Preliminary interpretation of the upper crustal structure beneath Prince Edward Island

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Received 20/02/85, revised 26/06/85, accepted 05/07/85.

ABSTRACT. A reconnaissance magnetotelluric survey of Prince Edward Island was undertaken during 1983 to aid in the assessment of the geothermal energy potential of the province. At ten locations, measurements were made in the period range 0.0026-1820 s, and, in general, the data quality was very high.

Beneath the whole of the Island, to a depth of around 200-600 m, is a moderately resistive zone of some 150 Ωm. Underlying this is a highly conducting zone of 10 Ωm down to 1250 m at the most north-westerly point, and to about 3000 m beneath the centre of the eastern part of the island. This layer can be associated with shale sequences found by drilling.

Beneath these shale sequences, there is a dramatic difference in rock type for the western, compared to the eastern, part of the island. Underlying the eastern half, at depths of some km, is a moderately resistive sedimentary sequence of around 150 Ωm. For the western part of the Island there is a resistive zone which can be identified from the borehole logs as pre-Carboniferous bedrock. The topography of the upper surface of this resistive zone is shown to be consistent with the known gravity anomaly in the region.

Key words : magnetotelluric method, geothermal energy, Prince Edward Island.

Annales Geophysicae, 1986, **4**, B, 2, 157-164.

INTRODUCTION

The programme for the assessment of the geothermal energy potential of Atlantic Canada is now in its fifth year and has entered its final phase — that of generating new data at specific targets of interest. Due to its inherent sensitivity to porosity variation of sedimentary rock (see, for example, Hutton, 1976), the magnetotelluric (MT) technique was considered to be a viable approach for ascertaining the structural shape of sedimentary basins within the Maritime Provinces of Canada.

In this work, the preliminary interpretation of the first of three magnetotelluric surveys is described. It was undertaken under contract to the University of Toronto by one of us (AGJ), with personnel of the Earth Physics Branch (EPB), using the EPB PHOENIX real-time MT data acquisition system plus field equipment on loan from Michigan Technical University. The survey was of a reconnaissance nature to map the electrical conductivity variations with depth within the Magdalen Basin underlying Prince Edward Island (PEI). The Magdalen Basin is the largest and deepest sedimentary basin in the Atlantic Margin of Canada, and it extends over parts of northern Nova Scotia, south-eastern New Brunswick, and all of PEI. Borehole bottom-hole temperature data available at the time of the survey (Drury, 1983) exhibited a generally low temperature gradient across the Island (< 20 mK/m) — the one exception being of 26 mK/m in a 2768 m deep well at a location north-west of Summerside (see fig. 1). However, a shallow borehole, of 450 m, drilled in October, 1984, near to this well indicated a gradient of only 14 mK/m. The depth to the base of the mainly Permo-Carboniferous sediments is believed to decrease significantly from about 9000 m under the eastern part, to 4000 m beneath the western part, of the Island (Drury, 1983). Lithological sections from four other wells drilled on PEI (van der Poll, 1983), at locations # 2, # 5, # 7 and # 11 (fig. 1) are listed in table 1. In the western part of the Island, a gravity high and associated magnetic anomaly, striking approximately north-east (geographic), was interpreted by Garland (1953) as either due to an uplift in the pre-Carboniferous basement of some 2500 m with a width of 16 km, or due to a variation in the type of basement rock, namely to volcanic and intrusive, of the Caledonian Mountain variety. As these rocks are more resistant to erosion, Garland (1953) proposed that a highland may well

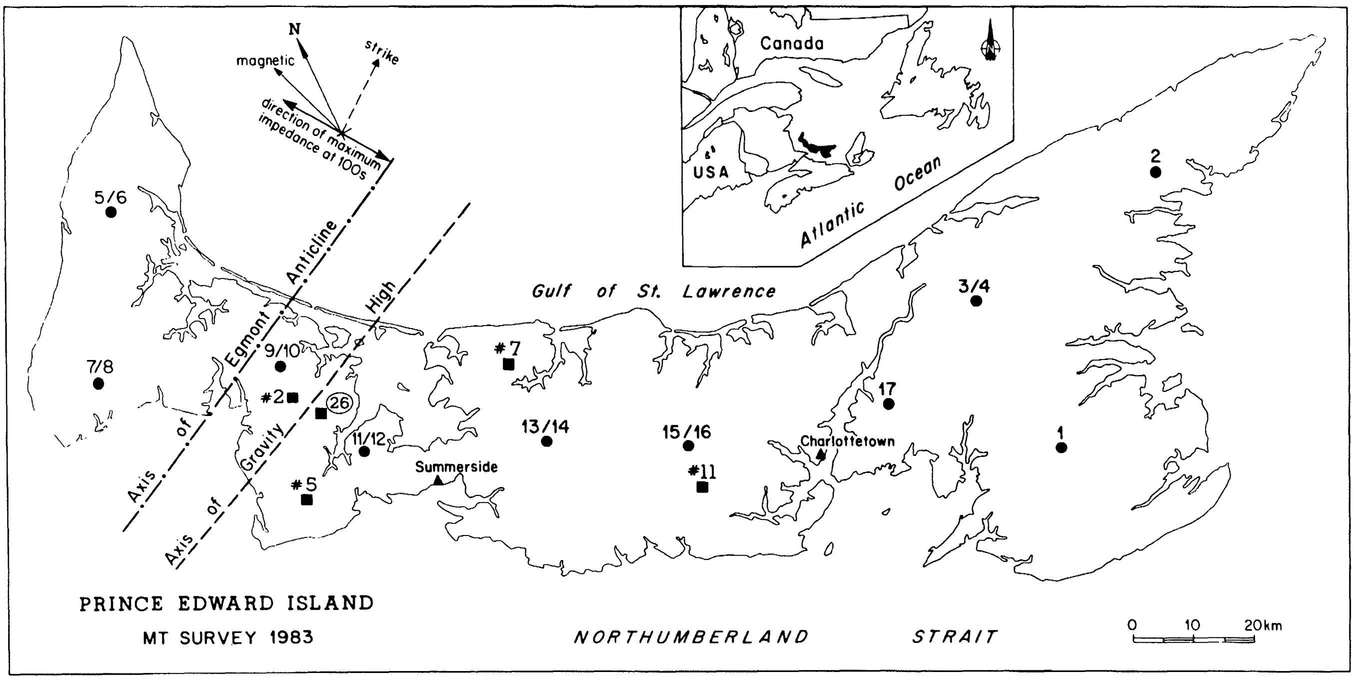

Figure 1
Map of Prince Edward Island showing the locations of the MT *sites (circles), the high temperature gradient (square with circled* 26*), the boreholes discussed in the text (squares), the axes of the gravity high and the Egmont anticline, and the direction of maximum impedance for the western sites at* 100 s.

have existed along a line through western PEI before and during the deposition of the Carboniferous and later sediments. This basement ridge would then correspond in position with the gravity and magnetic anomalies. Also, the axis of the Egmont sedimentary anticline coincides very closely with the axis of the gravity high. This basement ridge hypothesis of Garland's is supported by the log from well # 2 that struck pre-Carboniferous basement at a depth of 1408 m, and is conjectured to be a north-easterly extension of the fault-bounded Kingston Uplift of New Brunswick (van der Poll, 1983).

In total, MT measurements were made at ten locations distributed fairly evenly over the Island (fig. 1). At seven of these locations, measurements were made of nine electromagnetic field components, these being five components (H_x, H_y, H_z, E_x, E_y) at a « local » site and the four horizontal components (H_x, H_y, E_x, E_y) at a « remote » site, where « remote » here means within 1 km of the local site. At the other three locations, only the five « local » field components were measured. The signals from the « remote » locations were used as the « instrumental variables » (Reiersol, 1950; Akaike, 1967) on the « local » signals to remove auto-power bias from the least-squares estimation procedure, and accordingly to provide the well-known « remote-reference » (Gamble *et al.*, 1978) estimates of the MT impedance tensor elements. The locations in figure 1 with two numbers are those at which « remote-reference » measurements were made. In this report, only the odd numbered sites of such pairs are discussed because their responses were better estimated, whilst the responses from the even numbered sites of each pair were more scattered and had larger associated statistical error.

OBSERVED RESPONSES

Structural strike direction

The structural strike of PEI is indicated by (a) the direction of the axis of the gravity high (N55E — fig. 1), (*b*) the direction of the axis of the Egmont anticline (N55E — fig. 1), (*c*) the structural shape of the Magdalen sedimentary basin, and (*d*) the strike of the MT impedance tensors observed for locations on the western half of the island (N35W, see below). All four of these concur that the structural strike is approximately N55E (see fig. 1). Accordingly, this paper will discuss the responses in a rotated reference frame such that all « parallel » responses — equivalent to E-polarization — are in a direction N55E, whilst all « perpendicular » responses (B-polarization) are in a direction N35W.

Niblett-Bostick responses

The Niblett-Bostick transformations (Niblett and Sayn-Wittgenstein, 1960; Bostick, 1977; Jones, 1983*a*) of the apparent resistivity curves, rotated into the structural strike directions, are illustrated in figure 2 (site 3 not shown as the responses were not well estimated). It is evident from the figure that the electrical conductivity structure of the upper crust beneath the western part of the Island is radically different from that beneath the eastern part. At depths shallower than 1 km, the responses are virtually 1-*D* at all locations. Between 1-10 km however, the responses at the western sites (5, 7, 9 and 11) imply a different electrical conductivity in one direction compared to the orthogonal one, whereas the eastern stations (15, 17, 1 and 2) are still (to within the data accuracies) 1-*D*. There occurs a « transition zone » between sites 11 and 15, as illustrated

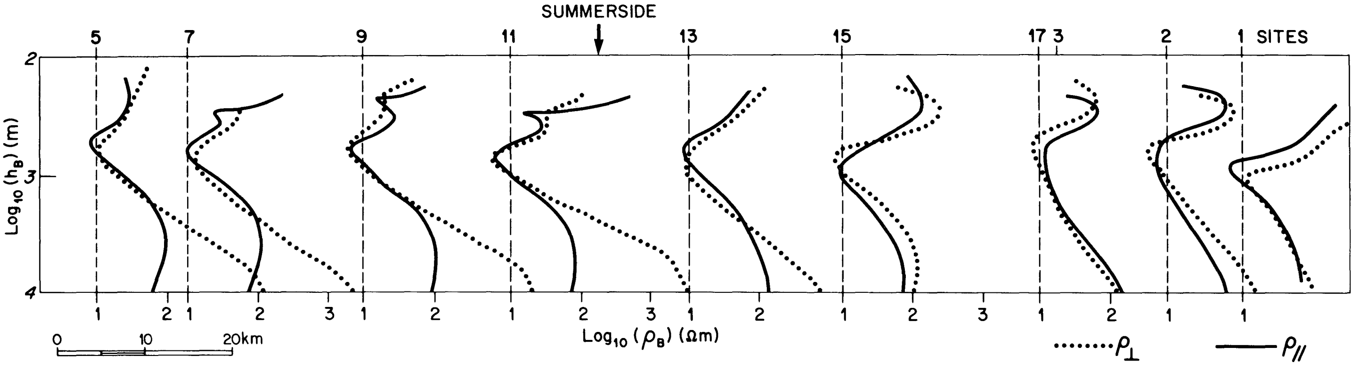

Figure 2
« *Niblett-Bostick* » *transformations of the response functions observed at all the* « *local* » *sites in the rotated reference frame* N55E.

by the response observed at site 13. Of the responses available, those for site 5 were deemed indicative of the « western » response, whilst the data from site 17 were chosen to represent the « eastern » response.

Western response, site 5

Figure 3 illustrates the rotated parallel and perpendicular MT apparent resistivity and phase curves, together with their 95 % confidence intervals, observed at site 5. These orthogonal responses are equal to one another at all periods shorter than about 8 s, attain maximum separation at about 100 s, then appear to begin to coalesce at periods of 1000 s and greater. In figure 4 are shown the impedance polar diagrams at periods of : *a* : 3.5 s; *b* : 10.75 s; *c* : 42.7 s; *d* : 113 s; *e* : 450 s; and *f* : 900 s, where the measuring axis was N22W. The extremely low $|Z_{xx}|$ compared to $|Z_{xy}|$ at periods below 10 s, and above approximately 1000 s (not shown), is indicative of a 1-*D* conductivity structure. Also, the geomagnetic transfer functions (not shown here) are low at these periods. However, between 10-100 s the shape of the impedance polar diagrams imply a 2-*D* structure, with the major axis of anisotropy approximately N15W of magnetic north, and the real part of the geomagnetic transfer functions maximise at 100 s. As the declination for PEI is approximately N22W of true north, the major axis is N35W geographic. This direction is called « perpendicular », rather than « parallel », because these western sites are on the *resistive* side of a 2-*D* lateral inhomogeneity. This feature, of 1-*D* – 2-*D* – 1-*D* with increasing period is also displayed at sites 7, 9, and 11, and, with a smaller degree of 2-*D*, at site 13.

Eastern response, site 17

In contrast to the above responses, figure 5 displays those observed at site 17, which are considered to be characteristic of the eastern stations. The orthogonal responses are 1-*D* at all frequencies less than approximately 100 s, and the diagonal elements are never large compared to the off-diagonal terms (see fig. 6 for the impedance polar rotation plots at the same periods as for fig. 4).

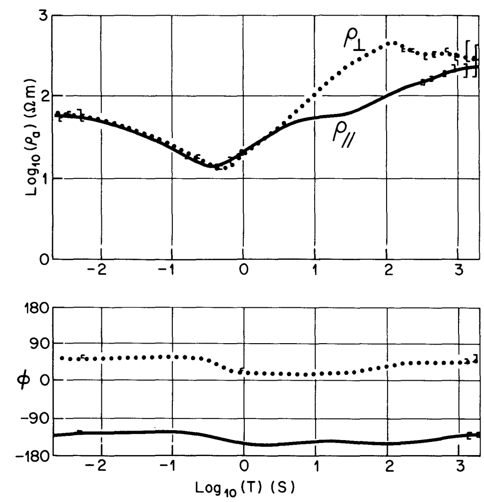

Figure 3
Rotated MT *response functions observed at site* 5 *(see fig.* 1*), together with their associated* 95 % *confidence intervals (only plotted when greater than the size of the data points).*

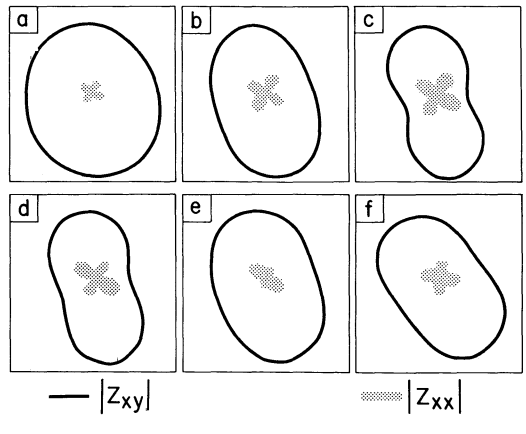

Figure 4
Normalised impedance rotation diagrams for the MT *impedance tensors observed at site* 5 *at periods of; a* : 3.5 s; *b* : 10.75 s; *c* : 42.7 s; *d* : 113 s; *e* : 450 s; *and f* : 900 s. *(Note : the observational axis was* N22W.*)*

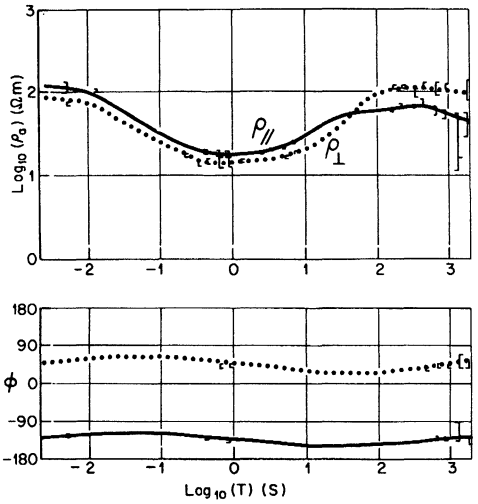

Figure 5

Rotated MT *response functions observed at site* 17 *(see fig.* 1*), together with their associated* 95 % *confidence intervals (only plotted when greater than the size of the data points).*

ONE-DIMENSIONAL INVERSIONS AND NUMERICAL MODELLING

All the responses from the « local » sites were inverted to best-fitting 1-*D* layered earth models by Fischer's algorithms (Fischer *et al.*, 1981 ; Fischer and Le Quang, 1981). The two orthogonal responses from each location, together with each station's « average » response (see below), were inverted independently of one another.

The upper crustal structure, as derived from a pseudo-2-*D* composite of the individual 1-*D* interpretations, is shown in figures 7, 8 and 9. Figure 7 illustrates the model determined from inversions of apparent resistivity and phase with the telluric vector perpendicular to the structural strike direction (i.e., N35W), and figure 8 is for the telluric vector parallel to the strike direction (N55E). Hence, figure 7 is equivalent to the « *B*-polarization » mode of induction, whilst figure 8 is for the « *E*-polarization » mode. Figure 9 illustrates the simplified 2-*D* composite model obtained from those 1-*D* models that were best-fitting to the « Berdichevsky » averaged responses (Berdichevsky and Dmitriev, 1976).

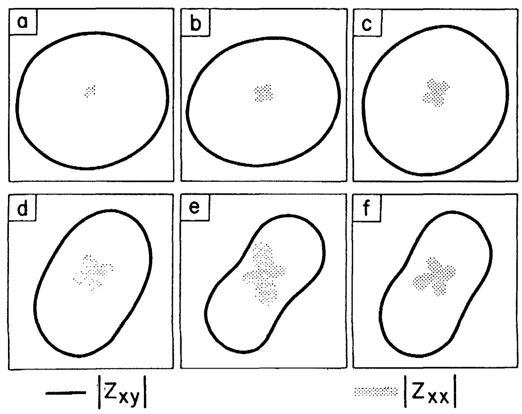

Figure 6

As for figure 4 *for site* 17.

This average, with an impedance given by $Z_{AV} = (Z_{xy} - Z_{yx})/2$, has the property that it is invariant under rotation, and is considered by many workers to be highly suitable for 1-*D* interpretation because it is less affected by deviation from the 1-*D* case than is either Z_{xy} or Z_{yx} (Berdichevsky and Dmitriev, 1976 ; Mbipom and Hutton, 1983 ; Jödicke *et al.*, 1983). Also shown in figure 9 are simplified versions of the lithological logs from the four boreholes (# 2, # 5, # 7, # 11).

The thrust of this work is the 1-*D* aspects of the data. However, as a preliminary investigation of the cause of the 2-*D* responses observed for the western stations, a 2-*D* thin-sheet modelling study of the likely « coast-effect » was undertaken using the programmes of Schmucker (1971). The model used to represent PEI was of a horst-like structure with the shallow seas of the Gulf of St. Lawrence and the Northumberland Strait on either side of the land mass. Beneath the moderately resistive sediments is the thick shale sequence, underlain by more resistive sediments. For this model in the period range 10-1000 s, and for both the *E*- and *B*-polarizations, the coast-effect is not observable on the MT responses at distances greater than 10 km from the coast. Such a small distance for the « coast-effect », compared to the more typical many hundreds of kilometers at 1000 s period (see, for example, fig. 13 of Jones, 1981*b*), is certainly due to the strong attenuation of the anomalous electromagnetic fields at the coast by the underlying highly-conducting shale layer. Two-dimensional modelling of a 3-*D* structure was shown by Jones (1983*b*) to be valid provided that the ratio of the length of a body to the skin depth in the host medium is greater than one. Assuming that the « host » is, for this model, represented by the shale layer, then the skin depth in a 10 Ωm layer at 1000 s is of the order of 50 km. The island is over 100 km long, and therefore the approximation is considered to be valid.

Accordingly, we conclude that the 2-*D* response functions observed on the western half of the Island are due to underlying structure, rather than coast or island effects, because :

1) The 2-*D* responses are not observed at all sites, **only** those on the western half of the Island.

2) The axis of strike corresponds **exactly** with the axes of strike of the Egmont anticline and of the gravity high.

3) 2-*D* modelling indicates that the conducting shales have a profound affect on the well-known anomalous electromagnetic fields at, or near, PEI's coastline by attenuating the fields so strongly that a « coast-effect » *per se* is only observable on the MT responses within 10 km of the coast.

4) The island-effect causes a « DC-like » shift of the apparent resistivity curves at the low frequency limit (see, for example, Larsen, 1977). This shift might be dissimilar for the two apparent resistivity curves due to the 3-*D* shape of the Island. However, the separation between the two curves would be preserved at all long periods, and therefore the curves would not coalesce. As can be seen in the observations, the curves for the western stations do indeed appear to coalesce at the longest periods, although this feature must be born out by longer period measurements.

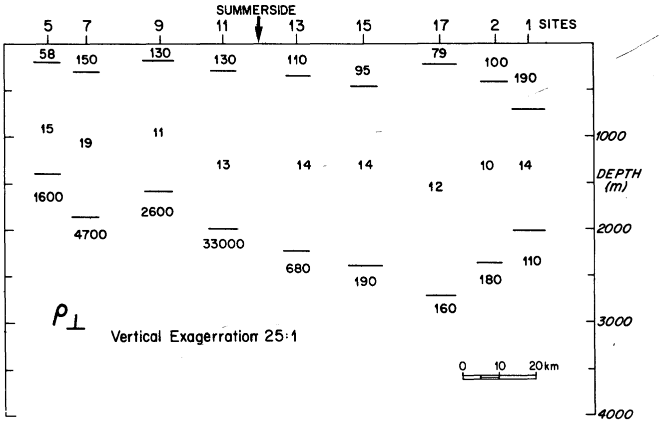

Figure 7
A pseudo-2-D model for B-polarization mode induction created by compiling the 1-D inversions of the responses at each location.

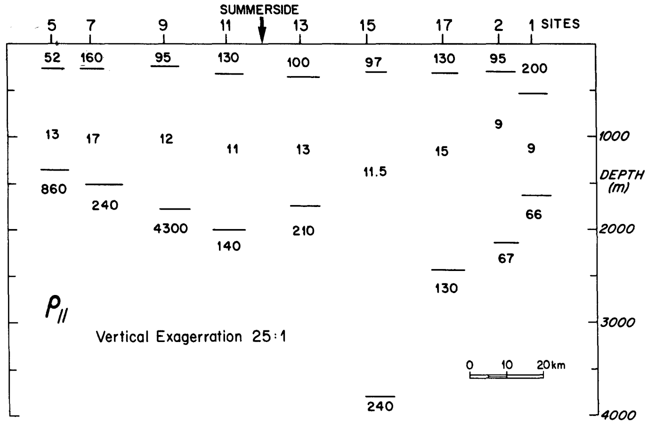

Figure 8
A pseudo-2-D model for E-polarization mode induction created by compiling the 1-D inversions of the responses at each location.

DISCUSSION

The correspondance between the lithologies of the four wells indicated in figure 9, detailed in table 1, and the geoelectric model of figure 9 is extremely good. The depth to the resistive zone beneath site 9 is within 150 m of that given by the well log depth to basement (1551 m for the 1-*D* model compared to 1408 from drillhole information). A deepening resistive zone towards the east is also in agreement with the logs from wells # 5 and # 7, which exhibit a deepening volcanic zone. Also, the absence of any volcanic material in the log of well # 11 is in excellent agreement with the interpretations from the eastern station — particularly site 15. Below site 15, a resistivity interface at 3124 m, associated with the lithological boundary, is acceptable to the observations.

The implication from the upper layers of the interpretation (fig. 9) is that the PEI redbeds are moderately resistive — of the order of a hundred Ohm m — whereas the Pictou Group « coal measures » sequences, which are comprised of sandstones and shales, are an order of magnitude more conducting, i.e., of the order of ten Ohm m. The underlying sedimentary sequences beneath the eastern half of the Island, i.e., the Pre-Pictou strata listed for well # 11, are more resistive again — of the order of several hundreds of Ohm m.

One point which could be challenged, given the uncertainties in the data and the non-uniqueness of the models derived, is whether the topography shown for the top of the resistive zone is real or not. The position of the rise corresponds extremely well with the positions of the Egmont anticline and the axis of the gravity high (fig. 1). As mentioned in the Introduction, van der Poll (1983) believes that the pre-Carboniferous rock found in well # 2 is probably caused by a topographic basement rock high, which he conjectured to be a subsurface north-eastward extension of the fault-bounded Kingston Uplift of New Brunswick. Certainly, the latest structural map of New Brunswick (Fyffe *et al.*, 1982) and residual gravity map (Chandra *et al.*, 1980) show features that are consistent with this hypothesis. Accordingly, the topography mapped by the MT interpretation should also have an expression in the gravity field. A gravity anomaly that would be consistent with this topography may, to first approximation, be modelled by the triangle illustrated in figure 10*b*. Shales have a density of around 2.3-2.4 $\times$ 10^3 kg/m^3, whilst pre-Carboniferous basement and volcanic rocks are typically around 3.0 $\times$ 10^3 kg/m^3. Such a density contrast of 650 kg/m^3 for the 2-*D* body, with the dimensions and depth as illustrated in figure 10*b*, would give a surface gravity anomaly as shown in figure 10*a* (full line). Also given in figure 10*a* (dashed line) is the gravity profile measured by Garland (1953). The peak amplitudes are 7 mgal for the numerical body, and around 10 mgal for the observed peak above the regional background. Also, the anomaly wavelengths are quite similar. Hence, the numerical body inferred from the topography in the MT interpretations does somewhat describe the observed gravity anomaly. The asymmetry exhibited by the gravity observations (fig. 10a, dashed line) is also reflected in the fact that the topography from the MT inversions is asymmetric. However, given the MT data set at hand, a more thorough comparison of the gravity and MT observations is not warranted. The implications from the 1-*D* models are that this resistive zone is some 8-10 km thick, which is far too thick for a volcanic/intrusive layer. However, this thickness is one of the least well-resolved model parameters, and accordingly is not considered to be reliable.

Preliminary modelling indicates that the observed 2-*D* aspects of the data from western sites cannot be attributed to the « coast-effect ». It is also considered unlikely to be due to any « island-effect », although this has, as yet, to be tested. The present interpretation is that the « *E*-polarization » — or rho-parallel — impedances are responding to the two-dimensionality of the underlying structure. Thus, we are observing the well-known « false conducting layer » effect on « *E*-polarization » responses on the resistive side of a lateral inhomogeneity in conductivity. The results of more quantitative modelling will be reported on in a future paper.

Table 1

Lithological logs of boreholes discussed herein.
Well # 2, Imperial Port Hill No. 1, *Drilled* : 1958.

Depth (m)	Sequence
0	
	Pictou Group : PEI redbeds, brownish red sandstone and bright red shale
445.0	
	Transition sequence : « coal measures » to redbeds, grey and reddish brown sandstone, red shale
579.1	
	Pictou Group « coal measures » : grey sandstone, grey and red shale, coaly material
1408.2	----non-conformity----
	Granitic basement
1417.0	----base----

Well # 5, Imperial Wellington Station No. 1, *Drilled* : 1958.

Depth (m)	Sequence
0	
	Pictou Group : PEI redbeds, mainly medium to coarse grained sandstone-bright red shale
478.5	
	Pictou Group : Transition sequence, « coal measures » to redbeds, grey and red sandstone and shale, minor coaly fragments
740.7	
	Pictou Group « coal measures » : grey sandstone, minor conglomerate, grey and red shale, pyrite and coaly fragments
1252.7	----disconformity----
	Pre-Pictou strata : mainly Canso (?) or Windsor Group, red shale, minor white limestone, red sandstone, anhydrite evaporites
1468.2	
	Horton-Windsor Groups (?), mainly mafic volcanic rocks with interbedded arkosic sandstone, conglomerate
1764.8	
	Mainly reddish, brown-chocolate, brown, and grey shale, minor sandstone; interbedded anhydrite and salt in interval 2100-2744 m
2960.8	----base----

Well # 7 Hudson's Bay Irishtown No. 1, *Drilled* : 1972.

Depth (m)	Sequence
0	
	Pictou Group : PEI redbeds, sandstone and shale
792.5	
	Pictou Groups : Transitional sequence, « coal measures » to redbeds, brownish-red and grey sandstone and shale
865.6	
	Pictou Group : « coal measures », mainly grey sandstone, grey and reddish brown shale
1585.0	----disconformity----
	Pre-Pictou strata : mainly Windsor and Horton Groups present
1915.1	
	Windsor salt, limestone, minor red shale, anhydrite and arkose
2541.4	
	Mafic volcanic rocks, grey-brown sandstone, conglomerate and shale
3026.7	
	Shale, mafic volcanic rocks, reddish-grey sandstone, becoming conglomerate towards base
4107.8	----base----

Well # 11 Soquip et al. *Tyrone No.* 1, *Drilled* : 1975.

Depth (m)	Sequence
0	
	Pictou Group : PEI redbeds, red sandstone and siltstone
941.8	
	Pictou Group « coal measures » : grey sandstone, grey, greyish-green and reddish-brown siltstone, coaly material, minor conglomerate
3124.4	----disconformity----
	Pre-Pictou strata : mainly Canso and Windsor Groups : major break between Canso and Pictou. Canso Group, dark brown to greyish-brown sandstone, and siltstone becoming coarse and conglomeratic towards base; very minor limestone
3901.4	
	Windsor Group : conglomerate, silty limestone, oolite, sandstone, anhydritic sandstone
4157.5	
	Windsor Group : evaporites, mainly anhydrite
4166.6	----base----

CONCLUSIONS

In this paper we have described the preliminary interpretation from an MT survey conducted on PEI during 1983. The responses from the ten recording locations were uniformly 1-*D* from the highest frequency of 384 Hz (0.0026 s) to around 10 s period. This implies that the top 2.5 km of this region of the Magdalen sedimentary basin is fairly uniform laterally. A 1-*D* interpretation at valid frequencies indicates that there is a marked order of magnitude change in conductivity laterally, at a depth of about 2.5 km, between the eastern and western halves of the Island. The resistive zone beneath the western sites can be associated with a topographic basement high found in the log from well # 2. At periods longer than 10 s, the sites on the eastern half of the Island remain 1-*D*, whilst those on the western half exhibit 2-*D* effects. We believe that this two-dimensionality is not due to any « coast- » or « island-effect », but rather to the conductivity structure beneath the Island.

By far the most perplexing and interesting feature, however, is the point at which the two zones beneath the shale layer are juxtaposed. The structure is within the vicinity of site 13, the responses of which are two-dimensional, but not as much as those further to the west. Also, the below shale resistivity is greater for site 13 than for sites further east. Accordingly, site 13 represents the approximate location of the « transition zone » between sediments and basement rocks. It is interesting to note that the highest geothermal gradient was measured in a well close to site 11 (fig. 1), which would suggest that the area within the vicinity of this transition zone is an excellent candidate for further geothermal energy potential exploration. However, as mentioned in the Introduction, a 450 m deep hole, drilled in 1984 near to the above well, gave a gradient of only 14 mK/m. This latter result does not necessarily mean that the high gradient previously observed is in error, only that it cannot be confirmed. Thermal models can be constructed which can explain a high gradient at depth with only a low gradient closer to the earth's surface. Notwithstanding this apparent aspersion, the potential stratigraphic trapping possibilities inherent in the « transition zone » warrant its continued attention. It was on the basis of this that a « follow-up » MT survey was undertaken during 1984 with eleven more densely spaced sites between sites 9 and 15. The data from that survey have yet to be analysed, and will be reported on in due course.

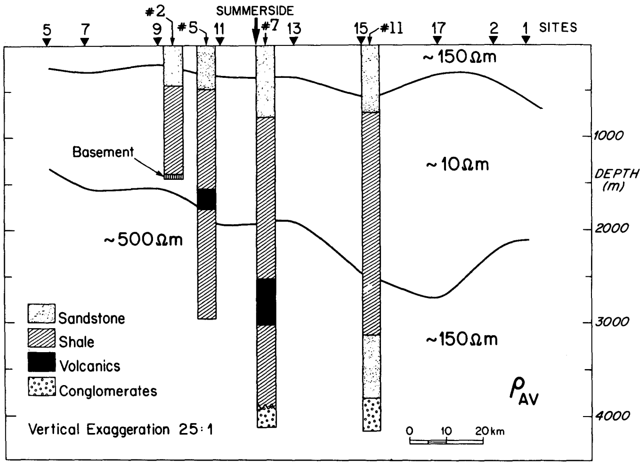

Figure 9
A geoelectric model for the structure beneath PEI.

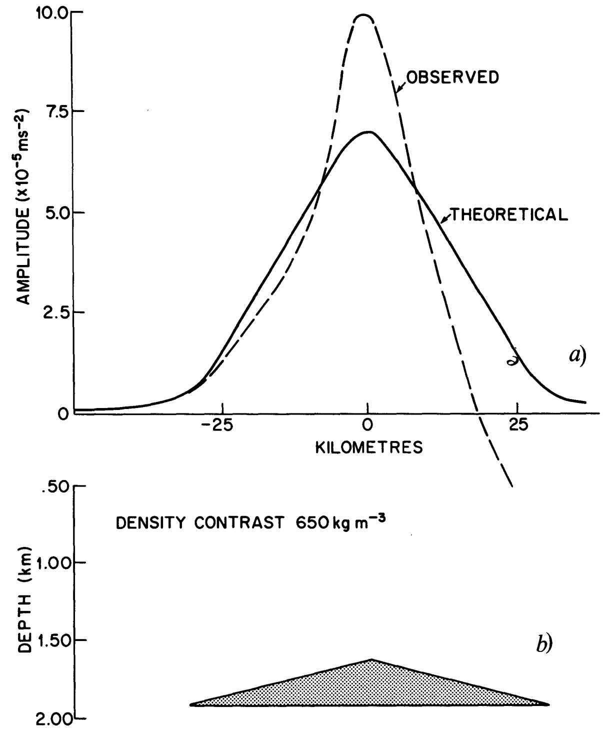

Fig. 10 (*a*)
Observed gravity anomaly for western PEI *(dashed line) with a theoretical response (full line) exhibited by the body.*

Acknowledgements

This work was undertaken as a contract to the University of Toronto from the Earth Physics Branch as DSS reference 20 SU 23235-3-0848, and was funded by the Geothermal Energy Programme. We wish to acknowledge the efforts of Dr. R. Niblett who acted as our Scientific Authority, and of Dr. R. Kurtz for his time in preparing the instruments for field use. We also thank the support staff provided by EPB, Ms. L. Laverdure and Ms. C. Michaud, who worked hard to provide good data. The remote-reference recording was made possible by the generous loan of field instrumentation by Dr. C. Young of Michigan Technical University — we thank both Chuck Young and his student, A. Koivunen, for their time and help. The free time given by Mr. B. Lo of the University of Toronto ensured a high productivity for the survey — we are extremely grateful to him for this. We also thank Dr. Gaston Fischer for providing the coding of his inversion routines. Contribution of the Earth Physics Branch 1207.

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