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THE HAT CREEK COAL DEPOSIT; A GEOPHYSICAL CASE HISTORY

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Summary

The Hat Creek Valley encloses one of the world's thickest known coal deposits. The coal response to magnetics, electromagnetics, induced polarization, various downhole logging techniques and gravity surveys are examined.

The magnetic method was used for field mapping of geological units and was particularly useful in detecting volcanic rocks and burned zones. Electromagnetic methods detected conductive fault zones with varying degrees of success, while an induced polarization survey gave poor results because of the scarcity and habit of polarizable minerals in the deposit. Downhole logging techniques were used to correlate geologic units between drillholes.

The gravity method directly detected the low density coal and yielded one of the world's largest recorded gravity anomalies over a body of economic importance. Analysis of the gravity data indicates a faulted coal deposit of variable width and depth, extending continuously for 19 km. Possible coal reserves are estimated at 1.5 - 1.8 x 10^{13} kg (17 - 20 billion tons).

INTRODUCTION

In 1974 B.C. Hydro and Power Authority examined alternatives to its hydroelectric and petroleum derived power sources. As part of this program, a coal deposit in the Hat Creek Valley in British Columbia was reexamined as a possible thermal energy source. Coal occurrences in the valley had been discovered in the previous century and were not considered to be of metallurgical quality.

The Hat Creek Valley is located 193 km northeast of Vancouver, B.C., midway between the towns of Lillooet and Ashcroft and 16 km west of the Trans-Canada Highway. Railheads are at Pavilion on the B.C. Railroad, 24 km to the northwest, and at Ashcroft, on the C.P. and C.N. Railroads, 37 km to the east.

Studies are currently determining the feasibility of a 2,000 Megawatt power plant fueled by coal from the Hat Creek deposit.

This paper presents a brief exploration history of the deposits and the role that geophysics has played in this program. The responses of various geophysical tools are presented in brief and those tools which detected coal are presented in detail.

EXPLORATION HISTORY

The Hat Creek coal deposits were first reported by G.M. Dawson of the Geological Survey of Canada in 1877 and 1894. The exposures were located along the creek banks at the northern end of the Hat Creek Valley where overburden cover had been removed by creek erosion.

Several hundred tons of coal a year were produced from the area and sold to local communities from 1933 to 1947. In 1957 a subsidiary of B.C. Electric Ltd. (later British Columbia Hydro and Power Authority) optioned the initial Crown Grant claim and conducted extensive surface diamond drilling. Exploration of the property was discontinued because of the growing prominence of hydroelectric power developments.

Exploration of the Hat Creek deposit began again in 1974 in a search for alternate energy sources. At the recommendation of the B.C. Ministry of Mines and Petroleum Resources drilling south of the known deposit lead to the realization that further deposits could be expected in the valley.

B.C. Hydro acquired coal licenses for the entire upper Hat Creek Valley and began reconnaissance drilling of the full 19 km length of the valley. As part of this reconnaissance program, geophysical testing was conducted to assess the viability of various geophysical techniques over a section having the largest surficial width of coal in the north end of the valley. The methods used in these test cases were: Induced Polarization, Vertical Loop E.M., Total Field Magnetics and Gravity. As a result of the initial test surveys, further gravity and magnetic surveys were conducted over the upper Hat Creek Valley in early summer 1975, in conjunction with a continuing exploratory drill program. Downhole logging of all drillholes had been conducted since the initiation of the 1974 program.

In 1976, drilling shifted to the north end of the valley over Area 1, as part of a feasibility study for a proposed thermal plant. A VLF-EM survey was conducted in 1976 to obtain information regarding fault locations as part of this study.

GEOLOGICAL SETTING

Regional: The Hat Creek coalfield constitutes part of an intermontane basin formed in a graben near the western margin of the Interior Plateau. The mountains bordering the valley rise 300 meters above the valley floor. Rocks in the Hat Creek Valley are common to the widespread and irregularly distributed Tertiary volcanic and sedimentary outcrops found in a belt through the south-central interior of British Columbia bounded by Prince George in the north and Princeton to the south.

Mapping of the sedimentary strata around the Hat Creek Valley suggests a stratigraphic thickness in excess of 1300 meters and comprised entirely of continental sedimentary rocks which include more than 490 meters of coal measures.

Interpretation of the stratigraphic succession suggests that the overall trend upward in the sedimentary sequence is toward increased subsidence relative to deposition. The Coldwater Formation, the lowest in the sequence, consists of coarse clastic rocks; it is followed by the Hat Creek Coal Formation which in turn is followed by lacustrine sedimentary rocks of the Medicine Creek Formation. Subsequent to coalification the strata were broadly folded, faulted, uplifted and partially eroded. The sequence was then blanketed by Late Tertiary volcanic sheet flows which were, in turn, subjected to glacial erosion and deposition.

The geology of the Hat Creek Coal deposit has, until recently, been difficult to determine due to the paucity of outcrops in the area. The bedrock has been obscured by glacial moraines, till debris, alluvium and colluvium.

The valley of Upper Hat Creek is largely underlain by Tertiary sediments that form an elongated sedimentary basin-like structure which has been dissected and tilted and conforms to the valley walls. The basin lies north-south along the valley of Upper Hat Creek for a length of about 24 km with an average width of about 5 km. The valley sides at higher elevations are comprised of terraces of older volcanic rocks which lie in the footwalls of the bounding faults. Younger volcanic rocks occur as outliers in the valley bottom and along the margins of the valley.

The basement rocks which underlie and flank the sedimentary rocks are marble and volcanic rocks.

It is considered that a geologic section through the valley floor would be as follows (youngest to oldest):

A. Glacial moraines, till, alluvium and colluvium.

B. Tertiary volcanic outliers of Finney Lake Beds (lahars with some coarse clastic rocks).

C. Sedimentary beds of the Medicine Creek, Hat Creek Coal and Coldwater Formations (siltstones, claystones, coal, basal sandstone and conglomerates).

D. Volcanic rocks of the Kamloops group and marble and metavolcanic rocks of the Cache Creek group.

Important structural features superimposed on the basin are post-depositional and possibly syn-depositional gravity faults. The main faults cross the north end of the valley in a northeast direction and are spaced about 2 km apart. Another major fault system roughly trends parallel to the valley walls and is probably related to the Fraser River Fault system, lying approximately 6 km to the west. It is considered that movement on the syn-depositional faults may have been equal to the rate of sediment accumulation. A favorable peat forming environment probably existed for some time.

Zones of coal have been recognized within the measure but are not easily discernable. A few unique marker horizons in the rock layers have been found. Repetition due to faulting or folding does not account for thicknesses in excess of 490 meters of coal, a condition that is, to date, unique.

Results of analyses to 1977 have indicated that the coal has an estimated overall quality of 12,800 KJ/kg with an ash content of 29% and a moisture content of 25%. Further quality testing is being conducted.

Two deposits of near surface coal have been discovered in the Upper Hat Creek Valley: No. 1 in the north end of the valley, in the area of the original showing, and No. 2, located about 8.8 km south of Area 1.

The structure of the No. 1 deposit is described as an asymmetric syncline with an adjacent faulted anticline and syncline on the east; the structures plunge at about 25° to the south. The deposit extends over 2100 meters where it is down dropped south of the No. 8 fault The deposit is about 2100 meters at its widest point and an apparent thickness of 445 meters has been encountered. Overburden and waste cover varies from 0 to more than 240 meters.

The structure of the No. 2 deposit is a partial syncline with an adjacent anticlinel, as in Area 1; again the structure is terminated by east and west faults. The stratigraphy is similar to that in the No. 1 deposit. Drilling has not been as extensive as in the No. 1 deposit but it is estimated that the deposit is 610 meters wide, greater than 580 meters thick, and about 5500 meters long. Overburden depths range from 18 to 140 meters.

GEOPHYSICAL RESPONSES OF LINE 79000N

As previously mentioned, a geophysical test program was carried out in 1974 in order to assess which geophysical system would respond to a large measure of coal located in the northern end of the valley. Line 79000N was chosen, and a number of geophysical systems were used; including, I.P., Vertical Loop EM, Magnetics and Gravity.

The following includes a brief summary of each method. Borehole Geophysics and Gravity will be summarized in separate sections.

Induced Polarization

The instrument used for the Induced Polarization survey test was a McPhar variable frequency unit utilizing a 60 meter dipole-dipole spacing and frequencies of .31 and 5.0 Hertz. Four "n" spacings were recorded.

Frequency effects range from negligible to low. It is considered that the absence of definitive I.P. effects associated with the coal body is due to the scarcity and habit of the sulphide minerals found in the deposit. Sulphur accounts for about .5% of the total dry weight of composite samples taken from drill holes. Most of the sulphur is organic, with a very small proportion found as iron sulphides, indicating that polarizable minerals are scarce. In addition, much of the iron sulphides have been found as non-disseminated nodules, further reducing the I.P. effect by lowering the available metallic surface area. It is noted that the higher valued frequency effects are found predominently in the n=3 and n=4 spacings and that these may be caused in part by inductive coupling caused by the conductive overburden and bedrock. A small F.E. anomaly at 198E may be attributable to magnetite in a baked claystone observed on surface further north as is the minor F.E. recorded on the 3n and 4n readings centered at 188E.

The recorded apparent resistivities are low and range from a high of 112 ohm-ft/2 π and a low of 2.4 ohm-ft/2 π. This agrees with resistivity tests conducted on several core samples which yielded values less than 10 ohm-ft/2 π.

Resistivity lows recorded across the line do not necessarily correlate with drilled occurrences. It is considered that the host rock and the coal have comparable low resistivities; therefore, the resistivity method is not considered to be a viable exploratory method in the Hat Creek environment.

Electromagnetic Methods

The test line was surveyed by the vertical loop electromagnetic method, using a McPhar S 1/5 vertical loop and set-up method with the transmitter 365 meters from the test line. Readings were taken at 30 meter intervals. Measurements were made at 1,000 and 5,000 Hertz.

No discrete conductor axes were defined. It is noted that east dip angles around 200E correlate with the lowest apparent resistivities recorded in the I.P. survey, which also correlates with near surface coal, but as thick coal underlies the major portion of the test line, the response is not meaningful in an exploratory sense for Hat Creek.

Magnetics

During the summer of 1975, a reconnaissance magnetrometer survey of 160 line kilometers was conducted throughout the length of the valley. Readings were taken at 30 meter intervals on lines 610 to 1220 meters apart. The purpose of the survey was to aid in mapping tertiary volcanic rocks and perhaps aid in determining depth to basement. The instrument used for the survey was a staff-mounted Geometric Model G816 proton precession magnetometer.

Across the valley floor, the magnetic profiles are characterized by low-amplitude - short-wave length.anomalies (50 gammas), considered to be caused by volcanic boulders prevalent in the overburden. Tertiary volcanic rocks, characterized by large amplitude (about 500 gammas) anomalies, were consequently discovered by field mapping.

Baked claystones discovered in the northern part of the Area 1 deposit have a magnetic response similar to the volcanic rocks. Underground natural combustion of coal has resulted in some thermal metamorphism and partial fusion of inter-bedded claystones. It is considered that at the temperatures necessary to fuse the claystone (700 - 1000^{o}C) magnetic minerals were formed. The collapse of roof rocks associated with the burn has apparently caused an enclosed area which is known as Dry Lake Basin. In 1977 a detailed magnetic survey was used to map the areal extent of the burned zone; diamond drill holes provided information on the thickness.

A unique area of low magnetic relief with no magnetic character exists on the upper bench on the east side of the valley. The overburden was subsequently found to be loess (wind deposited sand, silt and clay).

The western contact between volcanic rock and the Coldwater Formation is easily discernable by the abrupt steep gradients over the volcanic units.

A magnetic lobe to the west of the Area 1 deposit originally thought to be tertiary volcanics has been found to be granitic and volcanic slide debris from a nearby mountain.

Average values from the ground survey are close to that of an aeromagnetic survey flown at 300 meters elevation, indicating that the depth to basement in the valley is large.

OTHER METHODS

Very Low Frequency Electromagnetics (VLF-E.M.)

A VLF-E.M. survey was conducted over 17.6 line kilometers to further define the strike and location of known and suspected faults adjacent to and within the Area 1 coal deposit. The survey was limited in extent due to a powerline on the eastern side of the deposit and by the low resistivity environment which severely limited depth of penetration to about 30 meters.

The instrument used for the survey was a Geonics E.M. 16 with a 15 meter station interval. It was originally intended to use Cutler, Maine and Seattle, Washington transmissions for the survey, but the Seattle station overrode the Cutler signal. Readings from the Cutler station were then discontinued.

As expected, the VLF-E.M. data was highly disturbed. The data was further reduced by Fraser filtering.

Borehole Geophysics

Since 1974, all drill holes have been logged as a necessary requirement of Coal Act regulations. Gamma ray, bulk density, caliper, resistance and neutron logs were conducted. Squeezing ground limits the effectiveness of the caliper and resistance logs that require an open hole. The neutron log proved unreliable due to the varying moisture content of the rock which is unrelated to the hydrocarbon content. The most reliable methods are gamma ray and bulk density surveys, which can be taken through the steel wall casing. Qualitative correlations have been made between drill holes leading to a four zone concept in the Area 1 deposit. These correlations can be made in the central, relatively undisturbed portion of the coal body, but faulting and disruptions on the extremities initially negated easy correlation between holes; however subsequent drilling has allowed for correlation of zones and the division to some subzones. Locally individual beds can be correlated. Some success has been obtained in quantitative estimation of ash content from the density logs.

Gravity Method

As part of the ground geophysical test program over line 79000N, gravity methods were used in an attempt to determine which system would respond to the known coal measure. It was concluded at that time that gravity would not yield a distinctive coal-related response.

A reappraisal of the early gravity data was performed by the authors in June, 1975. The analysis included a review of new drilling results and a comparison of the geophysical systems over the test line. As shown on Fig. the calculated gravity profile over the test line is in reasonable agreement with the observed field, based on the geologic model derived from drilling over the test line.

It was concluded that the gravity method was a useful indicator for delimiting the coal deposit, and that a more comprehensive gravity program was justified.

As a result, a 40 line kilometer test survey over what is now known as the "No. 2 Deposit" was attempted. Initial results confirmed the presence of massive accumulations of coal. The survey was expanded to a full 144 line kilometers to cover most of the Upper Hat Creek Valley.

The first results, in the form of Simple Bouguer (not terrain corrected) gravity were used to define zones of near surface coal on a broad scale. Exploratory drilling locations in the Southern portion of the valley to this point had been based primarily on easy road access. With the use of the gravity results, drilling was further confined to the areas of maximum anomaly. New drilling confirmed that a zone of near surface, extremely thick coal existed. It was quickly dubbed the "No. 2 Deposit".

The gravity results were further processed by performing terrain corrections by the accepted method of Agar (1972). These final values appear in the plan map, Fig. .

Gravity Interpretation

The complete Bouguer Gravity map is the relative gravity field observed on the varying surface of the valley, reduced to mean sea level. Unfortunately, this field is not produced by one simple structure, but is comprised of the sum total of various geologic structures on the surface and at depth. In the specific case of the Hat Creek Valley:

$$\Delta g_o = \Delta g_r + \Delta g_v + \Delta g_c + e$$

Δg_o	=	observed gravity field (reduced to sea level, etc.)
Δg_r	=	regional caused by broad, deep structures (geosynclines, intrusives, etc.)
Δg_v	=	higher frequency local regional caused by the sedimentary filled valley.
Δg_c	=	effect of the coal lying within the sedimentary basin.
e	=	error (random, assuming observations free from systematic effects).

The first phase of the interpretation is to isolate the Regional gravity effects caused by the geologic structures of non-importance and remove them from the composite gravity data. Gravity anomalies produced from broad trending, deep seated structures produce a planar "trend" over the limits of the Hat Creek Valley. The effect associated with confined sedimentary basins characteristically fits a low order polynominal.

The process of removing unwanted "Regional effects" from the Bouguer Gravity is known as Regional Residual Separation. It must be emphasized there is no unique residual gravity map. (Nettleton, 1954). In a large part, this separation is arbitrary and depends on the interpretor's judgement and on the methods used.

Over the years, different separation techniques have been developed: visual smoothing, derivatives, wavelength filtering and polynomial filtering, among others. Skeels (1967) clarified the concepts of residual gravity and proposed a modified polynomial fitting method as a computational tool.

This method fits a low order polynominal to the Bouguer Gravity where the fitted polynomial is based on those points on the gravity profiles, or plan maps, that are in the interpretor's judgement, "outside" the source material of interest. Urlych (1968) compared wavelength filtering, the centerpoint "ring method" and the modified polynomial of Skeels. Ulrych demonstrated that this polynomial method minimizes the creation of pseudo-anomalies, or those anomalies which are caused by the separation process.

The modified polynomial method was used to separate geologic features on the Bouguer Gravity at Hat Creek. Agocs (1951) showed that the best fitting plan or regional can be fitted to the observed data by the method of least squares. The equations can be easily modified to solve for trend surfaces of a low order polynomial. Computer programs were written to fit polynomials to the data points which the interpretor judged to be "less anomalous".

The assumption about the nature of the background Regional (the conglomerate/siltstone filled valley at Hat Creek) was tested on line 84,000N. The gravity effect along this profile line, judged to be based on the 2.22/2.65 gms/cc contrast, was considered to be free of effects emanating from the coal measures.

The Bouguer Gravity and the fitted polynomial shown in Fig.   are closely matched, indicating that the sedimentary-filled valley produces a broad second order polynomial type gravity feature.

The next step in the process was to fit second and third order surfaces to the data in three dimensions. The resulting regionals were examined on each profile line. The second order polynomial gave a more accurate representation of the background gravity feature. On each profile line, the various regionals were then fitted to the data by considering the "less" anomalous points and by the criteria of separating the anomalous field in the least distorting manner (Ulrych, 1968). The less anomalous points were determined from breaks in the slope on each profile line and available geologic information which gave approximate residual amplitudes.

The resulting regional field in three dimensions is shown on Fig.   , the residual field on Fig.   . The regional field is the effect of the surrounding 2.22 gms/cc valley against the greater (2.65 gms/cc) density basement rocks. As expected, this appears as a "trough" shaped feature.

The resulting residual Map, Fig.   , represents the effect of the coal and the surrounding medium. Most of the other effects have been removed. In some areas pseudo-anomalies or distortions are produced. These features are caused by the fitted polynomial surface diverging sharply on the flanks of the coal anomaly. Geologically, they can be identified by higher density volcanic rocks on the southwest side of the valley and by the steep limestone cliffs in the east portion of the valley. In this area, coal measures are located close to these features.

The residual map clearly shows extremely large anomalies over the areas of the No. 1 and No. 2 deposits. The derived residual anomaly (-20 milligals) in the largest known gravity anomaly recorded over a body of economic importance (excluding salt domes). By comparison, most metallic deposits display anomalies of less than 1 milligal.

The residual gravity map indicates the difference in size and extent of the two Hat Creek deposits. The gravity feature apparently trends towards the southeast beyond the limits of the survey.

The results of surface exploration drilling program is superimposed on the residual gravity (Fig.). As shown, the No. 2 deposit appears to be characterized by a body of near surface coal flanked by steeply dipping faults. The geometry is confirmed on the gravity profiles by the presence of sharp gradients.

Gravity modelling was carried out on many of the survey lines. Accurate drilling information was available for the study of the No. 1 deposit, however, substantially less information was available for the analysis of the No. 2 region. The center portion of the No. 2 coal measure has not, to date, been drilled through.

An interesting 5 mgal feature is noted south of the No. 2 deposit, a No. 3 anomaly which has not been drilled to date. Interestingly a nearby hole has encountered coal at depth.

MODELLING

Results of modelling of the residual gravity field on selected cross section lines are presented.

Numerous modelling techniques are available for both the forward and inverse gravity solutions. Forward modelling refers to the calculation of gravity values for a particular model of known density and shape. The inverse solution involves the automated adjustment of an initial model until an accurate fit to the observed data is achieved. Agar (1974) determined that the direct (forward) modelling techniques are less cumbersome and can yield adequate results.

Forward modelling of the Hat Creek residual gravity was accomplished using the method of Talwani et al (1959). The gravitational attraction of an n-sided two dimensional body, Fig. (assumed infinite length in the y direction) is given by:

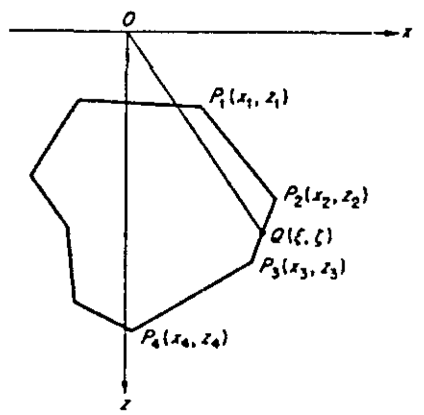

Fig. · Cross section of a two-dimensional body represented by means of a polygon.

$$\Delta g(0) = 2G\,\Delta\rho \iint_S \frac{\zeta\, d\xi\, d\zeta}{\xi^2 + \zeta^2} \qquad (10\text{-}6)$$

$$\xi = a_k\zeta + b_k$$

where $a_k = \dfrac{x_{k+1} - x_k}{z_{k+1} - z_k}$ and $b_k = \dfrac{x_k z_{k+1} - x_{k+1} z_k}{z_{k+1} - z_k}$

The gravity effect at 0 is given by (10-6), and if we integrate first with respect to ξ, this becomes

$$\Delta g(0) = 2G\,\Delta\rho \oint \tan^{-1}\frac{\xi}{\zeta}\, d\zeta$$

$$\doteq 2G\,\Delta\rho \sum_{k=1}^{n} \int_{z_k}^{z_{k+1}} \tan^{-1}\left(a_k + \frac{b_k}{\zeta}\right) d\zeta$$

$$= 2G\,\Delta\rho \sum_{k=1}^{n} \frac{b_k}{1 + a_k^2}\left[\frac{1}{2}\ln\left(\frac{x_{k+1}^2 + z_{k+1}^2}{x_k^2 + z_k^2}\right)\right.$$

$$\left. + a_k\left(\tan^{-1}\frac{x_{k+1}}{} - \tan^{-1}\frac{x_k}{}\right)\right]$$

This method was used for the interpretive work at Hat Creek. A more practical approach to gravity modelling in two dimensions can be carried out by dividing a causative body into small rectangular prisms. Each prism can then be assigned a specific density.

This method will be used in future model studies of the residual data.

MASS OF COAL DEPOSIT

A simple calculation that can be performed using the residual map is the determination of the excess mass responsible for a given anomaly. (In the case of Hat Creek we are actually calculating mass deficiency).

Gauss' Thorem permits a conversion of volume intergral to a surface intergral; in this case the excess mass M may be determined by the intergration of the residual field (from Grant & West, 1967).

$$2\pi GM = I + \mathcal{R}(X,Y)$$

where

$$I = \int_{-X}^{X}\int_{-Y}^{Y} \Delta g(x,y)\, dx\, dy$$

and where $\mathcal{R}(X,Y)$ is a remainder term.

The remainder $\mathcal{R}$ is calculated on the assumption that the entire mass M is concentrated at its mass center. This is a rather satisfactory approximation for a distribution of any shape, provided we are sufficiently far from it. Accordingly, if the center of mass of M is at $(\bar{x},\bar{y},\bar{z})$, we may write

$$\mathcal{R} = 2\pi GM - GM\bar{z}\int_{-X}^{X}\int_{-Y}^{Y} [(x-\bar{x})^2 + (y-\bar{y})^2 + (z-\bar{z})^2]^{-3/2}\, dx\, dy$$

which after some simple manipulation reduces to

$$\mathcal{R} = 2\pi GM - 4GM \tan^{-1}\frac{XY}{\bar{z}\sqrt{X^2+Y^2}}$$

provided that $|\bar{x}| \ll X$ and $|\bar{y}| \ll Y$. Finally, if we put $R = \sqrt{X^2+Y^2}$, we have

$$4GM = \left(\tan^{-1}\frac{XY}{\bar{z}R}\right)^{-1} I \qquad (10\text{-}2)$$

The intergral I in the above equation for the Hat Creek data was determined in two different ways: numerically, using a Simpson's Rule evaluation of the data points, and by using a planimeter on the contoured map. The two results were compatible within the methods used.

The total mass of the coal within the map regions is in excess of 9×10^{12} kilograms and could approach $1.5 - 1.8 \times 10^{13}$ kg. This figure is based on the following assumptions:

1. correct Regional - Residual separation.

2. coal density = 1.2 - 1.5 gms/cc.
   surrounding rock = 2.2 gms/cc.

3. homogenous coal sequence

Conclusions

Various geophysical systems were used over the Hat Creek Valley as an aid in determining the shape and extend the coal field. Of the test methods (I.P., E.M. methods, magnetics, and gravity) the gravity method readily detected the low density coal and indicated two extremely large, thick coal deposits. The magnetic method was used for regional geologic mapping and useful in delimiting Tertiary volcanics and burned zones. Elecromagnetics detected some fault zones, while an induced polarization survey gave poor results. Downhole logging techniques proved useful in correlating geologic units in the center of coal body, but faulting and disruptions on the west side of the coal deposits made hole to hole correlation difficult. Density logs have been used with some success to estimate the ash content of the coal.

Analysis of the gravity data indicates a faulted coal deposit extending about 19 km with possible coal reserves of $1.5 - 1.8 \times 10^{13}$ kg.