined with bricks, which have a fairly high magnetization of an origin similar to that of clinker. When shafts are unlined, small negative anomalies may be produced due to the void/wall rock contrast. Such an anomaly, however, may be masked by magnetic surface debris and some voids or filled workings may not produce any form of recognizable anomaly.

In spite of the interpretative difficulties that may be encountered with magnetic surveys, the method is popular because of the speed with which the data can be gathered and low costs. Hasbrouck and Hadsell (1976) estiamte that a month's rental of a magnetometer would run about the cost of one 60-meter boring. Accordingly, magnetic surveys often offer more that can be gained than can be lost by their performance.

E.6.0 STATE OF THE ART

Magnetic surveys have long been used for mineral exploration and the level of development of the method is very high. This technology is readily transferable to coal and it appears probable that advances in the state-of-the-art will result from additional compilation of case histories, in particular with regard to the mapping of clinker and igneous intrusions, so that improvements can be made in interpretation.

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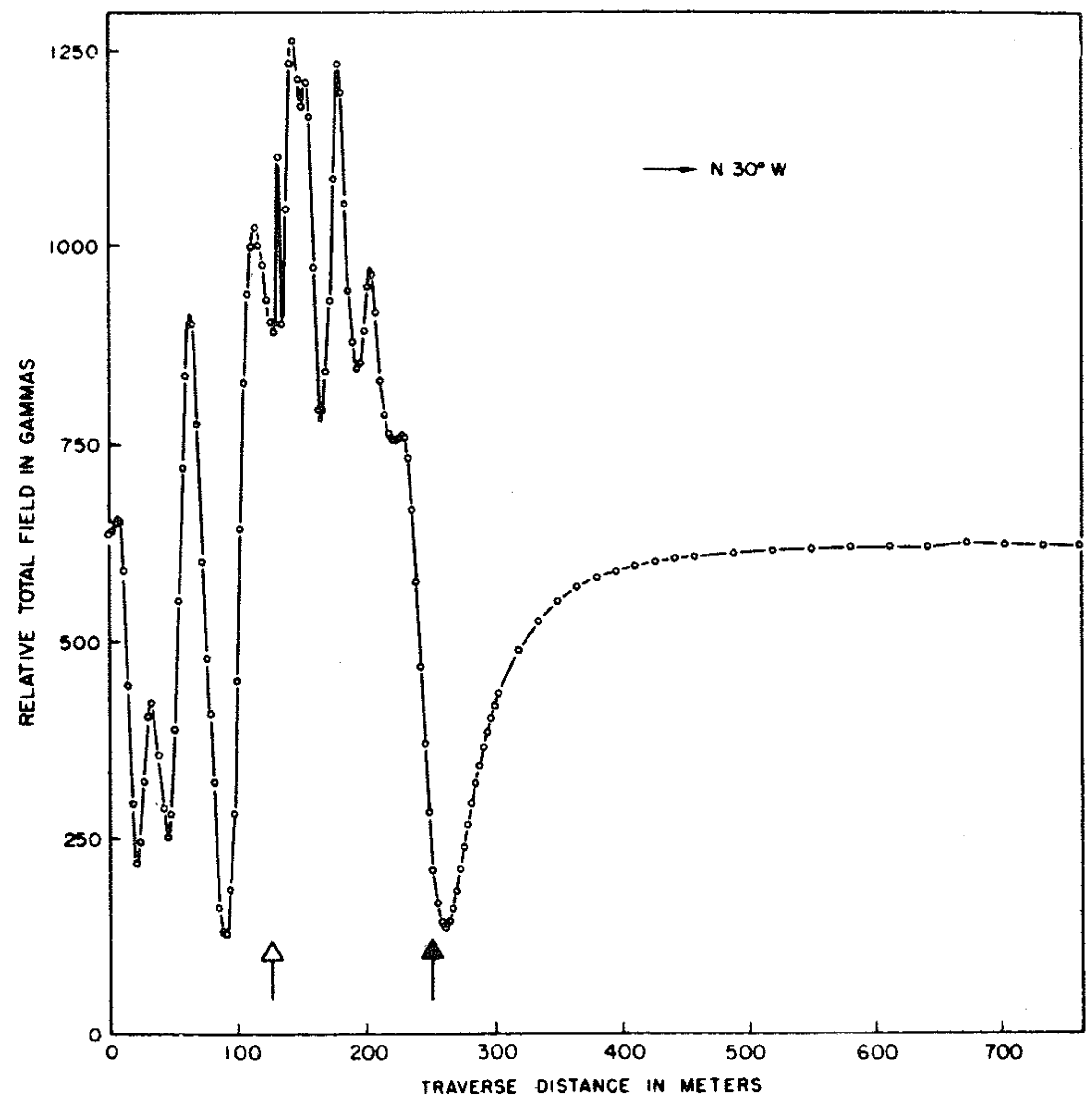
APPENDIX E
FIGURES



LEGEND:

- EDGE OF CLINKER BASED ON SOIL COLOR CHANGE
- EDGE OF CLINKER BASED ON MAGNETIC PROFILE

FIGURE E-1

MAGNETIC PROFILE ACROSS EDGE OF A CLINKERED AREA NEAR GILLETTE, WYOMING

REFERENCE:
HASBROUCK AND HADSELL, 1978

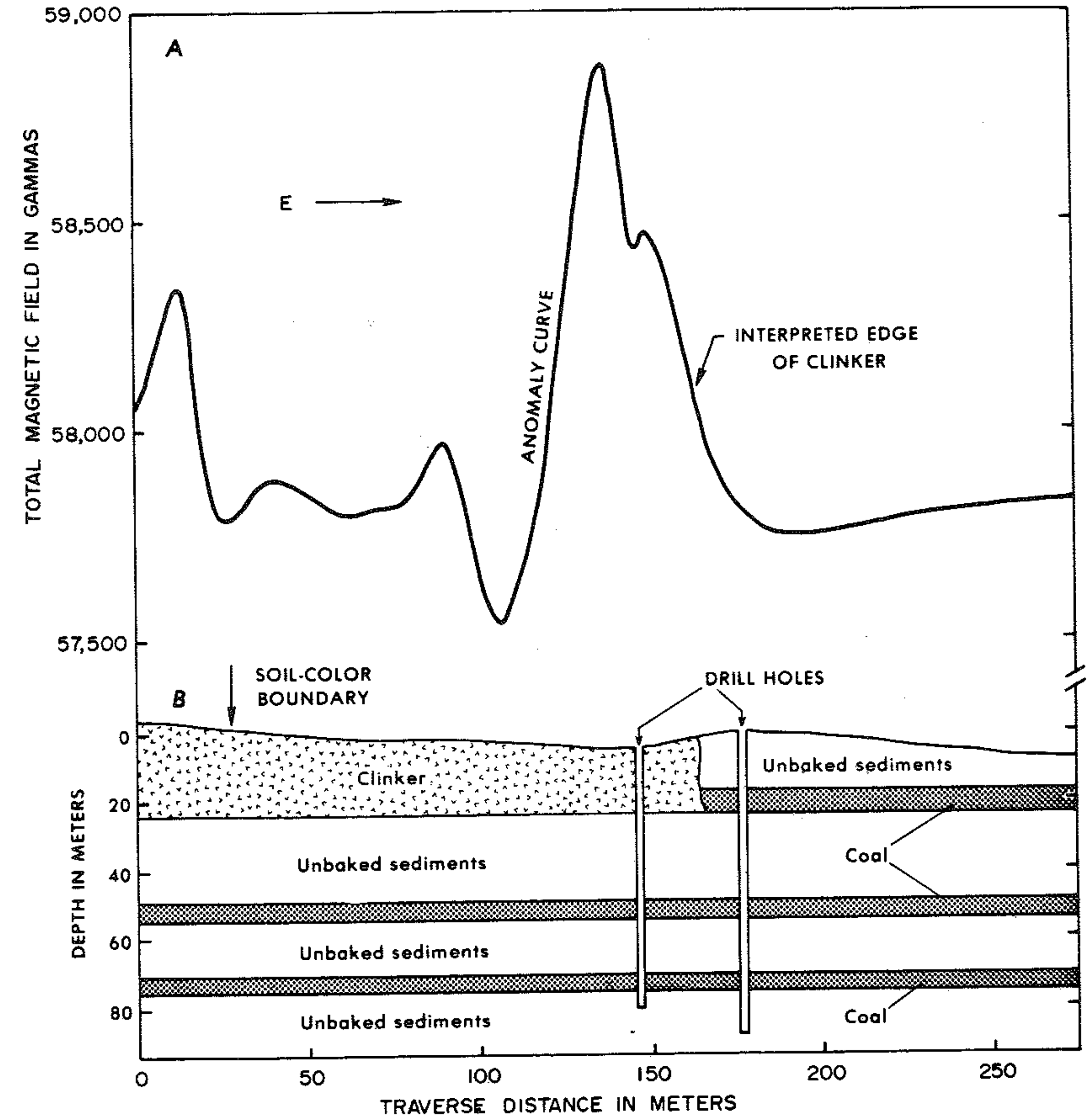
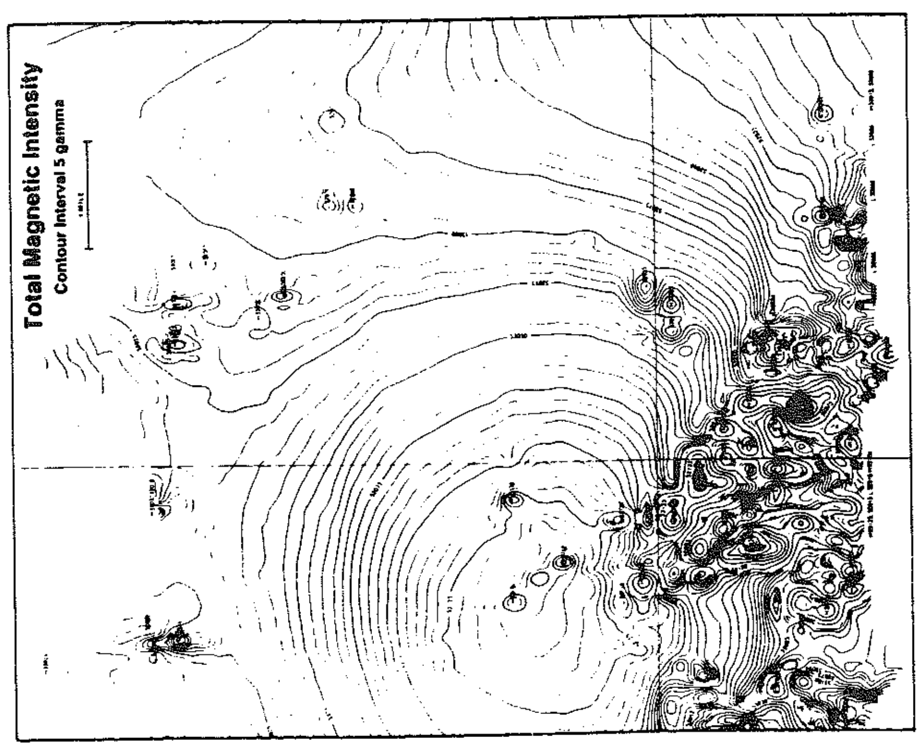


FIGURE E-2

MAGNETIC PROFILE ACROSS A CLINKERED AREA IN DECKER, MONTANA

REFERENCE:
HASBROUCK AND HADSELL, 1978.



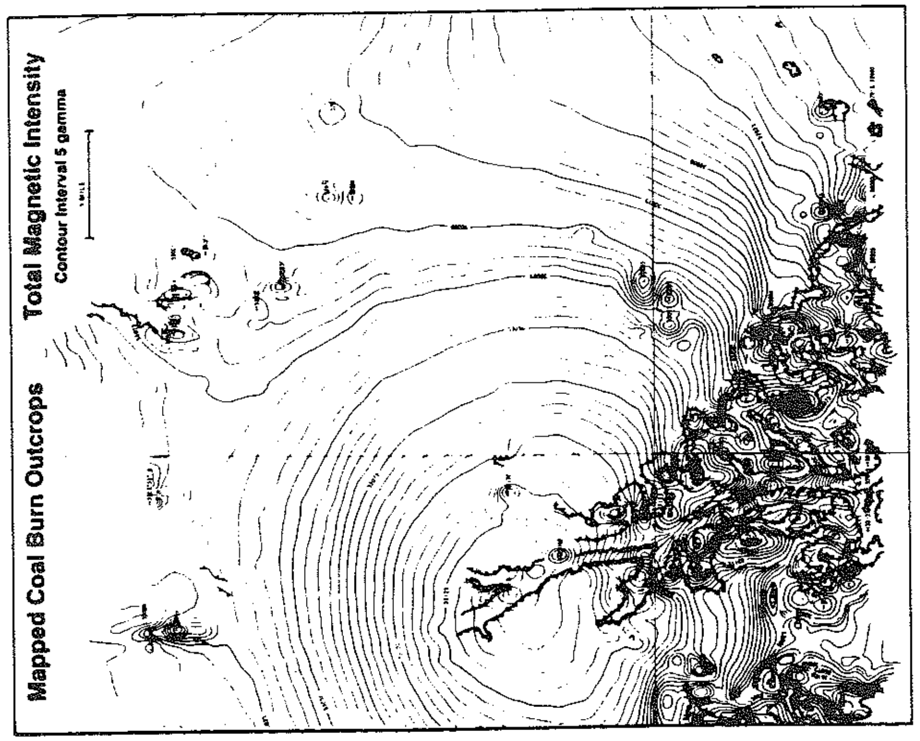


FIGURE E-3

AEROMAGNETIC SURVEY OF
KANE COUNTY, UTAH
AND CORRELATION WITH MAPPED
COAL BURN OUTCROPS

REFERENCE:
FRIEDBERG AND CROSBY, 1981
REPRODUCED THROUGH THE COURTESY
OF AERO SERVICE

APPENDIX F
GRAVITY

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GRAVITY

F.1.0 GENERAL DESCRIPTION

The gravity method is sensitive to changes in subsurface density distribution. Therefore, any geologic feature or parameter which has sufficient density expression can, in principle, be detected by the gravity method. In addition, when sufficient control is available, it is possible to map the feature or parameter in three dimensions. Of fundamental importance to the successful application of the gravity method is the understanding that no absolute measurements of the gravitational field are made; the method responds only to variations in the gravitational field. In areas where there is no lateral variation of subsurface density distribution, the gravity method will yield no information other than the fact that the subsurface is probably laterally homogeneous in terms of density.

Depending on the instrument, a gravity meter has an accuracy ranging between approximately one part in 10^7 to one to two parts in 10^9 of the total gravitational field of the earth. Because the intensity of a gravitational field is determined by the density and distribution of the mass creating the field, a knowledge of the gravitational attraction at many points on the surface serves as an indirect indicator of changes in density and distribution of subsurface masses.

F.2.0 PHYSICAL PRINCIPLES AND CONTRAINTS

F.2.1 Background Theory

This method is based on Newton's law of gravitation: the force between two particles of mass m_1 and m_2 is directly proportional to the product of the masses and inversely proportional to the square of the distance between the centers of the particles $(F = \gamma \frac{m_1 m_2}{r^2})$. Since density is mass per unit volume, it follows that, on a large body such as the earth, areas with an above average density will exert more force on a mass at the surface (of the earth) than will areas having a lower than average density. The unit of measurement of a gravity survey is the milligal (mgal) where a milligal is 10^{-5} m/sec^2.

F.2.2 Information Derived from Measurements

As the density of coal is usually lower than surrounding rocks in a coal sequence, the gravity method offers a rapid and relatively inexpensive means of locating cutouts of thick coal seams at depths suitable for surface mining. If knowledge of the density distribution of sediments in a given area can be reasonably determined, the gravity data can be used to extend knowledge of coal distribution to areas with poor borehole control (Hasbrouck and Hadsell, 1978).

The gravity method is also useful for mapping surficial material. Common applications in this area include mapping the bedrock profile of buried valleys and determining the thickness of soil over bedrock. This application can be useful in detecting buried valleys which may cut near surface coal or lignite deposits, a common condition in areas that have been glaciated in the northern U.S. The resolving power of the gravity method for these applications is generally less than that of the refraction or resistivity methods, but this limitation may be offset by lower costs, in some cases. Density contrasts may be greater than velocity or resistivity contrasts and the gravity method may result in more accurate results. Successful utilization of the gravity method for these applications requires knowledge of the subsurface material densities involved and may require the drilling of borings for control.

A powerful use of the gravity method is locating abandoned workings or other voids. An underground opening presents a density contrast because it is characterized by the absence of material. The degree of density contrast decreases, however, if the opening is filled with water or sediment. Assuming the geometry of a horizontal cylinder, which is a reasonable model for an abandoned adit, the minimum cavity size that can be detected from the surface can be calculated as a function of depth if the host rock density and instrumental sensitivity are known. The list below gives the results of such calculations for a coal density of 1.4 g/cc and a high instrumental sensitivity. The LaCoste & Romberg Model-D gravity meter has a sensitivity of one to two μgals (0.001 to 0.002 mgals) and a minimum detectable anomaly with this instrument is assumed to be 10 μgal for this exercise (note that depth is measured from the surface to the center of the cavity):

DEPTH (m)	DETECTABLE RADIUS (m) (air-filled cavity)	DETECTABLE RADIUS (m) (water-filled cavity)
5	0.9	1.7
10	1.3	2.5
20	1.9	3.5
30	2.3	4.2
50	2.9	5.5

An illustration of the model used to determine these results is shown in Figure F-1. It should be noted that for deep targets the width of the anomaly increases in direct proportion to the depth so that deep anomalies are usually more difficult to identify than shallow anomalies of the same amplitude.

The gravity method also provides a means for locating igneous features in sedimentary sequences and can complement the use of the magnetic method in the location of dikes which may intersect or intrude a coal seam. Further, the gravity method can be used to distinguish between mafic and sialic rocks in igneous and metamorphic terrains.

F.2.3 Site Constraints

The gravity method may be used over a wide range of geologic and hydrologic conditions to detect and map geologic features or parameters with sufficient density and hence gravitational expression, but the resolving power of the method falls off rapidly with depth.

Results of gravity surveys can be adversely affected by several factors discussed below:

- Geologic Noise - Local density inhomogeneities, regional gradients, and bedrock relief may act singly or together to obscure anomalies caused by the target geologic feature. Bedrock relief, for example, may produce an anomaly identical to that produced by an underground opening, or coal cutoff.

- Topographic Noise - In areas of high topographic relief, lack of detailed knowledge of subsurface density distribution may result in incomplete topographic corrections. Incomplete topographic corrections can reduce instrumental sensitivity or completely obscure the target feature.

- Position Error - Errors in gravity station elevation and latitude can result in erroneous corrections which adversely affect the gravity survey. The control of elevation is the most critical factor, as a gravity meter will vary readings by three μgal/cm just by changing elevation.

Also important is an understanding of the inherent ambiguity of gravity data inversion. While a given subsurface configuration will produce a unique data set, the converse is not true. In theory, any given data set will fit an indefinite number of models. Knowledge of the local geology and subsurface control from borings or other geophysical techniques must be input to the interpretation process if reasonable results are to be obtained. The validity of any model must be tested not only by comparing the observed anomaly with the theoretical or calculated anomaly, but also by consistency with other available information.

The gravity method appears to be best used as a reconnaissance tool in conjunction with other techniques. Results based solely on gravity exploration should be viewed as approximate.

F.3.0 SURVEY TEST PREPARATION

A surface gravity survey requires that the station locations be surveyed highly accurately. Elevation control is especially critical. As shown in the sample calculations in Section F.2.3, the minimum detectable

underground openings were based on an instrument sensitivity of 0.02 mgal. The free air correction, which accounts for the distance of the observation station from the center of the earth, is 0.094 mgal/ft or three μgal/cm (Dobrin, 1960), which explains the precision required in elevation when small anomalies are to be detected.

F.4.0 DEPLOYMENT OPTIONS

The gravity technique can be deployed following two basic options, from the surface or boreholes. Airborne gravity measurements are another recently available option, but accuracies are insufficient for most coal work. When used from boreholes, the gravity method has the potential for calculating accurate densities to distances of about 30 meters from around a borehole. This implies that the method has some application in the identification of voids, but the technique would naturally be omnidirectional, and it would not be possible to obtain anything other than depth control. Accordingly, borehole gravimetry is unlikely to have serious application to coal exploration/characterization, and the discussion of deployment option has been limited to surface surveying.

F.4.1 Equipment

Gravity is measured by a gravimeter. This instrument has at least a sensitivity of about 0.02 mgal and works on the principle of a highly sensitive balance. A mass on a highly sensitive spring is displaced as the gravity field changes. These displacements are magnified optically, mechanically, or electronically to provide a readout in milligals. Gravity equipment has been commercially available for over 50 years by a number of manufacturers. The most sensitive equipment is the LaCoste & Romberg Model-D gravity meter which has a digital readout and a sensitivity of one to two μgals.

F.4.2 Operation

A gravity survey is normally conducted on foot or from specially configured vehicles carrying the gravimeter from station to station. The station spacing used is dependent on the target. Hasbrouck and Hadsell (1978) report that coal cutoffs were mapped with about a 30-meter grid, but this station separation could have been greater. The detection of abandoned workings would require a very close grid, similar to that used when magnetic surveys are used for the same purpose. Gravity measurements are normally achieved in a few minutes time per station, as accurate leveling is required.

F.4.3 Analysis

Several corrections must be applied to raw gravity data before it can be interpreted, including the corrections necessary to reduce the readings to a common datum elevation and an instrumental drift correction. The data is plotted both as a contour map and as profiles and examined to determine whether there is a regional gradient present. If present, the regional effects are removed and the data is recontoured and profiled.

Anomalies in the data can be modeled based on established methods for deriving the gravitational attraction of differently shaped bodies with a different density contrast to surrounding material. As there is no unique solution, the models used should be based on the best available geological/geophysical data derived from other means. Once a satisfactory model has been developed, the interpretation is established in terms of the distribution of real earth material.

F.5.0 CASE HISTORIES

Hasbrouck and Hadsell (1978) provide examples of the use of the gravity method to identify coal cutoffs and buried glacial valleys which cut lignite deposits. They cite an example of a gravity survey conducted in 1931 over the Onakawana lignites of Ontario, Canada, published by Miller (1940). The results of this survey (Figure F-2) clearly show the inverse correlation between gravitational attraction and lignite thickness. In this example, the gravity survey was conducted after the borings were drilled. Had the gravity survey been conducted first, it would probably have been possible to prepare a more accurate profile with fewer borings. From an example of their own work in Campbell County, Wyoming (Figure F-3), the gravity contour map provides a better confirmation of the edge of the coal cutout than that provided by the borings, as well as confirming the depth and thickness of the coal seam.

Success is also reported in locating buried glacial stream channels in the Beulah-Zap Known Recoverable Coal Resource Area (KRCRA) of North Dakota. These glacial outwash streams cannot be detected from the surface, but may be a kilometer wide, 100 meters deep, and 10 kilometers long. The delineation of buried channels without the use of borings can greatly increase the effectiveness of borings.

The gravity method, consistent with its traditional use in mineral exploration, also has been applied on a regional basis in defining the limits of a coal deposit. Verma, et al. (1976), document the results of gravity measurements over the Raniganj Coalfield, India, where 450 gravity measurements were made over a rectangular area approximately 50 x 100 kilometers. With the results of this study, the overall depth and structure of the basin were defined.

On a much smaller scale, high-precision gravity (microgravimetric) measurements have also been used to detect subsurface cavities, such as mine shafts and tunnels. Dresen et al. (1975), reports that the gravity method has been used successfully to locate abandoned shafts in longwall mining areas in the Federal Republic of Germany. Butler (1980) provides a comprehensive discussion of the microgravimetric technique for numerous geotechnical applications and provides several case histories.

F.6.0 STATE OF THE ART

The gravity method has been applied to problems of mineral exploration and mining, including coal applications for over 50 years. Instrumentation and analytical techniques are now well advanced. Development of this technique for use from a helicopter for rapid reconnaissance is being developed and one company, Carson Helicopters of Perkasie, Pennsylvania, already offers airborne services with a precision of 0.1 mgal at flight speeds of 60 miles per hour. Future developments will probably see greater application of the existing technology for microgravimetric surveys and continued development of the airborne technique.

APPENDIX F
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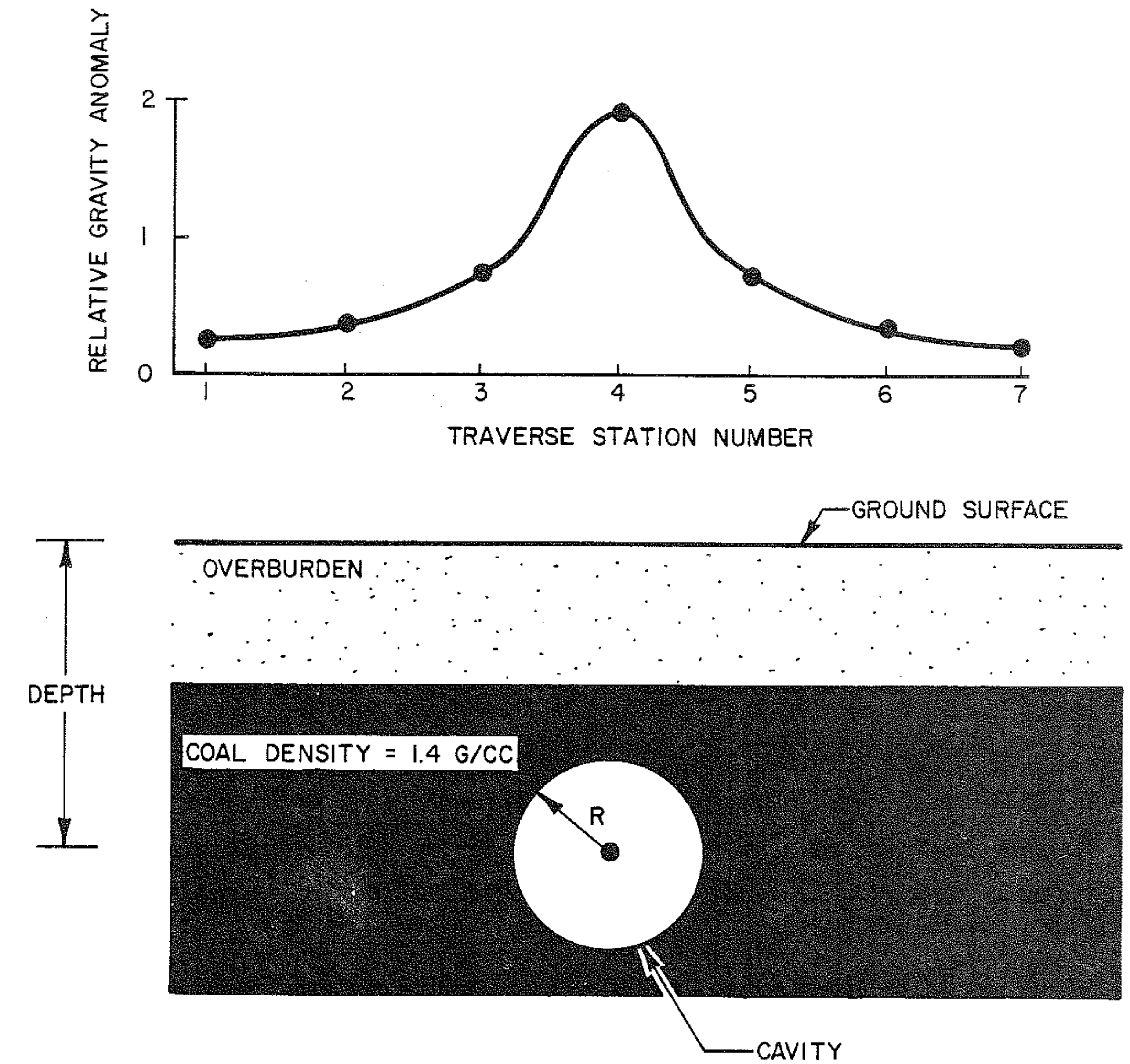
FIGURES

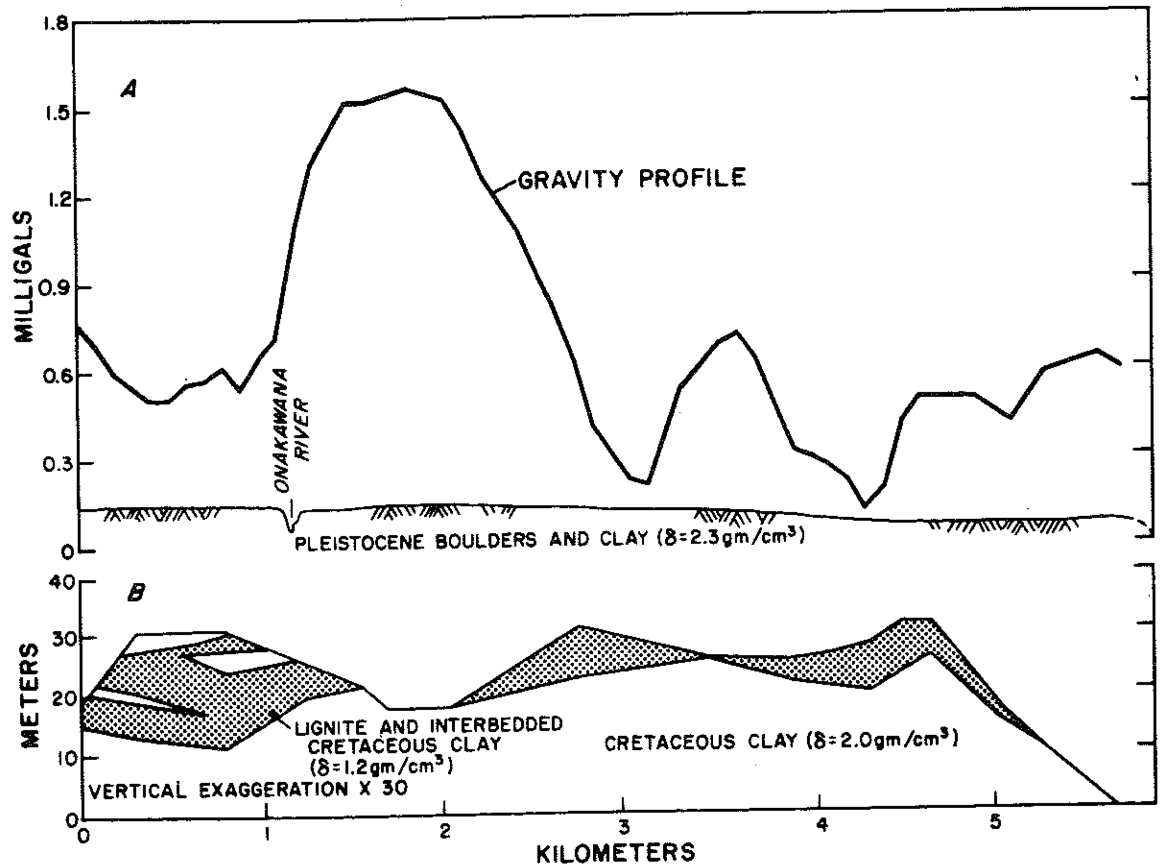


NOTES:

1. OVERBURDEN DENSITY IS ARBITRARY BUT UNIFORM.
2. CAVITY MAY BE DRY OR WATER FILLED.
3. VERTICAL PLANE THROUGH LINE OF TRANSVERSE INTERSECTS CENTER OF CAVITY.
4. SENSE OF ANOMALY IS NEGATIVE.

FIGURE F-1

SCHEMATIC REPRESENTATION OF GRAVITY METHOD TRAVERSE OVER SUBSURFACE CAVITY IN COAL



NOTE:

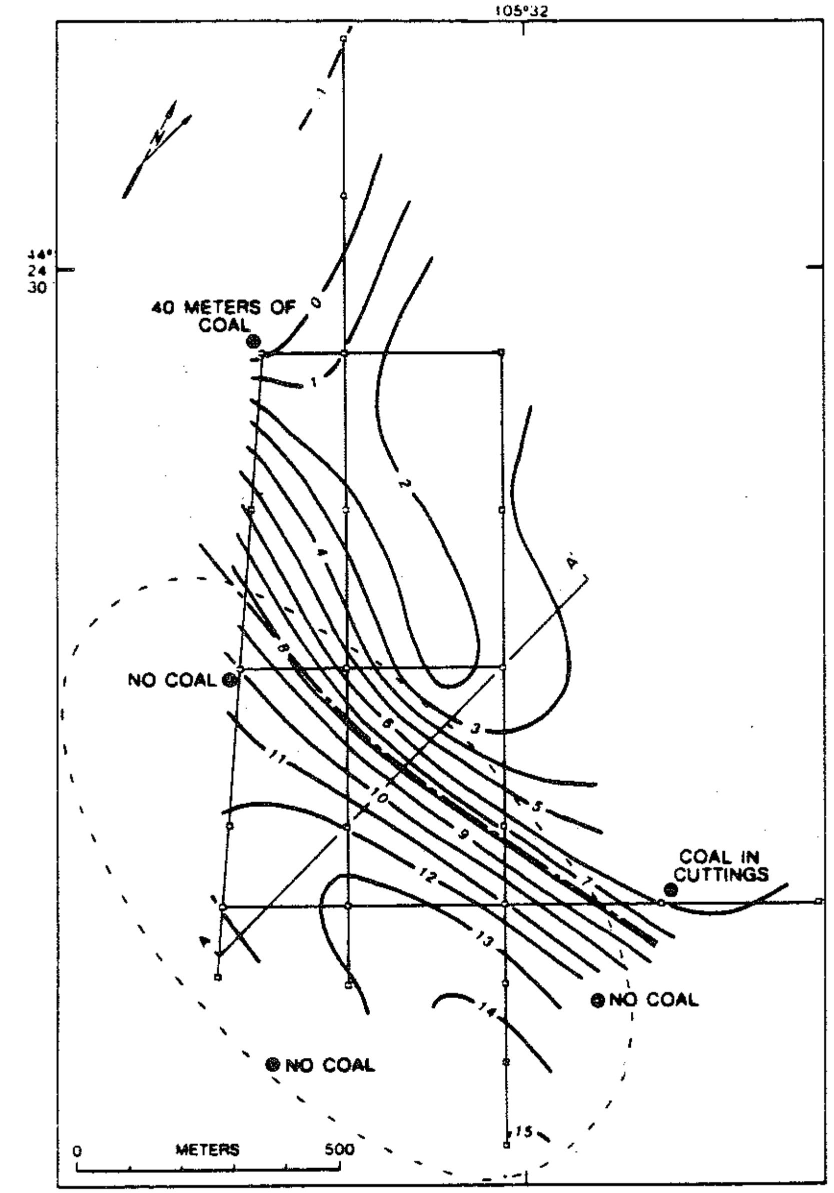
SURVEY CONDUCTED IN 1931
WITH TORSION-BALANCE INSTRUMENT
AT 100 METER INTERVALS.

FIGURE F-2

GRAVITY PROFILE ACROSS THE ONAKAWANA
LIGNITES OF ONTARIO, CANADA

REFERENCE:

MILLER, 1940 (AS MODIFIED BY
HASBROUCK AND HADSELL, 1978).



NOTE:

CONTOURS IN GRAVITY UNITS (0.1 MGAL);
SUSPECTED CUTOUT SHOWN BY
ELLIPTICAL DASHED LINE;
INTERPRETED CUTOUT FROM A
POSSIBLE CHANNEL SHOWN BY
DOT-DASH LINE.

FIGURE F-3

DELINEATION OF COAL SEAM CUTOUT
IN CAMPBELL COUNTY, WYOMING WITH
A GRAVITY SURVEY

REFERENCE:

HASBROUCK AND HADSELL, 1978.

APPENDIX G

ELECTRICAL METHODS

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ELECTRICAL METHODS

G.1.0 GENERAL DESCRIPTION

Coal has a high electrical resistivity compared to most other sediments in a coal sequence. As such, it is a good target for geophysical methods which measure the electrical properties of earth materials. Three methods can be used to electrically explore coal: self-potential (SP), induced polarization (IP), and electrical resistivity. The most important application of all of these techniques is from boreholes and for this reason they are discussed in the borehole logging appendix (Appendix H). The SP and IP methods are also applied almost exclusively from boreholes with regard to coal exploration and are not further discussed in this appendix.

The resistivity method has been used from the surface to determine subsurface geological features since the beginning of this century. Successful applications to coal exploration have been documented as early as 1934 (Ewing, et al., 1936), but since that time the technique has been used infrequently. The technique has the ability to resolve the stratigraphy and structure of near-surface coal and is now being developed as a powerful tool for detecting voids.

G.2.0 PHYSICAL PRINCIPLES AND CONSTRAINTS

G.2.1 Background Theory

According to Ohm's Law, the electrical potential between any two points in an electrical circuit is equal to the applied current multiplied by the resistance offered by the path. Ohm's Law is expressed by the formula:

$$E = IR$$

where

E = electrical potential

I = applied current

R = resistance

The resistivity of a conductor is defined as the resistance multiplied by the cross sectional area divided by the length. In the form of an equation, the expression is:

$$\rho = RA/L$$

where

ρ = resistivity

R = resistance

A = cross sectional area

L = length

Resistivity depends only on the material nature of a conductor, and not on its dimension. The resistivity method consists of transmitting electrical current into a ground and measuring the associated response. The relationship between the transmitted current and the response is used to deduce the subsurface resistivity distribution.

The usual method of measuring earth resistivity is the four-electrode method (Figure G-1) although other variations are sometimes used. A known current, I, is transmitted into the ground through two current electrodes, C1 and C2. A potentiometer is used to measure the associated voltage across two potential electrodes, P1 and P2. Apparent resistivity is then calculated according to an expression involving the ratio of potential to current, as well as a geometric factor based on electrode configuration. If the earth is electrically homogeneous in a volume which is large compared to the electrode configuration, then the apparent resistivity will equal the true resistivity. Otherwise, the apparent resistivity must be viewed as a means to represent the distribution of electrically homogeneous materials.

The three most common electrode configurations for the four-electrode method are (Figure G-1):

- Wenner
- Schlumberger
- Dipole-dipole

In the Wenner configuration the electrodes are uniformly spaced. The Schlumberger configuration is similar to the Wenner except that the distance between current and potential electrodes is kept at least five times as large as the spacing between potential electrodes. In the dipole-dipole configuration, the current and potential electrodes are adjacent to each other and separated by a constant spacing, but the separation between the current and potential electrode groups is equal or greater than that constant spacing between common electrodes.

The Wenner and Schlumberger configurations are most often used for vertical investigation whereas the dipole-dipole configuration is most often used for lateral investigation. The Schlumberger configuration is less sensitive to lateral inhomogeneity than the Wenner and involves less field effort because the potential electrodes are usually

stationary. Surface electrical surveys may be conducted to provide the greatest resolution in a vertical and/or horizontal sense. Vertical resolution is enhanced by performing vertical electrical soundings, also known as electrical drilling, while lateral variations are best detected by horizontal profiling.

The vertical electrical sounding (VES) method consists of systematically expanding a Wenner or Schlumberger electrode configuration in line about a point. Measurements of potential and input current are made for each set of electrode spacings. The resultant plot of spacing versus apparent resistivity is interpreted to yield the subsurface resistivity distribution with depth beneath the point.

The horizontal profiling method has three variations. The first variation consists of making measurements with a fixed-spacing Wenner, Schlumberger, or dipole-dipole electrode configuration at several locations. The change in apparent resistivity as a function of location is then representative of lateral change. VES soundings are usually made to locate the subsurface objective and to determine the optimum fixed spacing for the electrodes. The second variation is to make VES soundings at several locations and compare the resulting subsurface resistivity distributions to determine lateral change. This variation results in more complete information. The third variation is to make dipole-dipole measurements with the current or potential dipole fixed and the other dipole located at increasing distances along a line. The fixed dipole is then advanced down the line and the process is repeated. The measurements from this variation can be interpreted to yield a resistivity "cross section" beneath the line.

G.2.2 Information Derived From Measurements

As applied from the surface, the resistivity method provides information on the lateral and vertical variations in earth electrical properties. These variations can then be interpreted in terms of a subsurface geological model. In terms of coal exploration/characterization, the method has the potential for mapping shallow coal seams and identifying discontinuities which may affect them, such as cutoffs, seam splits, faults, washouts, etc. Another potential application is the detection of near-surface voids.

G.2.3 Site Constraints

The homogeneity of subsurface conditions greatly influences the probability of success of an electrical survey. The electrical method is capable of defining vertical variations in resistivity up to about five layers of different electrical properties. Interpretation is impeded if too many layers are present, particularly if the layers also exhibit lateral variations. The presence of layers of very low resistivity can impede current penetration and the ability to resolve specific features. Wet clay or highly mineralized water can act as such a low conductivity layer. Similarly, a highly resistive layer, such as another coal seam, can prevent current from reaching the target of interest. Man-made constraints include buried culverts or other pipelines, metallic fences, transmission lines, or other sources of EM disturbances.

G.3.0 SURVEY TEST PREPARATION

The only preparation required for a resistivity survey is the surveying of electrode positions. In areas of thick vegetation, the lines need to be cleared to prevent the tangling of the electrical cable.

G.4.0 DEPLOYMENT OPTIONS

The electrical resistivity technique can be deployed from the surface, underground, or in boreholes. Borehole deployment is discussed in Appendix H. Underground deployment would theoretically be similar to surface deployment, but no trials of electrical methods used in underground coal mines are reported in the literature. The electrical resistivity method could be used to detect hazards in advance of a working face, but would have more limited range and resolution than radar. Some potential may exist for monitoring roof conditions with an apparatus to continuously monitor variations in resistivity, but adequate research has not been conducted into this possible application. Accordingly, discussion of deployment is limited to measurements from the surface.

G.4.1 Equipment

Resistivity surveys measure the electrical response of the earth to an applied current. The basic components of a field resistivity system are electrodes, cables, current source, and potentiometer.

- Electrodes - Two types of electrodes are used in resistivity surveys; current electrodes are used to pass current into the earth and potential electrodes are used for voltage measurements with the potentiometer. Current electrodes may be stainless steel or copper rods, buried copper screens, drill steel in a borehole, or buried metal culverts. Potential electrodes may be stainless steel rods or porous containers filled with copper sulfate.

- Cables - Resistivity cables carry the current from the source to the current electrodes and the signal from the potential electrodes to the potentiometer. The cables must be well insulated to prevent short circuits and electrical leakage. The cables to the current electrodes must be capable of carrying the full output from the current source. Cables from the potential electrodes are usually light duty because high currents do not flow through them.

- Current Source - The current source consists of a power supply (generator or batteries) and shaping circuitry to produce a DC, commutated DC, or AC signal. Capacities may range from a few watts to several kilowatts depending on the objectives of the survey. Also included are devices to measure and regulate the current. Some current sources have switches to select different sets of electrodes.

- Potentiometer - The potentiometer measures the voltage between the potential electrodes. Potentiometers may include special circuitry to reject undesirable noise. Sometimes small current sources are combined with a potentiometer into a single device commonly called a megger.

Electrical resistivity equipment may be purchased from numerous instrument manufacturers, listed in "The Geophysical Directory."

G.4.2 Operation

A resistivity crew typically consists of one man to operate the current source and potentiometer and to record the readings. Two or three helpers move the electrodes according to the survey plan. Under conditions where the operator cannot have visual contact with the helpers who are moving the electrodes it is convenient to have radio communication so that there is no risk of current flow when a helper still has an electrode in his hand.

G.4.3 Analysis

The analysis of resistivity data is conducted in two steps. The first step is to reduce the raw field data into a form more suitable for interpretation. The second step is the actual interpretation which results in a determination of the subsurface resistivity distribution from the reduced data.

The reduction of resistivity data is usually simpler than that for other geophysical techniques since no corrections for elevation or position are made. The first step in resistivity data reduction is the conversion of measured input current and observed potential for each electrode spacing to apparent resistivity. This conversion is accomplished by forming the ratio of observed potential to input current and then multiplying the ratio by a geometric factor based on electrode configuration and spacing. For example, for the Wenner configuration, the geometric factor is given by $2\pi A$ where A is the electrode spacing in meters. The second and final step in data reduction is to construct an apparent resistivity curve by plotting apparent resistivity versus electrode separation on log-log graph paper.

The preferred method of resistivity data interpretation is curve matching either by hand or with the aid of a computer. The initial step is selection of an appropriate model based on comparing the general characteristics of the observed apparent resistivity curve (slope, inflection points, maxima, and minima) with a catalog of theoretical curves for the appropriate electrode configuration. Due to computational complexity, the theoretical curves generally are available only for horizontally layered resistivity models. The selection of an appropriate model fixes the number of discrete resistivity layers as well as the sense of resistivity contrast (high-low or low-high) at each layer boundary. Determination of layer thicknesses and resistivities is accomplished by further comparison of the observed apparent resistivity curve with more specific theoretical curves (for the general model) which are calculated for a wide range of layer thickness and resistivity values. The correct values are those for which the variation between the observed and theoretical curve is minimized. Alternatively, the correct values may be determined by direct borehole measurement.

Currently, catalogs of theoretical curves are available for models containing up to three layers and all possible combinations of relative resistivity contrasts (i.e., high-low-high, low-high-low, etc.). Inversion of data for up to five layers can be accomplished by using special procedures.

The advent of modern high-speed digital computers has revolutionized both the reduction and inversion of resistivity data. One obvious limitation of the hand curve-matching method is that only a finite number of models can be contained in any one catalog of curves. With digital computers it is feasible to calculate the theoretical curve for any combination of layer thickness and resistivity values quickly and economically. Further, after selecting a general model, iterative routines can be employed which optimize the solution by trial and error until a specified degree of conformance between the observed and theoretical curve is obtained; such routines are both rapid and highly objective. An example of a computer program for resistivity inversion is CRIMPA (Complete Resistivity Intepretation and Modeling Package Automatic) developed by Dr. Charles Stoyer of the Colorado School of Mines. CRIMPA handles models with up to five layers and any combination of layer thicknesses and resistivities.

Although the final inversion of resistivity data is best performed with a digital computer, the hand curve-matching method is extremely useful for obtaining approximate results in the field. Such results can provide valuable information for directing the field activities.

G.5.0 CASE HISTORIES

Few case histories of the use of the electrical resistivity technique are reported in the literature, except for its application in boreholes. Nevertheless, a sufficient number of examples are documented to demonstrate the usefulness of the method under the proper conditions.

A highly successful example of the use of electrical resistivity methods for coal exploration in eastern Pennsylvania is reported by Ewing, et al. (1936). In this early survey, anthracite subcrops were located by a fixed-spacing horizontal profile technique. In one of the exploration areas, drilling had been abandoned because of the large number of barren holes. After the electrical prospecting had defined probable subcrops only three unsuccessful borings were drilled.

In a more recent example, Verma and Bhuin (1979) report that coal seams in the Jharia coalfield in India could be mapped to a depth of about 20 to 30 meters using the electrical resistivity method. Small faults could be detected, as well as a probable basic igneous intrusion. Verma, et al. (1980), report specifically of the ability of the technique to locate faults in the Jharia coalfield. Profiles and soundings clearly delineated two known faults and a quartz dike. The results of Verma and Bhuin (1979) and Verma, et al. (1980), are especially useful in that they provide a comparison of results for different electrode configurations.

The use of the electrical resistivity method to map subsurface cavities is widely reported in the literature; for example, Barker and Worthington (972), Worthington and Barker (1977), Dearman, et al. (1977), Higginbottom (1976), GRB Singer, Inc. (1971), Maxwell (1975, 1976), and Podio (1978). The most advanced system for locating voids has been developed by Southwest Research Institute (Peters, et al., 1980) under contract to the U.S. Bureau of Mines.

The system developed by the Southwest Research Institute, known as the Earth Resistivity Data Acquisition System, is an automated implementation of the pole-dipole electrical resistivity survey technique. The pole-dipole configuration is a modification of the dipole-dipole, where one of the current electrodes is set far from the rest of the spread, effectively at infinity. As many as 64 electrodes are placed at two-meter increments along the survey line. A digital controller unit automatically samples and records measurements between electrodes at a rate of two seconds per reading. A 300-meter traverse can be surveyed in about four hours. The data analysis is completely computerized and works on the basis of obtaining a best fit of a void model to the data set. This system has been used in other than a coal environment and has successfully detected voids with depth-to-diameter ratios of up to 15:1. Tests at the Brown Badgett, Inc., Busick Mine near Central City, Kentucky (Peters, et al., 1980) showed some indication of detecting deep voids, but results were not entirely successful. Research has continued with this technique and resolution of voids within coal is being significantly improved (Condon, USBM, personal communication, April 1981).

G.6.0 STATE OF THE ART

The current limit of technological development of the earth resistivity technique is in the use of an automated system in the detection of voids. A key feature of this concept is the use of a computer-controlled switching unit to automatically measure at different electrode spacings. Future development along these lines would be the development of the computer software to allow for this high resolution, automated technique to be used in the generation of subsurface models of the entire earth material penetrated, and not just testing goodness of fit to models of voids.

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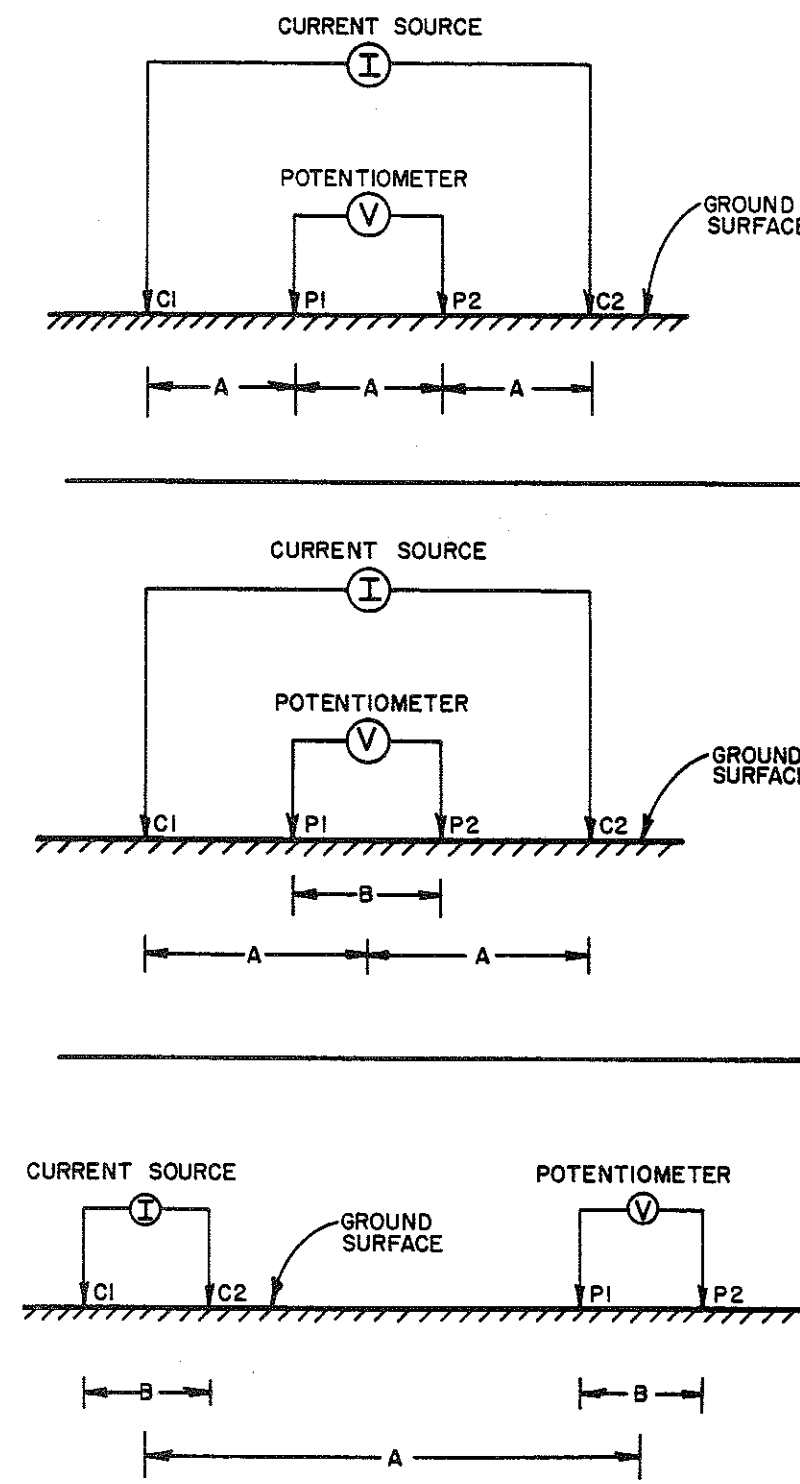
APPENDIX G
FIGURE



WENNER CONFIGURATION
ρ_A = APPARENT RESISTIVITY = $2\pi A \frac{V}{I}$

SCHLUMBERGER CONFIGURATION
ρ_A = APPARENT RESISTIVITY = $\frac{\pi A^2}{B} \frac{V}{I}$ $(B<0.4A)$

DIPOLE-DIPOLE CONFIGURATION
ρ_A = APPARENT RESISTIVITY = $\pi\left(\frac{A^3}{B^2} - A\right)\frac{V}{I}$

NOTE:
C1, C2 = CURRENT ELECTRODES
P1, P2 = POTENTIAL ELECTRODES

FIGURE G-1

SCHEMATIC REPRESENTATIONS OF COMMONLY USED ELECTRODE CONFIGURATIONS OF THE ELECTRICAL RESISTIVITY METHOD

APPENDIX H

BOREHOLE LOGGING

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BOREHOLE LOGGING

H.1.0 GENERAL DESCRIPTION

Borehole logging includes more than one dozen geophysical techniques involving the lowering of sensing devices into a borehole and continuously recording some physical parameters of the rock, fluids contained in the rock, or other parameters of the borehole. Each method has its advantages and limitations, so a suite of logs is usually recommended. The output can be digitized, so that each log can be easily rescaled as necessary to make comparison with other logs efficient and to transmit the data quickly from the field to the office for processing and analysis. Analog recording (using a chart recorder) also can be done in the field to assure the field crew that the data are complete and reliable.

Quantitative logging of coal seams has been conducted for many years, but only recently has quantitative borehole logging been extensively applied to coal exploration. Borehole techniques, together with surface geophysics, coring, sampling, and laboratory analysis, in situ testing, and geologic and stratigraphic analysis, are used for delineating the edges of the coal seams, and characterizing the structure of the coal deposit overburden and floor (faults, joints, folds, channel sands, clay layers, bed thickness, strata dip, coal quality, and mined-out areas).

Borehole logging is not yet a substitute for coring and testing, but is rather a series of supplementary techniques that can reduce the number of costly core holes and tests recommended for a complete program. It has the potential for replacing coring in all but specialized investigations. It also has the advantage of giving in situ data and data on stratigraphic intervals for which no or only partial core recovery has been realized. Cases are documented where very poor core recovery was translated into "insufficient reserves" where the truth obtained from logging justified mining ventures (Miller and Moore, 1980).

The different borehole logging techniques are based on measurements of a variety of physical properties and can be categorized into the following groups:

- Nuclear
  - natural gamma
  - gamma gamma (density)
  - neutron
  - neutron/gamma spectra
- Electrical
  - spontaneous potential (SP)
  - resistivity

  - resistance
  - induced polarization
- Acoustic
- Temperature
- Mechanical
  - caliper
  - fluid movement
- Visual

Other more exotic types of borehole logging techniques, including radar, seismic reflection, gravity and cross hole methods, such as seam wave transmission and HFEM are discussed in the appendices dealing with the surface and underground deployment of these techniques. The following paragraphs define the main characteristics of the methods outlined above.

H.1.1 Nuclear Logging

Nuclear logging involves the lowering of sensing devices to record radioactivity either naturally occurring or through backscatter and attenuation from a radioactive source in the borehole. These techniques include natural-gamma, gamma-gamma, neutron, and neutron-gamma spectra logging.

Natural Gamma Logging

The natural gamma log is a passive type log where measurements are made of naturally occurring gamma radiation and an active radiation source is not required. Natural radiation is produced primarily from the isotopes of potassium, uranium and thorium, which are generally more abundant in clays. Coal and other sedimentary rocks such as sandstone and limestone normally give low natural gamma readings, unless they contain abnormal amounts of uranium or other radioactive material. An example of the typical response to a coal seam is shown in Figure H-1.

The natural gamma log is normally used qualitatively for lithologic correlation and quantitatively for estimates of porosity and permeability based on clay content. The relative ease with which this technique can be used to determine lithologic correlation makes it a powerful tool in analyzing depositional environments (Miller and Moore, 1980).

Instrumentation for the natural gamma sonde consists of a scintillation type receiver and associated counting circuitry. The basic elements of a borehole natural gamma radiation measurement system are depicted in Figure H-2. Because the gamma radiation can be detected through steel casing and through drilling and groundwater fluids, the technique can be used in a wet or dry hole and in a cased or uncased hole. The ability to measure through drill pipe is an important advantage in areas where keeping the hole open is difficult. In coal exploration, this technique is used in conjunction with gamma-gamma logging and as an alternative to methods unusable because of casing or fluids present, nonconductivity of drilling muds, or in very electrically resistive formations.

Radiation penetrates rock on the order of one foot, thus one sees a "bulk" sample. A large penetration radius can reduce the vertical resolving power, but by analysis of the continuous profile, boundaries can be resolved to within a few centimeters.

Gamma-Gamma Density Logging

The gamma-gamma log uses an active gamma source to measure bulk density and is commonly known as a density log. Gamma-gamma logging measures gamma radiation backscattered and attenuated within the borehole and surrounding rock from a source in a probe. The signal received (for a given geometry) is a function of density. The radiation source elements commonly are Cesium-137 or Cobalt-60 although one high resolution source utilizes Americum-241 (Fishel and Mayer, 1979).

The gamma-gamma sonde consists of the radioactive gamma source and one or two receivers, and associated counting circuitry. Most sondes have mechanical arms to hold the sonde against the wall. The basic elements of a borehole gamma-gamma density system are illustrated in Figure H-3.

Shales and porous formations such as some sandstones and limestones have low gamma-gamma readings; however, coal exhibits high gamma readings (low attenuation, effective backscatter) because coal absorbs little energy, being of low bulk density. Therefore, coal can be distinguished from other rock types based on the combined low natural gamma response and low density (Figure H-1), as long as the coal is not contaminated with material which would cause it to be a natural source.

The spacing of the source and sensor determine the depth of penetration and the vertical resolving power. Generally speaking, the minimum bed thickness that can be resolved is the same as the separation between the source and detector. Abshier, et al. (1979), Fishel and Mayer (1979) and Reeves (1976a,b) report four different types of gamma-gamma density logs:

- Long Spacing Density (LSD) - This tool can resolve beds about 48 cm thick to within 22 cm.
- High Resolution Density (HRD) - A bed 24 cm thick can be resolved to within ± 9 cm.
- Bed Resolution Density (BRD) - Beds 15 cm thick can be identified and resolved to within ± 5 cm.

- Extremely High Resolution Density (EHR) - Beds as thin as 2 cm thick can be resolved with this tool.

A comparison of the responses of the LSD and BRD tools is presented in Figure H-4.

Although increased resolution is a highly desirable characteristic, the decrease in source/detector spacing, which allows for increased resolution, also restricts penetration (Samworth, 1974). The decrease in penetration means that the high resolution tools are much more subject to problems where the hole size is erratic or rock around the hole is badly fractured. For this reason, log interpretation requires knowledge of the borehole shape as determined by the caliper log (Section 1.5). Most logging companies recommend that high resolution logs be accompanied by an LSD type of log.

Gamma-gamma logs can be run in cased holes, although the casing will signficantly interfere with the logs with the highest resolution. Where casing is present, the techniques can be used to locate cavities and cement outside the casing.

The gamma-gamma log is one of the most powerful tools for identifying and characterizing coal. Where high resolution probes have been used, such as the BRD or EHR instruments, good empirical correlation has been established between probe response and ash content of the coal (Fishel and Mayer, 1979).

Neutron Logging

In neutron logging, neutrons are released from a source in the probe and the resultant radioactivity is detected after interaction in the hole and surrounding formations.

A downhole neutron source emits a continuous flux of energetic neutrons which reduce in energy as they migrate spherically away from the source, across the drill hole and through the formation. A radiation detector senses either the low energy neutrons or the gamma radiation resulting from slow neutron absorption.

The detected neutron or gamma ray response is primarily a function of the hydrogen content of the borehole environment. If the rocks have a high hydrogen content, the neutrons are slowed down and captured by the hydrogen nuclei at small distances from the source, whereas if the hydrogen content is low, they travel a relatively large distance before reaching thermal velocities.

The number of neutrons arriving at the detector indicate the hydrogen distribution in the formation--the lower the number, the greater the hydrogen nuclei content. For most rocks the main source of hydrogen is water and the neutron log can be used to infer porosity. Porosity determination from neutron logs assumes that all hydrogen within a formation is in the form of pore fluid (water) and that the formation is saturated. Log response is affected by hole diameter, mud salinity, mud density, mud-cake thickness, and the presence of casing. These effects can be minimized using special correction charts if the source of perturbation can be quantified. The use of a sidewall neutron log in an uncased hole reduces many of these effects. Caliper logging to determine borehole diameter is necessary to quantitatively interpret a neutron log.

The neutron log is indicative of porosity in porous rocks, such as sandstones, but gives misleadingly high porosities for coal horizons because hydrogen is present in the form of hydrocarbons, as well as water. A similar situation exists where water is chemically bonded to the rock, as in the case of gypsum. Miller and Moore (1980) report that many service companies are reporting excellent results and resolution in coal with the neutron log in Appalachian coal fields. However, the method is not widely used because of situations for which the neutron might not clearly define a coal boundary, such as when wet clay or methane or water charged sand is next to the coal.

The three major types of neutron logs are neutron-gamma, neutron-thermal, and neutron-epithermal. The first type responds to gamma rays produced by slow neutron absorption, but is influenced by other sources of gamma-radiation. The second and third types differ in the energy range of slow neutrons over which their receivers are sensitive. Of the three, the neutron-epithermal type is the most accurate and least sensitive to external effects.

The neutron sonde consists of a radioactive neutron source, one or two receivers, and associated counting circuitry. The sidewall log also contains mechanical arms to hold the sonde against the wall. Basic elements of a borehole neutron logging system are shown in Figure H-4.

Neutron/Gamma Spectra Logging

A modification of the neutron log measures the spectrum of gamma radiation produced when rock is bombarded with neutrons. When atoms from a specific element are hit by a neutron, the gamma energy is released at a specific diagnostic energy level, usually measured in electron volts or mega-electron volts (MeV). For example, hydrogen releases gamma rays at 2.223 MeV and aluminum, a key constituent of ash, releases gamma rays at 1.779 MeV (Senftle et al., 1978).

Equipment to measure the induced gamma spectrum is still being developed, but a successful prototype has been tested in coal and consists of a Californium-252 source and a germanium-lithium gamma ray detector (Senftle, et al., 1978). This source is not sufficiently energetic to cause all elements to release diagnostic gamma rays, but many of the important elements, including H, Al, Si, Fe, Ti, C, Ni, S, and C can be identified and their concentrations determined quantitatively.

A detraction of the neutron/gamma ray spectra logging method is the length of time required to log a hole. Senftle, et al. (1978) report that it took 34.1 minutes to obtain the gamma ray spectrum from each discrete depth. Thus, logging is not continuous and rates are measured in meters per hour and not per minute, as with most logging techniques. The technology of compensating for borehole size and condition still needs to be refined before the technique can be used routinely for quantitative analyses.

H.1.2 Electric Logging

Electric logging includes spontaneous potential (SP), resistance, and resistivity logging. It involves measuring electrical properties of the surrounding rock and fluids. In resistance and resistivity logging, an electric current is applied to layers of rock, and resistance to this flow is measured. In SP-logging, the probe detects natural potentials that develop electrochemically or electrokinetically between borehole fluids and the surrounding rock. In all electric logging, the hole must be uncased and wet, although there is an electromagnetic induction device which can be used to measure resistivity in a dry or a wet hole.

Spontaneous Potential (SP) Logging

Spontaneous potentials are naturally occurring electrical potentials arising chemically and physically at the contacts between the drill hole fluid and the subsurface materials, as well as at the contacts between the various lithologic units and their contained fluid. The spontaneous potential or SP log measures and records these potentials. Qualitative uses for the SP log include lithologic correlation between drill holes and location of permeable beds. Quantitative uses include determination of bed thickness and formation water resistivity.

The sonde for SP logging consists of an oxidized lead or iron electrode. The SP measurement is the potential between the downhole sonde and a reference electrode at the surface. Also, a differential SP measurement can be made between two separate electrodes on the sonde. The basic elements of a borehole SP measurement system are shown in Figure H-6.

Because coal seams are poor conductors of electricity, SP logs are generally blind to coal and lignite beds. Abshier, et al. (1979) has noted that SP logs sometimes show a slow rise in voltage at the center of the coal bed, followed by a slow voltage decline to the bed boundary. This is interpreted to be caused by a leak in the resistivity section of the logging tool (the SP log is usually combined with a resistance or resistivity logging sonde), which allows a voltage leak up the body of the tool. Abshier, et al. (1979), consider that SP logs are normally not useful for coal and lignite logging.

Resistance Logging

Resistance logging consists of measuring the resistance, in ohms, of the in situ materials between an in-hole electrode and a surface electrode, or between two in-hole electrodes. A constant current is maintained between the two electrodes and the potential difference is measured. Resistance logging is also called single-point, point-resistance, or single-electrode logging.

Qualitative uses for resistance logging include lithologic correlation between drill holes and location of fractured zones. Quantitative uses include determination of bed thickness. The resistance log is sensitive to changes in drill hole diameter (caving, washouts, and fractures) and in areas of hole enlargement will primarily measure electrical properties of the drilling fluid. Thin lithologic units with resistivities higher than that of the drill hole fluid may be indistinguishable. In the case of logging through coal, the resistive formations such as a clean sandstone may mask the actual boundary of the coal. The method will accurately distinguish coal/shale contacts, however.

The sonde for resistance logging is similar to the SP sonde and often both measurements are made simultaneously with a single sonde. One variation of the resistance log is the differential-resistance log which measures the resistance between two in-hole electrodes. The basic elements of a borehole resistance measurement system are illustrated in Figure H-7.

Resistivity Logging

Resistivity logging consists of measuring the resistivity in ohm-meters or ohm-feet of the in situ materials by means of an electrode configuration of current and potential electrodes within a sonde. The electrode configuration and operational principles are similar to those applied from the surface as discussed in Appendix G.

The earliest devices used in resistivity logging can be categorized as normal or lateral tools and the logs produced from this equipment are known as short-normal, long normal or lateral curves. All have electrode spacings which are too wide to be of much use in providing the vertical resolution necessary for coal logging (Davis, 1976). Resistivity devices used by most companies for logging coal are known as laterolog or focused-beam log, illustrated in Figure H-8. With this deployment, a closer electrode spacing is used and a mechanical spring forces the electrodes against the side of the borehole and overcomes many borehole and side bed distortions, providing good vertical resolution (Moran and Chemali, 1979). The resistivity method still has the difficulty of the other electrical techniques in that the coal seam may not be resolved if it is adjacent to a highly resistant bed such as clean sandstone or the bed is thinner than the electrode spacing.

An innovative adaptation of the focused-beam log is known as the dipmeter (Wroot, 1979). The dipmeter employs three electrode arrays which simultaneously record different responses at different azimuths within the borehole. Correlation between the three curves, when interpreted with the hole caliper data and magnetic declination angle, allows for a determination of the sedimentary or structural dip. Knowledge of dip, together with lithology, makes the dipmeter a powerful tool in providing the geologist with an understanding of depositional environment. A dipmeter developed by BPB Instruments, Ltd. can be used in a three-inch (7.6 cm) borehole. An example of a dipmeter log is provided in Figure H-9.

Induced Polarization (IP)

The induced polarization (IP) technique has been used for about the past thirty years from the surface as a mineral exploration tool. Measurements consist of introducing an electrical pulse into the ground and then measuring the slow decay of voltage following cessation of the pulse. The electrode configurations are similar to those used in the electrical resistivity measurements. The method is particularly sensitive in the detection of disseminated conductors within a highly resistive mass, such as disseminated sulfides in a porphyry copper deposit.

When used from a borehole, the method has the potential for quantifying the amount of disseminated conductors within a coal seam, such as sulfur or pyrite. Merkel and Snyder (1977) report that an IP log was able to demonstrate that a Wyoming coal seam has a sulfur content of less than 0.6 percent.

H.1.3 Acoustic Logging

Acoustic (or sonic) logging measures the transit time of an acoustic pulse (a high frequency compressional seismic wave) from an electromechanical source to a receiver. The velocity of the formations penetrated is determined by multiplying the reciprocal of travel time by the transmitter to receiver spacing. The basic elements of a borehole acoustic velocity measurement system are shown in Figure H-10.

There are two main kinds of sonic probes. The BHC (Borehole Compensated) tool reduces the error due to hole-size changes and tilt of the probe. This is accomplished by using two transmitters and either two or four receivers. The other type is a Continuous Vertical Array (CVA), which is discussed in Appendix B and consists of a vertical string of geophones with a line of seismic sources on the surface. The sonic log can be made in a wet or dry uncased hole.

The radius of investigation (depth of penetration and vertical resolving power) is typically three times the wavelength of the pulse or three times the velocity in rock divided by the frequency. Typical values of velocity in coal are 1,800 meters per second in lignite and 2,700 feet per second in bituminous coal. Because common frequencies of the transducers are about 20,000 hertz, the radius of investigation would be about 0.3 meter in lignite and 0.4 meter in bituminous coal.

Sonic measurements respond to changes in density, compaction, carbon, and moisture content and will give an indication of coal rank (Reeves, 1979). In combination with data from density logs, values of the porosity and compressive strength may be determined and information may be gained about rock type, formation moisture, and fracture conditions (Jackson, 1981). Knowledge of the seismic velocity and density together also allows for the conversion of high resolution seismic reflection time sections into depth sections or generate synthetic seismograms, as discussed in Appendix B.

H.1.4 Temperature Logging

Temperature logs are continuous records of the temperature of the drill hole environment. The temperature recorded is for the fluid surrounding the sensor, which may or may not be representative of the temperature in the surrounding material. The temperature log is generally performed as a function of depth, but may also be run at a constant depth as a function of time. Temperature logs are usually performed in uncased fluid-filled holes, although cased holes may be used.

Qualitative applications for temperature logs include identification of aquifers, location of permeable zones, and mapping of ground water flow. Quantitative applications include location of grout beyond a casing after cementing and determination of geothermal gradient. The geothermal gradient can be determined only when the drill hole fluid has reached thermal equilibrium with in situ materials and there is no vertical fluid movement. Logging speed should be slow enough to allow the sonde to respond to temperature changes. Mixing of the drill hole fluid by movement of the sonde must be considered.

Temperature logging sondes contain a thermistor which changes resistance as a function of temperature. The resistance is monitored on the surface and electronically converted to temperature. The differential-type sonde contains two separate thermistors and the difference in temperature between the thermistors is measured. Another type of differential sonde uses a single sensor with an electronic memory to store readings which are compared with previous readings to determine temperature differential. The basic elements of a borehole temperature measurement system are illustrated in Figure H-11.

Coal and, in particular, lignite usually have lower conductivities than the other sediments typically found in a coal sequence. Thermal gradients should therefore be higher in coal than in most other sedimentary rock. This observation has been confirmed by Beck (1977), who notes that a temperature gradient log can be used to distinguish coal and sandstone from a resistivity log. Resolution is a main problem of temperature gradient logging and its main application remains in the

detection of ground water flow in a borehole. The technique also has a natural application where it is prudent to have knowledge of the ambient rock temperature of a coal seam to be mined.

H.1.5 Mechanical Logging

Mechanical devices for downhole measurements include equipment to measure borehole diameter (caliper log) and mechanical rotors, impellers, and vanes to measure the flow of fluid. Where precise knowledge of the downhole deviation of a borehole is required, verticality measurements can be made within a borehole.

Caliper Logging

The caliper log is a continuous record of the average diameter of a drill hole. Most caliper sondes consist of one to four feelers or bow springs which follow the wall of the hole. The feelers or springs are mechanically connected to potentiometers. As the feelers or springs move, the circuit resistance changes. Resistance changes are converted to diameter by surface circuitry. The basic elements of a borehole caliper measurement system are depicted in Figure H-12.

The primary application of caliper logs is to measure hole diameter so that diameter effects on other logs can be corrected. Other appliations are based on inferences from hole diameter and include lithologic identification, stratigraphic correlation, location of fractured and caved zones, and computation of material quantities for grouting.

Fluid Movement Logging

Fluid movement logging is used to measure vertical movement of fluid within a drill hole. Measurements can be made as a function of depth or as a function of time at a fixed depth. The two main types of fluid movement devices are the impeller flowmeter and the tracer injector. Both types should be centralized in the hole to avoid velocity distortion.

The impeller flowmeter consists of an impeller mounted in an annular housing with the axis of rotation parallel to the drill hole axis. The number of revolutions per unit time are counted, averaged, and electronically converted to velocity. In the moving mode, the hole is logged in both directions at the same speed. The fluid velocity is equal to one-half the difference in velocity as recorded in each direction. The logging direction in which the lowest velocity is measured is the same direction as the fluid movement. In the stationary mode, the flowmeter is held in one position and velocity is recorded as a function of time.

The tracer injector consists of a device used to inject a thermal, conductive, or radioactive tracer which is detected at some fixed distance by a thermistor, fluid conductivity device, or radiation detector. The tracer injector is used only for stationary measurements. The flow velocity is determined by measuring the time interval between injection and detection. The basic elements of a borehole fluid movement measurement system are shown in Figure H-13.

Common applications of fluid movement logging include the determination of fluid movement in drill holes open to multiaquifer artesian systems and the determination of relative permeability under imposed hydraulic pressures. Except where ground water problems may be present, the use of a fluid movement system to log through coal seams is limited.

Verticality Logging

Boreholes are seldom perfectly vertical, but they usually exhibit some horizontal deviation which is commonly magnified with increasing depth. When it is necessary to know the variation of horizontal position with depth, such as when a borehole intersects abandoned workings, or cross hole measurements are being made to determine physical properties between two boreholes, the deviation of the borehole is measured by means of verticality logging.

Precise deviation is determined by the use of a sonde which uses a small camera to photograph a magnetic compass and a leveling bubble simultaneously at specific time intervals while the sonde is lowered at a fixed rate down the borehole. Other methods substitute the magnetic compass for a precise gyroscope which indicates deviations by sending an electrical signal to a surface recorder. In some cases, the sonde is lowered along runners to maintain position within the borehole.

H.1.6 Video Logging (Borehole TV)

Borehole TV logging in an uncased hole that is dry or that contains a relatively transparent fluid can be used to identify stratigraphic boundaries, the presence of coal, and the presence, condition, extent, and orientation of fractures and voids. Some borehole camera probes are small enough to traverse NX-size holes in the shallow-depth range (0 to 100 meters). Deeper holes require a larger camera which would fit down a hole of at least six inches (15 cm) in diameter. The output is a visual image that can be observed at the surface and simultaneously recorded on videotape with voice notation. The image is in black and white.

Coal has a high reflectance, a conchoidal surface texture, and is black or dark gray. It can be distinguished visually in black and white from most other rock types usually encountered in coal-bearing strata, except that in some cases coal looks similar to black shale. Mudcake sometimes obscures the view of the rock at the side of the borehole. A borehole camera which contains a spotlight and lateral mirror or prism attachment is useful for looking into mined-out areas and gaping joints.

H.2.0 PHYSICAL PRINCIPLES AND CONSTRAINTS

H.2.1 Background Theory

The background theory for all but the nuclear logging methods is presented in the appendices relating to the surface and underground application of the geophysical techniques. Background theory to the nuclear methods is outlined briefly in Section H.1.1.

Coal is characterized by unique physical properties which form the basis for the response of different logs, summarized in Table H-1.

The values provided in Table H-1 should be considered as typical and may vary beyond those presented. In particular, natural gamma response may be high if uraniferous salts are present in the coal, such as has been documented in lignite deposits of the Black Hills (Davis, 1977). Density will increase with increase in ash content; resistivity is dependent on moisture content; and acoustic velocity is affected by depth of burial.

H.2.2 Information Derived from Measurements

The information derived from measurements is discussed in general in Section H.1.0 and is outlined in Table H-2. No one tool by itself provides unique characterization of a coal seam, and it is standard procedure to run a suite of logs where the coal may be distinguished by the response of different logs. Usually a coal seam can be positively identified by a comparison of natural gamma, gamma-gamma density, and caliper logs.

The physical properties of the coal and surrounding rocks are also determined by the combined interpretation of different logs. Reeves (1979) discusses the combination of logs to form Coal Quality and Strength Index Logs. The Coal Quality Log is a quantitative interpretation of density from a density log, in combination with the natural gamma log, which can be used to define ash content. Figures H-1, 14, 15, and 17 provide examples of dual plotting of the natural gamma and density logs to define lithology and ash content of the coal. The Strength Index Log (Figure H-16) combines the density and acoustic (sonic) logs to infer rock strength which has shown favorable correlation with the results of triaxial strength tests.

Borehole logs have a variety of additional uses pertaining to the calibration of surface geophysical surveys including:

- Gamma-gamma - The gamma-gamma log can be used to construct a vertical density profile to provide control for gravity surveys.

- Acoustic (sonic) - The acoustic log can be used to construct a vertical velocity profile to provide control for seismic reflection and refraction surveys. When combined with density information, sonic data can be used to construct a vertical acoustic impedance profile for seismic reflection modeling studies.

- Resistance/resistivity - The resistance or resistivity log can be used to construct a vertical profile to provide control for electrical resistivity surveys.

H.2.3 Site/Physical/Interpretive Constraints

Limitations specific to each borehole technique are presented in Table H-2. In addition to these specific constraints, the logging techniques are all subject to limitations of a general nature.

The primary limitation of borehole logging is one of lateral sampling ability. While borehole logging is considered to be an efficient technique for measuring physical properties in the immediate vicinity of the borehole wall, it must be noted that most conventional borehole logs are representative of only a small volume of the subsurface adjacent to the borehole.

Confidence regarding global property representation may be improved if log signatures can be traced from one borehole to another or if subsurface conditions are known to be relatively continuous. Correlation of several specific horizons or intervals can be made between two adjacent boreholes only if the same distinctive repetition of signature is seen in both boreholes. Correlation of a single horizon, where the dip and strike are unknown, is possible only with data from four different boreholes. It follows that stratigraphic correlations between specific horizons are generally difficult when only two or three boreholes are available. It is appropriate, therefore, to examine the logs from adjacent boreholes for general similarities. If adjacent boreholes exhibit the same general characteristics, it is likely that the logs are representative of the subsurface.

Further limitations to the application of borehole logging are:

- Interpretation of borehole logs is considered an art. The numerous factors influencing log response are difficult to analyze quantitatively. Even when theoretically derived equations are available, empirical data are required to determine unknowns in equations; therefore, direct empirical methods may be more reliable. This generally applies to the determination of properties such as permeability and water chemistry rather than to correlation.

- The spontaneous potential, resistance, caliper fluid movement, temperature, and sonic logs can generally be run only in open uncased boreholes. Additionally, the borehole must be fluid filled for all the above logs except the caliper. The open borehole requirement can lead to scheduling difficulties and higher costs, especially in areas where the subsurface is unstable.

- The minimum diameter opening through which most logging tools will pass is about two inches, and three inches is preferable. Due to differences in tool design, any boring program should include an investigation of available tool diameters.

- Caliper logging in soft or unconsolidated formations may cause caving or hole enlargement. Error in hole size corrections can results from this behavior.

In general, most of the limitations are known in advance and it is possible to account for them by judicious planning of the techniques used and methods used in log interpretation.

H.3.0 SURVEY TEST PREPARATION

Site preparation activities should be based on the type of survey to be conducted. Preparation includes the drilling of the boreholes and their casing, if appropriate. Where nuclear logging techniques are being used, it may be necessary to obtain permits for their use.

In addition to the aspects of site preparation, the accurate calibration of the logging equipment is the most important factor in determining the reliability of the results. The components of a borehole logging system which require calibration are the recorder, surface control circuits, and borehole sensor. These various components are usually calibrated as a unit with field reference standards. The sensor is exposed or connected to the standard and the associated recorder response is checked and adjusted accordingly. Listed below are descriptions of the field reference standard for the most important logs:

- Natural Gamma - The field standard consists of a gamma source for which the API radiation is defined at a fixed distance from the source. Calibration is checked by placing the source at the specified distance from the borehole gamma sensor and the noting response.

- Gamma-Gamma - The field standard consists of a set of blocks constructed of different materials (e.g., plastic, aluminum, magnesium) with known densities. Calibration is checked by placing one of the blocks over the borehole sensor and noting the response. The procedure is repeated for the remaining blocks.

- Neutron - The field standard consists of a set of blocks constructed of different materials (e.g., paraffin, plastic) with known hydrogen content. Calibration is checked in the same fashion as for gamma-gamma.

- Spontaneous Potential - The field standard consists of a precision adjustable voltage source which is connected across the borehole SP electrode and ground. Calibration is checked for several different voltages.

- Resistance - The field standard consists of a precision adjustable resistor which is connected across the borehole resistance electrode and ground. Calibration is checked for several different resistances.

- Resistivity - The field standard is a material of known resistivity normally provided by the tool manufacturer.

- Acoustic (Sonic) - The field standard consists of a precision pulse generator. The surface sonic circuitry is triggered by an initial pulse and stopped by a subsequent pulse occurring after a known interval. This procedure is repeated for several different time intervals corresponding to different velocities.

- Temperature - The field standard consists of a precision adjustable resistor. The sensing element (thermistor) is bypassed and a known resistance is connected across the surface circuitry. This procedure is repeated for several different temperatures. For precision thermal logging, ice-bath calibration of the termistor is also performed.

- Caliper - The field standard consists of a metal paddle with holes drilled at known separations. Calibration is checked by slipping the paddle over the borehole tool, placing the caliper arm in one of the holes, and noting the associated response. This procedure is repeated for several different radii.

- Fluid Movement - The field standard consists of a precision adjustable voltage source. The impeller assembly is bypassed and a known voltage is input directly to the surface circuitry. This procedure is repeated for several different voltages corresponding to different fluid velocities. Tracer injector devices require calibration of the recorder time base with a time interval counter.

H.4.0 DEPLOYMENT

H.4.1 Equipment

The necessary tools and equipment to conduct geophysical borehole logging can include:

- Downhole probe or sonde
- Electrical cable to which the sonde is attached
- Powered winch to hoist the sonde
- Measuring sheave to determine depth
- Weight indicator
- Power supply
- Surface control circuits
- Recording system

The characteristics of these individual components are summarized below:

- Downhole Probe - The probe or sonde contains the instrumentation necessary to conduct the physical measurement of interest and to prepare the signal for telemetering through the cable to the surface. Specific detail on sondes is contained in Section H.1.0.

- Electrical Cable - Logging cables are steel-armoured and contain one to seven conductors. Diameters range from 3/16 to 9/16 inch. The cable is used to carry electrical signals and supply voltages between the surface circuitry and the sonde, as well as to physically hold the sonde.

- Powered Winch - The cable is spooled on a powered winch to raise and lower the sonde. The winch also includes collectors or slip rings to preserve electrical continuity between the sonde and the surface circuitry.

- Measuring Sheave - The measuring sheave is a pulley with a calibrated diameter used to determine the length of cable in the hole.

- Weight Indicator - The weight indicator measures cable tension so that cable stretch corrections can be made. These corrections are usually negligible for borehole depths less than 1,000 feet.

- Power Supply - The power supply is usually a generator mounted in the logging vehicle. The power supply furnishes all power required by the sonde, surface circuitry, winch, and recorder.

- Surface Control Circuits - Surface circuitry provides efficient control of the logging to be performed. Control panels permit the selection of circuitry needed for a given operation or group of simultaneous operations. Appropriate safety features are incorporated to protect equipment and operating personnel.

- Recording System - The logging signals are generally recorded by a a photographic camera driven in synchronous motion with the probe in the hole. In cerain logging units, the log is automatically traced in ink on paper. For computer processing, logging data can also be recorded simultaneously on magnetic tape.

H.4.2 Operation

The field procedures for borehole logging are virtually identical regardless of the parameter to be measured. A sensor or sonde is lowered slowly into a borehole using a wireline and winch. Appropriate measuring scales and instrument settings are selected while the sonde is descending. After the sonde reaches the bottom of the borehole, the winch is reversed and a continuous record of the measured parameter as a function of depth is made from the bottom of the hole to the ground surface.

H.4.3 Analysis

The analysis of borehole logging data consists primarily of correcting the field data for hole size, casing and fluid type and then converting the results to the desired property.

Within the borehole environment there are several effects which must be corrected if the logging data are to be used for quantitative purposes. Even when the data are used for qualitative purposes, an awareness of

borehole effects will aid in preventing the situation where log response caused by external factors is interpreted as being due to lithologic changes. The borehole parameters which most frequently impact logging interpretation are:

- Hole size
- Casing composition, size, and thickness
- Mud type, density, and resistivity

These effects can usually be corrected if the parameters can be quantified. Hole size is particularly important when conducting any of the nuclear logs (gamma, gamma-gamma, neutron), and can be measured directly with a caliper. The appropriate correction is determined directly from charts pertaining to the particular borehole sonde being used. Casing composition, size, and thickness can be determined from drilling logs or completion records; again, appropriate corrections are determined from charts for the particular sonde (note that only the nuclear logs are run in cased holes). Mud type, density, and resistivity can affect spontaneous potential, resistance, and nuclear logs. While spontaneous potential and resistance logs are used primarily for qualitative applications, a knowledge of mud resistivity allows the interpreter to anticipate log response as a function of lithology; for example, when the mud resistivity is relatively low, the resistance log will become insensitive to high resistivity formations. Mud resistivity can be determined in the field with standard test cells. Similarly, mud type and density affect the nuclear logs, but can be corrected if these parameters are known. Test kits are available so that these parameters can be determined in the field.

Borehole corrections are becoming less important for certain types of tools. Modern sidewall sondes, particularly nuclear or focused-beam resistivity, overcome the need for many corrections either by the fact that the sensor is held against the borehole wall or that corrections are applied in real time by the surface control circuitry. Sidewall nuclear logs often contain built-in calipers which provide hole size information to the surface control circuitry so that appropriate corrections can be computed and applied to the data.

The conversion of borehole logging data to a desired property can be accomplished in several ways. Many modern logging devices contain built-in circuitry or minicomputers which perform the conversion in real time. Gamma-gamma devices, for example, actually measure the absorption of gamma rays primarily by Compton scattering. The related density is usually calculated from the absorption data on on-board circuitry or computers.

A second means of conversion can be accomplished by referring to standard charts. Sonic velocity, for example, can be converted to porosity by comparison with published charts for specific lithologies and fluid velocities. In a somewhat similar manner, coal density can be converted to ash content when comparisons can be made with laboratory test results. The conversion may be assisted by a computer, as illustrated in Figures H-1 and H-15.

A third means of conversion can be accomplished by cross-plotting techniques. These techniques are similar to matrix solution of simultaneous equations as they require more than one measurement to accomplish the conversion. Cross-plotting charts are available from most of the major logging companies to facilitate the process. Basically, these charts are constructed with one type of borehole measurement on the ordinate and a different type of borehole measurement on the abscissa. For example, cross-plot charts are available for sonic velocity and neutron porosity measurements. The values for each type measurement are plotted on the respective axis. The point on the plane of the chart with those coordinates indicates the grain density of the subsurface independent of porosity.

A final means of conversion consists of utilizing digital computers to implement conversion from charts or by solution of systems of simultaneous equations. The major advantage of computer conversion is the speed with which large amounts of data can be processed. It is perfectly feasible, for example, to cross-plot two types of borehole measurements at one foot increments for the entire logged interval. The resultant display can be used to spot trends such as the major lithologies in the subsurface and chemistry in terms of ash, carbon and moisture content, or rock strength. These three derived properties have been taken as examples of the extension of interpretation that can be achieved from the combination of different logs.

Lithology

The input for lithology programs are gamma ray, density, and caliper logs. Density is first compared with a coal cutoff. These are simultaneous equations based on volume analysis and the solutions are plotted as a computer generated log (Figure H-17) showing variation of rock matrix in depositional fashion (Reeves, 1979). The simultaneous equations are as follows:

$$GR_{log} = (GR_{matrix} \times Vol_{matrix}) + (GR_{shale} \times Vol_{shale}) \times (GR_{poros} \times Vol_{poros})$$

$$Density_{log} = (Density_{matrix} \times Vol_{matrix}) + (Density_{shale} \times Vol_{shale}) + (Density_{poros} \times Vol_{poros})$$

$$100\% = Vol_{matrix} + Vol_{shale} + Vol_{poros}$$

where

GR = gamma ray (API units)

matrix = gamma ray (API units) - density (linear) cross plot

poros = porosity in the formation

Vol = bulk volume

Ash content and a general indication of coal rank have been obtained from the suite of logs outlined for the combination coal tool. Improved density values and computer graphics allow detailed analysis of individual units of a seam. The cross plot of a density log against a resistivity log is an indicator of coal rank, as the density log will respond more to ash than to moisture and carbon and the resistivity log will respond mainly to carbon so that the cross plot will represent carbon plotted against ash (Reeves, 1976).

Chemical Analysis (Carbon, Moisture, Ash Contents)

Chemical analysis using the digital results of sonic, neutron, density, and natural gamma logs involves the solution of a matrix of simultaneous equations by computer. The equations represent a mathematical model of the coal seam. The general form of the equations is presented by several authors (e.g., Bond, et al., 1971; Kowalski and Fertl, 1977) as follows:

$$1.0 = A + C + M$$

$$\rho_b = A\rho_a + C\rho_c + M\rho_m$$

$$\Delta t = A\Delta t_a + C\Delta t_c + M\Delta t_m$$

where

A,C,M = ash, carbon, moisture content in percentages

ρ_b = bulk density of the formation in kg/m^3

ρ_a, ρ_c, ρ_m = bulk density of ash, carbon, and moisture in kg/m^3

Δt = transit time for the sonic pulse in μs/m

$\Delta t_a, \Delta t_c, \Delta t_m$ = transit time of ash, carbon, and moisture in μs/m.

Rock Strength

Sonic and density logs have been combined to produce a strength index log. This log is based on a formula (Bond, et al., 1971) which uses sonic and density values to calculate a dynamic elastic modulus of deformation as follows:

$$E_D \approx \frac{\rho}{(\Delta t)^2} \times (3.36 \times 10^9 \text{ psi})$$

where

E_D = modulus of deformation (millions of pounds per square inch)

ρ = bulk density of the formation, including contained fluids, in grams per cubic centimeter

Δt = transit time for a sonic pulse in microseconds per foot

3.36×10^9 = Schlumberger strength index.

An example of a strength index log is provided in Figure H-16.

H.5.0 CASE HISTORIES

Numerous examples of geophysical borehole logging of coal can be found in the literature. Excellent examples of geophysical logs through coal are provided by Davis (1976), Eisler, et al. (1979), Fishel and Mayer (1979), Kayal (1979), Kowalski and Holter (1975), Kowalski and Fertl (1977), Miller and Moore (1980), Peeters and Kempton (1977), Reeves (1971, 1976 a, b, 1979), Samworth (1974, 1979), Samworth and Cherrie (1976), Senftle, et al. (1978), and Wroot (1979). Fewer examples are available which discuss the importance of logging for reserve evaluation, but some good examples have been published (Johnson, 1977; Leblang and Svenson, 1977; Miller and Moore, 1980).

One of the best case histories of the use of geophysical logging and the importance of the logging on reserve estimation is presented by Miller and Moore (1980) for Appalachian coal fields. These authors note that natural gamma, density, resistivity, caliper, spontaneous potential and temperature logs have been used in the logging of Appalachian coal. In some areas a neutron tool is being used. Attempts at acoustic (sonic) logging have been promising, but the tool remains basically in the developmental stage for slimhole applications.

One of the best tools for logging Appalachian coal has proved to be the natural gamma ray log, because of the relatively low amount and often total absence of limestone beds and the low ash nature of many of the coal seams. With the general absence of limestone, the gamma log is a good indicator of grain size and the log display reflects paleoenvironmental energy levels. As many of the Appalachian coal seams are low in ash content and the coal is often surrounded by potassium-rich shale beds, the coals contrast sharply with the associated rock units on the natural gamma log.

The density log is the best tool for making a positive identification of the coal. Because Appalachian coals are often soft and thin, the EHR density tool is best suited for logging. Penetration is limited with the EHR tool, as is the quantitative data that can be obtained from the log, but Miller and Moore (1980) consider that this is acceptable for characterizing the metallurgical coals that comprise a considerable portion of the Appalachian coals. A deeper penetrating density log would be more important to obtain the quantitative data required for the characterization of steam or thermal coal to determine coking characteristics. These authors note that although geophysical logs may begin to provide moisture, sulfur, Btu values, ash and carbon readouts, logs do not have the ability to measure such factors as fluidity, fusion temperature, contraction and expansion characteristics, etc.

A typical example cited by Miller and Moore (1980) to define the importance of borehole logging for reserve estimation is that of a slope development in McDowell County, West Virginia. A 4,000-acre tract was drilled in 32 locations without geophysical logging and "proven" reserves were calculated at 6 million tons in the Fire Creek seam. Review of natural gamma logs from gas well tests on the property suggested that more reserves were actually present. The site was redrilled and with the help of geophysical logs it was found that the seam was more than twice as thick as had been reported from the original cored holes which had poor recovery of the coal. Reserves are now calculated at 15 million tons of in-place coal. The original reserve boundary prior to geophysical logging and the actual boundary based on geophysical logs is shown in Figure H-18.

H.6.0 STATE OF THE ART

Borehole geophysical logging is a mature technology. Virtually all of the logging techniques developed for the oil and gas industry have been modified for "slimhole" as required for coal. High resolution density and resistivity logs can now be expected to detect the boundaries of coal beds to within one or two inches and to resolve equally thin splits or ash partings within the seam. The use of cross-plotting techniques has enabled some quantitative analyses to be performed for ash and sulfur content, moisture, and Btu values.

One tool which is still under development and shows great promise for the coal industry is the neutron-gamma spectra log, which enables the quantitative analysis of the elemental constituents of coal. Determination of the chemical characteristics of the coal which can be derived from knowledge of the elemental constituents remains a topic of future research.

APPENDIX H

REFERENCES

APPENDIX H

LIST OF REFERENCES

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APPENDIX H

TABLES

TABLE H-1

TYPICAL LOGGING TOOL RESPONSES TO COAL

LOG TYPE	ANTHRACITE	BITUMINOUS	LIGNITE
Natural Gamma (API Units)	Low (20-25)	Low (20-25)	Low-Moderate (30-40)
Gamma-Gamma	1.4-1.8	1.2-1.5	0.7-1.5
Neutron (Porosity Index)	Very High 55-70	Very High 55-70	Very High 55-70
Acoustic Velocity (m/sec)	2,500-3,300	2,200-2,700	2,000-2,300
Resistivity (Ohm-m)	High 1,000-10,000	High 50-2,000	Moderate-High 20-2,000

TABLE H-2

INFORMATION DERIVED FROM BOREHOLE LOGGING TECHNIQUES

LOGGING METHOD	DIRECT MEASUREMENT	DIRECTLY DERIVED PROPERTIES	INDIRECTLY DERIVED PROPERTIES	TYPICAL RESPONSE OF COAL	LIMITATIONS FOR COAL LOGGING
Natural gamma	Natural radioactivity	Radioactive element content	Lithology - estimates of porosity and permeability based on clay content; ash content	Low gamma ray production	Gamma ray logs invalid when coal is contaminated with radioactive minerals - very clean sands can have same response as coal.
Gamma-gamma (density)	Backscatter of gamma radiation	Density	Lithology, ash content coal thickness	Low density, dependent on ash content	Beds thinner than tool spacing will not be resolved. Highly fractured rocks may indicate misleading low density results; affected by varitions in width of borehole
Neutron (neutron-gamma or neutron-neutron)	Backscatter of neutrons	Hydrogen content	Lithology, porosity, presence of hydrocarbons	High apparent porosity due to presence of hydrocarbons	Beds thinner than tool spacing will not be resolved. Erratic borehole diameter, variation of moisture content and fracturing will affect results.
Neutron (gamma spectra)	Spectrum of gamma rays from neutron bombardment	Detection and measurement of quantities of certain elements	Lithology, ash content	High carbon response - response to other elements such as sulfur, aluminum (in ash) will be as dictated by coal chemistry	Method is slow and may be affected by borehole diameter variations. Bed resolving power may be poor because measurements are not continuous.
Spontaneous potential	Natural voltage potentials	Identification of permeable beds	Lithology	Usually none	The method usually does not respond to coal.
Resistance	Electrical resistance	Electrical resistance	Lithology	High resistance	Borehole diameter variations can affect results - highly resistive sandstones can be confused with coal.
Resistivity	Electrical resistivity	Electrical resistivity	Lithology - sedimentary dips when dipmeter measurements are made.	High resistivity	Borehole diameter variations affect results, although this effect is greatly reduced by use of laterologs or focused-beam or dipmeter devices. Beds thinner than tool spacing will not be resolved and highly resistive sandstones can be confused with coal.
Acoustic	Acoustic (Sonic) wave velocity	Acoustic (sonic) wave velocity	Coal rank, strength characteristics of roof and floor rock	Low velocity	Variations of borehole diameter and rock fracturing may affect results. Beds thinner than tool spacing may not be resolved. Loose, clean sands can be confused with coal.
Temperature	Thermal gradient	Variations of thermal conductivity	Lithology - ground water movement	Low thermal conductivity (high thermal gradient)	Fluid movements may alter temperature profile - bed resolution is low.
Caliper	Borehole diameter	Hole stability	Lithology, in some cases	No typical response	Washouts wider than caliper arms will not be detected.
Fluid movement	Flow of borehole fluid	Ground water movement	Dewatering characteristics	No typical response	Drilling mud may restrict ground-water flow.
Borehole TV	Visual observation	Voids, fractures, ground-water flow, texture, grain size	Lithology, hydrology	No typical response	Particulate matter in drilling fluid can obscure vision.

APPENDIX H
FIGURES

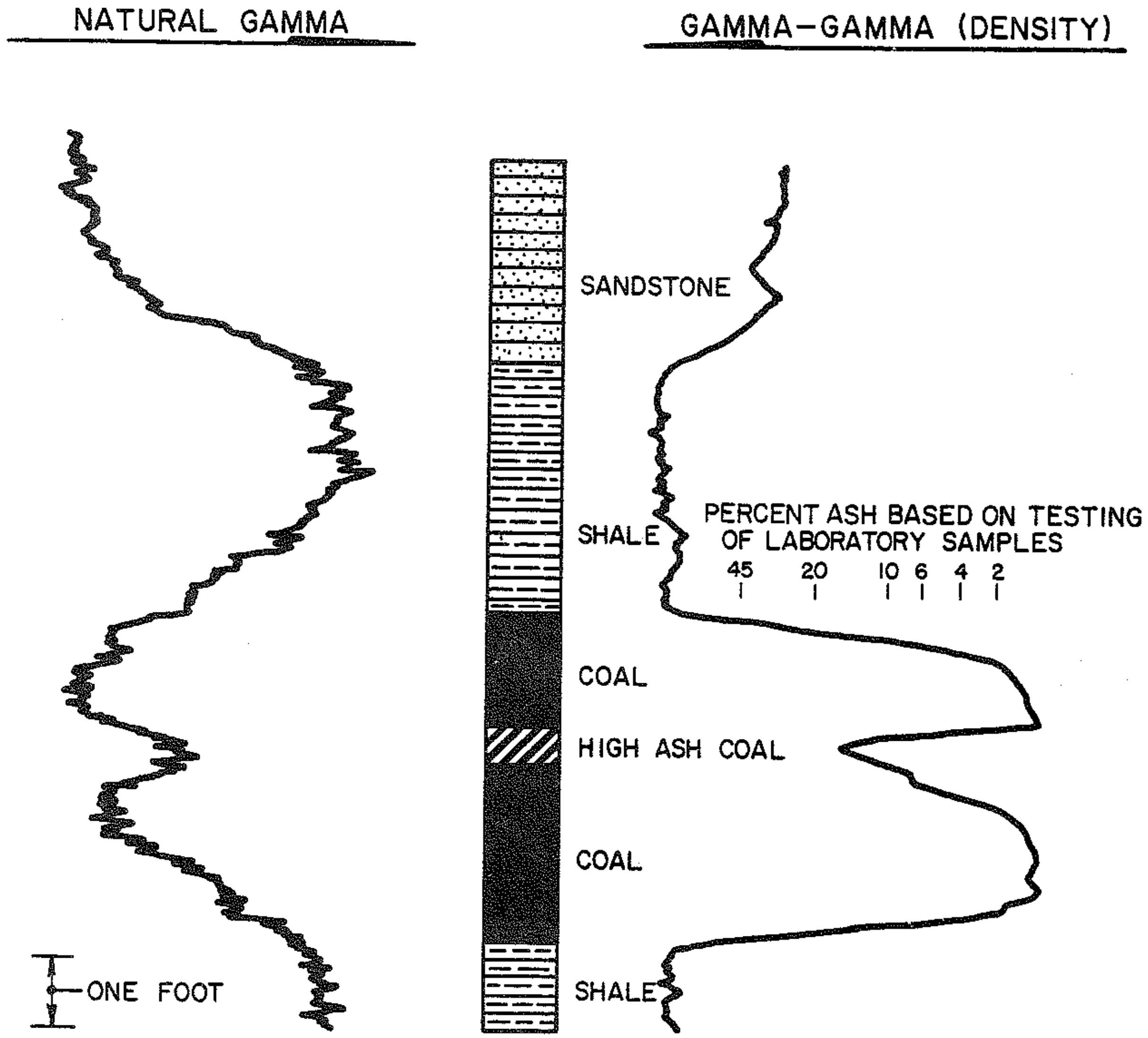


FIGURE H-1

EXAMPLE OF NATURAL GAMMA AND GAMMA-GAMMA (DENSITY) LOGS THROUGH TYPICAL COAL SEQUENCE

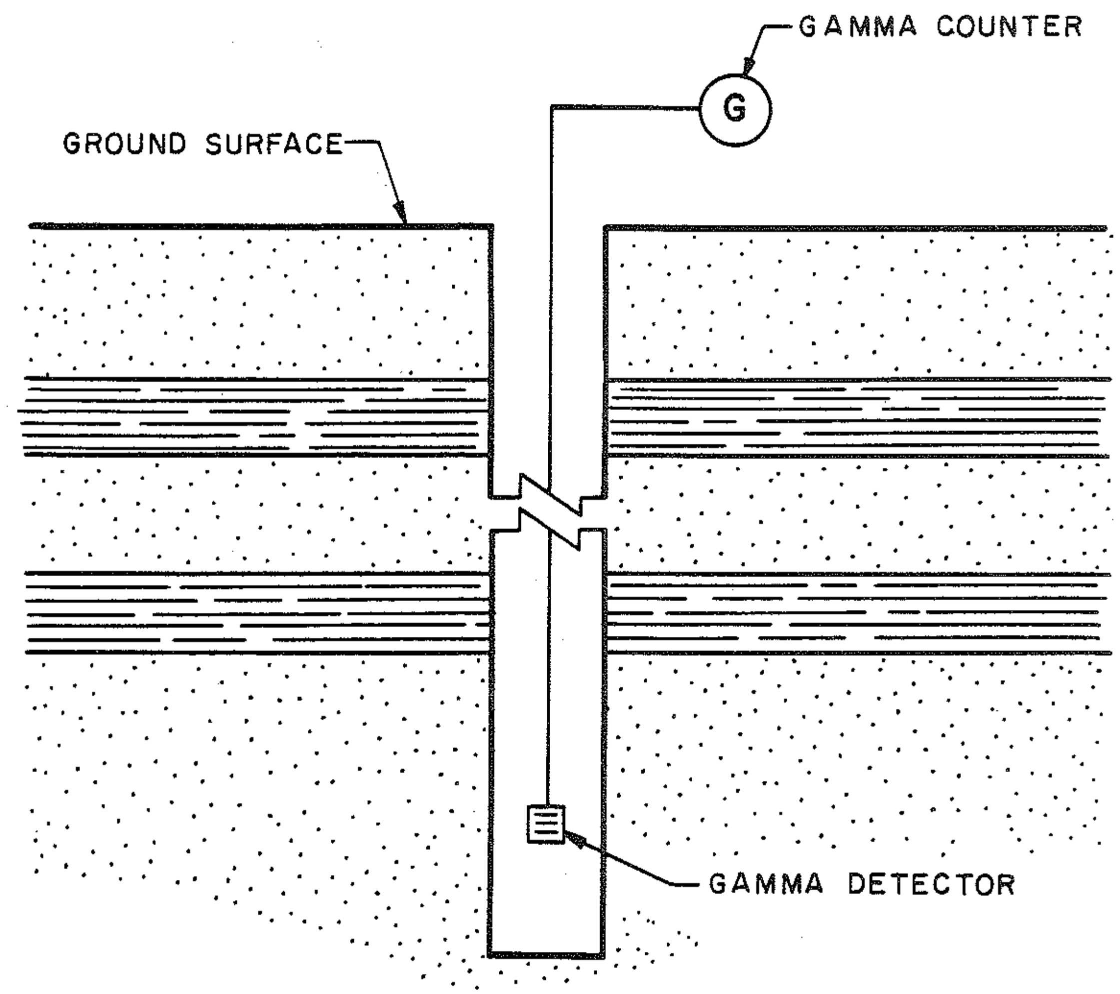


FIGURE H-2

BASIC ELEMENTS OF BOREHOLE NATURAL GAMMA RADIATION (NGR) MEASUREMENT SYSTEM

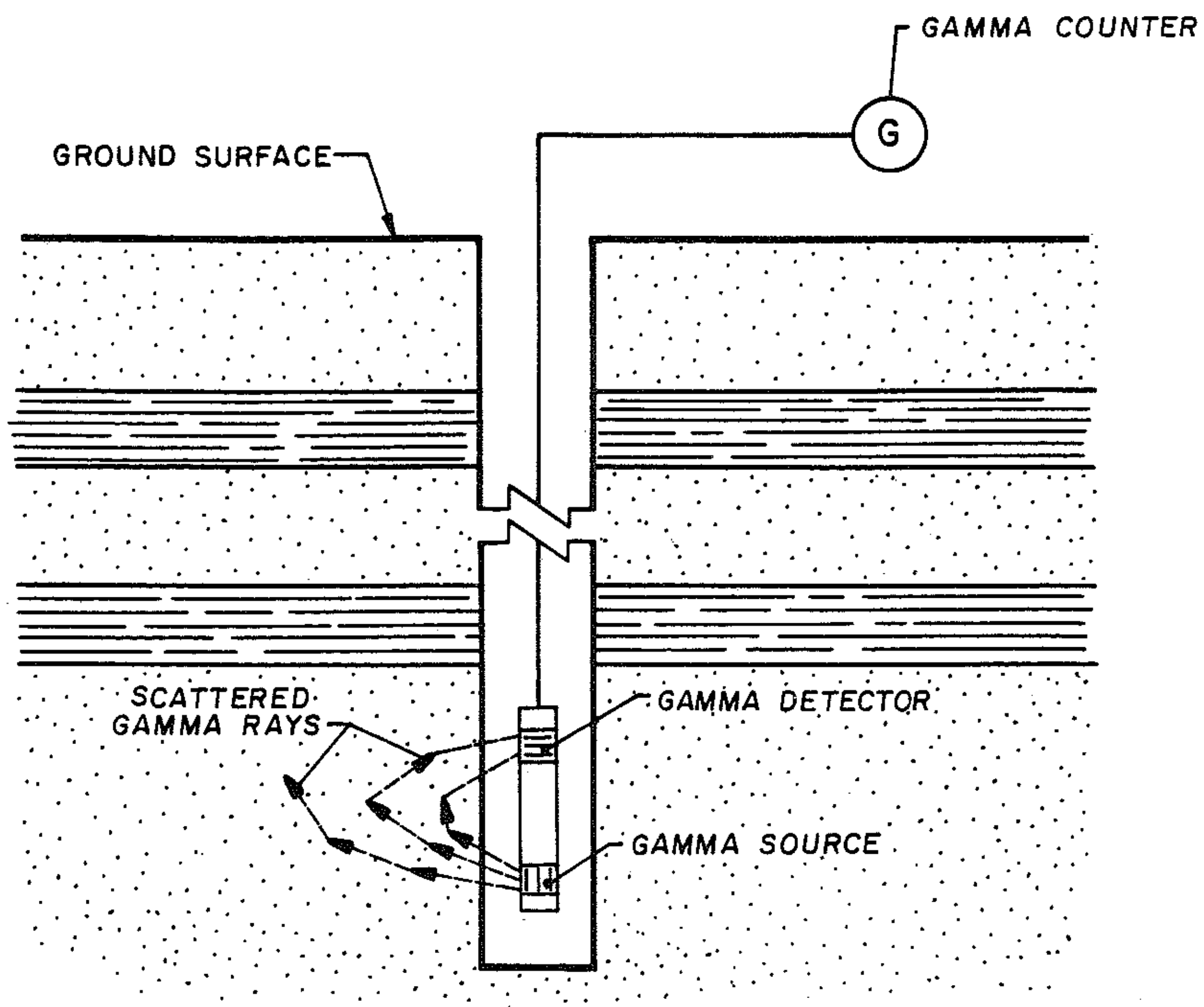


FIGURE H-3

BASIC ELEMENTS OF BOREHOLE GAMMA-GAMMA DENSITY MEASUREMENT SYSTEM

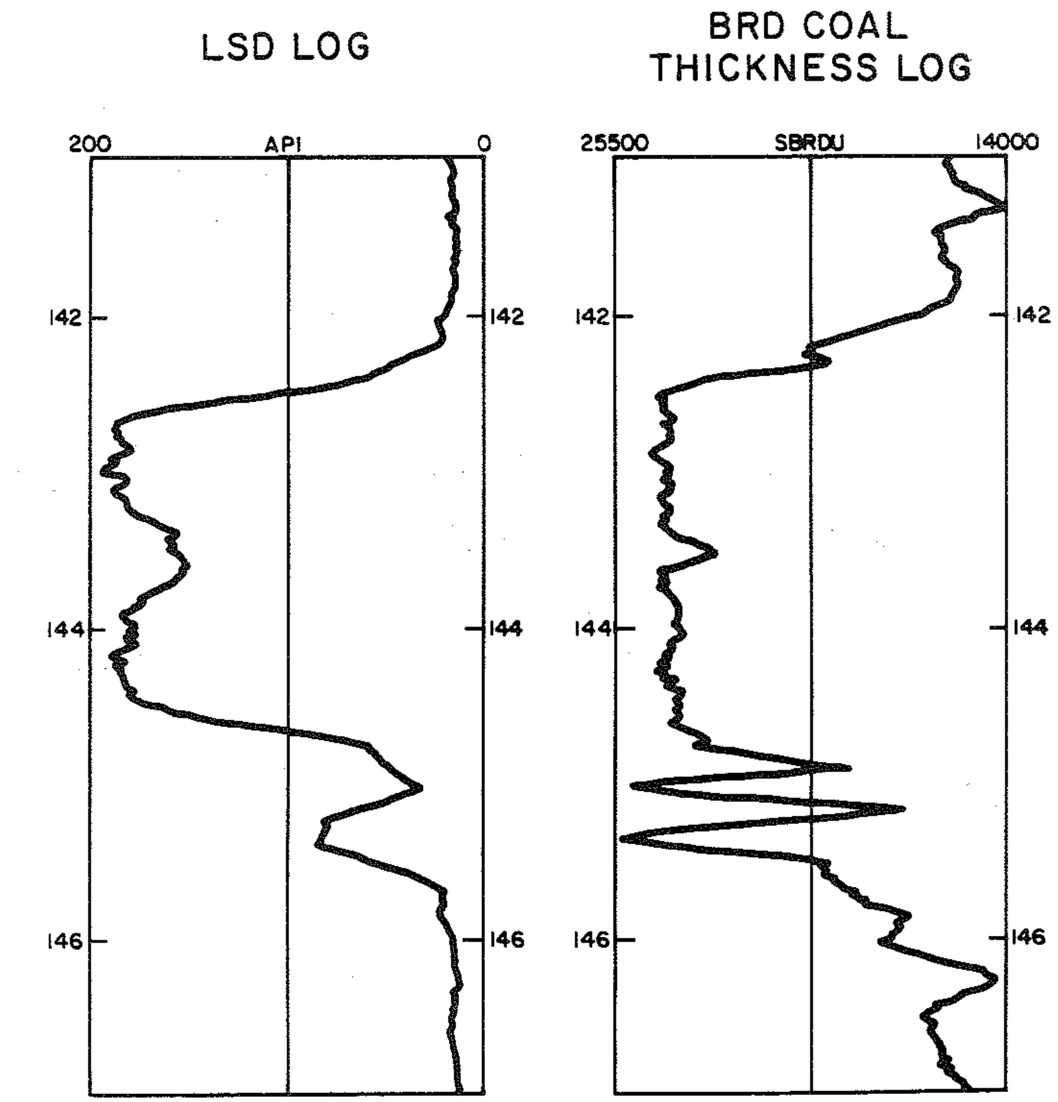


FIGURE H-4

EXAMPLE OF LSD AND BRD LOGS

REFERENCE:

PROPRIETARY INFORMATION PROVIDED COURTESY OF BPB INSTRUMENTS

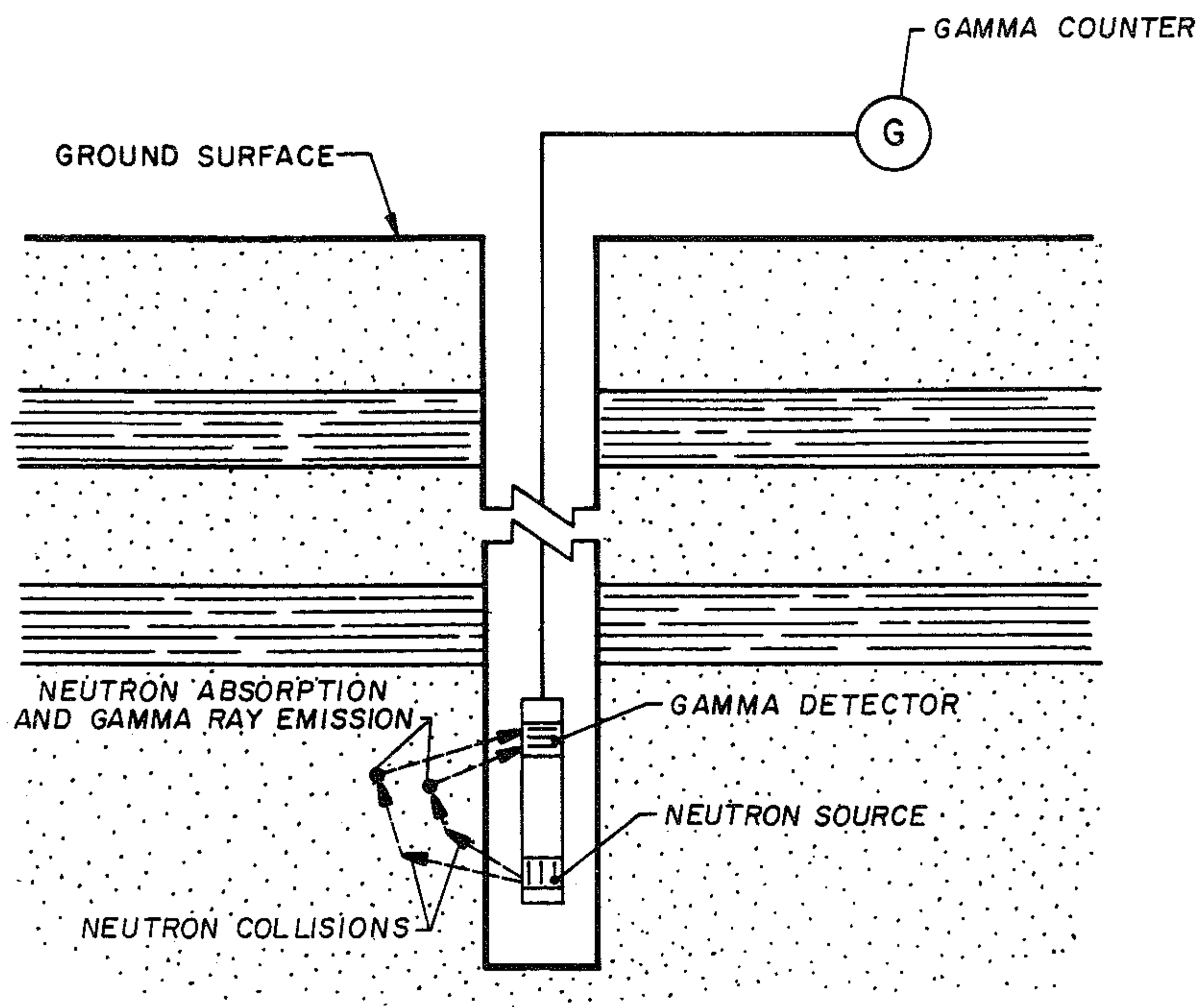


FIGURE H-5

BASIC ELEMENTS OF BOREHOLE NEUTRON (N) MEASUREMENT SYSTEM

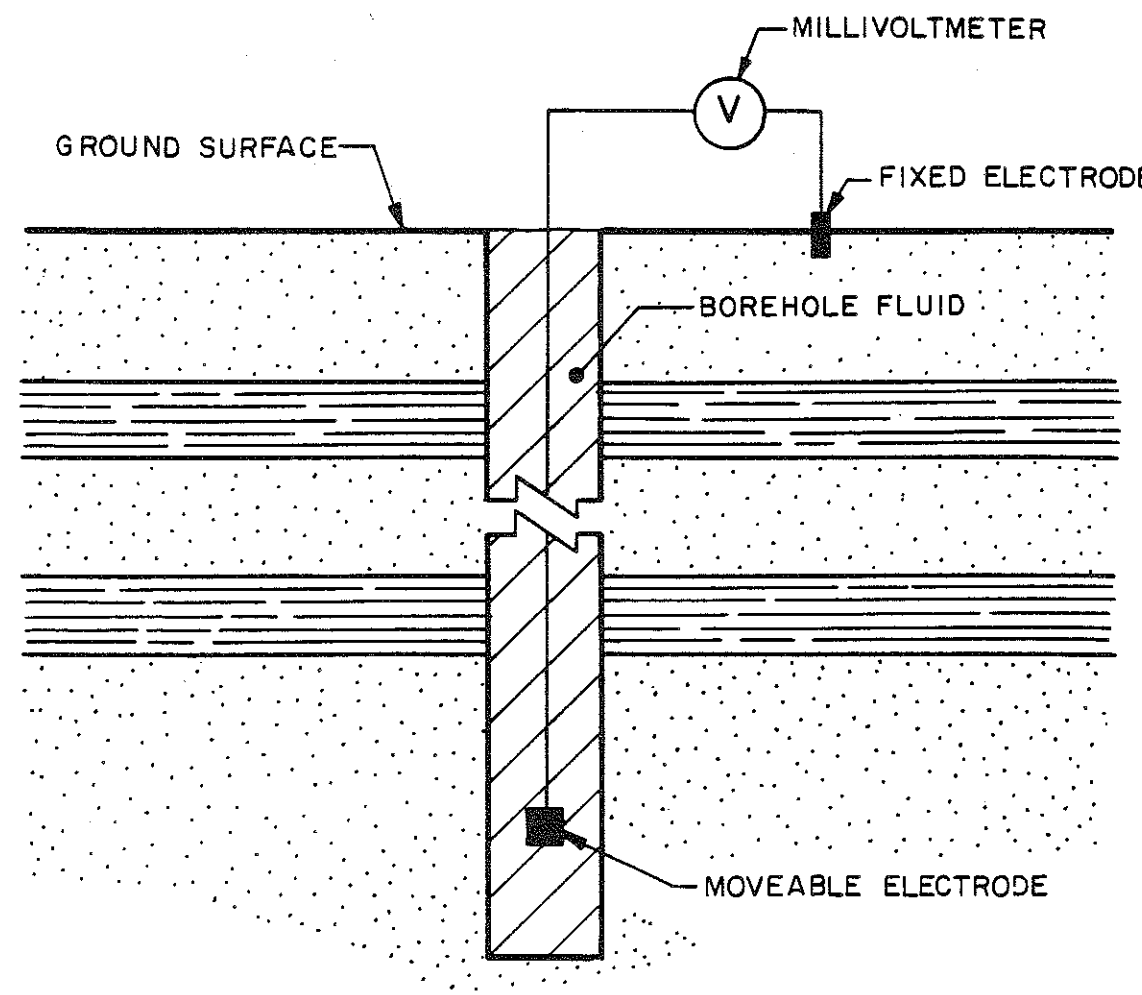


FIGURE H-6

BASIC ELEMENTS OF BOREHOLE SPONTANEOUS POTENTIAL (SP) MEASUREMENT SYSTEM

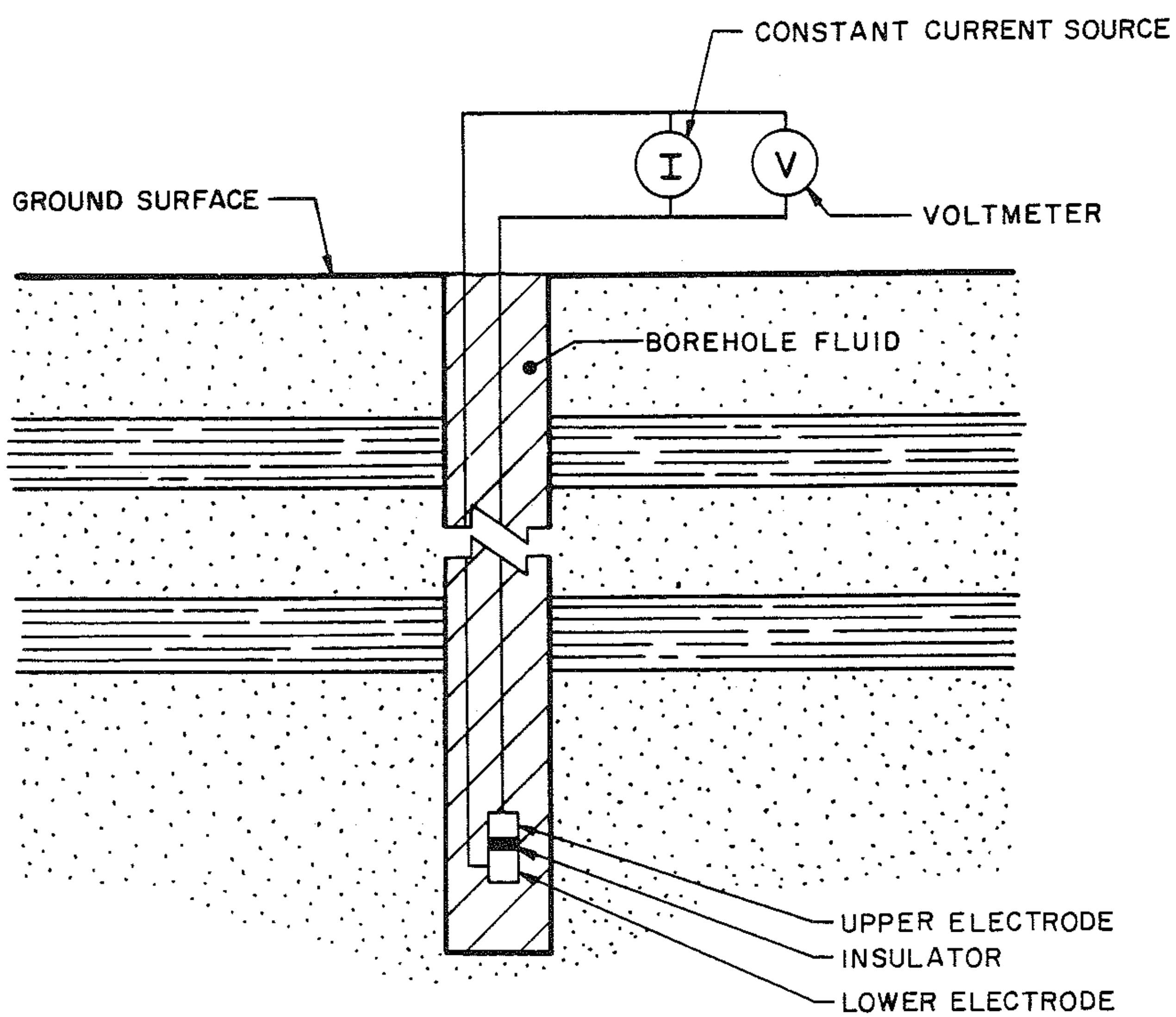


FIGURE H-7

BASIC ELEMENTS OF BOREHOLE
RESISTANCE (R) MEASUREMENT SYSTEM

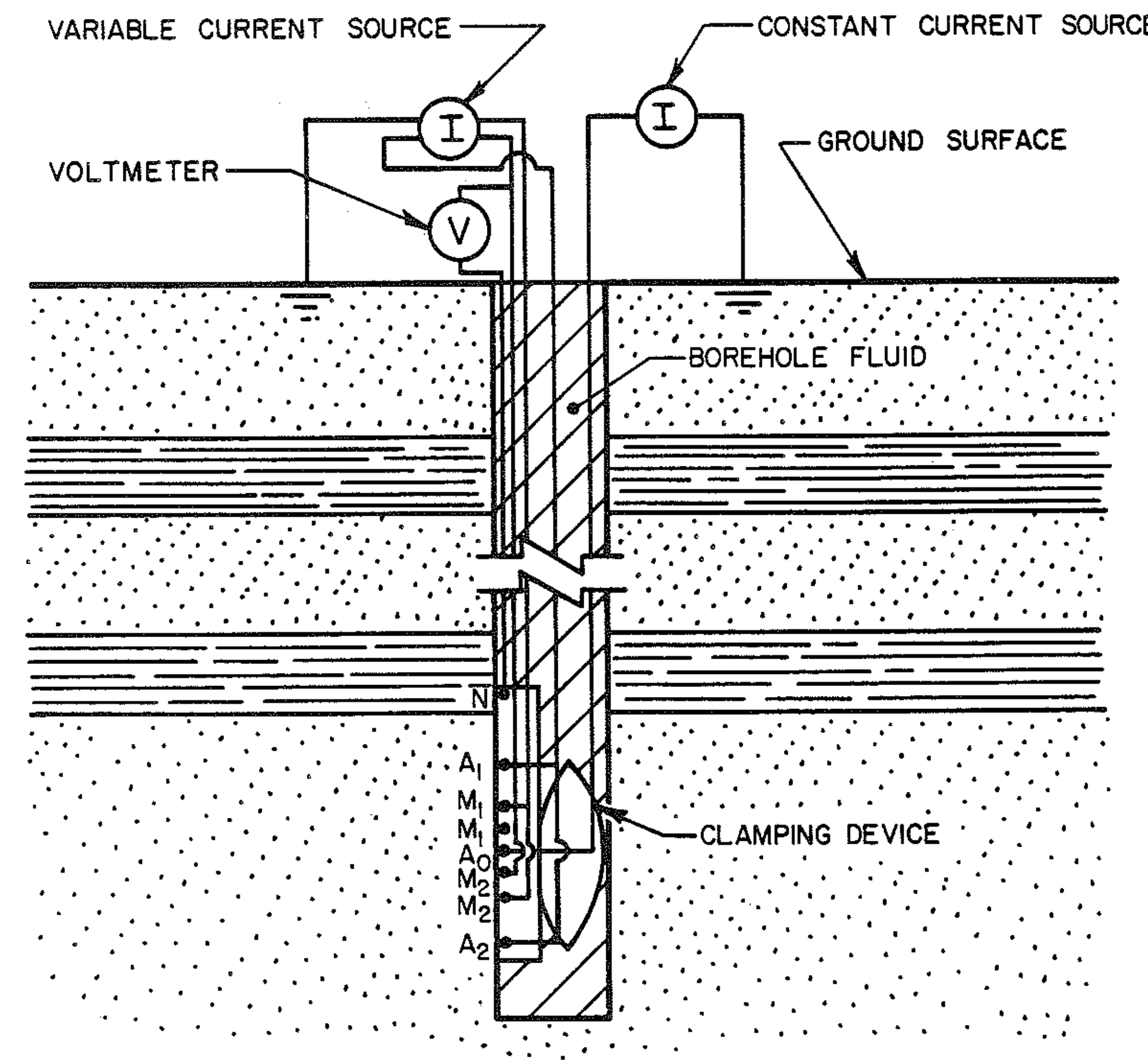


FIGURE H-8

BASIC ELEMENTS OF BOREHOLE
FOCUSED—BEAM MICRO-
RESISTIVITY (ρ) SYSTEM

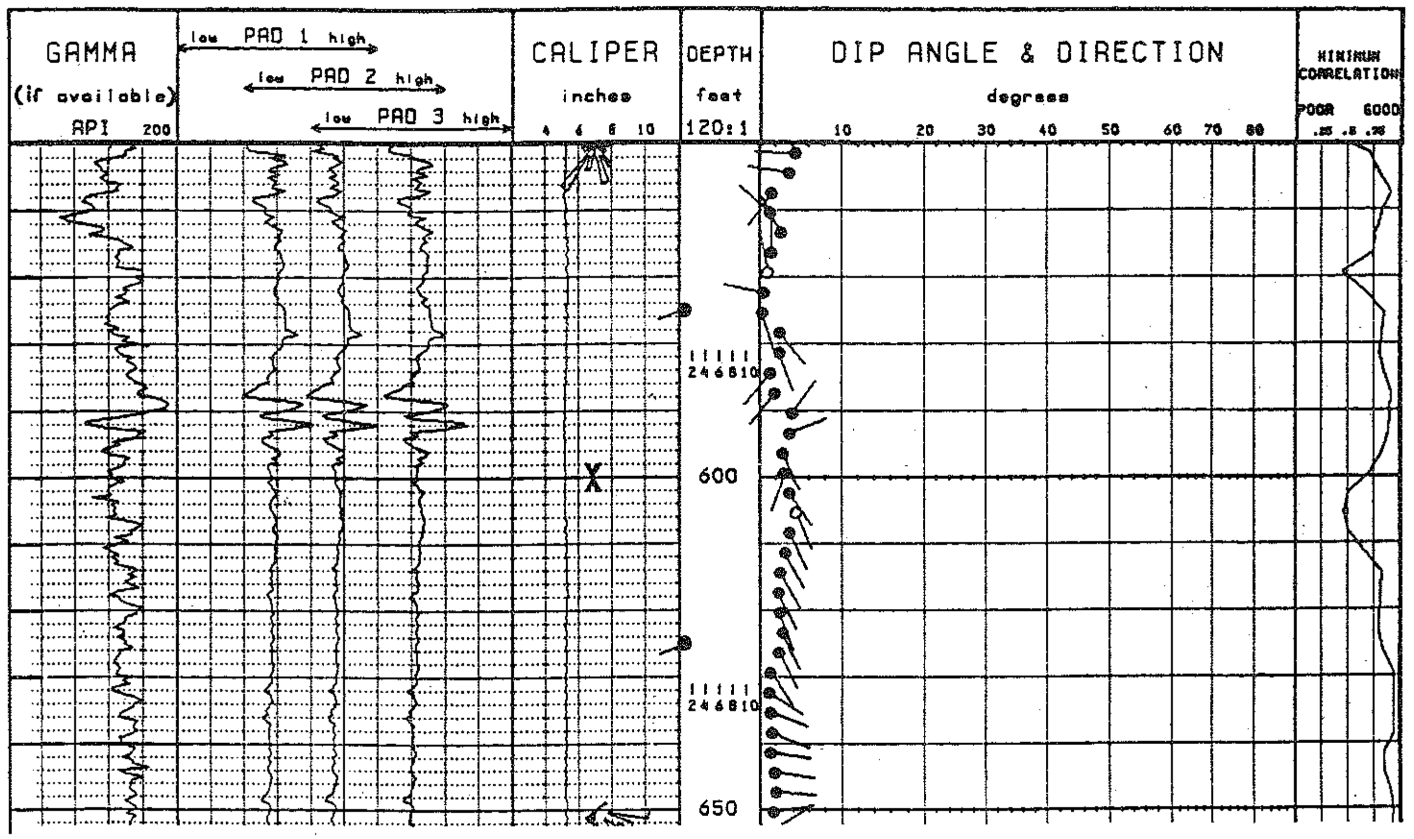


FIGURE H-9

EXAMPLE OF DIPMETER LOG

REFERENCE:

PROPRIETARY INFORMATION PROVIDED COURTESY OF BPB INSTRUMENTS

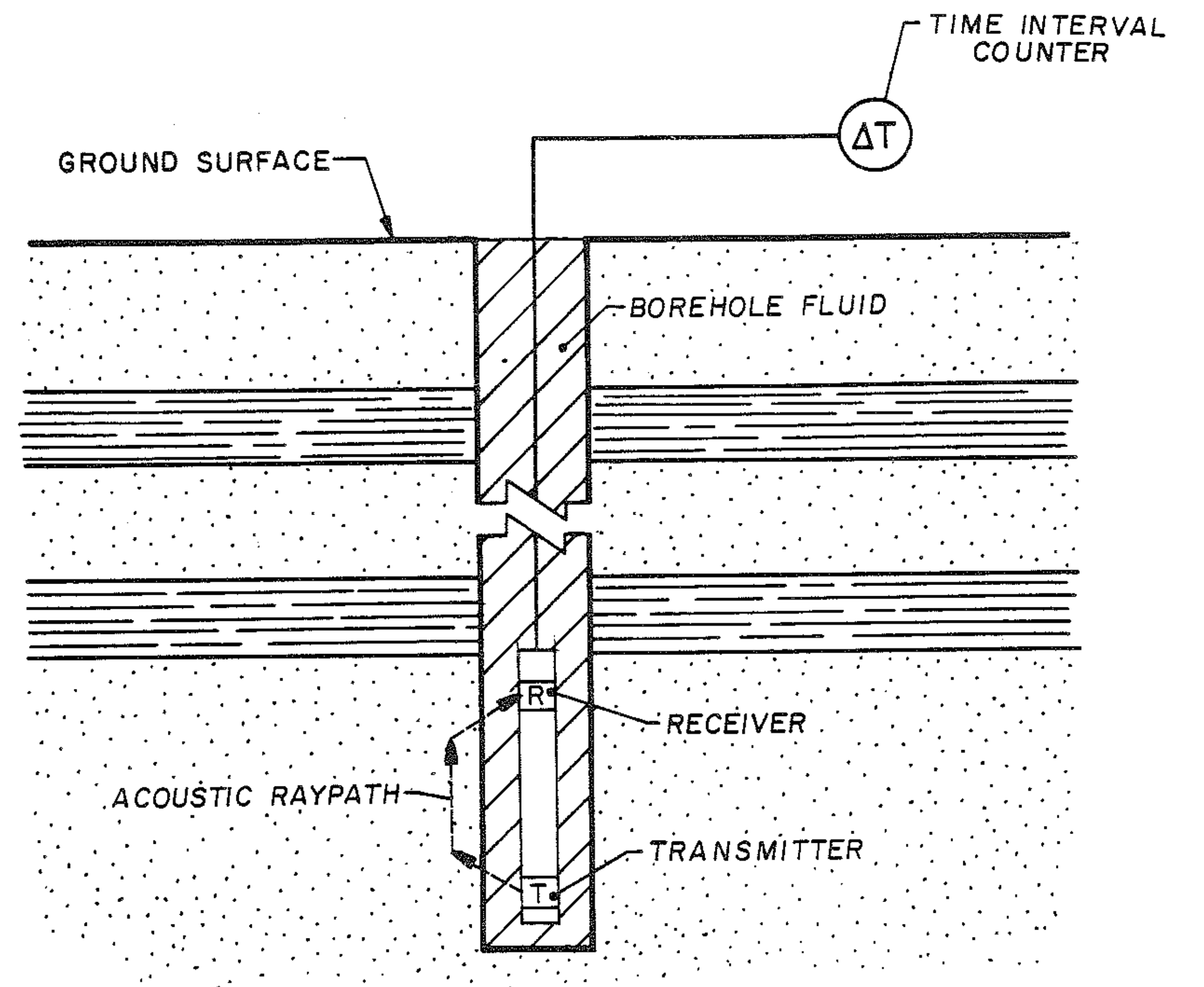


FIGURE H-10

BASIC ELEMENTS OF BOREHOLE ACOUSTIC (SONIC) VELOCITY (ΔT) MEASUREMENT SYSTEM

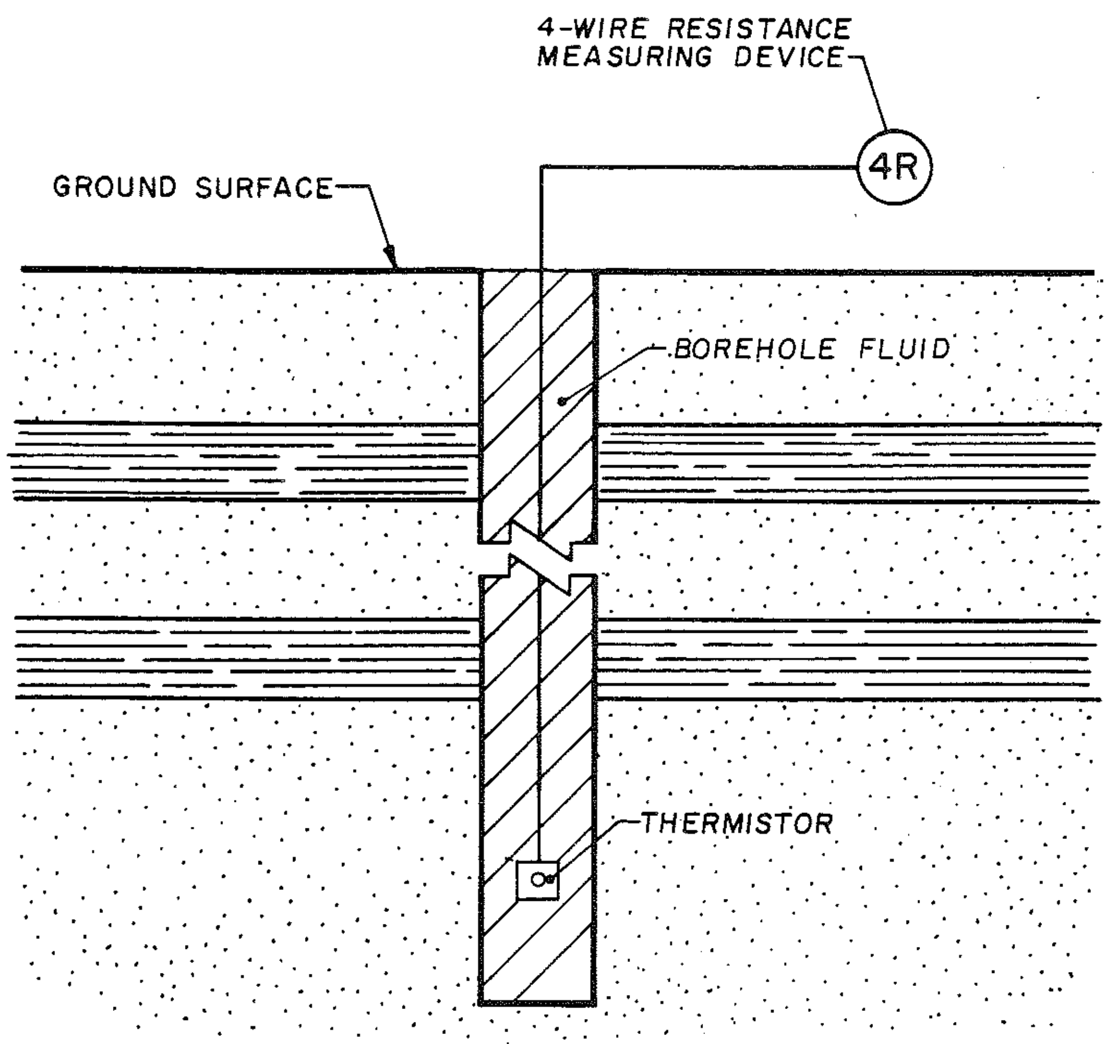


FIGURE H-11

BASIC ELEMENTS OF BOREHOLE
TEMPERATURE MEASUREMENT SYSTEM

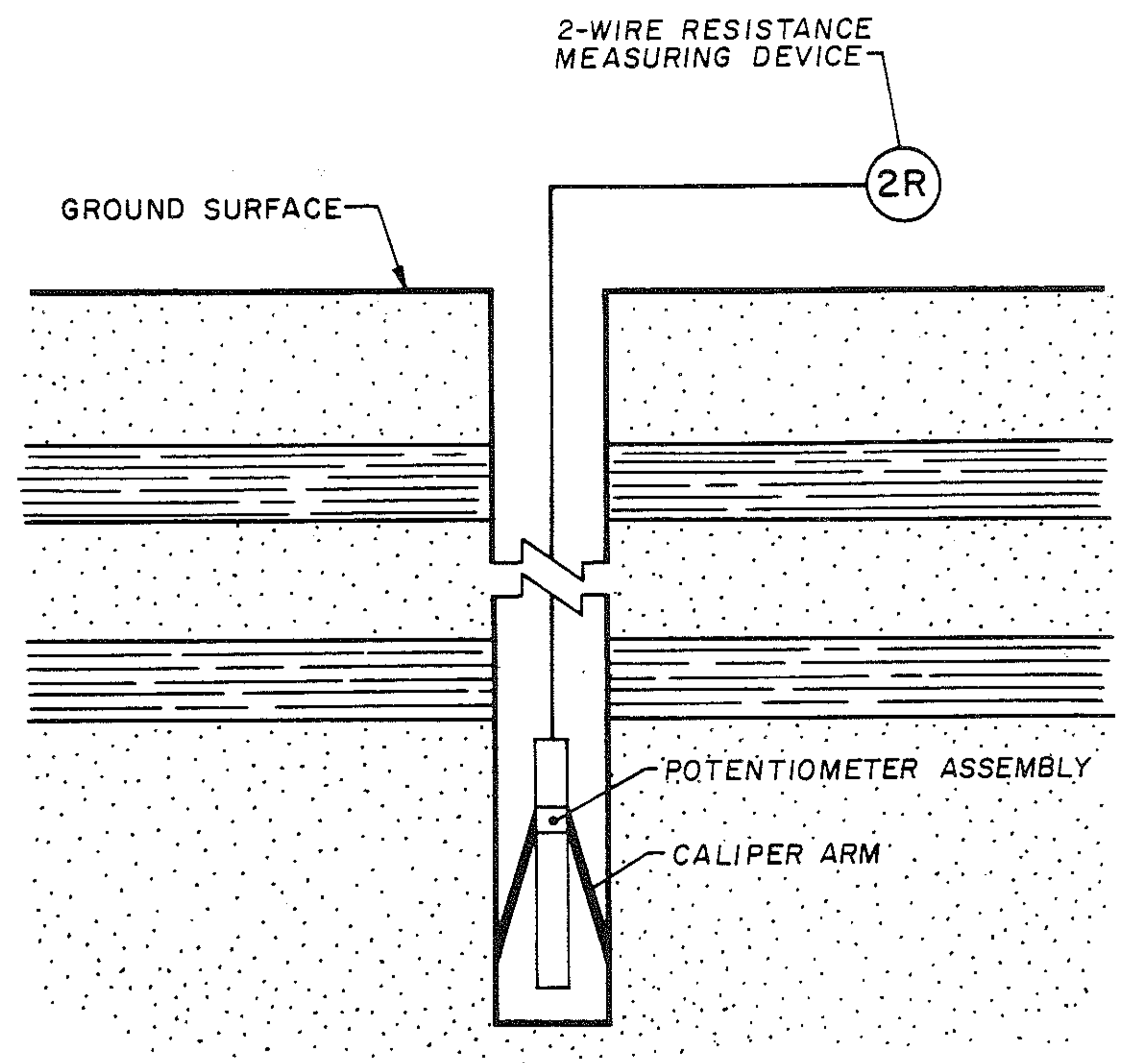


FIGURE H-12

BASIC ELEMENTS OF BOREHOLE
CALIPER MEASUREMENT SYSTEM

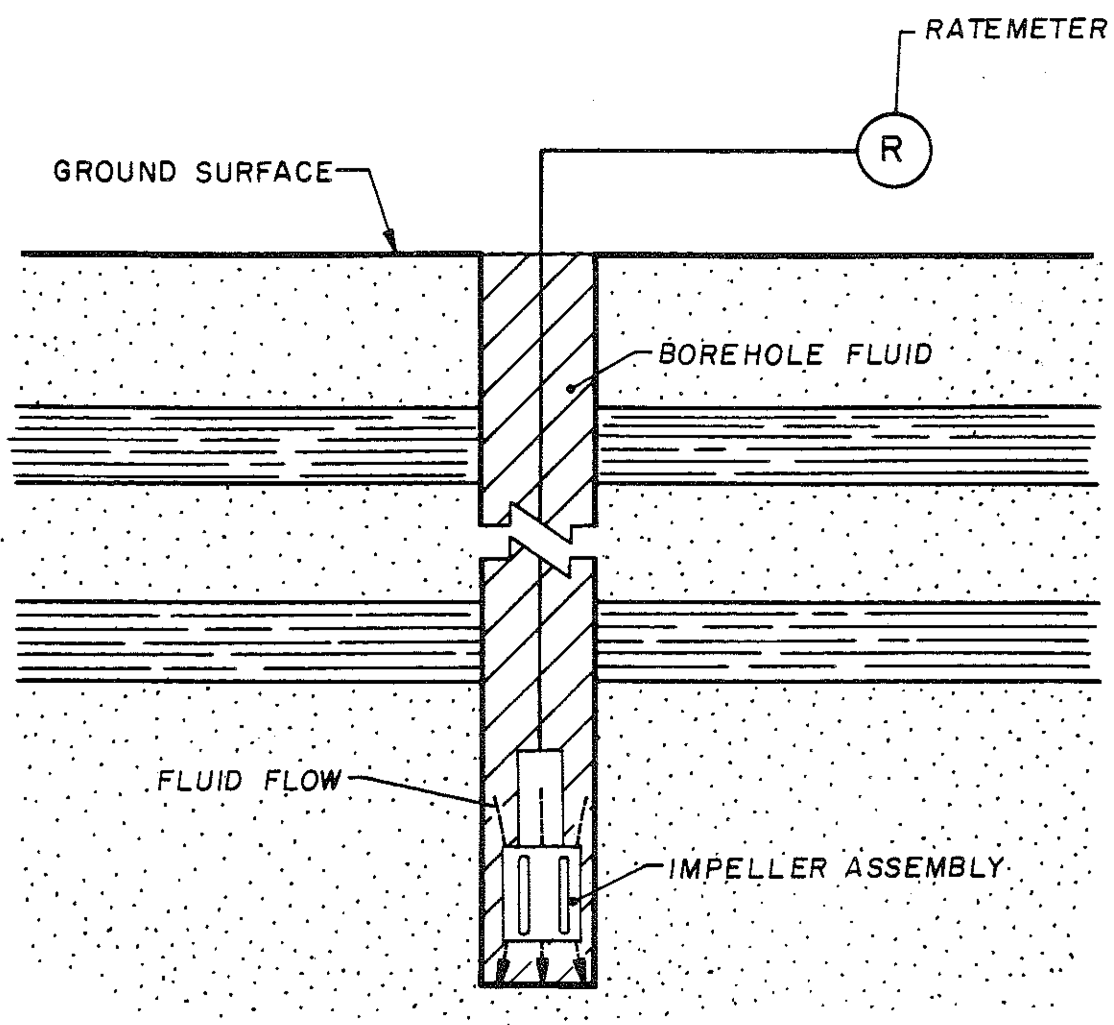


FIGURE H-13

BASIC ELEMENTS OF BOREHOLE
FLUID MOVEMENT
MEASUREMENT SYSTEM

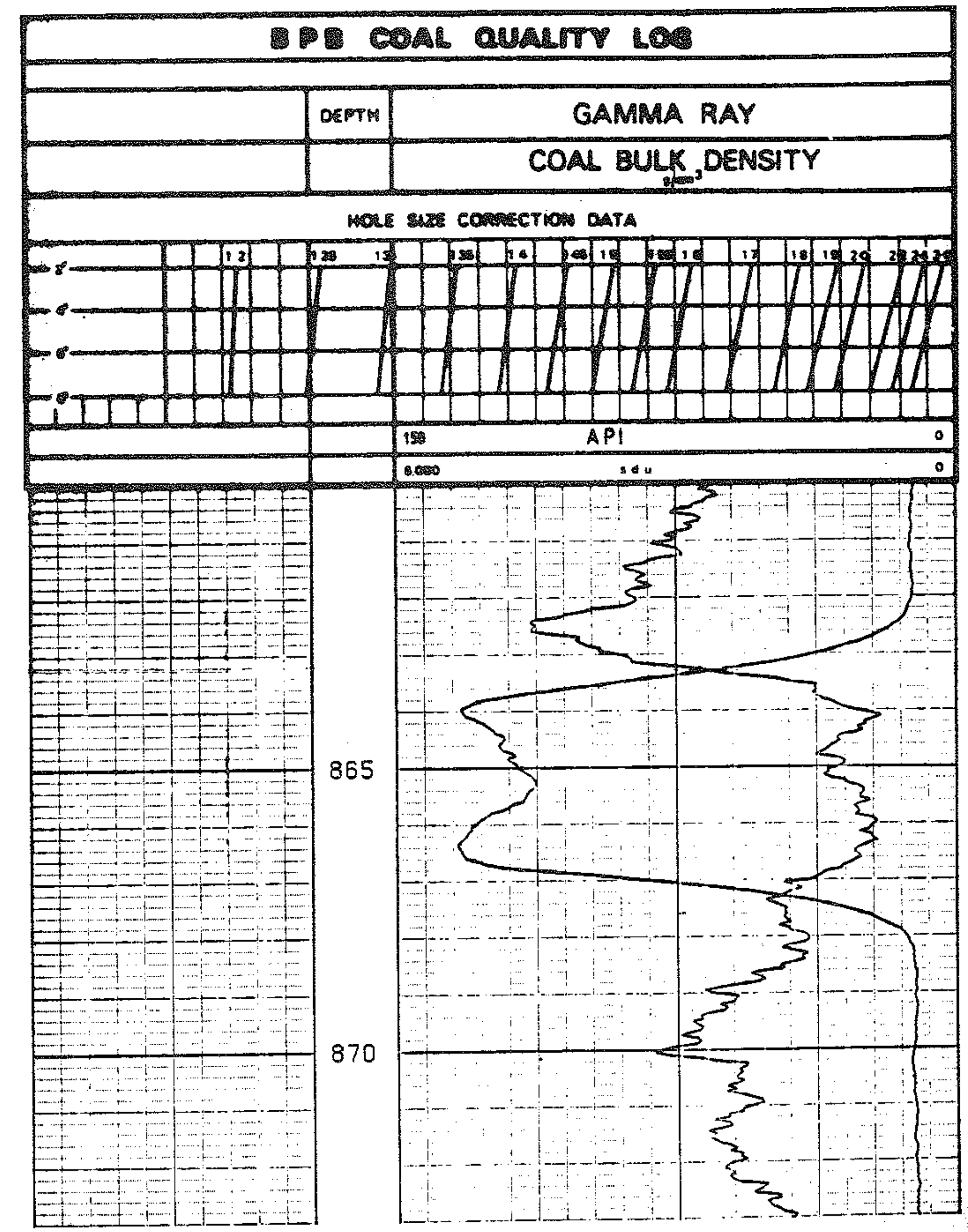


FIGURE H-14

EXAMPLE OF BPB COAL QUALITY LOG

REFERENCE:
PROPRIETARY INFORMATION PROVIDED
COURTESY OF BPB INSTRUMENTS

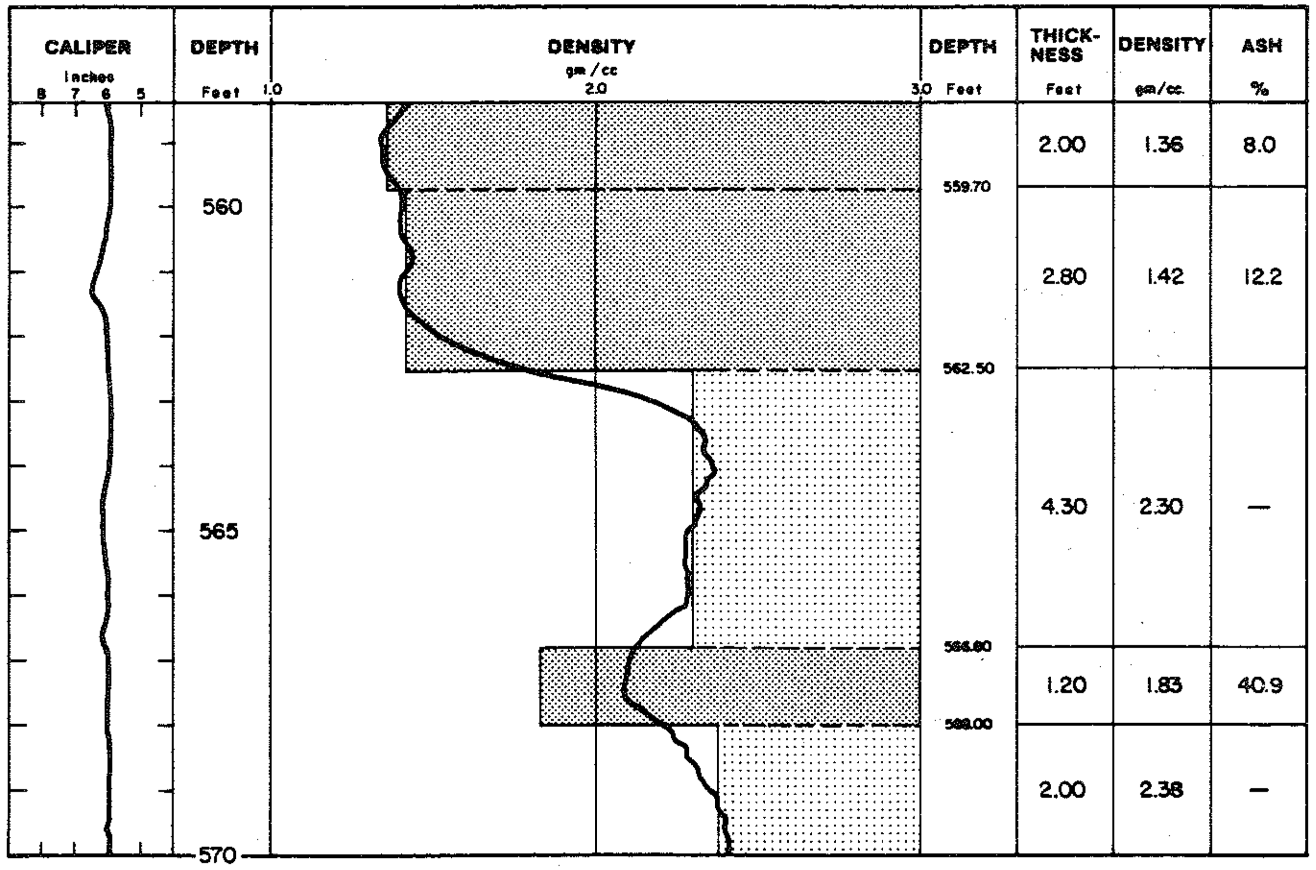


FIGURE H-15

COMPUTER ASSISTED ASH ANALYSIS

REFERENCE:
PROPRIETARY INFORMATION PROVIDED
COURTESY OF BPB INSTRUMENTS

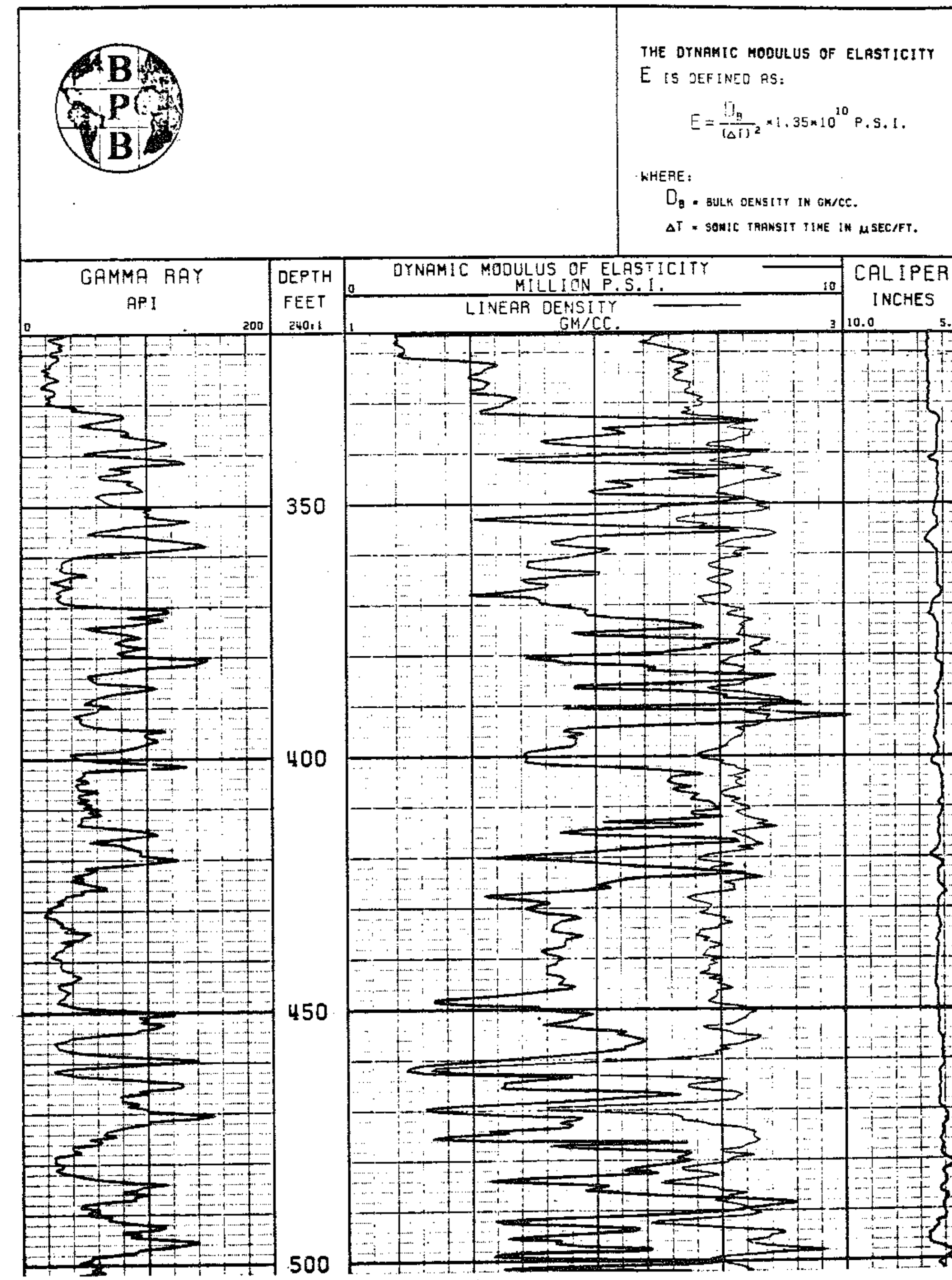
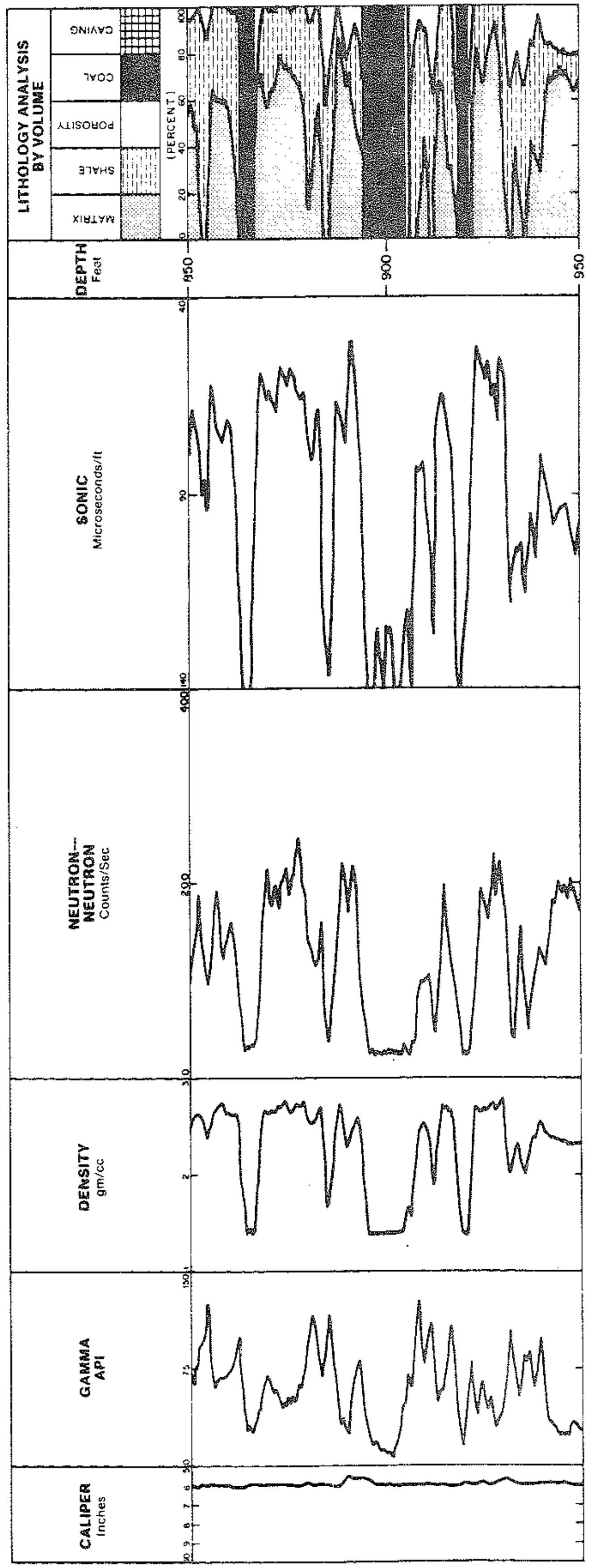


FIGURE H-16

EXAMPLE OF STRENGTH INDEX LOG

REFERENCE:
PROPRIETARY INFORMATION PROVIDED
COURTESY OF BPB INSTRUMENTS



Reference: Proprietary information provided courtesy of BPB instruments.

RESPONSES OF CALIPER GAMMA DENSITY NEUTRON AND SONIC LOGS OVER COAL AND SURROUNDING STRATA AND COMPUTER GENERATED LITHOLOGY LOG

FIGURE H-17

RESPONSES OF CALIPER, GAMMA, DENSITY, NEUTRON AND SONIC LOGS OVER COAL AND SURROUNDING STRATA AND COMPUTER GENERATED LITHOLOGY LOG

REFERENCE:
PROPRIETARY INFORMATION PROVIDED COURTESY OF BPB INSTRUMENTS.

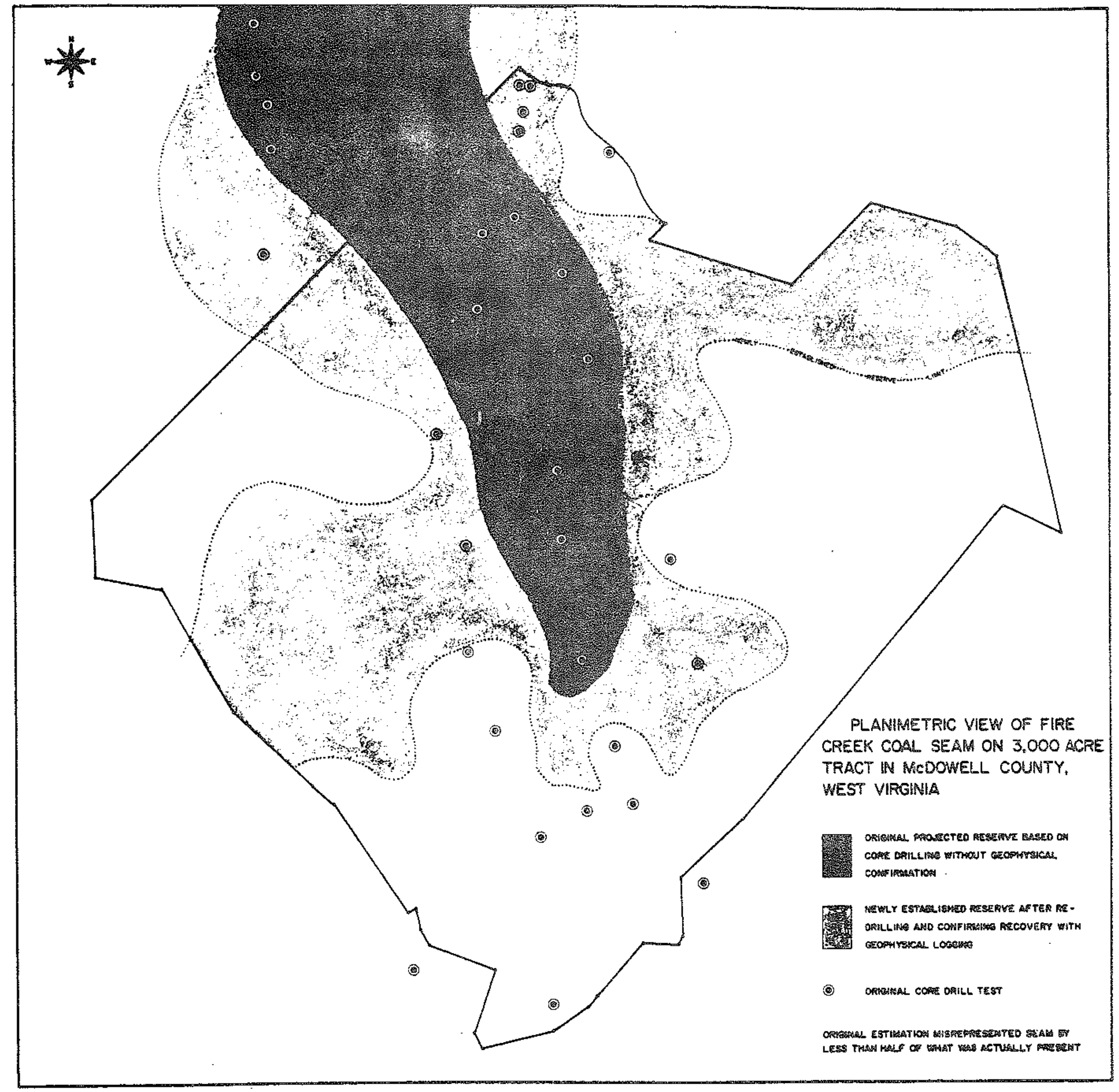


FIGURE H-18

EXAMPLE OF REVISION OF COAL RESERVE BOUNDARIES BASED ON GEOPHYSICAL LOGGING

REFERENCE:

COPYRIGHT 1980 "SPE-AIME" SEPT. 1980
SPEJ SPE 9466 55TH ANNUAL TECHNICAL CONFERENCE AND EXHIBITION OF THE SPE-AIME, DALLAS, TEXAS SEPT. 21-24, 1980
AFTER MILLER, M.S. AND MOORE, M., 1980

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