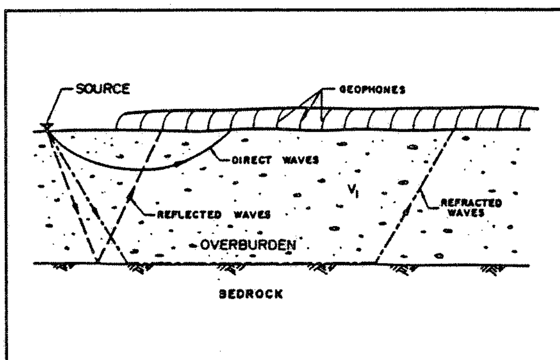
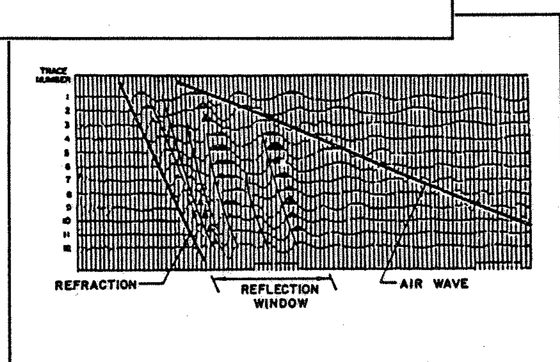
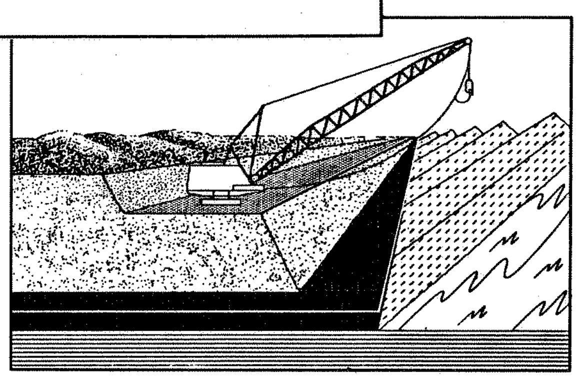
Information Series 112

Surface Geophysical Coal Research Project 1984–1986

Final Report







ALBERTA RESEARCH COUNCIL

Alberta Geological Survey

SURFACE GEOPHYSICAL COAL RESEARCH PROJECT
1984 to 1986
FINAL REPORT

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for

TransAlta Utilities Corporation
acting on behalf of the
Surface Geophysical Coal Research Joint Venture
Dennis J. Nikols, TAU, Chairman

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DISCLAIMER

EXECUTIVE SUMMARY

The Surface Geophysical Coal Research Project was funded jointly by industry and government. Half from the Alberta/Canada Energy Resources Research Fund, administered by Alberta Energy through the Alberta Office of Coal Research and Technology and half from the Surface Geophysical Coal Research Project joint venture group consisting of TransAlta Utilities Corporation, Luscar Ltd., Fording Coal Ltd., Esso Resources Canada Ltd., Alberta Research Council and Saskatchewan Power Corporation.

The research was carried out by a professional team assembled from the Coal Mining Research Company (Operations Manager), Geo-Physi-Con Co. Ltd., (geophysics) and Alberta Research Council, Terrain Sciences Department (geology).

The primary objective of this three year study was the cost effective application of surface geophysical techniques to plains coal exploration and mine planning. Other major objectives were:

(1) The location of subcrop, washouts and glacially deformed bedrock.
(2) Detection of subsurface strata and their continuity.
(3) For targets depths of 10 to 70 metres; the development of reflection seismic techniques and the application of refraction seismic and electrical techniques.

Geophysical methods tested were refraction seismic, reflection seismic, crosshole seismic, direct current sounding, direct current profiling, fixed frequency electromagnetic induction (EM). Target sites were selected at the Highvale, Genesee, and Paintearth mines.

The primary conclusion is that surface geophysical, particularly seismic and direct current, techniques have proven to be successful and cost effective for the location of subcrop, washouts,

glacially deformed terrain and stratigraphic continuity in the 10 to 70 metre range. The cost effectiveness increases with target depth because while drilling costs increase substantially with depth the geophysical costs increase only slightly.

Also surface geophysical techniques are most effective when used as a part of an integrated geophysical and geological program. These techniques provide a comparatively high number of data stations per kilometre (50 for direct current profiling and 400 for seismic reflection for example) that results in relatively clear definition of both the anomalous and uniform areas. This information then allows the project manager to focus drilling only on the areas of interest yielding therefore the most economical and efficient use of the drilling funds.

Recommendations are:

(1) Surface geophysics should be adopted as one of the principal tools for plains coal exploration and development.
(2) For intermediate exploration stage, reflection seismic and direct current sounding methods should first be considered, and at mine planning stage, methods selection will depend more on the specific target type.
(3) Selection of the appropriate geophysical techniques should take into consideration: (i) the operating environment, (ii) the geologic framework and, (iii) a firm statement of specific mapping objective, including the depth of interest and the lateral and vertical resolution desired.

ACKNOWLEDGMENTS

The research project for which this final report is submitted was funded (in part) from the Alberta/Canada Energy Resources Research Fund, jointly established by the Government of Canada and the Government of Alberta, and administered by Alberta Energy through Office of Coal Research and Technology.

The participating representatives[1] from the Alberta Office of Coal Research and Technology representing Alberta Energy and from each member of the joint venture[2] are as follows:

o Alberta Office of Coal Research and Technology	Thomas Sneddon
o Alberta Research Council	Mark Fenton
o Esso Resources Canada Ltd.	Allister Peach
o Fording Coal Ltd.	Donald Mills
o Luscar Ltd.	Keith Hebil
o Saskatchewan Power Corporation	Neil Worsley
o TransAlta Utilities Corporation	Dennis Nikols

The contribution of the above representatives for their ideas and direction to the project is acknowledged.

The authors also acknowledge Dr. Bob Labun for his great effort in improving the processing of the reflection seismic data and Dr. D. Lawton for his advice and assistance in the analysis of all the seismic data.

Thanks is also given to K. Gates for typing of the manuscript.

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[1]representative at time of completion of project.

[2]member organization at time of completion of project

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1. INTRODUCTION

1.1 Background

Two of the fundamental principles of mineral exploration and mine planning are (1) the greater the concentration of subsurface data the more reliable the evaluation of the resource and (2) geotechnical/geological mining problems are most economically solved by a combination of foreknowledge of their presence and proactive design rather than trying to implement a remedial solution subsequent to their discovery by the mining process.

A combination of surface geophysics and drilling has been, for decades, the most cost effective method to acquire subsurface data on the deep targets associated with petroleum exploration and development. The conventional procedure for plains coal exploration and development however had been to drill on a grid. The benefit from incorporation of surface geophysical techniques with the much higher spatial data density had not been utilized.

The literature indicated seismic and electrical geophysical techniques appeared to be most applicable to the comparatively shallow depths of interest to surface coal mining. Prior to the 1980's, shallow seismic reflection techniques were tested at depths of about 200 m in Australia, Great Britain and Eastern Europe (Lawton 1983). Modification of field procedures and improved data analysis equipment, both developed in Alberta, had reduced this operating depth to 70 m by 1982 (Lawton 1983). At the same time, the Pre-mining Conditions Group of the United States Bureau of Mines, Denver Center, was investigating the feasibility of operating the 10 to 40 m range. Preliminary investigations toward the application of electrical methods within the target zone were also being investigated during this period.

Also from 1974 to 1983, staff of the Terrain Sciences Department, Alberta Research Council (ARC) had been developing expertise in the recognition of glacially deformed bedrock; one of the major targets of concern to coal exploration and mine planning.

Dennis Nikols, TransAlta Utilities Corporation (TAU) based upon knowledge of the above, initiated in 1983 discussions with ARC, Geo-Physi-Con Co. Ltd., and Coal Mining Research Company (CMRC) about the potential application of surface geophysical methods at the Highvale Mine. The result was the implementation of a pilot study south of Pits 03 and 04.

Following the completion of the 1983 TAU study, D. Nikols presented the results to other members of the coal industry which lead to the formation of the Surface Geophysics joint venture to further develop the use of surface geophysics for the exploration and mine planning in the plains coal industry. A proposal for a three year program was submitted by TAU, on behalf of the joint venture, to the Alberta Office of Coal Research and Technology (AOCRT). Further details of the program were given in a supplemental application for funding in August 1984.

1.2 Funding and Organization

This research project is funded 50% from the Alberta/Canada Energy Resources Research Fund, jointly established by the Government of Canada and Government of Alberta, and administered by Alberta Energy through the Alberta Office of Coal Research and Technology. The Surface Geophysics joint venture funds the other 50% and is comprised of TransAlta Utilities Corporation, Luscar Ltd., Fording Coal Ltd., Esso Resources Canada Ltd., Alberta Research Council and Saskatchewan Power Corporation.

This project was directed by an executive committee with Dennis Nikols, TransAlta Utilities Corporation, as Chairman (Figure 1.1). Project operations were managed by the Coal Mining Research Company. Research was the responsibility of the Alberta Research Council, Terrain Sciences Department (geology) and Geo-Physi-Con Co. Ltd., (surface geophysics).

The project team consisted of:

- Donald H. Green, P.Eng. and subsequently Raymond G. Chopiuk, P.Eng., Project Manager and Project Mine Engineer, Coal Mining Research Company.
- Mark M. Fenton, Ph.D., P.Geol., Project Geologist, Alberta Research Council.
- John G. Pawlowicz, C.E.T., Project Geological Technologist, Alberta Research Council.
- Carolyn Sterenberg, P.Geol., Geologist, Alberta Research Council.
- James Henderson, B.Sc., President, Geo-Physi-Con Co. Ltd.
- Anthony Sartorelli, P.Eng., Senior Engineer, Geo-Physi-Con Co. Ltd.
- Michael Pesowski, P.Geoph., Geophysicist, Geo-Physi-Con Co. Ltd.

1.3 Purpose and Objectives of Research Project

The purpose of this project is to determine the effectiveness of using surface geophysical techniques in locating and defining specific coal mine planning and exploration targets in the plains setting.

The primary objective was to demonstrate the cost effective application of surface geophysical techniques for plains coal exploration and mine planning.

SURFACE GEOPHYSICS PROJECT

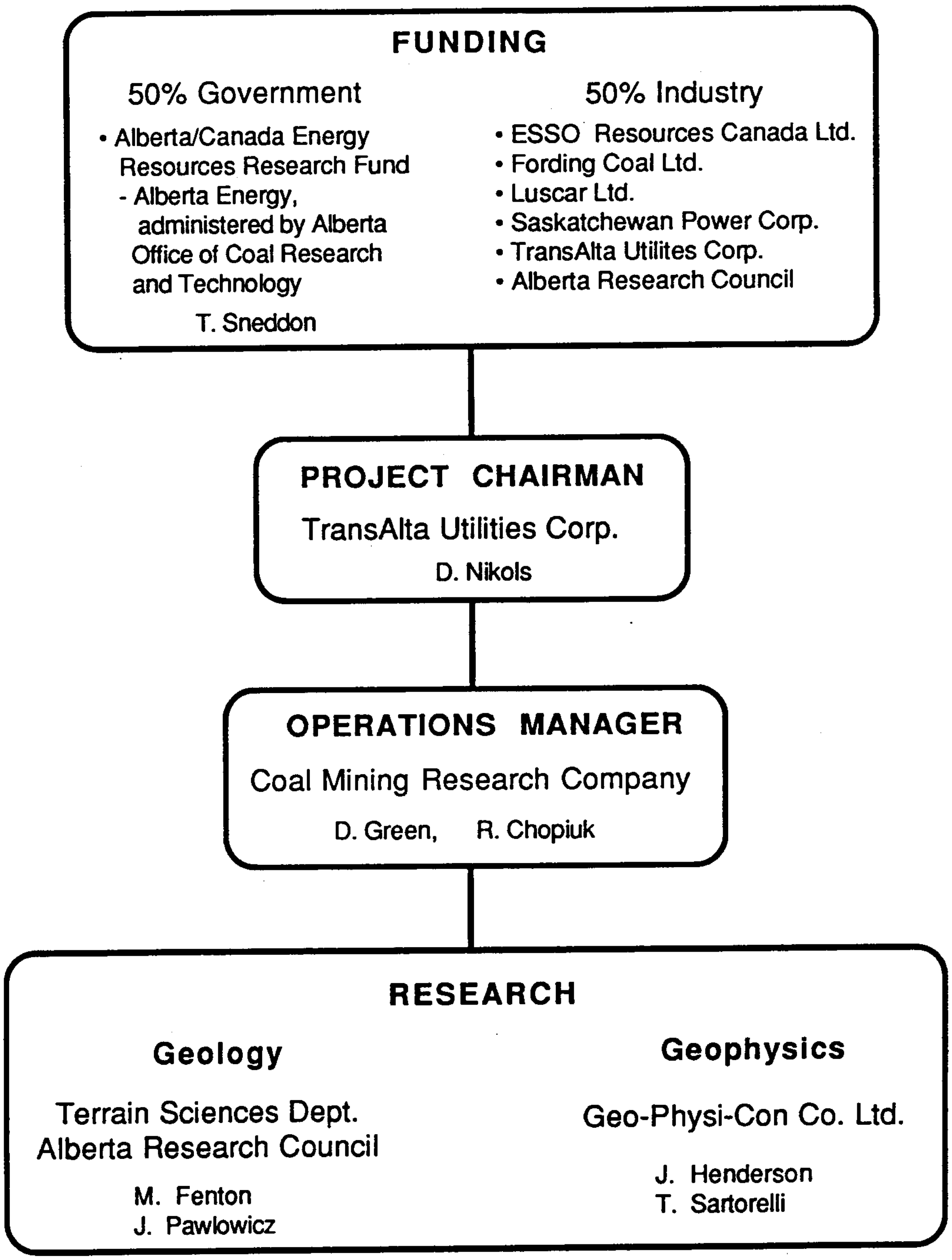

Figure 1.1 Project organization and funding.

Specific objectives were:

- o Location of: subcrop
  washouts
  glacially deformed bedrock.
- o Detection of subsurface strata and their continuity.
- o For targets depths of 10 to 70 metres:
  - development of reflection seismic techniques.
  - application of refraction seismic and electrical techniques.
- o Enhanced methods of data acquisition, processing and interpretation.
- o Application of techniques to the widest possible range of locations and material types.
- o Detection of the till - bedrock contact.
- o Correlation of downhole and surface geophysical data.

1.4 Scope of Work

The research for Surface Geophysical Coal Research Project was conducted over a three year period with study sites selected from three different mine areas.

The first year of the program in 1984, consisted of studies at Luscar's Paintearth Mine and Pit 2 of TransAlta Utilities' Highvale Mine. These studies succeeded in defining:

- o The thickness of overburden till.
- o The lateral location of coal subcrop.
- o Identification of glacial overthrusting and the lateral boundaries of glacial disturbance.
- o The thickness of overburden till.

The results of these studies are detailed in the report Surface Geophysical Project 1984, Highvale Mine and Paintearth Mine, Volumes 1 to 5.

In 1985, the second year of the program consisted of studies at Edmonton Power - Fording Coal's Genesee coal property and Luscar's Paintearth Mine. These studies succeeded in:

- Locating coal subcrop using reflection seismic and direct current profiling geophysical methods.
- Correlating reflection seismic events to specific coal seams.
- Establishing the continuity of the coal.
- Determining that refraction seismic velocity anomalies are correlatable to geological units in the overburden.
- Showing that an integrated surface geophysical/geological investigation can be less costly than a conventional program without geophysics.

The results of these studies are detailed in the report, Surface Geophysical Project 1985, Genesee and Paintearth Mine Sites Volumes 1 to 3.

The third and final year of the program in 1986 consisted of a detailed study at the Genesee coal property owned by Fording Coal Ltd., and Edmonton Power. The studies showed that:

- Drilling targets can be defined by using the combined geophysical and geological approach.
- Geophysical methods alone may quantify a variety of geological targets.
- The combined approach is suitable for replacing the conventional infill drilling method for defining mining problem areas.

Geological targets successfully identified were:

- o Coal subcrop.
- o Continuity and depth of coal.
- o Areas of structurally deformed materials.

The results of this study are detailed in Surface Geophysical Project 1986, Genesee Mine Area, Geological Report and Surface Geophysical Project 1986, Genesee Mine Area, Geophysical Report.

The significant results arising out of all three years of the surface geophysical study are presented in this report Surface Geophysical Coal Project, 1984 to 1986, Final Report.

Over the duration of this project, large amounts of geophysical and geological data were collected from annual field programs, resulting in numerous interim reports. A list of all reports produced for this project is available in Appendix 10.1.

2. TECHNICAL METHODS

2.1 Geology

Geologic information was collected in order to provide control for the geophysical tests and prove up the targets in each area. These targets included glacially deformed terrain, coal subcrop, buried channels and stratigraphic continuity. Over the three year duration of the project, a glaciotectonic unit classification scheme has evolved which describes the types and degrees of deformation of the sediment (Pawlowicz 1986). The understanding and interpretations made at each site were based on data collected by the following means.

2.1.1 Airphoto Interpretation

The first step in the investigation was the preparation of an airphoto reconnaissance map of the Highvale, Whitewood and Genesee study areas (Fenton 1983, 1984, 1985, Moell et al. 1985a). Areas where bedrock had been deformed and displaced by glacial thrusting were identified and possible study targets were chosen based on the airphoto interpretation.

2.1.2 Drilling

Drilling was carried out at all sites to provide the subsurface geologic control. Drilling methods employed were:

- Wireline core.
- Conventional rotary.
- Reverse circulation.
- Auger drilling.

The first three methods utilized drilling mud for circulation while auger drilling and sampling was dry. All wireline coreholes were logged for lithology, structure and relative hardness of the sediment. Reverse circulation and rotary boreholes produce chips and were lithologged only. Auger drilling with solid stem auger produced bulk sample that was logged for lithology and sampled for moisture content. Auger drilling with hollow stem auger produced a 2 foot oriented core that was logged for lithology and structure (Moell et al. 1985b).

2.1.3 Downhole Geophysical Logging

Downhole geophysical logs were run in all except the auger holes. Conventional lithologic identification was carried out utilizing the geophysical log suite. A typical suite is shown in Figure 2.1. In some cases the data obtained from the log suite aided in the recognition of the glaciotectonic unit boundaries. Experience gained in using all the logs, especially sonic and density proved useful in recognizing glaciotectonic units in holes where the geologic data was inconclusive (Moell 1985a). The usual suite of logs run in each hole consisted of:

- Natural gamma.
- Focused electric.
- Caliper.
- Density (gamma-gamma).
- Sonic (interval transit time).

Additional logs run in selected holes included:

- Duel spaced neutron.
- Dipmeter (3 pad microresistivity + analysis).
- Strength index (synthetic log produced from mathematical combination of sonic and density data).

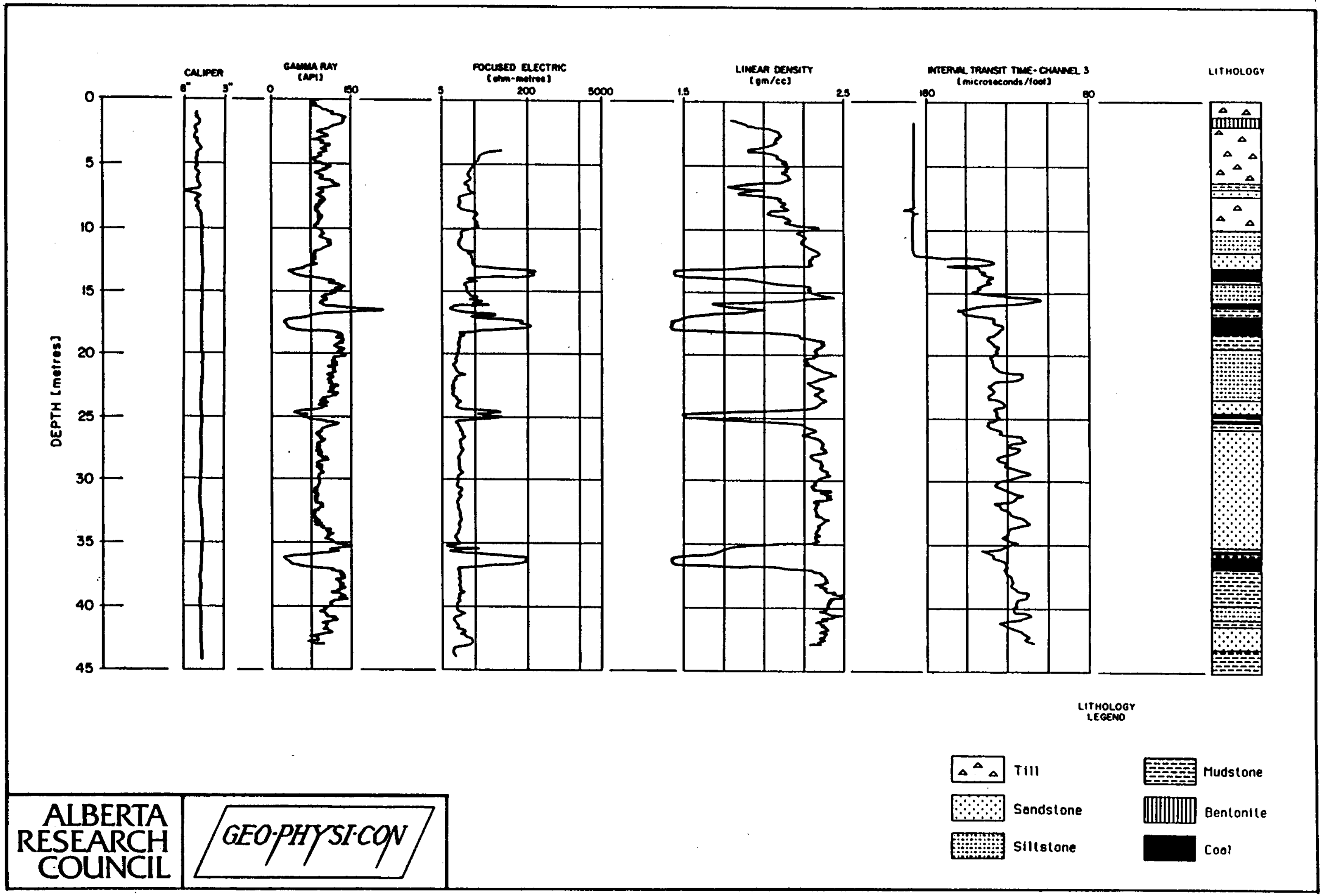

Figure 2.1 Typical suite of downhole geophysical logs used in this study.

2.2 Surface Geophysics

Surface geophysical measurements are routinely used in many resource development industries to provide an estimate of subsurface structure or to delineate specific subsurface targets. The successful application of surface geophysical measurements for these purposes relies on the existence of suitable contrasts between the physical properties of target strata and those of surrounding materials. The unique physical properties of coal make it a suitable target for detection by geophysical methods. For this reason seismic and electrical surface geophysical methods have been tested for this research project. The physical properties of the materials that are being measured, followed by descriptions of the physical basis upon which these methods operate are presented in this section. A more in depth explanation is presented in Appendices 10.2 and 10.3.

The manufacturer's specifications for the instrumentation used to perform geophysical surveys are provided in Appendix 10.4.

2.2.1 Physical Properties

The physical properties of bedrock and unconsolidated surficial sediment commonly present in plains coal mining areas are generally well known as a result of mining activities and the extensive downhole geophysical logging of most drillholes. Typical ranges for physical properties of coal and surrounding rocks are illustrated in the downhole geophysical logs from the Genesee test site in Figure 2.1.

Coal is distinct from other materials in that it exhibits very low density, low gamma ray, and very high resistivity. The low gamma response is not useful for surface geophysical studies due to the high absorption of gamma rays by overlying materials. The sonic velocity in coal is also not substantially different from surrounding materials. However, the impedance contrast (product of density and velocity) is large, due to the low density of coal. These resistivity and impedance properties indicate that coal represents an excellent target for exploration using surface based electrical and reflection seismic techniques.

Major contrasts in sonic velocity are also known to occur at the boundary between unsaturated materials and saturated materials or bedrock. The sonic velocity in saturated materials and bedrock are in general quite similar. A large shear wave velocity difference, however, is often apparent when bedrock is of sufficient competency. These features indicate that the depth to bedrock and its anticipated strength can be determined using refraction seismic methods.

The electrical resistivity of unconsolidated materials and bedrock are dependent upon the preponderance of clayey materials (McNeil 1980). Generally, granular materials are more resistive than fine-grained materials, and sandstones more resistive than shales. These features allow estimation of the variation of material type or bedrock lithology to be made using a variety of electrical geophysical prospecting methods.

2.2.2 Seismic Methods

Plane wave solutions to the equations of motion governing seismic energy propagation within the subsurface indicate that energy propagation is restricted to two body wave modes. These are the compression and the shear wave. The compression wave causes particle vibration along the direction of energy flow, while for the shear wave this vibration is transverse to the direction of energy flow. Within a small distance of the earth's free surface an elliptically polarized Rayleigh wave (ground roll) can also occur. This wave mode is mainly responsible for the dissipation of source generated energy. All of these wave types are created by the release of seismic energy. The partition of energy between the different wave types depends on the source design and source coupling to the earth.

Each of these wave types propagate at a characteristic velocity. The velocity of the compression wave is the highest of the three. The velocity of the shear wave is intermediate in value and approaches the velocity of the ground roll as the ratio of compression wave to shear wave velocity (the velocity ratio) increases. The velocity of propagation of the shear wave is also basically independent of the presence and type of pore fluid (Kolsky 1963 and White 1983).

The velocity ratio is an important parameter characterizing the dynamic elastic moduli of earth materials. Standardly used moduli include Poisson's ratio, the Shear modulus, Young's modulus, the modulus of Bulk compressibility, and the Lame compressibility modulus. Relations for these moduli in terms of the velocity ratio and material bulk density are presented in the various geophysical reports submitted as a part of this project.

The velocity ratio has been found to be a useful indicator of anticipated bedrock material strength. Structurally weak bedrock has been observed to exhibit velocity ratios about 2 to 3 times as large as more competent bedrock materials. This difference arises out of anomalously low shear wave velocity exhibited by less competent bedrock. Accurate characterization of the velocity ratio depends on the ability to measure the propagation times of compression and shear waves independently (Sartorelli et al. 1986).

Both the compression and shear waves can reach surface geophones along a variety of wave paths. These may be either direct wave paths or wave paths that have been reflected or critically refracted, according to Snell's laws, from subsurface strata exhibiting contrasts in seismic velocity or seismic impedance.

Three general seismic methods have been applied during this study. Each of these relies on the propagation of seismic body wave energy along the types of wave paths described above. The direct path is utilized for crosshole seismic studies, where the source and geophone are placed at the same depth in adjacent boreholes separated by relatively small distances. The critically refracted wave paths are utilized for surface based refraction seismic studies. The critically refracted wave carries information about the seismic velocity of critically refracting strata, as well as the velocity and thickness of overlying materials. The energy arriving along either direct or refracted wave paths represents travel time minimums, and the arrival times are linear in terms of distance, for layers with constant velocity.

The reflected wave paths are not minimum time paths, so that reflected events need be recognized admist energy arriving via other travel paths. This causes complications in the use of the reflection seismic method at shallow depth. The square of reflected arrival times are linear with the square of distance between source and geophone for layers of constant velocity.

2.2.2.1 Refraction Seismic Method. Either the compression wave or the shear wave can be critically refracted along boundaries between materials where the lower material has a velocity greater than the upper material. The compression wave is most often used for this purpose since the identification of the moment at which the compression energy arrives at a geophone is simplified by the fact that this energy appears before energy transmitted by other modes. When the shear wave is used, the energy arrives at a time later than energy propagated by the compression wave. To unambiguously define the shear wave arrival at a geophone, use is made of the fact that the shear wave is polarizable. That is, the shear wave exhibits a phase reversal on two records when each record corresponds to oppositely directed source energy. The shear wave can be polarized in either a horizontal or vertical direction. For refraction seismic applications, horizontally polarized shear waves are used since these waves do not create other types of waves when they are incident on a horizontal geologic boundary.

2.2.2.2 Reflection Seismic Method. A major advantage of the reflection seismic method is that it presents a very direct way to locate subsurface boundaries which exhibit a contrast in acoustic impedance. Other advantages of the method over refraction techniques include the ability to probe to depths much greater than the source to sensor separation and the ability to sense the presence of a subsurface boundary characterized by a velocity inversion, i.e., a decrease in material velocity below a subsurface boundary.

Coal represents an excellent reflecting surface since the lower density of coal compared to the density of surrounding rocks creates a large contrast in acoustic impedance. The corresponding reflection coefficient is in the order of ± 0.3. Reflection coefficients for other boundaries exhibiting only minor velocity and density contrasts are in the order of ± 0.05 to ± 0.1. For this reason the surfaces of coal seams can be expected to correlate to the strongest events on reflection seismic records.

The need for high frequency content is critical for shallow compression wave reflection seismic studies. The dominant frequency controls the effective seismic wave length according to the relation

$$\lambda = v/f$$

where λ is the wavelength (m),
v is the average velocity (m/s), and
f is the frequency (hertz)

Vertical resolution of thin beds for the method can be expected to range between 1/4 and 1/8 of the dominant wave length achieved. Sartorelli et al. (1986) describes features of reflection seismic exploration at shallow depth in Alberta.

Little use has been made of the reflected shear wave to date even though the lower shear velocity will result in a wave length smaller than for the compression wave. Complications in this regard arise due to the small difference between the velocities of the shear wave and the ground roll. Consequently, large source offsets are required to open a suitable time window through which reflected shear waves can be observed. Investigations of a novel seismic source capable of delivering shear wave energy over relatively great distances are described in Geo-Physi-Con (1985c). The reflected shear wave may find application for investigations of deeper coal seams.

2.2.2.3 Crosshole Seismic Method. Crosshole seismic measurements are acquired to confirm the general thickness and velocity structure determined from refraction seismic measurements. The tests are performed in a set of three in line drillholes. A downhole hammer, capable of producing compression and vertically polarized shear waves, is used as the source. Propagation times of the compression and shear waves are measured along direct wave paths at depth intervals of 1 m to achieve the resolution required for this study (Geo-Physi-Con 1981).

2.2.3 Electrical Methods

The electrical resistivity of earth materials can be measured from the surface of the earth using a wide variety of techniques. However, plains coal deposits are generally located in low resistivity environments. The low resistivity arises from the preponderance of clayey material in the overburden and bedrock. The presence of low resistivity materials restricts the types of electrical exploration that can be beneficially employed. Two electrical exploration techniques have been routinely used during this project, as described below.

2.2.3.1 Direct Current Method. The direct current method has been employed in sounding and profiling modes. In both cases the measurements are sensitive to the large resistivity contrast between coal and surrounding rocks. In the sounding mode, direct current measurements can be used to derive the resistivity and thickness of strata overlying coal. A Schlumberger electrode array is preferred. The method is useful for determining the presence and depth to coal but does not often determine the thickness of coal seams. This results from the fact that the high resistivity of the coal insulates underlying strata from investigation. Penetration beneath coal can generally be expected to require larger source and array sizes than is practical.

Direct current profiling methods are performed using a pole-dipole array. These measurements yield very local estimates of earth resistivity and are used to determine the location of coal subcrop. The lateral precision with which the subcrop can be located depends to large extent upon the depth of burial of the coal and the complexity of the distribution of electrical resistivity for surrounding materials.

2.2.3.2 Fixed Frequency Electromagnetic Induction. The fixed frequency electromagnetic induction technique is used to obtain estimates of the variation of electrical conductivity (inverse of resistivity) within the subsurface. The presence of low resistivity materials at typical plains coal mine developments generally restricts the use of the method to determine a detailed resistivity-thickness section, as can be derived from direct current soundings. However, the measurements are useful for mapping the lateral extent and thickness of more resistive surficial materials (e.g., gravel or peat), large scale variation in bedrock lithology at depth, and serve to guide the location of direct current soundings which are much more sensitive to the occurrences of lateral variation in earth resistivity.

2.2.4 Other Methods

Other geophysical methods have been used for coal exploration in general, but have not been applied to any large extent in this study. They are described briefly below.

Transient electromagnetic soundings are a sophisticated electrical prospecting method that finds much use for exploration of targets at relatively larger depth than typically required in the plains coal mining areas. Its use for coal has mainly been to determine the thickness of sedimentary rocks overlying intrusives and delineating low resistivity marker horizons at depth.

Electromagnetic measurements at very low frequency (VLF) have been used in some areas in attempts to locate coal subcrop. The VLF system is a passive receiver. The transmitter signal is generated by high power, low frequency communication carrier waves used by the navies of the world. VLF measurements are operator sensitive, can be badly distorted in mountainous areas, and are skin depth limited. The skin depth is the depth at which the energizing field fall to about 37% of their strength at the ground surface. The skin depth, considering the usual operating frequency range and the general low resistivity environment for VLF measurements in prairies coal areas, can be expected to be less than 10 metres.

Electromagnetic measurements at very high (radar) frequency have previously been proposed as a method of exploration for plains coal reserves. The skin depth limitations at the high operating frequencies required are, however, quite overwhelming. Considering an operating frequency range of 10 to 100 megahertz and the low resistivity of typical surficial materials, the skin depth can be expected to be in the order of 0.2 to 1 metre.

Gravity measurements make use of the density contrasts of subsurface materials. The method is generally suitable for estimating the vertical and lateral extent of sedimentary basins, and sometimes major accumulations of coal. The Hat Creek deposit in British Columbia for example, was outlined using gravity surveys. Their use for identifying relatively thinly bedded coal seams at shallow depth cannot be expected to be feasible.

Magnetic measurements are used in some areas to locate coal subcrop. In these areas the coal subcrop had been burned creating a residual magnetic field in the clinker.

3. TARGET DESCRIPTION

The Surface Geophysics Project study areas are located in the vicinity of Lake Wabamun at the Whitewood, Highvale and Genesee Coal Mines and at the Paintearth Coal Mine near Forestburg (Figure 3.1) The geology varies between areas and targets within specific study areas. Short descriptions of the general geology and the primary targets for each study area are presented in the following sections.

3.1 Wabamun Lake Area

Wabamun Lake is located approximately 80 km west of the city of Edmonton (Figure 3.1). Active open mining pits at the Highvale and Whitewood Mines provide good exposures of the stata in the highwalls. The Genesee Mine which has not yet commenced mining operations has only limited bedrock exposures. Bedrock geology consists of Upper Cretaceous and Paleocene, non-marine, coal bearing rocks of the Paskapoo Formation (Figure 3.2). The coal deposits belong to the Ardley Coal Zone (Holter et al. 1975) which forms part of the Scollard Member as defined by Irish (1970) and Carrigy (1970). The Ardley Coal Zone in the Highvale and Whitewood Mines is a 15 m thick sequence of coal seams with mudstone and bentonite interbeds. The seams are identified from top to bottom, as seams 1 to 6. The Paskapoo Formation is regionally underlain by the Battle formation.

3.1.1 Highvale Mine

Studies were conducted in portions of the Pit 02, 03, and 04 areas (Figure 3.3). Stratigraphy of the overburden in the Pit 02 area is from top to bottom; till, in places a thin upper mudstone unit (Unit 40), 15 m thick sandstone-siltstone unit (Unit 60), and a lower mudstone unit (Unit 80) about 5 m thick. In places the bedrock sequence shows strong evidence of glacial deformation. The geologic setting at this pit serves a good example for using surface geophysical techniques

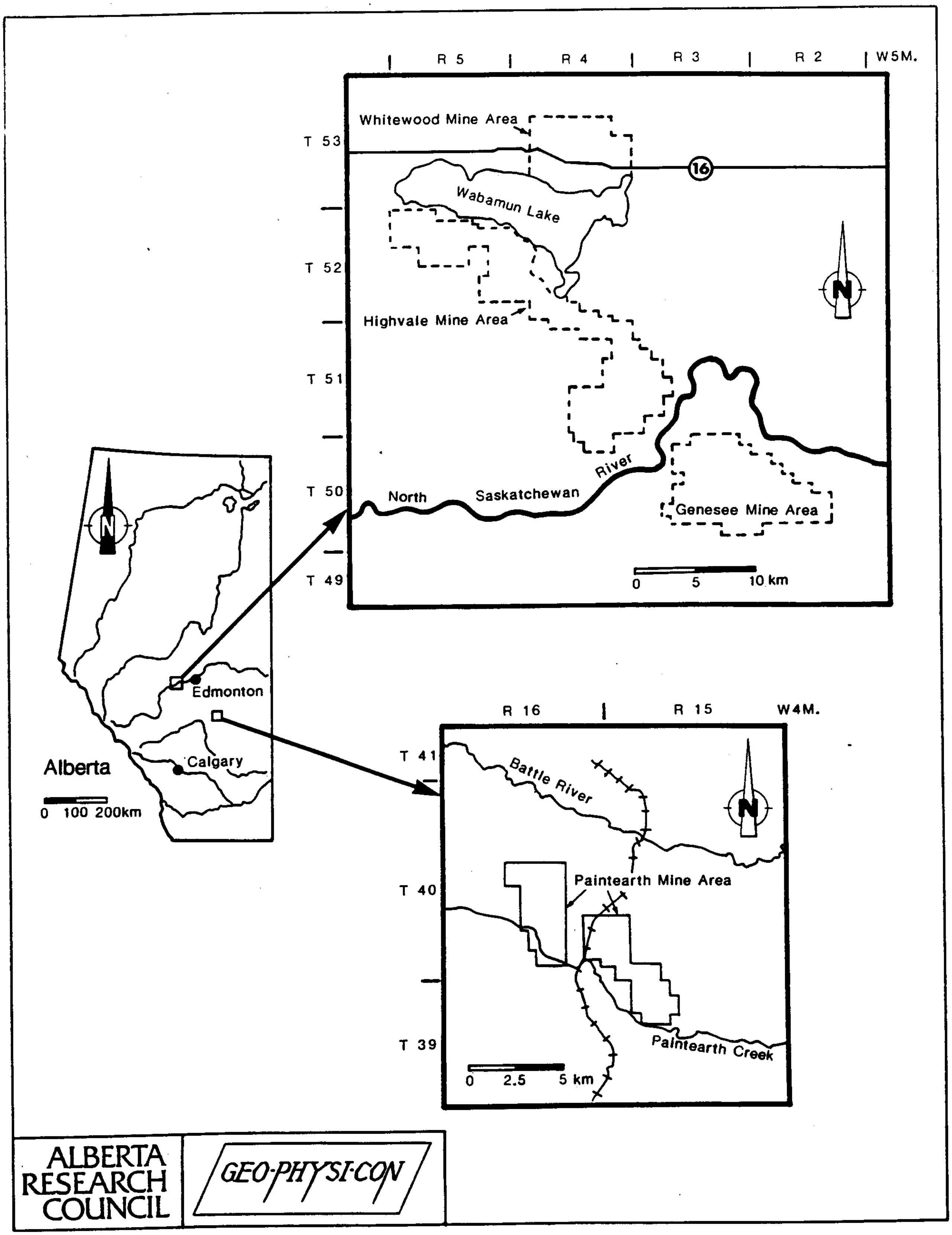

Figure 3.1 Location of the Whitewood Mine, Highvale Mine, Genesee Mine and Paintearth Mine study areas.

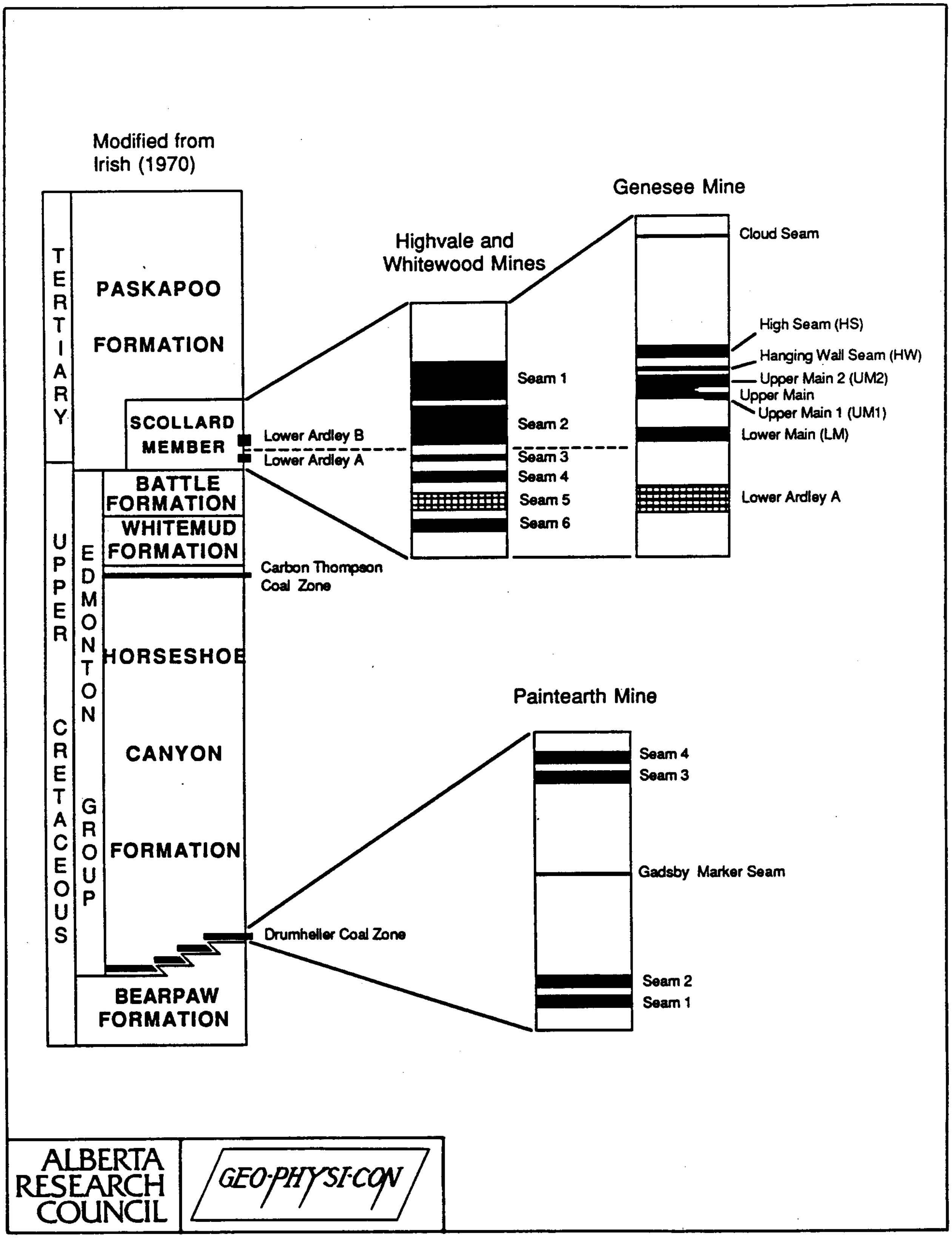

Figure 3.2 Stratitgraphy of Highvale, Genesee and Paintearth Mine areas.

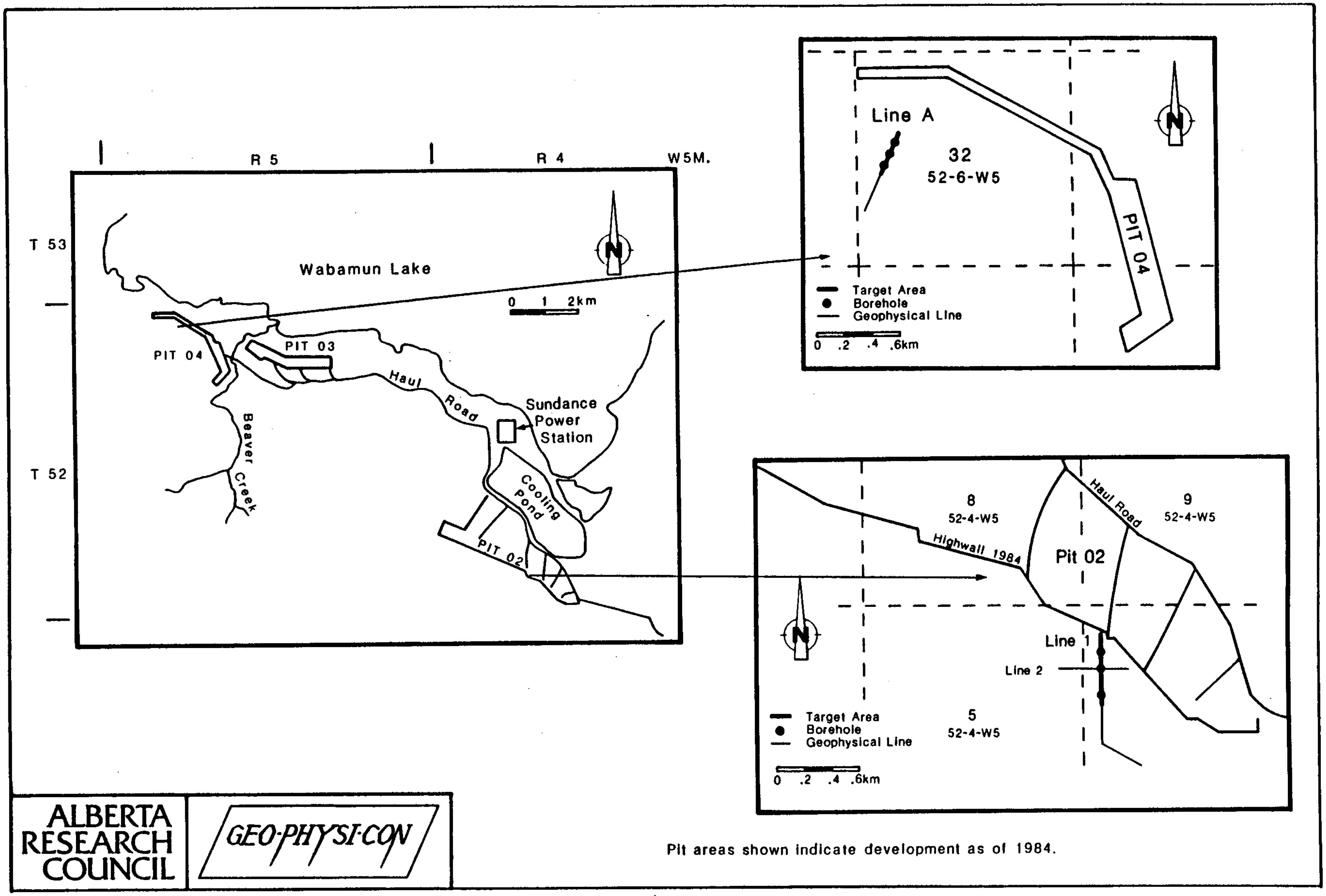

Figure 3.3 Map of study sites in the Pit 02 andf Pit 04 areas of the Highvale Mine.

to demonstrate stratigraphic continuity.

The geophysical test area at Pit 03 is shown in Figure 3.4. the stratigraphic setting is, from the top; about 3 m of till, a 20 m thick sandstone sequence (Unit 50), discontinuous mudstone layer (Unit 80) up to 5 m thick followed by the mineable coal seams. Evidence for glacial deformation of the bedrock exists throughout much of the Pit 03 study area, forming the target for geophysical tests.

In the Pit 04 area, tests were conducted on a NE trending line (Figure 3.3) to recognize and delineate deformation terrain. The test line intersects a NW trending ridge of highland formed from glacially thrust and deformed bedrock. Stratigraphy consists of a till mantle over a 25 m thick deformed mudstone/siltstone. This rests on 10 to 15 m of undeformed interbedded mudstone/siltstone that overlies the coal sequence.

3.1.2 Whitewood Mine

The Whitewood Mine is located on the north side of Wabamun Lake (Figure 3.1). The geophysical targets here were primarily the coal subcrop along the north side of the mine and secondarily the deformed bedrock. The surficial geology generally consists of till and clay interbeds overlying discontinuous unconsolidated layers of preglacial sand and gravel. The bedrock is interbedded mudstone, siltstone and sandstone overlying the six seam coal sequence. The bedrock along the north side of the mine has been subjected to glacial tectonism in many places.

3.1.3 Genesee Mine

The Genesee Coal Field is located 25 km southeast of Wabamun Lake (Figure 3.1) on the subcrop of the Ardley Coal Zone. The bedrock is composed of typical Paskapoo sandstones and underlain by finer

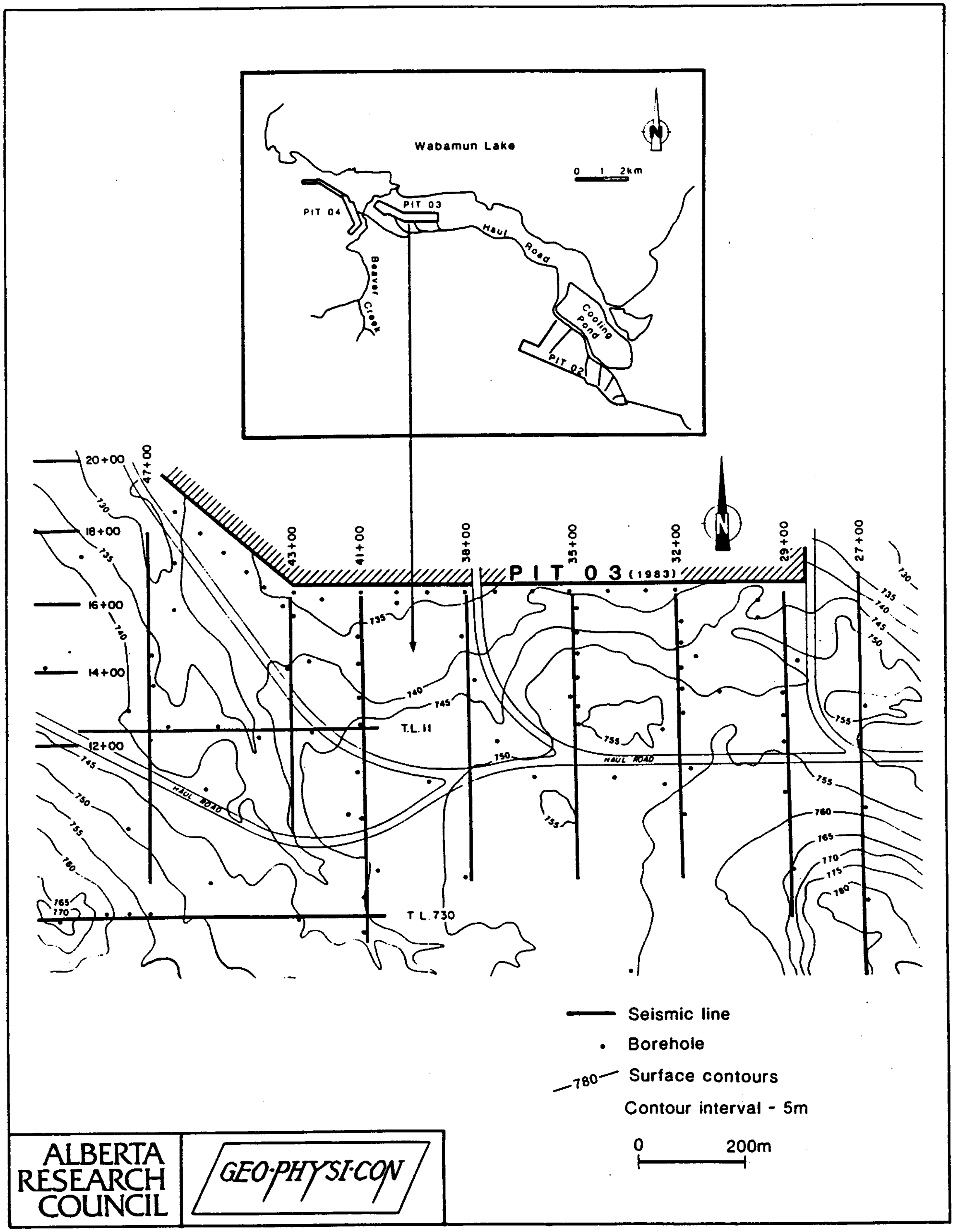

Figure 3.4 Map of the Pit 03 area in the Highvale Mine.

grained clastics of the Scollard Member which is much thicker here than at Highvale. The coal seams are separated by thicker interbeds of sandstone, siltstone, mudstone with minor bentonite and concretionary horizons. The mineable resources come from the Lower Ardley B coal zone which is correlatable with seams 1 and 2 from the Highvale Mine (Figure 3.2). The Lower Ardley A which correlates with seams 3, 4, 5 and 6 is uneconomic. Three mineable seams are present in the Lower Ardley B and are locally named, from top to bottom, High Seam (HS), Upper Main seam (UM), and Lower Main seam (LM) as shown in Figure 3. Two targets selected here were a buried glacial channel cut into the bedrock and the coal subcrop.

3.2 Paintearth Mine

The Paintearth Mine area is located about 200 km southeast of Edmonton (Figure 3.1). The mineable coal is distributed among four seams in the Lower Horseshoe Canyon Formation (Figure 3.2) which is comprised of interbedded bentonitic shales and feldspathic sandstones. The coal seams are, from bottom to top, seams 1 to 4. The interburden that separates seams 1 and 2 from seams 3 and 4 is about 20 m thick and is characterized by four coarsening upward cycles. Locally the upper portion of the bedrock including seam 4 has been glacially deformed. This deformation was targeted for delineation in a portion of the mine area.

4. TARGET RECOGNITION

The exploration objectives proposed for surface geophysical research during the extent of the coal project varied according to which sites field tests were to be conducted. The following examples describe results of the geophysical surveys for the major targets.

Examples are drawn from all sites at which field work was conducted, as well as selected results from the TransAlta Utilities Corporation, Whitewood and Highvale Mines, and Fording Coal Ltd., Genesee Mine area for which field studies were conducted outside of the present surface geophysical research project.

4.1 Buried Channel

In the second and third year of the study, the investigation focused on a site, at the Genesee Mine, known to cover a buried channel. The results showed the effectiveness of the geophysical methods and led to a reinterpretation of the channel geometry and the location of the coal subcrop.

4.1.1 Genesee, Site 1 - Line 2

The buried channel is located in section 9 at test site 1. Figure 4.1 shows the location of four test lines on which several surface geophysical methods were run to delineate the channel which trends north-south and has eroded into the bedrock causing the removal of a sizable portion of the coal seams. During glaciation the channel was infilled with sediment resulting in generally flat featureless terrain. The results from a segment of Line 2 between stations 400 and 900 illustrate the profile of the east edge of the channel in Figure 4.2.

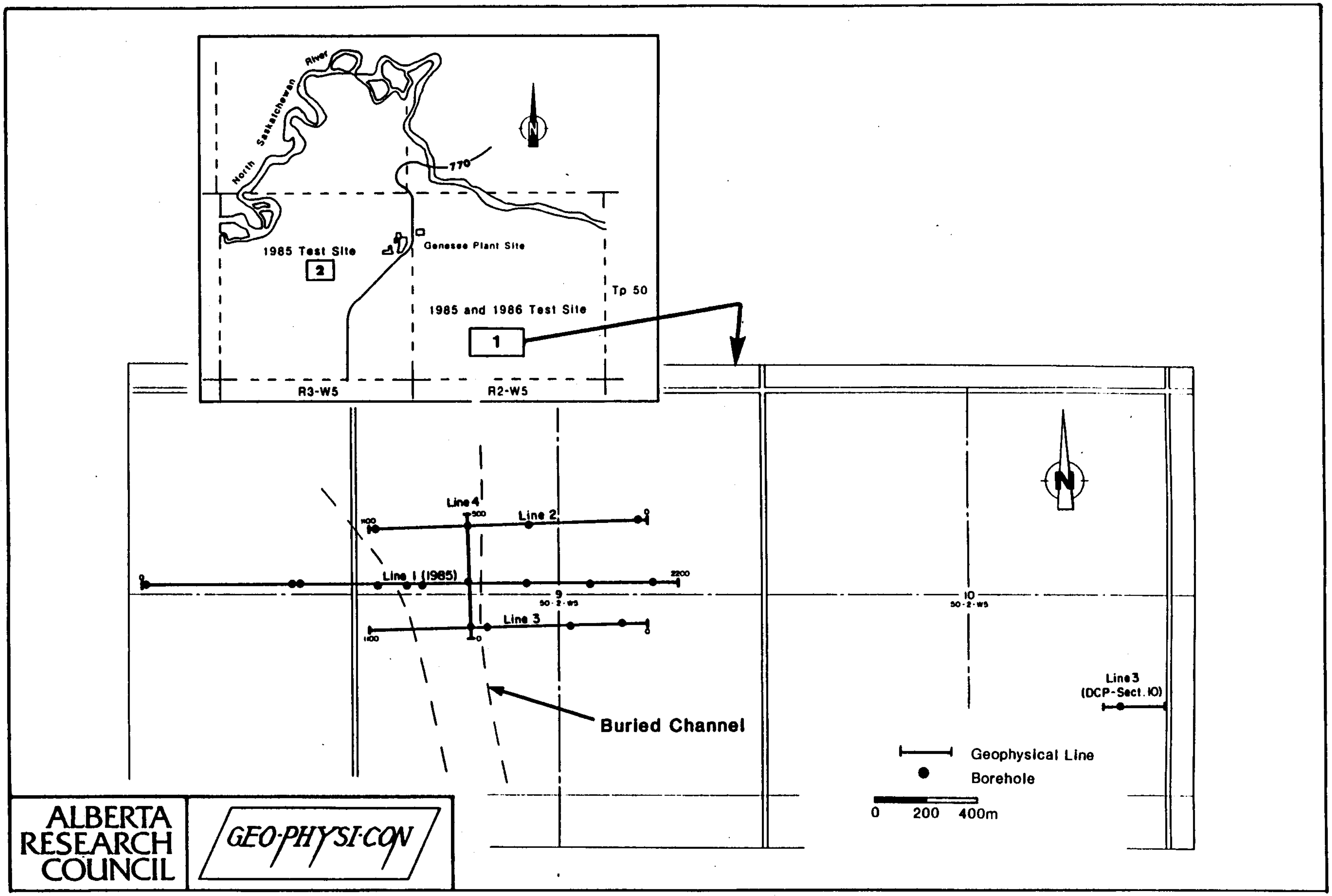

Figure 4.1 Map of Site 1 (buried channel site) in the Genesee Mine area.

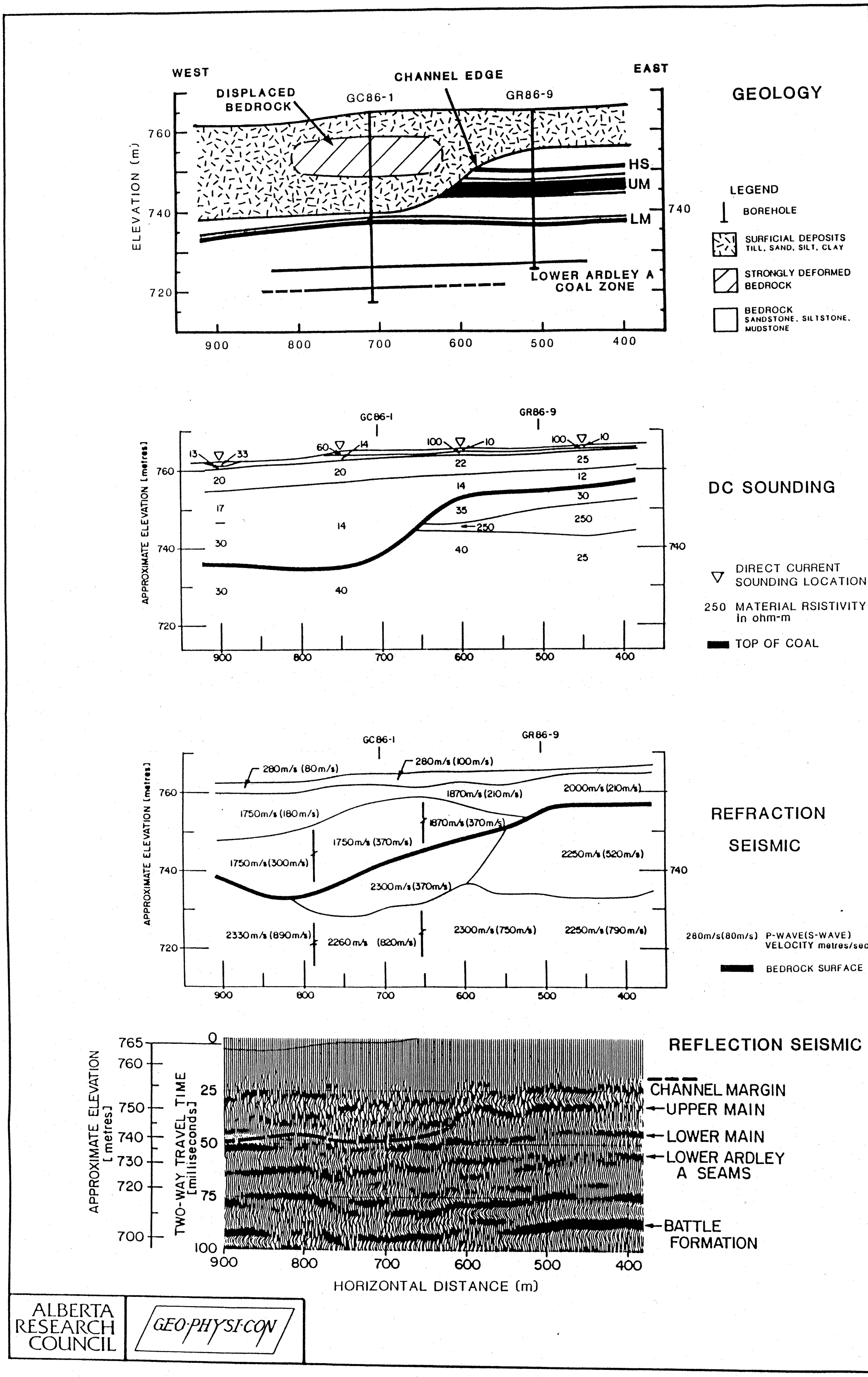

Figure 4.2 Location of buried channel using direct current sounding, refraction seismic and reflection seismic methods from Line 2, Site 1 in the Genesee Mine area.

The geologic section in Figure 4.2 shows that the channel is located west of station 600. The surface of the land is flat with no depression to indicate its position. On this line, the width of the channel is greater than 500 m; the western edge was not intersected. Depth to bedrock is about 25 m within the channel and 10 m outside the channel. Surficial sediment is mostly clay till with minor deposits of clay and silt at surface. Channel fill contains surficial deposits and large blocks of displaced bedrock material.

All the sediment overlying bedrock is poorly consolidated. Bedrock is composed of sandstone, siltstone, mudstone and coal typical of the Ardley Coal Zone. The only evidence of deformation in the bedrock is a high degree of fracturing near surface that was likely caused by loading from the glaciers. The coal seams appear flat-lying and, except for the Lower Main which extends beneath the channel, subcrop at the channel edge between stations 550 and 650.

The geophysical methods tested were reflection and refraction seismic and direct current sounding. All drillholes were located based on the interpretation of geophysical data.

Figure 4.2 shows the geoelectric section composites from a number of direct current soundings. Soundings traced the upper coal seam to the channel edge at about station 600.

The sediment filling the channel is characterized by relatively low resistivity in comparison to the surrounding bedrock. The absence of shallow lying high resistivity zones (coal) west of station 600 indicates that the channel extends across the entire western portion of the survey line.

The refraction seismic section in Figure 4.2 shows the interpretation of shear and compression wave measurements. The bedrock surface corresponds to the location of the darkened boundary marking the upper extent of materials exhibiting compression wave velocity greater than 2000 m/s. Bedrock materials show a range of shear wave velocities. The low shear wave velocity observed at the base of the channel indicates that this bedrock may be less competent. The increase in shear wave velocity of channel fill materials west of station 550 as compared to overlying unconsolidated sediments is indicative of the presence of displaced bedrock materials. The thickness of these materials cannot be inferred from the refraction seismic data.

The reflection seismic section in Figure 4.2 shows a segment of the seismic data collected from survey Line 2. The channel edge is associated with the subcrop of the Upper Main seam at about station 600. The Lower Main seam is seen to be present beneath the channel throughout this area. The darkened events on the reflection seismic section correspond to the upper surfaces of low impedance zones. Each trace represents data from up to six different source to geophone geometries, and correspond to 2.5 metre intervals along the survey lines.

All three geophysical methods showed a change in physical properties of subsurface sediment west of station 600. Results from drilling confirmed that these changes were due to different sediment types found within a buried channel that had cut into bedrock. The channel edge and coal subcrop were also proven correct from drillhole data.

4.2 Subcrop

Through the course of this study it has been found necessary to define how the terms 'subcrop' and 'location of subcrop' were to be used. In this report subcrop represents the entire width of the subsurface outcrop of a coal seam.

Several study sites were chosen to test the usefulness of surface geophysical methods in locating coal seam subcrop. Location of subcrop is indicated by the station locations on the test line which represent the width of the subcrop projected to surface.

Surface geophysical measurements in most cases would locate subcrop at a single point because measurements only indicate the presence or absence of coal. In addition to the examples described in this section some of the examples described under other target recognition categories also illustrate the location of coal subcrop.

4.2.1 Genesee, Site 2 - Line 2

Methods for the detection of the coal subcrop at the Somas site, Genesee Mine, was tested in 1985. The following results are taken from Line 2-2 which is located at the NW edge of the coal field and oriented NW to SE in order to intersect the anticipated subcrop at right angles (Figure 4.3).

The geophysical method tested was common offset reflection seismic profiling. This method utilizes the density contrast of coal with respect to surrounding materials to locate the subcrop. The necessary measurements can be conveniently and economically obtained when overburden is relatively thin (<10 m) over the subcrop.

Figure 4.4 shows the composite common offset traces recorded along Line 2-2 for sources placed 40 m to the east and west of the geophone stations. The event identified as the top surface of coal is clearly visible on the east half of each figure. In Figure 4.4a the last geophone seeing the coal was located at station 100. The source location for this trace was located at station 140. The subcrop of coal can then be expected to occur at station 120, halfway between the source and geophone locations. In Figure 4.4b the last geophone seeing coal was located at station 140. The source location for this trace was located at station 100. Both figures confirm the subcrop at the west edge of the coal to occur at station 120. It is necessary to gather

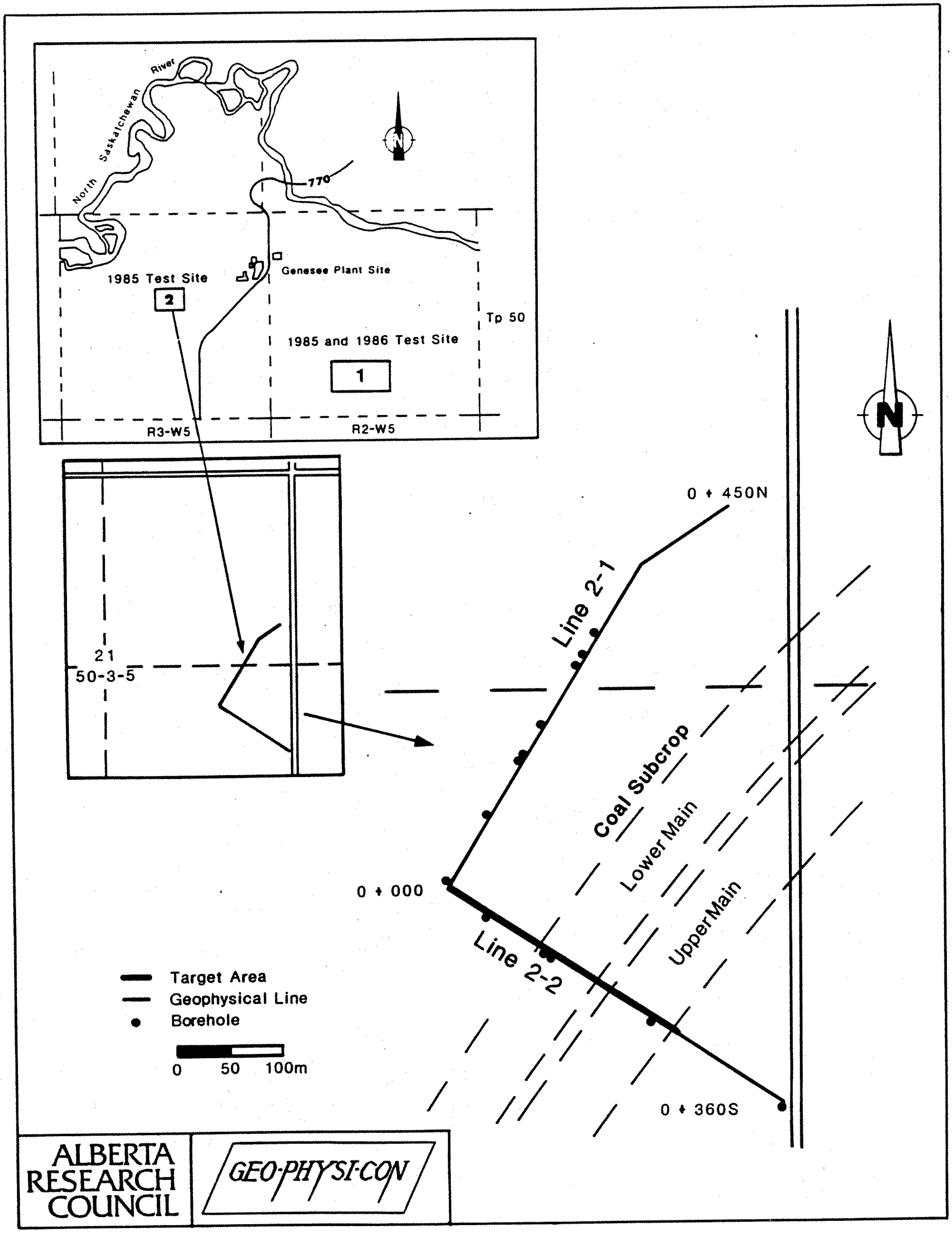

Figure 4.3 Map of Site 2 (Somos site) in the Genesee Mine area.

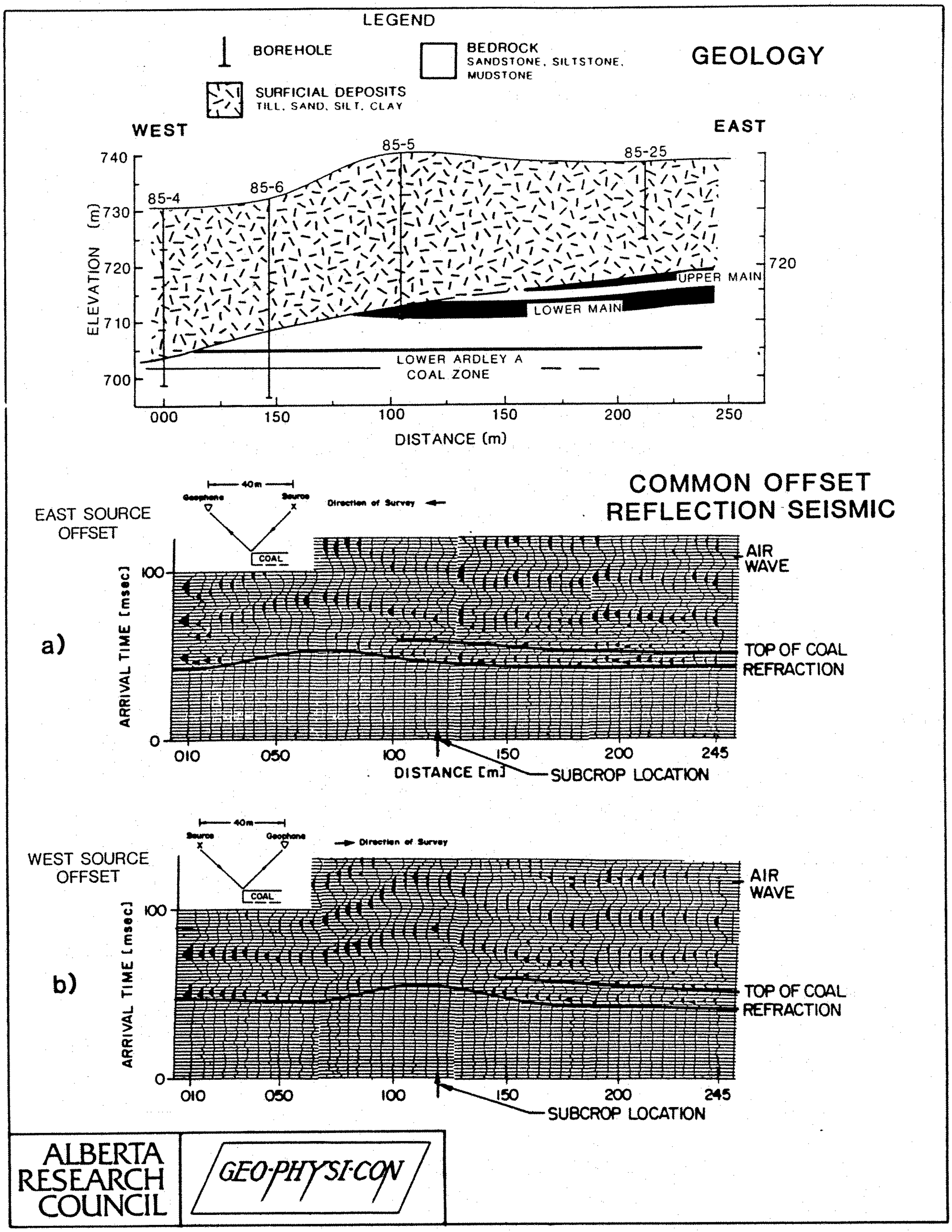

Figure 4.4 Coal seam subcrop located by using common offset reflection seismic data from line 2-2, Site 2 in the Genesee area.

data for both source - geophone orientations to reduce the possibility that subcrop location could be lost or confused amidst patterns of energy arrival resulting from seismic diffractions from the edge of coal seams.

The drilling results illustrate the geology in Figure 4.4. About 25 m of surficial sediment composed mostly of clay and till with sand an gravel deposits overlies bedrock. Surface topography decreases 10 m in elevation towards the NW and generally coincides with slope of the bedrock surface. Bedrock consists of horizontal interbeds of mudstone, siltstone, sandstone and coal with minor bentonite. The Upper Main and Lower Main seams, separated by a 1 m parting, have a cumulative thickness of 7 m. They subcrop between stations 075 and 200.

The results show that common offset reflection seismic is able to locate a shallow subcrop target to within about 50 m.

4.2.2 Whitewood Mine Site, Line 4

Common depth point reflection seismic measurements were undertaken to locate the subcrops of seams 3 to 6 along seven survey lines at the Whitewood Mine area during 1986. Results are taken from Line 4 located to the northwest side of Lake A (Figure 4.5).

The common depth point reflection seismic method, as used in this example, is basically similar to that used traditionally for hydrocarbon exploration, but scaled down to address the shallow depth range of interest. The method is superior to the common offset reflection data presented in Section 4.1.1 of this report in that more than one subsurface target layer can be monitored in a continuous fashion.

A time based reflection seismic structure section is shown in Figure 4.6. The line extends for 800 metres and clearly illustrates the

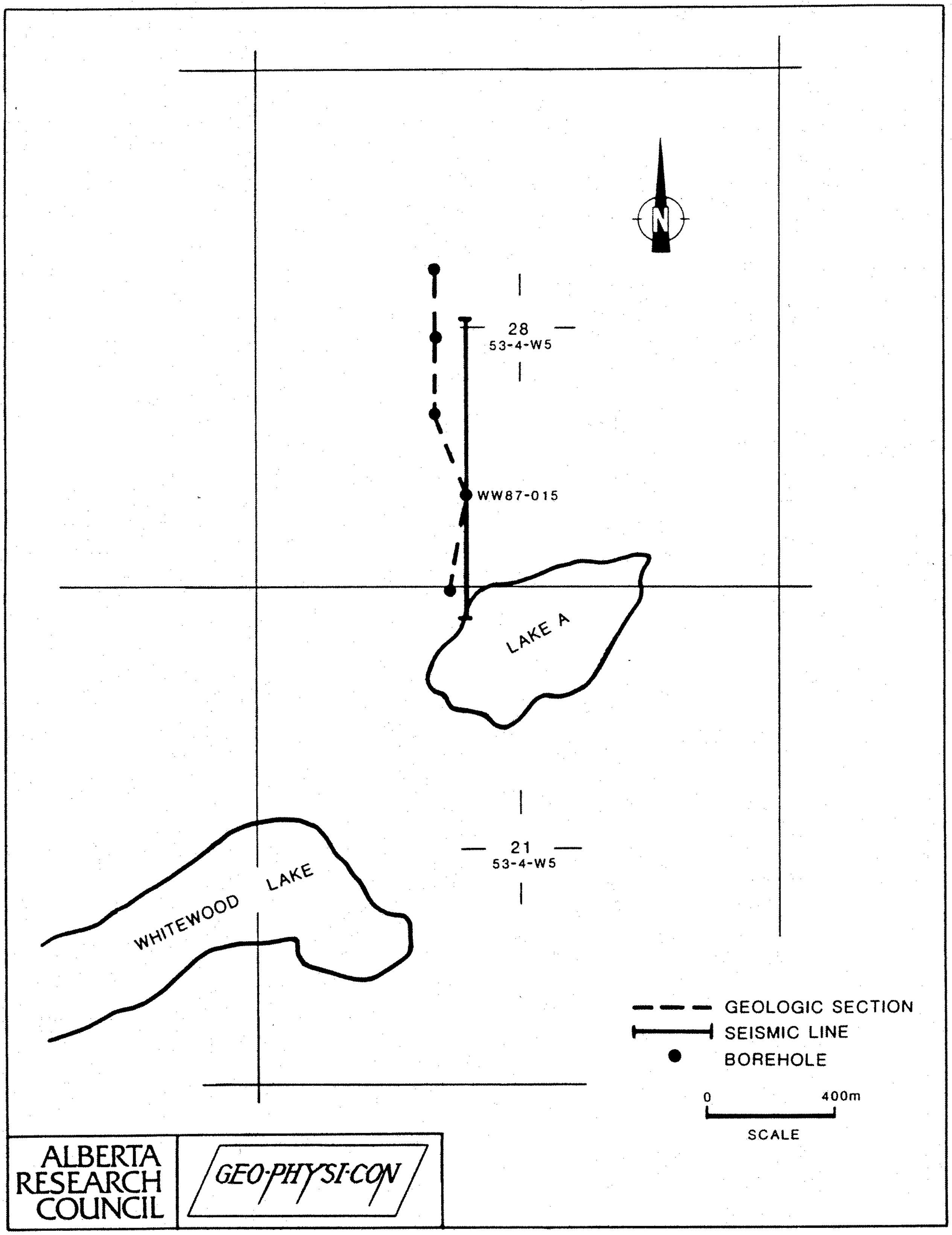

Figure 4.5 Location of reflection seismic line in Whitewood Mine area

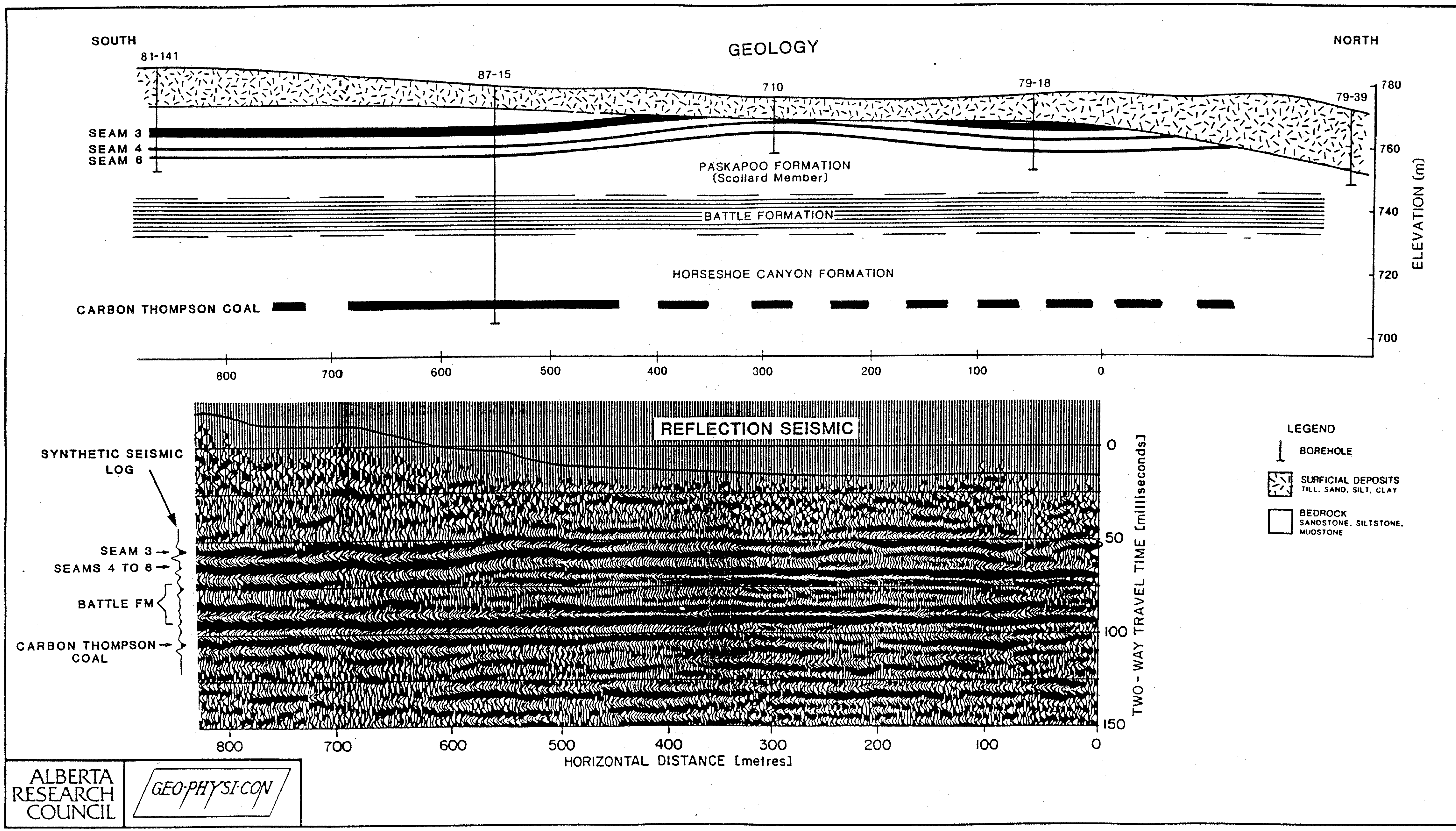

Figure 4.6 Use of common depth point reflection seismic method to locate subcrop in the Whitewoood Mine area.

high degree of detail that can be imaged from the subsurface. Darkened areas of the traces correspond to the upper surfaces of zones of reduced acoustic impedance to enhance the visibility of coal bearing sequences. Each trace has been composed from up to six different source geophone geometries. Each trace represents a 2.5 metre interval along the survey line.

The well defined event at about 50 milliseconds corresponds to number 3 seam. The event undergoes amplitude reductions between station 440 and 340 so that coal of the number 3 seam may be degraded or missing in this area. A similar amplitude reduction occurs in the vicinity of station 240. North of station 60 the event is not detected, indicating that seam 3 is absent. The deterioration of the trace between stations 60 and 440 makes it difficult to determine the proper position of the subcrop.

The darkened event immediately below seam 3 corresponds to the coal suite comprising seams 4 to 6. These seams are both thin and separated by relatively thin partings so that individual events corresponding to each seam cannot be separated. These lower seams undergo amplitude reductions in the vicinity of station 200 and 70. The event is not detectable north of station 40, indicating the absence of seams 4 to 6. Again, the subcrop cannot easily be located because of deterioration of the trace between stations 40 and 200.

Reflection events between 70 and 90 milliseconds correspond to the zone encompassing the Battle Formation. The zone between the Battle Formation and seams 3 to 6 is seen to be thicker north of station 600. The lowest event at about 100 milliseconds corresponds to a relatively thick coal sequence within the Carbon-Thompson zone of the Horseshoe Canyon Formation.

The tie between the reflection seismic time based structure section and site geology was made possible by synthetic modelling of downhole sonic and density logging of a borehole penetrating the Carbon-Thompson coal seams. A synthetic trace correlatable with strata in the vicinity of station 550, the borehole location, is shown at the left side of the figure for comparison.

The geologic section was drawn through preexisting borehole data points, with the exception of hole WW87-15, that were located 50 m west of the seismic line (Figure 4.5). This may account for minor interpretation differences between geologic and seismic sections.

In Figure 4.6, the geologic section shows depth of exploration into the Paskapoo, Battle and Horseshoe Canyon Formations. Two coal zone were identified, the Carbon-Thompson seams in the Upper Horseshoe Canyon Formation and the Ardley Coal Zone in the Paskapoo Formation. A three metre thick coal seam in the Carbon-Thompson Zone was intersected by one drillhole. It's lateral continuity could not be determined from drilling alone because of the insufficient depth of all other drillholes. The Ardley coal is shown to subcrop over a 500 m wide zone due to the slight flexure in seams. Seam 3, which subcrops near station 400 also appears as an outlier between stations 0 and 200. The Battle Formation was identified from geophysical logs as a high porosity, low density unit of mudstone. This differs from the overlying Paskapoo and underlying Horseshoe Canyon Formations which are typically composed of interbedded sandstone, siltstone and mudstone, and display a higher density. Surficial sediment, consisting of till overlying sand and gravel is 5 to 10 m thick and forms the low relief topography that slopes toward the east.

4.2.3 Genesee, Section 10

The target was the subcrop of coal seams situated beneath a thin overburden cover. The site investigated was located at the SE edge of the Genesee Coal field in Section 10 (Figure 4.1). Geophysical data was collected along four lines oriented east-west to intersect the subcrop. One hole was drilled to confirm the geophysical results from survey line #4 and is described in this section.

The direct current profiling method was used to locate the subcrop of the High seam and Upper Main seam. The method represents a convenient means by which coal subcrop can be located with excellent lateral resolution. Basically the method monitors the presence of electrically resistive coal amidst less resistive surrounding materials. The edge of coal can be identified from the lateral variation in the data.

Figure 4.7 shows the direct current data along the survey line. West of station 90 resistivity data for all array geometries are highest. This corresponds to the area in which both the High and Upper Main coal seams are present. Between stations 90 and 150, data is grouped at an intermediate resistivity level. This segment corresponds to the absence of the High seam but with the Upper Main seam still present. The marked decrease in resistivity data east of station 150 indicates that the subcrop of the Upper Main seam has been passed. The drillhole located on the basis of this data at station 110 encountered only the Upper Main coal seam, as predicted.

Figure 4.8 shows the expected location of the subcrop of the two coal seams prior to and after the direct current profiling survey. Results of the geophysical survey have increased anticipated reserves in this area.

The geologic section was constructed from one borehole on the survey line with the aid of preexisting cross sectional data from Fording (Figure 4.7). The topography is almost flat with a slight downward slope to the east. The surficial sediment which extends to 5 m in depth is composed mostly of till and conceals any indication of subcrop location of the seams. Coal seams intersected by drilling were Upper Main 2, Upper Main 1 and the Lower Main. The High Seam is absent.

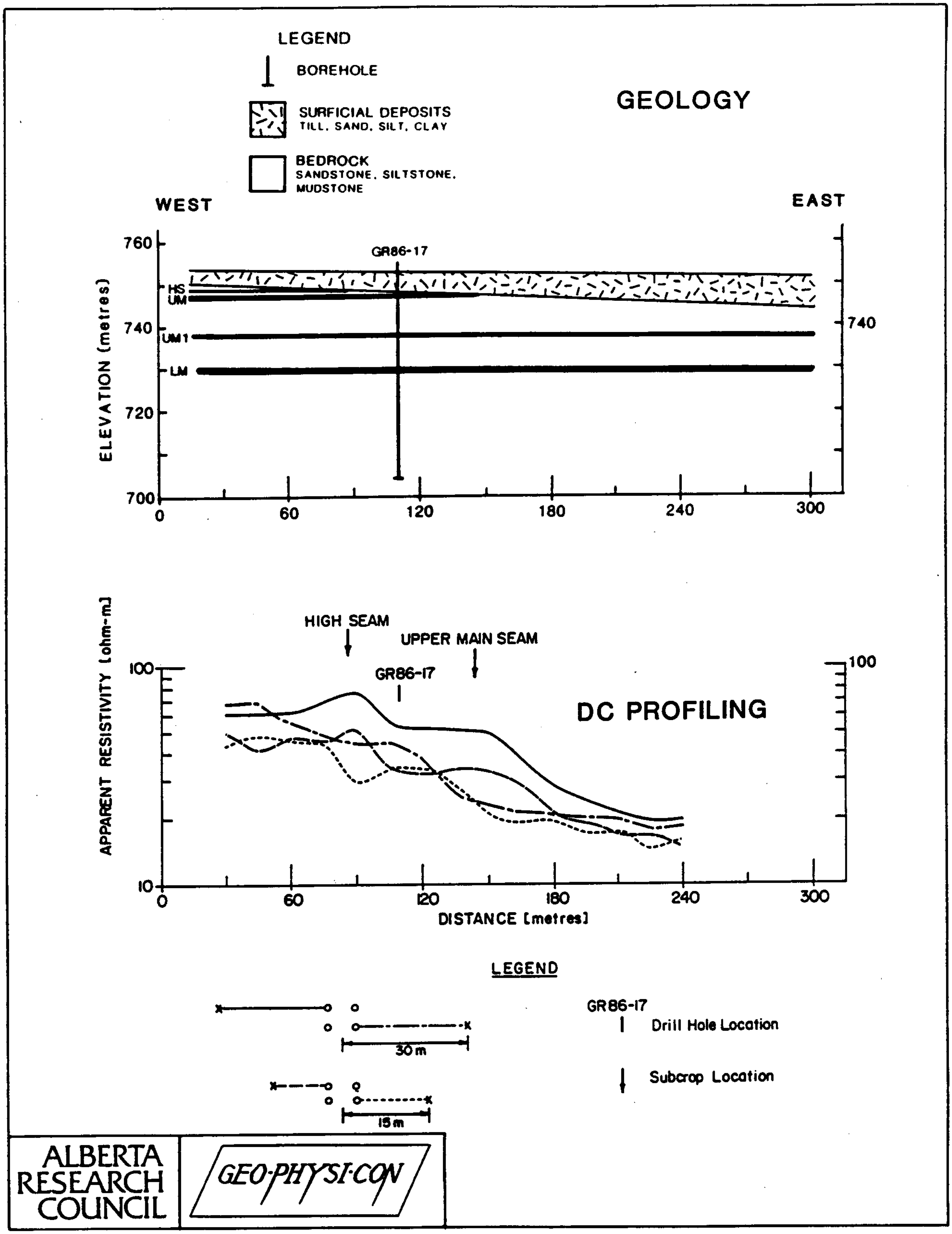

Figure 4.7 Use of direct current profiling to locate subcrop of shallow coal seams in section 10, Site 1 in the Genesee Mine area.

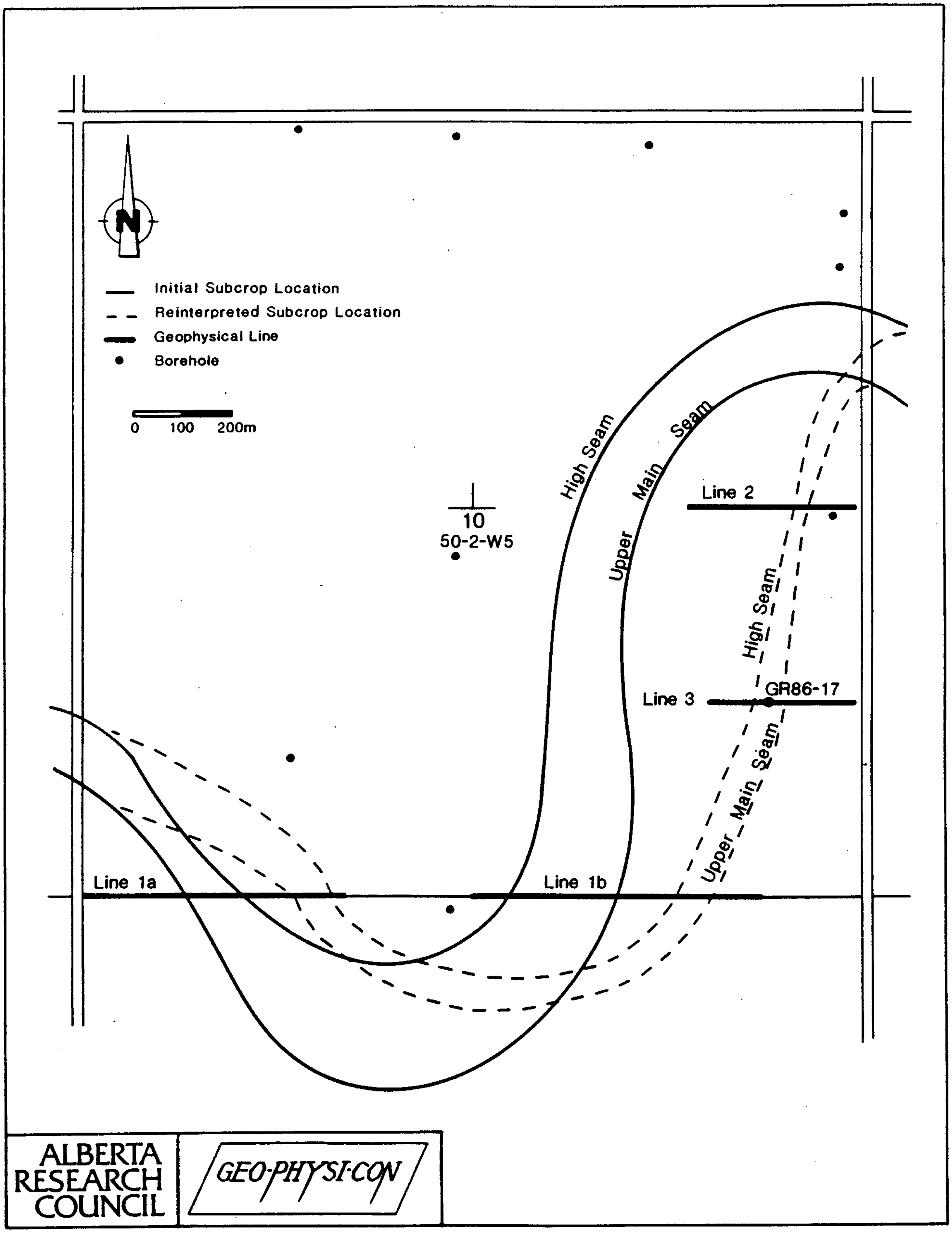

Figure 4.8 Map of section 10, Genesee showing reinterpreted subcrop location of High seam and Upper Main seam from direct current profiling data.

Drilling results show that the subcrop of High Seam lies to the west of the borehole while Upper Main 2 subcrops to the east. The subcrop of the Upper Main 2 seam is likely nearby because of the presence of till directly overlying the coal.

Drilling alone can only indicate the presence or absence of coal seams at individual drillhole locations, thereby allowing you only to guess at where a seam subcrops between holes. The results illustrated in Figures 4.7 and 4.8 using an integrated surface geophysical/drilling approach shows how the level of confidence for making geologic interpretations greatly increases.

4.2.4 Genesee, Site 1 - Line 2

The absence of coal seams in the buried channel site at Genesee (Figure 4.1) provided another opportunity to test for coal subcrop. Line 2 intersected the east edge of the channel where the upper coal seams subcropped (Figure 4.2). A detailed description of geologic and geophysical results was given in the channel target discussion in Section 4.1 of this report.

From the geophysical results in Figure 4.2 it can be seen that DC sounding and seismic reflection successfully detected subcrop of the coal. The data presented in this section was collected and interpreted prior to drilling and used to better locate target borehole positions.

4.3 Deformation Terrain

In recent years the recognition of deform terrain has become increasingly important to the geotechnical planning and operations in open pit mines. Large scale failures in highwalls have been attributed to glacially deformed bedrock in several of the prairie mines. Deformation terrain is characterized by bedrock that has been deformed by glacial action, resulting in a weak, less competent sediment in comparison to similar undeformed material. Recognition and delineation of the terrain is often difficult because of changes to the land surface by subsequent glacial processes.

Research has shown that deformation terrain is widespread and that mine planning should attempt to define the distribution of these problem areas. The following examples show how surface geophysical techniques can be used to detect and determine the distribution of deformed bedrock.

4.3.1 Paintearth Mine, Line 2

Deformation terrain was intersected at the test site in the Paintearth Mine area. Results discussed are drawn from Line 2 (Figure 4.9), located some 500 m east of the advancing open pit. Line 2 is oriented in an east to west direction perpendicular to the pit. The test site is situated in typical prairie terrain, with flat to low relief which shows no geomorphic evidence of the extent of the deformed bedrock. Geophysical data and drillhole data were collected during 1984. Further interpretation of the geophysical data resulted in additional drilling during 1985.

Figure 4.10 shows the interpreted geologic section and pertinent results of surface geophysical measurements including direct current soundings, and refraction and reflection seismic profiling. Drillholes were located on the basis of the interpretation of the geophysical data.

The geoelectric section shows the results of direct current soundings along the survey line. The top surface of coal bearing strata is clearly visible in this data. Significant penetration beneath the upper coal bearing strata could not be achieved with electrode arrays and transmitter power levels used.

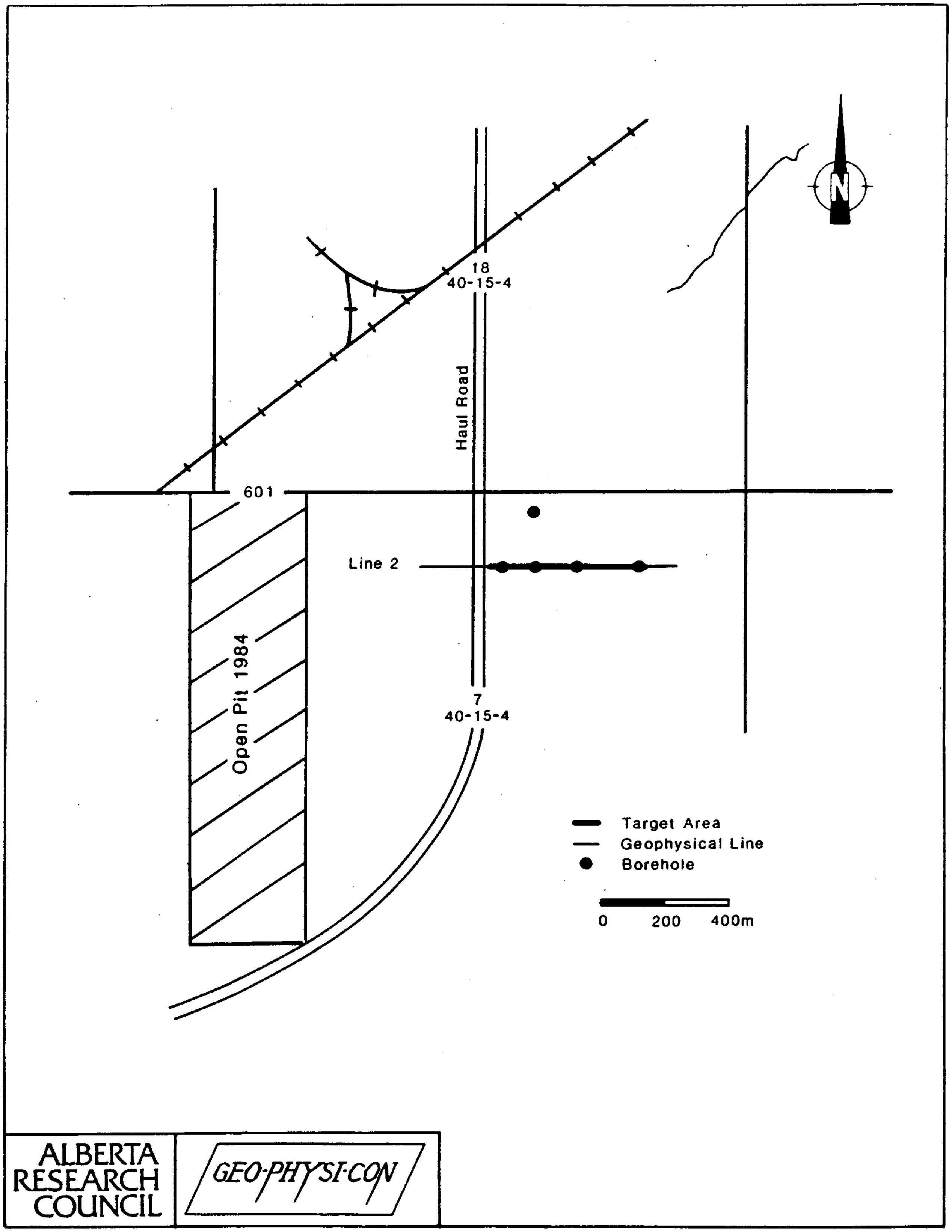

Figure 4.9 Map of the Paintearth Mine area study site.

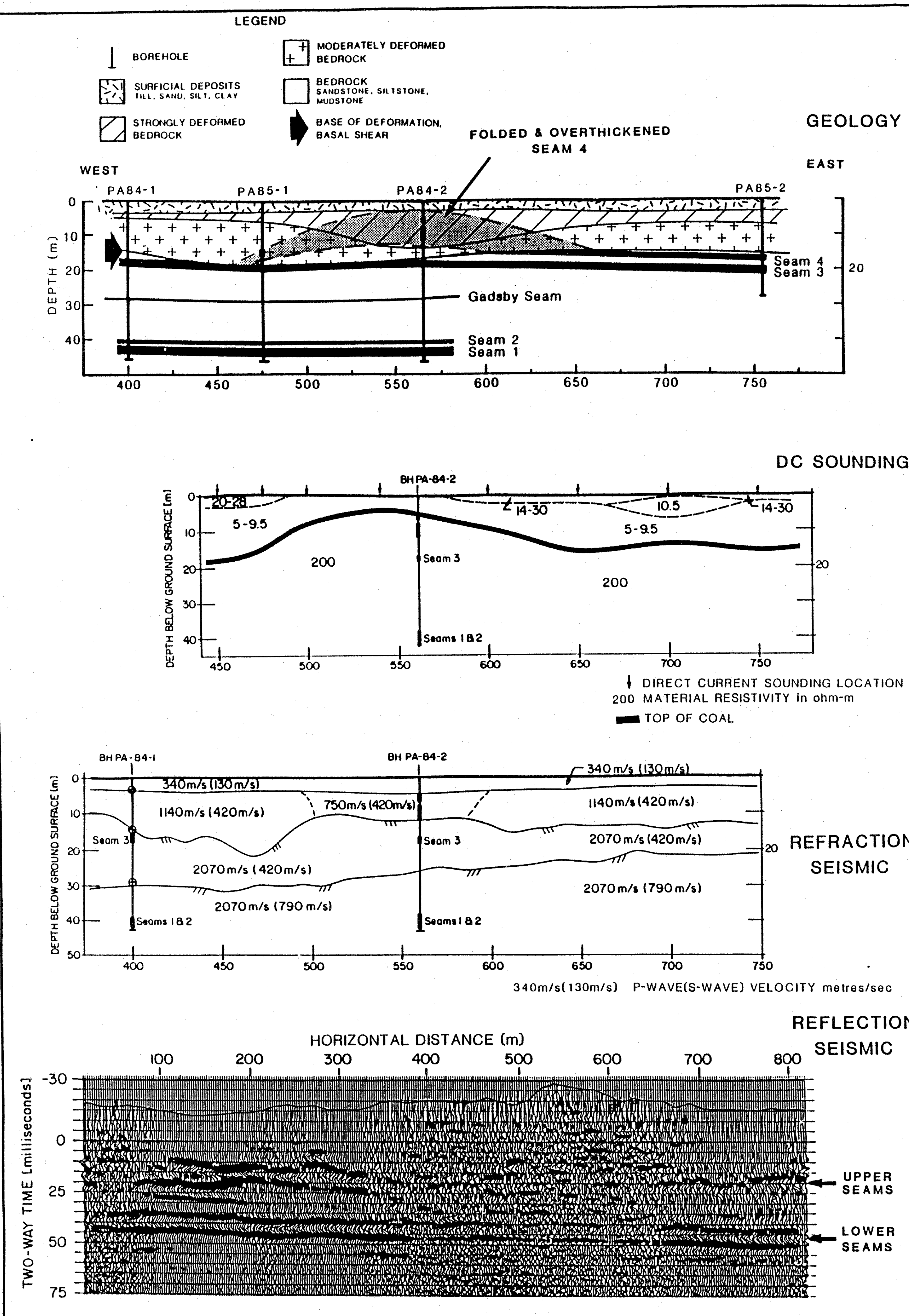

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Figure 4.10 Detection of deformation terrain using direct current sounding, refraction seismic and reflection seismic methods from Paintearth Mine study site.

Shear and compression wave data is shown in the refraction seismic in Figure 4.10. The boundary between materials characterized by compression wave velocities of about 1150 m/s and 2070 m/s correlated to the depth of deformed bedrock. The compression wave velocity of 2070 m/s also indicates that the lower bedrock may be saturated. The shear wave velocity undergoes an increase at larger depth signifying that the effects of deformation extend below the location of the basal shear zone. Very low compression wave velocities were observed for the materials including the overturned and folded coal seams between station 450 and 650.

The reflection seismic, time based, structure section in Figure 4.10 shows data that was obtained using a 12 channel binary gain seismograph. This represents an early (1984) attempt to obtain reflection seismic data in support of shallow coal studies. Nonetheless the data clearly illustrate the continuity of Seams 1 and 2 (at about 45 milliseconds) across the site, and also the disruptions of Seams 3 and 4 in the vicinity of stations 450 to 650. The data traces represent up to four different source to geophone geometries and occur at a 2.5 metre interval along the survey line. Darkened areas of the traces correspond to zones of increased acoustic impedance. The clearly defined darkened events bound the upper and lower sequences of two coal seams.

The simplified geologic section in Figure 4.10 shows evidence of glacial deformation. Surficial sediment, consisting mostly of till, mantles deformed bedrock which is present at varying depths along most of the survey line. Evidence of deformation is most easily recognized in seam 4, the upper coal seam, which is absent near station 400 and is folded and overthickened between stations 450 and 650. A basal shear zone identified at about 15 m in depth accounts for displacement of bedrock overlying seam 3 through much of the section. Strongly deformed bedrock, characterized by high angle bedding and shattered rock is thickest between stations 450 and 650. To the east and west of this zone, the displaced bedrock maintains a competent, horizontally bedded appearance. There was little evidence of deformation beneath the basal shear zone.

4.3.2 Highvale Mine, Pit 04

Deformation terrain identified through airphoto interpretation (Fenton 1983), was expected to occur in the uplands of the Pit 04 area of the Highvale Mine. Data obtained from investigations in 1984, were taken from a 400 metre segment of Line A (Figure 3.2) which was oriented northeastward to intersect a northwestward trending topographic high. The results are presented in Figure 4.11.

The surface geophysical method selected was refraction seismic. Both shear and compression wave measurements were made in the hopes of obtaining low velocity units that would correspond to the vertical and lateral extent of the deformation areas. A crosshole seismic test was also carried out to calibrate the surface measurements.

The refraction seismic section in Figure 4.11 shows the interpretation for shear and compression wave data gathered at the site. Compression wave data indicated the presence of low velocity unsaturated sediments overlying high velocity saturated bedrock at shallow depth. The shear wave velocity data illustrated the presence of an anomalous incompetent bedrock zone characterized by low shear velocity and a high velocity ratio, encompassing the upper 30 metres of bedrock and thinning towards the base of the slope. Geologic and downhole geophysical log data have identified this material to be deformed. Refraction data shows that the zone of incompetent bedrock extends below the basal shear zone identified from drilling. This indicates that the effects of deformation are present below this basal shear zone.

Dipmeter logs have been interpreted for drillholes located at stations 130, 205 and 290, and aid in detecting the base of deformation (Figure 4.11). The fit with the seismic data at drillhole 408 is good.

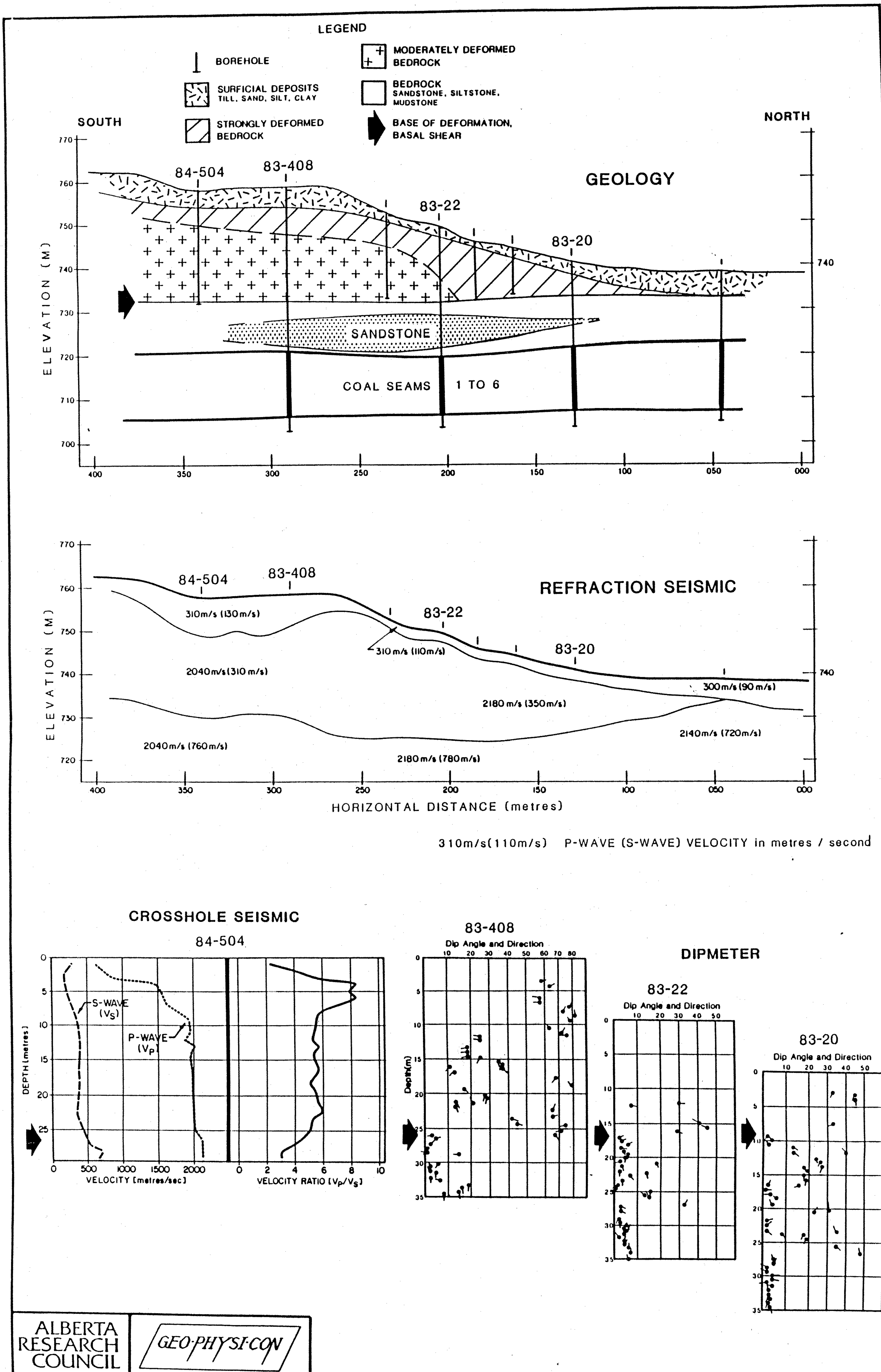


Figure 4.11 Use of refraction seismic data to indicate depth of deformation in overburden material from Line A, Pit 04 area in the Highvale Mine.

For the other two drillholes the base of deformation is above the base defined by the seismic measurements. In each of the cases the base of deformation indicated on the dipmeter logs is not as sharp as is the case at drillhole 408.

Crosshole seismic measurements were performed at drillhole site 84-504. The measurements confirm the general compression and shear wave velocity structure determined from surface based refraction measurements. The compression and shear wave velocities and the corresponding velocity ratios are shown as a function of depth in Figure 4.11. The base of deformation corresponds to the increase in shear velocity and decrease in velocity ratio at about 28 metres. There is hardly any variation in the compression wave (sonic) velocity at this level. The high velocity ratio materials above 9 metres depth occur as a result of these materials being basically unconsolidated (low shear wave velocity) and saturated (high compression wave velocity). It is to be noticed that the shear wave velocity profile is not affected by saturation of materials at about the 4 metre depth.

Lithologic data from drilling on Line A confirms the presence of glacially deformed bedrock in the overburden as shown in the geologic section (Figure 4.11). The overburden was divided into four recognizable glaciotectonic units. Surficial deposits consisting mostly of till were thickest on top of the upland south of station 250 and at the base, north of station 100. Deformed bedrock underlies the surficial sediment to increasing depths below the upland in all but the extreme north end of the section. Depth of deformation was identified by a basal shear zone at about 26 m near station 300. The overlying bedrock was divided into two deformation units, strongly deformed and moderately deformed. The basal shear zone in bedrock appears to begin at the base of the hill near station 100. The coal sequence and remaining bedrock underlying the basal shear appeared undeformed.

Piezometric data collected from wells installed on Line A indicate depth to groundwater is less than 3 m on the highland and greater than 5 m on the lowland (Moell 1985c).

4.3.3 Highvale Mine, Pit 03

Much of the strata in the Pit 03 study area has been glaciotectonically deformed. The objective here was to determine the vertical and lateral distribution of deformed sediment. Figure 3.4 shows the location of the area of investigation at the Highvale Mine. This site illustrates an integrated multi-stage approach to using airphoto interpretation, surface geophysics and drilling (Figure 4.12).

The local stratigraphy consists of less than 5 m of till at surface, underlain by a sandstone unit up to 35 m thick which overlies a mudstone less than 5 m thick. Underlying the mudstone is the 14 m thick mineable coal sequence. A large transported mass of bedrock overlying till was recognized north of the haul road between line 3200 and 3800.

The study began first with an airphoto interpretation and examination of the preexisting drillhole data. The upper map in Figure 4.12 shows several terrain types that were identifiable and mapped in the Pit 03 area. The important boundaries in this figure are the southern extent of Unit 1 (thrust terrain) which approximately follows the haul road and Unit 4 (possible in situ deformation along valley sides) which follows a southeast trending depression. These correlate well with both seismic and borehole results.

The second stage was a refraction seismic survey which obtained compression and shear wave measurements along all lines shown in the grid in Figure 4.12. The southern boundary of deformed and weak bedrock was determined on the basis of the presence of materials characterized by anomalously low shear wave velocity and a correspondingly large velocity ratio, since bedrock materials in this

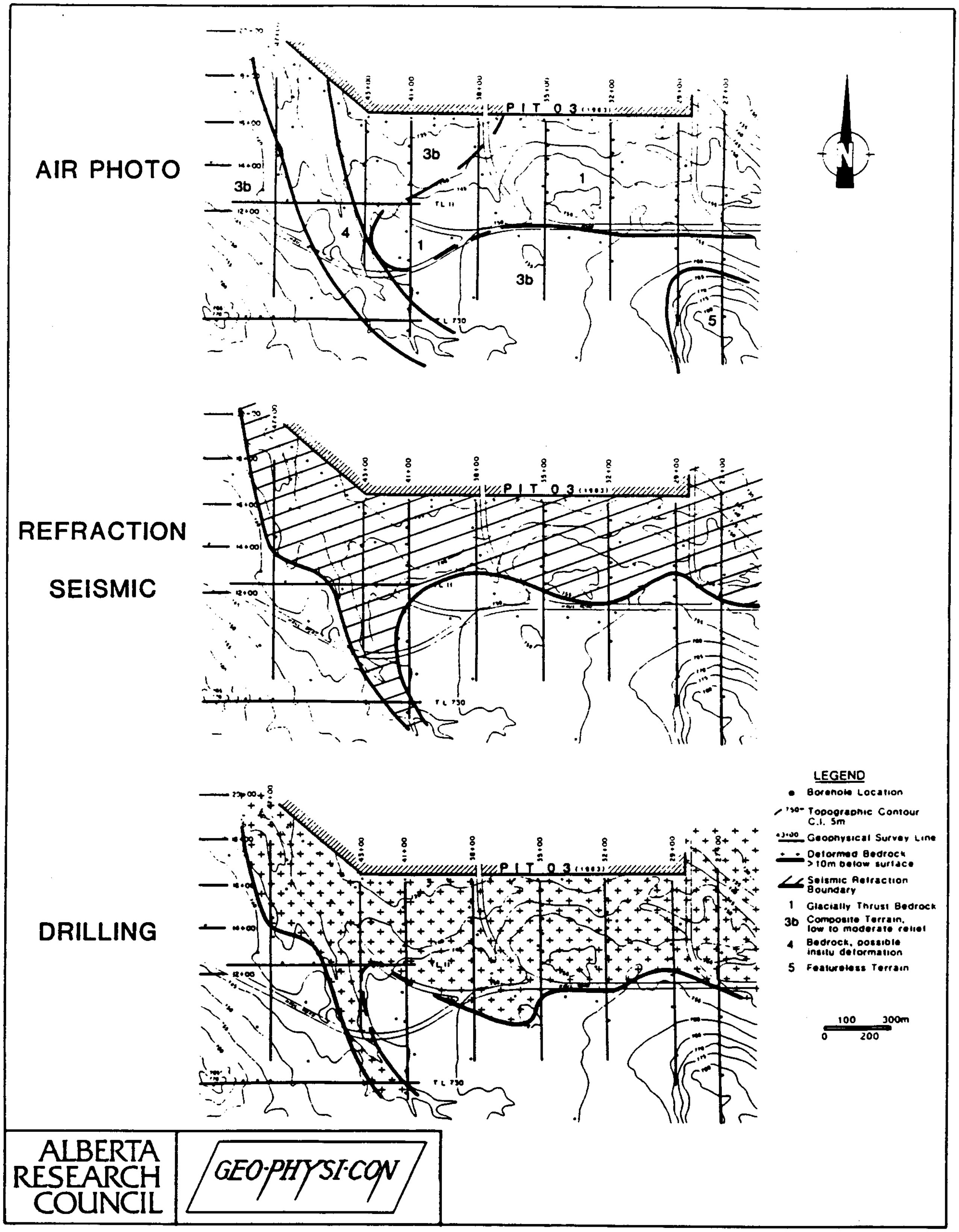


Figure 4.12 Comparison of airphoto, refraction seismic and drilling results to delineate deformed bedrock south of Pit 03 in the Highvale Mine.

region are known to be saturated (Moell et al. 1985b). The thickness of weak bedrock materials is generally greater than 20 metres with a rapid thinning in the vicinity of the boundary. Other isolated areas within the survey grid, especially in the vicinity of Beaver Creek, show a similar structure. In some areas on the southern uplands the presence of deformed rock has been inferred based on a combination of anomalously low compression and shear wave velocity. These materials are expected to be unsaturated but of less concern due to their small thickness.

A geologic interpretation made from additional drilling data was the last stage of the investigation and is shown in the lower map in Figure 4.12. The patterned area indicates the lateral extent of incompetent material that is present continuously from surface to depths greater than 10 m.

The 10 m depth was used for 3 reasons: 1) in order to correlate as closely as possible with the seismic data, 2) throughout most of the area, the bedrock near surface is usually poorly consolidated due to either weathering and/or glacial deformation, and 3) the top 10 m of overburden is likely of little concern to mining and highwall stability.

Deformation was strongest close to the pit and decreased in intensity towards the south. The segment of the boundary between lines 2700 and 4300 represents a transition zone from deformed to undeformed bedrock rather than a sharp boundary. The northwest trending deformed area between lines 4100 and 4700 follow a depression containing an intermittent stream. The positioning of the curve in the boundary between stations 3800 and 4300 could not accurately be determined because borehole data came only from auger drilling which was unable to penetrate below 10 m due to refusal at a hard cemented horizon. Nearby borehole data suggests that this area may be underlain by displaced bedrock; further drilling will have to be done to confirm this.

A comparison of the airphoto, surface geophysics, and geology (drilling) results shows there is general agreement between the three.

4.4 Continuity of Stratigraphy

Stratigraphic continuity is an important mapping objective that can be met using surface geophysical techniques. The ability to define stratigraphic continuity effectively over large areas of terrain can aid the selection of optimal drillhole location and density, as well as provide a basis for interpolation of continuity of subsurface structure between drillholes.

4.4.1 Genesee, Site 1 - Line 1

Line 1-1 at the Genesee Mine area (Figure 4.1) extends in an east to west direction for a length of 2 kilometres. The line crosses over terrain that contains the buried channel (see Section 4.1 of this report), coal seam subcrops and splits (Figure 4.13). Geophysical measurements along this line were obtained in 1985. Lithologic data was collected from drilling in 1985 and 1986.

The shallow high resolution reflection seismic technique was employed along the survey line. Measurements were the first obtained using newly developed seismic recording instrumentation. Results of the survey area shown in the form of a reflection seismic, time based, structure section in Figure 4.13. Darkened events in the figure correspond to the upper surfaces of zones of reduced acoustic impedance, making coal bearing strata more visible. Each trace on the figure was derived from stacking of up to 6 different data channels with different source to geophone geometries. Each trace represents a 2.5 metre interval along the survey line.

The Lower Main coal seam appears as the continuous darkened event at scale times of about 50 milliseconds. The seam is present

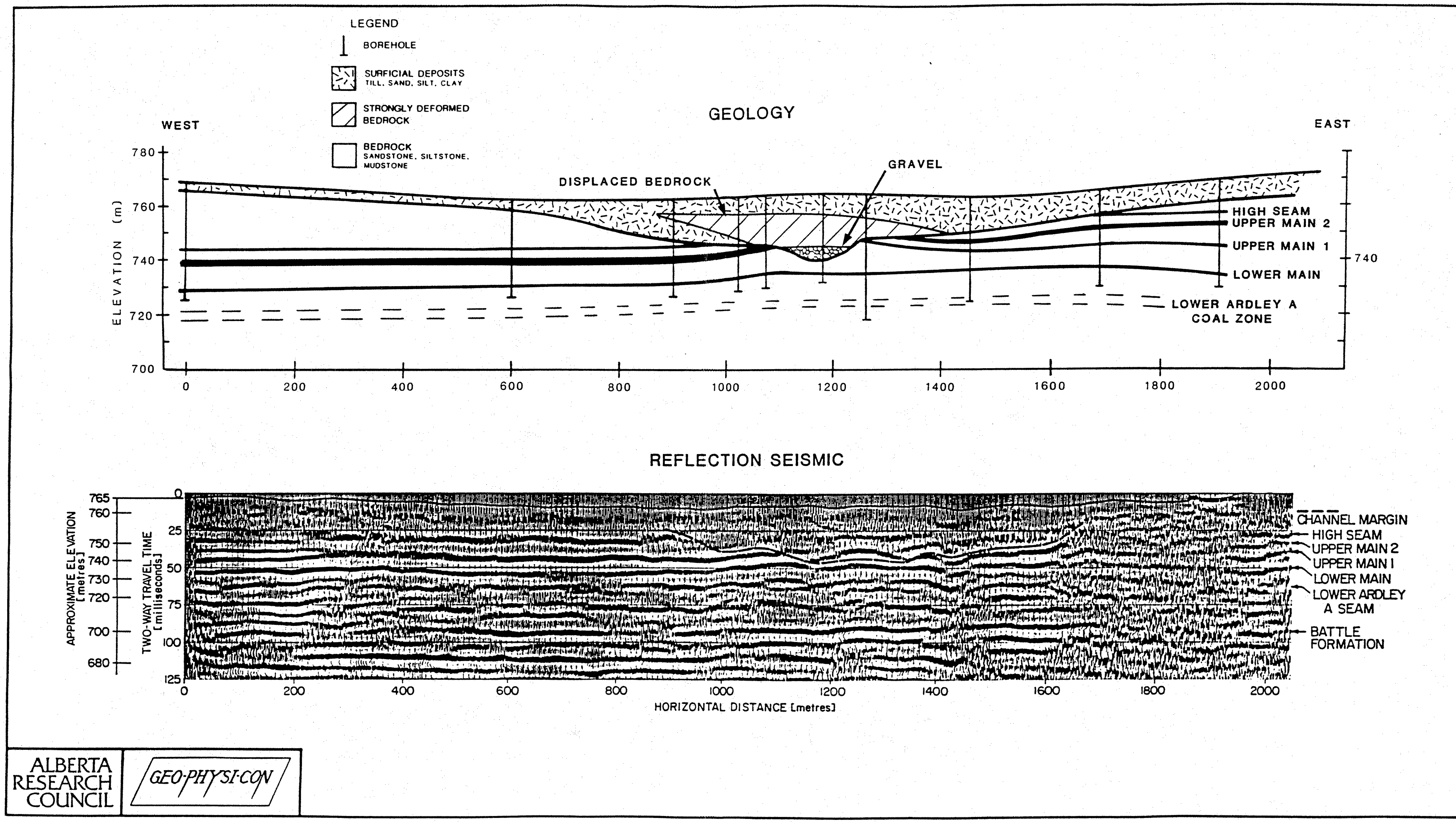


Figure 4.13 Continuity of stratigraphy using reflection seismic method from Line 1, Site 1 in the Genesee Mine area .

along the entire line. Below it the Lower Ardley A coal zone and the surface of the Battle Formation have been identified using ties with synthetic seismograms developed from downhole sonic and density logging. The Upper Main seam shows up as the darkened event at scale times of about 40 milliseconds. This seam subcrops at the channel edge on the west and east side at station 1100 and 1360, respectively. The Upper Main seam splits to the east of station 1780. The High seam occurs at very shallow depth and consequently could not be well imaged with the data. Evidence of the High seam appears at scale times of about 30 milliseconds west of station 300, at its subcrop at the side of the channel at station 980 and at about scale times of 25 milliseconds east from station 1620. The channel itself lies between stations 980 and 1600 and exhibits a divergence of reflected events. The domelike feature between stations 1200 and 1350 may be caused by a displaced bedrock mass. The presence of this mass means there is anomalously low velocity sediments within the channel above the coal seams.

Good control for the geologic interpretation was provided by data from nine drillholes. The coal seams are the best indicators of continuous stratigraphic beds. The upper coal seams have been eroded between stations 900 and 1600 by a channel. West of the channel area, the High seam, Upper Main and Lower Main seams are present with a slight regional dip to the west. Parting thickness between seams is relatively uniform; 3 m separates High seam from Upper Main and the Lower Main is 8 m below. East of the channel, coal seams diverge as partings increase in thickness. The UM seam splits into UM1 and UM2 along a parting that measures up to 6 m thick. The LM was not eroded by the channel and is present throughout the entire area. The bedrock is composed of horizontally bedded mudstone and siltstone with numerous channel sandstones. The buried channel is composed of surficial sediment consisting of clay, silt and till with minor amounts of sand and gravel. Large masses or blocks of glacially displaced bedrock material are also present within the channel.

4.4.2 Highvale Mine, Pit 02

Geophysical tests in the Pit 02 area of the Highvale Mine illustrate the use of direct current sounding measurements for recognizing lithostratigraphic units characterized by distinctive ranges of electrical resistivity. Results are drawn from Line 1 (Figure 3.3) for which field work was conducted in 1984.

Figure 4.14 shows the geoelectric section composited from the results of six direct current soundings. Four general subsurface layers are recognizable. The upper of these consists of a thin zone characterized by resistivities in the order of 4 to 8.5 ohm-m. Beneath this a thick and more resistive layer is present which is expected to be sandstone based on characteristic resistivities in the order of 15 to 20 ohm-m. A thin, low resistivity layer occurs beneath the sandstone and above the top surface of coal. Only the top surface of coal bearing strata can be identified, since the high resistivity of the coal insulates lower strata. Penetration through the coal could only be accomplished using much higher transmitted power levels and larger arrays than would be practical.

The geologic section of Line 1 in the Pit 02 area is illustrated in Figure 4.14. Stratigraphy from surface is 3 to 5 m of surficial sediment composed mostly of clay till, overlying 10 to 15 m of sandstone, overlying 7 to 10 m of mudstone/siltstone which overlies the 13 m thick coal sequence. The lithologic units maintain a relatively uniform thickness with generally horizontally bedded structures throughout the section.

The electrical data has provided a very accurate representation of the thickness of gross lithologic units as shown from drilling. This method would also detect lateral changes in conductivity resulting from different lithologies associated with facies changes or channels (see Section 4.1 of this report).

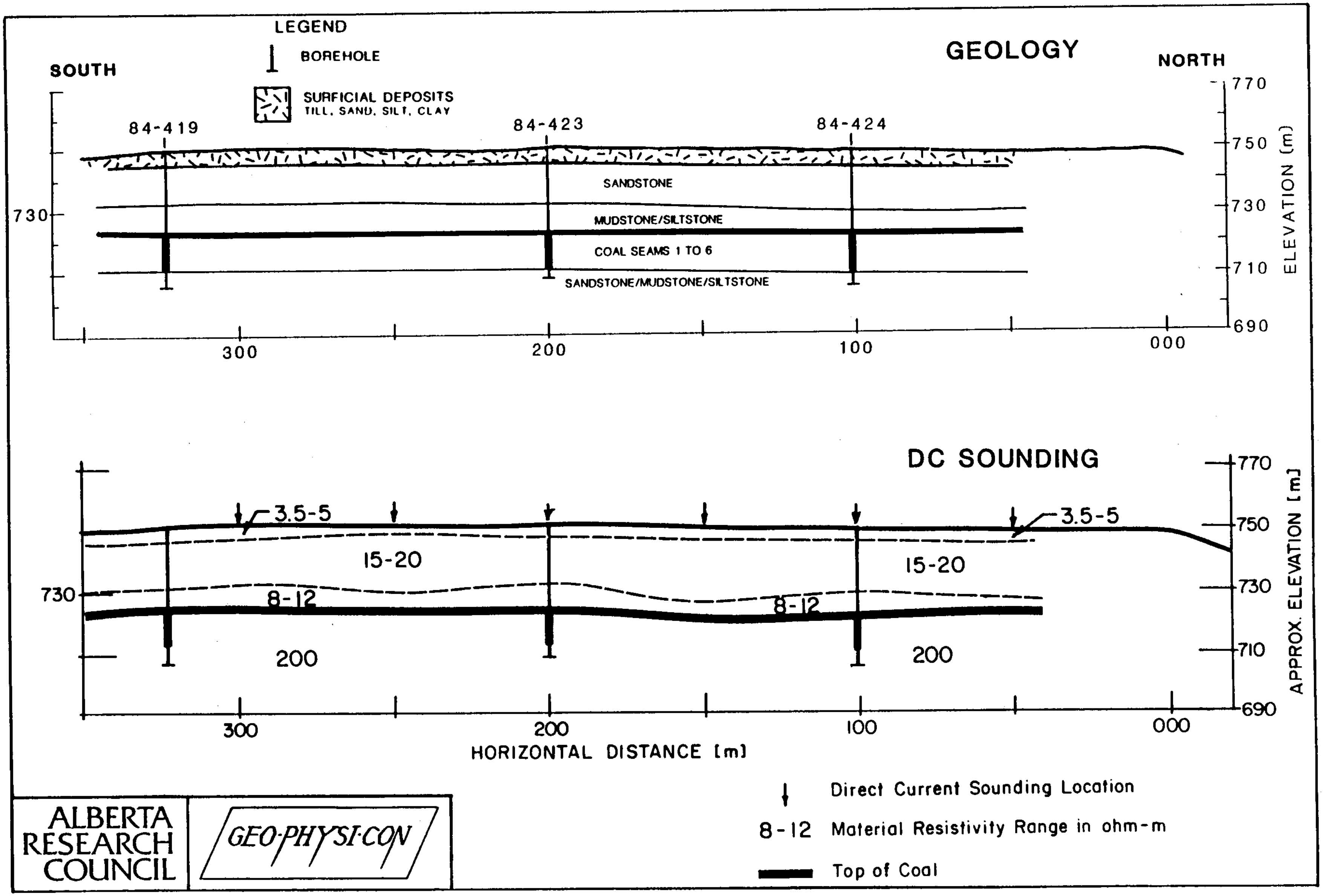


Figure 4.14 Use of direct current sounding to show continuity of stratigraphic beds from Line 1, Pit 02 in the Highvale Mine area.

5. SURFACE GEOPHYSICS COST BENEFIT ANALYSIS

5.1 Introduction

There is a general principle to mining risk minimization; do not discover and subsequently solve mining problems in the pit with the mining equipment, rather discover and define these problems ahead of mining and apply sound engineering principles to solving them by means of a combination of avoidance, application of mining techniques and equipment selection. Early recognition and definition of problem areas results in minimizing the costs and risks of mining.

This study has shown that surface geophysical techniques are successful in defining a variety of targets. However, the practical application of these methods requires a look at what it will cost to use geophysics in comparison to existing drilling programs.

An approximate cost/benefit analysis between surface geophysical and conventional drilling methods is presented in this section. In Appendix 10.5, a hypothetical field program comparing the effectiveness of using surface geophysics and drilling versus drilling alone has been gratefully prepared by Don Mills of Fording Coal Ltd.

5.2 Surface Geophysics Cost Effectiveness

The cost effectiveness of geophysical exploration arises from the fact that geophysics returns data at much higher spatial density than drilling, although a higher degree of uncertainty may be inherent in the geophysical results. Thus, much more data can be collected with geophysics at similar costs as drilling alone. However, the integrated use of drilling and geophysics can be used to meet exploration objectives which satisfy required levels of confidence at lower cost than drilling alone.

Three examples are presented which illustrate the cost relationships between drilling and geophysics. The examples represent typical mine planning targets. The costs of different geophysical methods are used and drilling costs at different borehole spacings and depths are shown.

Drilling cost estimates were supplied by two joint venture participants, TransAlta Utilities Corporation and Fording Coal Limited. Table 5.1 shows the drilling costs averaged on a per hole basis for the purpose of comparison with geophysics. Geophysical survey costs were provided by the project's geophysical contractor, Geo-Physi-Con Co. Ltd., and are outlined in Table 5.2.

5.2.1 Deformation Terrain

This study has shown that the most useful geophysical method for detecting and delineating glacially deformed terrain is a combined compression and shear wave refraction seismic survey. Drilling to delineate the extent of deformation terrain requires a high percentage of coreholes.

The depth of drilling for this purpose, given the sites tested to date, is about 30 m. The average cost of a 30 m corehole is in the order of $4920.00 (Table 5.1). This compares to a similar cost of obtaining compression and shear wave refraction seismic data over a distance of 1 kilometre. Over that distance, about 100 data stations are gained with geophysics compared to only one for drilling (Table 5.2).

Figure 5.1 shows the relative costs of drilling at spatial densities of 1/2, 2 and 5 coreholes per kilometre (best, average and worst case coverage) over a distance of 6 kilometres. The cost of geophysics alone and geophysics supported by drilling at 1/2 and 2 holes per kilometre spacing is also indicated. The graph shows that as the

Table 5.1
DRILLING COSTS ON A PER HOLE BASIS

1. ROTARY DRILLING COSTS (Rev. Circ.)	HOLE DEPTH Shallow 15 m		Medium 30 m		Deep 60 m	
Mine (1 or 2)	1 $	2 $	1 $	2 $	1 $	2 $
drilling cost	450	800	900	1500	1800	2800
borehole geophysics	600	750	700	900	800	1000
site (site geology, supervision, materials, surveying, overhead)	200	400	340	900	650	1700
travel, accommodation	.75	200	100	300	150	400
office (report, word processing, drafting, overhead)	150	300	150	300	150	300
standby	250	300	250	300	250	300
land clearing	100	100	100	100	100	100
Total	1825	2850	2540	4300	3900	6600
Average of costs for mines 1 and 2	2340		3420		5250	
Mobilization	600	775	600	775	600	775
Average of cost of mobilization	690		690		690	
2. CORE DRILLING						
drilling costs	1120	1200	2250	2325	4500	4500
borehole geophysics	600	750	700	900	800	1000
site (site geology, supervision, materials, surveying, overhead)	280	600	560	1300	1100	2400
travel and accommodation	100	350	150	500	225	650
office (report, word processing, drafting, overhead)	200	300	200	300	200	300
standby	200	250	200	250	200	250
land clearing	100	100	100	100	100	100
Total	2600	3550	4160	5675	7125	9200
Average cost for mines 1 and 2	3075		4920		8165	
Mobilization	600	775	600	775	600	775
Average of cost of mobilization	690		690		690	
other-geotechnical	n/a	3650	n/a	3650	n/a	3650
-piezometer	n/a	2750	n/a	2750	n/a	2750
-coal quality	400	500	400	500	400	500

Cost estimates based on 1986 data.

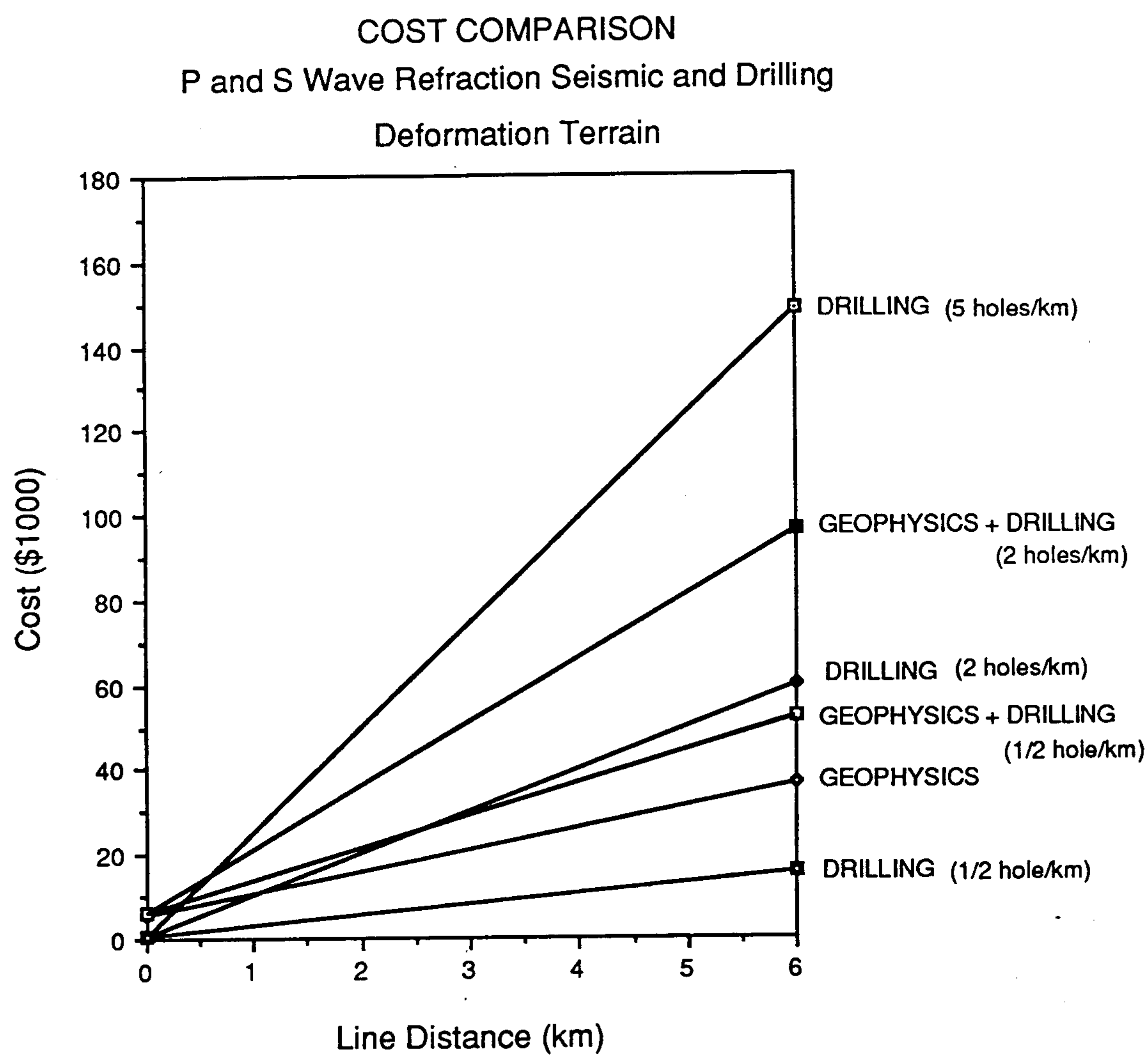
Table 5.2
GEOPHYSICAL SURVEY COSTS ON A PER KILOMETRE BASIS

Geophysical Method	Daily Field Costs	Productivity	Data Analysis Costs (per field day)	Approximate Rate/ Kilometre	Number of data stations per kilometre
D.C. Soundings	1800	1.0 km	600	2400	10
D.C. Profiling	1750	.75 km	400	2865	50
Fixed Frequency EM	1800	5.0 km	600	480	50
P-Wave Refraction Seismic	2040	1.04 km	600	2538	100
S-Wave Refraction Seismic	1840	0.91 km	600	2681	100
Reflection Seismic	5300	1.50 km	2200	5000	400
Crosshole Seismic	1800	n/a	600	n/a	n/a
Mobilization and Demobilization	3000	exclusive of reflection seismic which would require additional $3000.00			

* If performed in conjunction with a seismic survey, approximate rate/kilometre would be $2533.00

NOTE: Mob. Costs - Refraction P & S - $5400 (incl. 1 x-hole)
- Refraction P - $3000 (n. incl. x-hole)

Cost estimates based on 1986 data.



Drilling
- 100% core
- depth 30 metres
- $4920 / hole
- mobilization $690

Geophysics
- combines P & S wave refraction seismic
- $5219 / kilometre
- 100 data stations / kilometre
- mobilization $5400 (includes 1 x-hole test)

Cost estimates based on 1986 data.

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Figure 5.1 Cost comparison graph of P and S wave refraction seismic and drilling for detecting glacially deformed terrain to depths of 30m.

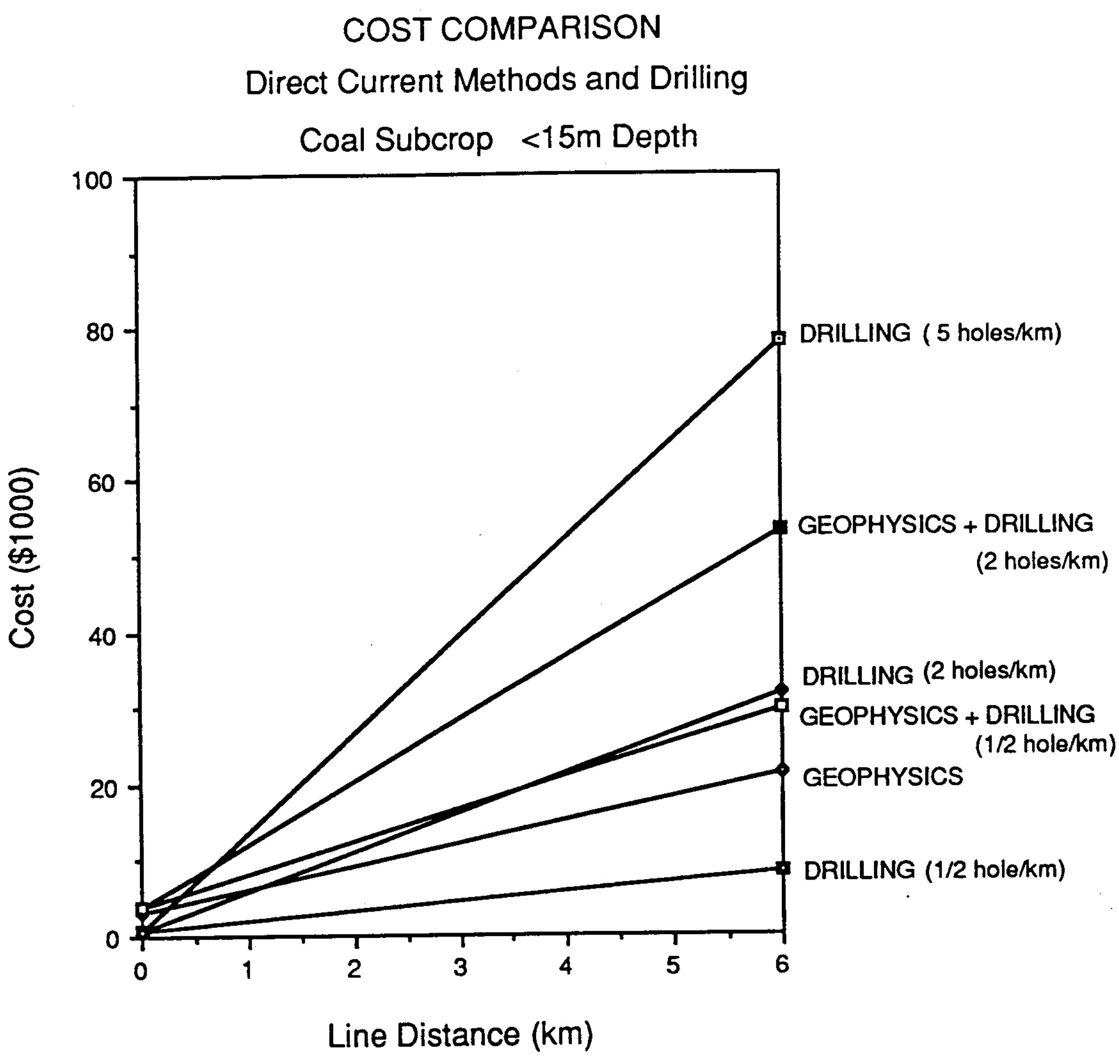
use of drilling alone increases to more than 2 holes per kilometre spacing, it becomes more cost effective to use a combination of geophysics and drilling. This approach would maximize information gathered per dollar because the geophysical results could be used to locate optimal drill targets. The cost benefit of using geophysics becomes more apparent as the drilling density and the total line coverage increases in a field program. For a small program, the relatively high cost of mobilization for geophysics may not warrant its use.

5.2.2 Coal Subcrop - <15 m Depth

The most cost effective geophysical method of detecting shallow coal seam subcrop is direct current profiling. Drilling to locate subcrop requires only a low percentage of coreholes. The depth of drilling for this purpose would be about 15 m. The average cost per hole, considering 80% rotary and 20% coreholes, is then calculated to be in the order of $2580.00 (Table 5.1). This is about 80% of the cost of collecting direct current profiling measurements supported by one direct current sounding measurement over 1 km of terrain. Over this distance, data is recorded from about 50 direct current data stations (Table 5.2). Figure 5.2 shows a similar relative cost relationship as Figure 5.1. As the drillhole density increase, the use of surface geophysics becomes more cost effective. Again, from this study it has become evident that undertaking a program using direct current methods supported by limited drilling optimizes the ratio of information gathered per dollar cost.

5.2.3 Geologic Targets - 15 to 100 m Depth

Seismic reflection measuring techniques and processing have greatly improved over the course of this study to yield reliable information regarding stratigraphic continuity, subcrop, washouts and structures between 15 and 100 m in depth.



Drilling
- 80% rotary & 20% core
- depth 15 metres
- $2580 / hole
- mobilization $690
- coal quality $450 / corehole

Geophysics
- DC profiling plus 1 DC sounding
- $3500 / kilometre
- 50 data stations / kilometre
- mobilization $3000

Cost estimates based on 1986 data.

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Figure 5.2 Cost comparison graph of direct current methods and drilling for locating shallow coal seam subcrop within 15m from surface.

Drilling to delineate these targets in this depth range may require a ratio of rotary to coreholes of about 4 to 1. For the purpose of our cost comparison, an examples are illustrated for a drilling depth of 30 m and another at 60 m (Figures 5.3 and 5.4). The average drilling costs are estimated to be about $3810.00 and $5930.00 per hole, respectively (Table 5.1). Realistic costs for 1 km of reflection seismic are in the order of $5000.00. Again, these costs are similar to the cost of one drillhole although the volume of information gained over 1 km through reflection seismic studies is high by comparison.
Table 5.2 shows that reflection seismic yields data from 400 stations in 1 km.

The graphs in Figures 5.3 and 5.4 illustrate relative cost breakdowns. The relationships of the geophysical to drilling costs are similar to those used previously for deformation terrain and shallow subcrop. A comparison of Figure 5.3 to Figure 5.4 shows that drilling costs rise substantially with the increase of drilling depth, whereas surface geophysical costs remain constant. A combination of reflection seismic profiling and selected drilling for control can optimize data acquisition within restricted budgets.

The examples illustrated in Figures 5.1, 5.2, 5.3 and 5.4 show that the relative costs between geophysics and drilling are similar for each case. The cost of running one kilometre of surface geophysics can be roughly equal to the cost of a drillhole, depending on the rotary to core ratio and the depth of drilling. The main benefit of using surface geophysics is that a greater volume of data can be collected over an area than through drilling alone. Experience from this study has shown that an integrated approach using surface geophysics supported by limited drilling will provide the maximum amount of information per dollar cost. The relative costs of this kind of approach, which are shown in the graphs, indicate that an integrated program can be comparible to the cost of drilling alone. The figures also show that surface geophysical methods become more cost effective as drillhole spacing gets closer and drilling depths increase.

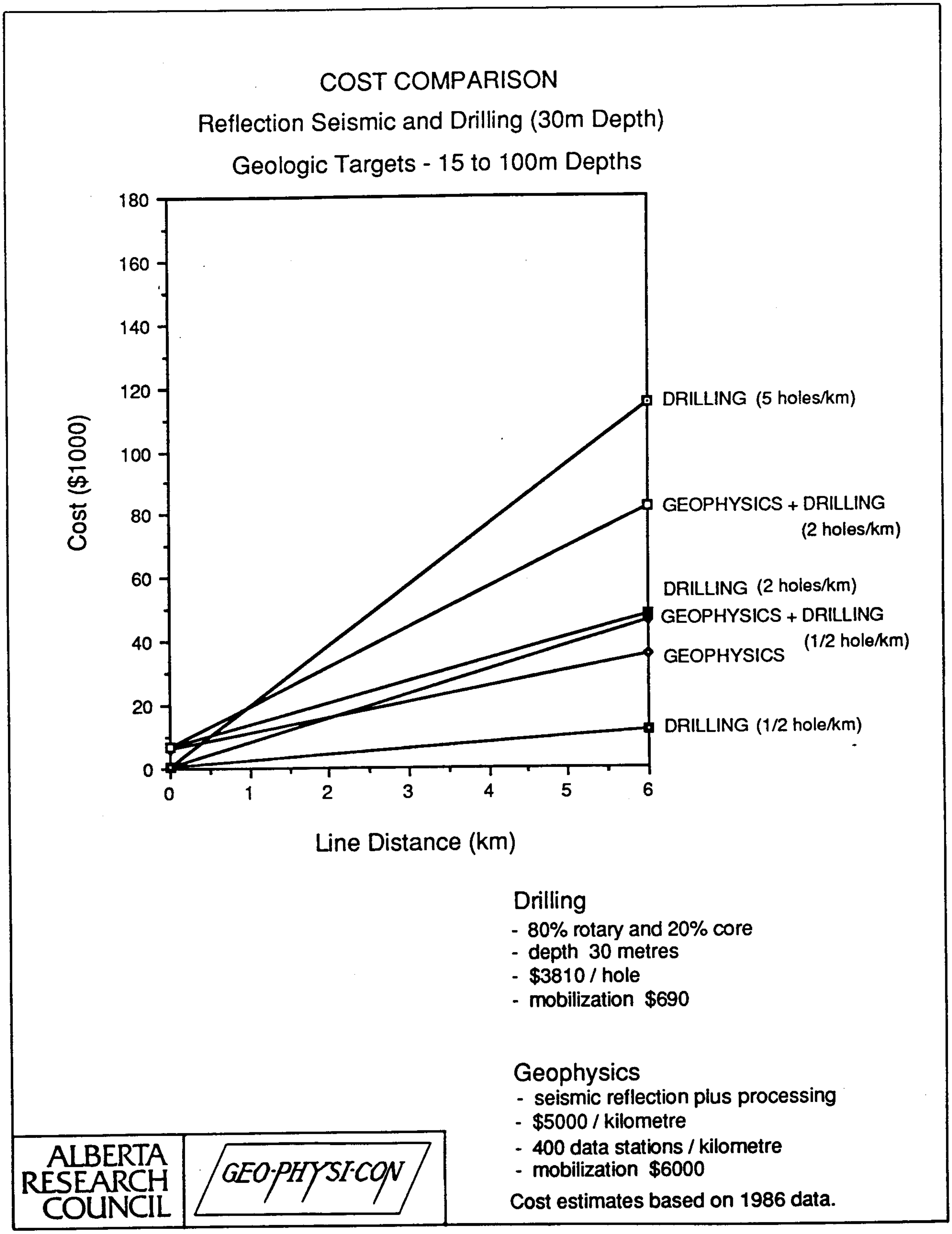
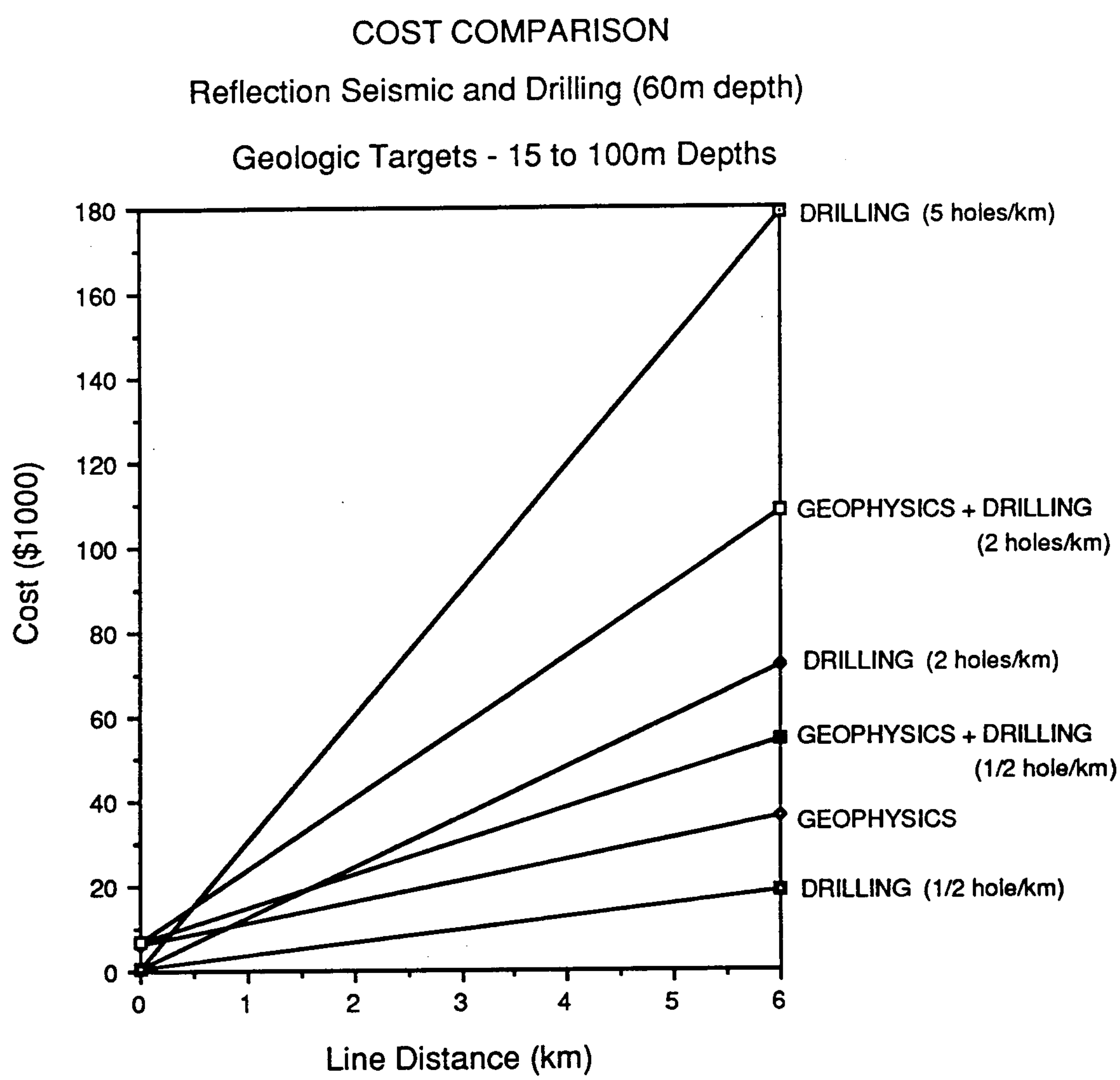


Figure 5.3 Cost comparison graph of reflection seismic and drilling (30m holes) for geologic targets between 15 and 100m in depth.



Drilling
- 80% rotary and 20% core
- depth 60 metres
- $5930 / hole
- mobilization $690

Geophysics
- seismic reflection plus processing
- $5000 / kilometre
- 400 data stations / kilometre
- mobilization $6000

Cost estimates based on 1986 data.

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Figure 5.4 Cost comparison graph of reflection seismic and drilling (60m holes) for geologic targets between 15 and 100m in depth.

6. APPLICATION OF GEOPHYSICAL TECHNOLOGY

6.1 Exploration Strategy

At the very early stages of exploration, regional geologic studies, airphoto analysis, and drilling over a coarse grid are required to gather preliminary data regarding the development of an area as an economic coal prospect. Such information is presently available for most areas of interest in the foreseeable future.

The next stage of exploration requires more detailed geologic and airphoto study and a more dense exploratory drillhole pattern. It is at this stage of exploration that surface geophysical technology can be valuable. The main benefit of geophysical exploration is the availability of continuous subsurface information, showing both the uniform and anomalous features over an area. Localized exploration by drilling can then be planned in an efficient and cost effective manner. The two main geophysical methods that should be considered at this stage are reflection seismic and direct current soundings. Both have demonstrated an ability to directly sense the presence of coal and each can be used to monitor the continuity of coal and surrounding strata.

The following stages of exploration mainly concern mine development. The geophysical mapping objectives addressed during the present coal study belong to this category. Targets such as channel location, subcrop location, presence or absence of incompetent bedrock masses, and other local geologic features that may affect the economics of mining have been shown to be identifiable using geophysical technology. The location of abandoned mine workings is another target in this category. However, geophysical technology has yet to be seriously applied to this problem.

The economics of incorporating geophysical technology into the exploration strategy has been discussed in Section 5. It is reasonable to expect that as the depth to economically mineable coal increases the cost benefit of geophysical exploration will also increase.

6.2 Increase in Ability and Decrease in Cost with Time

At the beginning of the surface geophysical research program little or no geophysical ability had been demonstrated as being useful for the exploration of coal resources in Alberta. Initial studies, however, indicated that seismic and electrical techniques could be advantageously applied. The confidence and experience gained from these studies is best illustrated in the examples outlined in Section 4.

The costs of performing geophysical exploration have decreased throughout the research program, since the experience gained has resulted in more efficient data acquisition procedures being used. More efficient procedures require less field effort and field effort is the major component of cost. Recording instrumentation has also improved. The main example is the seismograph with which reflection seismic data is recorded. Larger data channel capacity, and increased dynamic range have allowed the productivity of surveying to increase dramatically. Coupled with improvements in reflection seismic data processing, it is fair to say that the results illustrated in Section 4.2.2 can be produced at less cost than earlier results as illustrated in Section 4.4.1.

6.3 Limitations to the Use of Geophysical Methods

Limitations to the use of the geophysical methods tested during the coal research program can be grouped into three general categories:

- Limitations imposed by site conditions and site geology.
- Limitations of the methods themselves.
- Limitations arising from the trade offs between cost, depth of penetration and required resolution.

In terms of site conditions, a first consideration is time of year. The presence of seasonal frost can negate the use of direct current techniques, since it is difficult to force sufficient current into the frozen ground. Seasonal frost also creates a high seismic velocity layer. Direct arrivals through this layer attenuate over short distances. This high velocity layer can adversely affect reflection seismic measurements for which data at close source offsets is required for shallow studies. Highly irregular topography and the presence of swampy ground (no shear wave propagation) are other important site specific constraining factors.

The complexity of the geologic section can also pose some limitations. In terms of complexity, such things as large dips of strata and the presence of multiple layers with physical properties similar to target strata must be considered. Dip has not been a limitation for prairie work. Correlation with downhole geophysical logging can often aid isolation of the response of target strata in geophysical measurements in complex geologic environments. Of course in the event that the contrasts in physical properties of the various lithostratigraphic units of interest is not present, then geophysical exploration could not be used to advantage.

Each of the geophysical methods is characterized by certain geometrical constraints. For instance, in direct current soundings depth of penetration is gained at the cost of lateral resolution and requirements for large power sources. The situation is similar for refraction seismic methods because the limited data channel capacity would require larger spacing between geophones to attain larger depths of exploration. The refraction seismic method is also limited in its ability to resolve in terms of thickness a sequence of thin layers with slightly different velocities on a sequence in which deeper strata are characterized by lower velocity than overlying strata. Crosshole seismic measurements are used to reduce the possibilities of serious depth conversion errors in these circumstances. The main limitation for the reflection seismic method is data acquisition at very shallow depth. Ground roll, airwaves, refracted, direct and reflected waves all occur virtually simultaneously within depths of less than 10 metres.

The limitations described above are not absolute. Often data acquisition geometries can be tailored to optimize data recovery from very shallow or very deep zones of interest. Generally the increased field effort required will affect cost. For example, there are cases of reflection seismic sections being developed for the upper 5 metres of the subsurface, gained by placing geophones at spacings of less than 1 metre. The productive rate of surveying in this instance is very low so that the cost per kilometre would be very high. Similarly it would be possible to gather direct current sounding measurements to large depths of exploration. Much more field time would be required to obtain information at a single station, thus, increasing the effective acquisition costs.

The advantages and limitations for each geophysical method are summarized in Appendix 10.6.

6.4 Integration of Geologic and Geophysical Exploration

The roles of geologic and geophysical exploration for coal are closely interrelated. Proper planning of a geophysical exploration program in terms of applicable methods, data acquisition geometries, and appropriate target strata depends on the availability of a reasonable geologic model for the area in question. Similarly, the availability of continuous geophysical information can aid in planning the proper location and density of geologic exploration with drillholes to satisfy specific mapping objectives.

Specific geologic information, such as downhole geophysical and lithologic logging, can often be readily incorporated into the interpretation of geophysical data. Perhaps the best case of this is the use of downhole sonic and bulk density logging to support the interpretation of high resolution reflection seismic data. The downhole logs are used to produce a detailed log of the acoustic impedance structure in the subsurface. This data is used to create synthetic seismograms of the reflection seismic response of the subsurface by convolution with theoretical seismic wavelets matching the dominant frequency content of the seismic data. By this process major features imaged in the reflection seismic data can be assigned definite geologic significance. Similarly a well interpreted reflection seismic section basically makes available a sonic log at every trace location along the seismic survey lines.

6.5 Site Specific Considerations

Geophysical technology cannot be considered as being available "off the shelf". Successful application of the appropriate techniques requires consideration of the operating environment, the geologic environment, and a firm statement of specific mapping objectives including the depth range of interest and the lateral and vertical resolution desired. Theoretical modelling of anticipated target responses can be performed to judge the feasible use of appropriate methods prior to any field studies. In new or geologically complex areas a field test can often be designed to demonstrate the compliance of geophysical measurements with the specific objectives. This strategy will ensure that exploration budgets can be allocated wisely and enable optimal data recovery from both geologic and geophysical studies.

6.6 Seismic Data Processing

This project has resulted in marked improvements in the data processing capabilities applied to shallow reflection seismic data. Further improvements can yet be achieved. If successful, this could extend the applications of surface geophysics beyond that of continuity definition to potentially quantifying depth, areas of coal thinning and coal quality degradation.

Success of applying good shallow reflection seismic results lies ultimately in the hands of the processing companies. They are vitally important in making meaningful interpretations of the raw data. Up until now, few companies have been willing to try processing high resolution data from such shallow depths. The reason is that nobody has ever done it before. The firms that have been applying existing techniques to this data are doing so because of the current slowdown in oil industry activity. A lot of time and energy has gone into making the processing successful, especially from Bob Labun who is currently with Riley's Seismic Processors and additional assistance from Don Lawton from the University of Calgary. Normally, the two way travel time sampling rates that the processors work with is several milliseconds, however our shallow data has sampling rates of 1/4 millisecond. Because of the unavailability of specific software for shallow seismic data, processing static corrections are done manually, compared to automatic statics that are carried out with deeper work from oil industry. The manual procedure is tedious, time consuming and costly. The two companies that have done our processing in the past, Digitech and Beaver, have gone out of business. Currently Riley's is the only firm handling our processing needs.

An important point to remember however, is that the quality of data collected in the field has a great influence on what the processors are able to do with it. In other words, bad data in will usually produce poor results. Since completion of this research project, Geo-Physi-Con Co. Ltd., has acquired improved seismic recording instruments which can now output data at industry standards. Having the data at industry standards means that other companies should be able to do the processing.

Presently shallow reflection seismic data processing needs are being met satisfactorily. However, concerns that may affect the future development of processing capabilites are:

i) Few seismic processing companies are able or willing to do this work.

ii) What if the company that currently does our processing were to go out of business.

iii) If or when the oil industry activity picks up their incentive for processing, our work may diminish because of the time consuming manual procedures required.

iv) The industry presently does not want to develop automated static correction procedures for processing of shallow seismic data. This may be due to the limited amount of current work in this field or their perception that there is a restricted market in shallow seismic work.

7. CONCLUSIONS

Presented are the major conclusions resulting from the investigations and experience gained from the project.

1) Surface geophysical techniques can be used cost effectively for plains coal exploration and mine planning problems. Improvements in data acquisition techniques and equipment in the field, and data processing have led to reduced costs. Also as the use of geophysics increases, continued improvements should result in further cost reduction.

2) Surface geophysics has proven to be successful in recognizing and delineating many of the targets and problems associated with exploration and mining of coal. The unique properties of coal have made it a good target for geophysical methods to detect. Surface geophysics can define; subcrop, washouts and glacially deformed bedrock, and can both recognize individual subsurface stratigraphic units and demonstrate their continuity.

3) Development of reflection seismic techniques in the target depth range of 10 to 70 m has been achieved. Both data acquisition techniques and data processing can now be successfully applied to defining targets at shallow depths.

4) The use of refraction seismic and direct current methods have also proven to be effective in depths to 70 m. Refinements of these techniques for specific targets has shown them to be very useful. The experience gained has now made them routinely operational.

5) The vertical and lateral resolution of surface geophysical techniques has shown to be in good agreement with subsequent drilling. However, no level of accuracy can be guaranteed for each of the methods.

6) Experience from this study has shown that an integrated surface geophysics and geological surface mapping and drilling program can be the best and most cost effective approach to meeting the objectives of an exploration program. The large volume of data collected from geophysical surveys can be used to identify anomalous areas, resulting in optimal target locations for drilling.

7) Surface geophysics is much more effective for demonstrating stratigraphic continuity than is drilling. This is achieved through a higher sampling rate along a survey line with geophysical methods than the single point of data from a drillhole.

8) Selection of the appropriate geophysical techniques requires careful consideration of:

   (i) the operating environment,
   (ii) the geologic framework, and
   (iii) a firm statement of specific mapping objectives including the depth range of interest and the lateral and vertical resolution desired.

9) The cost benefit of surface geophysics increases as the depth of exploration increases. Drilling costs will be higher with increased target depths, even from 30 to 70 m, whereas geophysical costs will remain the same.

10) The geophysical techniques, for both fieldwork and subsequent data processing, are greatly improved over those available at the initiation of the project. Further improvements have been made since completion of the study with the acquisition of much more sophisticated seismic recording instruments.

11) The fixed frequency electromagnetic induction technique proved rather ineffective in the typical plains setting where conductive clay rich surficial sediments are present. The conductive

materials restrict the capability of the method to determine a detailed resistivity thickness section. However, measurements in more resistive surficial materials such as gravel or peat can be very useful for mapping.

12) The best demonstration of success of the project is the adoption on an operational basis by the industry participants of the geophysical techniques.

8. RECOMMENDATIONS

8.1 Recommendations for use of Surface Geophysics in the Plains Coal Region

1) Surface geophysics should be adopted as one of the principal tools for plains coal exploration and development.

2) The integrated use drilling and surface geophysics is strongly recommended for maximum benefits in an exploration program. Drilling should be carried out subsequent to the geophysical surveys to provide suitable control. All holes should be geophysically logged and coreholes should be drilled as needed for specific targets.

3) The geophysical methods recommended for coal investigations in the plains setting are:

   i) Reflection seismic and direct current sounding for the intermediate exploration stage.
   ii) Reflection seismic, refraction seismic, direct current sounding and direct current profiling at the mine planning stage. Crosshole seismic tests should also be performed if needed to calibrate refraction seismic results.

4) A coal development strategy should proceed as follows:

   i) Widely spaced drillholes at the initial exploration stage.
   ii) An integrated program of surface geophysics, drilling, and airphoto interpretation for subsequent exploration, and early mine planning.
   iii) More detailed surface geophysical surveys and drilling to provide the higher quality data needed for later mine planning.

5) Support should be given to improve data processing capabilities as applied to the reflection seismic method. The current level of processing capabilities can be maintained and/or improved upon by:

i) Industry performing sufficient shallow seismic work to keep the processing activity alive. If the processing companies continue to receive high volumes of shallow data, processing needs can be met. With increased work, they would in all probability look at developing automated static corrections for a quicker turn around, resulting in lower costs in the long run.

ii) Having a research organization develop and maintain the required processing techniques for shallow seismic data. This would have to be undertaken through a new research project, but should guarantee the availability of processing techniques.

We believe the latter idea is the most practical given the current economic condition in industries such as coal and the relative slowness of high resolution seismic to be applied across Alberta.

8.2 Recommendations for Future Investigations

1) Consideration should be given to evaluating the surface geophysical techniques in the foothills region. This is a geologic regime in which the techniques have yet to be tested. From this study the use of surface geophysical techniques in the plains setting, where the operating environment and geologic framework are relatively simple and straightforward, has proven to be very successful. The success of this project and experience gained should be carried forward into new ground. The higher relief topography and more complex structural geology of the foothills would be more challenging for surface geophysics. However, the same obstacles must be overcome by current methods of data collection with conventional drilling. If the methods are successful in the

foothills, surface geophysics would provide continuous information between drillhole points and a combination of surface geophysics and geological drilling may prove to be more cost effective than drilling alone.

2) A study should be undertaken to quantify the relationship between the dynamic moduli measured by the geophysical techniques and the static moduli measured from samples in the geotechnical laboratories. Samples should be collected from one or more of the crosshole sites to obtain actual laboratory measurements of selected geotechnical properties so these data can be compared to those calculated for the same properties from the surface geophysical measurements. This could be a research project well suited to the university, perhaps a doctoral thesis.

3) Consideration should be given by AOCRT to supporting a Professional Development Program on Surface Geophysical Coal Applications. The project's geophysical contractor, Geo-Physi-Con Co. Ltd., or CMRC might be considered for this task. Program objectives should include:

   i) The dissemination to mining professionals in the coal industry of the geophysical methods and applications developed in this research program.

   ii) Widespread adoption of surface geophysics by these professionals, leading to a greater knowledge of overburden, bedrock and coal conditions ahead of mining, and to a preplanned and engineered optimization of pit design and selection of excavation equipment. This would have a significant positive impact on improving the efficiencies of pit operations, increasing coal recovery and reducing mining costs.

   iii) A handbook and short course to achieve i and ii. This approach would also have the advantage of being marketable in Canada and internationally.

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10. APPENDIX

10.1 Surface Geophysics Project Reports List

The following is a list of all reports completed for the Surface Geophysics Project. Copies of the documents have been submitted to the Alberta Office of Coal Research and Technology, Edmonton, Alberta.

Downhole geophysical log data were collected from 45 boreholes and are available for viewing by appointment with the Alberta Research Council, Terrain Sciences Department, Edmonton, Alberta.

Geo-Physi-Con, 1987: Surface geophysical joint venture (1986), Genesee Mine. Unpublished report (C86-17) prepared for Alberta Research Council by Geo-Physi-Con Company Limited, Calgary, Alberta, January 1987, 40 p., plus figures and appendices.

Geo-Physi-Con, 1986: Surface geophysical project 1985, combined refraction seismic and electrical surface geophysical study, Genesee Site. Unpublished report (C85-24) prepared for Coal Mining Research Company by Geo-Physi-Con Company Limited, Calgary, Alberta, March 1986, 31 p., plus figures and appendices.

Geo-Physi-Con, 1986: Surface geophysical project 1985, shallow reflection seismic study, Genesee Site. Unpublished report (C85-24) prepared for Coal Mining Research Company by Geo-Physi-Con Company Limited, Calgary, Alberta, March 1986, 25 p., plus figures and appendices.

Geo-Physi-Con, 1985: Surface geophysical project 1984, combined electrical and seismic surface geophysical test surveys, Highvale Mine, Pit 02 and Paintearth Mine. Unpublished report (C84-25, C84-28) prepared for Coal Mining Research Company by Geo-Physi-Con Company Limited, Calgary, Alberta, February 1985, 50 p., plus figures and appendices.

Geo-Physi-Con, 1985: Surface geophysical project 1984, shallow reflection seismic studies, Highvale Mine and Paintearth Mine. Unpublished report (C84-25, C84-28) prepared for Coal Mining Research Company by Geo-Physi-Con Company Limited, Calgary, Alberta, Feburary 1985, 50 p., plus figures and appendices.

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Green, D.H. 1985: Surface geophysical project 1984, Highvale Mine and Paintearth Mine, project synthesis report, volume 2. Unpublished report prepared for TransAlta Utilities Corporation by Coal Mining Research Company (CMRC report #85/14-C), March 1985, 21 p., plus figures and appendices.

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Sterenberg, C.E. 1986: Surface geophysical drilling program, Genesee Mine area, core lithologs, field program August 1986. Unpublished report prepared for Coal Mining Research Company by Terrain Sciences Department, Alberta Research Council, October 1986, 62 p.

10.2 Physical and Interpretive Principles for Surface Seismic Methods

10.2.1 Reflection, Refraction and Crosshole Seismic Methods

The paths along which energy may be propagated between a source of seismic energy and a geophone, for a simple two layered ground, are shown schematically in Figure 10.1.

The direct path is utilized for crosshole seismic studies, where the source and geophone are placed at the same depth in adjacent boreholes separated by relatively small distances. The refracted wave paths are utilized for surface based refraction seismic studies. The energy arriving along either direct or refracted wave paths represents travel time minimums, and the arrival times are linear in terms of distance, for layers with constant velocity. It is evident from the figure that only the refracted wave path carries information about both the thickness of overlying material and the refractor velocity.

The reflected time paths are not minimum time paths, so that reflections need be recognized amidst energy arriving via other travel paths. The square of reflected arrival times is linear with the square of separating distance, for layers of constant velocity.

10.2.2 Seismic Wave Types

Energy propagation within an elastic earth is governed by the wave equation. Solutions for the equations of motion for an isotropic earth indicate that energy propagation is restricted to three primary modes. These are:

i) A body wave of cubical dilatation (compression wave), causing particle motions parallel to the direction of energy propagation.

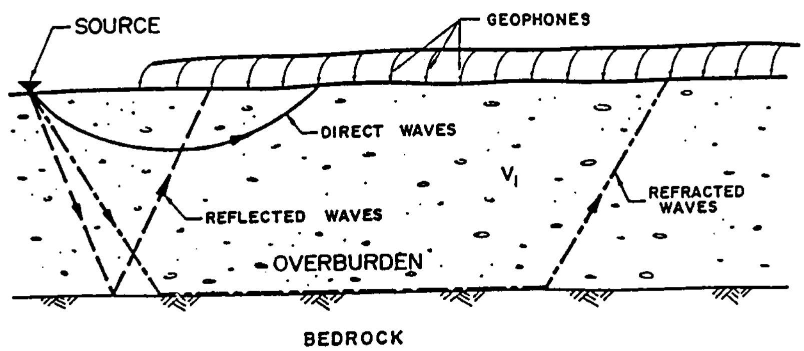


Figure 10.1 PATHS OF SEISMIC WAVES

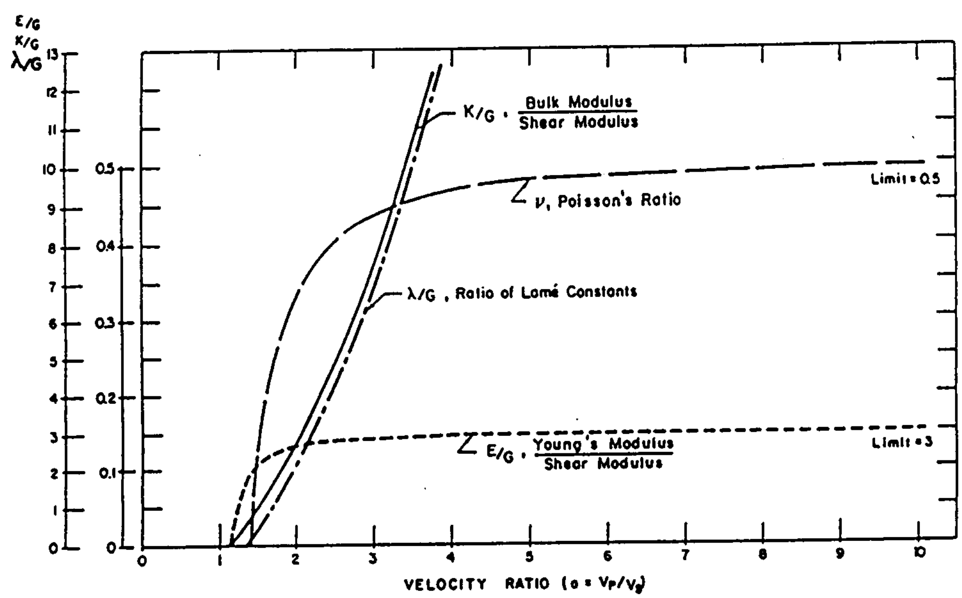


Figure 10.2 RELATIVE DYNAMIC MODULI

ii) A body wave of pure rotation (shear wave), causing particle motions transverse to the direction of energy propagation.

iii) A wave confined to the near surface (Rayleigh wave), causing particle motions that are elliptical, being both parallel and perpendicular to the horizontal direction of energy flow.

Each of these wave types propagate with a characteristic velocity that is a function of the elastic properties of the earth. The velocity of propagation of the compression wave (V_p) is the largest of the three. The velocity of propagation of the shear wave (V_s) is intermediate in value. The velocity of propagation of the Rayleigh wave (V_r) approaches V_s, as the ratio V_p to V_s (the velocity ratio) increases.

10.2.3 Relations Between the Elastic Constants

The theory of elastic wave propagation in layered media indicates that several dynamic elastic moduli can be derived from the three measured quantities listed below:

i) Bulk density, ρ.

ii) Velocity of propagation of shear waves, V_s.

iii) Velocity of propagation of compression waves, V_p.

These three parameters are related to the dynamic elastic moduli by the expressions:

Shear Modulus, (Lame Rigidity Modulus) $G = \rho V_s^2$

Young's Modulus, $E = \rho \dfrac{(V_s^2 (3V_p^2 - 4V_s^2)}{(V_p^2 - V_s^2)} = G \dfrac{(3a^2 - 4)}{(a^2 - 1)}$

Bulk Modulus, $K = \rho \, (V_p^2 - 4/3 \, V_s^2) = G \, (a^2 - 4/3)$

Poisson's Ration, $\nu = \frac{(V_p^2 - 2V_s^2)}{2(V_p^2 - V_s^2)} = \frac{a^2 - 2}{2(a^2 - 1)}$, and

Lame Compressibility Modulus $\lambda = G(a^2 - 2)$

where $a = V_p/V_s$

Figure 10.2 shows the values of the dimensionless ratios E/G, K/G, λ/G and ν as a function of the velocity ratio, a. It is apparent from the figure that, as the velocity ratio becomes larger, the material will essentially behave as an incompressible fluid. Consequently, saturated materials often show a large velocity ratio, especially if the compressional velocity of the unsaturated material is less than the compressional velocity of water (about 1600 m/s). The water, itself, will not transmit a shear wave.

10.2.4 Refraction Seismic Method

Either the compression wave or the shear wave can be refracted along boundaries between materials where the lower material have a velocity greater than the upper material. The compression wave is most often used for this purpose since the identification of the moment at which the compression energy arrives at a geophone is simplified by the fact that this energy appears before energy transmitted by other modes. When the shear wave is used, the energy arrives at a time later than energy propagated by the compression wave. To unambiguously define the shear wave arrival at a geophone, use is made of the fact that the shear wave is polarizable. That is, the shear wave exhibits a polarity reversal on two records when each record corresponds to oppositely directed source energy. The shear wave can be polarized in either a horizontal or vertical direction. For refraction seismic applications, horizontally polarized shear waves are used since these waves do not create other types of waves when they are incident on a horizontal geologic boundary. For crosshole studies vertically polarized shear waves are used.

The method of data processing for refraction seismic data, using either compression or shear waves, requires that the times of the wave arrival be measured at a number of geophones for locations of the source to both sides of the geophones. For any particular geophone recording arriving energy that travels a refracted path from a source at each side of the geophone, the difference in the arrival times is related to the velocity of the refracting surface. Additionally, the sum of the arrival times from each source to the geophone is related to the thickness of material above the refracting surface. This method is often referred to as the plus-minus or delay time method. Its use for a simple two layer structure is shown in Figure 10.3 and is described briefly below.

The first arrival times are plotted as a function of distance (Figure 10.3a). The difference in arrival times at each geophone from shots offset to either side of the geophone are also plotted as a function of distance (Figure 10.3b). On this plot, the difference in arrival times for geophones recording refractions from each direction fall on a straight line. The slope of this line is $2/V_2$, where V_2 is the compressional (or shear) velocity characteristic for the lower material. It is assumed that the velocity determined along the surface of the refractor is identical to the velocity within the refractor, i.e., the materials are isotropic. Crosshole velocity measurements are used to confirm material isotropy. For each geophone that recorded arrivals refracted from the lower material, the delay time (Figure 10.3d), is computed. The depth to the lower material is related to the delay time by the function shown in Figure 10.3c.

Critical to the accurate determination of depth to refractors are the delay time, the values of overburden velocity, and the travel time between the source locations (reciprocal travel time). These parameters are derived from the time distance plot (Figure 10.3a).

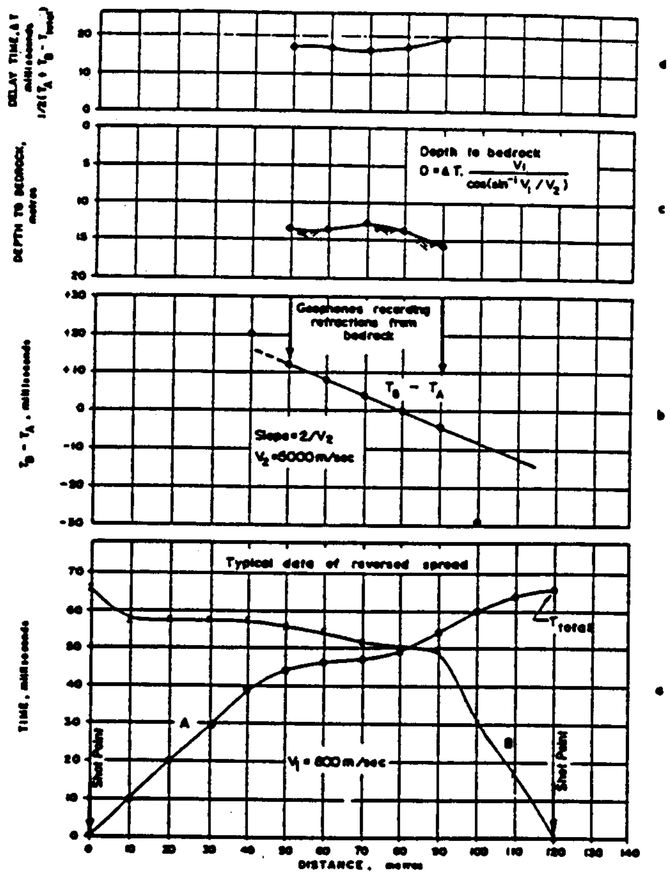


Figure 10.3 REFRACTION SEISMIC DELAY TIME ANALYSIS

10.2.5 Reflection Seismic Method

A major advantage of the reflection seismic method is that it presents a very direct way to locate subsurface boundaries which exhibit a contrast in acoustic impedance. Other advantages of the method over refraction techniques include the ability to probe to depths much larger than the source to sensor separation and the ability to sense the presence of a subsurface boundary characterized by a velocity inversion, i.e., a decrease in material velocity 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

$$RC = (Z_{1+1} - Z_1)/(Z_{1+1} + Z_1)$$

where Z_1 and Z_{1+1} are material impedances above and below a subsurface boundary, respectively.

Coal generally represents an excellent reflecting surface since the lower density of coal compared to the density of surrounding rocks creates a large contrast in acoustic impedance. The corresponding reflection coefficient is in the order of ±0.3. Reflection coefficients for other boundaries exhibiting only minor velocity and density contrasts are in the order of ±0.05 to ±0.1. For this reason the surfaces of coal seams can be expected to correlate to the strongest events on reflection seismic records.

The reflection seismic method is highly developed for applications to deep exploration targets. However, there are a number of complicating factors which hamper the application to exploration in the shallow subsurface.

The greatest complication arises in trying to identify reflected events amidst energy arriving via a variety of other transmission modes. The wave types responsible for interference include a direct wave through air, refracted and ground roll (Rayleigh surface waves). Generally, these interfering wave modes propagate at different velocities. A time window (Figure 10.4) in which reflections can be identified is generally present between the onset of refracted waves and the arrival of surface (or air) waves. The width of this window (the depth of exploration) is a function of the source to sensor separation. Practical limits on the size of the time window are imposed by the attenuation of signal strength which increases with travel path length, the asymptotic merging of reflected and refracted arrivals at large source separations, and amplitude and phase variations of the reflected wavelet when the reflection angle of incidence exceeds the critical refraction angle.

Another serious complication is due to the relatively long duration of the source wave form with respect to the short travel times for reflections from shallow horizons. The effect of the finite source duration is to produce overlap and smearing between closely spaced reflected events. This causes reductions in frequency content and resolution. Improvements to the frequency content and resolution are problems usually addressed during data processing (deconvolution).

The need for high frequency content is critical for shallow reflection seismic studies. The dominant frequency controls the effective seismic wave length according to the relation

$$\lambda = v/f$$

where λ is the wavelength (m),
v is the average velocity (m/s), and
f is the frequency (hertz)

Vertical resolution for the method can be expected to range between 1/4 and 1/8 of the dominant wave length achieved.

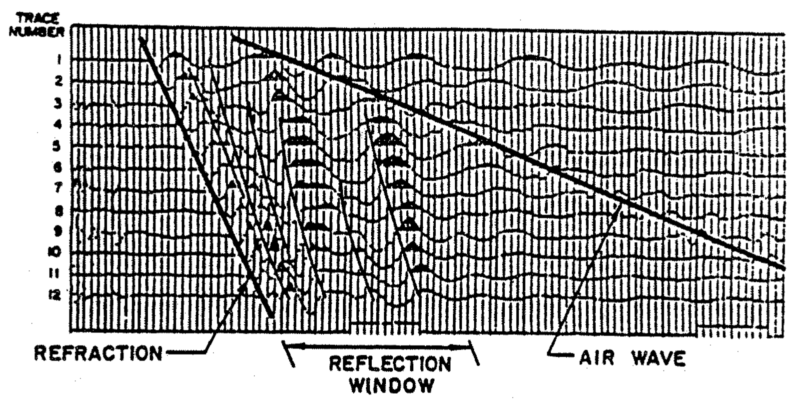


Figure 10.4 ILLUSTRATION OF TIME WINDOW

Data processing of common depth point reflection seismic measurements is carried out on main frame computers at contract data processing firms, making full use of software applied to traditional hydrocarbon exploration reflection seismic data. The short record lengths and large number of events at early time have required some modifications of the usual processing sequence.

The most difficult step in the processing sequence is the selection of adequate static corrections. Difficulties in this regard arise mainly from the incomplete refraction static information available due to the use of short cable lengths, the non uniformity of shot coupling within the wide variety of near surface materials encountered at any one site, and the relative size of the static corrections with respect to the wavelet period and short travel times characteristic of these studies. Static corrections are applied to the data in a number of steps including elevation corrections to datum, trim statics, and surface consistent shot and geophone statics.

Data deconvolution has been handled in a variety of ways. Generally frequency domain deconvolution has proven most effective with recent data sets. Deconvolution of the data is an essential step to increase signal to noise ratios, and maximize frequency content and ultimate resolution.

Trace gathers, velocity analysis and normal moveout corrections are applied prior to stacking of the data. Frequency wave number (F) filtering is used to remove remnant wide angle diffraction and other low velocity events. Time variant band pass filtering is applied to post stacked data. The time variant filtering allows maintenance of optimal frequency content throughout the processed time sections.

10.2.6 Crosshole Seismic Method

Crosshole seismic measurements are made in sets of three drillholes. Generally the drillholes are closely spaced (less than 6 metres apart) so that first breaks correspond to energy arrival along direct wave paths and not critically refracted wave paths. A downhole mechanical source (hammer) capable of producing both compression waves and vertically polarized shear waves is placed in one of the end drillholes of the group of three. Triaxial geophone packages are placed in the other two drillholes. A schematic of this arrangement and hammer detail is shown in Figure 10.5.

The hammer has two anchor plates which are hydraulically forced against the drillhole wall to lock the hammer striker plate in place. The hammer weight can strike the plate upwards and downwards, imparting vertically polarized shear waves (S waves) into the ground. Reversing the direction of the hammer impact results in reversal of the directions of first motions of the vertically polarized shear waves. Only a small percentage of the input energy is transmitted as compression waves (P waves).

The triaxial geophones record one vertical and two horizontal components of ground motion. No provision for orientating the horizontal component geophones is made. The geophones are held in place with air filled bladders, which are inflated after the geophones are lowered to the same depth as the hammer.

Signals from single upward and downward blows of the hammer are recorded at appropriate gain and trace size to facilitate recognition of the shear wave signal at each hole for either blow. Crosshole measurements are obtained at depth intervals of 1 metre. Productivity of surveying with the crosshole method is about one set of drillholes at a site per day.

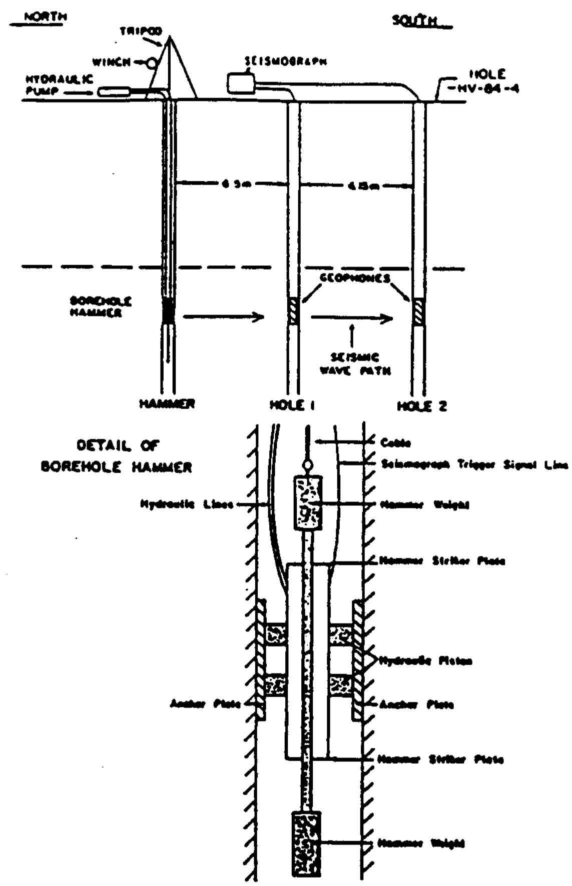


Figure 10.5 CROSSHOLE SEISMIC METHOD

The arrival of shear and compressions waves are visually identified on seismic records. The velocity ratio, as a function of depth, is then determined as the ratio of shear wave arrival time divided by compression wave arrival time. This ratio is independent of the exact distance between drillholes. The shear and compression wave velocities are found by dividing the separating distance divided by the appropriate arrival times. Dynamic elastic moduli then follow from the relations given in Section 10.2.3.

10.3 Physical and Interpretive Principles for Direct Current Sounding and Profiling (DCS and DCP), and Fixed Frequency Methods

10.3.1 DCS Method

Direct current soundings are one of the oldest and most commonly used methods for determining earth resistivity. Operation of the system in the Schlumberger configuration, as used during the test survey, is illustrated in Figure 10.6.

Current is driven into the ground through one pair of electrodes (I_1 and I_2). The potential established in the earth by this current is measured with a second pair of electrodes (P_1 and P_2). To study the variation in resistivity with depth, the spacing between the current electrodes is altered. Figures 10.6a and 10.6b show schematically the distribution of current flow at two electrode spacings. At close electrode spacing (Figure 10.6a), the currents dominantly flow near the surface and the potential field is virtually not influenced by the second layer. With increased spacing, part of the current flow is located in deeper layers, so that the potential measured includes the influence of the deeper layers.

The DCS method is effective for determining the presence of electrically resistive strata at depth, since resistive strata present a barrier to current penetration. Coal is known to be more electrically resistive than overlying rocks at prairie coal mine sites and consequently, can be easily mapped using this method. However, it is difficult to determine the bottom surface of coal seams using the DCS method since the coal insulates lower strata.

The direct current sounding data are converted to apparent resistivities and plotted against one half the current electrode separation, on a log-log scale. The resultant curves are compared to a set of master curves to determine preliminary estimates of the

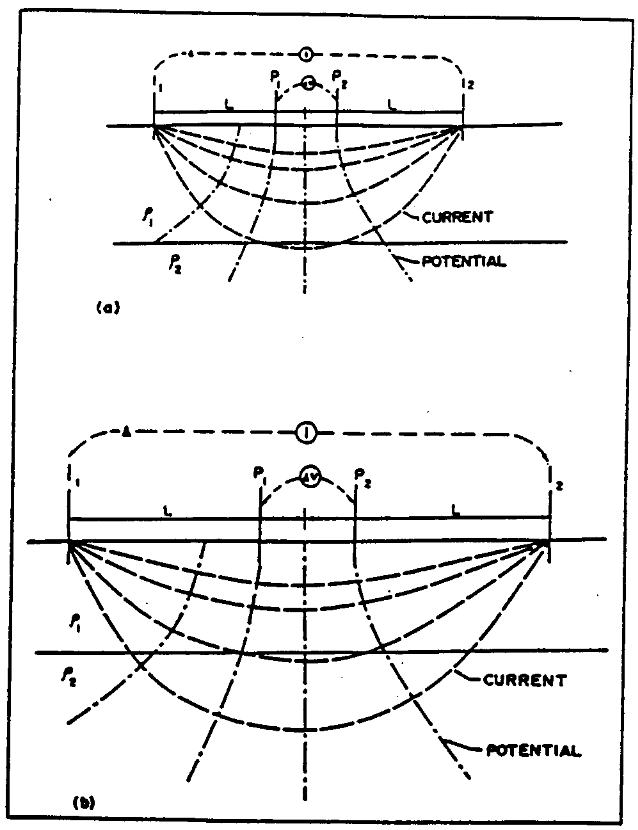


Figure 10.6 CURRENT AND POTENTIAL FIELD DISTRIBUTION FOR DIRECT CURRENT SOUNDING METHOD

resistivity and thickness for distinctive subsurface strata. The resistivity and thickness of each layer are then adjusted, using computer algorithms, until a match of the field and model data is found.

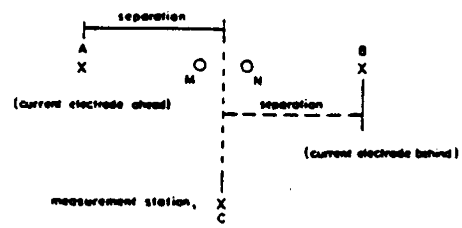
The fact that current electrode separations need be 4 to 5 times greater than the depth of exploration illustrates the dependence of the method on lateral homogeneity in each resistivity. Additionally, interpretations based on DCS data should be correlated to the results of drilling. This is required since DCS data can be affected by equivalence. Equivalence occurs when a range of resistivities and thicknesses can be assigned to a particular subsurface layer, each combination of which yields nearly the same apparent resistivity curve.

10.3.2 DCP Method

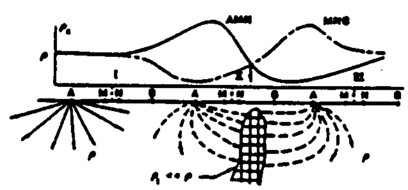
Direct current profiling (DCP) is a method that may be used to trace the location of abrupt lateral changes in resistivity of subsurface materials. The method is well suited for the location of coal subcrop, where resistive strata (coal) lie to one side of the subcrop and conductive materials to the other side.

A variety of different electrode configurations can be used with this method. The arrangement utilized during the present study is illustrated in Figure 10.7 and is generally referred to as pole-dipole configuration. One of the current electrodes (A), as well as both potential electrodes (M and N), are located along the survey line. The other current electrode (C) is located away from the survey at a distance large enough to neglect its influence. This electrode acts as a current sink.

The depth of exploration of the array is controlled by the distance from current electrode (A) to the midpoint of the potential electrodes. This distance is called the separation. The distance to the current sink (electrode C) should be at least 10 times the separation.



a) Electrode configuration of DCP method.



b) Schematic of current filament and apparent resistivities caused by presence of a confined, conductive body.

Figure 10.7 SCHEMATIC OF ELECTRODE CONFIGURATION AND CURRENT FILAMENT DISTRIBUTION FOR DCP METHOD

Each of the lines are surveyed twice, once having the current electrode (A) ahead of the pair of potential electrodes and once with this electrode behind the potential electrodes. The same sink electrode is used for both directions of survey. This double coverage provides the most diagnostic information concerning the subcrop location.

The physical principles involved in pole-dipole DC profiling are illustrated in Figure 10.7b. The figure shows schematically the current patterns over a conductive body (of resistivity ρ_1) emplaced in a subsurface of homogeneous resistivity, ρ. Note that electrode (A) is labelled as B for the arrangement in which the on line current electrode is behind the pair of potential electrodes.

When the measurement array is located at a large enough distance so that is is not influenced by the body (position I, in the Figure 10.7b), then current from electrode (A) spreads radially and the apparent resistivity (proportional to current density) is equal to the real resistivity of the subsurface. Closer to the anomalous body (position II), the presence of the body alters the current pattern causing distortions in the apparent resistivity curves. Surveying in the reverse direction reverses the sense of the distortions. For the very simple example presented in the figure, the location of the crossovers in the apparent resistivity plots for each direction of survey intersect directly over the anomalous body. The depth to the anomalous body can be estimated in a qualitative sense by performing the survey at two or more electrode separations or by obtaining direct current sounding data along the survey lines. The distortions appearing at the edge of a resistive plate (coal subcrop) can be more complex than illustrated in Figure 10.7.

10.3.3 Fixed Frequency Electromagnetic Induction (EM) Method

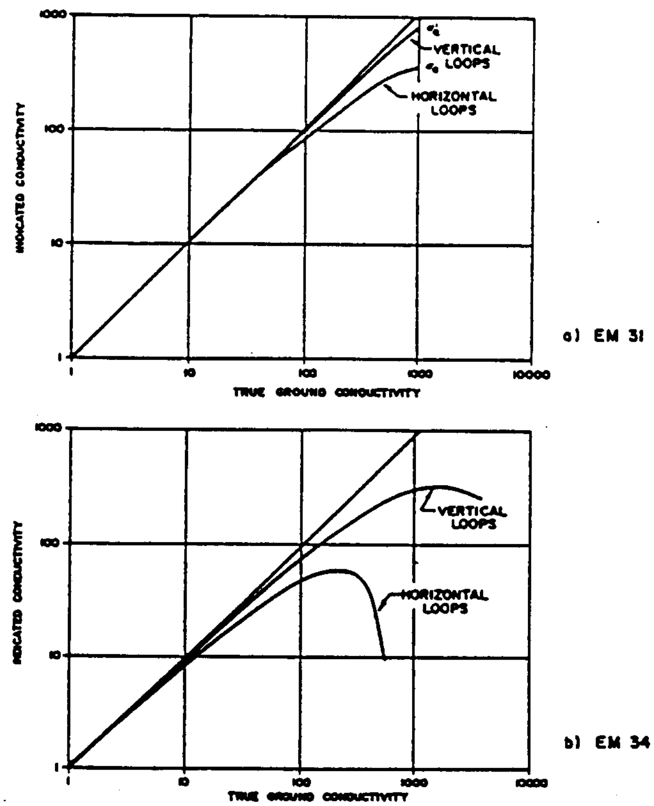
In the EM method, eddy current flow is induced in the ground by the time varying magnetic field of a vertical or horizontal magnetic dipole transmitter operating at a fixed frequency. This eddy current flow induces a secondary magnetic field which, together with the primary field, is sensed by a similar receiver dipole. The ratio of the primary and secondary fields is related to the conductivity of the subsurface.

The instrument parameters, frequency and coil separation, are selected so that operation can be described by the low induction number approximation over a relatively large range of terrain conductivity. In this sense, each induced eddy current loop is independent of the others and the measured (apparent) conductivity can be treated as a linear superposition of the responses of strata within the exploration range of the array used.

The effective exploration depth of the EM equipment can be varied by changing one or more of loop spacing, loop orientation (vertical or horizontal), or height above the ground. The effective depth of exploration is a relative value only. It is usually taken to be the depth at which the geometric factor describing the contribution of strata below this depth falls to about 37% of its value at ground surface over terrain homogeneous in conductivity with depth. This concept is useful for visualizing the conductivity stratification of the ground where EM data to a number of exploration depths is available.

Figures 10.8a and 10.8b show the compliance of EM31 and EM34-3 measurements with the low induction number approximation, as a function of ground conductivity. In each figure the straight line at the left represents perfect correlation between instrument readings and ground conductivity.

In Figure 10.8a it is apparent that the EM31 represents ground conductivity very well for values of ground conductivity of less than 90 mmho/m (resistivity greater than 11 ohm-m). Figure 10.8b shows that the EM34-3 does not respond as well when ground conductivity increases above about 50 mmho/m (resistivity less than 20 ohm-m). In either case



Source: Geonics Ltd.

Figure 10.8 EM 31 AND EM 34 INDICATED VERSUS TRUE GROUND CONDUCTIVITY the response of vertical loop orientations is better.

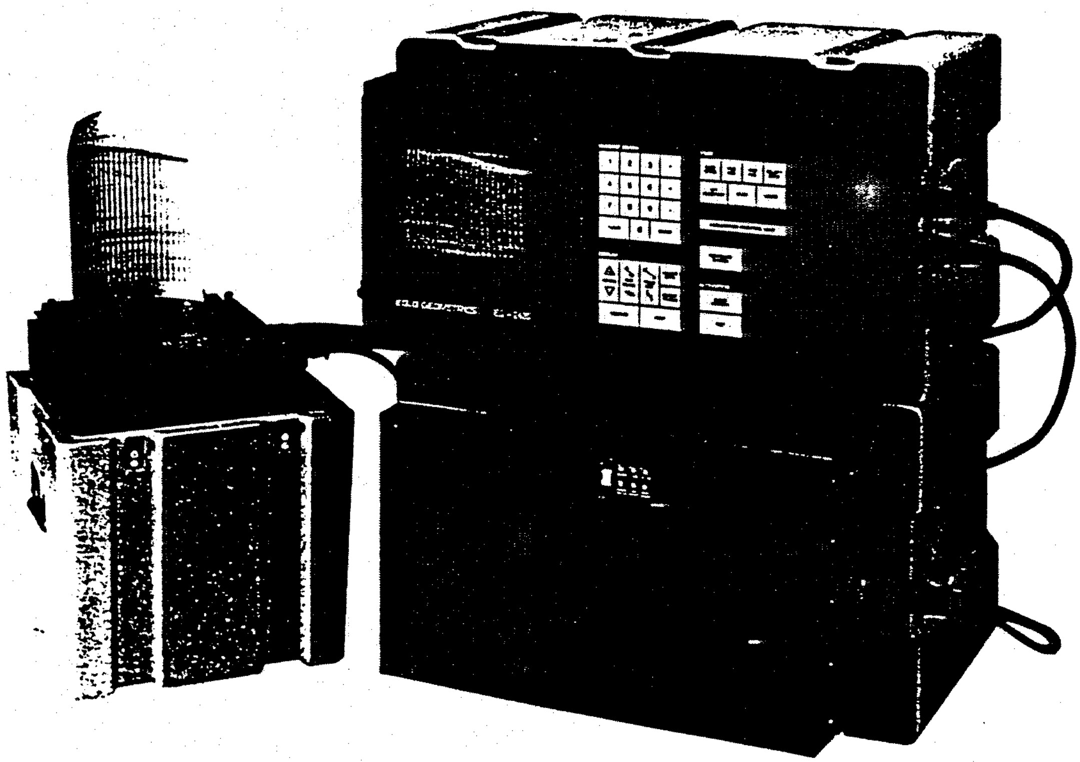
It should be noted that the figures represent the response over earth of uniform conductivity. This is a worst case, since often the highly conductive materials appear only at depth and are of limited thickness.

10.4 Surface Geophysical Instrumentation

Manufacturer's specifications for the instrumentation used to perform geophysical surveys are included in this section.

Reflection Seismograph

Model ES-2420



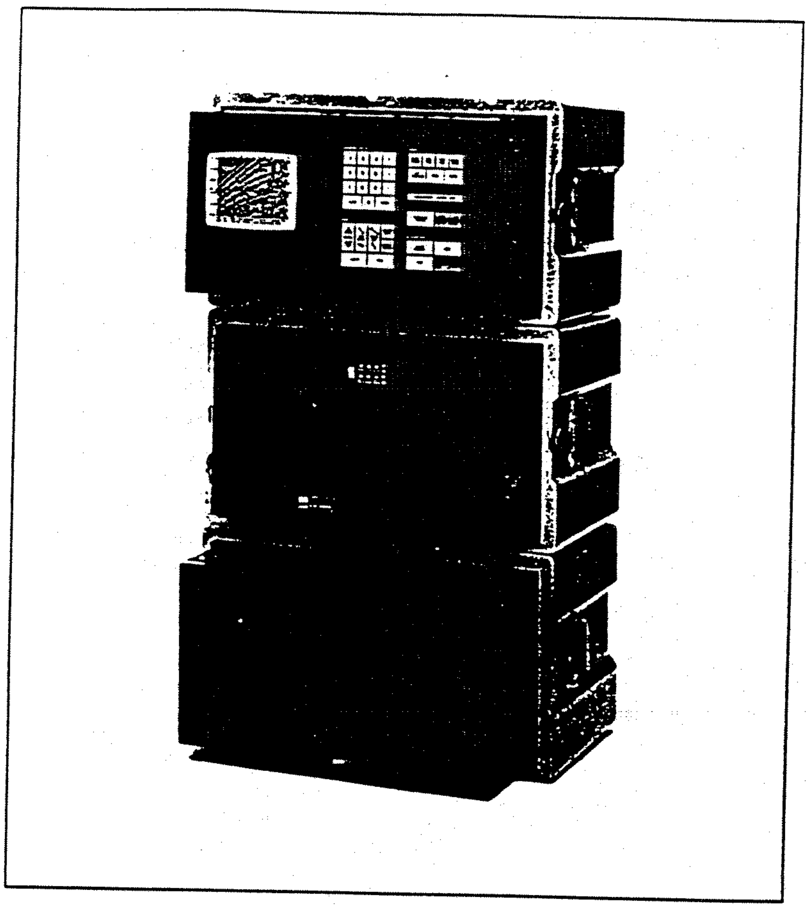
Features

- Instantaneous floating point (IFP) with 15-bit resolution
- Built-in summer—use with low-amplitude energy sources
- High resolution CRT graphics data display
- Front-panel control of acquisition parameters—fast resetting of parameters in the field
- ¼-millisecond sampling on any number of channels
- In-field processing—built-in correlator
- Easy operation—interactive system is self-teaching
- Expandable—to 512 channels

EG&G GEOMETRICS

Reflection Seismograph

Model ES-2420



A 100-channel system requires one expansion module. The System can be expanded up to 512 channels.

The ES-2420 is a high performance reflection seismograph that uses the very latest technological innovations to improve the quality of seismic data and simplify the seismic acquisition task. Although the ES-2420 can "write" a tape in real time like a conventional seismograph, its principal distinguishing characteristic is its data storage and display functions, allowing the operator to interact with the system and the field process. The result is an improvement in data quality, confidence, and reliability, and a drastic simplification of the acquisition task.

Superior Performance Features

The ES-2420 has the basic functional characteristics of a reflection seismograph: instantaneous floating point amplifiers (IFP), precise amplitude resolution, appropriate input filters, and digital recording in SEG format. It also has performance features that are unusually superior, including ¼-millisecond sample rate for up to 512 channels; front-panel-selectable alias, notch and low-cut filters, and tape recording in SEG-D multiplex or demultiplex format. In addition, the system has a graphics CRT display, built-in stacker, front-panel setting of acquisition parameters, and processing ability.

Flexible, Convenient, Modular

The ES-2420 is modular, its size depending on the scope and nature of the task required. A minimum system consists of an Acquisition Control Unit with from 4 to 28 channels, and a Tape Drive. Larger systems would include one or more Expansion Modules, an Electrosensitive Plotter, and a larger or second Tape Drive. Each Expansion Module supports up to 72 additional channels. The maximum number of channels possible is 512.

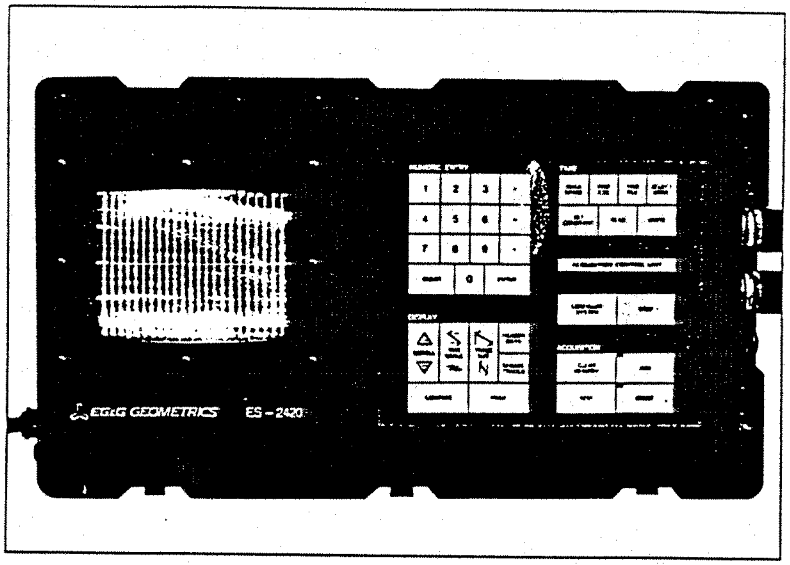
System and Operation Description

The Acquisition Control Unit is the heart of the system. It provides the digital control circuitry for the acquisition process, tape control, and supports up to 28 acquisition channels. The internal operating system emphasizes easy operation. Operating controls are located on the front panel, as are the controls required to set up survey parameters. Virtually anyone with an understanding of seismic theory can teach themselves to run the system by interacting with the menus and controls. The organization of the menu interaction system for configuring the system also makes it easy for a non-technical person to conduct surveys.

To see how the system is operated in the field, consider the front panel keyboard. The keys are grouped according to function: Numeric Entry, Display, Tape, Configure/Stop, and Acquisition.

Since parameters are stored in memory, the system is ready to take data as soon as it's powered up. Push ARM, in the Acquisition group of controls, and the CRT display shuts off. Fire your energy source, and the acquired data is stored in the seismograph's memory and automatically displayed on the CRT screen.

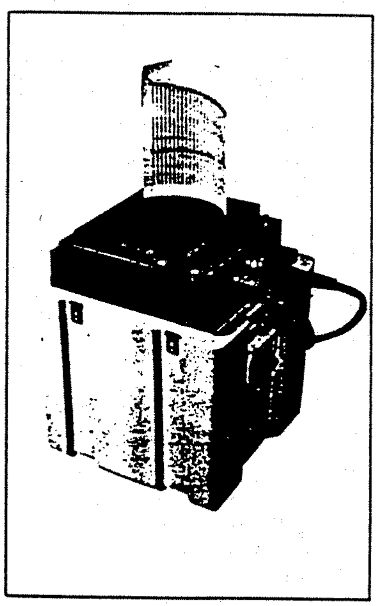
To examine the record, you may wish to expand the display and look at just a portion of it in different scale factors. These adjustments are made by using the DISPLAY group of controls. The SCROLL and TIME SCALE controls zoom in on a particular portion of the record. Timing lines are superimposed on the screen and labeled. The TRACE SIZE control adjusts the trace amplitudes so the reflection signals are at their most easily recognizable level.



All controls needed for operating the system and setting survey parameters are logically grouped on the front panel keyboard.

Since you can see the trace instantly, you can quickly recognize good or bad records. If you want to check the acquisition parameters, push HEADER DATA. The screen will display a table with sample rate, filter settings, constants, file number, and all the other recording parameters that were used to gather the data. To retrieve traces, push SEISMIC TRACES.

Once the display is optimized, you can write the conventional field record on the ES-2420's accessory plotter. Push the PRINT button, and the electrosensitive plotter produces a high-contrast record made by burning a silver aluminum coating off black paper. Records are annotated with alpha-numeric header information and can be plotted in either wriggle trace or variable area. The plotter uses no chemicals. Records can be duplicated on office copiers, and don't fade in sunlight.



The electrosensitive plotter produces a high-contrast record that is an exact duplicate of the CRT display.

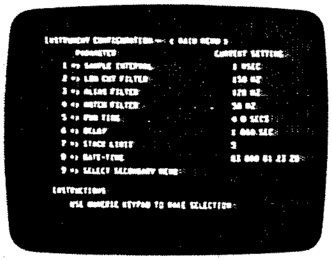
The plotted record will have the same scale factors as those shown on the CRT, so will look just like the display. The full record, including the portion "off screen," can be plotted. However, since you already see the record on the CRT, you might elect not to make field paper records, since you have accomplished your principle purpose of certifying record quality. Any function or display on the CRT can be written to the plotter.

If you are satisfied with the record, the next step is to record the data on tape. All you do is press one key in the TAPE group of keys, "WRITE." As a safety feature, the controller checks to see if the tape is positioned at the end of the last record, writes the data from the memory onto the tape, writes an End-of-File message, and increments the file number. If you want to see if the correct data is on tape, you can play it back into the memory. Press BACKSPACE. The tape backs up one file. Press READ to read the tape into the seismograph memory, and data will be displayed on the CRT. You can check it visually, or use the automatic tape verify test that compares data-in-memory and data-on-tape bit-by-bit.

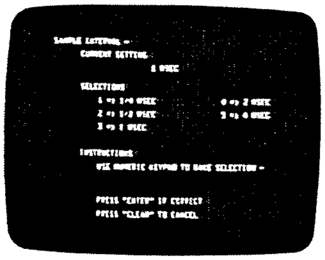
For specialized surveys including VSP, research, and teaching applications, on-site monitoring of contractor's data, and small-scale surveys, the flexibility of viewing the data immediately and changing parameters for improvement will save time, decrease cost, and guarantee that data is the highest quality possible.

Direct-to-Tape Mode of Operation

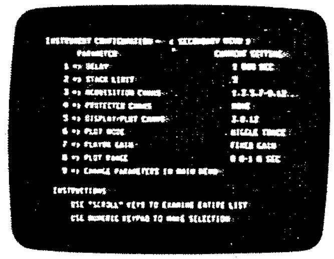
The direct-to-tape mode is used in time-critical acquisition programs, including marine and well seismics. Even in these situations the memory, CRT, and nonoscillograph-type plotter will still be invaluable for spot-checking data acquisition. Fast front-panel setting of acquisition parameters will help to improve data within strict time limitations.



Parameters that you want to adjust often are placed on the Main Menu. To change a parameter, for example the Sample Interval, you would press "1".



The sample interval menu is displayed and you follow instructions for changing its setting.



Parameters that are not going to be changed during a survey are placed on the Secondary Menu. Changes are made to these parameters in the same way as on the Main Menu.

Setting Acquisition Parameters

To set the acquisition parameters, press the key labeled CONFIGURE SYSTEM. The seismic traces disappear and the screen displays a list called the Main Menu. A typical main menu might contain the sample interval, low-cut filter, alias filter, notch filter, run time, delay, stack limit, and date-time settings. The current setting for each of these parameters shows to the right of the screen, and instructions are provided to the operator, in this case "Use Numeric Keypad to Make Selection."

To change a setting, press the number on the keypad which corresponds to the parameter in the table. For example, to set the sample interval, press "1." The CRT changes to another display, the menu for sample interval. The menus differ slightly for each parameter, but the format is always the same: name of parameter, current setting, a list of what choices are available, and instructions on what to do next. In the case of sample interval, you press the key corresponding to the desired number and then press ENTER. To correct an error or return to the Main Menu, press CLEAR.

The last item on the Main Menu is number 9, "Select Secondary Menu." When key 9 is pressed, the Secondary Menu, which lists all parameters and their settings is displayed. The SCROLL keys in the DISPLAY group of controls are used to scroll the secondary menu up and down on the screen so the whole list can be examined. Changes are made on the secondary menu just as on the main menu. The last item on the Secondary Menu is "Change Parameters in Main Menu." This function allows you to select which items are listed on the Main Menu.

Usually, parameters which are not going to be changed during a survey are placed on the Secondary Menu, and parameters that you want to adjust quickly are placed on the Main Menu.

This system for setting the acquisition parameters is very powerful and at the same time very simple. Since the operator selects from a checklist and interacts with the screen, learning is fast and easy. If you know the basics of seismic data acquisition, you can virtually teach yourself how to operate the ES-2420 just by pressing buttons and following instructions.

In-field Processing

The ES-2420 will allow rudimentary processing of the displayed data. The raw field data cannot be altered (except for summing), but the portion read into memory can be processed. This last capability allows you to look beyond the raw field data to see what signals could be extracted by subsequent computer processing at the data center, and therefore aids in selecting the best parameter settings and field procedures. Moreover, you won't risk time and money gathering data on the assumption that eventual processing will produce clear selections. Specific algorithms include bandpass digital filters, cross-correlation, normal moveout (NMO) corrections, common offset gathers, and CDP stack. Since many of these normally require massive computer power, some compromises will be made for the field computations (for example, you will need to pick a velocity for NMO and stack), but you will be able to establish in the field that further processing will produce good reflection data.

Post-acquisition processing aids in setting acquisition parameters by letting you see how final processing will affect the data.

Specifications

Acquisition Control Unit (ACU)

Sample Interval
Front-panel-selectable from ¼, ½, 1, 2, or 4 milliseconds. Independent of number of channels in stack-to-memory mode.

Low-Cut Filter
Settings selectable from 5 to 320 Hz in 5-Hz increments. Attenuation slope 18 db/octave.

Alias Filter
Six frequencies, front-panel-selectable, linear phase. 6-db corner frequencies: 45, 90, 180, 360, 720, and 1440 Hz. Attenuation 80 db at 128, 256, 512, 1024, 2048, and 4096 Hz.

Notch Filter
Selectable 50- or 60-Hz notch filter, down 60 db at notch frequency.

Date and Time
Internal clock with battery backup provides calendar date and 24-hour time of day, recorded on tape.

Acquisition Mode
Data can be either stacked to system memory or written directly to tape. When writing to tape, internal memory is used as a buffer to match tape drive speed to data sample rate. Maximum sample rate limited by tape drive speed in some cases.

Run Time
Keyboard-selected, will stop acquisition after run time has elapsed. Used to stop tape in direct-to-tape mode or to shorten memory actually used (shortens recording time and avoids storage of excess data on tape).

Channel Selection
Selects which channels are used for acquisition and which ones are displayed.

Display Mode
Displays records in either variable area or wiggle trace format at selectable scale factors. Plotted record will match the CRT-displayed record.

Computation Functions
Optional post-acquisition processing allows preliminary analysis of data quality. Functions include: bandpass digital filters with selectable corner frequencies, cross-correlation, common offset gathers, common depth-point stack, and more.

Drive Select
System can support multiple tape drives with automatic or manual selection of active drive.

Word Size
Signal is digitized to a resolution of 15 bits plus a 4-bit exponent representing 6-db gain steps.

Tape Format
Data is recorded in either SEG-D multiplexed, or SEG-D demultiplexed format, front-panel-selectable. Instrument parameters are recorded where supported by the format and include filter settings, sample rate, time and date, and more.

Maximum Stacks
Any number of successive signals may be stacked into the memory. The system may be set to stop after a predetermined number of stacks.

Delay Start
The start of acquisition may be delayed up to 9.999 seconds and varied in precise one-millisecond increments.

Memory Protect
Any channels may be protected so that they will not erase, stack, or accept data from the geophones or tape recorder.

Controls
All recording and other parameters may be set from the front panel, except preamp gain.

Test Functions
Built-in self-test functions include: geophone resistance and leakage, noise monitor, pulse injection, staggered tone burst, fixed-frequency sine wave memory test, tape verify against memory, and set to fixed gain.

Playback Gain
Data is displayed and plotted with choice of fixed-gain, fixed-gain-normalized (traces equal amplitude), or AGC. The AGC is digital with a selectable window length.

Expansion Module
Equivalent to Acquisition Control Unit, allows expansion of number of channels in increments of 8 to maximum of 72 per module. No controls except power switch and power supply voltage monitors, so extra channels become an extension of the ACU.

Maximum Record Length
In stack to memory mode; depends on sample rate and memory length.
¼ ms = 4.096 seconds
½ ms = 8.192 seconds
1 ms = 16.384 seconds
2 ms = 32.768 seconds
4 ms = 65.536 seconds
In direct-to-tape mode, the system can record indefinitely.

Record Initiation
Requires arm signal from front panel switch or external signal (switch closure or saturated NPN transistor to ground). Starts acquiring data on same basis. If front panel switch is used in either case, an output signal is provided for controlling an external device equivalent to a saturated NPN transistor to ground.

Acquisition Specifications

Dynamic Range:	>100 db
Crossfeed Isolation:	80 db
Distortion:	0.05%
Noise:	.5 microvolts rms

Number of Channels
Any multiple of 4 to 28 channels in basic module; to 512 channels with expansion modules.

Plotter
Digital plotter plots data on 8.5-inch-wide paper. Plots in variable area or wiggle trace as determined by CRT display. Annotates plot with alpha-numeric header information, time lines, and recording parameters. Has minimal controls since plotting, including the setting of scale factors and time period to be plotted, is controlled by the ACU. Time required to plot depends on scale factor and selection of time interval plotted.

Digital Tape Recorder
Portable tape recorder available with system; 7½-inch reel, 1200 ft tape, 37.5 ips, 1600 bpi. Optional tape drives with 2400 ft reel, 6250 bpi. Tape functions generally controlled by ACU (except for Load, Power, Rewind, On-line).

Physical
Acquisition Control Module:
length: 28 inches (71 cm)
width: 16 inches (41 cm)
height: 23 inches (58 cm)
weight: 130 lbs (60 kg)
Digital Tape Recorder: Same as ACU
Power: 11 to 14 volts DC, 40 amps
Environmental: 0 to 40°C
Weatherproof enclosure

EG&G Geometrics reserves the right to alter specifications without notice.

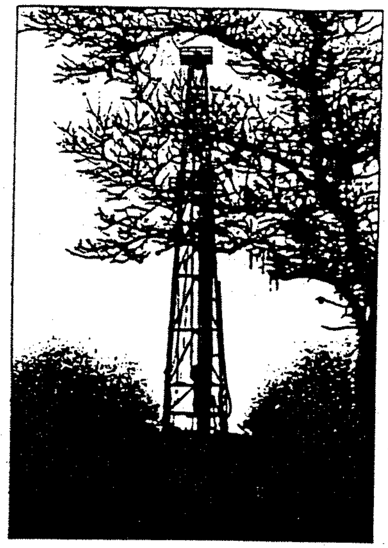
EG&G GEOMETRICS
395 Java Drive
Sunnyvale, California 94089, U.S.A.
Tel: (408) 734-4616
Telex: 357-435

EG&G GEOMETRICS
International Corporation (GIC)
18 Gertrude Street
Arncliffe, 2205, Australia
Tel: 597-4744 Telex: AA22624

Applications

Vertical Seismic Profiling (VSP)

The ES-2420 is perfectly suited to VSP. Size and weight of the ES-2420, including the built-in stacker makes it easy to transport to the location. Its data monitor and processing features let you qualify your data Configuration of the system by front-panel-control saves valuable downhole and rig time.

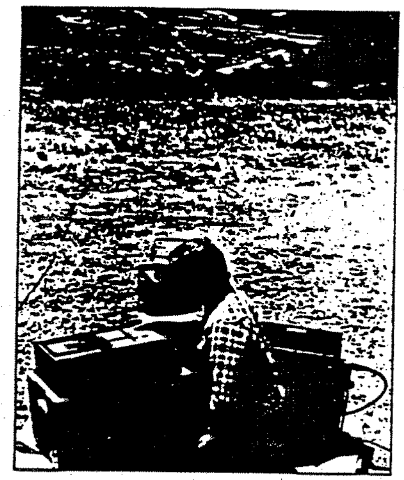


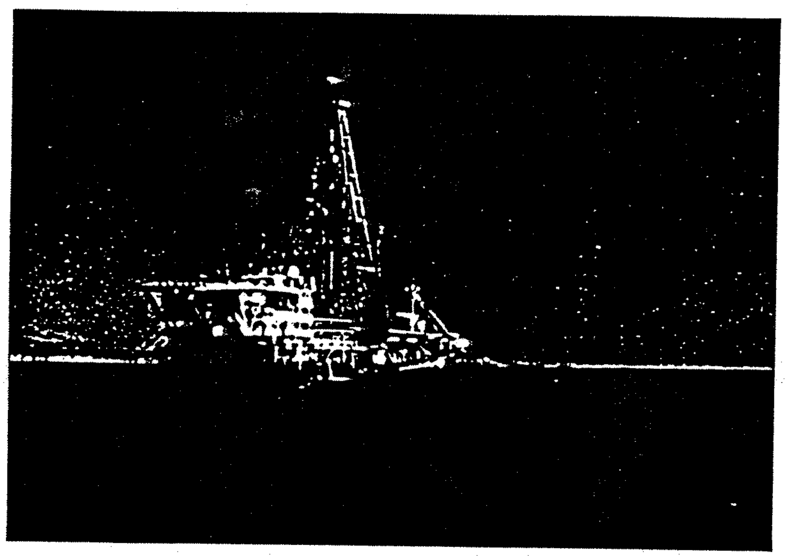
Small-Scale Surveys

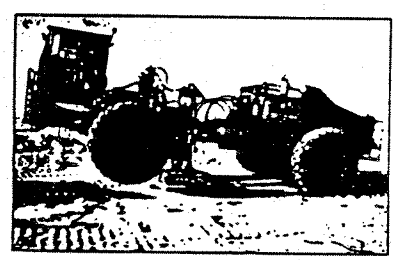
Disproportionately high mobilization costs including instrument configuration, have traditionally made short acquisition programs infeasible. The front panel parameter configuration, built-in test features, and overall flexibility make the ES-2420 ideal for small-scale surveys. The ES-2420 is ideal for filling in gaps between lines for small, and high-resolution projects.

Marine Surveys

The ES-2420 provides high-resolution sampling for shallow marine surveys. It will support multiple tape drives, and automatically switch over from one drive to the other. Because of its portability and simple power requirements, it can be easily installed temporarily on small boats for quick surveys, and yet is suitable for dedicated vessels.

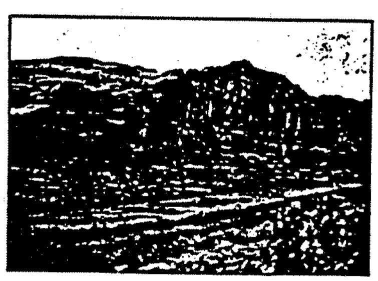






High Resolution Reflections/Engineering Site Investigations

Since the ES-2420 can sample at ¼-millisecond intervals with up to 512 channels, it is particularly suited for high resolution surveys. High-resolution applications include shallow petroleum exploration, coal development, mineral deposit evaluation, geologic hazard mapping, engineering site studies, and groundwater exploration.



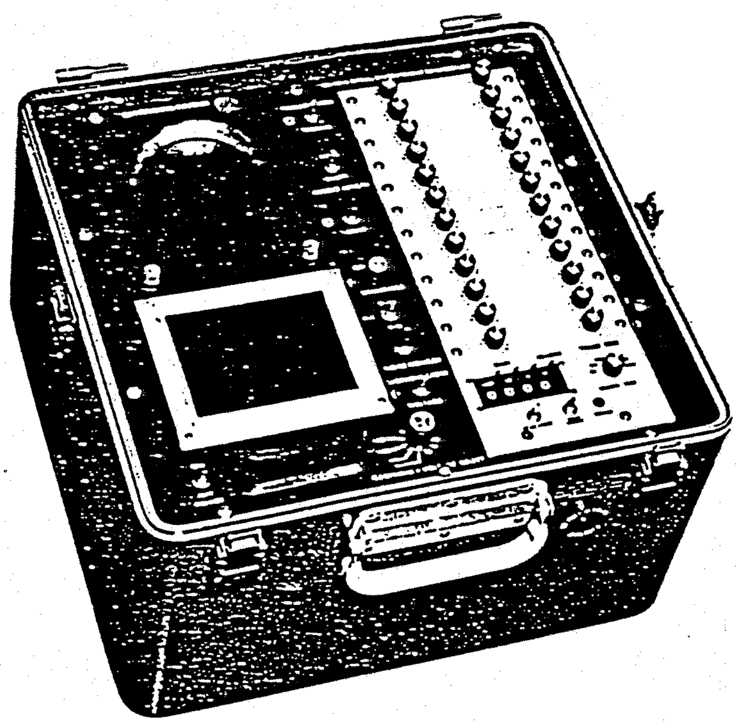
Surveys Using Mechanical Energy Sources

Whenever mechanical energy sources are used, several repeated signals are usually summed to obtain an adequate signal-to-noise ratio. Normally this is done by either writing several tape records and summing them later at the processing center, or by using an auxiliary summer in the field. The ES-2420 has a summer built into the system which improves the reliability of the components, reduces the weight, size, complexity, and power consumption of the total system, and eliminates the substantial cost of a separate summer.

geoMetrics/nimbus

MULTICHANNEL SIGNAL
ENHANCEMENT SEISMOGRAPH
MODEL ES-1210

Preliminary Data Sheet



* *Signal enhancement* for greater sensitivity, improved waveform definition, and more accurate time measurements. Operates under high noise conditions and surveys to greater depths without explosives.

* *Multichannel oscillograph* provides permanent records on high-contrast, sunlight proof, reproducible paper with wiggle trace or variable area format.

* *Daylight-visible CRT monitor* displays the signal stored in memory.

* Compact, lightweight and portable. Ruggedly packaged in weatherproof case.

* Optional digital magnetic tape recorder for computer compatible data storage.

The Nimbus ES-1210 Multichannel Signal Enhancement Seismograph is unique in its combination of CRT display, signal enhancement and oscillograph recording in a single small field instrument. Simple to use yet powerful in performance, this new instrument is ideally suited for all shallow geologic investigations for mining, construction and geologic exploration.

Signal enhancement is a term used to describe the stacking process used in the ES-1210. The seismic signals for each hammer blow or shot are digitized and stored in a computer-like memory in the instrument. Unlike conventional analog seismographs, the record is not made at the instant of the hammer impact or explosion. Instead, it is held indefinitely and printed at the operator's convenience. If the impact or explosion is repeated, the seismograph will add the new signal and the old one, storing the sum back in the memory. As this process is repeated, the signal will grow larger and larger, thus enhancing its appearance on the display or oscillograph record. Seismic noise in the earth, which provides the most significant limitation in depth penetration, is random and does not add in the signal enhancement process at the same rate that the true signal does. As a result, surveys can be performed to about three times the depth that could be realized without enhancement using an equivalent energy source.

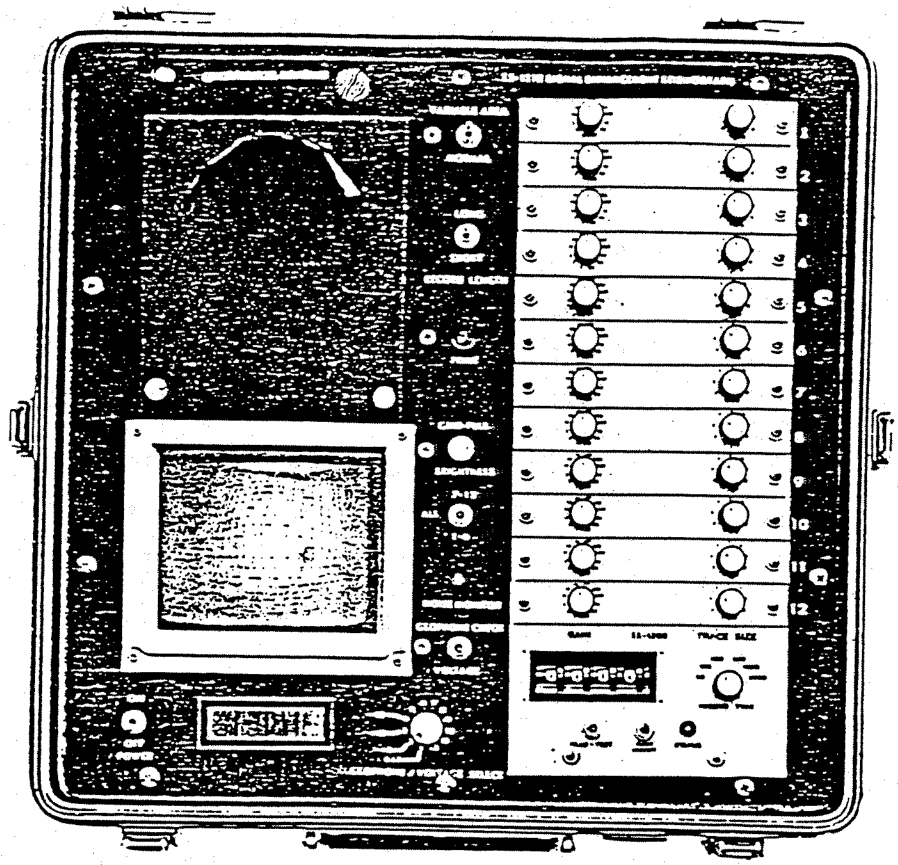
Signal enhancement is also a significant improvement in making shear wave velocity measurements. These types of surveys are important because of the dynamic parameters of foundations can be calculated from shear wave velocities, liquid saturation can be discriminated from other conditions with equivalent P-wave velocities, and shear strength can be estimated. The most reliable shear wave studies are made with mechanical sources, which means that signal enhancement is often a requirement.

Signal enhancement provides other, less obvious advantages, even when using explosive sources. Since the playback gain of the signal stored in memory is adjustable, there is less guess work involved in getting good records. Multiple copies can be made without reshooting the blast. Since the frequency response is not limited by galvanometers and paper speed, a higher time resolution is available, an important factor when working in high-velocity materials.

The signal stored in the memory is displayed on the built-in CRT monitor, and the display will have the same appearance as the paper record. A paper record can be made as often as necessary, at will, without disturbing the data stored in memory. The trace size control can be changed to optimize the record for an application. The gain may be set high for sharp breaks on the P-wave arrivals, and a hard copy made. Then the gain can be turned down for better shear waves or reflections and another copy made.

Both the CRT and oscillograph record in conventional wiggle trace and variable area. A wiggle trace record, like that of a conventional seismograph, would be selected for refraction and shear wave studies. Variable area recording (often seen on examples of petroleum reflection records) is best for reflection because that presentation emphasizes coherent events and resembles geologic structure.

The CRT display is especially important in three other situations. When working in areas with significant background noise, the display gives an instant observation of the signal quality so that it is immediately known whether to repeat impacts, freeze specific channels, or erase and start over. The other use is in shallow reflections. The instant examination of all the channels simultaneously is important in recognizing these events in the record. The third use of the CRT display is in gain selection. With the NOISE MONITOR switch depressed real time signals are shown on the CRT and the gain setting for each channel can be chosen appropriately.



CONTROLS AND FEATURES

Amplifier (input) GAIN is controlled by a 12-position switch, selectable from relative gain of 1 to 5000 in steps of 1-2-5-10 etc. Each amplifier has a 10 bit by 1024 sample memory which stores the digitized signal. Playback gain is controlled over a 20 to 1 range by the TRACE SIZE control. Pulling up the trace size control freezes the memory on that particular channel so that it will not further enhance or erase, thus saving the data while allowing operation on the other channels. Playback or display are not affected by memory freeze.

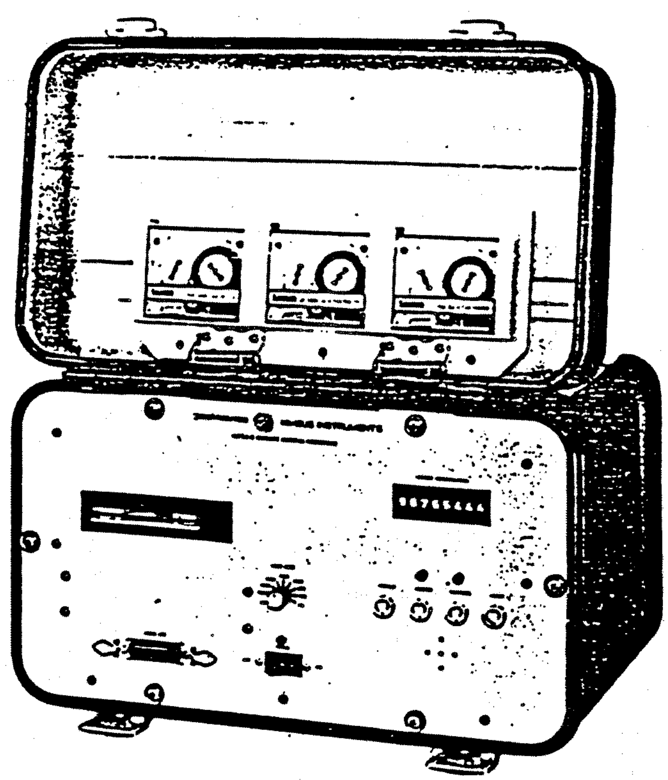
Enhancement control electronics include the RECORD LENGTH control, which selects total time of the record among 50, 100, 200, 500, 1000 or 2000 milliseconds. The record DELAY postpones the start of the record up to 9.999 seconds in one milliseconds increments, allowing you to look later in time, delete unnecessary leading portions of the signal, and maintain faster sampling rates for later events. CLEAR MEMORY controls erases the data stored in the memory. An interlock is provided (both READ and CLEAR must be used) to prevent accidental erasure of valid data. TEST provides a start command to take a record in lieu of hammer switch or blaster.

The CRT display is five inches (13 cm) diagonal measurement. It displays all 12 channels simultaneously or switch selected combinations of six channels as desired. It has a special light filter to allow direct viewing in sunlight without special hoods. The bezel will fit standard oscilloscope cameras so that photographs may be made of the display if desired. Timing lines may be superimposed on the CRT at will by pulling up on the BRIGHTNESS control. The timing line intervals vary, depending on the record length, so that appropriate resolution and clarity is maintained.

A digital voltmeter is provided to measure the battery voltage, internal power voltages, and individual geophone resistances. The NOISE MONITOR, when selected, couples the amplified geophone signals to the CRT display. This allows monitoring the instantaneous background noise so that records may be made during quiet periods.

The data stored in the memory may be accessed externally. An optional digital tape recorder, the G-724S, is available to provide computer compatible storage of the data. The G-724S will store 10 full records (120 channels) in a reduced resolution, 8-bit format, or you can store 5 records (60 channels) in the full 10-bit format. The G-724S serves as its own playback device, outputting the data in an RS-232 format which is directly interfaceable to most computers including desk top models.

G-724S Digital Recorder



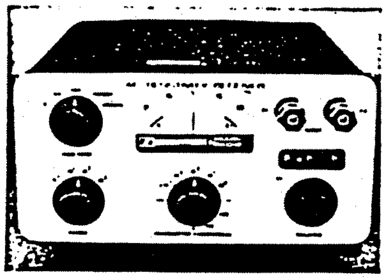
Nimbus ES-1210

SPECIFICATIONS

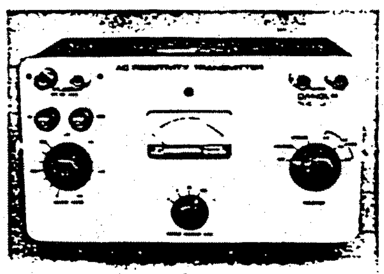
Basic refraction and reflection system includes: 12-channel exploration seismograph, 12-volt battery pack, 110/220 volt charger, power cord, hammer switch, and instruction manual.

Signal Enhancement:	samples, digitizes, and stores signal in a random access memory. Repeated signals are added while random noise is cancelled or limited.
Memory Size:	10 bits by 1024 words on each channel.
Sample Interval:	switch selectable 50, 100, 200, 500, 1000, or 2000 microsecond[s]
Record Length:	switch selectable 50, 100, 200, 500, 1000, or 2000 millisecond[s]
CRT Display:	5" diagonal measurement CRT, daylight visible without hoods, switch selectable time lines, camera compatible, and displays wiggle trace or variable area record display.
Oscillograph:	permanent record of all 12 channels simultaneously on 4" wide electrosensitive paper. Record will not fade in light, and reproduces on copying machines.
Noise Monitor:	ambient vibrations displayed on CRT allowing timing of energy source during quiescent periods and the optimization of gain adjustments.
Timing:	crystal controlled, .01% accurate, time lines are switch selectable on CRT and high or low resolution on oscillographic record.
Precision Delay:	postpones start of record up to 9.999 seconds in one millisecond increments.
Digital Meter:	indicates battery voltage, geophone resistance on each channel power supply voltages.
Digital Output:	a panel connector to allow digital recording of signal stored in memory on optional digital recorder Model G-724S.
Record Initiation:	by contact closure, saturated NPN transistor, or negative 5-volt pulse.
Standard Size/Weight: (seismograph)	14 X 15 X 15 inches (36 X 38 X 40 cm) lid closed 38 pounds (17 kg)
Power Requirements:	12 volts, 3.5 amperes
Seismograph Case:	Heavy duty aluminum with lid and water tight seal.

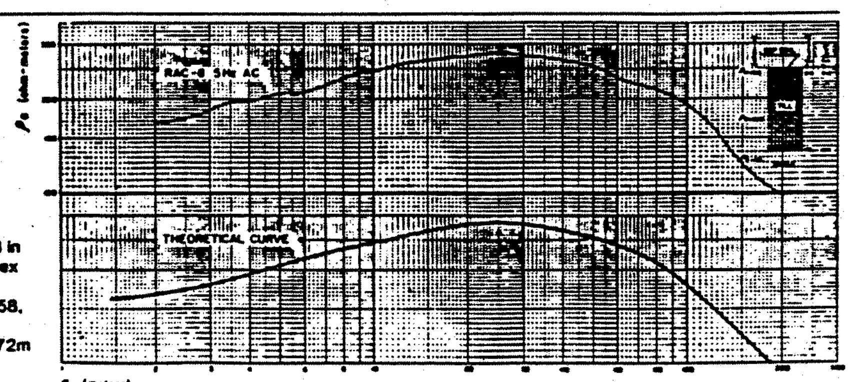
Technical Description of RAC-8 Low Frequency Resistivity System



Complete System	
Measurement Range	.0001 to 10,000 ohms
Accuracy	In range .0001 to .0003 ohms, ±5% In range .0003 to 10,000 ohms, ±2%
Operating Temperature Range	−10° to +50°C
Operating Frequency	5 Hz square-wave
Total Weight	11.8 kg
Receiver	
Range	.0001 to 1.0 volt
Input Impedance	10 Megohms
Instrument Noise	Less than 0.3 microvolt rms (about 1.5 microvolts peak-to-peak) on most sensitive range with input shorted.
Band Width	±0.185 Hz
Powerline Noise Rejection	An applied 50 or 60 Hz disturbance 150 times (43.5 dB) greater than a normal input signal will not affect the reading at any range. Both the signal and disturbance on the input should never exceed 3 V peak to peak in order to maintain accuracy ±2%. When ordering an RAC-8, the purchaser should specify the frequency of powerlines in the proposed survey area. For universal operation, a filter for the other frequency is offered as an option.
Common Mode Noise Rejection	A common mode voltage (applied between case and shorted "INPUT" terminals) of 1 volt peak to peak for a 5 Hz square-wave, or 7 volts peak to peak for a 50-60 Hz sine wave will not affect reading on any range.
Power Supply	Two 6V-1 Ampere-hour Globe GC 610-1 internally mounted, sealed lead acid accumulators. Connector provided for external charger. Batteries provide over 100 hours of operation in field work on a 25% duty cycle.
Dimensions	268 mm x 190 mm x 95 mm
Weight	3.2 kg
Transmitter	
Output Current Levels	0.1, 1, 10, 100, 333 mA, switch selectable
Current Stabilization	0.5%



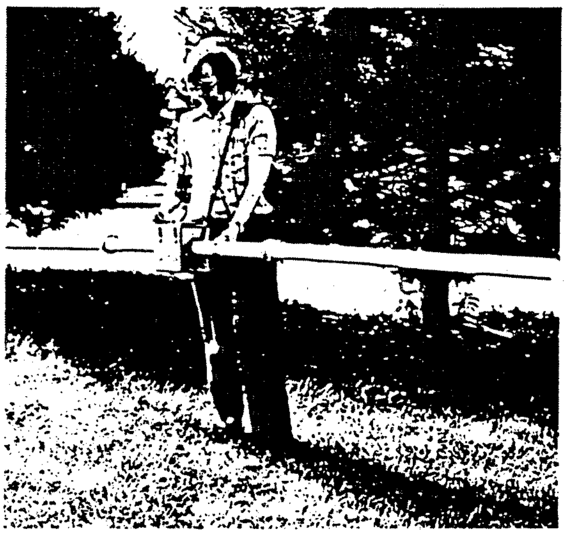
Output Voltage	Maximum 1000 V peak-to-peak. Actual output voltage depends on the current level and load resistance.
Output Power	Maximum 80 W
Operating Frequency	5 Hz square-wave
Operating Position	Transmitter must be operated vertically within ±30° maximum. For transportation this is not required and instrument can be stored in any position.
Protection	Automatic circuit breaker turns off when the load on the "OUTPUT" terminals is interrupted, or if it is shorted while voltage is set over 60 V.
Load Precautions	Not more than one fully wound reel of wire (1000 m, inductance ±0.2 Henry) can be in series with the transmitter load, in order not to affect measuring accuracy. With large electrode separations (several km) no reeled wire should be in the transmitter circuit, particularly if a high current level is required, to prevent inductive surges.
Power Supply	The power supply is composed of two independent battery sets mounted in a common detachable compartment, which is attached to the bottom of the transmitter housing. Set No. 1: Two 6 V — 1 Ampere-hour Globe GC610-1 sealed lead-acid accumulators providing a supply for electronic circuits of the constant current regulator. Capacity is sufficient for over 100 hours of operation in the field. Set No. 2: Two 6 V — 6 Ampere-hour Globe GC660-1 sealed lead-acid accumulators providing a main power supply with 80 W maximum. This battery set limits actual field work duty of the instrument to maximum 40 hours.



Wenner array depth sounding using RAC-8 in electrically noisy industrial area near Scintrex plant in Concord, Ontario. The section is interpreted as a 3 layer case with ρ_1 = 158, ρ_2 = 290 and ρ_3 = 55 ohm-meters. The upper layer is 2.8 m of topsoil followed by 72m of till overlying shale.

TERRAIN CONDUCTIVITY METERS

ONE MAN - CONTINUOUS READING



EM31

The Geonics EM31 provides a measurement of terrain conductivity without contacting the ground using a patented inductive electromagnetic technique. The instrument is direct reading in millimhos per meter and surveys are carried out simply by traversing the ground.

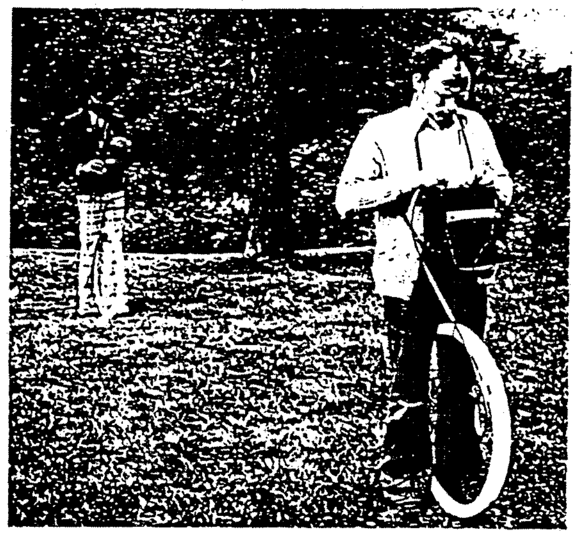
The effective depth of exploration is approximately six meters making it ideal for engineering geophysics. By eliminating ground contact, measurements are easily carried out in regions of high resistivity such as gravel, permafrost and bedrock. Over a uniform half space the EM31 reads identically with conventional resistivity and the measurement is analogous to a conventional galvanic resistivity survey with a fixed array spacing. Interpretation curves supplied with each instrument often permit an estimate of a layered earth.

The advantages of the EM31 are the speed with which surveys can be carried out, the ability to precisely measure small changes in conductivity, and the continuous readout which provides a previously unobtainable lateral resolution.

Specifications

MEASURED QUANTITY	Apparent conductivity of the ground in millimhos per meter.
PRIMARY FIELD SOURCE	Self-contained dipole transmitter
SENSOR	Self-contained dipole receiver
INTERCOIL SPACING	3.66 meters
OPERATING FREQUENCY	9.8 kHz
POWER SUPPLY	8 disposable alkaline 'C' cells (approx. 20 hrs life continuous use)
CONDUCTIVITY RANGES	3, 10, 30, 100, 300, 1000 mmhos/meter
MEASUREMENT PRECISION	±2% of full scale
MEASUREMENT ACCURACY	±5% at 20 millimhos per meter
NOISE LEVEL	<0.1 millimhos per meter
OPERATOR CONTROLS	• Mode Switch • Conductivity Range Switch • Phasing Potentiometer • Coarse Inphase Compensation • Fine Inphase Compensation
DIMENSIONS	Boom: 4.0 meters extended, 1.4 meters stored Console: 24 x 20 x 18 cm Shipping Crate: 155 x 42 x 28 cm
WEIGHT	Instrument Weight: 9 kgm Shipping Weight: 23 kgm

TWO MAN - VARIABLE DEPTH



EM34-3

Operating on the same principles as the EM31, the EM34-3 is designed to achieve a substantially increased depth of exploration and a readily available vertical conductivity profile.

The underlying principle of operation of this patented non-contacting method of measuring terrain conductivity is that the depth of penetration is independent of terrain conductivity and is determined solely by the instrument geometry i.e. the intercoil spacing and coil orientation. The EM34-3 can be used at three fixed spacings of 10, 20, or 40 meters and in the vertical coplanar (as shown) or horizontal coplanar mode. In the vertical coplanar mode, the instrument senses to approx. 0.75 of the intercoil spacing. In the horizontal coplanar mode, the instrument can sense to 1.5 times the intercoil spacing. For the horizontal coplanar mode, however, coil misalignment errors are more serious than in the vertical mode so greater care must be exercised to achieve the maximum 60 meter depth.

Simple operation, survey speed and straight forward data interpretation makes the EM34-3 a versatile and cost effective tool for the engineering geophysicist.

Specifications

MEASURED QUANTITY	Apparent conductivity of the ground in millimhos per meter
PRIMARY FIELD SOURCE	Self-contained dipole transmitter
SENSOR	Self-contained dipole receiver
REFERENCE CABLE	Lightweight, 2 wire shielded cable
INTERCOIL SPACING & OPERATING FREQUENCY	• 10 meters at 6.4 kHz • 20 meters at 1.6 kHz • 40 meters at 0.4 kHz
POWER SUPPLY	Transmitter: 8 disposable 'D' cells Receiver: 8 disposable 'C' cells
CONDUCTIVITY RANGES	3, 10, 30, 100, 300 mmhos/meter
MEASUREMENT PRECISION	±2% of full scale deflection
MEASUREMENT ACCURACY	±5% at 20 millimhos per meter
NOISE LEVEL	< 0.2 millimhos per meter
DIMENSIONS	Receiver Console: 19.5 x 13.5 x 26cm Transmitter Console: 15 x 8 x 26cm Coils: 63cm diameter
WEIGHTS	Receiver Console: 3.1 kg Receiver Coil: 3.2 kg Transmitter Console: 3.0 kg Transmitter Coil: 6.0 kg Shipping Weight: 41 kg

10.5 Surface Geophysics versus Drilling: Hypothetical Comparison

Following is a hypothetical field program to compare the effectiveness of using Surface Geophysics and drilling versus drilling alone. The area of investigation is the buried channel in the Genesee study area.

Over the term of the surface geophysics project, the purpose of using geophysics in conjunction with drilling was to not only define the limits of the channel, but to test the various geophysical methods for their effectiveness. In this comparison certain surface geophysical surveys would be reduced or omitted. Fixed frequency electromagnetic induction (EM) measurements would be omitted due to the high conductivity of the clay rich surficial sediments. Reflection surveys would be reduced to every second line and used as a check against refraction and direct current tests. Direct Current Profiling (D.C.P.) not employed in the channel during the research project could be used effectively with Direct Current Soundings (D.C.S.), refraction (S and P wave) and crosshole tests. This is based upon the success of locating coal subcrops in the Paintearth study area, and adjacent to the Genesee study area in Section 10, Tp 50, Rg 2, W 5 (Fording Coal 1986). Utilizing surface geophysical methods in this manner allows the client to gain the most information per exploration dollar spent.

One advantage of using surface geophysics is that the less expensive electrical measures such as D.C.S. and D.C.P. could be used in a first pass, delineating coal subcrops and bedrock irregularities. A second phase of geophysics employing refraction, crosshole measurements and reflection could be performed on existing lines or on intermediate lines. Once all the geophysical data is measured or interpreted, infill drilling along the survey lines could be selectively pursued.

Drilling without surface geophysics has some disadvantages. To define the coal subcrop, channel limits, outline zones of disturbed bedrock forces the client to adopt a "hit or miss" approach. First, client may propose a number of shallow rotary holes, grouped in pairs on either side of the coal subcrops. Secondly, the client would have to proportion the number of core to rotary holes in an effort to define the channel composition, zones of bedrock disturbance and to gather an appreciable amount of recoverable coal for laboratory analysis. Unconsolidated materials could be encountered in core drilling resulting in poor recovery and lost time. The extra time required to complete such a program increases the likelihood of encountering down time due to bad weather, a factor which is budgeted in many Alberta exploration programs.

An advantage of having the extra drilling is the tighter drillhole density and the amount of samples available for laboratory analysis. However, this may result in a disproportionate amount of isopach and quality data over a small area and could bias any classical statistical analysis of the overall deposit.

Realistically, an exploration manager may not feel that they require that much definition in outlining a buried channel and may be satisfied with a rougher boundary. However, using surface geophysics in conjunction with less drilling removes many doubts in the interpretation and increases one's confidence in their deposit.

10.5.1 Exploration Program Using Surface Geophysics and Drilling

Figure 10.9 presents a hypothetical exploration program using surface geophysics and drilling. It is overlain on the Genesee study area showing the updated subcrops interpreted after completion of the 1986 field program. The proposed program is only one approach to obtain a similar density of data as did the research project, but utilizing only those surface geophysical tools which were found to be effective.

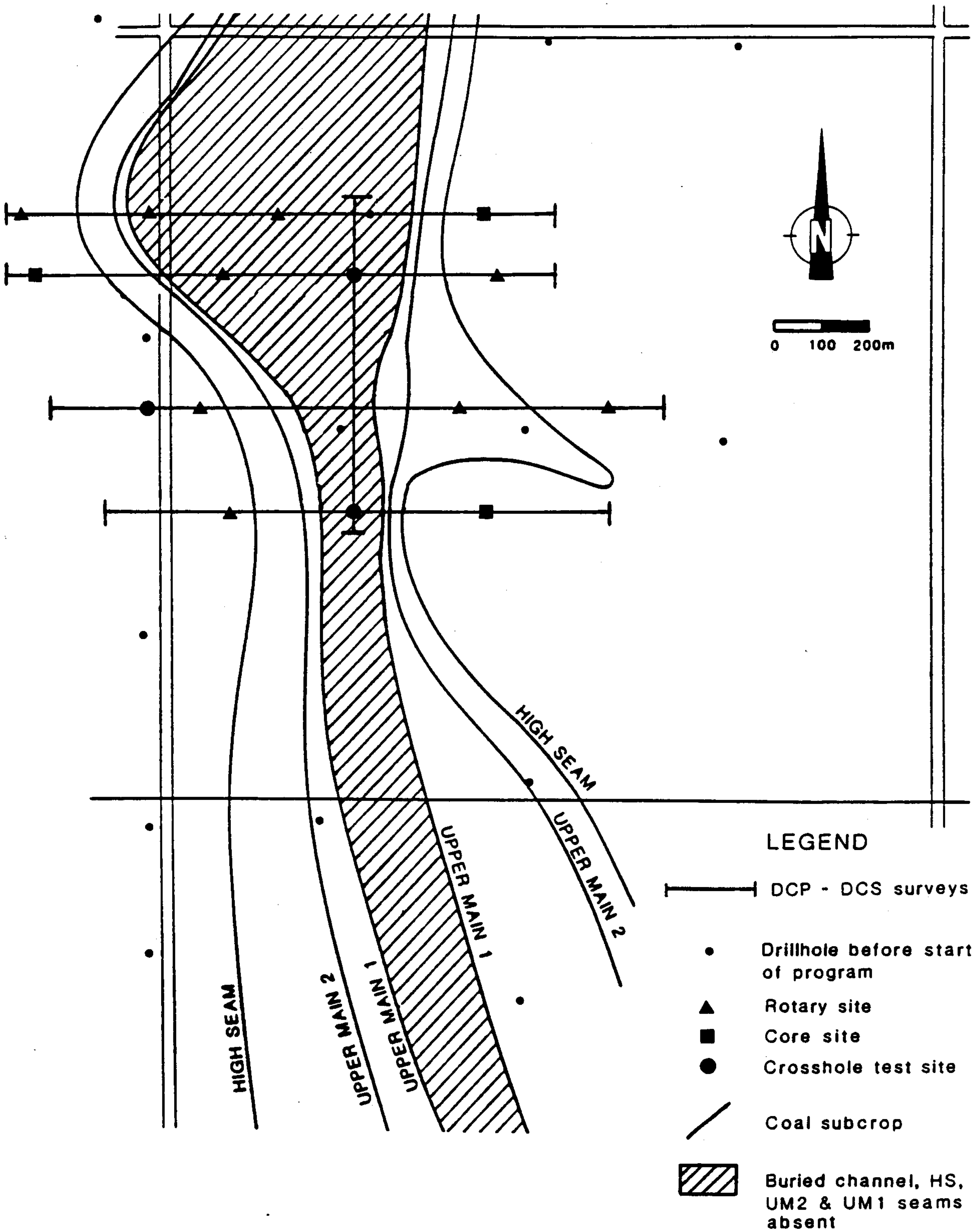


Figure 10.9 Hypothetical exploration program using surface geophysics and drilling.

The integrated program of surface geophysics and drilling would proceed as follows:

1. Location of coal subcrop using direct current soundings and direct current profiling.
2. Definition of channel characteristics, disturbed bedrock, etc. Refraction (S and P wave) on Lines A, C & E, (optional refraction on Line D).
3. Confirmation of coal continuity below channel. Reflection on Lines A & C (optional on B & D).
4. Cross-hole Tests (3 locations); in order to substantiate surface refraction. (Rotary Conventional drilling).
5. Confirmation drilling (after analysis of surface geophysical results). Rotary drilling within the channel limits and along the survey lines and coal subcrops. Coreholes in areas of complete coal section.

10.5.2. Exploration Program Using "Drilling Only"

Figure 10.10 presents the hypothetical "drilling only" program. The areas of interest in both cases is larger than the actual project study area. The selection of rotary or coreholes in Figure 10.10 is not shown as the decision would be highly subjective.

The methodology of the "drilling only" program would be:

Assumption: The client wishes to obtain similar amount of information about the deposit as provided by surface geophysics and drilling.

1. Drill along section road to establish position with respect to the channel edge. (Rotary)
2. Step-out drilling to firm up coal subcrops on west side of channel. (Rotary and core)

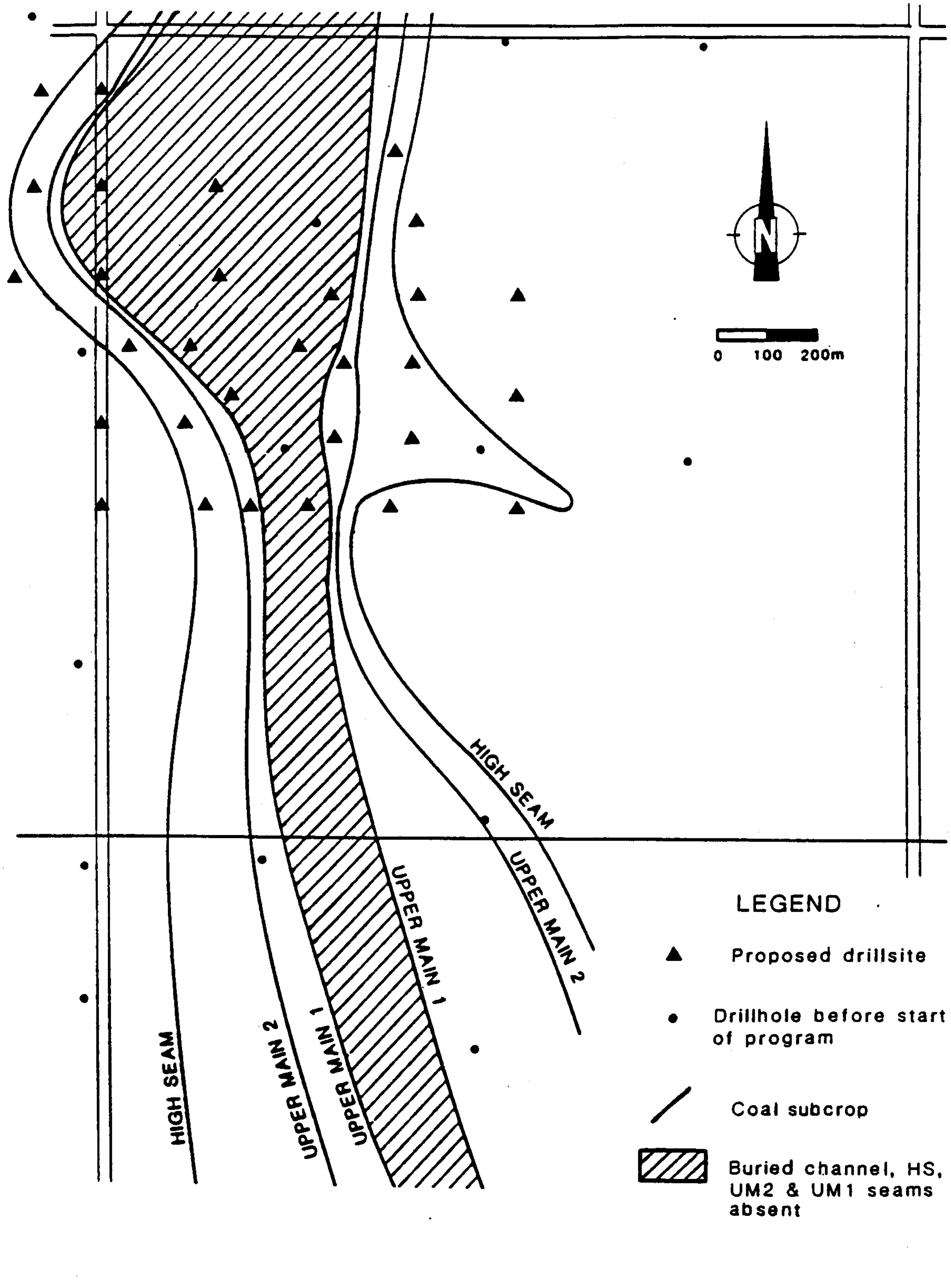


Figure 10.10 Hypothetical "drilling only" program.

3. Delineate east side of channel and coal subcrops. (Rotary and core)
4. Determine channel composition by drilling some holes near the channel center. (Rotary)

10.5.3 Comparison of Programs

Tables 10.1 and 10.2 contain the projected costs of conducting each field program. The optional reflection and refraction surveys are not included in Table 10.1. This extra work would add approximately 15% to the geophysical budget (Subtotal A). In Table 10.2, Case I-V supply some options to the proportion of drillholes that would be rotary reverse circulation, conventional or coreholes. Cases I and II would unlikely provide a comparable amount of information to the program using surface geophysics due to the lack of geotechnical core data. The number of holes drilled increase in Case III through V with a rotary pilot hole accompanying each corehole.

Total expenditures (given the assumptions noted on both Tables) favour the drilling programs in Cases III and IV. Case V, which would provide the most reliable data of the drilling options, is comparable in cost to the combined surface geophysics/drilling program. However, the number of days required to complete Cases III through V is two to three times the time needed in the surface geophysical drillhole program. If a foul weather factor was included in each Table, it is probable that the surface geophysical program would also be less expensive than Cases III and IV.

Table 10.1

EXPLORATION PROGRAM COSTS USING SURFACE GEOPHYSICS WITH DRILLING

<u>Surface Geophysical Method</u>

	Km. of Survey	($) Rate/km	Cost
D.C.P.	3.74	2533	$ 9473
D.C.S.	3.74	2408	8976
Refraction (S & P)	3.0	5219	15657
Reflection	1.1	5000	5500
Crosshole Tests -	3 sites (2 holes/site) $2400/day x 1.5 days		3600
Mobilization & Demobilization			3000
+ Reflection			3000
Number of Days to conduct program: 13 days			
Total distance of survey: 11.58 km			
Subtotal A			$ 49206

<u>Drilling</u>*

Type	($) Rate /Day	Number of Holes	No. of Days Required	Cost
Rotary (Conventional)	2600	6	2.5	$ 6500
Rotary (Reverse)	2600	9	4	10400
Core	2700	3	3	8100
Subtotal B		18	9.5	$ 25000
TOTAL				$ 74206

Note:
- Average depth of holes - 30 meters.
- Does not include laboratory analysis.
- Geological supervision and office work.
- Assumes no down time due to foul weather.

* Includes downhole logging, mobilization and demobilization and drilling incidentals.

Table 10.2

EXPLORATION PROGRAM COSTS USING ONLY DRILLING

	Rotary			
	Reverse	Conventional	Core	Cost
($) Rate/Day*	2600	2600	2700	
Case I				
No. of Holes	-	30	-	
No. of Days Req'd	-	13	-	33800 (13 days)
Case II				
No. of Holes	15	15	-	
No. of Days Req'd	7	6.5	-	35100 (13.5 days)
Case III				
No. of Holes	10	20	5	
No. of Days Req'd	5	9.0	5	49400 (19 days)
Case IV				
No. of Holes	10	20	10	
No. of Days Req'd	5	9.0	10	63400 (24 days)
Case V				
No. of Holes	10	20	15	
No. of Days Req'd	5	9.0	15	76900 (29 days)

Note:
- Average depth of holes - 30 meters.
- Costs do not include laboratory analysis, geological supervision, office work.
- Assumes no down time due to foul weather.

* Includes downhole logging, mobilization & demobilization and drilling incidentals.

10.6 Summary of Uses, Advantages and Limitations of Geophysical Methods

The results and experience gained from this study have led to a better understanding of what surface geophysics can and cannot do for coal investigations in the plains. The advantages and disadvantages of each geophysical method may be summarized as follows in Table 10.3.

Table 10.3

GEOPHYSICAL TECHNIQUES - USES, ADVANTAGES, LIMITATIONS

METHOD	USES & ADVANTAGES	LIMITATIONS
1) Reflection Seismic	- directly monitor coal seams, continuity, subcrop, as well as litho-stratigraphic sequences characterized by contrasting seismic impedances. - can be tied to known geology using downhole sonic and density logging.	- minimum depth of exploration 10 m. - thickness of coal seams generally unresolved due to effective wavelength of seismic energy being larger than thicknesses involved.
a) Common Offset Technique	- generally less expensive due to recording of few data channels and use of surface seismic source. - field analysis of results. - maximum penetration 100 metres,restricted by source strength.	- bias towards single subsurface reflecting horizons. - generally low signal to noise ratios.
b) Common Depth Point (CDP) Technique	- maximum penetrations generally exceed requirements for surface coal mining and depend on source strength, coupling, and geophone array. - recovery of a detailed image of the seismic impedance structure within the subsurface. - high dynamic range and multifold coverage create significant improvement of signal to noise ratio and ultimate resolving ability.	- generally more expensive due to sophistication of recording equipment required, large number of data channels, source preparation and need for data processing. - turnaround time for results dependent on data processor.

cont'd ...

Table 10.3 (Cont'd)

METHOD	USES & ADVANTAGES	LIMITATIONS
c) Shear wave Reflection (CDP) Technique	- independence from pore fluids. - shorter wavelength (higher) resolution) due to lower velocity of propogation. - elastic properties of materials can be estimated when used in combination with acoustic reflection. - identification of low velocity (weak bedrock) and high velocity (strong bedrock) zones.	- minimum depth of exploration 70 metres due to small difference in shear and ground roll velocities. - processing techniques to be developed. - initial field tests performed to date, only. - requires development of suitable signal generator. - shear wave penetration is poor.
d) Vertical Seismic Profiling (VSP) Tomagraphy, 3D-Seismic	- 3 dimensional subsurface imaging and time to depth conversion functions. - exploration objectives include abandoned workings, and foothills coal exploration applications.	- developmental at this stage. - generally quite expensive. - acquisition instrumentation and suitable data processing to be developed.
2) Retraction Seismic (compression and shear wave)	- generally inexpensive. - depth to bedrock. - saturated, unsaturated. surficial materials and bedrock. - depth of exploration from surface to over 100 metres (compression wave). - depth of exploration within upper 50 metres (shear wave) currently dependent on strength of source mechanism.	- requires velocity contrasts between materials to be in the order of 1.5 to 1. - resolutionless in sequences of thin beds having rapidly varying velocities. - depth conversion failure where velocity structure does not increase with depth.

cont'd ...

Table 10.3 (Cont'd)

METHOD	USES & ADVANTAGES	LIMITATIONS
	- delineation of weak (strong) bedrock masses.	- shear wave penetration poor in swampy areas.
	- estimation of elastic parameters of subsurface materials.	- high velocity arrivals through seasonal frost can be detrimental.
	- field analysis of velocity thickness structure.	
3) Crosshole Seismic	- obtain compression and shear wave velocity profiles as a function of depth.	- requires 3 drillholes.
	- only method for use of vertically polarized shear waves.	
	- results used to confirm velocity thickness structure obtained from refraction seismic.	
	- field analysis of results.	
4) Direct Current Resistivity	- identification of litho-stratigraphic variation in low resistivity environments.	- poor input current coupling in seasonal frost.
	- field analysis of data.	
a) Direct Current (DCS) Technique	- location of upper surfaces of coal as a result of high resistivity of coal.	- resolution loss in areas of laterally highly variable resistivity.
	- coal continuity and subcrop mapping, abandoned workings.	
	- penetrations in the order of 50 metres, constrained by available power and array length.	

cont'd ...

Table 10.3 (Cont'd)

METHOD	USES & ADVANTAGES	LIMITATIONS
b) Direct Current Profiling (DCP) Technique	- excellent lateral resolution of coal subcrop in very shallow subsurface.	- relatively low rate of production, depending on station spacing.
	- penetration depth gained at loss of lateral resolution.	
5) Electromagnetic Induction	- no restriction in seasonal frost.	- generally impervious to the presence of thin resistive strata.
a) Fixed Frequency (EM) Technique	- excellent lateral resolution.	- little resolving power in low resistivity environments.
	- high rate of productivity.	
	- most useful for mapping thickness of resistive strata overlying clay, shale, etc.	
	- peat thickness.	
	- granualar materials.	
	- location of DCS stations.	
b) Transient Electromagnetic Sounding (TEM method).	- greatest electromagnetic coupling to the subsurface.	- too large scale for mapping of features of interest to prairie coal mine operations.
	- extremely large depths of penetration.	
	- total thickness of coal bearing basins.	
6) Others		
a) Radar	- small wavelength, high vertical resolution.	- skin depth limited, depth of penetration in the order of centimetres in the usual low resistivity environment.
	- possible use for in seam coal studies.	

cont'd ...

Table 10.3 (Cont'd)

METHOD	USES & ADVANTAGES	LIMITATIONS
VLF	- high rate of productivity. - field analysis of data. - some application to coal subcrop.	- skin depth limited, depth of penetration in the order of 10 to 20 metres in usual low resistivity environment. - operator sensitive measurements. - little ability to resolve moderately complicated geoelectric structure.
Gravity	- abandoned workings - regional sedimentary basin studies.	- costly to obtain sufficient data density and accompanying topographic survey detail to model shallow subsurface.
Magnetics	- location of clinker coal.	