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AN ELECTRICAL ANOMALY IN THE ALBERTA FOOTHILLS THRUST BELT

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ABSTRACT

Results are presented of Resistivity and Chargeability depth soundings, conducted in the Waiparous Creek area of the Alberta Foothills Thrust Belt, which indicate the presence of a horizontal layer of unusually high electrical resistivity at a depth of approximately 30 m. This layer was found to have limited lateral extent and to be discordant with the bedding of the rock units in which it is located. At every site where the resistive layer was found the chargeability readings proved to be anomalously high, but this effect appeared to originate in the rocks both within and above the resistive layer.

The genesis of this layer is discussed in terms of the possibility that hydrocarbons seeping upward from depth have interacted with bacteria located in the near-surface rocks, as has been detailed in studies of the Ashland gas field by Oehler and Sternberg (1984). There appears to be a strong parallel between the characteristics of that case and of the Waiparous Creek site.

The polarization effects were found to be strongly attenuated in the near-surface layers when frost was present.

INTRODUCTION

The initial aim of this study was to employ a modern, commercially available, transient-current electrical exploration system to determine whether consistent electrical property contrasts can be detected between sites in the Alberta Foothills Thrust Belt that are known to lie directly over proven hydrocarbon reservoirs, and sites with no known hydrocarbon association.

The initial phase of this project was described in an earlier companion paper (Duckworth, 1983), in which a detailed description of field methods was provided. To summarize that description: these surveys consisted of geometric depth soundings of resistivity and chargeability using a Pole-Pole electrode array. Electrode separation was expanded logarithmically from 1 m to 400 m in each sounding. A 50% duty cycle signal of 8-s period (2 s on, 2 s off) was used, with polarization measured as the integral chargeability from 450 to 1450 ms after the termination of each current pulse.

Tests were first conducted in the area overlying the Wildcat Hills gas field, along the 1a Highway west of Calgary (Duckworth, *ibid.*). The outcrop in that area is predominantly Cretaceous Brazeau, with a 30-m thickness of overburden consisting of the unconsolidated remnants of the bed of glacial Lake Calgary. The area is electrically noisy because of the abundance of pipelines and powerlines associated with the gas field, so that reliable data are difficult to obtain. However, this earlier work showed that contrasts between the electrical properties of sounding sites that had no association with reservoirs were just as large as contrasts found between sites on and sites off reservoirs. This indicated that the type and geochemical condition of the rock underlying each site — including the superficial material — was the main cause of contrasts between sites, rather than the presence or absence of reservoirs. It was clearly necessary to establish the normal range of background electrical responses that could be expected from the various outcropping rock groups in the Foothills, and this need became the focus of the later work.

This change of emphasis required the selection of a test area that could provide access to outcrops of all the major Cretaceous rock units. Such access is available in the Burnt Timber Syncline, a relatively simple structure along the western edge of the Alberta Foothills Thrust Belt. This simplicity allows the rock types underlying any sounding site in that area to be easily identified.

The outcrop map and cross section of this area (taken from Geological Survey of Canada Map 1347A, Geology of Lake Minewanka) is shown in Figure 1a. The area is free of accumulations of unconsolidated glacial material, so that outcrops of all the upper Cretaceous rock units are common. A seismic refraction survey, used to establish a depth for weathering in the area, showed a two-layer structure with the top layer corresponding to the unconsolidated material with a depth on the order of 2 to 3 m at most.

The Waiparous Creek area of the Burnt Timber Syncline was chosen for this project because the track along Waiparous Creek provides reliable all-weather

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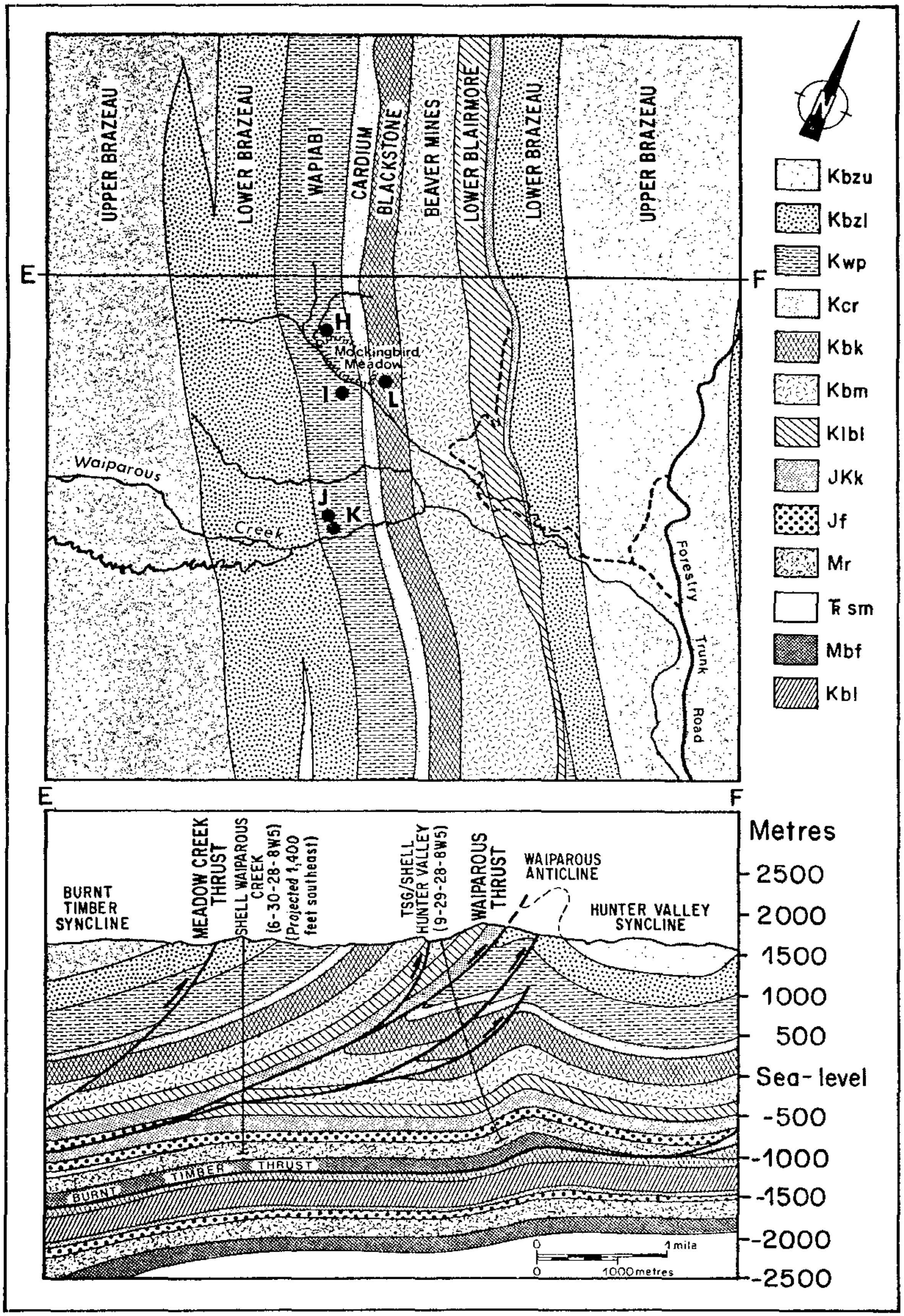


Fig. 1a. Location and geological map taken from Geological survey of Canada Map 1347A. Geology of Lake Minewanka. Locations of test sites are shown.

access to the syncline. Sounding site locations are shown in Figures 1a and 1b. The detailed location diagram in Figure 1b covers the area of Mockingbird Meadow, where most of the soundings were located.

The early results from the Waiparous Creek area showed that the Mockingbird Meadow locality displayed electrical characteristics that indicated horizontal layering where the outcrops showed steep dips. This surprising discordance demanded that most of the survey be devoted to detailing these effects, to ensure that the early results were not spurious.

INTERPRETATION METHODS

The depth sounding results for the Waiparous Creek area are presented in Figure 2 in the form of log-log plots of resistivity versus electrode spacing. No matter what orientation was used for the electrode array, the results for all the sites in Mockingbird Meadow showed a particularly uniform character, thus forcing the conclusion that essentially the same electrical structure lay under every site, and that only a horizontal (one-dimensional) layer model could meet this requirement.

A one-dimensional horizontal layer interpretation was therefore applied to each set of data, with the result that only two of the fifteen data sets could not be matched by such a model. The two unmatchable sets were clearly affected by local resistivity effects in the surface over which those sounding sites lay.

Alternative interpretations in terms of more complicated two- or three-dimensional structures could not have been more successful and hence were not used.

The layer model used to interpret each set of observed sounding data is shown superimposed on each respective diagram in Figure 2. The horizontal spacing axis is used as a depth axis for the layer model.

The data presented in Figure 2 consist of the original observed resistivity (R) and chargeability (m). The theoretical resistivity data points for the layer model that produced the best fit to the observed data are also shown. In most cases, the fit of these two sets of resistivity data is so close that any attempt to fit smooth curves to both data sets will produce the same curve. The observed and theoretical data sets are therefore indistinguishable in these cases. However, the theoretical data values were computed for an electrode spacing range of 0.1 to 1000 m whereas the observed data cover only the range 1 to 400 m.

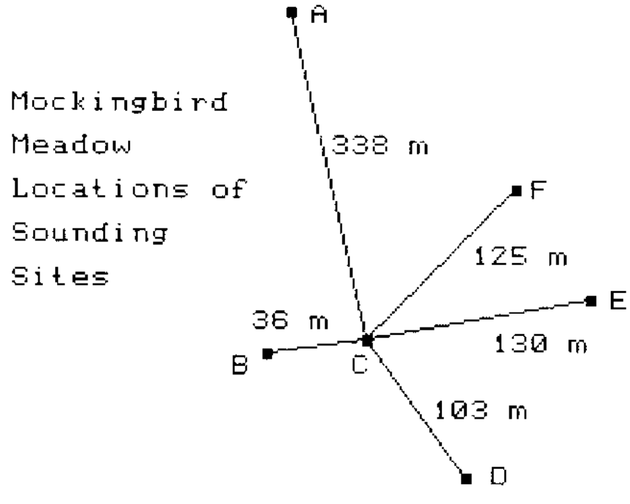


Fig. 1b. Locations of test sites within Mockingbird Meadow

The logarithmic type of presentation used in Figure 2 makes it difficult to appreciate the relative importance of the various layers in each model. Therefore, the layer models were replotted by using a linear depth scale arranged along the vertical axis, as shown in Figure 3.

It is necessary to emphasize that, while a good fit to the observed data was obtained with the layer model in all the cases shown in Figures 2 and 3, the confidence that can be placed on the validity of this model is high only in the case of sites A to F, which lay in the immediate zone around Mockingbird Meadow.

Only one case was found where the chargeability data displayed any recognizable structure, and in that case the structure was clearly related to the resistivity layering. As a result, the interpretation of these results in terms of structure was confined to the resistivity data.

The match between the observed and theoretical resistivity data sets was achieved by means of an interactive iteration procedure, in which the observed and theoretical data sets were shown together graphically on a computer-generated video display. The format of the screen display was identical to that shown in Figure 2. The selection of parameters for each new computation of the theoretical data set was completely under the control of the operator, as was also the visual evaluation of the match between the two data sets.

This procedure was developed in preference to a pseudo-inversion by means of automatic iteration (as described by Hoversten *et al.*, 1981) or a true inversion procedure (as described by Koefoed, 1979), because it allows the operator to retain a high degree of flexibility in controlling the geologic input to the interpretation. *For an experienced operator, the extra time taken to reach an interpretation is not significant unless large numbers of sounding data sets are to be processed.*

This operator-controlled procedure is much more meaningful for interpreters who are interested only in the geologic end-product. Visual estimation of the quality of match can not be dramatically improved by having the computer provide any form of correlation factor, and any attempt to have the software produce a numerical statement of the confidence one may have in the interpreted parameters has little meaning because the Equivalence Principle (Koefoed, 1979) allows wide ranges in the estimates of these parameters. This results from the low resolution of the resistivity method, which allows widely different geological models to produce good matches to the observed data within the error caused by

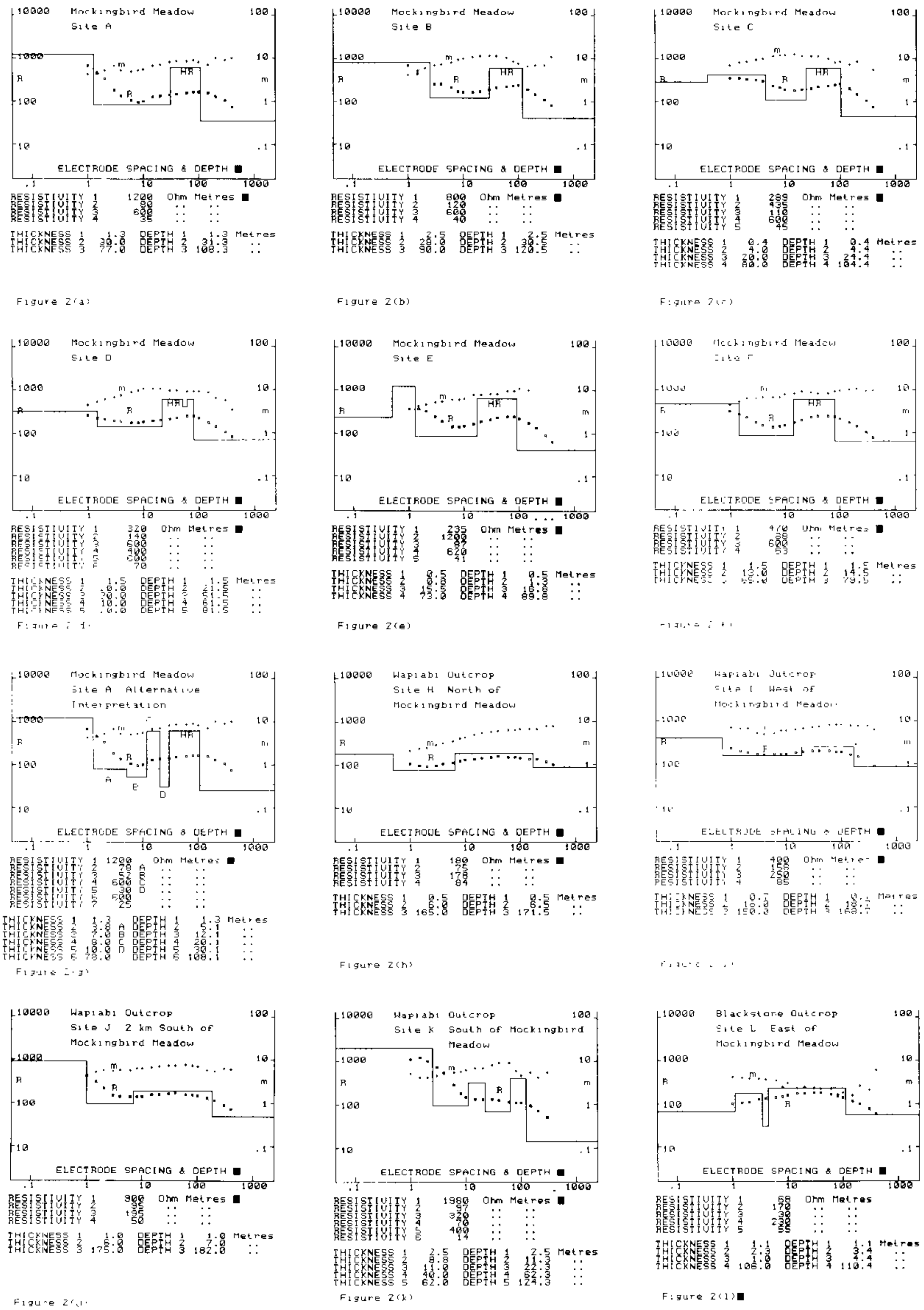


Fig. 2. Observed and theoretical data for sites in and around Mockingbird Meadow, including the layer models used in computing the theoretical data. Note that the observed resistivity is shown for electrode spacing ranging from 1 to 400 m while the theoretical data are shown for electrode spacing ranging from 0.1 to 1000 m.

the noise intrinsic to any data set acquired under normal field conditions. An example of this effect was provided by Flathe (1976) in which depth estimates were shown to be capable of errors of more than 100% because of the equivalence problem. An example of this effect is shown later by the discussion of Figures 2a and 2g.

The theoretical data sets were generated by means of a linear filter algorithm described first by Gosh (1971) and developed by Das and Verma (1980), using a filter published by Koefoed *et al.* (1972).

RESULTS

A feature of results for the whole Wapiarous area was that the resistivity depth sounding profiles indicated generally higher resistivities for the outcropping rock units than for those same rock units seen in downhole logs. However, because the holes are cased the available logs do not provide information in the depth range 0 to 300 m, so that no direct information is available on the resistivities of rocks in the near-surface environment.

The visible outcrops in this area display a steep and consistent westerly dip, which creates a strong impression that any depth sounding results will be unlikely to show horizontal layer characteristics. Consequently, when horizontal layer characteristics did appear in the early results it was a considerable surprise. It proved possible to match these observed effects with theoretical data for models containing as many as five layers.

MOCKINGBIRD MEADOW RESULTS

The test sites located in and around Mockingbird Meadow (sites A to F, Figs. 2, 3), proved notably unusual in the high resistivity and lateral continuity of the layer denoted HR, at a depth on the order of 30 m. This layer displays a dip of no more than 10 degrees to the west, and extends over an area approximately 600 m long in the northwest-southeast direction and approximately 200 m in the northeast-southwest direction.

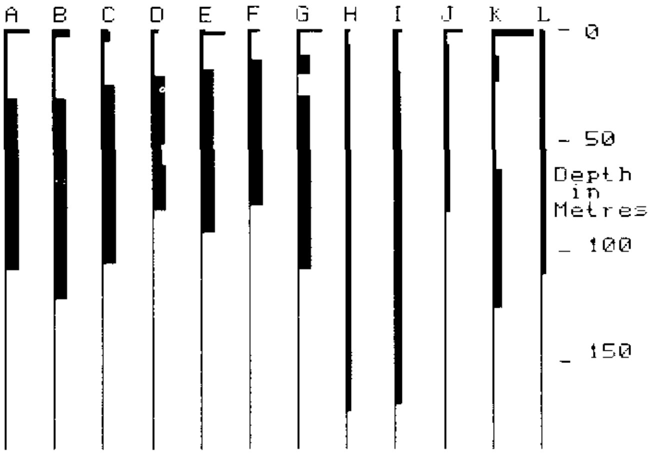


Fig. 3. Linear scale display of the layer models used in Figure 2, showing the anomalous character of sites A to F and the relative thicknesses of the layers

The rock units immediately underlying this area are the Wapiabi, Cardium and Blackstone, which are well exposed in a local creek bank and can be seen in these outcrops to exhibit a consistent westerly dip of 55 to 65 degrees. This clearly indicates that the almost horizontal layer HR transgresses the bedding of the local lithology.

A second feature of this group of results is that, at each site showing the high-resistivity layer HR, the chargeability sounding curve showed a consistent and repeatable trend (one site was repeated 5 times from 1980 to 1983) to values in excess of 10 ms. By comparison, most of the chargeability sounding curves that were observed on the Cretaceous outcrop in the Foothills area, but outside the Waiparous creek area, showed consistent and repeatable trends which prevented those curves from exceeding chargeabilities of 6 ms (for the instrumental settings specified earlier, which were used throughout these surveys). These high chargeability values in the Mockingbird Meadow area appear to be associated with the resistive layer HR and the layer immediately above it. However, no distinction between these layers can be made in the chargeability depth profiles.

The resistive layer HR, and the layer immediately above it, are not located in the unconsolidated superficial material because that material can be seen in outcrops to be no more than 2 or 3 m thick, while layer HR is located at a depth of approximately 30 m. The Wapiabi shale underlies most of the Meadow and, at sites not associated with the Meadow, it displayed a resistivity on the order of 200 ohm-metres in the same depth range as layer HR (sites H, I, J and K in Figures 2 and 3). By comparison, layer HR shows a resistivity of 600 ohm-metres in the interpretations provided in Figure 2.

The resistivities in the layers immediately above layer HR are on the order of 100 ohm-metres, which is very similar to the resistivities shown by the Wapiabi in logs from nearby drillholes. This suggests that weathering has not played a major role in creating the high-resistivity layer HR.

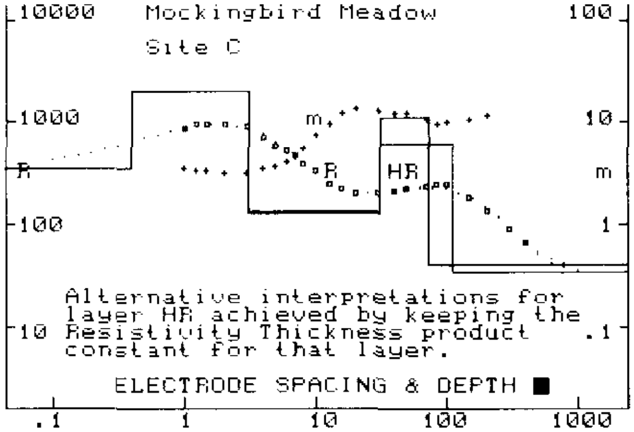
A resistivity of 600 ohm-metres for layer HR should be regarded as a minimum, because this is the lowest resistivity value that will permit a good match between the observed and theoretical data. An upper limit could not be placed on this resistivity -- on the basis of the depth sounding data — because equivalent models in which the product of the resistivity and thickness of layer HR was kept constant while resistivity was increased (Equivalence Principle — Koefed, 1979; Flathe, 1976) allowed equally good matches to the observed data. An example of such an alternative interpretation is provided in Figure 4, which shows two different layer models that give equally good data fits for site C in Mockingbird Meadow. A resistivity of 1100 ohm-metres for layer HR is perhaps too high, because it is more typical of low-porosity crystalline metamorphic rocks than marine shales such as the Wapiabi. Thus higher resistivities for this layer seem to be improbable.

Thus the 600 to 1100 ohm-metre resistivity of layer HR appears to be at least three times and possibly more than five times the average 200 ohm-metre resistivity than the Wapiabi exhibits in other Foothills areas, for the same depth range as layer HR.

A second example of the equivalence of different layer structures is shown in Figure 2g, which illustrates the use of a seven-layer model to match the data for site A which were matched by a four-layer model in Figure 2a. The four-layer model is shown in Figure 2g in dashed form. It is clear that the more complicated model does not achieve a significant improvement in the match between observed and theoretical data. This case shows that a high-resistivity layer could exist above layer HR without being recognizable in the resistivity measurements. Actually, the influences of layers C and D mutually cancel so that they show little or no effect on the over-all response curve, yet both would be significant for the geological description of the site if they actually exist.

MODELS FOR THE ORIGIN OF THE LAYERING

Only a detailed petrographic study of the rocks underlying Mockingbird Meadow will allow the cause of this unusual layering to be fully explained. Such a study will require the drilling of the site and, until then, any discussion of the origin of this layering can be only speculative. However, such speculation can begin with the observation that layer HR probably was created by a process related to the present ground surface, because the layering is very nearly parallel to that surface.



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RESISTIVITY 1  350   350  Ohm Metres ■
RESISTIVITY 2 2000  2000   ..    ..
RESISTIVITY 3  130   135   ..    ..
RESISTIVITY 4 1100   600   ..    ..
RESISTIVITY 5   40    35   ..    ..

THICKNESS 1  0.4  0.4 DEPTH 1  0.4   0.4
THICKNESS 2  2.7  2.7 DEPTH 2  3.1   3.1
THICKNESS 3 28.0 28.0 DEPTH 3 31.1  31.1
THICKNESS 4 41.0 80.0 DEPTH 4 72.1 111.1
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Fig. 4. Equivalent interpretations of the resistive layer are possible, and this example for Site C shows that the resistive layer can be interpreted as being much thinner and more resistive. A lower limit of 600 ohm-metres can be put on the resistivity of layer HR by the matching process, but the upper limit can be set only by geologic considerations.

As mentioned earlier, the chargeability depth sounding curves show no distinction between layer HR and the layers above it, so it can be inferred that layer HR and those above it have much the same chargeability. Therefore, whatever process increased the resistivity of layer HR was possibly associated with another that made both layer HR and the overlying layers more polarizable than the same rock units located outside the Mockingbird Meadow area. In this context, the chemical alteration of the clays present in the shale might provide such an increase in polarizability, as shown by Vaquier *et al.* (1957). However, an alternative explanation might be provided by the model proposed by Oehler and Sternberg (1984) who, in a study of the rocks overlying the Ashland Gas Field, found a resistive layer in the depth range 10 to 20 m. The lateral distribution of this layer correlated poorly with the local surface geology but well with the lateral distribution of the gas field 1000 m below. They also found that this layer displayed anomalously high polarization effects. In downhole studies of the layer, they were able to correlate the strong polarization with a zone of pyrite that had been introduced into a sandstone unit near its base. They ascribed the high resistivity of this same layer to a reduction in porosity caused by calcite having been introduced into the sandstone in this same depth interval. However, it is possible that the pyrite may also have contributed to the increase in resistivity of the sandstone, as described in an earlier paper (Duckworth, 1981). The model proposed by Oehler and Sternberg for emplacement of the pyrite and calcite in this layer involved the vertical seepage of methane, hydrogen sulphide and carbonate ions from the gas pool. The creation of pyrite and calcite from these materials was seen as involving the action of bacteria and ions already existing in the sandstone near the surface.

While the depth of the resistive layer HR in Mockingbird Meadow is somewhat greater than that of the layer seen by Oehler and Sternberg (*ibid.*), there appears to be a strong parallel between the two situations in that a resistive layer is associated with high polarizability in both cases. In using the IP method for metallic mineral exploration, an association of high polarizability with high resistivity is extremely uncommon; polarizable bodies are normally found to be low-resistivity bodies. In the Ashland Field case the calcite and pyrite were found in the same layer, but it appears that the emplacement of two such dissimilar minerals could occupy very different depth ranges even if they have a common source in depth. Thus the greater depth range for the strong polarization than for the high-resistivity layer HR, seen in Mockingbird Meadow, may reflect a different depth range of emplacement for two dissimilar minerals. This suggests that, if pyrite is the cause of the strong polarization effects in the Wapiabi shale below Mockingbird Meadow, it will be found in the depth range from as little as 10 m to at least the bottom of layer HR, while calcite would be confined to layer HR.

Diagenetic pyrite is a common occurrence in the marine shales of this area, but polarizability results suggest that, if a late emplacement of epigenetic pyrite is the cause of this anomaly, it will be found in concentrations significantly higher than are normal for diagenetic pyrite.

Discordance with the local geology was a feature of the Ashland Field anomaly and is the outstanding feature of the Mockingbird Meadow anomaly, so that in this sense the parallel between the two cases is very strong.

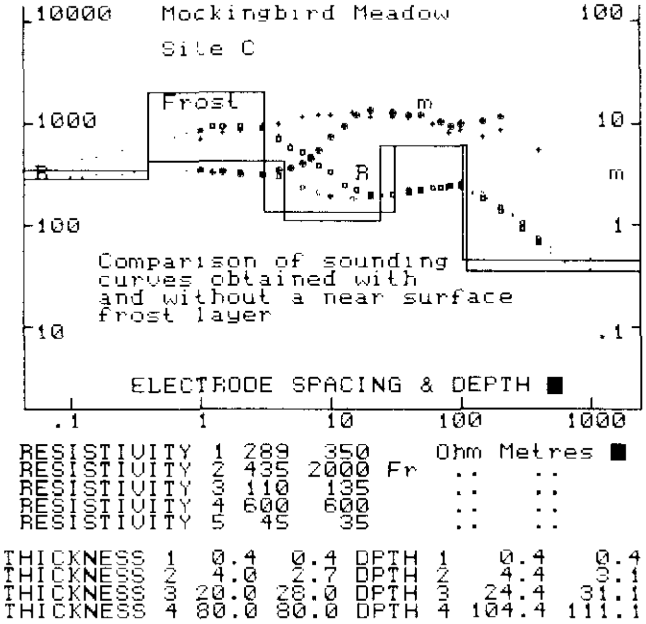
In that the Waiparous Creek area is stratigraphically identical to zones to the north and south that are active gas producers, it seems possible that a gas reservoir could be located under the Mockingbird Meadow area, and that this might account for the unusual electrical character of layer HR in the manner described by Oehler and Sternberg (*ibid.*). However, it might be expected that any seepage from a reservoir that in this area will probably be located at a depth of at least 3 km (based on ther 3-km depth to the Wildcat Hills Field 20 km southeast of the anomalous area, and the fact that shallower-target rock units appear to have proved unproductive in the drilling conducted throughout this area for the past 20 years) would be dispersed over a much larger surface area than that presented by the anomalous zone detected around Mockingbird Meadow. The requirement that pre-existing ions and bacteria be available in the near-surface rocks, in order to produce and fix the pyrite and calcite, could cause the anomalous zone to be localized by the availability of those agents rather than by the availability of the materials being supplied from any gas reservoir.

As Mockingbird Meadow is naturally clear of the dense pine forest that covers the whole Foothills Thrust Belt, it can be inferred that these anomalous effects are related to the effects that created the meadow. Alternatively, it might be inferred that the meadow is there because of unusual subsurface conditions, which cause pine trees to be unable to grow in this location. These views had to be abandoned when it was found that two sites (A and F) in the trees to the north of the Meadow showed a character very similar to that observed at sites in the middle of the Meadow. In addition, although site D was located on the Blackstone outcrop and the electrode array was expanded northward across the Cardium outcrop (as inferred from visible outcrops located just north and south of the Meadow), it nevertheless produced a picture that was not significantly different from those found in the rest of the anomalous area. This leads to the conclusion that layer HR transgresses from the Wapiabi to the Blackstone through the Cardium. If local subsurface drainage was the cause of layer HR, then this transgression through very different rock units is hard to explain, because it seems logical that any such drainage would have been strongly controlled by the greater porosity of the Cardium sandstone. Site L, discussed later, was on a track along the eastern margin of the meadow. It had surface conditions very similar to those in the middle of the meadow, yet it produced results quite different from those found elsewhere in the meadow. Thus it appears that that the meadow is fortuitously located on the anomaly.

TEMPERATURE EFFECTS

An additional feature of the Mockingbird Meadow test area can be seen in the sounding results shown in Figure 5, which were obtained by repeating the sounding at site C. The pronounced difference between these sounding curves was caused by a frost layer in the ground, which was present in May 1980 when the first test was conducted and absent in August 1983 when the second was conducted. In both cases the ground surface was dry and clear of snow. A preliminary report of this effect described in an earlier paper Duckworth (1983) included the results of repeated tests at this site over a three-week period in May 1980. Those tests showed a progressive increase in chargeability as the ground thawed out but the 1983 results show clearly that the thawing effects seen in 1980 were not complete.

The Oehler and Sternberg (*ibid.*) model would ascribe the strong polarization effects seen in this area to an epigenetic, late emplacement of pyrite within the shales. If that is the cause of the IP effects at Mockingbird Meadow, then the decrease of the polarization effect as the shales were frozen in unexpected, because laboratory studies of the IP response of rock samples conducted by Kay and Duckworth (1983) found that the polarization characteristics of samples containing metallic mineralization similar to pyrite increased noticeably when those samples were frozen. This laboratory result



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RESISTIVITY 1 289   350    Ohm Metres ■
RESISTIVITY 2 435  2000 Fr  ..    ..
RESISTIVITY 3 110   135     ..    ..
RESISTIVITY 4 600   600     ..    ..
RESISTIVITY 5  45    35     ..    ..

THICKNESS 1  0.4   0.4 DPTH 1   0.4   0.4
THICKNESS 2  4.0   2.7 DPTH 2   4.4   3.1
THICKNESS 3 20.0  28.0 DPTH 3  24.4  31.1
THICKNESS 4 80.0  80.0 DPTH 4 104.4 111.1
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Fig. 5. An expected decrease of the resistivity in the upper layers was observed as a frost layer thawed out, but the dramatic enhancement of the chargeability that accompanied the thawing was not expected.

was found to be consistent with the so-called Cole-Cole model for the IP effect, which Pelton *et al.* (1978) showed to be very successful in describing the observed IP behaviour of rocks at normal temperatures. Thus, the results from the Mockingbird Meadow field survey show behaviour exactly opposite to that of the laboratory results. This contrast suggests that the polarization effect in Mockingbird Meadow may not be caused by the presence of a metallic mineral such as pyrite (at least in the near-surface rocks).

The local outcrops of the Wapiabi do not show visible pyrite mineralization, but do display colouration typical of the weathering of iron minerals.

The marked difference in dielectric permittivity of water and ice (80 versus 6) appears to indicate a possible cause of the observed decrease in polarizability with freezing. However, the dielectric permittivity of water has never been seen as providing a significant contribution to the Induced Polarization effect because of the low frequencies involved in the manifestation of that effect. The IP effect has been determined to be an electrochemical phenomenon (Klein and Shuey, 1976) which, in mineralized rocks, involves the storage of charge at the interfaces between pore fluid and metallic mineral due to the build-up of ions at these interfaces. In nonmineralized rocks a similar bunching of ions in pores constricted by clays is also seen as being a cause of the IP effect. If the formation of ice in pores is able to prevent charge transfer across metallic interfaces (*i.e.* the fluid in contact with the interface would have to freeze), then this will reduce the charge-storing capacity of a rock. However, it seems likely that the interfaces will be the last component of a rock to freeze, because the high concentrations of ions at these interfaces will reduce the freezing point of the water near them to well below the freezing point of the bulk water in the pores. Similar considerations apply to the freezing of clay-bearing rocks, because of the high concentrations of ions associated with the strong electric fields at the surfaces of clay particles. It therefore appears that the effect observed in Mockingbird Meadow is not easily explained by any of the models of the IP effect at present in use.

The high resistivity in the top layers when the frost was present was to be expected, but the pronounced enhancement of the chargeability (more than 200% for an electrode spacing of 8 m) due to the thawing of the frost will be explained only when samples of the rock underlying the site are obtained.

RESULTS FOR SITES OUTSIDE THE ANOMALOUS ZONE

One test was conducted 500 m north of the meadow, and the results are shown as the curve for site H in Figure 2h. Results for tests conducted south of Mockingbird Meadow are shown in Figure 2 (i-k). Site I lay just south and west of the meadow while the other two sites were approximately 2 km south. In the cases of sites H, I and J the electrode system was laid along the strike of the outcrop, while for site K it was laid perpendicular to strike from the same centre used for site J. All four sites were located on the Wapiabi outcrop.

The aim of the tests at sites J and K was to determine if the Wapiabi Shale displayed any bedding-controlled anisotrophy in its resistivity. The complex layer model derived for site K probably resulted from irregularities in the electrical properties of the surface over which the electrode array was laid. Thus it appears that, despite the visually apparent differences, the curves for sites J and K are very similar and show no significant anisotropy in the resistivity of the Wapiabi shale.

The chargeability results for sites H, I, J and K show a general trend toward higher values for larger electrode spacings, but it is not possible to identify any layering in these results. The chargeability results for site I, which was closest to the meadow, are comparable to those of sites at the edge of the anomaly in the meadow (*e.g.* site A), but sites H, J and K show significantly lower chargeabilities than the sites in the meadow, particularly for small electrode spacings. For instance, site C showed a chargeability of 12 ms for a spacing of 10 m while site J showed 6 ms for the same spacing.

The evident similarity of resistivity profiles for sites H, I and J, which lie north and south of the meadow, and their dissimilarity to the responses found in the meadow, confirm that the effect found in the meadow is localized.

All the sites both in and out of the meadow were on level ground, and the water table was nowhere deeper than 2 m, as shown by local creeks and marshy ground. Thus it is improbable that differences in the character of the surface at the various sounding sites can account for this difference in results.

In the case of site H, the current electrode was situated on a bare outcrop of the Wapiabi Shale, so that the first two layers probably represent weathering effects in the shale. Layers 3 and 4 are more representative of the shale's true resistivity, although layer 3 may be due to the presence of lower-conductivity water of surface origin while layer 4 may contain water of the original marine origin. Layer 1 at site I was certainly the visible overburden, while layers 2 and 3 were probably due to weathering and the presence of water of surface origin. All three test sites (H, I and J) indicate a trend to resistivities on the order of 50 to 80 ohm-metres at a depth of approximately 170 m, which again is more typical for the resistivities seen in downhole logs for this area. In each case the more resistive third layer shows a resistivity of 170 to 250 ohm-metres.

Available tracks allowed only one test to be conducted to the east of the meadow and this is shown as the curve for site L in Figure 2l. The outcrop underlying this sounding was the Blackstone Shale. It is clear that the high-resistivity layer HR under the meadow does not extend under this site, and that the chargeability values for this site are much lower than in the meadow.

CONCLUSIONS

The facts that the observed data are consistent with a horizontally layered model for almost all the sites tested in the Waiparous Creek area, and that the resistivities shown by those layer models are higher than the resistivities seen for those same rocks in downhole logs, suggest that a pervasive alteration of the rocks of this area has taken place in the geological period associated with the present land surface. Weathering effects and the movement of meteoric water into the near-surface zones of the marine shales would account for a general moderate increase of resistivity, but it is difficult to see these processes being responsible for the extremely high resistivity layer under the meadow, or for the higher-than-normal IP effects seen in the same area.

A widespread alteration of this kind implies that the chemical agents that created the change were highly mobile and that their source was located at considerable depth. Alternatively, these agents were provided by the atmosphere and by near-surface movement of ground water.

A localized enhancement of these alteration effects, such as that found in the Mockingbird Meadow area, may well be controlled by the localized availability of surface-derived agents such as bacteria.

The type of survey used in these tests provides detailed information in depth but gives a discontinuous picture of the lateral variations of the electrical properties of an area. A future survey using continuous traverses at fixed electrode spacings would show if the anomalous area has clear limits. The optimum spacing for the electrodes for such a survey would be 60 m, because this was the spacing that gave the strongest polarization results in the anomalous area.

Although additional electrical surveys may aid in defining the lateral extent of these anomalous effects, the only means of arriving at an understanding of their origin is to obtain samples of the rocks involved. Such samples could be obtained by core drilling to depths of 100 m.

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