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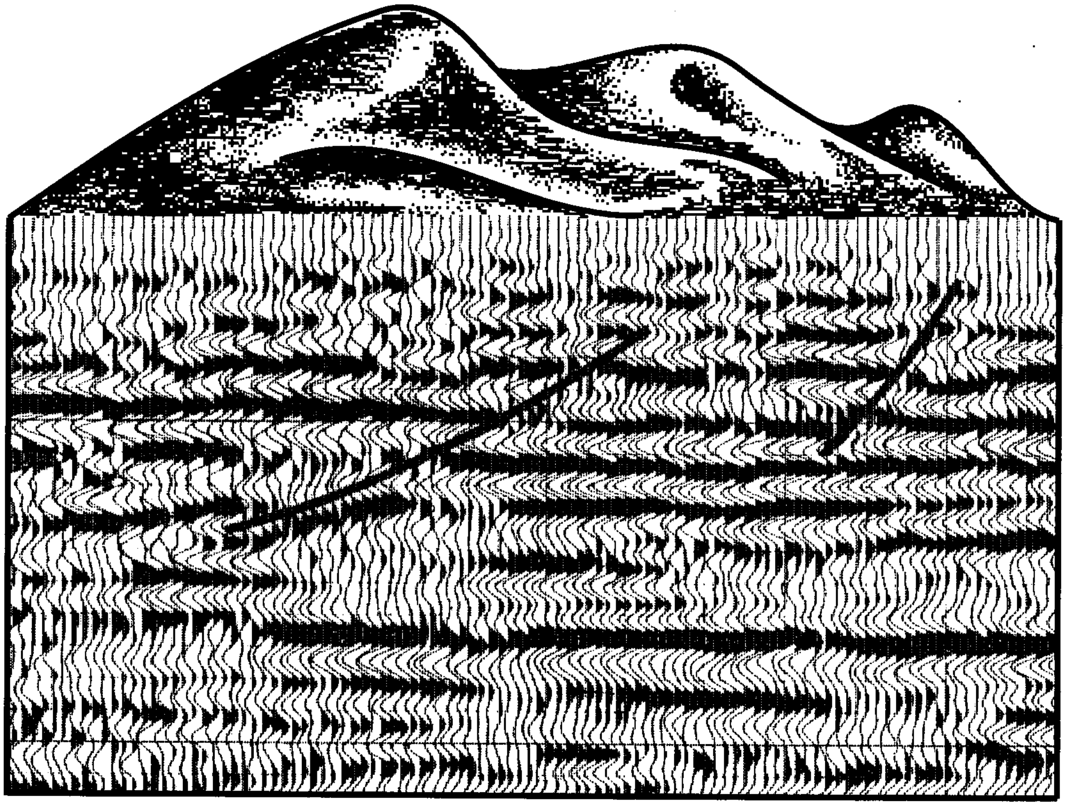
Foothills/Mountain Surface Geophysics Project
Final Report

Edited by: G.L. Hoffman and C.W. Langenberg



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SUMMARY

The Foothills/Mountain Surface Geophysics Project has been a joint-venture that was formed in 1988 by six coal-producing companies, together with government agencies, consultants and a geophysical company. For three years project participants studied the practical application of surface geophysical techniques at depths of 0 to 500 metres in geologically deformed coal-bearing strata in the Foothills and Mountain regions of Alberta, British Columbia and Nova Scotia. Geological objectives included mapping coal seam continuity and geometry; locating discontinuities; locating the subcrops of coal seams, faults and other marker beds; and detecting pods of tectonically thickened coal. The ultimate objective was to evaluate the cost-effectiveness of surface geophysical techniques as an exploration and resource delineation tool for coal deposits in geologically complex settings.

Much of the work involved reflection seismic techniques and focused on optimizing data acquisition and processing parameters. Data from six geologically different sites were used. Interpretations were tested by follow-up drilling or mining.

Electrical and electromagnetic techniques were used to fill in information from depths that are too shallow to be resolved by reflection seismic. The instruments are man-portable and could be used to obtain data in terrain that was too rugged to be accessed by truck-mounted seismic equipment. Direct-current profiling, various electromagnetic techniques, ground-penetrating radar and gravity surveys were evaluated. Nonseismic exploration can generally be conducted for a fraction of the cost of reflection seismic exploration.

The geophysical information significantly improved the level of confidence in the geological interpretation at most of the test sites, and it was concluded that surface geophysical techniques can make a practical and cost-effective contribution to solving geological problems at coal mines in the Foothills and Mountains. To maximize the benefit, they must be used in an integrated approach with conventional drilling. The recommended strategy is to use the first drillholes to make an initial geological interpretation, and to obtain calibrated sonic, density and resistivity logs that are needed for the interpretation of surface geophysical data. Subsequent surface geophysical surveys provide profiles that are compared with the existing interpretation, to pin-point problems and ambiguous areas for testing by follow-up drilling. This procedure is repeated in an iterative fashion as needed.

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1. INTRODUCTION

Allister R. Peach and Georgia L. Hoffman

Recognizing the potential for the application of surface geophysical techniques to geologically complex coal deposits in the Canadian Cordillera, a group of coal mining companies, contractors and government agencies formed a joint-venture in 1988 to test and assess the current state of the art. The project, called the Foothills/Mountain Surface Geophysics Project, was designed to be conducted over a three-year period, answering technical questions as they arose, and progressing into technically more difficult geological and topographical situations. A detailed report was submitted at the end of each year (Hoffman et al., 1989; Hoffman and Sartorelli, 1990; Hoffman et al., 1991). The present report summarizes the work.

1.1 Technical Objectives

The technical objectives were:

- to determine the applicability and limitations of surface geophysical methods in increasingly more complex geological settings;
- to demonstrate the cost-effectiveness of surface geophysics as an exploration and resource delineation tool; and
- to solve technical problems, and refine and enhance the techniques for future applications.

Techniques tested included reflection seismic, direct-current profiling, several types of electromagnetic induction profiling, gravity, and ground-penetrating radar.

1.2 Background

In the coal industry, large quantities of data are required in support of reserve evaluation and detailed mine design. Core drilling, open-hole drilling and downhole geophysics have traditionally provided most of this information, but there has been a growing interest in developing surface geophysical techniques to provide reliable supplementary data as a cost-effective way to maintain high levels of confidence.

During the 1980s, technological advances in data collection and processing improved the effectiveness of surface geophysical techniques in the depth ranges that characterize mineable coal deposits. A joint-venture that tested a variety of techniques in Alberta Plains coalfields obtained encouraging results (Green et al., 1988), and the use of surface geophysics at Plains coal mines has been increasing.

There is a clear need to extend the use of surface geophysics into the more complex coalfields of the Canadian Cordillera. As geologic complexity increases, the amount of data needed for reserve evaluation and mine planning also increases. As a result, large numbers of closely spaced holes are drilled annually at Foothills and Mountain coal mines. However, even at spacings of 200 m or less, geologic changes can be difficult to interpret between holes. Information from surface geophysics can provide a look between the drillholes, so that future holes can be targeted more effectively to intersect critical geologic features (Peach and Cochrane, 1991).

1.3 Scope of Work

The research has been done at a number of different sites (Figure 1-1) because geophysical response characteristics are to some extent site-specific, and comparison of results from different localities can yield new insights.

During the first year of the project (Phase 1, 1988-89), reflection seismic programs were conducted at the Coal Valley mine and the Smoky River mine in the Foothills of west-central Alberta, to document coal seam continuity and detect faults. Interpretation of the data and testing of the interpretations by subsequent drilling and mining activities continued into the later phases of the project.

The second year (Phase 2, 1989-90) focused on optimizing seismic data acquisition and processing parameters. Modifications to data acquisition parameters were added to a seismic program near Springhill, Nova Scotia; and reprocessing techniques were tested on an existing data set from the Tower property in west-central Alberta. The experience gained was then tested in a new seismic program conducted at the Telkwa property in northwestern British Columbia.

The final year (Phase 3, 1990-91) included three new field programs, as well as follow-up work on the data from Phases 1 and 2. A final reflection seismic program was conducted at the Mt. Leyland property in west-central Alberta; and combinations of electromagnetic techniques, direct-current profiling, ground-penetrating radar, and gravity were applied at the Chinook south property in southwestern Alberta, and at the Quintette mine in northeastern British Columbia.

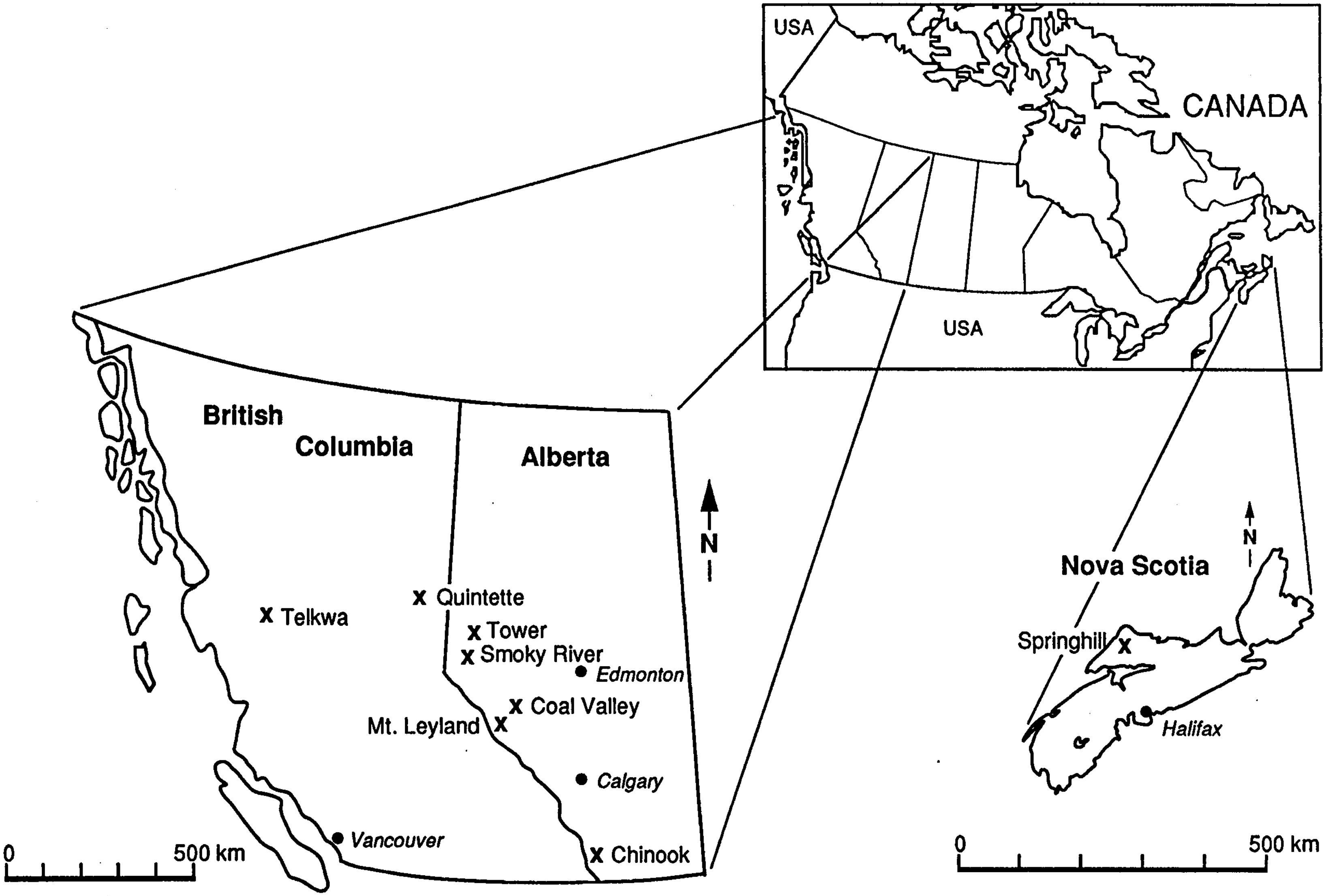


Figure 1-1. Location of study sites.

2. GEOLOGICAL AND TOPOGRAPHIC SETTING

Georgia L. Hoffman and C.W. Langenberg

The complexity of the geology dictates the density of exploration data points that is required to produce a given level of confidence about the geometry and reserves of a deposit, while the ruggedness of the topography dictates the degree of difficulty and thus the cost of obtaining the data. These two factors are usually related, with increasingly complex geology producing increasingly rugged topography, so that in the areas where the highest data densities are required, the data are also the most difficult and expensive to obtain because of access problems.

Hughes et al. (1989) proposed four categories of geologic type (low, moderate, complex and severe), which are used in the discussions below. They also discussed the data densities that are needed to achieve given levels of confidence about coal reserve tonnages, and noted that " ... indirect observation methods such as seismic profiling, or other geophysical techniques for determination of subcrop edges, may also be utilized for the determination of areal extent, provided that seam identification and the resolution of the technique can be adequately demonstrated" (Hughes et al., 1989, p.6).

The sites that were made available by the participating companies offered a wide variety of geological and topographic situations (Table 2-1). The general geological objectives were to determine the geometry of the coal seams; to define areas of seam continuity; to locate discontinuites (whether due to faulting or stratigraphic changes); and to locate the subcrops of coal seams, marker beds and faults. Pods of tectonically thickened coal were investigated at one site.

2.1 Description of Test Sites

Of the sites studied, the Tower property exhibits the lowest level of geologic complexity (Table 2-1). Lying near the outermost limits of the outer Foothills, the landscape is broadly rolling with gentle slopes and some swampy areas. The strata are very broadly folded and broken only occasionally by small-displacement faults. Within the test area, the strata dip at less than 5 degrees and the coal seams lie within the upper 70 m of the subsurface. The variety of surficial sediments at Tower (glacial till, sand, gravel and muskeg) allowed the effects of shot-coupling (efficiency of transmission of shot-generated energy into the subsurface) and data processing for noise attenuation to be examined.

Within the portion of the Coal Valley mine where the seismic survey was conducted, the coal seams lie within the upper 300 m of the subsurface and dip gently to the north. Fault frequency is generally low at the test site, but one of the objectives was to locate and define a major fault that was believed to be present (Sec. 3.4.1). The landscape at the Coal Valley site is rolling, with some swampy areas and reclaimed spoil piles. The slopes are gentle and were easily traversed by the geophysical trucks.

The Carboniferous strata at the Springhill site are the oldest studied, and are characterized by a moderate level of complexity. The coal seams are broadly folded with low to moderate dips and occasional faults. They lie at depths ranging from surface to as much as 1200 m. Unlike the Cretaceous and Paleocene coals of the western sites, the coal seams at Springhill contrasted with the surrounding strata in their sonic velocities as well as in their densities, which further strengthened their seismic reflectivity (Sec. 3.4).

Telkwa site is also characterized by moderate complexity. The landscape consists of broad hills, with moderate slopes along the survey lines. The strata are broadly folded with moderate dips ranging up to about 35 degrees, broken by occasional high-angle faults. The coal seams of interest lie at depths of up to 350 m in the test area.

The Smoky River mine, the Quintette mine and the Mt. Leyland property all cover Lower Cretaceous strata in an inner Foothills setting with complex geology and steep to very steep slopes. Tight folds are present with steep to overturned limbs, and offsets by thrust faults are common. Much of the topography at these sites is rugged. Steep slopes at Smoky River were negotiated carefully by the seismic trucks. Nonseismic techniques were applied in the Transfer area of Quintette, along steep cut-lines that were passable only by foot.

The site at the Chinook property was chosen to cover an area of severe geologic complexity where thrust faulting and folding have produced a series of irregular pods of tectonically thickened coal. The topography ranges from moderate slopes to the very steep walls of abandoned open pits. Nonseismic techniques were used, and the surveys were conducted along cut-lines that were passable by foot.

2.2 Geologic Data

Each geophysical survey was planned using the operating company's geological maps, structure contour maps and cross-sections, which were derived from their current interpretation of outcrops, drillholes, downhole geophysical logs, and for the Smoky River site, underground mine data. Geological targets were chosen for investigation, and appropriate geophysical techniques were then selected according to the strata and targets in question.

For the Smoky River and Mt. Leyland sites, the data were entered into a computer-based model by the Geological Survey Department of the Alberta Research Council. This model, using the TRIPOD software (Charlesworth et al., 1989), analyzed and displayed the data from drillholes, mining and outcrops and compared them with those from the seismic profiles.

2.3 Interpretation Strategy

During the three years of the project, it was noted that seismic data are different from drilling data in that they are subject to different types of inherent limitations, and they influence the thoughts of the geologist, and thus the resulting interpretation, in a somewhat different manner. As a result, when used together in an iterative fashion, the two types of data tend to reinforce each other and compensate for each other's deficiencies. The result is a stronger overall interpretation with a higher degree of confidence.

Drilling data (core samples and downhole geophysical logs) present an essentially one-dimensional view at a single point in the area of interest. In most cases the depths, lithologies, thicknesses and attitudes of the beds can be determined at that point with a high degree of confidence. However, the geometry and continuity between holes must be inferred. Information from surface outcrops, if available, can be used to aid this process, but most sites include areas where the bedrock geology is obscured by surficial sediments.

Reflection seismic data present a two-dimensional image of the reflectors in the subsurface beneath each survey line. Data from a tie-line perpendicular to the others can facilitate the correlation of the reflectors from line to line, giving a more three-dimensional view, like that provided by fence diagrams. However, there can be significant uncertainties about the identity and depth of the reflectors, and about the resolution of faults and thin beds (vertical resolution can be expected to range between 1/4 and 1/8 of the dominant wavelength achieved). These problems can usually be overcome using data from the drillholes. Sonic logs can provide good estimates of the seismic velocities, and data from the sonic and density logs, used together in synthetic modeling, can predict the response signatures of the seismic reflectors. Therefore whenever possible, calibrated sonic and density logs should be obtained from some or all of the drillholes.

Discontinuities in the reflectors on a seismic profile can be used to locate areas where geologic problems exist, but the meaning of discontinuities can be difficult to assess. They may represent areas of faulting, very steep dips, overturned folds, or stratigraphic changes; or they may simply be the result of noise-related problems in the data, as occurred at the Smoky River site (Sec. 3.4.3). The seismic profiles should thus be used as a guide for subsequent rounds of drilling, with the holes being targeted to investigate such features. This allows for much more efficient use of the drilling budget, compared to trying to intersect critical structural features and problem areas by drilling "blind."

The nonseismic techniques provide information about the near-surface strata that are not resolvable by reflection seismic techniques. The electrical and electromagnetic methods can often be used to locate and map the subcrops of coal seams, faults and marker beds, and to determine the magnitude and direction of dip. The data are usually plotted in a two-dimensional profile form and, depending on the spacing and layout of the survey lines, can provide a somewhat three-dimensional view of the shallow subsurface (e.g., the York Creek site, Sec. 3.1-3.3). Good site coverage can usually be obtained with these techniques because they are relatively inexpensive to apply, and can be applied in areas that are not accessible by vehicle. Only small crews on foot, narrow cut-lines, and inexpensive data processing are required. These techniques can be used as a complement to a seismic program, or can be used alone.

2.4 Recommendations

The general strategy that has been successful during this project, and is recommended for similar situations, is:

1. Start with geologic mapping and drilling, placing priority on obtaining some high-quality, calibrated downhole geophysical logs (especially sonic, density and focused resistivity). The logs will allow the most effective geophysical techniques to be selected, and will aid in the interpretation of the resulting data.

2. After the drilling information has been interpreted as usual, the geologists and geophysicists together select the geophysical techniques and plan the geophysical program(s). Nonseismic techniques can be used to locate subcrops and investigate the near-surface strata. Reflection seismic surveys can be used to map reflectors and locate discontinuities in deeper strata.

3. The geophysicists interpret the geophysical data together with the geologists, and compare the results with the those of the previous geologic interpretation. Areas where the two interpretations disagree are identified, and the possible causes of the conflicts are considered. This may be an iterative process involving both reprocessing or reinterpretation of the geophysical data, and reinterpretation of the geologic data. A new interpretation is produced.

4. The geologists plan the next series of drillholes, targeting them to intersect and prove critical geologic features that were indicated by the geophysical results, and to resolve any areas that remain ambiguous.

5. This cycle is repeated as required to increase the data density and level of confidence for reserve delineation or mine planning.

To illustrate this strategy, several contrasting examples from the test sites are discussed in Section 3 of this report, and three hypothetical cases that illustrate cost-effectiveness are presented in Section 4.

Table 2-1: Geology and Topography of Test Sites

Property & Province	Region	Age	Geologic Complexity	Topography	Geophysical Techniques
Tower Alberta	Outer Foothills	Paleocene	Low	Broadly Rolling	Reflection Seismic
Coal Valley Alberta	Outer Foothills	Paleocene	Low	Broadly Rolling	Reflection Seismic
Springhill Nova Scotia	Appalachian	Pennsylvanian	Moderate	Moderate Slopes	Reflection Seismic
Telkwa British Columbia	Intermontane	Lower Cretaceous	Moderate	Moderate Slopes	Reflection Seismic
Smoky River Alberta	Inner Foothills	Lower Cretaceous	Complex	Steep Slopes	Reflection Seismic
Mt. Leyland Alberta	Inner Foothills	Lower Cretaceous	Complex	Moderate Slopes	Reflection Seismic
Quintette Shikano Pit British Columbia	Inner Foothills	Lower Cretaceous	Complex	Flat (Pit Floor)	DCP, EM* & GPR
Quintette Transfer Area British Columbia	Inner Foothills	Lower Cretaceous	Complex	Very Steep	DCP, EM*
Chinook South Alberta	Front Ranges	Jurassic-Cretaceous	Complex to Severe	Moderate to Very Steep	DCP, EM* VLF & Gravity

* DCP = direct-current profiling; EM = electromagnetic induction profiling (excluding VLF); VLF = very low-frequency electromagnetic induction; GPR = ground-penetrating radar

3. GEOPHYSICAL TECHNIQUES AND RESULTS

A.N. Santorelli and J.D. Henderson

3.1 The Gravity Method

Gravity surveys are used to determine the location and extent of subsurface features or materials with densities that contrast strongly with those of surrounding materials. In coal industry applications, the method can be useful for the delineation of areas where there is localized thickening of coal seams, and for the location of abandoned underground mine workings. The former application was tested in the York Creek area of the Chinook South property in southwestern Alberta.

Gravity is a potential method. Gravity measurements are affected equally by variations in the densities of all materials that are equidistant from the measurement station. Data are corrected to a datum elevation and datum latitude. The size of data corrections is often many times greater than the differences in corrected data at nearby measurement stations. Lateral resolution of the extent of subsurface target structures is to a large degree dependent upon the spatial density of gravity measurement stations.

The gravity survey at the York Creek site used a relatively coarse grid of measurement stations. Data were reduced using a sequence of corrections to produce the standard Bouguer gravity anomaly at each measurement station. The maximum variation in Bouguer anomaly across the site is about 1 part in 35 (Figure 3-1). A comparison of Bouguer anomaly contours with the location of locally thickened coal seams known from drilling and structural models shows that these zones generally lie within areas of relatively low Bouguer anomaly, as would be expected, demonstrating that gravity measurements can be useful for locating areas with a high potential for structurally thickened coal seams.

3.2 The Direct-Current Profiling Method

Direct-current profiling is used to delineate the lateral extent of subsurface features characterized by an electrical resistivity greater than that of surrounding materials. Applications to coal exploration and development include the delineation of coal seam subcrops and contacts between bedrock units of contrasting resistivity, under conditions of moderate overburden thickness (up to 25 metres). The direct-current profiling method has been used with success in the Alberta Plains, as described by Green et al. (1988). During the present study the method was successfully applied in more mountainous terrain at the Quintette property in northeastern British Columbia, and at the York Creek site described above. Results from York Creek are presented to illustrate the method.

Direct-current profiling was performed at the York Creek site to four different exploration depths at 20-metre station intervals along survey lines. Apparent resistivity data obtained along Line Y13 are shown in Figure 3-2. The data indicate that resistivity increases with depth of exploration. The extent of the York Seam subcrop is clearly indicated by the four-fold increase in apparent resistivity (500 to 2000 ohm-m) observed at largest depth of exploration between stations 130 W and 40 W. The subcrop of the Cadomin Formation (a resistive conglomerate) is similarly apparent between stations 210 W and 190 W.

The lower panel in Figure 3-2 shows the apparent resistivity data from direct-current profiling, contoured as a function of effective depth of exploration. The figure shows the lateral extent of the Cadomin Formation and York Seam subcrop, the relative difference in cover, and the general increase in resistivity of underlying bedrock to the east of the York Seam.

3.3 Electromagnetic Induction Profiling Methods

Electromagnetic induction profiling methods differ from electrical resistivity methods such as direct-current profiling in that the former are more sensitive to subsurface features of contrasting low resistivity (high conductivity), while the latter are more sensitive to features of high resistivity. Speed of application is greater for electromagnetic induction because coupling is achieved by induction and no electrodes need be placed in the ground. Uses in coal exploration and development include fault location, overburden delineation and the location of contacts between bedrock units of contrasting resistivity. Again, results from the York Creek site are used to illustrate the method.

Three induction methods were used at York Creek: frequency-domain electromagnetic induction (FEM), horizontal-loop electromagnetic induction (HLEM), and very low-frequency (VLF) electromagnetic induction. The former two systems consist of a transmitter and receiver separated by a constant distance that generally determines the effective range in exploration depth. The latter system uses an infield receiver only, which senses the local variation in induced field (due to local geological conditions) arising from the operation of high-powered naval communication systems at locations remote from the site.

Figure 3-3 shows the HLEM (Max-Min) in-phase and quadrature phase data (percentage of primary field) at two frequencies along Line Y13 at the York Creek site. The zero-crossings at station 250 W and 160 E correspond to the known locations of thrust fault traces. The fault traces are also clearly evident in HLEM data from other survey lines at the site. The width of the zero-crossing anomaly is a function of measurement array length. The symmetry of the shoulder-trough-shoulder signature is an indication of fault dip. At station 250 W the signature is quite symmetric and the fault dip can be expected to be near vertical. At station 160 E the sharp shoulder is on the down-dip side of the fault and the dip is expected to be much lower.

HLEM data can be quite noisy in areas of irregular mountainous terrain. FEM data (Figure 3-3, upper panel) are often as good as HLEM for locating faults and are superior for soil-type delineation purposes. VLF surveys are hampered by the need to survey along lines in a radial direction relative to the source. Thus it is often not possible to obtain optimal coupling across strike of geologic features unless a portable VLF transmitter is placed at the site.

3.4 The Reflection Seismic Method

A major advantage of the reflection seismic method is that it presents a very direct way to locate subsurface boundaries that exhibit a contrast in acoustic impedance. Advantages, compared to other seismic techniques such as refraction, include the ability to probe to depths much larger than the source-to-sensor separation, and the ability to detect subsurface boundaries characterized by velocity inversion (i.e., a decrease in velocity in the material below a subsurface boundary).

Acoustic impedance (Z) is the product of sonic velocity and material density. Generally, the acoustic impedance contrast is expressed in terms of a normal incidence reflection coefficient RC:

$$RC = (Z_2 - Z_1)/(Z_2 + Z_1)$$

where Z_1 and Z_2 are material impedances above and below the subsurface boundary, respectively.

Coal is generally an excellent reflecting material because the low density of coal creates a large contrast in acoustic impedance at a coal/rock contact. The reflection coefficient for a coal/rock contact is generally of magnitude 0.3. Reflection coefficients for other boundaries exhibiting only minor velocity and density contrasts are of magnitude 0.05 to 0.1. For this reason the surfaces of coal seams generally correlate with the strongest events on reflection seismic records.

During the three years of the Foothills/Mountain Surface Geophysics project, reflection seismic exploration was performed at six different sites (Coal Valley, Smoky River, Springhill, Tower, Telkwa, and Mount Leyland; Figure 1-1).

The results from three of the sites are discussed below. The reflection seismic techniques employed were similar to typical hydrocarbon exploration methods in that multichannel, common-midpoint data were acquired and analyzed using contract mainframe computer facilities and hydrocarbon industry standard processing packages. The range of data acquisition parameters used is shown in Table 3-1.

Table 3-1: Seismic Data Acquisition Parameters

Instrumentation	GeoMetrics ES2420, 96 - 120 channel
Sample Rate	0.25 millisecond
Record Length	1.0 - 1.5 second (4000 - 6000 samples/trace)
Antialias Filter	720 Hertz
Low-Cut Filter	20 Hertz
Notch Filter	out
Format	SEG-D
Geophones	28 - 30 Hertz, 9 per group
Geophone Array	Geophones clustered at stations
Geophone Interval	5 - 10 metres
Array Geometry	Site specific
Shot Size	25 - 125 grams
Shot-Hole Depth	5 metres
Shot-Point Interval	20 - 40 metres
Fold Coverage	12 - 15

3.4.1 The Coal Valley Site

The site at the Coal Valley mine in the outer Foothills of Alberta is characterized by gently rolling topography and relatively flat-lying coal seams which generally lie within the upper 300 metres of the subsurface. The objectives of the seismic surveys were to image the major coal seams and to obtain information about suspected faulting. At the outset, the presence of one or more faults had been inferred from previous drilling but the exact locations and types of faults were not known; faults had not actually been intersected by any of the holes.

Reflection seismic data obtained during the first year of the program provided a good image of the Mynheer Seam (Figure 3-4). The data also indicated the existence of a strongly reflective lower horizon, which was interpreted to represent a repeat of the lower portion of the Mynheer Seam caused by thrust faulting. Drilling at the site during the following two years of the research program confirmed the presence of these features.

The experience with the thrust fault at Coal Valley is a good example of the effectiveness of combining reflection seismic surveys with drilling programs. The seismic profiles provided a guide to where to drill for possible faults by showing discontinuities in reflectors and repeated reflectors. Holes 5484 and 5485 were therefore drilled 40 metres deeper than previous holes in the area (e.g., Hole 5243) because of the seismic information. It would have been far less cost-effective to try to locate and interpret these structures by drilling "blind," without the seismic evidence.

3.4.2 Springhill Site

Coal seams in the Springhill area of Nova Scotia vary from surface outcrops to depths in the order of 1200 metres. This large range in the depth of the targets creates the need to adjust data acquisition geometries along survey lines to ensure that an adequate time-window is maintained through which relevant and consistent reflections from coal seam horizons can be obtained.

Data acquisition geometries, consisting of a 96-channel split-spread array, at 5- and 10-metre geophone group intervals, were tested at the site, as part of the second year of the program. Data obtained using a 5-metre group interval can yield seismic profiles with enhanced lateral resolution, compared to data obtained using 10-metre group intervals. However, as depth of the target increases, more of the useful short-array data becomes contaminated with ground-roll, air wave, and other shot-generated noise. The effect varies depending upon shot-hole efficiency and the type and condition of near-surface materials. Similarly with larger acquisition arrays, as the depth of the target decreases reflection angles increase and an asymptotic merging of desired reflected energy with critically refracted energy occurs. Thus the optimal array geometry can depend significantly on the depth and nature of both the targets and the overlying materials.

Figures 3-5 and 3-6 show seismic profiles derived from the 5- and 10-metre group interval data, respectively, along Line 1 at the site. Three major groups of reflection events, corresponding to known sequences of coal seams, are indicated in each of these figures. The two profiles are quite similar. Figure 3-5 (5-metre data) exhibits better lateral resolution for subsurface features of finite extent. Figure 3-6 exhibits better vertical resolution over the time interval extending from 100 to 500 milliseconds. The resolution of shallow events in Figure 3-5 is not as good as might generally be expected. The per-kilometre cost of reflection seismic data acquisition and processing is inversely proportional to geophone group interval. A larger group interval may be warranted for exploratory type surveys undertaken to locate optimal drillhole locations.

3.4.3 The Smoky River Site

The site at the Smoky River mine in the inner Foothills of Alberta is characterized by moderately steep bedrock-controlled slopes. The coal seams lie at depths in the order of 300 metres. Seam dips are moderate with respect to topography. Underground mining progressed through one of the seams after the seismic surveys were done.

Reflection seismic profiles were recorded along two survey lines oriented parallel to the direction of dip of the coal seams (perpendicular to geologic strike) during the first year of the research program. Results were characterized by relatively poor signal-to-noise ratio, and the coal seams appeared on seismic profiles with less clarity than those from the surveys at other test sites. The upper panel of Figure 3-7 shows one of the seismic profiles; the lower panel shows coal seam elevations derived from the interpretation of seismic data and compared with elevation data from the Alberta Research Council geologic model obtained from drilling and underground mining data (Sec. 2.2). The identification of the reflectors on the seismic profile is based on synthetic models of the seismic response calculated from the sonic and density logs from two of the drillholes. These are shown superimposed on the profile at the drillhole locations.

The poor signal-to-noise characteristics of the seismic data from the Smoky River site are mainly attributed to poor shot-coupling to the subsurface arising from the thin and weathered nature of the surficial material at this site, the difficulty in placing shot holes to the desired depth, and windy conditions at the time of the survey. The results of surveys conducted later in a similar geologic setting at the Mount Leyland site indicate that better profiles may have been obtained if data were also acquired along at least one survey line oriented parallel to geologic strike.

It is apparent that use of reflection seismic profiling methods in mountainous areas with moderately structured coal seams requires further development. Results to date suggest that reflection seismic data can be used to support exploration where some drillhole control is available. Results as yet do not warrant use of the method for the detailed planning required to support underground mine development in mountainous areas.

3.5 Ground-Penetrating Radar

Ground-penetrating radar is similar to the reflection seismic method in that the two-way travel time of energy pulses reflected from subsurface horizons is measured. The reflectivity of subsurface horizons is controlled by the contrast in electromagnetic impedance at the horizons. The impedance depends on material conductivity, material dielectric permittivity, and frequency of radar operation. Radar signal strength is severely attenuated in the presence of subsurface materials of moderate electrical conductivity.

Radar reflection surveys were undertaken with some success in the Shikano Pit at the Quintette mine in northeastern British Columbia. Results from Line 1 in Figure 3-8 clearly show a number of dipping reflective interfaces that correlate with the known coal seam subcrop locations. No dipping reflectors are readily evident along Line 12. It does not appear that radar reflection images are yet able to resolve interburden variation or coal seam thickness. The effective depth of exploration attained using ground-penetrating radar was in the range of 5 metres at the Shikano Pit site for radar operation at a frequency of 100 MHz.

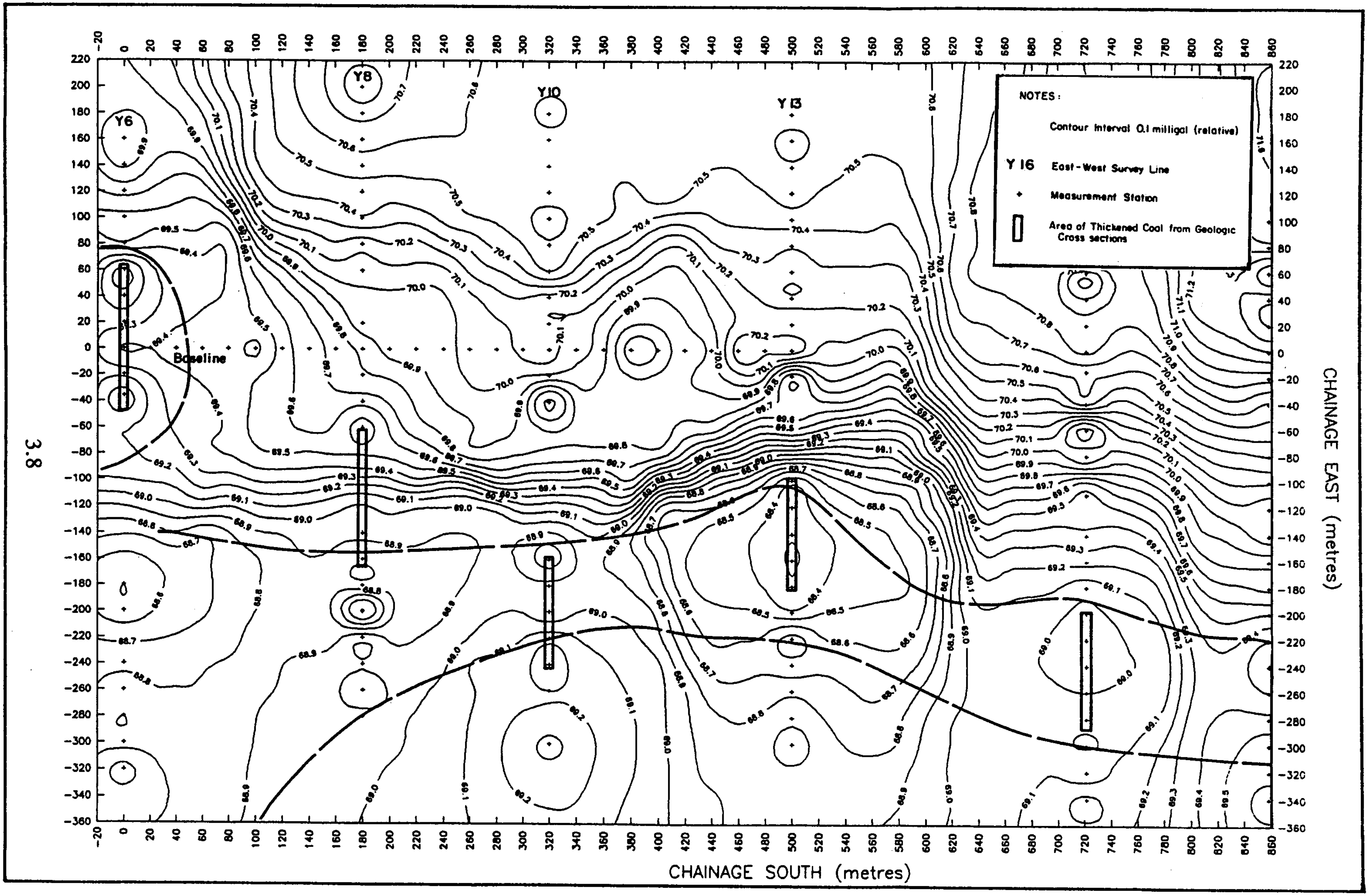


Figure 3-1. Reduced Bouguer gravity contour map, York Creek site.

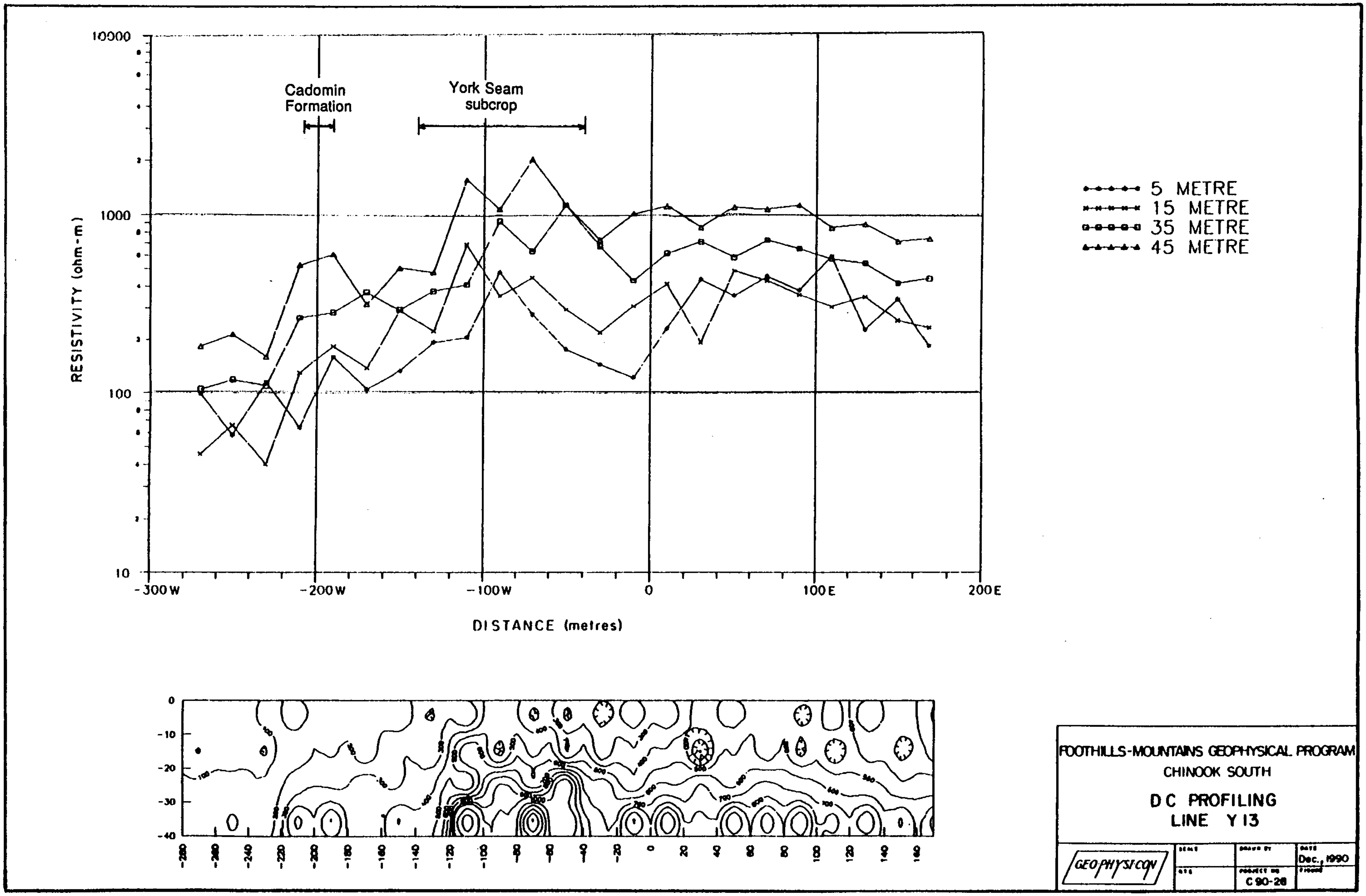


Figure 3-2. Direct-current profiling data, York Creek site, Line Y13.

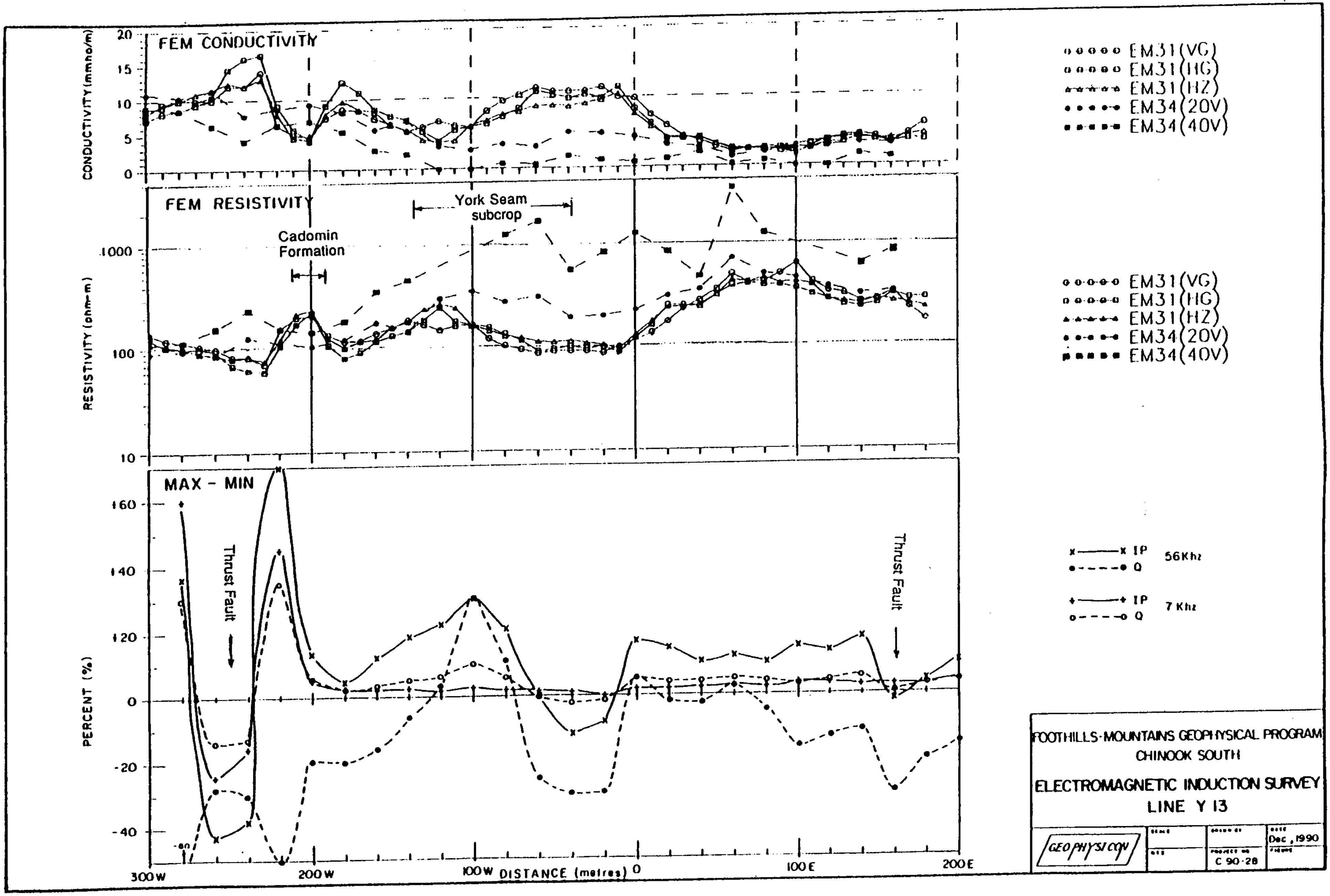


Figure 3-3. Electromagnetic induction data, York Creek site, Line Y13.

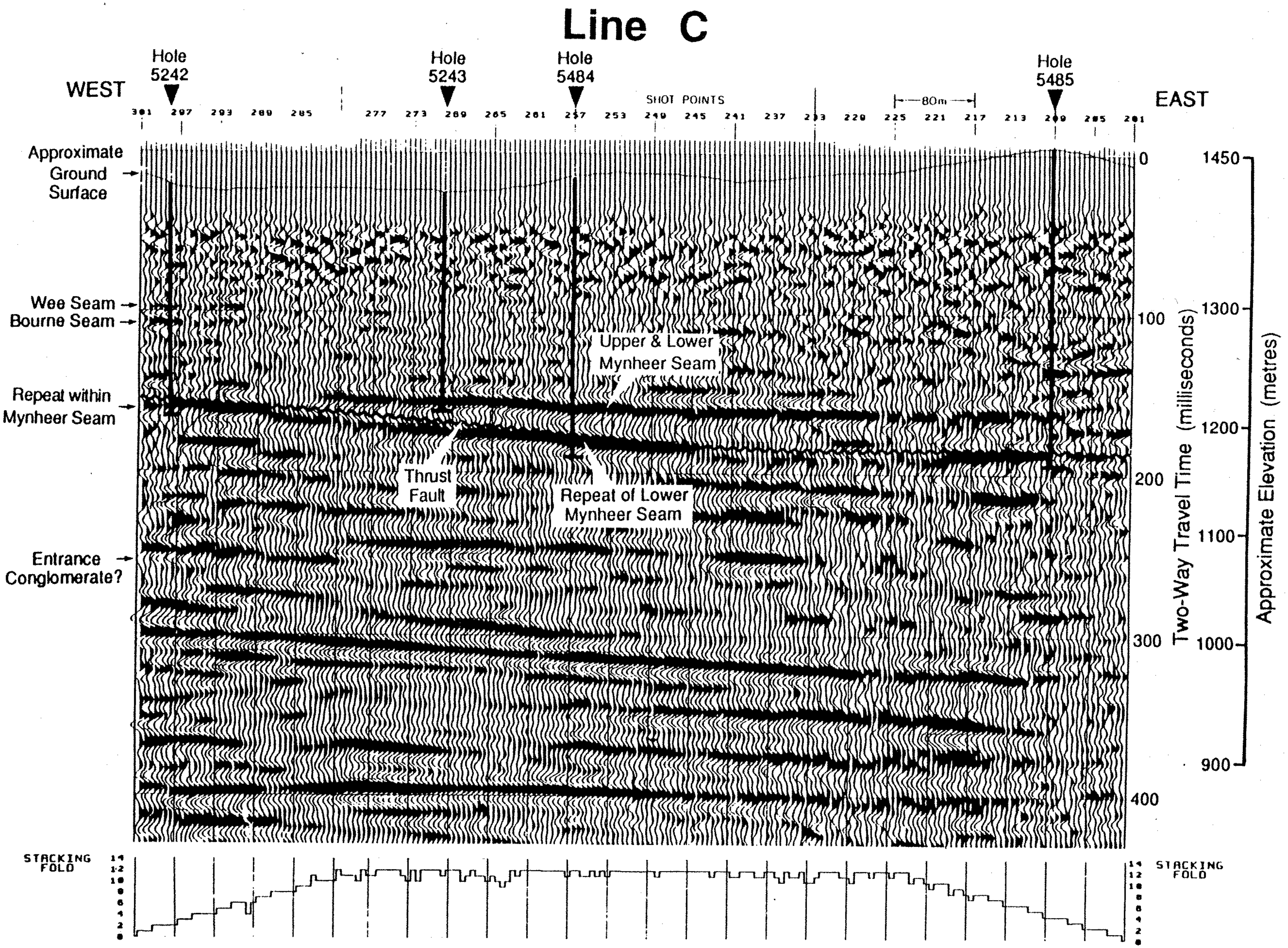


Figure 3-4. Reverse polarity reflection seismic profile, Coal Valley site, Line C.

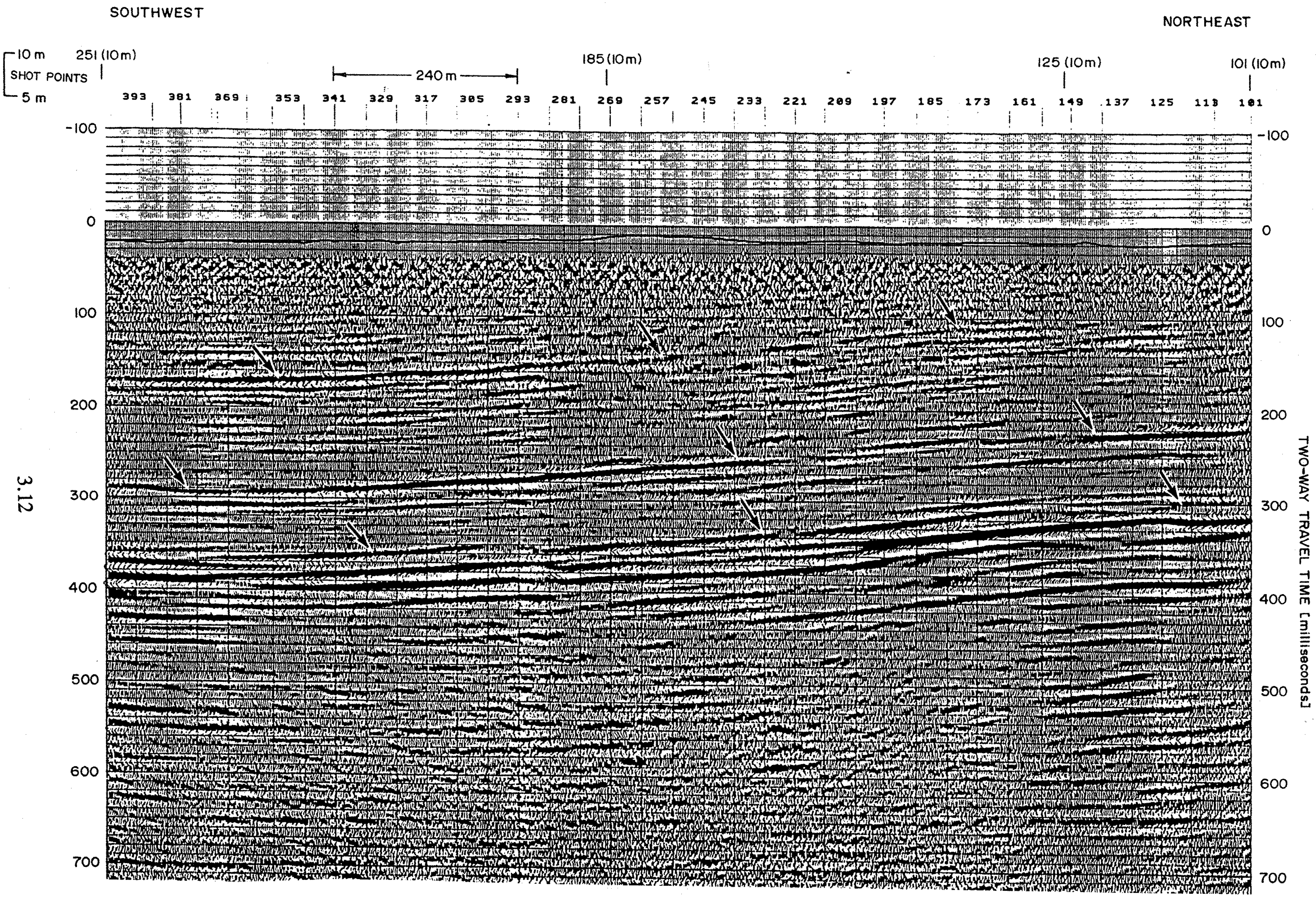


Figure 3-5. **Reverse polarity reflection seismic profile, Springhill site (5 m geophone group interval). The three coal seams are indicated by arrows.**

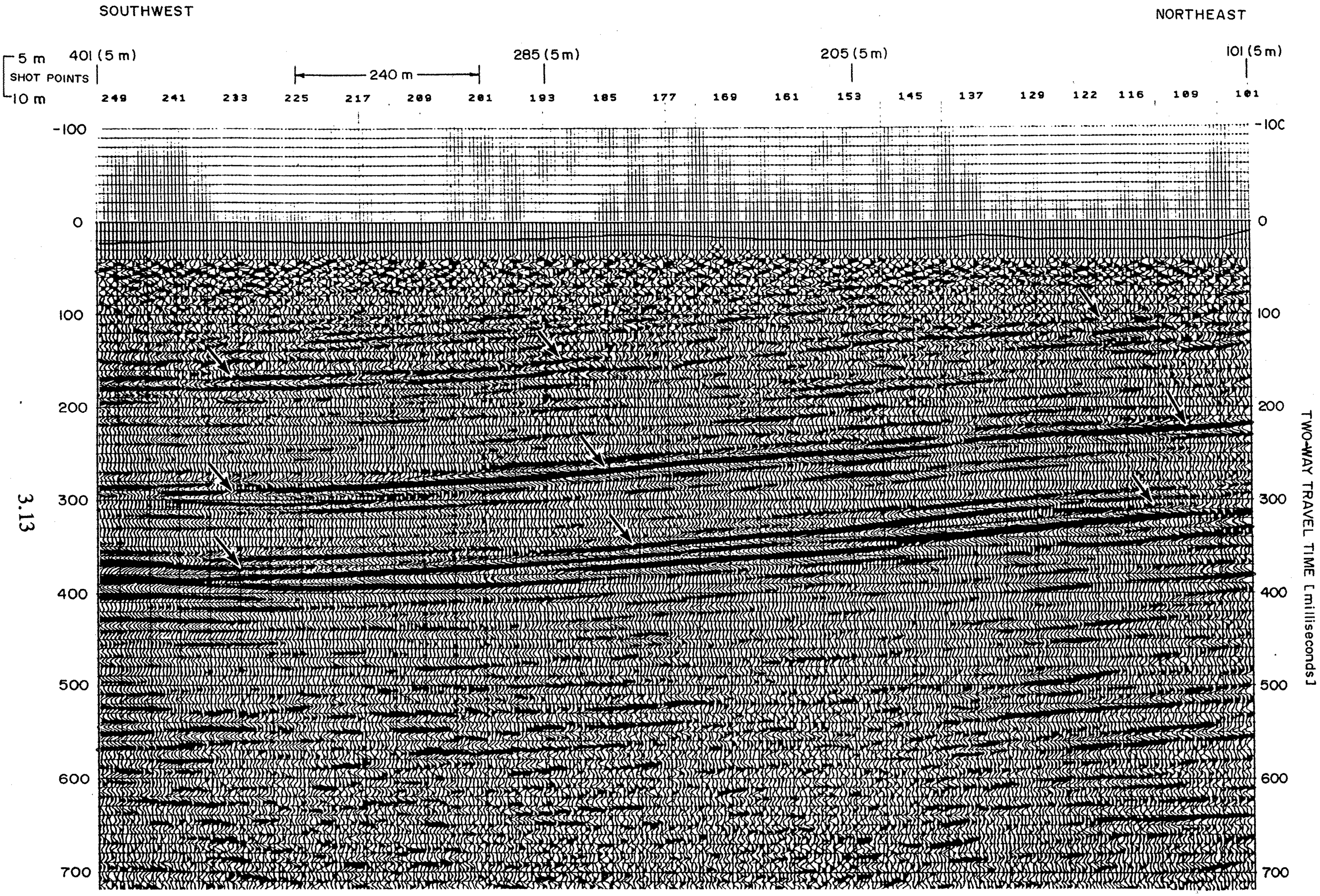
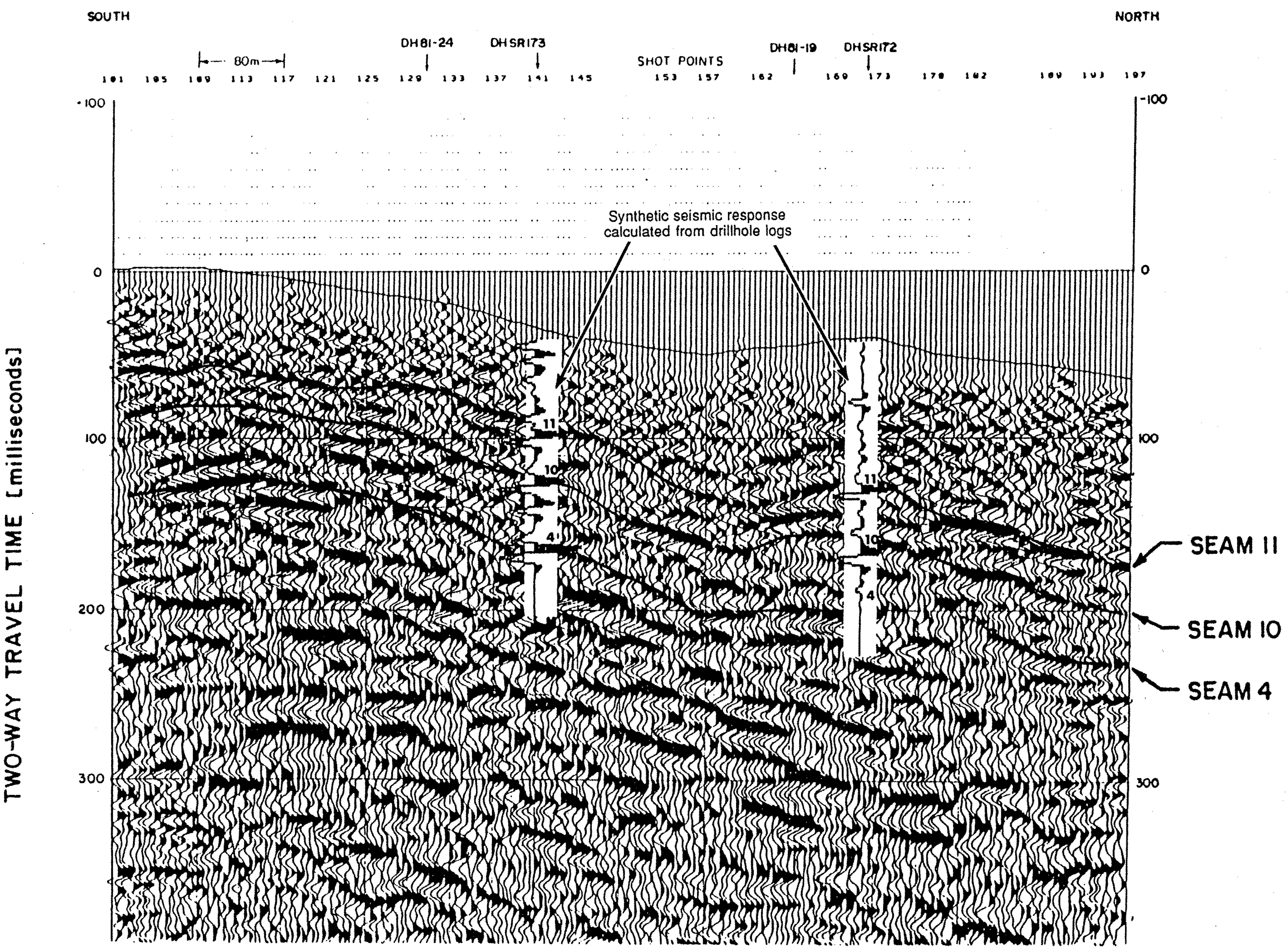


Figure 3-6. Reverse polarity reflection seismic profile, Springhill site (10 m geophone group interval). The three coal seams are indicated by arrows.


SOUTH
NORTH
80m
DH81-24
DHSR173
SHOT POINTS
DH81-19
DHSR172
101 105 109 113 117 121 125 129 133 137 141 145 153 157 162 169 173 178 182 189 193 197
Synthetic seismic response calculated from drillhole logs
TWO-WAY TRAVEL TIME [milliseconds]
-100
0
100
200
300
11
10
4
SEAM 11
SEAM 10
SEAM 4

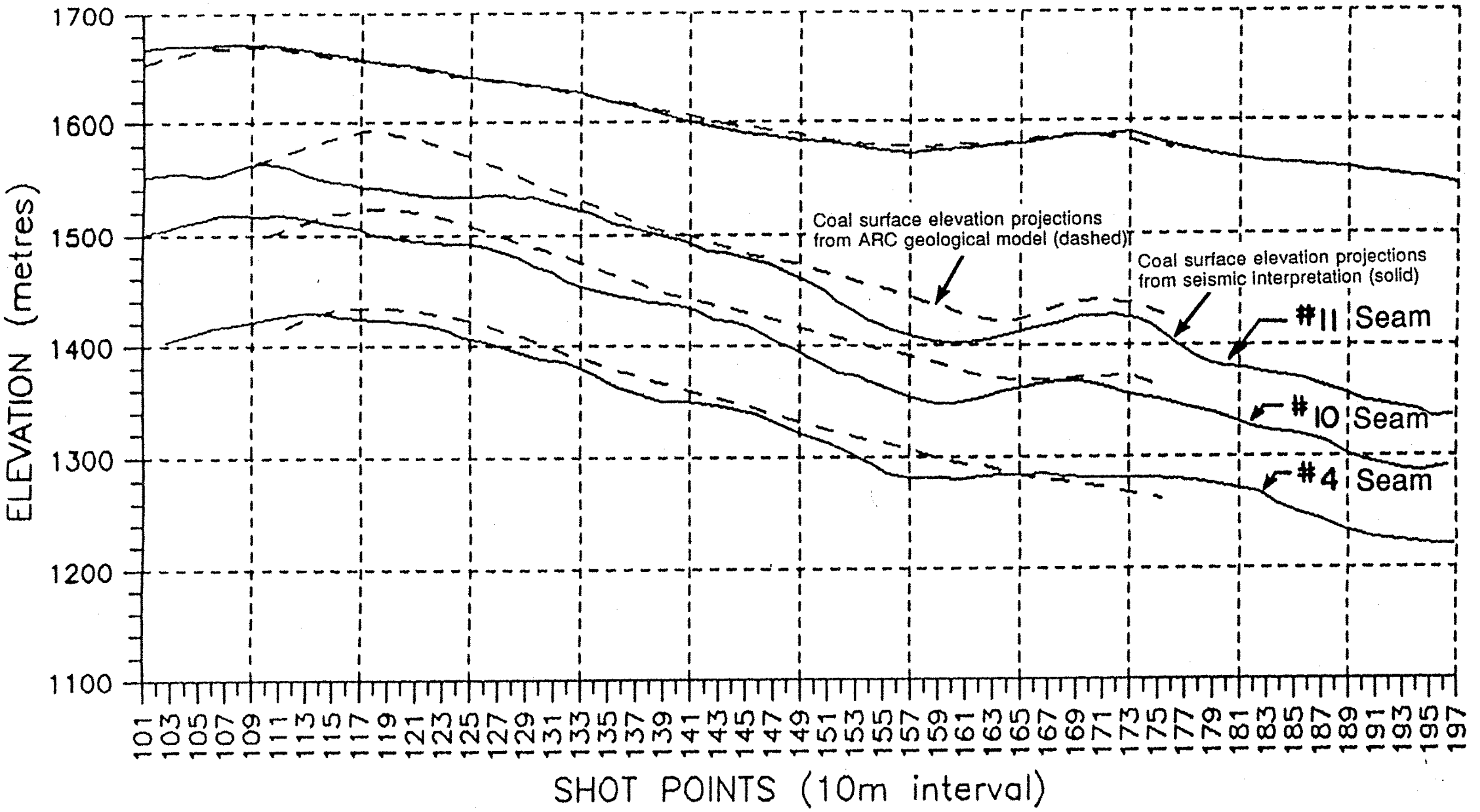


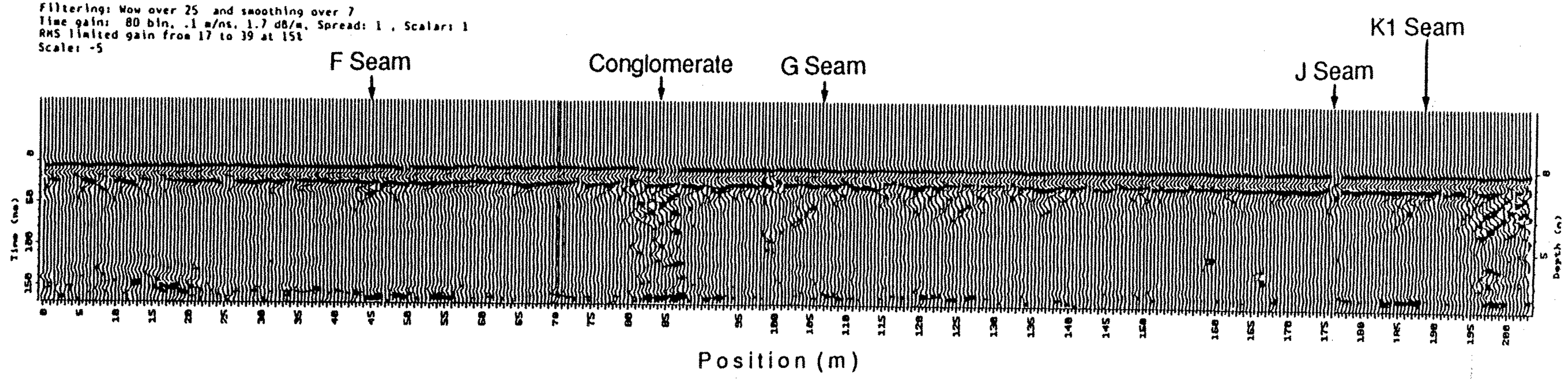
Figure 3-7. **Comparsion between reverse polarity seismic profile (upper panel) and data from geologic model (lower panel), Smoky River site.**

COAL MINING RESEARCH COMPANY
SMOKY RIVER COAL
LINE 2 (94000E)

GEO·PHYSI·CON
SCALE
N.T.S.
DRAWN BY
PROJECT NO.
C 89-01
DATE
March, 1990
FIGURE

```
File: PITL1AS
Comment: 100 MHz 1 m sep 1 m step
Stacking:  16  in hardware *  16  in software
Averaging: off
Debias: on from 1  to 30
Filtering: Wow over 25  and smoothing over 7
Time gain:  80 bin, .1 m/ns, 1.7 dB/m, Spread: 1 , Scalar: 1
RMS limited gain from 17 to 39 at 15%
Scale: -5
```

Line 1



```
File: PITL5AS
Comment:
Stacking: off
Averaging: off
Debias: on from 1  to 30
Filtering: Wow over 25  and smoothing over 7
Time gain:  90 bin, .1 m/ns, 3 dB/m, Spread: 1 , Scalar: 1
RMS limited gain from 17 to 39 at 15%
Scale:  5
```

Line 12

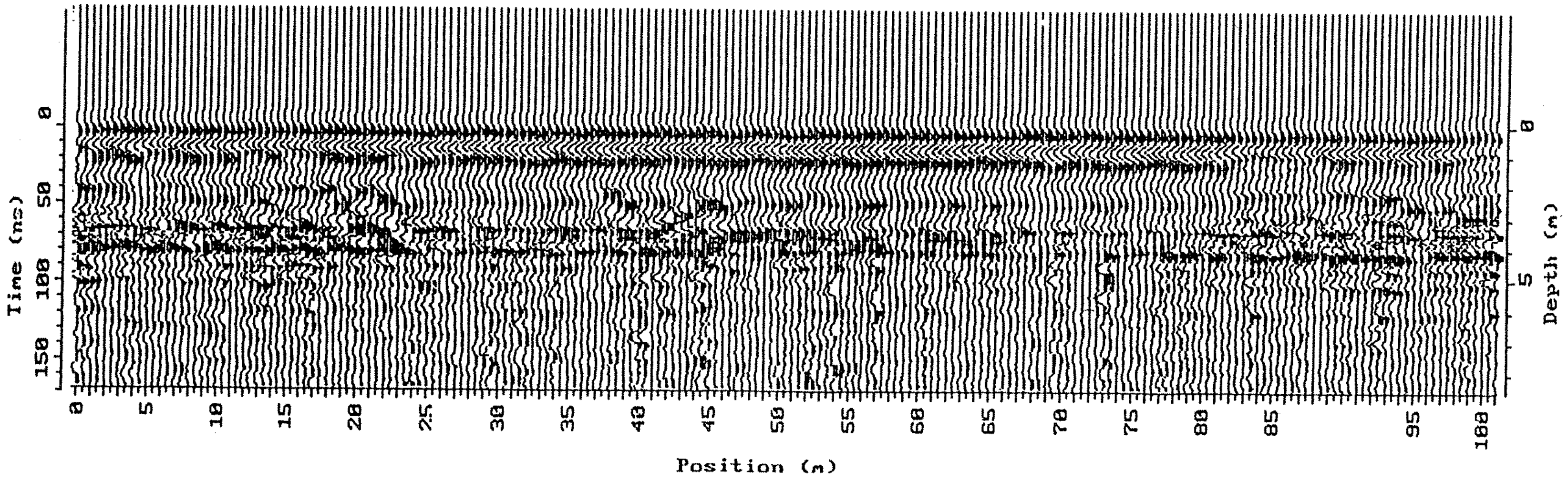


Figure 3-8. Ground-penetrating radar profiles, Shikano Pit floor, Quintette.

4. COST EFFECTIVENESS

Allister R. Peach, Kathryn J. Cochrane and Georgia L. Hoffman

The major benefit of adding surface geophysics to a conventional drilling program may be that the geophysical data provide a different type of perspective on the geology of a deposit. A drillhole presents an essentially one-dimensional look at a given point in the deposit. Lithologies, depths, thicknesses, etc. can be determined easily, but correlations between drillholes can be uncertain, particularly in geologically complex terranes. Geophysical profiles present a more two-dimensional view, but lithologies, etc., are much less certain. Each type of information can be used to enhance the interpretation of the other, allowing the geologist to construct a three-dimensional geological model with a higher degree of confidence (Sec. 2.3).

Three hypothetical cases are presented below to illustrate the cost-effectiveness of integrating surface geophysics with conventional drilling programs. The criteria for deposit type and reserve/resource delineation are based on Hughes et al., 1988.

4.1 Case 1: Early Exploration

The first hypothetical case involves the early stages of the exploration of a Moderate/Complex Geology Type coal deposit in a Foothills setting. The terrain is moderately hilly and the bedrock geology is obscured by a veneer of unconsolidated sediments (Figure 4-1a). The area is underlain by coal-bearing strata that have been affected by tectonic deformation. Typical data-point spacing required to determine an Indicated resource category for this type of deposit would be 500 m, while 200 m would be required for a Measured reserve category.

Coal is intersected by the first two drillholes, DH1 and DH2. Interpretation suggests a simple, gently dipping monocline (Figure 4-1a). When DH3 is completed to define the subcrop, a small near-surface flexure is added to the otherwise simple interpretation (Figure 4-1b). It is not until DH4 is completed to confirm continuity at depth that the thrust faulting is detected (Figure 4-1d). If DH4 were not drilled deep enough to intersect the repeated coal sequence, it would even be possible to interpret this structure as an anticline (Figure 4-1c).

Using an integrated program of drilling and geophysics instead, DH1 would demonstrate the presence of a coal-bearing sequence. Calibrated geophysical logs obtained from this hole, including sonic, density and resistivity, would allow the responses of reflection seismic, electrical and electromagnetic methods to be modeled. The subsequent geophysical program would include a reflection seismic survey, with a geophone spacing of 5 m to observe near-surface strata, and completion of an electrical or electromagnetic survey to locate the coal seam subcrops. With the geophysical results, optimum locations could be planned for subsequent drillholes. DH2, DH3 and DH4 could then be drilled in more effective locations, and it might be possible to delete one of the holes without sacrificing confidence in the accuracy of the interpretation.

4.2 Case 2: Reserve Delineation

The second hypothetical case involves delineation of a Measured coal reserve category in a coal deposit of the Moderate to Complex geology type in an inner Foothills setting. The deposit consists of a coal zone 5 m thick lying at depths of 0 to 100 m, covering an area of 15 km^2 (3 by 5 km). Delineation of a Measured reserve would require a data-point spacing of 250 m, for a total of 273 data points (Figure 4-2).

Using a drilling-only approach, holes would be required at all nodes of the grid, requiring 273 holes with a total depth of 13 650 m. Total reserve delineation cost at a drilling cost of $50 per metre would be $682,500.

Integrating geophysics into the reserve delineation strategy, a program could include 160 drillholes for control and calibration; 30 km of reflection seismic surveys with a geophone spacing of 5 m to prove seam continuity and structure; and 20 km of electromagnetic surveys (HLEM or EM-31) for subcrop delineation. Total cost would be $600,000, with a saving of $82,000. An additional benefit would be that most of the drillholes could be planned on a more informed basis with regard to structure and depth.

4.3 Case 3: Underground Mining Reserves

The third hypothetical case involves an underground mining setting with an average depth to coal of 350 m. The geology type is Low (Type B) to Moderate. The required data point spacing would be 500 m, or 77 data points (Figure 4-3). Using drilling as the only source of data, 77 holes would be required, for a total of 26 950 m. At $75 per metre this would amount to $2,021,250.

In areas like this where the average depth to coal is high, drilling costs are higher. The use of surface geophysics to identify optimum locations for the drillholes, to ensure that they intersect critical structures, is especially effective in these situations.

In an integrated program of drilling and geophysics, only 39 holes would be drilled with a total depth of 13 650 m. The remainder of the data would come from 30 km of reflection seismic surveys. Total cost would be $1,203,750, a difference of $817,500. The geophysics would indicate areas of structural concern to allow more effective use of the drillholes.

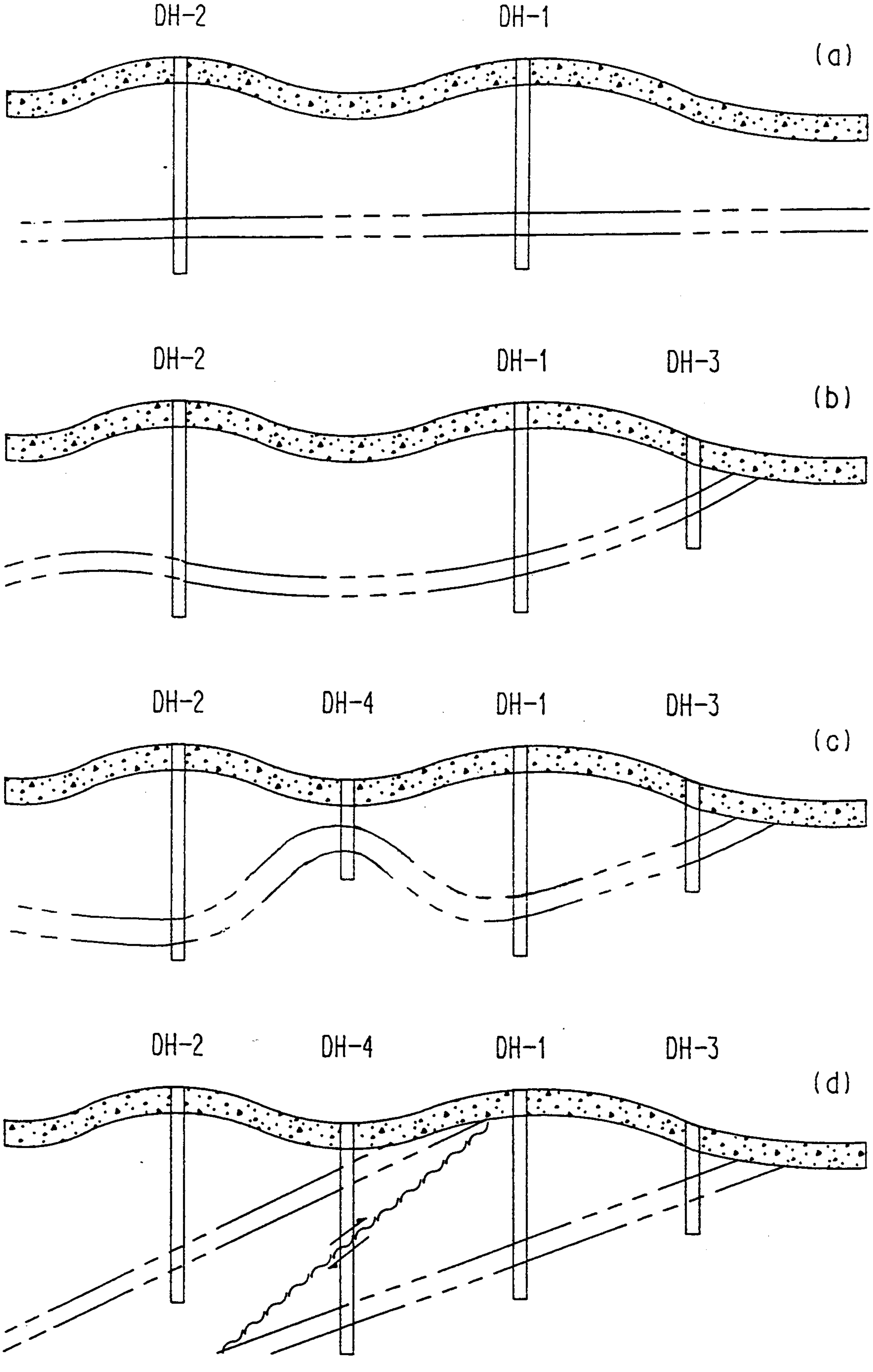
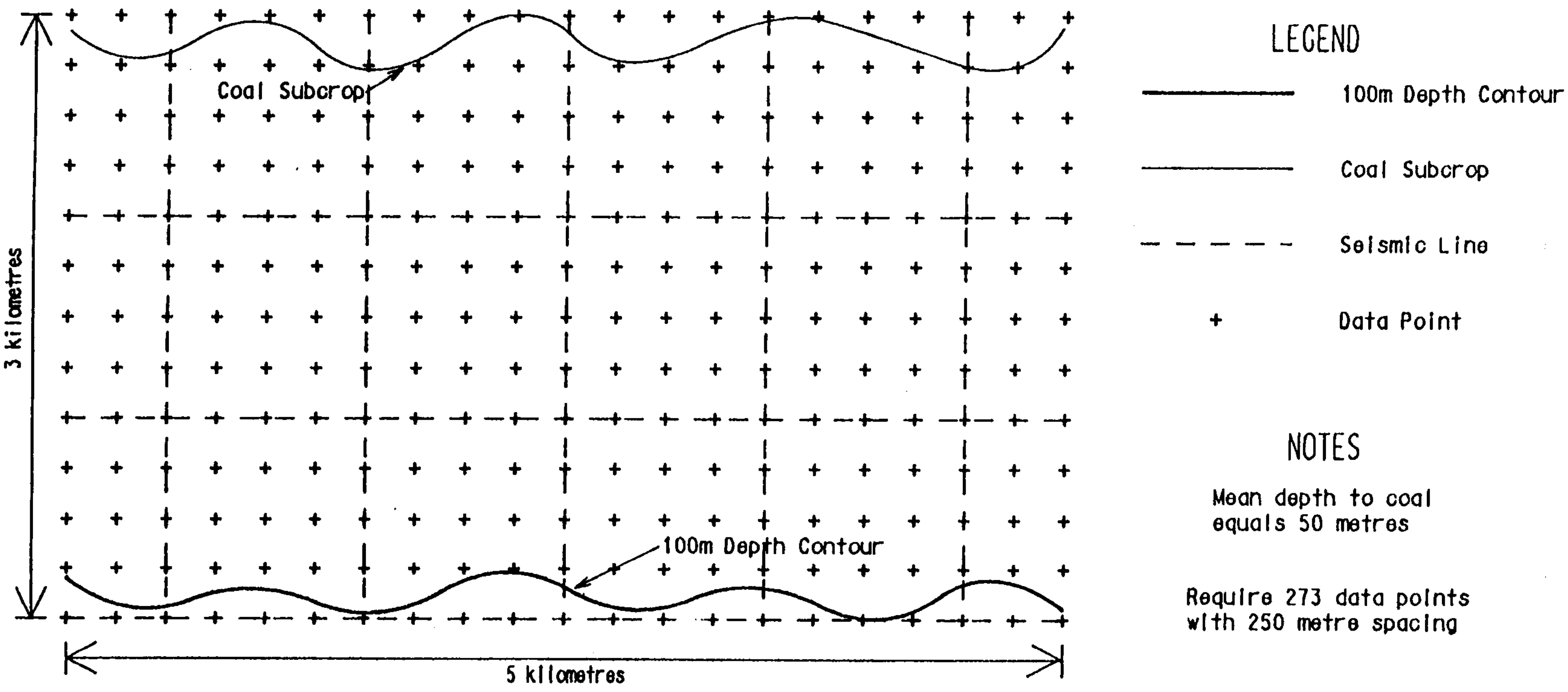


FIGURE 4-1. Hypothetical Case 1: Evolution of Interpretation

FIGURE 4-2. Hypothetical Case 2 : Foothills Coal Deposit, Moderate to Complex Geology Type, Measured Reserve Category



NOTES

Mean depth to coal equals 50 metres

Require 273 data points with 250 metre spacing

ALTERNATIVE A

Drilling Only

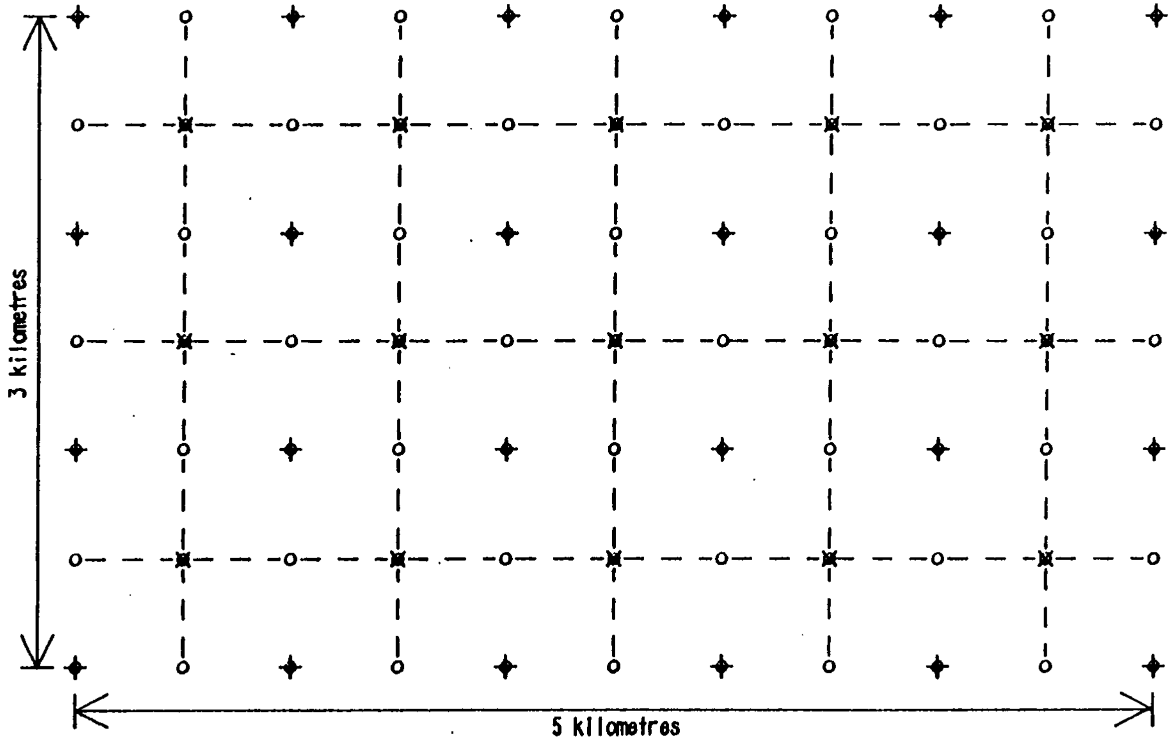
- 273 drillholes (mean depth = 50 m)
- total cost approximately $682,500

ALTERNATIVE B

Drilling Plus Geophysics

- 30 km reflection seismic survey
- 20 km subcrop mapping by EM survey
- 160 drillholes (mean depth = 50 m)
- total cost approximately $600,000

FIGURE 4-3. Hypothetical Case 3 : Underground Mining, Foothills Coal Deposit, Low to Moderate Geology Type



LEGEND

– – – – –	Seismic Line
o	Grid Point
+	Center Point
×	Cross Point

NOTES

Mean depth to coal equals 350 metres

Require 77 data points with 500 metre spacing

ALTERNATIVE A

Drilling Only

- 77 drillholes, all grid points . (mean depth = 350 m)
- total cost approximately $2,021,250

ALTERNATIVE B

Drilling Plus Geophysics

- 30 km reflection seismic survey
- 39 drillholes (mean depth = 350 m) cross points and center points only
- total cost approximately $1,203,750

5. CONCLUSIONS

5.1 Reflection Seismic Techniques

Reflection seismic technology has advanced to the point where it can produce useful images of the subsurface in depth ranges that are relevant to coal mining. The reflection seismic surveys made significant contributions to the understanding of the geology at most of the sites. Coal is an excellent reflecting material because there is generally a large contrast in acoustic impedance at a coal/rock contact. As a result, coal seams can usually be identified on seismic profiles and their geometries, continuity and discontinuities can usually be evaluated. Calibrated sonic and density logs should be obtained from holes drilled along the seismic lines, so that synthetic modelling of the seismic response can be used to tie the processed seismic sections to the known geology.

In areas underlain by complex geology it is especially important to plan seismic line locations according to the known geology of the site. It was found that survey lines should generally be oriented perpendicular to the direction of geologic strike, connected by one or more tie-lines oriented parallel to strike. Reflection seismic data acquired perpendicular to strike were used to evaluate faulting and folding. Data acquired parallel to strike were generally of better quality, however. The continuity of the reflection events was generally better, so these results were used for correlation between profiles and with drillhole information.

It was sometimes difficult or impossible to evaluate small-scale faulting. At the Mt. Leyland site, which is underlain by strongly folded strata, variations in dip produced problems with out-of-place reflections and diffraction patterns that tended to obscure the effects of small-scale structures. At the Smoky River site, poor shot-coupling with the subsurface produced data with a poor signal-to-noise ratio in which small-scale structures could not be distinguished. At the Coal Valley site, a major thrust fault affecting the coal measures was clearly visible in the reflection seismic data.

Data acquisition geometries using 5- and 10-metre geophone group intervals were compared at the Springhill site. Depending on the depth of the target, the 5-metre spacing produced better lateral resolution and produced good results in a subsequent program at Telkwa. However, the cost of data acquisition and processing is based mainly on the number of records obtained. For a fixed length of line, the cost will be higher for small rather than large geophone spacing. The appropriate spacing will depend upon cost and the ability to meet the specified geological objectives.

5.2 Nonseismic Techniques

A variety of nonseismic techniques were applied at two sites, Chinook South and Quintette. With the exception of ground-penetrating radar, the instruments were easily portable by a small crew on foot, they could be used on very steep slopes, and they provided data from depth ranges that are too shallow to be explored effectively by reflection seismic methods. They were also comparatively inexpensive to apply.

At both sites, direct-current profiling was well suited to locating the subcrops of resistive units like coal seams. Electromagnetic induction methods were suited to locating conductive units such as marine shales and faults, and to discriminating between the relative thicknesses and lithologies of unconsolidated overburden materials.

A gravity survey was used to delineate areas known to be underlain by pods of tectonically thickened coal at the Chinook South site. The pods appeared to coincide with low-gravity anomalies accompanied by small lateral gradients.

The ground-penetrating radar surveys from benches in the Shikano Pit at Quintette achieved a maximum depth of penetration of about 5 m. Dipping coal seams could be identified on some of the profiles.

5.3 Cost Effectiveness

The overall conclusion is that surface geophysical techniques can make a practical and cost-effective contribution to solving geological problems at coal mines in the Foothills and Mountains. To maximize the benefit, they must be used in an integrated approach with conventional drilling. The recommended strategy is outlined in Sec. 6.

Much of the benefit comes from the fact that, compared to drilling, surface geophysical techniques provide a different type of look at the geology of the subsurface. A drillhole presents an essentially one-dimensional look at a given point, and correlation between holes can be uncertain. Geophysical profiles present a more two-dimensional view, but with less certainty about depths, lithologies, thicknesses, etc. Each type of information can be used to enhance the interpretation of the other, allowing a three-dimensional geological model to be constructed with a higher degree of confidence.

6. RECOMMENDATIONS

6.1 Reflection Seismic Techniques

Use of reflection seismic techniques can be effective in geologically complex coal-bearing strata. Survey line geometry and data acquisition and processing parameters should be planned on an informed basis, using conventional data from geological mapping and drilling programs.

6.2 Downhole Geophysical Logs

Calibrated sonic and density logs should be obtained from drillholes along the seismic lines so that the seismic response can be modeled and reflecting horizons can be identified. Focussed resistivity logs should also be obtained for interpreting the results of the nonseismic surveys.

6.3 Nonseismic Techniques

Electrical and electromagnetic techniques should be used to fill in data from depths that are too shallow for reflection seismic techniques. They should be used to locate the subcrops of lithological contacts, coal seams and faults. They should also be used where information about the relative thicknesses and lithologies of unconsolidated overburden materials is needed. They can provide data in rugged areas where access by truck-mounted equipment is not practical. Gravity surveys may be useful for locating pods of tectonically thickened coal.

6.4 Exploration and Interpretation Strategy

To obtain the maximum information from all techniques, it is recommended that conventional drilling programs and surface geophysical surveys be used together in an integrated approach. The recommended strategy is outlined below:

1. Start with geologic mapping and drilling. Obtain high-quality, calibrated downhole geophysical logs (especially sonic, density and focused resistivity). The logs will allow the most effective geophysical techniques to be selected, and will aid in the interpretation of the resulting data.

2. After the drilling information has been interpreted as usual, the geologists and geophysicists together select the geophysical techniques and plan the geophysical program(s). Nonseismic techniques should be used to locate subcrops and

investigate the near-surface strata. Reflection seismic surveys should be used to map reflectors and locate discontinuities in deeper strata.

3. The geophysicists interpret the geophysical data together with the geologists, and compare the results with the those of the previous geologic interpretation. Areas where the two interpretations disagree are identified, and the possible causes of the conflicts are considered. This may be an iterative process involving both reprocessing or reinterpretation of the geophysical data, and reinterpretation of the geologic data. A new interpretation is produced.

4. The geologists plan the next series of drillholes, targeting them to intersect and prove critical geologic features that were indicated by the geophysical results, and to resolve any areas that remain ambiguous.

5. This cycle is repeated as required to increase the data density and level of confidence for reserve delineation or mine planning.

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