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Geoelectric Field Modelling for Canadian Space Weather Services

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Summary

Evaluation of the impacts of space weather on ground infrastructure requires information on the size of geomagnetically induced currents produced by the space weather events. The estimation of these currents in places where they are/were not recorded, the numerical modelling is allpied. The most common approach in the modelling of the geomagnetically induced currents is based on the knowledge of the geoelectric field driving these currents while the most common way to estimate the geoelectric field is to use the geomagnetic data recorded in the area. The NRCan on-line service allows calculations of the geoelectric field in the vicinity of each NRCan Geomagnetic Observatory (http://www.geomag.nrcan.gc.ca/index-en.php or http://www.geomag.nrcan.gc.ca/index-fr.php). This report explains the details on the modelling used in electric field calculations and gives all the needed information on all components of the used models.

One of the most important components used to obtain electric field from measured magnetic field is the surface impedance. The report provides the details of the surface impedance models currently used for each observatory. Because there are currently more information on earth structure and also because some observatories have been moved to different locations, the updated surface impedance models are also presented.

A comparison of the new and old surface impedance models shows for the most of them the differences are not significant (BRD, VIC, FCC, IQA, SNK, BLC), or occurred only in the high frequency part (i.e. OTT, MEA). The exception is the models for STJ observatory, which give significant differences between old and new ones and, therefore, the new STJ model should be checked before use in the on-line service.

Comparison of the geoelectric field variations were calculated for 29 October 2003 (Halloween storm) with application of “new” and “old” models were done at several locations with the more dense the impacted infrastructure, such as power grids and pipelines. The results confirm that at the time of large high frequency fluctuations (i.e. during geomagnetic storm) the geoelectric field can be 30% different at many stations due to different earth models used. For the abovementioned STJ magnetic observatory the difference is up to 300%. The recommendation is, therefore, to validate the layered earth models by conducting MT surveys in the vicinity of observatories, specifically for the STJ observatory.

Introduction

Geoelectric field on the ground drives telluric currents (also named as "geomagnetically induced currents", further abbreviated as GIC) along ground infrastructure, creating operational problems for power grids and pipelines. In order to properly address their impacts, amplitude and direction of the geoelectric field at a given place and at a given moment of time are required.

Geoelectric field variations are made available through the NRCan on-line service at http://www.geomag.nrcan.gc.ca/plot-tracee/geo-en.php (in English) or at http://www.geomag.nrcan.gc.ca/plot-tracee/geo-fr.php (in French) for the most of NRCan geomagnetic observatories. They are not measured data but values calculated by the modelling process described in this report. The steps to derive the geoelectric field values include knowledge of the measured geomagnetic data (described in Part 1) and application of a simple theory presented in Part 2. Application of this theory involves the knowledge on the Earth resistivity variations with depth. The background information on Earth resistivity is presented in Part 3, with conductivity models used in calculations given in Part 3 (old models) and Part 4 (new models). The derived surface impedances and their comparisons are presented in Part 5 and samples of electric field variations are shown in Part 6, followed by the Conclusions and References. Additional information on the computational codes used to calculate the surface impedance and the geoelectric field based on geomagnetic field and surface impedance can be found in Appendix 1. Details on the models of the Earth resistivity variations with depth for multiple geomagnetic observatories can be found in Appendix 2.

1. Geomagnetic data

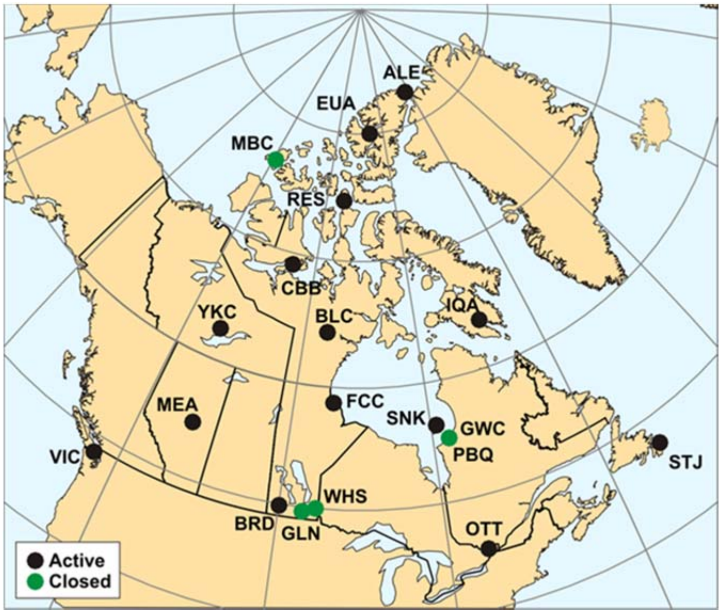

Figure 1. Map of Canadian magnetic observatories. The conversion of observatory naming from IAGA 3-letter code to the full name can be found in Table 1.

The 1-minute sampled geomagnetic data from Canadian Observatories are available from http://www.geomag.nrcan.gc.ca/index-en.php or from http://www.geomag.nrcan.gc.ca/index-fr.php. The measurements of three components of magnetic field are done by use of the fluxgate magnetometer (for instrument description see http://www.geomag.nrcan.gc.ca/obs/canmos-en.php), which samples the magnetic field at 8 Hz. The three component data are de-spiked and filtered using a rectangular filter over 9 data points, for resampling at 1 Hz. In turn, these 1 Hz data are further filtered with 49 point Gaussian filter, and resampled at intervals of 5 seconds and then filtered using a 19 point Gaussian filter and resampled at 1 minute intervals to obtain the definitive data which are placed on the web site for external use. The detailed description of the filters and the whole procedure can be found in the INTERMAGNET Technical Reference Manual at http://intermagnet.org/publication-software/technicalsoft-eng.php. These 1 minute digital data are available for all Canadian Observatories (see the map on Figure 1) for almost 40 years. The exact years of data availability for each observatory are listed below in Table 1.

Table 1. Location, 3-letter code and years of availability of digital data for Canadian magnetic Observatories.

Observatory name	**IAGA code**	**Latitude (°N)**	**Longitude (°E)**	**Years of data availability**
Alert	ALE	82.5	297.6	1978-current
Baker Lake	BLC	64.3	264.0	1974-current
Brandon	BRD	49.9	260.0	2007-current
Cambridge Bay	CBB	69.1	255.0	1972-current
Eureka	EUA	80.0	274.1	2007-current
Fort Churchill	FCC	58.8	265.9	1973-current
Glenlea	GLN	49.6	262.9	1982-2006
Iqaluit	IQA	63.8	291.5	1996-current
Meanook	MEA	54.6	246.7	1972-current
Ottawa	OTT	45.4	284.4	1973-current
Poste de-la-Baleine	PBQ	55.3	282.3	1984-2007
Resolute	RES	74.7	265.1	1974-current
St. John's	STJ	47.6	307.3	1972-current
Sanikiluaq	SNK	56.5	280.8	2008-current
Victoria	VIC	48.5	236.6	1973-current
Yellowknife	YKC	62.5	245.5	1975-current

2. Modelling of the geoelectric field for on-line service

This Part describes the method used to obtain geoelectric field from the known geomagnetic recordings at the Earth's surface.

For description of the geo-electromagnetic field, the coordinate system with axis x north, y east, and z vertically downwards is used. For the natural geomagnetic variations produced by space weather events (periods from 1sec to 24 hours) and earth resistivity above 1 Ohm·m, the displacement currents are small in comparison with conductivity currents. Therefore, electric and magnetic fields in the frequency domain can be given by the diffusion equations in frequency domain (see, for example, [1])

$$\frac{d^2E}{dz^2} = i\omega\mu\sigma E \tag{1}$$

$$\frac{d^2H}{dz^2} = i\omega\mu\sigma H \tag{2}$$

Solutions for each layer have the form

$$E = A(e^{-kz} + Re^{kz}) \tag{3}$$

and

$$H = A(\frac{e^{-kz}}{Z_0} - R\frac{e^{kz}}{Z_0}) \tag{4}$$

where A and R are the amplitude and reflection coefficient, $k = \sqrt{i\omega\mu\sigma}$ is the propagation constant, and

$Z_0 = \frac{i\omega\mu}{k} = \sqrt{\frac{i\omega\mu}{\sigma}}$ is the characteristic impedance (ratio of the electric and magnetic fields for the uniform media).

For our case, when the magnetic field at the surface of the earth (1st layer) is known from the magnetic observations, the electric field can be obtained from the ratio (impedance) of magnetic and electric fields

$$E_{surface} = Z_1 H_{surface} \tag{5}$$

The impedance at any layer n can be found by applying the recursion relation for the impedance of an N - layered half-space ([1], p.293).

$$Z_n = i\omega\mu\left(\frac{1 - r_n e^{-2k_n d_n}}{k_n\left(1 + r_n e^{-2k_n d_n}\right)}\right) \tag{6}$$

where d_n, k_n are the thickness and propagation constant of the layer n,

$$r_n = \frac{1 - k_n \dfrac{Z_{n+1}}{i\omega\mu}}{1 + k_n \dfrac{Z_{n+1}}{i\omega\mu}} \tag{7}$$

and for the last layer

$$Z_N = \frac{i\omega\mu}{k_N} \tag{8}$$

Thus, in order to find the variations of the geoelectric field, equations (5)-(8) need to be solved.

This can be done in the following steps (Figure 2):

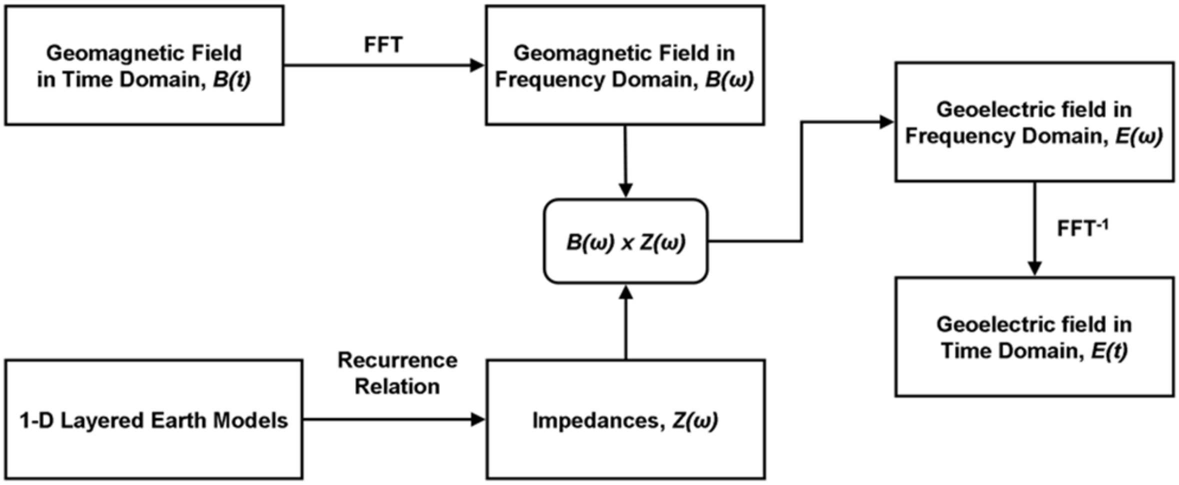

Figure 2. Schematics for calculation of electric field

1. The recordings of the magnetic field (*B(t),* nT) for the period of the interest are obtained from the geomagnetic observatory (see example in Figure 3a). A discrete Fourier transform of the series of *N* data points of magnetic field horizontal components, $B_{x,y}(t_k)$ gives the amplitude spectrum of the magnetic field horizontal components variations

$$B_{x,y}(\omega_n) = \sum_{k=0}^{N-1} B_{x,y}(t_k)\exp(i\omega_n t_k) \tag{9}$$

The variations of the amplitude spectrum for the north component of magnetic field B_x in frequency domain is shown in Fig 3b.

2. Obtain the surface impedance values $Z(\omega)$ from the Earth conductivity model of given observatory. Because the surface impedance is the ratio of the geoelectric to geomagnetic field, the values of the geoelectric field in the frequency domain can easily be calculated as the next step.

3. Multiply the geomagnetic field in frequency domain by the surface impedance gives the spectra of the electric field at the ground, as shown for the E_y component in Fig. 3d.

$$E_x(\omega_n) = Z(\omega_n)\,B_y(\omega_n)\,/\,\mu \tag{10}$$

$$E_y(\omega_n) = -\,Z(\omega_n)\,B_x(\omega_n)\,/\,\mu \tag{11}$$

where μ is magnetic permeability of free space,

4. An inverse discrete Fourier transform can then be used to find the electric field variations in the time domain (Fig. 3c).

$$E_{x,y}(t_k) = \frac{1}{N}\sum_{n=0}^{N-1} E_{x,y}(\omega_n)\exp(-i\omega_n t_k) \tag{12}$$

The illustrative examples of variations of the geomagnetic and geoelectric fields in time domain and frequency domain, *x* and *y* components, are shown in Figure 3, a-d.

In order to find the electric field at the location of the observatory, the values of the surface impedance are needed, which can be derived from the Earth resistivity (or its inverse, Earth conductivity) models for each observatory.

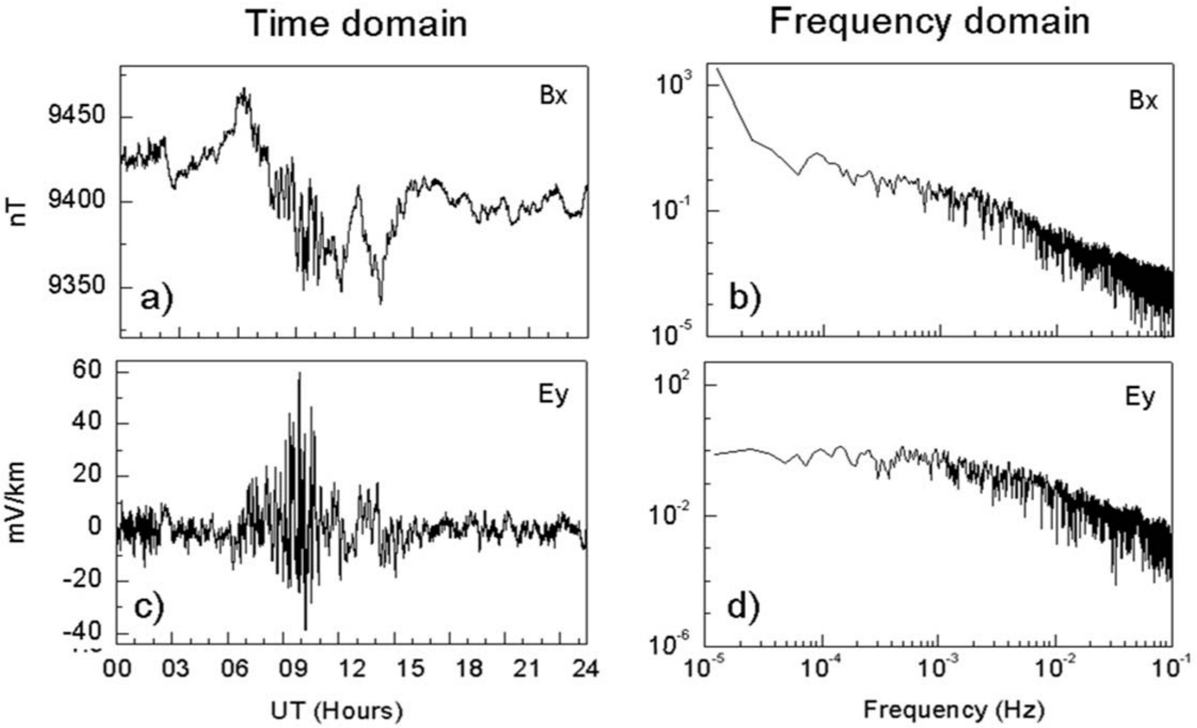

Figure 3. The variations of north-south component of magnetic field **(a)** in time domain (observatory recordings) and **(b)** in frequency domain (obtain by using FFT), and variations of east-west component of geoelectric field **(c)** in time domain and **(d)** in frequency domain, obtained as described above.

3. Background on Earth resistivity and its measurements

The size of the telluric electric fields produced by geomagnetic disturbances depends on the Earth resistivity down to the depth of penetration of the geomagnetic disturbances. We are concerned with geomagnetic field variations with periods from minutes to hours with penetration depths ranging from a few kilometres to hundreds of kilometres. Thus, we need information about the resistivity not just of the surface rock or soil layers, but deeper into the Earth.

On the large scale, Earth's interior structure is divisible into four main layers: crust, mantle, outer core, and inner core (Figure 4). Each layer can be further subdivided based on unique physical differences. The outermost, thin, rigid crust is underlain by the dense, hot layer of semi-solid rock of the mantle. Changes with depth of temperature and pressure, changes to abundance and distribution of conductive minerals, and pore volume and fluid composition all change the resistivity, going from higher resistivity in the crust to low resistivity in the mantle.

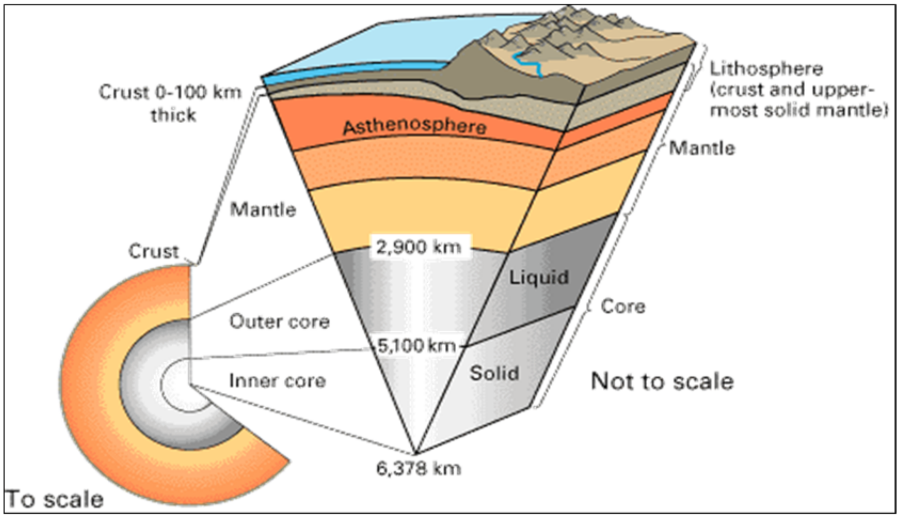

Figure 4. Schematics of the internal structure of the Earth

The resistivity of Earth materials varies widely, as shown in Figure 5, with a considerable overlap of range between different materials. Common rocks show a resistivity range from 10 to 100,000 Ohm·meters (Ω·m), with values for various rock types provided in Tables 2 and 3. Geologic age of the rock, particularly for sedimentary rocks, also has an effect on resistivity values as shown in Table 3, whereby compaction associated with increasing thickness of overlying rock reduces pore space and amount of inter-pore water thereby increasing the rock resistivity. Resistivity will vary among different types of sedimentary rock, being high where there is proportionally more limestone than shale and sandstone, and least for shale dominant rock especially if carbonaceous-rich.

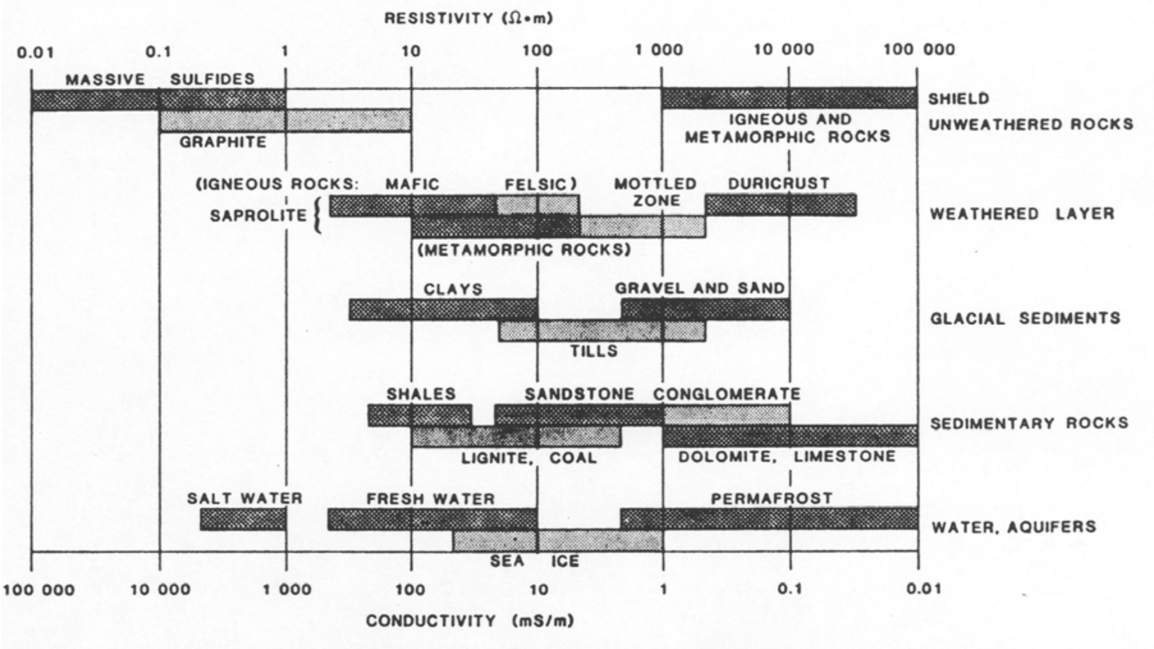

Figure 5. Range of resistivities for common Earth materials (from [2]).

Worldwide, the mid-to-lower crust exhibits lower resistivity compared to the upper crust (typically crystalline rock several km thick) due to temperature and pressure increasing with depth. However the entire crust has a higher resistivity than the underlying mantle. In the mantle the ever increasing pressure and temperature cause the olivine and pyroxene minerals to undergo a phase change to a more dense form that greatly decreases the electrical resistivity.

Table 2. Resistivity values for some common rocks (modified from [3])

Consolidated Sedimentary Rock	**Range (Ω·m)**	**Volcanic Rock (extrusive)**	**In situ (Ω·m)**
Argillite	74-840	Basalt	800
Conglomerate	2,000-13,000	Diabase	450
Dolomite	700-2,500	Diabase	450
Greywacke	400-1,200		
		Plutonic (intrusive) Rock	**In situ (Ω·m)**
Limestone	350-6,000	Gabbro	490
Sandstone	1,000-4,000	Diorite	7,000
Shale	20-2,000	Syenite	2,400
Slate	340-1,600	Granite	4,300

Table 3. Resistivity values for water-bearing rocks of various types [4]

Geologic age	**Marine sand, shale, greywacke**	**Terrestrial sands, claystone, arkose**	**Volcanic Rocks (basalt, rhyolite, tuffs)**	**Intrusive Rocks (granite, gabbro)**	**Sedimentary Rock (limestone, dolomite, salt)**
Quaternary, Tertiary	1 - 10	15 – 20	10 – 200	500 – 2000	50 – 5000
Mesozoic	5 – 20	25 – 100	20 – 500	500 – 2000	100 – 10000
Carboniferous	10 – 40	50 – 300	50 – 1000	1000 – 5000	200 – 100000
Pre-Carboniferous Paleozoic	40 - 200	100 – 500	100– 2000	1000 – 5000	10000– 100000
Precambrian	100 - 2000	300 - 5000	200 - 5000	5000- 20000	10000- 100000

Both the crust and mantle can exhibit lateral variations of electrical resistivity on scales of tens to hundred kilometres due to effects from deep-seated geological structure, tectonic mechanisms, and changes in pressure, temperature and mineralogy, such that regional resistivities are either higher or lower than globally averaged values [5].

Mechanisms that can alter the resistivity of crustal rocks and mantle include: changes to amount of minor constituents (such as graphite and sulphides) and their degree of interconnection; presence of partial melt fluids and aqueous fluids; and enhanced electronic conduction at grain-boundary films of carbon [6,7]. Subduction can drag down to crustal depths water saturated and carbonaceous and/or sulphide rich sediments which are more conductive than surrounding deep crust or mantle [8]. Overburden layer also exhibits a wide resistivity range, from below 10 Ω·m to10,000 Ω·m, which depends on porosity and groundwater and clay contents [9].

The magnetotelluric (MT) method is the geophysical technique with the ability to provide an image of the Earth's conductivity structure over a depth range from near surface to the deep mantle. The ratio of the electrical and magnetic field strengths, as a function of frequency, provides a measurement of electrical impedance which in turn is used to calculate the resistivity at various depths. The depth to which resistivity structures can be imaged depends on the depth of penetration of the electromagnetic fields. This is dependent on the presence of local near-surface structures of low-resistivity and the frequency and intensity of the natural electromagnetic variations [10]. The MT technique measures a "bulk" apparent resistivity of the Earth material over a large area at a range of depths.

In-situ measurement of resistivity are also possible, as done in oil and gas exploration wells by the use of probes lowered into a well, often to depths of thousands of meters. As well, an induction tool can measure resistivity up to 5m or more from the borehole and provides a good representation of resistivity through the surface of surrounding rock. Comparison of petroleum-well induction logs has shown a very good match with resistivity derived from MT soundings [11, 12]. Laboratory measurements of the resistivity exhibited by samples of different rock types also provides information whereby the resistivity of an area can be inferred if the geology of the area is known.

4. Old Earth resistivity models for different observatories

For each observatory we produced layered Earth model in which the conductivity changes in only one direction: vertically as presented in Figure 6. Lateral changes are taken into account by the changes in the resistivity models from observatory to observatory. Determination of the conductivity into the deep Earth is necessary because the low frequency magnetic field variations penetrate several hundred kilometres through the entire crust and into the mantle. Hence, the resulting surface geoelectric field is influenced by the combined response through several hundred km into the Earth's interior.

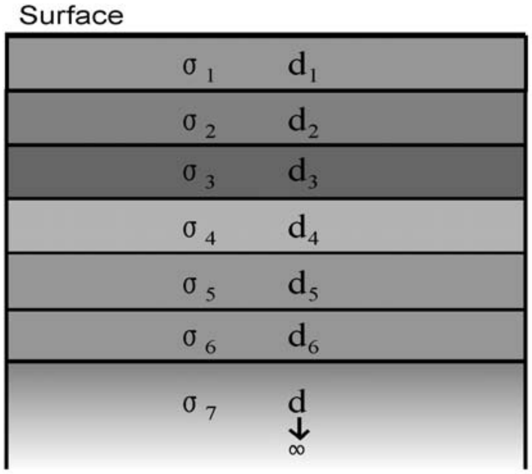

Figure 6. General scheme of the earth conductivity structure for 1-d layered conductivity model. Here σ is the conductivity and d is the depth of each layer, with the bottom layer of the half-space.

The layered earth conductivity models currently listed in Table 4 are currently used in the on-line geoelectric field calculations (later labelled as "old"). They were constructed for each geomagnetic observatory (except Eureka, EUA) and are based on results presented in two reports, [9] and [13], where the first one is presenting a detailed review of the magnetotelluric studies in Canada for each province, and the second one is a summary of the conductivity structures.

For most of the observatories, the 1D models for relevant provinces have been taken as the basis, i.e. model for Ottawa (OTT) is equivalent to the model for the provinces of Ontario and Quebec presented in Table 3.2.1, page A3-22 of [9], the model for St.John's (STJ) is equivalent to the Atlantic Canada model presented in the same Report, Table A3.5.1, page A3-102. For Resolute (RES), Cambridge Bay (CBB) and Yellowknife (YKC) the models for provinces of Ontario and Quebec presented in Table 3.2.1, page A3-22 of [9] were modified regarding the thickness of sediments. The different thicknesses were taken from the map presented on page A3-18 of [9]. This map is reproduced here as Figure 7, allowing to confirm that for CBB and YKC the sediment thicknessess can be assessed as 30m, while for RES it is mid-value between 3000 and 6000 m. Model for Victoria observatory (VIC) is based equivalent to one presented in Table 3.7, page 42 of [13], with the parameters of the top layers of crust taken as the average between numbers presented there. Model for Glenlea observatory (GLN) is taken from [13], page 39, Table 3.4, and is also attributed to the Brandon observatory (BRD).

Table 4. "Old" Earth conductivity models for Canadian magnetic observatories

RES		**CBB, YKC**		**ALE, IQA, BLC, SNK/PBQ**		**FCC**		**MEA**	
Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)
$4.5\cdot10^{3}$	0.01	300	0.01	$1.5\cdot10^{4}$	$5\cdot10^{-5}$	10	0.05	10.	0.05
$1.05\cdot10^{4}$	$1\cdot10^{-4}$	$1.47\cdot10^{4}$	$1\cdot10^{-4}$	$1\cdot10^{4}$	$5\cdot10^{-3}$	240	0.01	$1.99\cdot10^{3}$	0.01
$1.0\cdot10^{4}$	$3.33\cdot10^{-3}$	$1\cdot10^{4}$	$3.33\cdot10^{-3}$	$1.25\cdot10^{5}$	$1\cdot10^{-3}$	1475	$5\cdot10^{-4}$	$1.3\cdot10^{4}$	$5\cdot10^{-4}$
$7.5\cdot10^{4}$	$1\cdot10^{-3}$	$7.5\cdot10^{4}$	$1\cdot10^{-3}$	$2.0\cdot10^{5}$	0.01	$1\cdot10^{4}$	$1\cdot10^{-3}$	$1\cdot10^{4}$	$1\cdot10^{-3}$
$3\cdot10^{5}$	0.01	$3\cdot10^{5}$	0.01	$1\cdot10^{9}$	0.33	$7.5\cdot10^{4}$	$2\cdot10^{-3}$	$7.5\cdot10^{4}$	$2\cdot10^{-3}$
$2\cdot10^{5}$	0.1	$2\cdot10^{5}$	0.1			$3\cdot10^{5}$	0.01	$3\cdot10^{5}$	0.01
$1\cdot10^{9}$	0.33	$1\cdot10^{9}$	0.33			$2\cdot10^{5}$	0.1	$2\cdot10^{5}$	0.1
						$1\cdot10^{9}$	0.33	$1\cdot10^{9}$	0.33

OTT		**STJ**		**VIC**		**BRD/GLN**	
Thickness (m)	Conductivity (S/m)	Thickness (m)	Conductivity (S/m)	Thickness (m)	Conductivity (S/m)	Thickness (m)	Conductivity (S/m)
25	0.02	25	0.02	$4\cdot10^{3}$	0.002	20	0.05
$1\cdot10^{3}$	0.01	$1.5\cdot10^{4}$	$5\cdot10^{-4}$	$6\cdot10^{3}$	0.0067	180	0.01
$1.5\cdot10^{4}$	$1\cdot10^{-4}$	$8.5\cdot10^{4}$	0.003	$5\cdot10^{3}$	0.05	$1.48\cdot10^{4}$	$2.5\cdot10^{-5}$
$1\cdot10^{4}$	$3.33\cdot10^{-3}$	$3\cdot10^{5}$	0.01	$2\cdot10^{4}$	0.01	$1\cdot10^{4}$	$5\cdot10^{-4}$
$75\cdot10^{3}$	$1\cdot10^{-3}$	$2\cdot10^{5}$	0.1	$6.5\cdot10^{4}$	0.0033	$7.5\cdot10^{4}$	$1\cdot10^{-3}$
$3\cdot10^{5}$	0.01	$1\cdot10^{9}$	0.33	$3\cdot10^{5}$	0.01	$3\cdot10^{5}$	0.01
$1\cdot10^{9}$	0.33			$2\cdot10^{5}$	0.1	$2\cdot10^{5}$	0.1
				$1\cdot10^{9}$	1.0	$1\cdot10^{9}$	0.33

Models for Alert (ALE), Iqualuit (IQA), Baker Lake (BLC), and Poste-de la Bailaine (PBQ) were taken from [13], page 38, titled in the report as "model of conductivity for the Precambrian Shield of Quebec and Ontario". When Sanikilluiak (SNK) observatory has been built to replace PBQ, the model for SNK has been the same as for PBQ. Model for Meanook observatory (MEA) is taken from [13], page 41, Table 3.6, i.e. is the same as conductivity model for Edmonton Area; and model for Fort Churchill observatory (FCC) is taken from [13], page 40, Table 3.5, i.e. conductivity model for Churchill area. Later in some cases these models were slightly modified, i.e. the bottom conductive layer with the same conductivity has been added for consistency.

In order to use these models in the online service, i.e. to easily incorporate them into formulas (6)-(8), several files were prepared which contain the values of the real and imaginary parts of the surface impedance suitable for daily files of 1 minute magnetic data. The FORTRAN code used for preparation of these files is located in Appendix 1 (part 1.1). It should be noted that these files are to be used only with daily geomagnetic data with a sampling rate of 1 minute. The IDL code which runs on-line in order to produce the geoelectric field values and plots in both official languiages is presented in Appendix 1 (part 1.2).

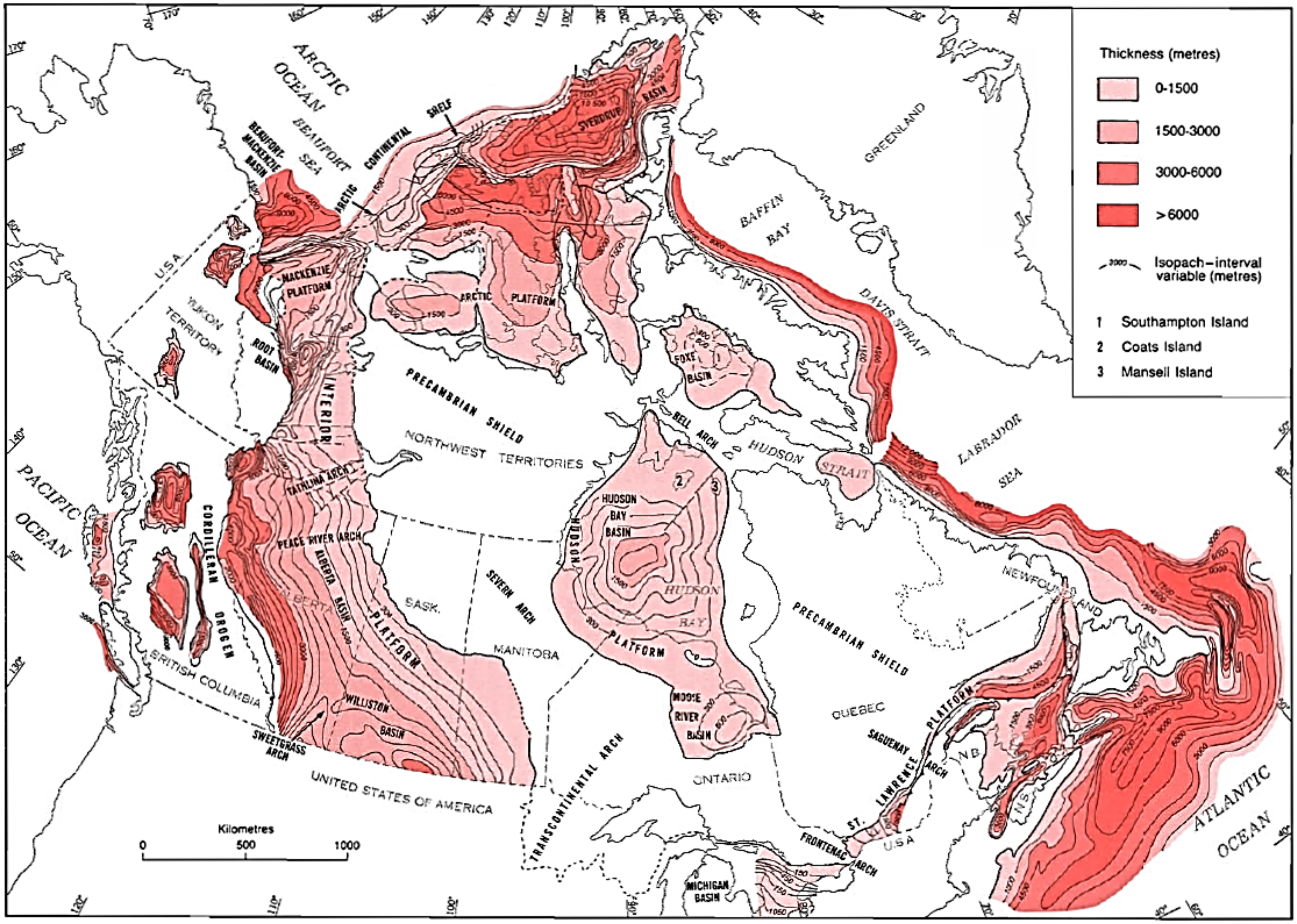

Figure 7. Location and thicknesses of the sedimentary basins in Canada, (from [14])

5. New Earth conductivity models for several observatories

Later, in 2016, several models were updated based on the latest available publications. As well, several changes were made in the geomagnetic observatory network, i.e two observatories were closed and moved to new locations, such as: GLN has been closed and BRD observatory opened, as well PBQ has been closed and SNK has been opened instead.

These new models are shown in Table 5 with the detailed descriptions and references located in Appendix 2. For completeness, the models which were not updated are placed in Table 6.

Table 5. New models for several observatories:

BRD		**FCC**		**SNK**		**BLC**	
Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)
70	0.033	40	0.033	40	0.033	10	0.01
930	0.04	450	0.02	250	0.02	200	0.02
12000	0.00022	14650	0.0001	12750	0.00006	11800	$0.2\cdot10^{-4}$
27000	0.00153	10000	0.00003	13000	0.00021	13000	$0.4\cdot10^{-4}$
28000	0.00033	18000	0.00004	13000	0.00017	13000	$2\cdot10^{-4}$
52000	0.0004	57000	0.0002	62000	0.0004	62000	$1.25\cdot10^{-4}$
$15\cdot10^4$	0.00478	$15\cdot10^4$	0.00478	$15\cdot10^4$	0.00478	$10\cdot10^4$	$5\cdot10^{-4}$
$16\cdot10^4$	0.02	$16\cdot10^4$	0.02	$16\cdot10^4$	0.02	$5\cdot10^4$	0.0044
$11\cdot10^4$	0.05	$11\cdot10^4$	0.05	$11\cdot10^4$	0.05	$16\cdot10^4$	0.02
$15\cdot10^4$	0.178	$15\cdot10^4$	0.178	$15\cdot10^4$	0.178	$11\cdot10^4$	0.05
$23\cdot10^4$	0.633	$23\cdot10^4$	0.633	$23\cdot10^4$	0.633	$15\cdot10^4$	0.178
$10\cdot10^4$	0.893	$10\cdot10^4$	0.893	$10\cdot10^4$	0.893	$23\cdot10^4$	0.633
						$10\cdot10^4$	0.893

IQA		**MEA**		**OTT**		**STJ**		**VIC**	
Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)
10	0.008	50	0.028	26	0.02	8	0.01	25	0.033
100	0.02	2000	0.1	900	0.004	3000	0.033	1000	0.04
1800	0.02	9000	0.0013	9100	0.0002	9000	$3.7\cdot10^{-4}$	8500	0.0016
1175	0.04	15000	0.0013	15000	0.01	11000	0.04	10500	0.0032
12000	0.0001	15000	0.0016	15000	0.005	11000	0.067	$1\cdot10^4$	0.011
13000	0.00625	61000	0.0018	$6\cdot10^4$	0.004	66000	0.05	$7\cdot10^4$	0.005
15000	$62.5\cdot10^{-4}$	$15\cdot10^4$	$26.6\cdot10^{-4}$	$10\cdot10^4$	0.0063	$15\cdot10^4$	0.0063	$5\cdot10^4$	0.0043
$6\cdot10^4$	$6.25\cdot10^{-4}$	$16\cdot10^4$	0.02	$16\cdot10^4$	0.035	$16\cdot10^4$	0.035	$10\cdot10^4$	0.005
$15\cdot10^4$	0.00478	$11\cdot10^4$	0.05	$11\cdot10^4$	0.125	$11\cdot10^4$	0.125	$16\cdot10^4$	0.025
$16\cdot10^4$	0.02	$15\cdot10^4$	0.178	$15\cdot10^4$	0.42	$15\cdot10^4$	0.42	$11\cdot10^4$	0.09
$11\cdot10^4$	0.05	$23\cdot10^4$	0.633	$23\cdot10^4$	0.89	$23\cdot10^4$	0.89	$15\cdot10^4$	0.5
$15\cdot10^4$	0.178	$10\cdot10^4$	0.893	$10\cdot10^4$	2.09	$10\cdot10^4$	2.09	$23\cdot10^4$	0.82
$23\cdot10^4$	0.633							$10\cdot10^4$	2.09
$10\cdot10^4$	0.893								

Table 6.Models which were not changed, the bottom layer has been adjusted for consistency

RES		**CBB, YKC**		**ALE, PBQ**		**GLN**	
Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)	Thickn (m)	Cond (S/m)
$4.5\cdot10^{3}$	0.01	300	0.01	$1.5\cdot10^{4}$	$5\cdot10^{-5}$	20	0.05
$1.05\cdot10^{4}$	$1\cdot10^{-4}$	$1.47\cdot10^{4}$	$1\cdot10^{-4}$	$1\cdot10^{4}$	$5\cdot10^{-3}$	180	0.01
$1.0\cdot10^{4}$	$3.33\cdot10^{-3}$	$1\cdot10^{4}$	$3.33\cdot10^{-3}$	$1.25\cdot10^{5}$	$1\cdot10^{-3}$	$1.48\cdot10^{4}$	$2.5\cdot10^{-5}$
$7.5\cdot10^{4}$	$1\cdot10^{-3}$	$7.5\cdot10^{4}$	$1\cdot10^{-3}$	$2.0\cdot10^{5}$	0.01	$1\cdot10^{4}$	$5\cdot10^{-4}$
$3\cdot10^{5}$	0.01	$3\cdot10^{5}$	0.01	$1\cdot10^{5}$	2.09	$7.5\cdot10^{4}$	$1\cdot10^{-3}$
$2\cdot10^{5}$	0.1	$2\cdot10^{5}$	0.1			$3\cdot10^{5}$	0.01
$1\cdot10^{5}$	2.09	$1\cdot10^{5}$	2.09			$2\cdot10^{5}$	0.1
						$1\cdot10^{5}$	2.09

6. Comparisons of the surface impedance models.

In general, when the conductivities in new model are higher than in the old model, the surface impedance of the new model should be lower than the old one (as per formulas (5)-(8)). At the same time, if at a given frequency and for a given conductivity the skin-depth (see formula (13) below) is much larger than the thickness of the layer, this layer will not be "seen" by this frequency. Comparisons of the old and new models are presented for the frequency domain in following plots (Figures 8-16). Left side figures are the amplitudes and phases of the surface impedances, right side figures are supplemental plots of the layered earth models for better understanding of the left plots. As can be seen from Figure 8, left plots, the amplitude of surface impedance in the new model is higher than in the old model, which should correspond to the case when conductivities of each layer to be less than for old model. At the same time, the top layer of new model has higher conductivity (right plot), which should correspond to lower surface impedance. But, because this top layer, with thickness of only 200 m, is too thin to be "seen" at frequencies from 10^{-5} to 10^{-2} Hz (Table 7), it does not affect the surface impedance and overall, the new model gives higher amplitude of impedance than the old one.

$$\delta = \sqrt{1/\pi f \mu \sigma} \qquad (13)$$

where f is a frequency in Hz, $\mu=\mu_0=4\pi\cdot10^{-7}$ is a magnetic permeability of free space in H/m, σ is the layer conductivity in S/m.

Table 7. Skin-depth for several frequencies (vertical) and conductivities (horizontal) values

σ, S/m	$5\cdot10^{-5}$ S/m	$1\cdot10^{-4}$ S/m	$5\cdot10^{-4}$S/m	$1\cdot10^{-3}$ S/m	$5\cdot10^{-3}$ S/m	$1\cdot10^{-2}$ S/m	$5\cdot10^{-2}$ S/m
Freq	Skin-depth, meters						
10^{-5}Hz	$2.23\cdot10^{7}$	$1.58\cdot10^{7}$	$7.1\cdot10^{6}$	$4.99\cdot10^{6}$	$2.2\cdot10^{6}$	$1.58\cdot10^{6}$	$7.1\cdot10^{5}$
10^{-4}Hz	$7.1\cdot10^{6}$	$4.99\cdot10^{6}$	$2.23\cdot10^{6}$	$1.58\cdot10^{6}$	$7.1\cdot10^{5}$	$4.99\cdot10^{5}$	$2.2\cdot10^{5}$
10^{-3}Hz	$2.23\cdot10^{6}$	$1.58\cdot10^{6}$	$7.1\cdot10^{5}$	$4.99\cdot10^{5}$	$2.2\cdot10^{5}$	$1.58\cdot10^{5}$	$7.1\cdot10^{4}$
10^{-2}Hz	$7.1\cdot10^{5}$	$4.99\cdot10^{5}$	$2.2\cdot10^{5}$	$1.58\cdot10^{5}$	$7.1\cdot10^{4}$	$4.99\cdot10^{4}$	$2.2\cdot10^{4}$

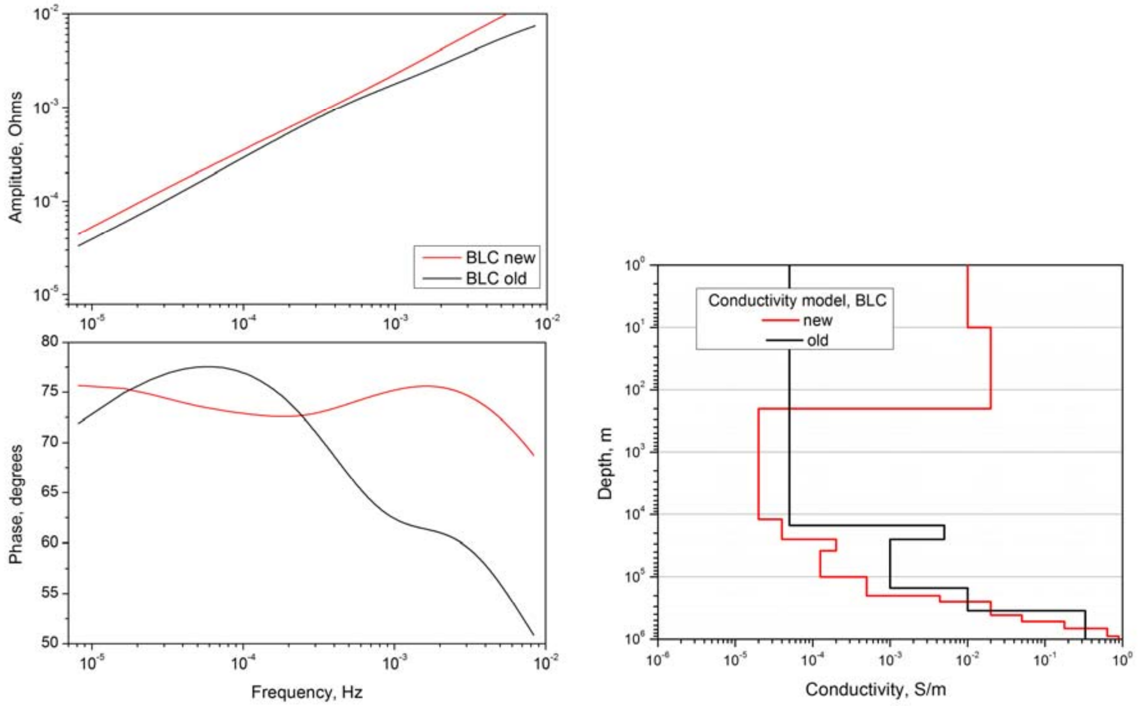

Figure 8. Baker Lake Observatory. Left-surface impedance, right-layered earth model

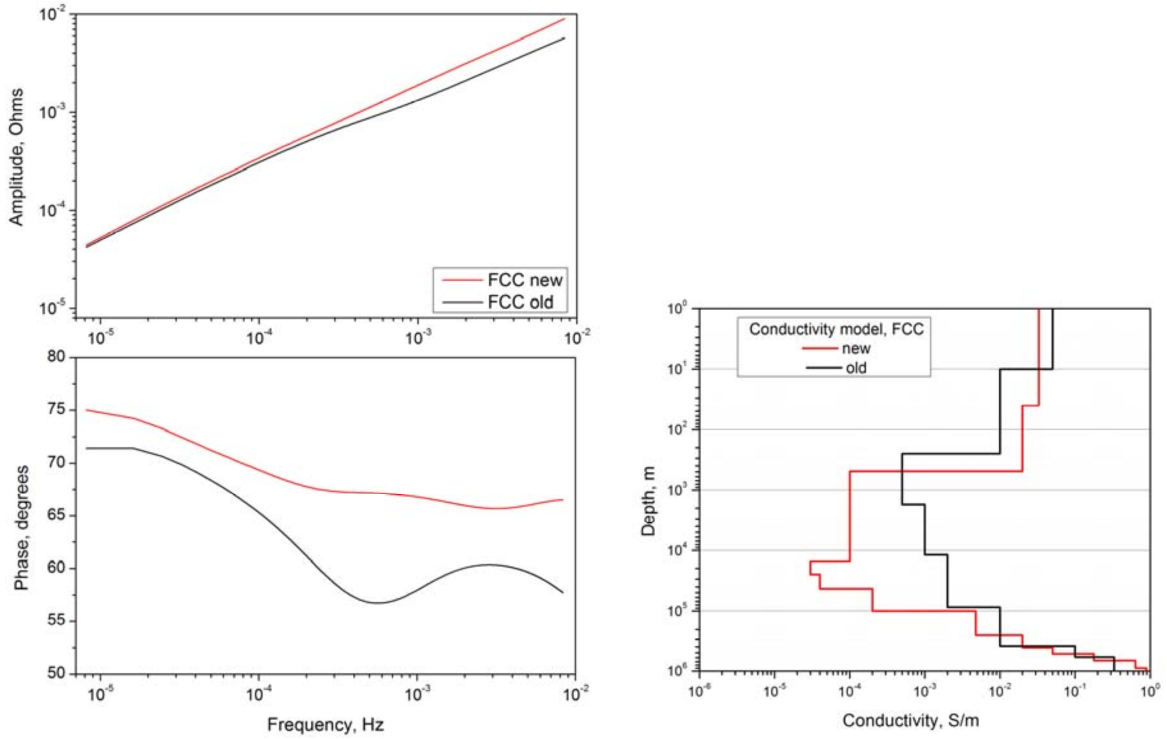

Figure 9. Fort Churchill Observatory. Left-surface impedance, right-layered earth model

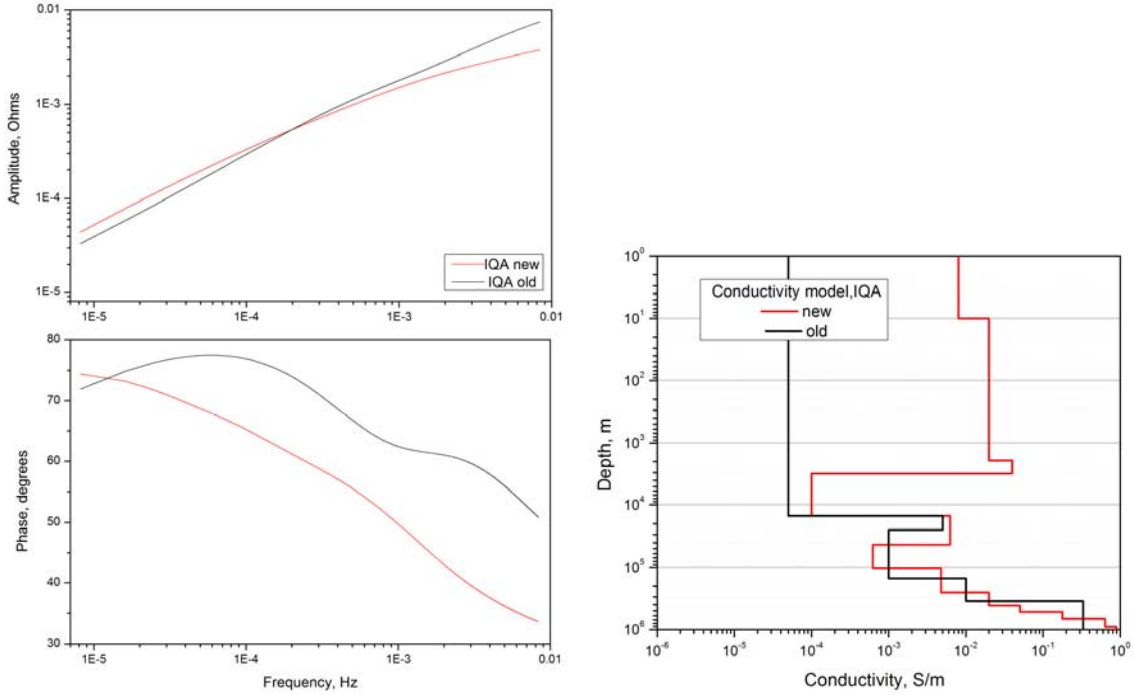

Figure 10. Iqaluit Observatory. Left-surface impedance, right-layered earth model

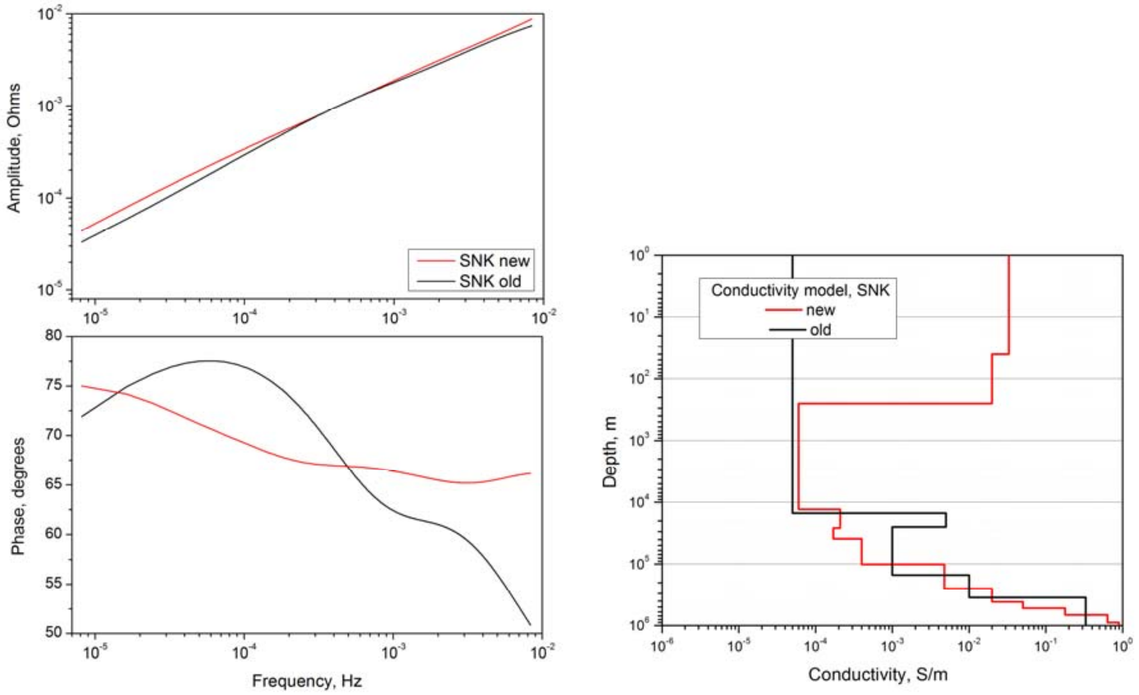

Figure 11. Sanikiluiak Observatory. Left-surface impedance, right-layered earth model

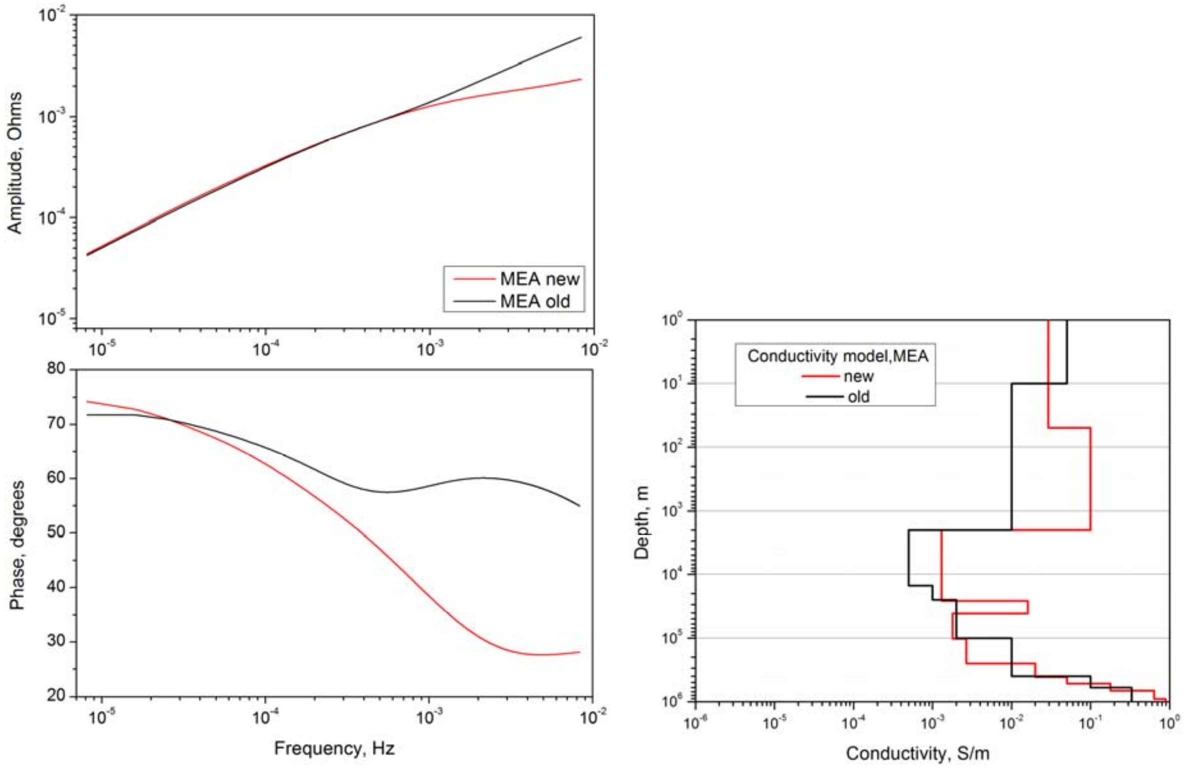

Figure 12. Meanook Observatory. Left-surface impedance, right-layered earth model

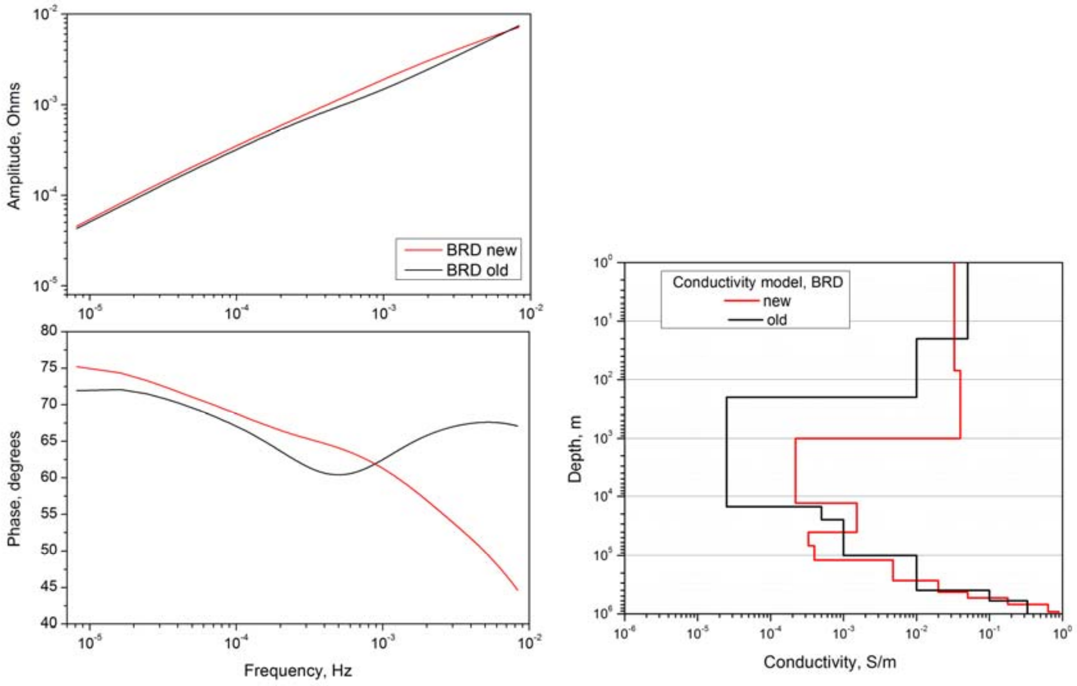

Figure 13. Brandon Observatory. Left-surface impedance, right-layered earth model

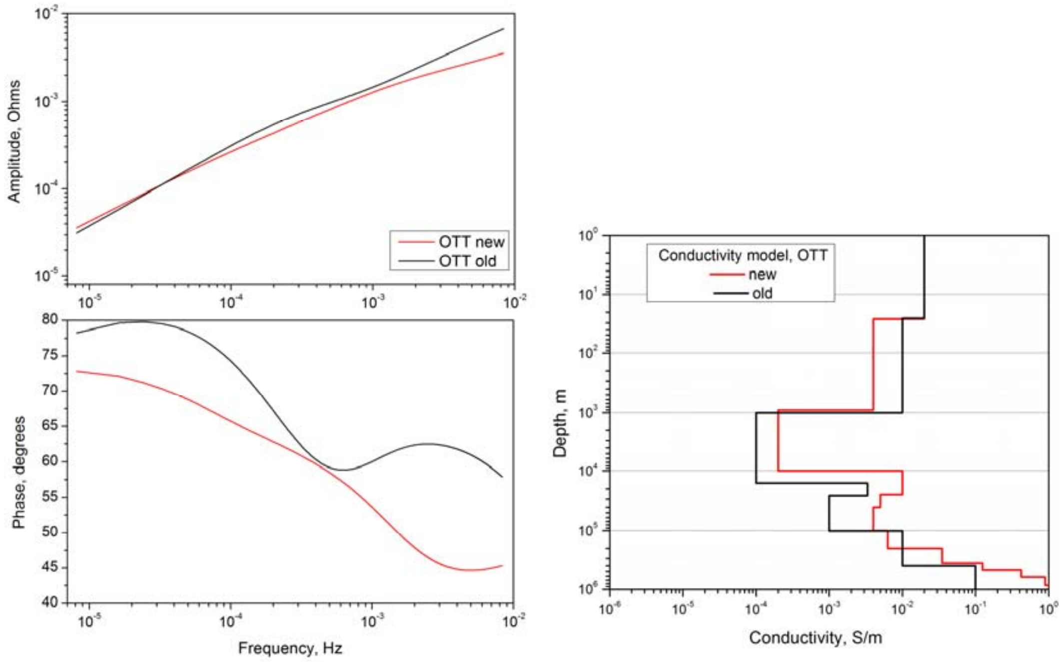

Figure 14. Ottawa Observatory. Left-surface impedance, right-layered earth model

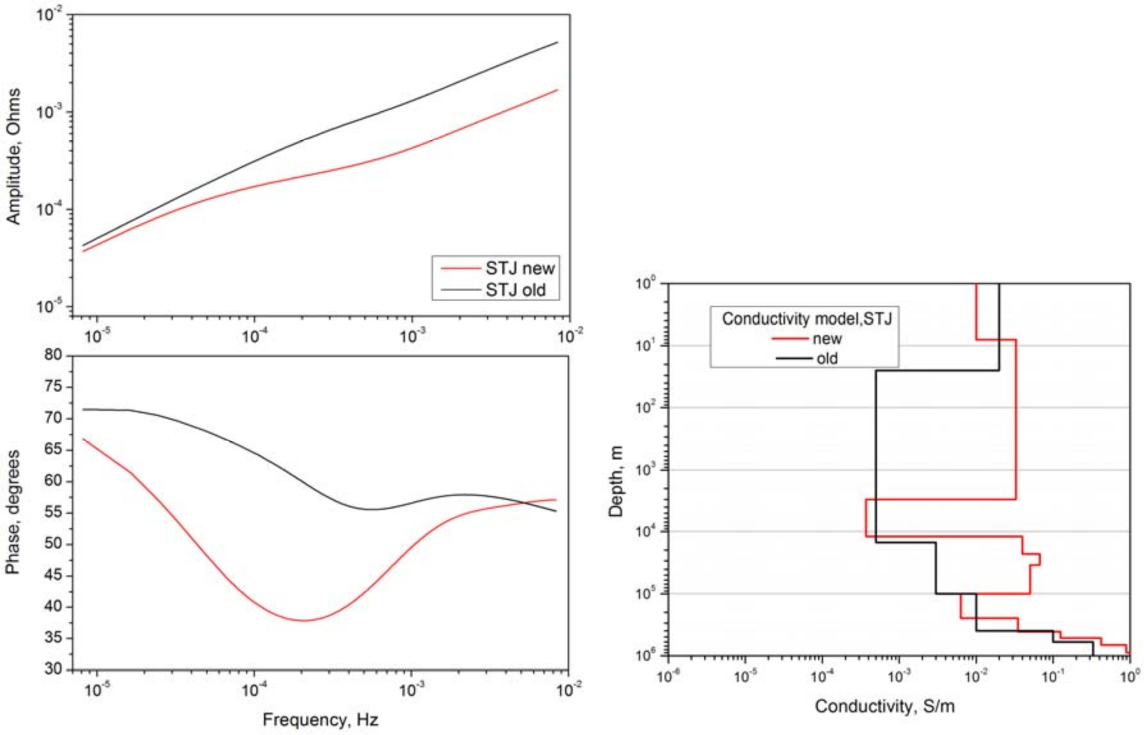

Figure 15. St. John's Observatory. Left-surface impedance, right-layered earth model

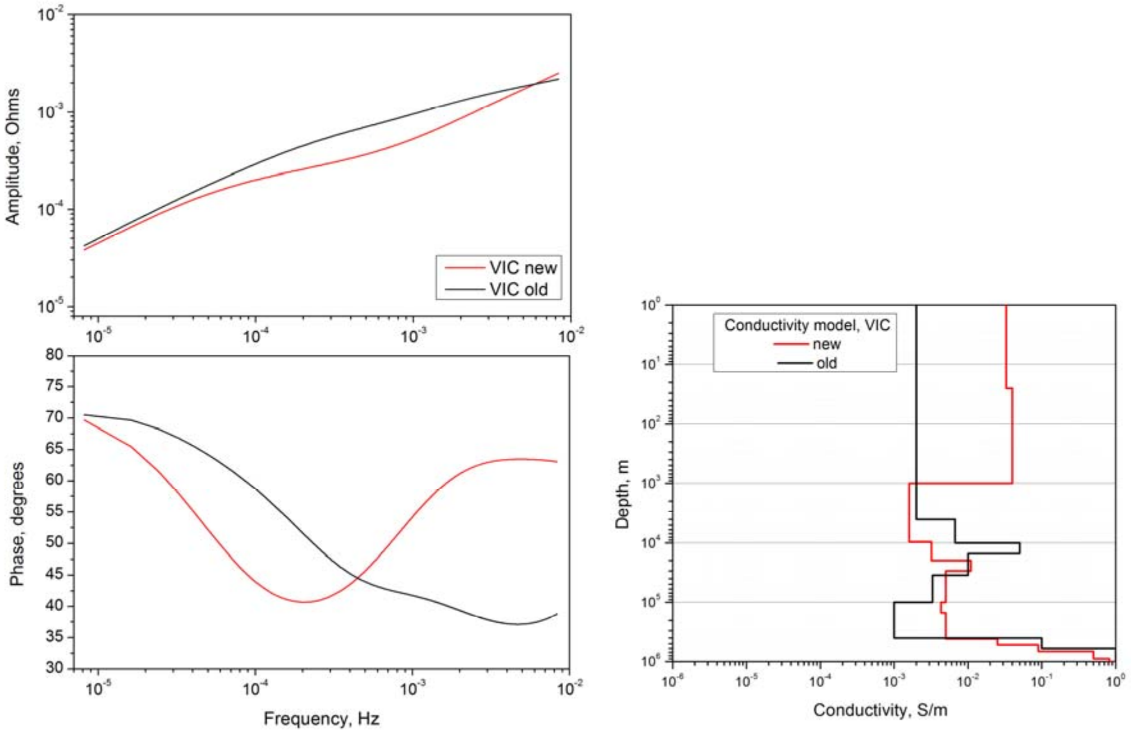

Figure 16. Victoria Observatory. Left-surface impedance, right-layered earth model

7. Comparison of modelled geoelectric field variations

New surface impedance models were introduced in the previous part and compared with the old ones. Application of these new models to the geoelectric field modelling will give different values of geoelectric field variation comparing with the results obtained with the use of old models. In order to illustrate this, the results of modelling for several geomagnetic observatories were compared for one specific day, 29 October 2003 (so-called Halloween Space Weather event, identified as one of the largest in the solar cycles 23 and 24), and are presented below in Figures 17-20.

The low latitude observatories were chosen because these locations have higher density of the critical infrastructure and, therefore, are more frequently used for incorporating modelled geoelectric field variations into GIC models, for example for assessment of GIC in Alberta (MEA, Fig. 17), Ontario (OTT, Fig. 18), British Columbia (VIC, Fig. 19) and Newfoundland (St. John’s, Fig. 20).

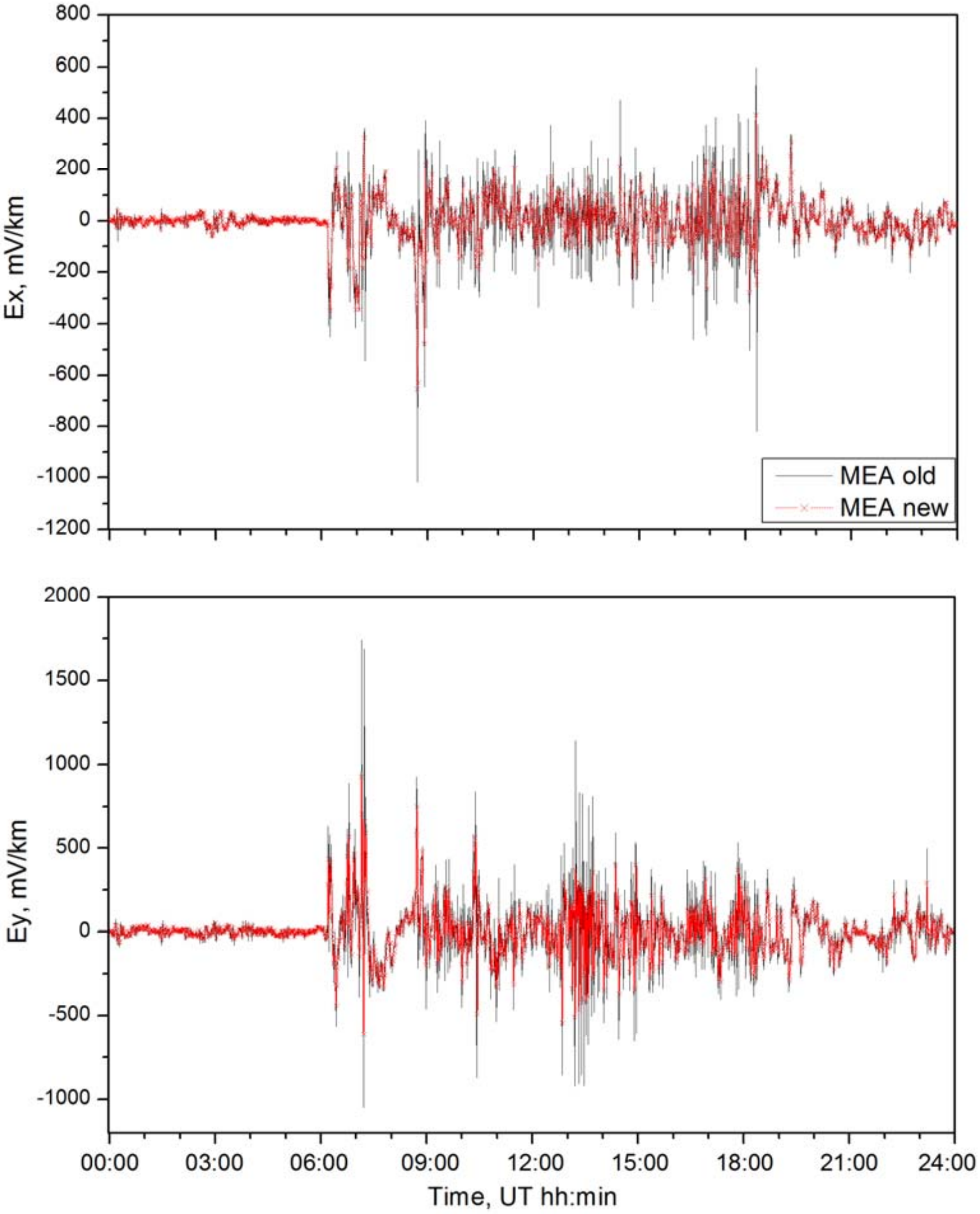

Figure 17. Modelled electric field for Meanook Observatory during space weather event of October 29, 2003. Top: X-component, bottom: Y-component.

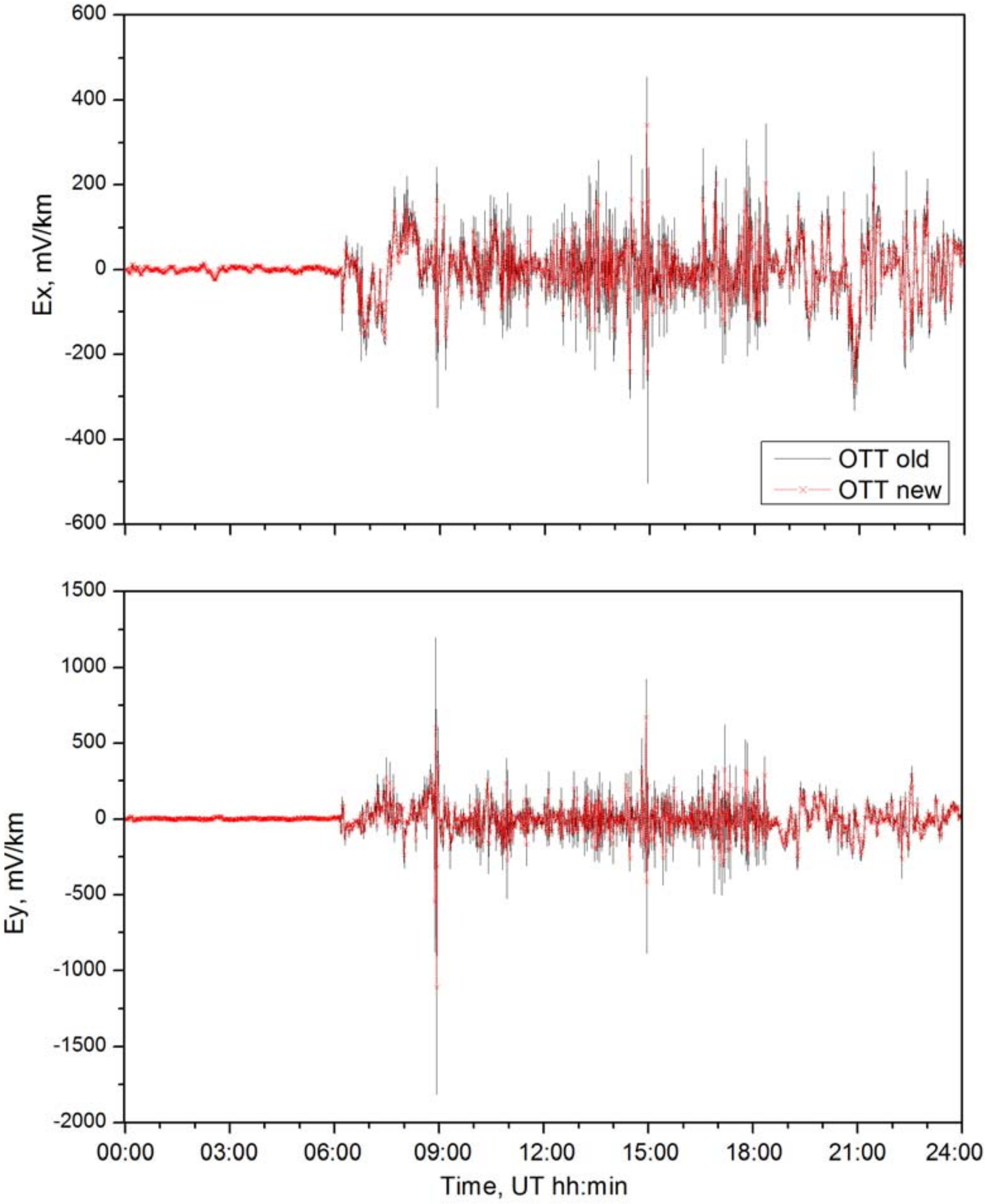

Figure 18. Modelled electric field for Ottawa Observatory during space weather event of October 29, 2003. Top: X-component, bottom: Y-component.

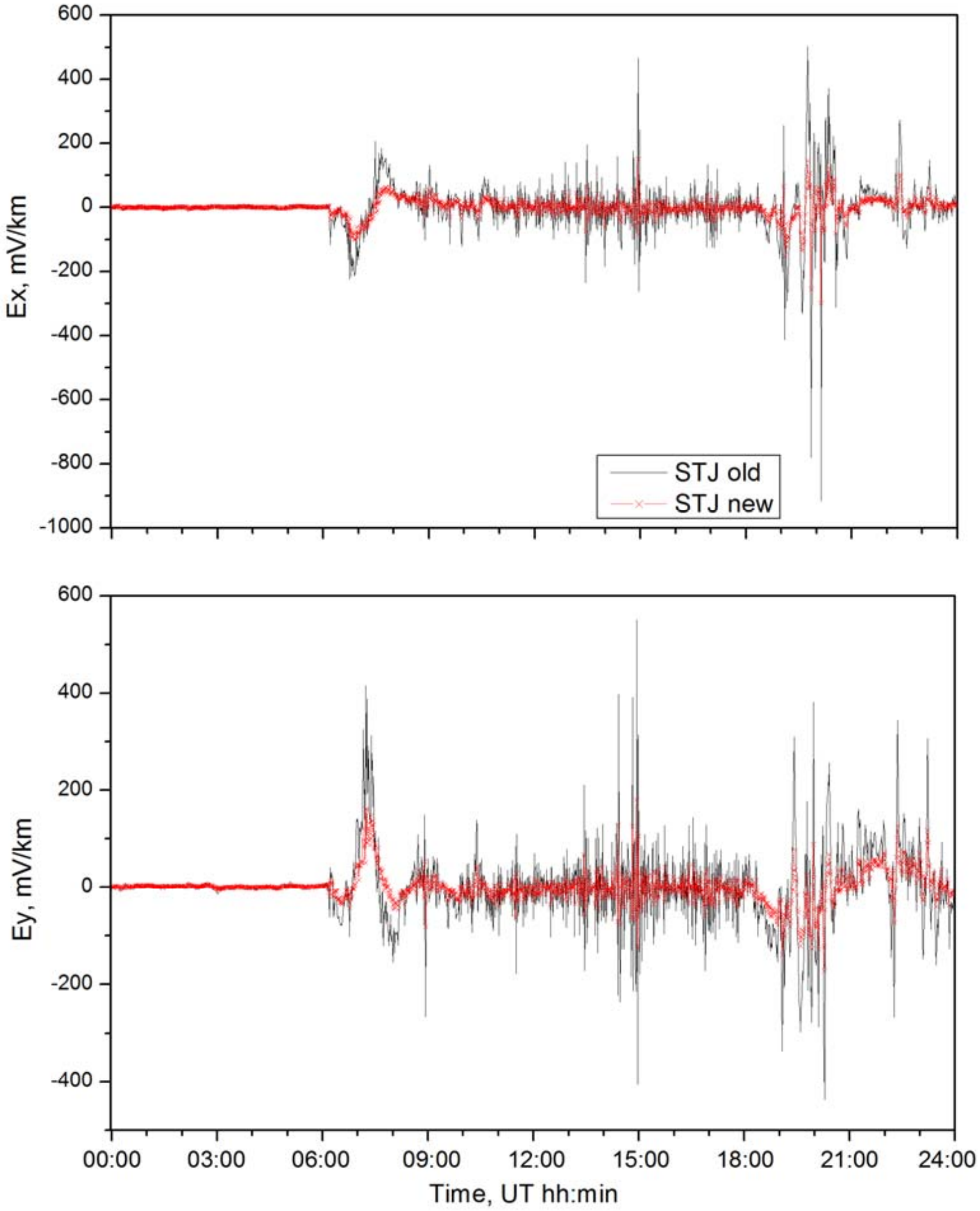

Figure 19. Modelled electric field for St. John's Observatory during space weather event of October 29, 2003. Top: X-component, bottom: Y-component

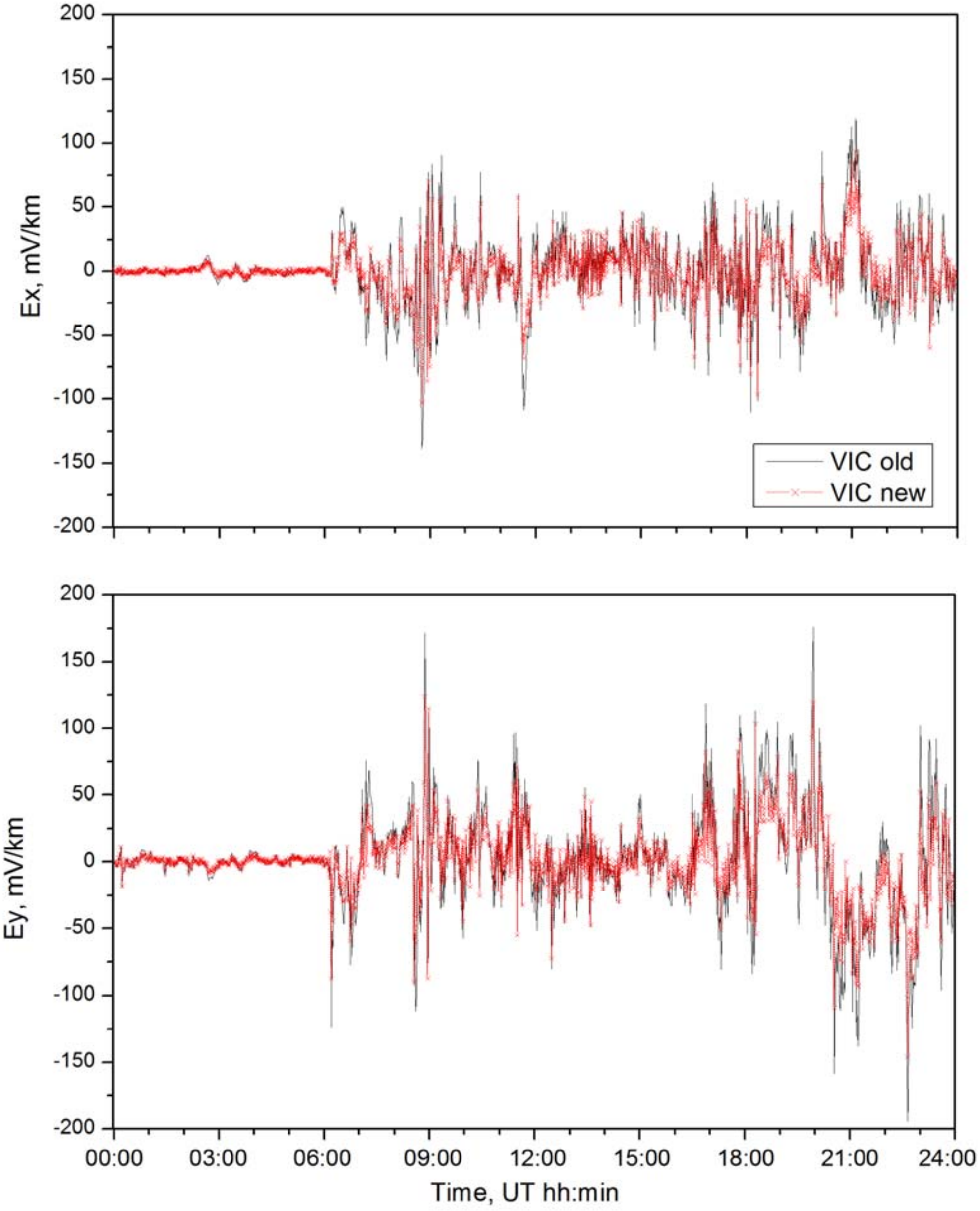

Figure 20. Modelled electric field for Victoria Observatory during space weather event of October 29, 2003. Top: X-component, bottom: Y-component.

It is clearly seen from the above figures, that for the most of the disturbed time during the day of 29 October 2003, i.e. after 06:00 UT, the geoelectric field calculated with use of the new layered Earth models are lower than geoelectric field calculated with the old models. This is consistent with the plots of the surface impedance for the relevant observatories, showing the new impedances are smaller in amplitude than the old ones (i.e. Figs. 12, 14-16).

Conclusions:

The NRCan on-line service allows calculations of the geoelectric field in the vicinity of each geomagnetic observatory (http://www.geomag.nrcan.gc.ca/index-en.php or http://www.geomag.nrcan.gc.ca/index-fr.php). It incorporates the simple plane wave modelling approach with surface impedances calculated from 1-D Earth resistivity models (layered Earth model). The list of models used in the on-line service with all details is provided. Several of them were updated and the new layered earth models are compared with the old ones. For most of them the differences are seen only in the high frequency part (i.e. OTT, MEA), or not significant (BRD, VIC, FCC, IQA, SNK, BLC). The exception is the layered earth model for STJ observatory, where the differences between new and old are quite significant practically over the whole frequency range.

Geoelectric field variations were calculated for 29 October 2003 (Halloween storm) with application of “new” and “old” models at several locations where the population in Canada is more dense and therefore the more dense the impacted infrastructure, such as power grids and pipelines. The results confirm that at the time of large high frequency fluctuations difference due to different earth models are significant (from 1.5 times for MEA, OTT, VIC, up to 300%,for STJ). The recommendation is, therefore, to validate the layered earth models by conducting MT surveys in the vicinity of the observatories.

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Appendix 1

Computer Codes
for
calculating the surface impedance and geoelectric field

L. Trichtchenko and D. Danskin

Table of Contents

A1.1. Code for surface impedance calculations (FORTRAN)

Below is the FORTRAN Code used off-line to calculate the surface impedance for a single observatory. Input data are daily files of XYZ components of the geomagnetic field for observatory at 1 minute sampling rate in INTERMAGNET format. Outputs two columns which represent real and imaginary parts of the surface impedance for this observatory and serve as “coefficients” for calculations of the geoelectric field (see Part 1.2 for the computer code).

```
C Calculations of real (ZR) and imaginary (ZI) parts of surface
impedance ZZ (i) for use with 1 day, 1min. INTERMAGNET data

C parameter npoint is power of 2 for FFT, agrees with size of the data
array, where d is thickness, sigma is conductivity of layers, see
formulas (6)-(8) of the report for details.

      parameter  (npoint=2**11)
      character*128 fileOUT
       REAL d(12),sigma(12) !should correspond to a number of layers
      REAL ZR(npoint),ZI(npoint),F(npoint)
      COMPLEX C(12) !should correspond to number of layers
      COMPLEX ZZ(npoint)


C Calculations of the surface impedance for new Ottawa model

C OTT model
     data
     d/26.,900.,9.1E3,1.5E4,15E3,60E3,10E4,16E4,11E4,15E4,23E4,10E4/
     data
     sigma/0.02,4E-3,2E-4,0.01,5E-3,4E-3,6.3E-3,3.5E-2,
     &0.125,0.42,0.89,2.09/
     N=12

C dt is Data sampling rate in sec
       dt=60.
      PI=acos(-1.0)
       TOPI=2.*PI
      do i=1, npoint
      F(i)=SNGL(i)/npoint/dt
      end do
      np2=npoint/2
C only half of interval needed, the other half is to be constructed in
C to become even (real) and odd (imaginary) functions in next code)

       do i=1,np2
        OMG=TOPI*F(i)
        call layered_Earth(sigma,d,OMG,N,c)
```

```
        ZZ(i)=(0.,1.)*OMG*c(1)*4.e-7*PI  !in Ohm
        ZR(i)=REAL(ZZ(i))
        ZI(i)=AIMAG(ZZ(i)) ! not inverted

       end do
C Output into file specified below:
      fileOUT='C:\Documents and Settings\Larisa\Desktop\Zonline
     &\OTT_1min.dat'
       open(unit=2,file=fileOUT)
C     read(2,*)
      write(2,'(a)') 'freq, Zreal, Zimag'

      do i=1,np2
      write(2,100) f(i),ZR(i), ZI(i)
C     write(2,100) f(i),ABS(ZZ(i)),ATAN(ZI(i)/ZR(i))*180./PI

 100   format(3(1X,E12.5))
      end do

222   continue
       stop
       end


       subroutine layered_Earth(sigma,d,omega,N,C)
! input parameters
!        sigma(N) - array of layer's conductivity
!        d(N) - layers depth
!        omega - external frequency
!        rnu - wavenumber=0 for plane wave case
!        N - number of layers (dimension of arrays)
!  output parameters
!        c1 - skin-depth of the 1-st layer (surface)
         real d(N),sigma(N)
         complex c(n),alpha2,gamma2,R,gamma
        PI=acos(-1.0)
        rnu=0. ! plane wave case
         Rmu0=4.0*pi*1E-7
         gamma2=Rnu*Rnu+(0.,1.)*omega*Rmu0*Sigma(n)
         C(N)=1./CSQRT(gamma2)
         do i=N-1,1,-1
          Alpha2=omega*Rmu0*Sigma(i)
          gamma2=Rnu*Rnu+(0.,1.)*Alpha2
          gamma=CSQRT(gamma2)
          R=(1.-gamma*C(i+1))/(1.+gamma*C(i+1))
      C(i)=(1.-R*exp(-2.*gamma*d(i)))/gamma/(1.+R*exp(-2.*gamma*d(i)))
         end do

        return
        end
```

A1.2. Code for geoelectric field calculations (IDL)

In this code the "electric_field_coef" are the surface impedance values obtained by the previous code

```
@find_data_files.pro
@message.pro
@utils.pro
@read_iaga.pro

pro LINTRND,dat,length,n_edge
;	remove the linear trend ,i.e.line between average n_edge points
;	in the beginning and end of datafile
;	ensure that zero padding at the end of the array is still maintained

	if length le n_edge then stop,'LINTRND:length<n_edge'
	if length le 10 then stop,'LINTRND:length<10'
	avb = mean(dat(0:n_edge-1))
	ave = mean(dat(length-n_edge:length-1))
	slope = (ave-avb)/(length-1.0)
	dat(0:length-1) = dat(0:length-1) - (avb+slope*findgen(length))
end

pro TAPER,dat,nsize,nw
	; cosine taper the ends of the data of length nsize
	; number of tapered points is controlled by nw

	if nsize le nw then stop,'TAPER: size < nwindow'
	if nsize le 10 then stop,'TAPER: size < 10'
	index = indgen(nw)
	indexk = reverse(nsize-index-1)
	DAT(index) = DAT(index)*0.5*(1.0+cos(!pi*(nw-index-1.0)/(nw-1.0)))
	DAT(indexk) = DAT(indexk)*0.5*(1.0-cos(!pi*(nw-index-1.0)/(nw-1.0)))
end

pro interp_bad_points,bvalue,b_bad,num
	if num gt 0 then for i=0,num-1 do begin
		index = b_bad(i)
		if index gt 0 then if bvalue(index-1) lt 40000 then begin
			low_value = bvalue(index-1)
			index_l = index-1
		endif
```

```
                n_value = n_elements(bvalue)-1
                while(bvalue(index) gt 40000 and index lt n_value) do index=index+1
                if index ne n_value then u_value = bvalue(index) else u_value = low_value
                if b_bad(i) eq 0 then begin
                        low_value = u_value
                        index_l = 0
                endif
                bvalue(b_bad(i))=(u_value - low_value)/(1.0*index-1.0*index_l)* $
                                (1.0*b_bad(i)-1.0*index_l) + low_value
        endfor
end

pro read_impedance,fileINz,npoint,Z
        ;READ IMPEDANCE DATA and calculate electric field in frequency domain
        catch, bad_file
        if bad_file ne 0 then exit,status=51

        openr,2,fileINz
        st = ''
        readf,2,st
        zr = fltarr(npoint)
        zi = zr
        f = zr
        for i=0,npoint-1 do begin
                readf,2,fi,zri,zii,format='(3(1x,e12.5))'
                f(i) = fi
                zr(i) = zri
                zi(i) = zii
        endfor
        close,2
        catch,/cancel
        Z = complex(zr,zi)
end

pro make_output_file,tt,etx,ety,outfile,yr,mn,dy,doy,lat,lon,site

        out_path = 'output_files/'
        catch, bad_file
        if bad_file ne 0 then exit,status=101

        openw,lun,out_path+strtrim(outfile,2)+'.txt',/get_lun
        printf,lun,yr,mn,dy,doy,lat,lon,site,$
                format='(i4,1x,i2,1x,i2,1x,i3," lat= ",f7.2," long= ",f7.2," site= ",a3)'
        printf,lun,'UT (min)   Ex(mV/km) Ey (mV/km)'
        n = n_elements(tt)-1
        for i=0,n do printf,lun,round(tt(i)*60),etx(i),ety(i), format='(i6,1x,f10.2,1x,f10.2)'
```

```
	free_lun,lun

	catch,/cancel
end


pro E_online1, fileINmag, fileINz
,s_hr,e_hr,AUTOSCALE=autoscale,FRENCH=french,OUTFILE=outfile
; Fourier Transform of Bx data
; tapering, padding with 0-s, reading Z from W-drive, multiplication
; and inverse transform in the form of E for one day,
; Using 1min. INTERMAGNET data and precalculated Z
	read_iaga,fileINmag,tt,bx,by,bz,bf,yr,mn,dy,doy,lat,lon,site
	b = where(bx lt 90000 and by lt 90000,num)
	if num eq 0 then begin
		no_data_to_plot,FRENCH=french
		return
	endif
	bx_bad = where(bx gt 40000 or by gt 40000,num)
	by_bad = bx_bad
	interp_bad_points,bx,bx_bad,num
	interp_bad_points,by,by_bad,num

	npoint = 2048
	nvals = 1440

	DATAX1 = FLTARR(npoint)
	DATAY1 = DATAX1
	DATAX1(0:nvals-1) = bx
	DATAY1(0:nvals-1) = by

	; calculate mean of the data values
	DATAX1(0:nvals-1) = DATAX1(0:nvals-1)-MEAN(DATAX1(0:nvals-1))
	DATAY1(0:nvals-1) = DATAY1(0:nvals-1)-MEAN(DATAY1(0:nvals-1))

	; Remove the linear trend
	n_edge = 10
	LINTRND,DATAX1,nvals,n_edge
	LINTRND,DATAY1,nvals,n_edge

	; Tapering the data
	TAPER,DATAX1,nvals,10
	TAPER,DATAY1,nvals,10

	read_impedance,fileINz,npoint,Z
```

```
; Fourier transform data, apply filter and inverse FFt
TOPI = 2.0*!PI
ETY = fft(-Z*fft(DATAX1,-1)*(1.0E6/(TOPI*200.0)),1)
ETX = fft(Z*fft(DATAY1,-1)*(1.0E6/(TOPI*200.0)),1)
ETY = float(ETY(0:nvals-1))
ETX = float(ETX(0:nvals-1))

; sub in flag for bad values
if num gt 0 then begin
        ETY(bx_bad) = 99999.0
        ETX(by_bad) = 99999.0
endif

ll = s_hr & ul = e_hr

b_good = where(tt ge ll and tt lt ul and etx lt 90000 and ety lt 90000,num_g)
if num_g eq 0 then begin     ; no data to plot which is value
        no_data_to_plot,FRENCH=french
        return
endif
if keyword_set(outfile) then begin     ; create download text files
        b_wr = where(tt ge ll and tt lt ul)
        make_output_file,tt(b_wr),etx(b_wr),ety(b_wr),outfile, $
                yr,mn,dy,doy,lat,lon,site
endif

common my_font, def_font, mean_lbl_size, c_size
c_size = c_size *0.5
many_plot_1,pos_y,2,.01
setup_xaxis,ll,ul
if keyword_set(french) then xtitle="heure, TU" else xtitle="Time, UT"

mean_etx = mean(etx(b_good))
mean_ety = mean(ety(b_good))
col = 32
bad_col = 200
if KEYWORD_SET(autoscale) then begin
        std_y = stdev(etx(b_good))
        !y.range=[-5,5]*std_y
        plot,tt(b_good),etx(b_good),position=pos_y(0,*), $

title=def_font+file_name_decode(FILE_BASENAME(fileINmag),FRENCH=french),$
                /nodata,charsize=c_size
        xyouts,0,(pos_y(0,1)+pos_y(0,3))/2.0,' E!Bx!N!C!C(mV/km)',/normal,$
                charsize=mean_lbl_size
        oplot,tt,etx,max_value=90000,color=col
```

```
;       if num gt 0 then oplot,tt(bx_bad),fltarr(n_elements(bx_bad)),$
;           psym=1,color=bad_col,symsize=0.5

        !x.tickname=" ; label x axis and ticks
        std_y = stdev(ety(b_good))
        !y.range=[-5,5]*std_y
        plot,tt(b_good),ety(b_good),position=pos_y(1,*),xtitle=xtitle,/nodata,$
            charsize=c_size
        xyouts,0,(pos_y(1,1)+pos_y(1,3))/2.0,' E!By!N!C!C(mV/km)',/normal,$
            charsize=mean_lbl_size
        oplot,tt,ety,max_value=90000,color=col
;       if num gt 0 then oplot,tt(bx_bad),fltarr(n_elements(bx_bad)), $
;           psym=1,color=bad_col,symsize=0.5
    endif else begin
        max_x = max(etx(b_good)-mean_etx,min=min_x)
        max_y = max(ety(b_good)-mean_ety,min=min_y)
        max_scale = max([max_x,max_y])
        min_scale = min([min_x,min_y])
        !y.range = [min_scale,max_scale]
        plot,tt(b_good),etx(b_good),position=pos_y(0,*),charsize=c_size, $

    title=def_font+file_name_decode(FILE_BASENAME(fileINmag),FRENCH=french),/no
data
        xyouts,0,(pos_y(0,1)+pos_y(0,3))/2.0,' E!Bx!N!C!C(mV/km)',/normal,$
            charsize=mean_lbl_size
        oplot,tt,etx,max_value=90000,color=col
;       if num gt 0 then oplot,tt(bx_bad),fltarr(n_elements(bx_bad)), $
;           psym=1,color=bad_col,symsize=0.5

        !x.tickname=" ; label x axis and ticks
        plot,tt(b_good),ety(b_good),position=pos_y(1,*),xtitle=xtitle,/nodata,$
            charsize=c_size
        xyouts,0,(pos_y(1,1)+pos_y(1,3))/2.0,' E!By!N!C!C(mV/km)',/normal,$
            charsize=mean_lbl_size
        oplot,tt,ety,max_value=90000,color=col
;       if num gt 0 then oplot,tt(bx_bad),fltarr(n_elements(bx_bad)),$
;           psym=1,color=bad_col,symsize=0.5
    endelse
end

pro
E_online,year,month,day,obs,loc_dir,s_hr,e_hr,AUTOSCALE=autoscale,FRENCH=french,OUT
FILE=outfile
    ; for the web
    if n_params() lt 7 then exit,status=20
```

```
        coefpath="electric_field_coef"
        web_start

        ; Execute the program with all graphically output being caught in Z buffer
        ; check for valid site with parameter file
        allow_sites=['ALE','BLC','CBB','FCC','GLN','IQA','MEA','OTT','PBQ','RES',$
                'STJ','VIC','YKC']
        b = where( strupcase(obs) eq allow_sites,num)
        if num gt 0 then begin
          fileINz = coefpath+'/'+strupcase(obs)+'_Z_1min.dat'
          fileINmag = find_data_files(year,month,day,obs,loc_dir,FRENCH=french)
          if strlen(fileINmag) gt 3 then begin
                E_online1,fileINmag,fileINz,s_hr,e_hr,AUTOSCALE=autoscale, $
                        FRENCH=french,OUTFILE=outfile
          endif else begin
                no_file_found,FRENCH=french
          endelse
        endif else begin
          not_char_site,FRENCH=french
        endelse
        web_end,OUTFILE=outfile,FRENCH=french
        exit,status=10
end
```

Appendix 2
Updated 1D Earth Resistivity Models

for

Selected
Canadian Magnetic Observatories

P. A. Fernberg and L. Trichtchenko

Table of Contents

Summary

This Appendix presents one-dimensional (1D) Earth resistivity models for selected Canadian magnetic observatories. Individual self-contained chapters have been provided for each observatory. Each chapter includes a brief description of information sources utilized, geological setting, regional-scale conductive features, references and figures, as well as a graphic 1D block model and accompanying summary table. The block model shows the division of Earth's internal structure into separate layers (e.g. upper, middle and lower crust, upper mantle) showing the change of resistivity with depth. The associated summary table for each 1D model provides details on the information sources and justifications for the assigned conductivity/resistivity values and thicknesses for each layer in the model. The values presented for each 1D model are based on the author's judgement and interpretation using publically available information currently available and could conceivably change as a result of other interpretation or subsequent geophysical surveys. For some cases more than one model has been provided for a particular observatory.

The purpose of the 1D Earth resistivity models is to serve as an input into the calculation of the Earth's surface impedance. This is then used with geomagnetic data to calculate the geoelectric field; which, in turn, provides the input into a system model for calculating geomagnetically induced current in technological infrastructure, such as pipelines and high-voltage power transmission network.

The models are based on:

- Literature search and review of information for crustal-scale geophysical data pertinent to the area proximal to the magnetic observatory;
- Collection and review of pertinent geological information regarding type of overburden and bedrock;
- Compilation and assembly of crustal-to-mantle depths and electrical resistivity values into unique 1D models for each observatory;

The information search was limited to publicly available information from government geological surveys and articles from scientific journals. The search for MT-derived electrical resistivity profiles was limited to crustal scale transects.

A2.1. Brandon magnetic observatory, Manitoba

General

Presented below is a derivation of a 1D block model representing the vertical variance of electrical resistivity for an area around the Brandon magnetic observatory which location is shown in Figure A2.1.1.

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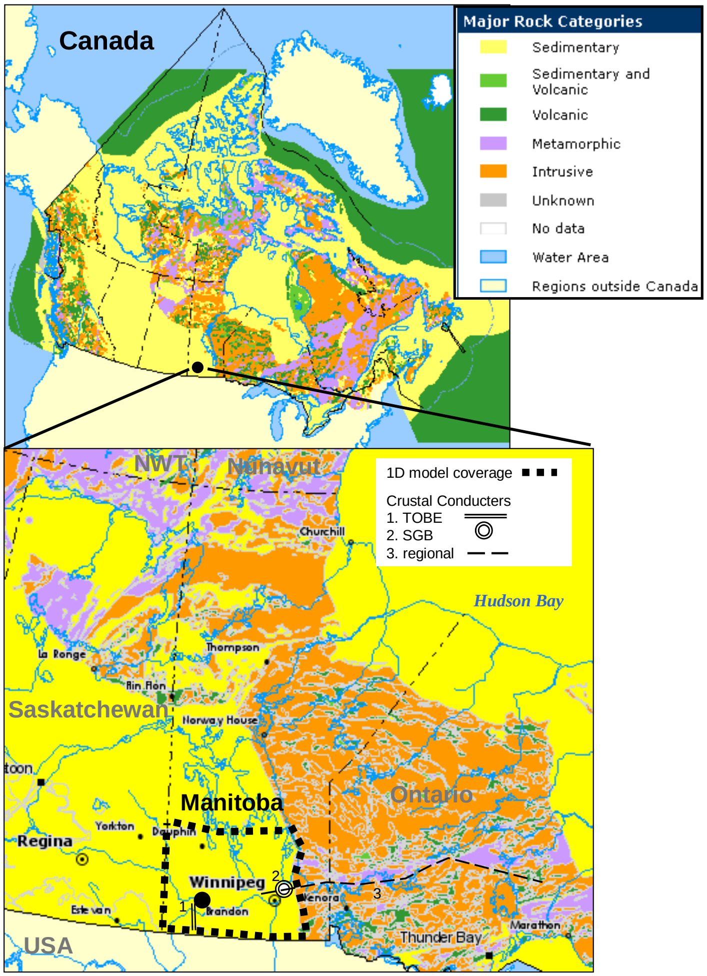
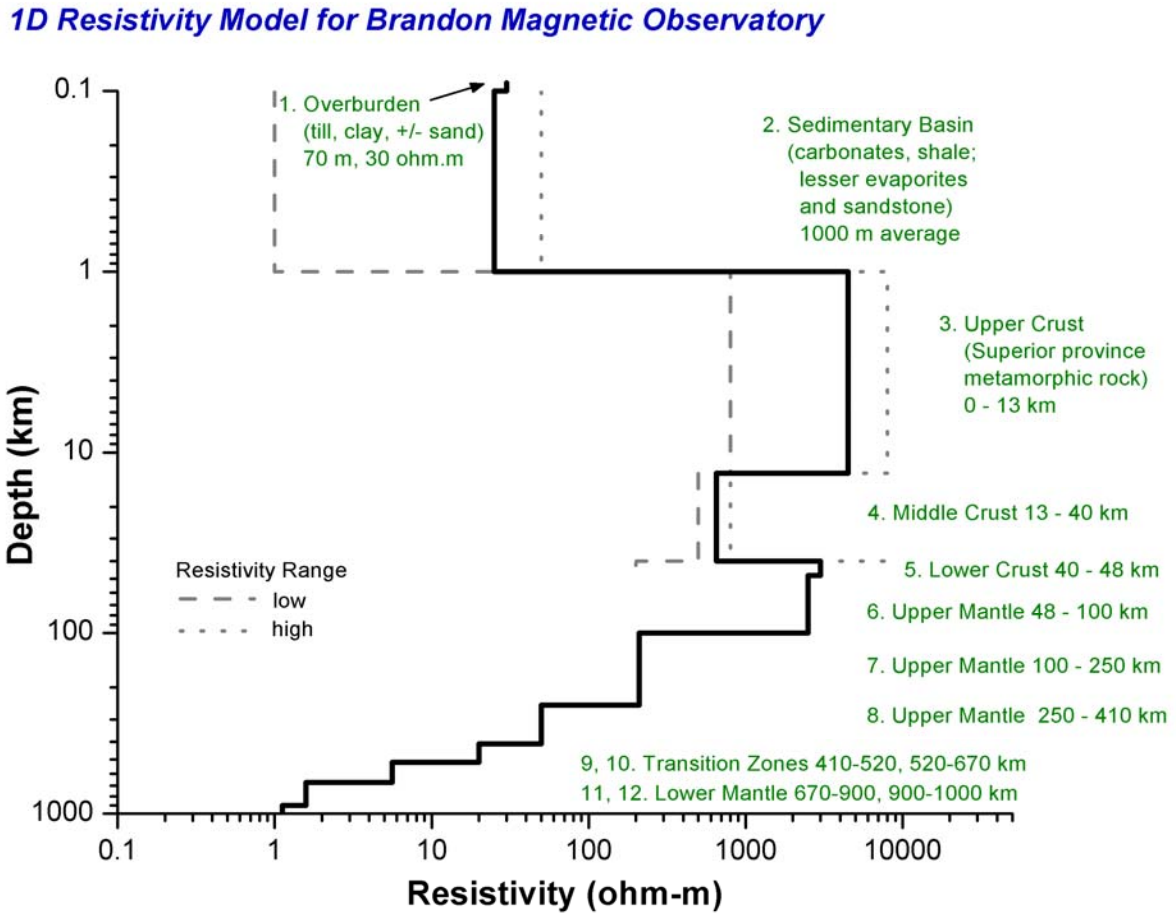


Figure A2.1.1. Major rock types underlying Manitoba and the Brandon magnetic observatory (Atlas of Canada). Shown is the area of coverage for the 1D Brandon model, and approximate locations of conductive anomalies within the crust.

The conductive anomalies are: The Thompson Belt (TOBE) anomaly due to the graphitic rich metasedimentary rock. It is a relatively narrow (<20 km) conductor (1-5 Ohm·m) extending vertically from top of the Precambrian basement to more than tens of kilometres deep, with a length of 50 km [1]. Enhanced conductivity (< 5 Ohm·m) also occurs in the Selkirk Greenstone Belt (SGB) partially due to presence of iron formations and sulphide mineralization; A regional deep-seated conductive (< 50 Ohm·m) anomaly associated with the southern margin of the Bird River-Separation Lake (in Manitoba), at 60-100 km depth [2].

The 1D Brandon model is presented in Figure A2.1.2 with accompanying Table A2.1.1.1 which summarizes individual layer depths, thickness, and resistivity/conductivity.



Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure A2.1.2. 1D Earth resistivity model proximal to the Brandon (Manitoba) magnetic observatory. Refer to Table A2.1.1 for additional details.

Table A2.1.1

1D Earth Resistivity Model for Brandon (Manitoba) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference [Confidence]		Reference [Confidence]		
1. Overburden	0 - 70 m [3, 4]	70 m	30 [1]	0.033	Variable depths, thickest between Portage and Brandon, area of Assiniboine Delta [3]; overall < 50m; increasing < 100m in pre-glacial valleys and < 150-200m around pre-glacial bedrock highs (e.g. Duck Mountain) [4]; 15-30m below Winnipeg [3]; 70-100m below Brandon [3]; MT survey indicates <100m [1]. Assigned 70m average based on [3]. Till (10-110m) overlain by glaciolacustrine clay (10-60m) overlain by glaciofluvial sand (10-30m). Sand plain common east of Brandon and at Sandilands [3,5]. Till is prevalent. Resistivity for tills range 20-100 ohm.m [10] Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [11]. MT survey indicates 5-30 ohm [1], assigned high-end of range.
	[I]		[I]		
2. Sedimentary Basin	70 < 2020 m [3,6,7]	1 km (midpoint)	25	0.04	Eastern side of Williston Basin underlies southwest Manitoba. Paleozoic carbonates (with minor interlayers of shale and evaporites) and a thin basal sandstone-shale; all overlain by Mesozoic shales. Depth from stratigraphic sections. Southwestward increasing thickness; ~ 110m below Winnipeg, ~1105m at Brandon, ~2020m at Manitoba / Saskatchewan boundary. Assigned midpoint value. Basin exhibits 3 resistivity ranges: 1-5 ohm.m Mesozoic and upper Paleozoic strata (shale dominant); 20-50 ohm.m lower Paleozoic carbonates; 2-3 basal sandstone containing shale and saline porewater [1]. Assigned midpoint 25 ohm.m, prevalent on 2D resistivity profile by [1-Fig.7].
	[I]		[I]		

Table A2.1.1 (continued)
1D Earth Resistivity for Brandon (Manitoba) magnetic observatory

Layer	Depth	Thickness	Resistivity (Ohm-m)	Conductivity (S/m)	Comments
	Reference [Confidence]		Reference [Confidence]		
3. Upper Crust	1 - 13 km [9] [I]	12 km	4500 [I]	0.00022	Lower depth scaled from seismic transect across southwest Manitoba and southeast Saskatchewan. Superior geological province underlies sedimentary basin. Includes intrusives (granites, diorites, and syenites), metamorphosed sediments and volcanics as schists and gneisses, and banded iron formation Resistivity range 800–8000 ohm·m [1, Fig.8]. Excludes influence of < 10 ohm.m TOBE anomaly. Assigned midpoint value.
4. Middle Crust	13-38 to 42 km [9] [I]	27 km	650 [1] [I]	0.0015	Variable lower depths scaled from seismic transect across southwest Manitoba and southeast Saskatchewan. Assigned average depth of 40 km. Resistivity range 500–800 ohm·m [1, Fig.8]. Excludes influence of TOBE anomaly Assigned midpoint value.
5. Lower Crust	38 to 42 - 48 km [9] [II]	8 km	3000 [1] [I]	0.00033	Lower depth scaled from seismic transect across southwest Manitoba and southeast Saskatchewan. Resistivity range 800–5000 ohm.m [1, Fig.8] Excludes influence of TOBE anomaly. Assigned midpoint value.
6. Upper Mantle	48 - 100 km [8] [III]	52 km	2500 [1, 2] [I]	0.0004	Used generalized lower depth [8]. Resistivity depicted on [1, Fig.8] extends only to depth of 60 km. Assuming same resistivity for entire layer thickness. Resistivity range 800-8000 ohm.m,[1, Fig.8] excluding influence of conductive TOBE and SGB anomalies. Lower resistivity beneath Winnipeg, higher below Brandon. Assigned midpoint value. Resistivity in southeast Manitoba ranges 200-1000

Table A2.1.1 (continued)
1D Earth Resistivity Model for Brandon (Manitoba) magnetic observatory

Layer	Depth	Thickness	Resistivity (Ohm-m)	Conductivity (S/m)	Comments
	Reference [Confidence]		Reference [Confidence]	Confidence	
7. Upper Mantle	100 - 250 km [8]	150 km	210 [8]	0.0048	Utilized Canada regional model [8] for all depths and resistivities below 100 km.
	[III]		[III]		
8. Upper Mantle	250–410 km [8]	160 km	50 [8]	0.02	---
	[III]		[III]		
9. Transition Zone	410–520 km [8]	110 km	20 [8]	0.05	---
	[III]		[III]		
10. Transition Zone	520–670 km [8]	150 km	5.6 [k]	0.178	---
	[III]		[III]		
11. Lower Mantle	670–900 km [8]	230 km	1.58 [8]	0.63	---
	[III]		[III]		
12. Lower Mantle	900–1000 km [8]	100 km	1.12 [8]	0.89	---
	[III]		[III]		

TOBE	Thompson belt
SGB	Selkirk Greenstone belt

NOTES:

Depth Confidence

I = best representation
    * overburden: geological report/map coverage of local area.
    * crust: seismic/gravity transects crossing local area, within 10 km.

II = likely representative
    * crust/upper mantle: geological and/or seismic transect of a regional nature.

III = possibly representative (measurements from general compilations).

Resistivity/Conductivity Confidence

I = best representation (measurements from site or nearby).
    * overburden: measurement by surface geophysical method and/or borehole in local area.
    * crust: measurement from resistivity survey, MT survey and/or borehole in local area.

II = likely representative (extrapolated from measurements taken at some distance from the site, typically greater than 100 km).
    * overburden: resistivity value obtained by geophysical measurement, including borehole logs.
    * sedimentary basin: value obtained by geophysical survey using variety of methods, including MT.
    * crust: value obtained by regional MT survey.

III = possibly representative (measurements from general compilations).

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A2.2. Fort Churchill magnetic observatory, Manitoba

General

Presented two 1D block models representing the vertical variance of electrical resistivity were considered necessary to capture the resistivity differences that occur in Earth's crust in the vicinity of Fort Churchill. The area of coverage includes northern and central Manitoba, extending about 800 km south, 500 km west and 350 km southeast of the observatory (Figure A2.2.1).

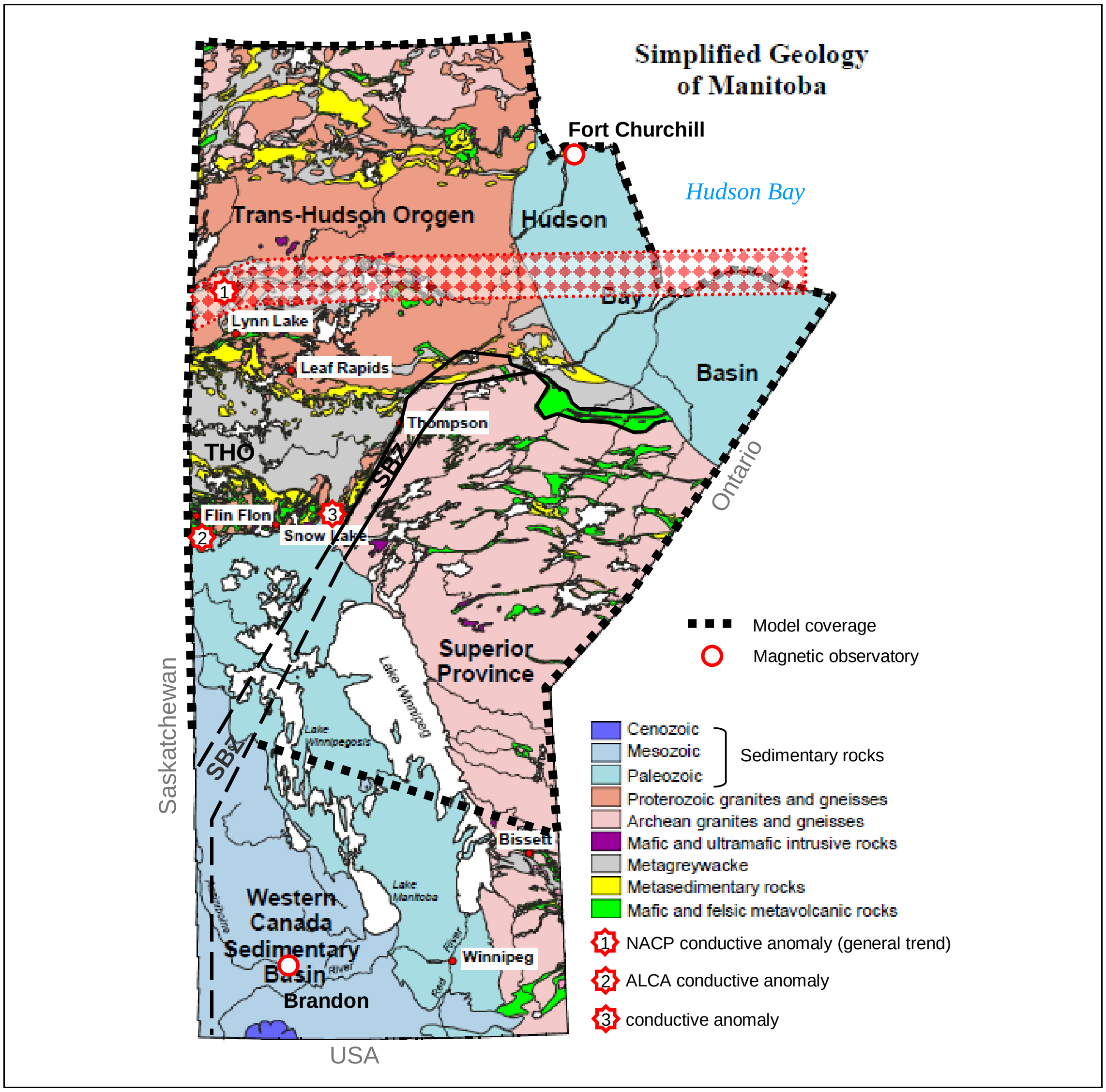
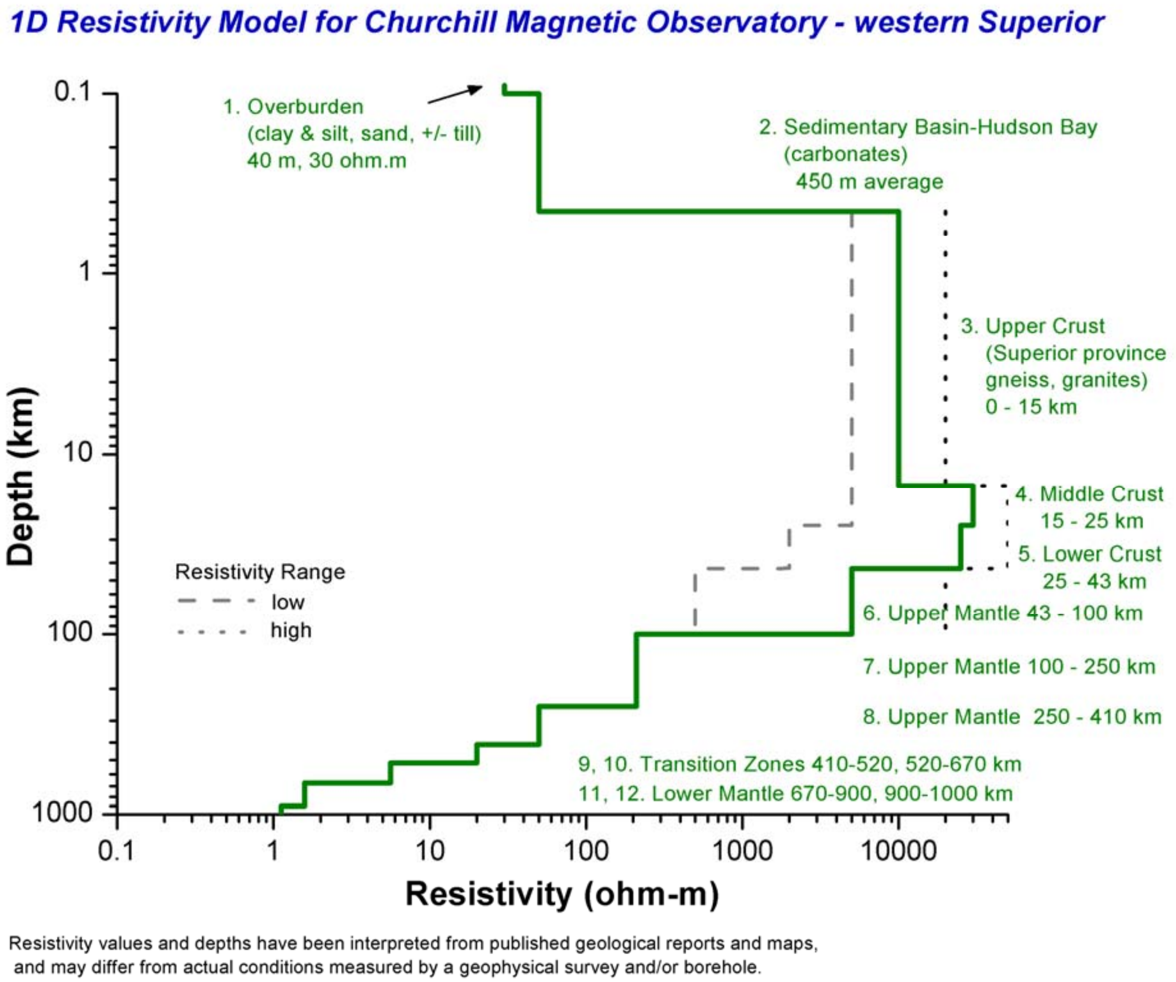


Figure A 2.2. 1. Major rock types underlying Manitoba and the magnetic observatories at Brandon and Churchill [1]. Shown in heavy dashed line is area of coverage for the Churchill 1D models. Approximate locations of crustal conductive anomalies are also shown. NACP location is from [2] abbreviated as: ALCA, Athapapuskow Lake Conductivity Anomaly. NACP, North American Central Plains. SBZ, Superior Boundary Zone . THO, Trans-Hudson Orogen.

The Fort Churchill 1D models are presented in Figures A2.2.2 and A2.2.3 below. Accompanying Table A.2.2.1 summarizes individual layer depths, thickness, and resistivity/conductivity for both models, and provides more details on the geological settings.



1D Resistivity Model for Churchill Magnetic Observatory - western Superior

Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure A2.2.2. 1D Earth resistivity model proximal to the Fort Churchill (Manitoba) magnetic observatory, for crust within the western Superior geological province, overlain by the Hudson Bay Basin. Refer to Table A.2.2.1 for additional details.

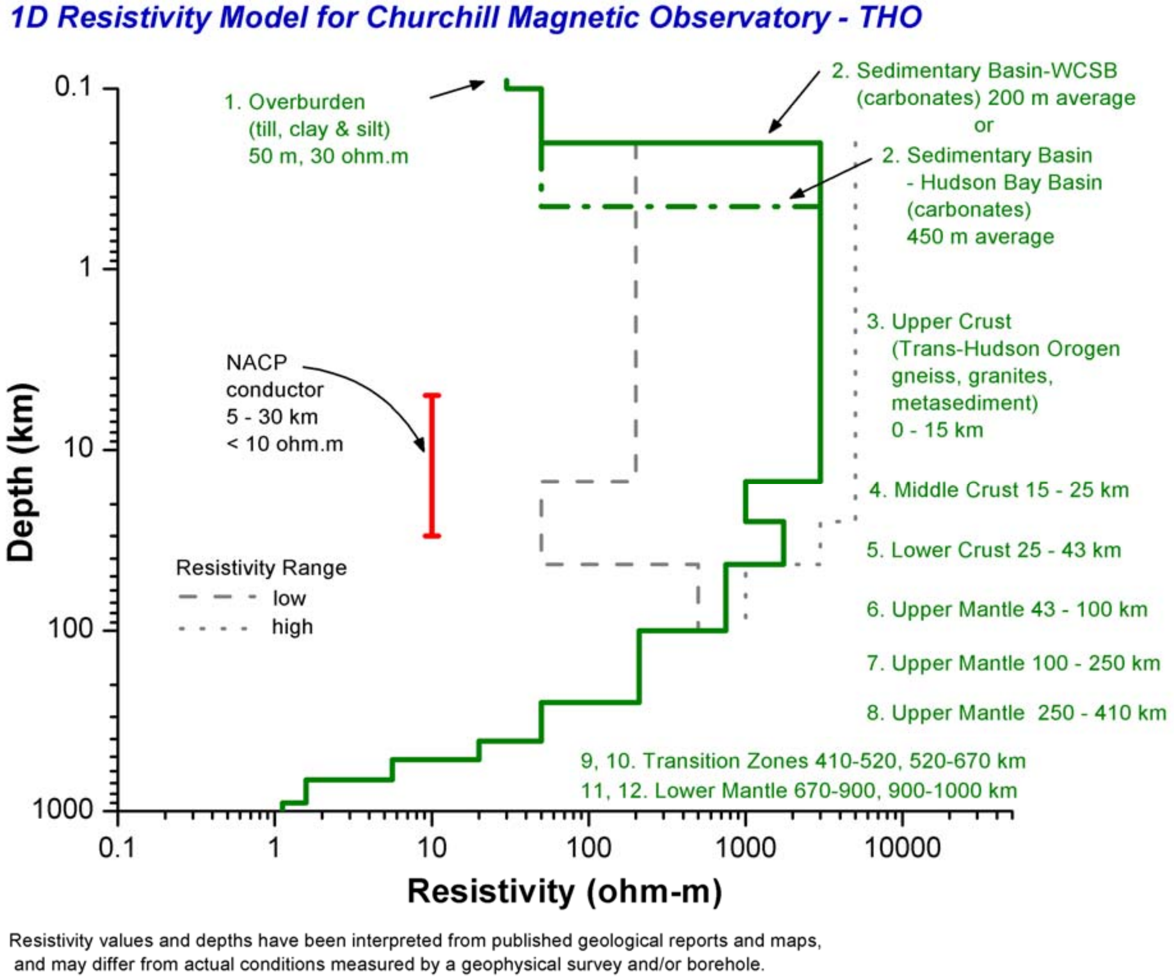


Figure A2.2.3. 1D Earth resistivity model proximal to the Fort Churchill (Manitoba) magnetic observatory, for crust within the Trans-Hudson Orogen, either overlain by the Western Canada Sedimentary Basin or Hudson Bay Basin (dashed green line). Conductivity and depth of North American Central Plains conductive anomaly also shown. Refer to Table A2.2.1 for additional details.

Table A2.2.1

1D Earth Resistivity Model Proximal to the Churchill (Manitoba) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference [Confidence]		Reference [Confidence]		
1. Overburden	0 – 40 m [3]	40 m	30 [4,5,6]	0.033	*HudsonBay Basin*: Variable materials and depth [3]. Majority of Layer 2 covered by (i) glaciomarine clay and silt, 1-20m thick, with (ii) glaciomarine sands and gravel (beach ridges, spits), 1-10m thick, up to 20 km inshore of coastline; all overlying glaciolacustine clay and silt, 1-20m thick, of former glacial Lake Agassiz. Silty and sandy tills underlie and protrude thorough glaciolacustrine and minor till deposits at western margin of Layer 2. Organic deposits (peat, muck), 1-5m thick, on top of glacial material common in Hudson Bay Lowland. Assigned estimated maximum thickness of 40m (20m glaciomarine clays and 20m glaciolacustrine clays). Resistivity for tills range 20-100 ohm.m [4]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [5]. MT survey in southeastern Manitoba across mixted glacial deposits indicates 5-30 ohm [6]. *WCSB*: Silty till and sandy till is prevalent, covered in areas by glaciolacustrine clay [7], < 50 m thick overall [8] *Superior Province & Trans-Hudson Orogen*: Till, 2/3 overlain by glaciolacustrine clay, 1-20m thick [3,7]. Sand-rich till prevalent in northwestern region of Manitoba, estimate < 10m thick.. Resistivity for tills range 20-100 ohm.m [4] For Layer 1 overall, assigned 30 ohm.m to reflect dominance of glaciolacustrine clays and silt covering sedimentary basins.
	[I]		[II]		

Table A2.2.1 (continued)

1D Earth Resistivity Model Proximal to the Churchill (Manitoba) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference [Confidence]		Reference [Confidence]		
2. Sedimentary Basin	*Hudson Bay* < ~900 m [9,10,11] [II]	*Hudson Bay* 450 m (midpoint)	*Hudson Bay* 50 [2, 6,12,13] [I, II]	0.02	*HudsonBay Basin*: Paleozoic strata, primarily carbonate (limestone +/- dolostone) with upper succession of argillaceous and sandy beds [9]. Gently dipping northeast, undeformed. Overlies Precambrian basement (Superior province and Trans-Hudson orogen). Depth from stratigraphic contour map indicates 300-900m along Hudson Bay shoreline, and 300m below Churchill [10]. Petroleum well, 375 km southeast of Churchill, intersect Precambrian basement at ~ 900m [11] Maximum onshore thickness of 884 m noted by [9]. MT survey [12] near Churchill Natural Studies Centre suggests varying depth to basement, revealed ~ 100m depth, increasing to 200m and then starting to taper out to edge of basin. Assigned midpoint thickness. Resistivity below CNSC varies 20-100 ohm.m [12]. Carbonate strata in WCSB in southeastern Manitoba ranges 20-50 ohm [6]. Assigned approximate midpoint value, 50 ohm.m, of range of resistivity determined by [12] which is also high end for carbonates as determined by [6]. *WCSB (north of latitude 51.5 N)*: Mainly Paleozoic strata (mostly carbonates) thickens southwestward to > 400 m [14]. Sedimentary rock south of Flin Flon (200m thick) varies 10-100 ohm.m [13] and 30 ohm.m [2], and in southeastern Manitoba 20-50 ohm.m [6]. Assigned approximate midpoint value, 50 ohm.m, based on range of resistivity determined by [13] which is also high end for carbonates as determined by [6].
	WCSB < 400 m [14] [II]	*WCSB* 200 m (midpoint)	*WCSB* 50 [2,6,13] [II]	0.02	

Table A2.2.1 (continued)

1D Earth Resistivity Model Proximal to the Churchill (Manitoba) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference [Confidence]		Reference [Confidence]		
3. Upper Crust	0 – 15 km [15,16] [II]	15 km	*Superior* 10000 [2,17] [II]	0.0001	Layer 3 comprised of two different geological provinces. Major MT transects [2,13,15] across southwest and northeast regions of model coverage. *<u>Superior Province</u>*: Lower depth scaled from seismic transect. Predominately granitoids and gneisses, with lesser amount of metavolcanics and metasediments occuring as narrow bands. Resistivity range 5000-20000 ohm.m, typically 5000-10000 with higher resistivity common to North Caribou Superterrane in east-central Manitoba [17]. >10000 ohm.m [2]; >50000 ohm.m [15]. Assigned 10000 ohm.m to reflect higher resistivity associated with crust of older Precambrian age (Archean)
			THO 3000 [2,13] [II]	0.00033	
					<u>Trans-Hudson Orogen</u>: Lower depth scaled from seismic transect, thickens in La Ronge area. (*not used for calculations*) Tectonic collage of mainly granites and gneisses and metasediments, and lesser amount of metavolcanics. Resistivity range 20-200 ohm.m [17]; 400-1000 ohm.m to depth < 7 km beneath CNSC area [12]; 500-5000 overall with 50000 within core of Sask craton (top at 10 km depth) [13]; 500-1000 ohm.m background with domain blocks of >10000 ohm.m [2]. Assigned 1000 ohm.m to reflect lower resistivity associated with crust of younger Precambrian age (Proterozoic), generally in range of 1000-5000 ohm.m; some crustal blocks 10000-50000 ohm.m. *<u>Conductors</u>*: NACP, 5-30 km, <10ohm.m; ALCA, 5-15 km, <10ohm.m [15]. Anomaly between 57.7°N, 94.2°W and 56.4°N, 94.7°W has top depth of 5 km, <25ohm.m [2].

Table A2.2.1 (continued)
1D Earth Resistivity Model Proximal to the Churchill (Manitoba) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference [Confidence]		Reference [Confidence]		
4. Middle Crust	15 – 25 km [16] [III]	10 km	*Superior* 30000 [2,17] [II]	0.000033	Lower depth scaled from Lithoprobe trans-continental seismic transect. *Superior Province*: Resistivity range 5000-50000 ohm.m, 20000-50000 for North Caribou Superterrane in east-central Manitoba and typically 5000-10000 northward of NCS. [187; >10000 ohm.m [2]; >50000 ohm.m [15]. Assigned midpoint 25000 ohm.m to reflect greater domination of higher resistive NCS and range of 10000-50000 ohm.m. *Trans-Hudson Orogen*: Resistivity range 10-50 ohm.m [18]; 1000-5000 with 50000 in core of Sask craton [13]; 500-1000 ohm.m [15]. Sask craton occurs at 10-25 km depth. Assigned low end value of resistivity range.
			THO 1000 [13,15] [II]	0.001	
5. Lower Crust	25 – 43 km [15,16] [II]	18 km	*Superior* 25000 [2,17] [II]	0.00004	Lower depth scaled from seismic transect, typically 42 [15] or 45 km deep [16], depth deceases westward to La Ronge then thickens again. Scaled 34-40 km on [13]. 48-55 km Moho depth reported by [16]. Assigned 43 km average depth *Superior Province*: Resistivity range 2000-50000 ohm.m, 20000-50000 for NCS in east-central Manitoba and typically 2000-10000 northward of NCS [17]; >10000 ohm.m [2]; >50000 ohm.m [15]. Assigned 25000 value based on 2000-50000 ohm.m range and continued depth continuation of highly resistive NCS. *Trans-Hudson Orogen*: Resistivity range 10-50 ohm.m [18], 1000-3000 [13]; 500-1000 ohm.m [2]. Assigned midpoint 1500 ohm.m based on range 500-3000 ohm.m
			THO 1750 [2,13] [II]	0.00057	

Table A2.2.1 (continued)
1D Earth Resistivity Model Proximal to the Churchill (Manitoba) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference [Confidence		Reference [Confidence]		
6. Upper Mantle	43 – 100 km [15,16,18]	57 km	*Super.,*5000 [2,17] [II]	0.0002	Used generalized lower depth [18]. *<u>Superior Province</u>*: Resistivity range 500-20000 ohm.m, 10000-20000 for NCS in east-central Manitoba and typically 500-5000 northward of NCS [17]. Applied 5000 ohm.m based on visual weighting of MT profile. *<u>Trans-Hudson Orogen</u>*: 500-1000 ohm.m [13]; 500-1000 ohm.m [2]; Assigned midpoint of range.
	[II, III]		*THO,* 750 [2,13] [II]	0.001333	
7. Upper Mantle	100 - 250 km [18]	150 km	210 [18]	0.004786	Utilized Canada regional model [18] for all depths and resistivities below 100 km.
	[III]				
8. Upper Mantle	250–410 km [18]	160 km	50 [18]	0.02	---
	[III]				
9. Transition Zone	410–520 km [18]	110 km	20 [18]	0.05	---
	[III]				
10. Transition Zone	520–670 km [18]	150 km	5.6 [18]	0.18	---
	[III]				
11. Lower Mantle	670–900 km [18]	230 km	1.58 [18]	0.63	---
	[III]				

Table A2.2.1 (continued)

1D Earth Resistivity Model Proximal to the Churchill (Manitoba) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Confidence		Confidence	Confidence	
12. Lower Mantle	900–1000 km [18]	100 km	1.12 [18]	0.89	---
	[III]			[III]	

ALCA Athapapuskow Lake Conductive Anomaly; CNSC Churchill Natural Studies Centre
NCS North Caribou Superterrane; Sk Saskatchewan
THO Trans-Hudson Orogen; WCSB Western Canada Sedimentary Basin

NOTES:

Depth Confidence
- I = best representation
  - * overburden: geological report/map coverage of local area.
  - * crust: seismic/gravity transects crossing local area, within 10 km.
- II = likely representative
  - * crust/upper mantle: geological and/or seismic transect of a regional nature.
- III = possibly representative (measurements from general compilations).

Resistivity/Conductivity Confidence
- I = best representation (measurements from site or nearby).
  - * overburden: resistivity measurement by surface geophysical method and/or borehole in local area.
  - * crust: resistivity measurement from resistivity survey, MT survey and/or borehole in local area.
- II = likely representative (resistivity values extrapolated from measurements taken at some distance from the site, typically greater than 100 km).
  - * overburden: resistivity value obtained by geophysical measurement, including borehole logs.
  - * sedimentary basin: value obtained by geophysical survey using variety of geophysical electromagnetic methods, including MT.
  - * crust: value obtained by regional MT survey.
- III = possibly representative (measurements from general compilations).

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A2.3. Sanikiluaq magnetic observatory, Nunavut

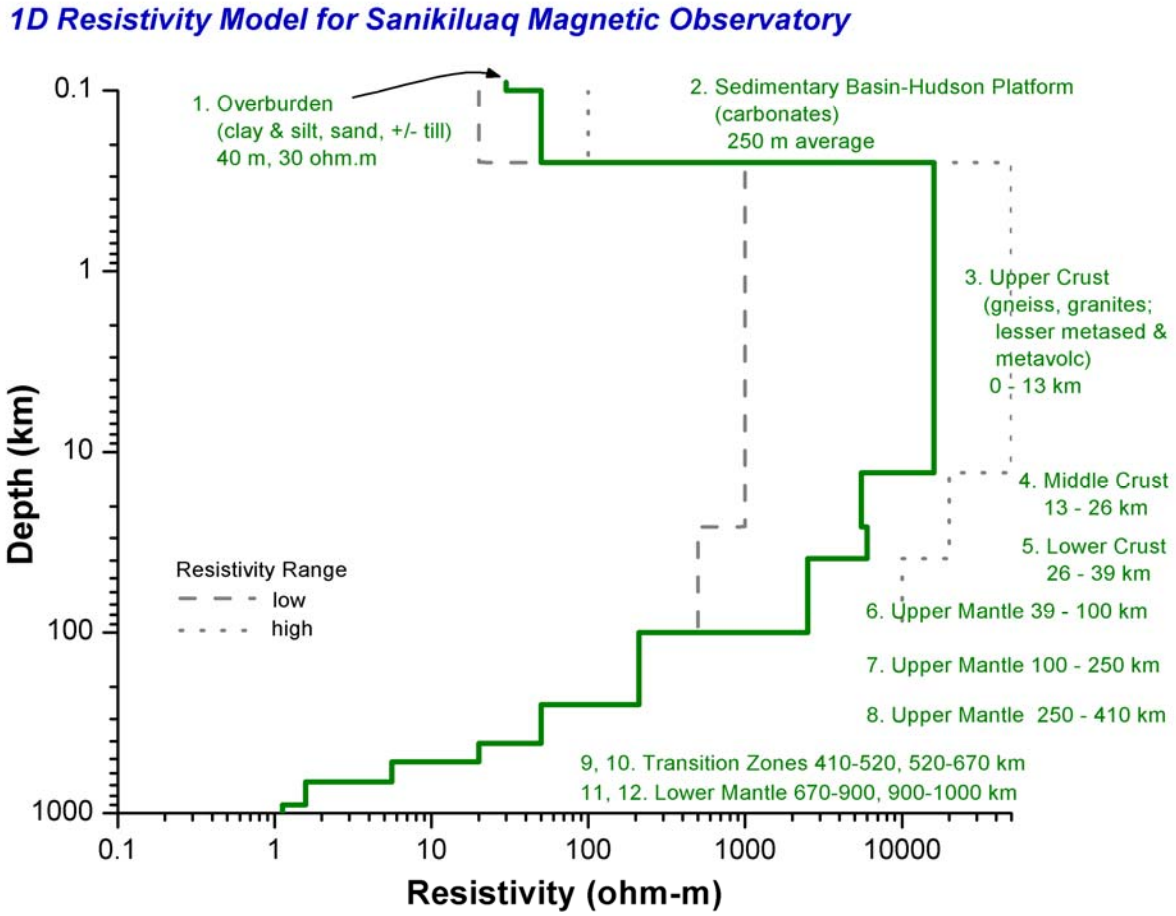
General

Presented is a 1D block model representing the vertical variance of electrical resistivity proximal to the Sanikiluaq magnetic observatory, located on Belcher Islands on the eastern side of Hudson Bay as shown in Figure A2.3.1. The area of coverage is a 500 km radius around Sanikiluaq, encompassing the northern margin of Ontario and northeastern region of Quebec as well as the eastern half of saltwater Hudson Bay. No magnetotelluric (MT) or seismic transects are known to cross the Belcher Islands. Assembly of the Sanikiluaq model relied mainly on the results of MT crustal-scale transects across the Trans-Hudson Orogen (THO) in north-central Manitoba, and Superior province in northwestern Ontario and northeastern Quebec, located 1200 km west, 800 km west and 600 km to the south, respectively. The North American Central Plains (NACP) conductive anomaly likely extends across the area of coverage beneath the Hudson Bay.

Figure A2.3.1. Map of the geological provinces underlying Nunavut, Ontario, Quebec and part of Manitoba. Shown in red are the various segments of the Circum-Superior Belt, formed along the margin of the Superior and also approximate limits of Trans-Hudson Orogen are presented as long-dashed line. Rae and Hearne geological provinces are allocated the same shade of grey because these two provinces are often combined as the Churchill geological province. Shown in heavy dashed line is the area of coverage, 500 km radius, for the Sanikiluaq 1D model (modified from Minifie et al., 2010, Fig. 1).

Presentation of Findings

The Sanikiluaq 1D model is presented in Figure A.2.3.2. Accompanying Table A2.3.1 summarizes individual layer depths, thickness, and resistivity/conductivity for the model. Note that Layer 2 – the Hudson Platform sedimentary basin – occurs only on land along the northern margin of Ontario. Resistivity values shown for Layers 3 to 6, upper, middle and lower crust, and uppermost mantle to 100 km depth, are an averaging of resistivity individually unique to the THO and Superior province.



Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure A2.3.2. 1D Earth resistivity model proximal to the Sanikiluaq (Nunavut) magnetic observatory. Sedimentary basin exposed only in northern Ontario. Crust and uppermost mantle layer resistivity were assigned midpoint value for average resistivity determined for of Trans-Hudson Orogen and Superior geological province. Refer to Table A2.3.1 for additional details.

Table A2.3.1
1D Earth Resistivity Model Proximal to the Sanikiluaq (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference [Confidence}		Reference [Confidence]		
1. Overburden	0 – 40 m [2]	40 m	30 [3-5]	0.033	*Sanikiluaq*: Estimate < 1m, discontinuous glaciomarine / marine clay and sand, some gravel, in bedrock depressions. Exposed bedrock > 75%. *Northeastern Superior Province (Nunavut)*: Glaciomarine deposits (gravel, sand, silt and clay; estimate < 20m total) along coastline up to 100 km inshore, then discontinuous till blanket (estimate < 3 m thick) or veneer (estimate < 1 m) [6] *Hudson Platform (Ontario)*: Till overlain by glaciomarine / marine gravel and sand; all overlain by < 4m peat deposits [6, 7], Assigned estimated maximum thickness of 40m (till estimated 20 m, with 20m glaciomarine clays or 20m glaciolacustrine clays), based on similar deposits along Hudson Platform in Manitoba [2]. Resistivity for tills range 20-100 ohm.m [4]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [5]. MT survey in southeastern Manitoba across mixed glacial deposits indicates 5-30 ohm [3]. For Layer 1 overall, assigned 30 ohm.m to reflect dominance of glaciolacustrine clays and silt covering nearshore of Hudson Bay.
	[II]		[II]		

Table A2.3.1 (continued)

1D Earth Resistivity Model Proximal to the Sanikiluaq (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference [Confidence]		Reference Confidence		
2. Sedimentary Basin	*Hudson Platform* < ~500 m [8,9]	*Hudson Platform* 250 m (midpoint)	*Hudson Platform* 50 [3,10-12]	0.02	*Sanikiluaq*: Layer 2 absent. *Northeastern Superior Province (Nunavut)*: Layer 2 absent. *Hudson Platform (Ontario)*: <500m thick along shoreline, thinning inland; ~2300m thick at centre of Hudson Bay [8,9]. Assigned midpoint thickness, 250m, within model coverage of nearshore area. Paleozoic strata, primarily carbonate (limestone +/- dolostone), lesser amount clastic sediments (sandstone, shale) and evaporites (gypsum, salt) with upper succession of argillaceous and sandy beds [8, 13]. Gently dipping northeast, undeformed. In Ontario, overlies Precambrian basement (Superior province and Trans-Hudson orogen). Resistivity below Churchill Natural Science Centre varies 20-100 ohm.m [10]. CNSC is 900 km northwest from model coverage area. Carbonate strata in WCSB in southeastern Manitoba ranges 20-50 ohm [3] and northwestern Manitoba ranges 10-100 [11] or averages 30 ohm.m [12] for a 200m thickness. Assigned approximate midpoint value, 50 ohm.m, of range of resistivity determined by [10,11] which is also high end for carbonates as determined by [3].
	[II]		[II]		

Table A2.3.1 (continued)

1D Earth Resistivity Model Proximal to the Sanikiluaq (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference Confidence		Reference Confidence		
3. Upper Crust	0 – 13 km [14,15]	13 km	16500 (midpoint)	$7.4 \cdot 10^{-5}$	Seismic transect, 500km northeast of Sanikiluaq, indicates average 10 km thickness in area south of Ungava Bay [14]. Assigned midpoint between 10 km and generalized depth of 15 km [15]. *Sanikiluaq*: Volcanic (basaltic massive and pillow flows, pyroclastics) and sedimentary rock (argillite, dolostone, limestone, quartzite, iron formation), intensely folded [24, 30]. Volcanics form part of Circum-Superior Belt, inbetween Trans-Hudson Orogen and Superior Province, continuing into Manitoba as the Superior Boundary Zone where resistivity is ~3000-10000 ohm.m [25].
	[II, III]		[II]		
	Trans-Hudson Orogen: In northeastern Manitoba, a tectonic collage of mainly granites and gneisses and metasediments, and lesser amount of metavolcanics. Minor exposed bedrock, mainly underlies Hudson Bay. Assigned 3000 ohm.m to reflect lower resistivity associated with crust of younger Precambrian age (Proterozoic), generally in range of 1000-5000 ohm.m; some crustal blocks < 80 or 10000-50000 ohm.m [11,16]. See Fort Churchill model for more detail. *Northern Superior Province (Ontario):* Includes northern part of NCS, IL, OSL and NSS. Predominantly granitoids and gneisses interspersed with belts of metasedimentary and metavolcanic rock [17]. NCS and OSL terranes have 50000 ohm.m resistive cores surrounded by 5000-20000 ohm.m [18]. Assigned midpoint 25000 ohm.m resistivity. *Northeastern Superior Province (Nunavut)*: Includes IN, TK, LM, G, LG and OPN domain/subprovinces. Predominantly granitoids and gneisses with belts of metasedimentary and metavolcanic rock [19]. Resistivity ranges 25000-50000 ohm.m within northern AT underlain by plutonic rock, south of James Bay [20]. OPT, plutonic rock dominant, in Chibougamou area, has 10000 ohm.m resistivity [21]. Assigned midpoint 30000 ohm.m resistivity. Layer 3 resistivity assigned midpoint value of range 3000-30000 ohm.m, encompassing both Trans-Hudson Orogen and northern and northwestern Superior province. NACP conductive anomaly, <10 ohm.m, possibly beneath Hudson Bay,				

Table A2.3.1 (continued)

1D Earth Resistivity Model Proximal to the Sanikiluaq (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference Confidence		Reference Confidence		
4. Middle Crust	13 – 26 km [14,15,26]	13 km	5750 (midpoint)	$2.1 \cdot 10^{-4}$	Seismic transect , 500km northeast of Sanikiluaq, indicates Layer 4 is 10-18 km in area south of Ungava Bay [14]. Transect south of James Bay in OPT shows variable bottom depth of 27-35 km [22]. Gravity survey shows 32 km depth [23]. Assigned a bottom depth midpoint between 18 km and 35 km
	[II, III]		[II]		
			Trans-Hudson Orogen: Resistivity range 10-50 ohm.m [24]; 1000-5000 [11]; 500-1000 ohm.m [16], averaging 1000 ohm.m [25]. Assigned low end value, 1000 ohm.m, of resistivity range 1000-5000. *Northern Superior Province (Ontario):* 50000 ohm.m resistive cores taper down into middle crust, surrounded by 500-20000 ohm.m [18]. >5000 ohm.m for middle and lower crust noted by [26]. Assigned midpoint 10500 ohm.m resistivity. *Northeastern Superior Province (Nunavut)*: Resistivity 200 ohm.m within northern AT [20] Layer 4 resistivity assigned midpoint value of range 1000-10500 ohm.m, encompassing both Trans-Hudson Orogen and northern Superior province. Possibility of conductive middle crust, ~ 200 ohm.m, in northeastern Superior (Nunavut).		
5. Lower Crust	26 – 39 km [14,22,27]	13 km	6000 (midpoint)	$1.67 \cdot 10^{-4}$	Lower depth measured from teleseismic study, 44 km on west coast of Quebec opposite Sanikiluaq and 32-36 km at Cape Smith Belt, 750km north of Sanikiluaq [27], and 39 km near James Bay [28]. Seismic transect, 500km northeast of Sanikiluaq, indicates average 36 km to crust/mantle boundary [14]. Transect south of James Bay in Opatica subprovince indicates 35-40 km bottom depth [22]. Gravity survey shows 41 km depth [23]. Assigned 39 km average depth from above measurements.
	[I, II]		[II]		

Table A2.3.1 (continued)

1D Earth Resistivity Model Proximal to the Sanikiluaq (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference Confidence		Reference Confidence		
5. Lower Crust (continued)					*Trans-Hudson Orogen*: Resistivity range 10-50 ohm.m [24], 1000-3000 [11]; 500-1000 ohm.m [12], averaging 1000 ohm.m [25]. Assigned midpoint 1500 ohm.m based on range 500-3000 ohm.m *Northern Superior Province (Ontario):* Influence of resistive core extends to lower crust. Resistivity ranges 500-20000 ohm.m [18]. >5000 ohm.m for middle and lower crust noted by [26]. Assigned midpoint 10500 ohm.m resistivity. *Northeastern Superior Province (Nunavut)*: Resistivity 200 ohm.m within northern AT (little change of resistivity with depth on MT profile) [20] Layer 5 resistivity assigned midpoint value of range 1500-10500 ohm.m, encompassing both Trans-Hudson Orogen and northern Superior province. Possibility of conductive lower crust, ~ 200 ohm.m, in northeastern Superior (Nunavut).
6. Upper Mantle	38 – 100 km [29]	62 km	2500 (midpoint)		Used generalized lower depth [29]. *Trans-Hudson Orogen*: 500-1000 ohm.m [11]; 500-1000 ohm.m [12]; Assigned midpoint value, 750 ohm.m, of range. *Northern Superior Province (Ontario):* Influence of resistive core (20000 ohm.m) extends to upper mantle. Resistivity ranges 500-10000 ohm.m [18], excluding core influence. Assigned midpoint 5000 ohm.m resistivity. *Northeastern Superior Province (Nunavut)*: Resistivity 200 ohm.m within northern AT (little change of resistivity with depth on MT profile) [20] Layer 6 resistivity assigned approximate midpoint value of range 750-5000 ohm.m, encompassing both Trans-Hudson Orogen and northern Superior province; possibly overestimated.
	[II, III]		[II]		

Table A2.3.1 (continued)

1D Earth Resistivity Model Proximal to the Sanikiluaq (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference Confidence		Reference Confidence		
7. Upper Mantle	100 - 250 km [29]	150 km	210 [29]	0.0048	Utilized Canada regional model [29] for all depths and resistivities below 100 km.
	[III]		[III]		
8. Upper Mantle	250–410 km [29]	160 km	50 [29]	0.02	---
	[III]		[III]		
9. Transition Zone	410–520 km [29]	110 km	20 [29]	0.05	---
	[III]		[III]		
10. Transition Zone	520–670 km [29]	150 km	5.6 [29]	0.178	---
	[III]		[III]		
11. Lower Mantle	670–900 km [29]	230 km	1.58 [29]	0.63	---
	[III]		[III]		
12. Lower Mantle	900–1000 km [29]	100 km	1.12 [29]	0.9	---
	[III]		[III]		

Table A2.3.1 (continued)
1D Earth Resistivity Model Proximal to the Sanikiluaq (Nunavut) magnetic observatory

CNSC	Churchill Natural Studies Centre
WCSB	Western Canada Sedimentary Basin

Northern Superior	
IL	Island Lake Domain
NCS	North Caribou Superterrane
NSS	Northern Superior Superterrane
OSL	Oxford-Stull Lake Domain

Northeastern Superior	
AT	Abitibi Terrane
BV	Bienville Subprovince
G	Goudalie Domain
IN	Inukjuak Domain
LG	La Grande Subprovince
LM	Lake Minto Domain
OPN	Opinaca Subprovince
OPT	Opatica Subprovince

NOTES:

Depth Confidence

- I = best representation
  - * overburden: geological report/map coverage of local area.
  - * crust: seismic/gravity transects crossing local area, within 10 km.
- II = likely representative
  - * crust/upper mantle: geological and/or seismic transect of a regional nature.
- III = possibly representative (measurements from general compilations).

Resistivity/Conductivity Confidence

- I = best representation (measurements from site or nearby).
  - * overburden: resistivity measurement by surface geophysical method and/or borehole in local area.
  - * crust: resistivity measurement from resistivity survey, MT survey and/or borehole in local area.
- II = likely representative (resistivity values extrapolated from measurements taken at some distance from the site, typically greater than 100 km).
  - * overburden: resistivity value obtained by geophysical measurement, including borehole logs.
  - * sedimentary basin: value obtained by geophysical survey using variety of geophysical electromagnetic methods, including MT.
  - * crust: value obtained by regional MT survey.
- III = possibly representative (measurements from general compilations).

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A2.4. Baker Lake magnetic observatory, Nunavut

General

The area of model coverage extends 500 km east and west, and up to 800 km north and south of the Baker Lake magnetic observatory (Figure A2.4.1), including the islands of Southampton and King William. It encompasses most of the Western Churchill geological province, which is divided into two domains, the Rae and the Hearne. The Rae Domain underlies the majority of the model coverage area. Coastal margins of the Western Churchill are overlain by either the Arctic or Hudson Platforms of sedimentary rock. Assembly of the Baker Lake 1D model relied mainly on the results of several magnetotelluric (MT) transects (see Fig.A2.4.1 caption and Table A2.4.1) undertaken during 2007-2012 as part of Natural Resources Canada's Geo-mapping for Energy and Minerals (GEM) program carried out across northern Canada. The GEM MT transects provided resistivity values for crust and uppermost mantle down to a 250 km depth. The Rae and Hearne domains are separated by the 2800 km long Snowbird tectonic zone, a major intracrustal geophysical lineament. A north-westerly dipping conductive (<6.5 ohm.m) zone separates the Rae Domain from the Hearne Domain.

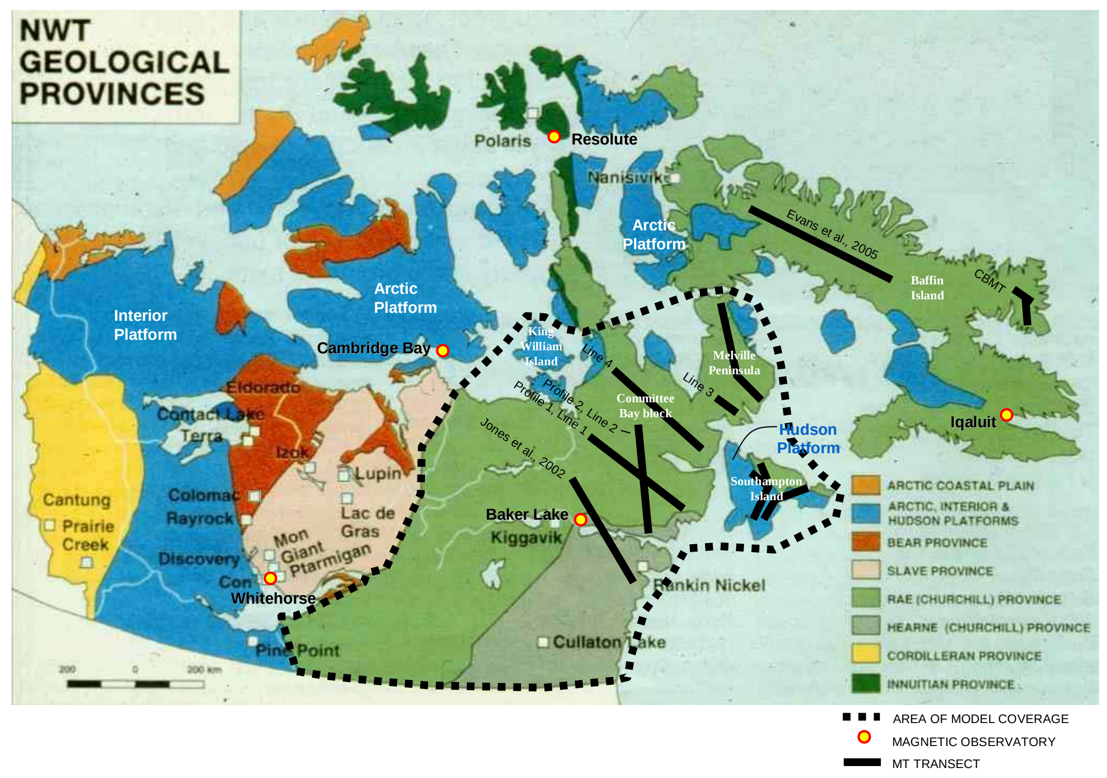
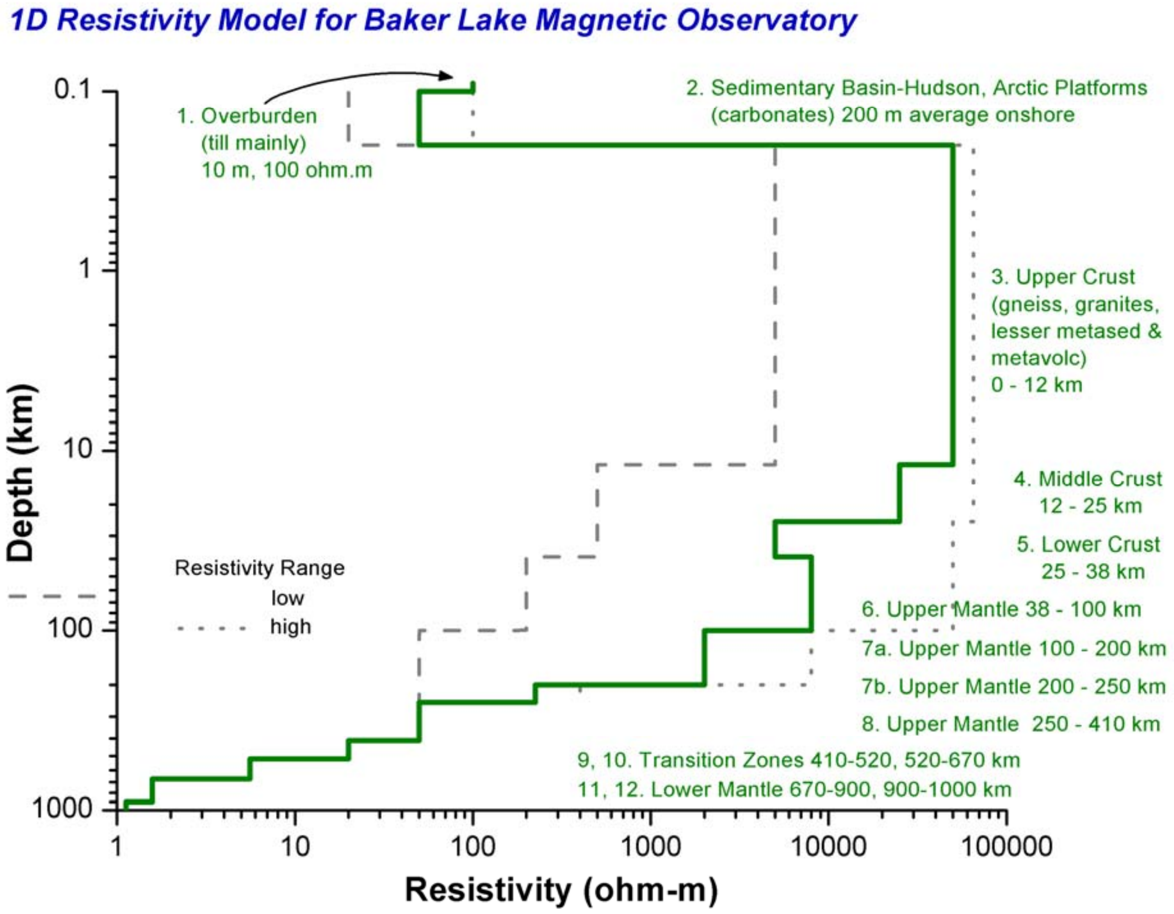


Figure A2.4.1. Area of coverage (dashed line) for the Baker Lake 1D model with respect to geological provinces. Western Churchill province is subdivided into the Rae and Hearne Domains. MT transects shown as thick lines (approximate position). MT survey crossing Baker Lake area described in [1]. Melville Peninsula MT survey described in [2]. Southampton Island transect described in [3]. Committee Bay block Profiles 1 and 2 described in [4], and Lines 1 to 4 described in [5]. MT transect across central Baffin Island [6]. Report on Cumberland Peninsula MT transect (CBMT) in southeastern Baffin Island [7]. White squares denote locations of mineral exploration activity and / or mines. Basic map is on http://www.miningnorth.com/resources, directory Maps, file Geological Provinces NWT.

Presentation of Findings

The Baker Lake 1D model is presented in Figure A2.4.2. Accompanying Table A2.4.1 summarizes individual layer depths, thickness, and resistivity/conductivity for the model.



1D Resistivity Model for Baker Lake Magnetic Observatory

Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure A2.4.2. 1D Earth resistivity model proximal to the Baker Lake (Nunavut) magnetic observatory, for crust within the Western Churchill geological province, in places overlain by the sedimentary Hudson Platform and Arctic Platform. Refer to Table A2.4.1 for additional details.

Table A2.4.1
1D Earth Resistivity Model Proximal to the Baker Lake (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
1. Overburden	0 - 25m range [8, 9]	10 m average	100 [10]	0.01	Till blanket (1-5m, 1-10m, 2-25m) and till veneer (<1m, <2m) is predominant [8,9,17]. Till thickness greater to the south. Unconsolidated sediments 40-100m thick over Thelon Basin [23]. Stoney tills on Melville Peninsula. Resistivity for tills range 20-100 ohm.m [10] in central and eastern Canada.
	[I]		[III]		
					Shorelines and inshore (<20 km from coast) typically covered by marine clay and silt and/or sand and gravel beaches. Marine deposits range 1-10m thick [8]. Central Botthia Peninsula more covered by marine deposited clay and silt [17]. Permafrost 100-500m, 200m below Baker Lake community. Thin to discontinous lag (sand, gravel ± sand pockets resulting from wave washing, 1-6m thick) common to much of Southampton Island, King William Island and Hall Beach area as beach ridges[8,17], also along shorelines rimming large lakes [9]. <u>Layer 1</u>, assigned 10m average overall thickness and high end of resistivity range 20-100 ohm.m for tills due to stoney nature of till and its extensive deposition
2. Sedimentary Basin	0 – > 500 m (offshore max.) [10-14].	200 m (onshore maximum)	50 [15,16]	0.02	<u>Hudson Bay Platform</u>: Covers 2/3 of Southampton Island. Paleozoic carbonate (limestone, dolostone, some shale) strata [13], 200m thick onshore [13] deeping 300-500m offshore [10-12]. Overlies Precambrian basement (Western Churchill province-Hearne Domain.
	[I]		[II]		
					<u>Arctic Platform</u>: East and west margins of Melville Peninsula and on King William Island. Paleozoic strata (mainly limestone, dolostone, siltsone, shale and conglomerate) [14]. East side of Melville Peninsula is the Foxe Basin, onshore thickness 150m [13], offshore thickness ~500m on isopach map [12]. West side of Melville Peninsula is Franklinian Basin, offshore thickness <depth 1500m on isopach map [12]. Resistivity range for Paleozoic carbonate-dominant sediments at: CNSC, 20-100 ohm.m [15]; WCSB in southeastern Manitoba, 20-50 ohm [16]. Paleozoic shale beds on Southampton Island, 10 ohm.m [3]. Unspecified Paleozoic sediments of Interior Platform in NWT, ~100 ohm.m over 1-2 km thickness [24]. Insufficient resolution on published profile of MT survey across Southampton Island [3].<u>Layer 2</u>, assigned 50 ohm.m based on mid-point of Paleozoic carbonate in Hudson Platform and high end for carbonates.

Table A2.4.1 (continued)
1D Earth Resistivity Model Proximal to the Baker Lake (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
3. Upper Crust	0 – 12 km [2-4]	12 km	50000 [4,5]	0.00002	Layer 3 comprised of two different geological domains within Western Churchill geological province, divided by Snowbird Tectonic Zone. Several MT transects [1-5,24]. MT surveys show resistivity change at 10-15 km, assigned midpoint ~ 12km as bottom depth of Layer 3. *Rae Domain*: Northern Melville Peninsula 5000->50000 ohm.m, [2, 18].
	[I]		[I]		
					South-central Melville Peninsula 4-5000 ohm, typcially 4 ohm due to Penrhyn Group metasediments (greywacke, marble, shale, ironstone, quartzite) [2, 18]; Committee Bay block Profile 1 shows 10000->50000 ohm.m, typically > 50000 [4,5]; Southampton Island 300-10000 to >50000 ohm.m [3]; Baker Lake area 6500-65000 ohm.m [1]; northern Baffin Island >10000 [19] *Hearne Domain*: Committee Bay block Profile 1 shows 10000->50000 ohm.m, typically > 50000 [4,5]; Baker Lake area 650-65000 ohm.m [1]. In Baker Lake area, zone of dipping “conductive crust” (<6.5 ohm.m) separates Rae Domain crust from Hearne Domain crust, coincides with Snowbird Tectonic Zone [1]. Layer 3 assigned >50000 ohm.m on basis of predominant high resistivity shown on latest MT profiles [2, 4,5] across Melville Peninsula and Committee Bay block, supported by high resistivity in Baker Lake area, parts Southampton Island and northern Baffin Island.

Table A2.4.1 (continued)
1D Earth Resistivity Model Proximal to the Baker Lake (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
4. Middle Crust	12 – 25 km [2-4, 21]	13 km	25000 (midpoint) [2,4,5]	0.00004	Used generalized lower depth, typical of Layer 4 in Canada [21]. *Rae Domain*: Northern Melville Peninsula 5000->50000 ohm.m [2, 18]; South-central Melville Peninsula, 100-500 ohm.m [2, 18]; Committee Bay block Profile 1, discontinous areas of 2000 ohm.m seperated by >50000 ohm.m masses [4,5,]; Profile 2 discontinous areas of 500-2000 ohm.m and >50000 ohm.m masses Southampton Island 300-10000 to >50000 ohm.m [3]; Baker Lake area 6500-65000 ohm.m [1]; northern Baffin Island 150 ohm.m [19] *Hearne Domain*: Committee Bay Profile 2, 2000-50000 ohm.m [4]; Baker Lake area, 65-6500 ohm.m [1]. Layer 4 resistivity assigned midpoint value of range 500-50000 ohm.m to reflect presence of “conductive” midlle crust (zones of 1000-2000 ohm.m)
	[I]		[I]		

Table A2.4.1 (continued)
1D Earth Resistivity Model Proximal to the Baker Lake (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
5. Lower Crust	25 – 38 km [1,20]	13 km	5000 (midpoint) [2,4,5]	0.0002	Variable lower depth based on teleseismic studies [1, 20]. MT profiles show resistivity changes at 34, 36-40 km [2,4,1]. Assigned midpoint 38 km, based on average of 11 teleseismic depth determinations ranging 35-41km [20]. Moho below Baker Lake 35 km.
	[I]		[I]		
		Rae Domain: 36-40 km, in places 34 km, thickens in northern part of domain [20]; average 39 km in vicinity of Baker Lake [1]. Northern Melville Peninsula, 5000->50000 [2], lower end of range dominant, assigned 10000 ohm.m. Southern Melville Peninsula, 100-500 ohm.m [2]. Committee Bay Profile 1 and Lines 1, 2 & 4, 500-2000 ohm.m, with >50000 ohm.m resistive roots [4,5]. Southampton Island 300-10000 to >50000 ohm.m [3]; Baker Lake area 6500-65000 ohm.m [1]; northern Baffin Island 150-10000 ohm.m, mainly 150 ohm.m [19] *Hearne Domain*: 38 km average [20]; 41-42 km [1]. Committee Bay Profile 2, ~2000 ohm.m [4]; Baker Lake area, 65-6500 ohm.m [1]. Layer 5 assigned midpoint value of range 500-10000 ohm.m to reflect greater predominance of a “conductive” lower crust.			

Table A2.4.1 (continued)
1D Earth Resistivity Model Proximal to the Baker Lake (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
6. Upper Mantle	38 – 100 km [1, 4, 22]	62 km	8000 [4,5]	0.000125	Used generalized lower depth [22]. *Rae Domain*: northern Melville Peninsula, 5000 ohm.m and south-central Melville Peninsula 100-500 ohm.m [2,18]; Committee Bay Profile 1, 10000->50000 ohm.m [4] Committee Bay Profile 2, 1000-8000 Line 1 [5]; Committee Bay Line 2 and Line 4, 8000 ohm.m [5]; Baker Lake area >65000 ohm.m [1]; Southampton Island anomalous 200-300 ohm.m [3]; northern Baffin Island >3000 ohm.m [19]. *Hearne Domain*: 10000 Committee Bay block Profile 2 [4]; Baker Lake area, 6500-65000 ohm.m[1] Layer 6 resistivity assigned 8000 ohm.m based on its dominance on latest MT profiles prepared by [4,5]. Resitivity ranges 1000 >50000 in eastern Nunavut, beconming more conductive at Melville Peninsula (5000 ohm.m) and Southampton Island (200-300 ohm.m).
	[I, III]		[I]		
7a. Upper Mantle	100 - 200 km [4,5]	100 km	2000 [4,5]	0.0005	*Rae Domain*: Committee Bay block, zonal variation, 2000-8000 ohm.m [5], typically ~2000 on Profile 1 but 10000-100000 ohm.m on Profile 2 [4]; ranomalous 50-300 ohm.m below Southampton island [3]; Baker Lake area >65000 ohm.m [1]. *Hearne Domain*: 10000-50000 Committee Bay block Profile 2 [4]; 6500-65000 ohm.m Baker Lake area [1]. Layer 7a resistivity assigned lower value of ~2000 ohm.m to reflect lower resistivity typical of uppermost mantle.
	[I]		[I]		

Table A2.4.1 (continued)

1D Earth Resistivity Model Proximal to the Baker Lake (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
7b. Upper Mantle	200 – 250 km [4,5]	50 km	225 [4,5]	0.0044	Lower depth of MT profiles coincides with general mantle depths of continental crust [22]. Resistivity typically 400 ohm.m in Committee Bay block of Rae Domain [4]; 50-80 ohm.m below Southampton Island [3]. Layer 7b assigned midpoint 225 ohm.m.
	[I]		[I]		
8. Upper Mantle	250–410 km [22]	160 km	50 [22]	0.02	---
	[III]				
9. Transition Zone	410–520 km [22]	110 km	20 [22]	0.050	---
	[III]				
10. Transition Zone	520–670 km [22]	150 km	5.6 [22]	0.178	---
	[III]				
11. Lower Mantle	670–900 km [22]	230 km	1.58 [22]	0.63	---
	[III]				
12. Lower Mantle	900–1000 km [22]	100 km	1.12 [22]	0.89	---
	[III]				

Table A2.4.1 (continued)

1D Earth Resistivity Model Proximal to the Baker Lake (Nunavut) magnetic observatory

NOTES:

Depth Confidence

- I = best representation
  - * overburden: geological report/map coverage of local area.
  - * crust: seismic/gravity transects crossing local area, within 10 km.
- II = likely representative
  - * crust/upper mantle: geological and/or seismic transect of a regional nature.
- III = possibly representative (measurements from general compilations).

Resistivity/Conductivity Confidence

- I = best representation (measurements from site or nearby).
  - * overburden: resistivity measurement by surface geophysical method and/or borehole in local area.
  - * crust: resistivity measurement from resistivity survey, MT survey and/or borehole in local area.
- II = likely representative (resistivity values extrapolated from measurements taken at some distance from the site, typically greater than 100 km).
  - * overburden: resistivity value obtained by geophysical measurement, including borehole logs.
  - * sedimentary basin: value obtained by geophysical survey using variety of geophysical electromagnetic methods, including MT.
  - * crust: value obtained by regional MT survey.
- III = possibly representative (measurements from general compilations).

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A2.5. Iqaluit magnetic observatory, Nunavut

General

Model is representing the vertical variance of electrical resistivity proximal to the Iqaluit magnetic observatory, located on Baffin Island, in eastern Nunavut.
The area of model extends over the entire Baffin Island, a length of about 1400 km and maximum width of 600 km, shown in Figure A2.5.1 as dashed area. Geologically, the area takes in part of the Western Churchill geological province-Rae Domain and the northeastern continuation of the Trans-Hudson Orogen (THO). Crystalline bedrock is dominant with overlying sedimentary strata of the Arctic Platform. Continuous permafrost is present on Baffin Island, up to 600 m deep in the north end and shallowing to 100m at the south end of the island. Assembly of the resistivity values for the Iqaluit 1D model relied mainly on the results of a 500-km long magnetotelluric (MT) transect undertaken across the central axis of Baffin Island in 2001-2002 [1, 2]. Further details on the tectonic makeup can be found in [3, 4, 5]. A more detailed map of regional bedrock geology has been prepared by de Kemp et al. [6].

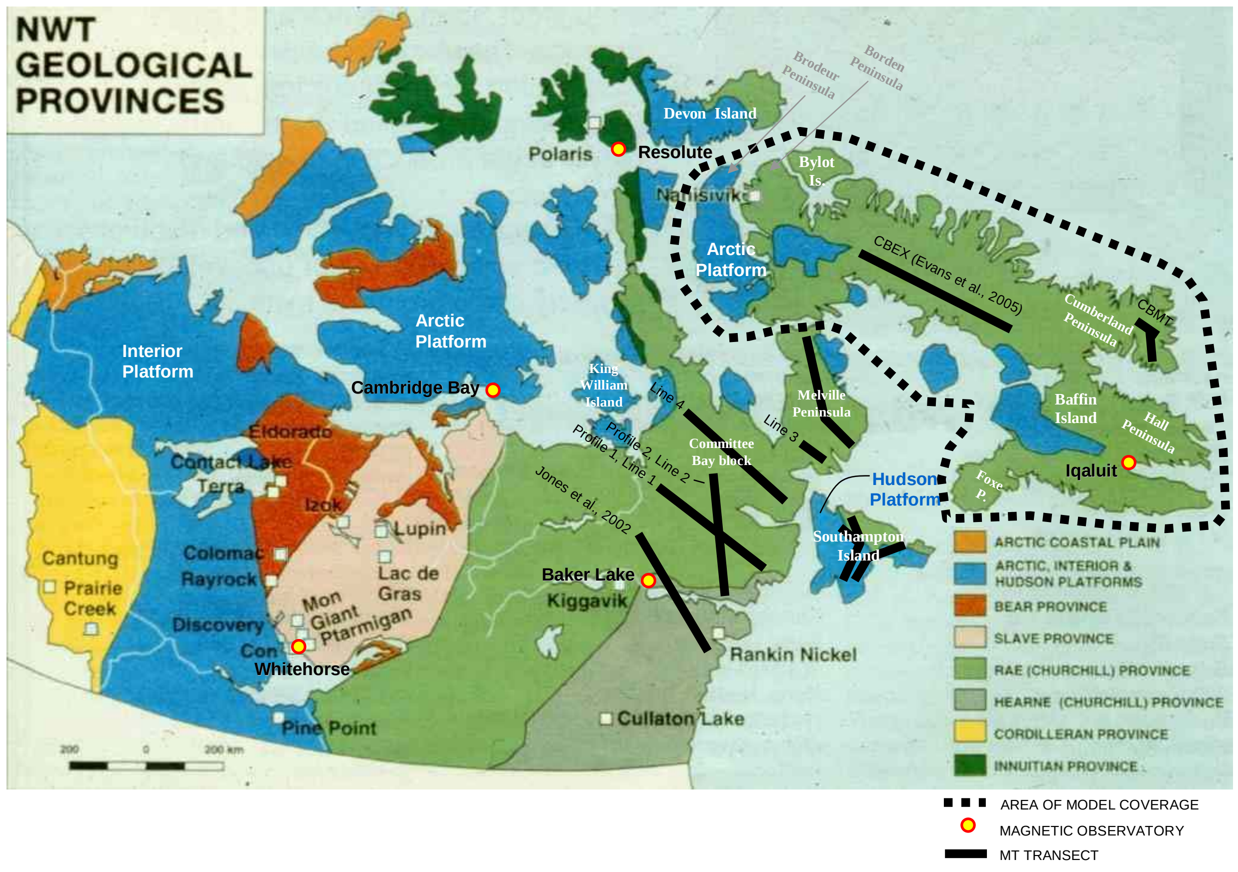
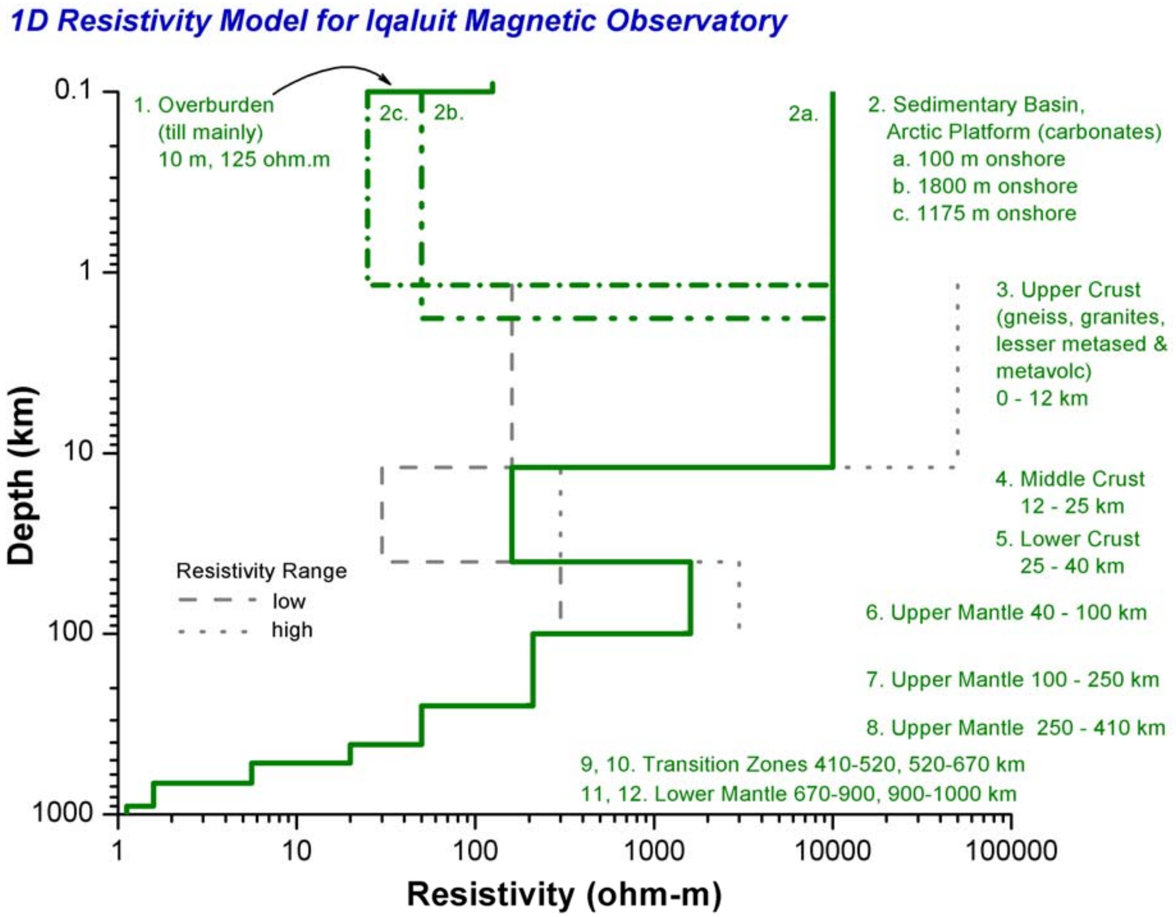


Figure A2.5.1. Area of coverage (dashed line) for the Iqaluit 1D model. MT transects shown as thick lines. MT transect across central Baffin Island described in [2]. Other MT surveys in eastern mainland Nunavut include Baker Lake area and described in previous Appendix A2.3, page 34 (1-D model for Baker Lake Observatory).

<u>Presentation of Findings</u>

The Iqaluit 1D model is presented in Figure A2.5.2. Accompanying Table A2.5.1 summarizes individual layer depths, thickness, and resistivity/conductivity for the model. Note that Layer 2 has been subdivided into three subzones to reflect the varying onshore thickness of sedimentary basin occurrences on Baffin Island. Resistivity value for Layer 6, uppermost mantle, is an averaging of resistivity individually unique to the Rae Domain and THO.



Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure A2.5.2. 1D Earth resistivity model proximal to the Iqaluit (Nunavut) magnetic observatory. Layer 2 – Sedimentary Basin – of varying onshore thickness. Refer to Table A2.5.1 for additional details.

Table A2.5.1.
1D Earth Resistivity Model Proximal to the Iqaluit (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
1. Overburden	0 - 40m range [7,8]	10 m (typical)	125 [9]	0.008	Within continuous permafrost region. Thickness variable: 200-600m at north end of Baffin and nearby islands [10]; ~100 m [11] or estimated 300-600 m [12] beneath Iqaluit.
	[I]		[I]		
		Baffin: Till veneer (<2m), discontinuous and till blanket (<10m), patchy, is predominant [7,13] except on parts of shoreline and in mountainous areas. Till moraine (< 20 to <40m) in southern areas near Iqaluit [7,8]. Till has sandy matrix, with cobbles and boulders. Resistivity for tills: range 50-200 ohm.mm in SE Baffin [9]; 20-100 [14] in central and eastern Canada; 25 (unfrozen) - < 300 frozen [15] Coastlines have patchy deposits of marine sediments, typically clay and silt veneer in south part of Baffin, and patchy glaciomarine sand and gravel blanket in central and north Baffin [7,8,13]. Deposits extend < 10 km inland except < 90 km at Cape Dominion. Offshore islands covered with glaciomarine coarse sediment, typically as veneer < 2m thick, sometimes as blanket < 20 m thick. Marine deposited silt and silty sand ranges: 1000-5000 ohm.m [9] in SE Baffin. In NWT, silty sand 300-1000 ohm.m (unfrozen) to 1000-3000 ohm.m (frozen) [16]; 30-1000 ohm.m [15] Iqaluit: Between bedrock ridges are mixed deposits of marine sediment (sand, silt & gravel) and glaciomarine delta (silt, sand, gravel, boulders), with lesser amount of glaciofluvial and alluvial sediments (sand, gravel) [17].Till veneer predominant surrounding community and Frobisher Bay. Layer 1, till dominant, assigned midpoint thickness based on common maximum thickness (<10m) and midpoint of resistivity range 50-200 ohm.m. Potentially could be higher, e.g. >300 ohm.			

Table A2.5.1 (continued)
1D Earth Resistivity Model Proximal to the Iqaluit (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
2a.Sedimentary Basin (central & southern Baffin Island)	0 – > 600 m (offshore max.) [18]	100 m (onshore midpoint)	50 [19,20,21]	0.02	Arctic Platform: Onshore thickness west side Baffin Island 20-180m, gently-tilted Paleozoic strata (limestone, dolostone, lesser shale). Offshore Foxe Basin ~600m, mostly Paleozoic strata (limestone, dolostone, shale, basal clastic), uppermost Silurian strata (limestone) [18].
	[I]		[II]		
		Resistivity range for Paleozoic carbonate-dominant sediments at: CNSC, 20-100 ohm.m [19]; WCSB in northcentral Manitoba, 10-100 ohm.m [21]; WCSB in southeastern Manitoba, 20-50 ohm [20]. Paleozoic shale beds on Southampton Island, 10 ohm.m [24]. Unspecified Paleozoic sediments of Interior Platform in NWT, ~100 ohm.m over 1-2 km thickness [25]. Layer 2a: Assigned 50 ohm.m based on mid-point of range for Paleozoic carbonate dominant sediments; possbily higher (~100 ohm.m) due deep permafrost (>100m) [11] or 300-600m [12].			
2b.Sedimentary Basin (northwest Baffin Island)	0 – >3000 m (offshore max.) [22]	1800 m (onshore maximum)	50 [19,20,21]	0.02	Arctic Platform: Brodeur and Borden Peninsulas have largest exposure of sedimentary basin on Baffin Island. Onshore thickness ~1800m, gently-tilted Paleozoic strata (limestone, dolostone, lesser siliclastics). Offshore Prince Regent Basin >3000m [22].
	[II]		[II]		Layer 2b: Assigned same resistivity for reason described in Layer 2a. Permafrost 400-600m in northern half of Baffin Island [10].
2c.Sedimentary Basin (north tip of Baffin Island)	<4 ~12 km (offshore max.) [23]	1175 m (onshore maximum)	25 [estimate]	0.04	Arctic Platform: Southern side of Bylot Island and limited exposure on north end Baffin Island, flat to gently-tilted Mesozoic / Cenozoic clastic sediments (sandstone, shale, mudstone). Onshore thickness ~1175m [26]. Offshore thickness of Eclipse Trough <4 km; Lancaster Basin 6 km; Baffin Basin 12 km [23].
	[II]		[III]		Layer 2c: Assigned estimated 25 ohm.m to reflect presence of more conductive shale and mudstone. Permafrost 400-600m in northern half of Baffin Island [10].

Table A2.5.1 (continued)

1D Earth Resistivity Model Proximal to the Iqaluit (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
3. Upper Crust	0 – 12 km [1,2]	12 km	10000 [1,2]	0.0001	Layer 3 comprised of Archean Rae domain (gneiss, lesser metavolc & metased), Paleoproterozoic Trans-Hudson Orogen (metasediments) and collage of microcontinents/cratonic blocks. Two MT transects, across central Baffin [1,2] and Cumberland Peninsula. Asigned ~ 12 km lower depth based on generalized MT survey resistivity change. *<u>Rae Domain</u>*: >10000 ohm.m [1,2]. On eastern mainland Nunavut, Rae Domain exhibits >50000 ohm.m [27,28] *<u>THO (Piling Group)</u>*: metasedimentary conductive zone (<4-160 ohm.m) at ~12km [1,2]. Similar conductive Penrhyn Group metasediments on south-central Melville Peninsula, southwest of Baffin Island. Upper 3 km is 6000 ohm.m. *<u>Cumberland Batholith</u>*: >10000 ohm.m; north margin of batholith exhibits localized conductors (<4 om.m) from 3 - 40km depth [1,2]. Correlative Whataman Batholith in Saskatchewan is >10000 ohm.m [29]. <u>Layer 3</u> assigned >10000 ohm.m on basis of predominance of resistive Rae Domain crust and Cumberland Batholith.
	[I]		[I]		
4. Middle Crust	12 – 25 km [1,2,30]	13 km	160 (midpoint) [1,2]	0.00625	Used generalized lower depth, typical of Layer 4 in Canada [30]. MT survey [1,2] shows resistivity change at some locations at 25km depth. Assigned a resitivity midpoint value, based on range 30-300 ohm.m, of conductive layer across most of central Baffin. Similar conductive middle crust on south-central Melville Peninsula.
	[I, III]		[I]		

Table A2.5.1 (continued)

1D Earth Resistivity Model Proximal to the Iqaluit (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
5. Lower Crust	25 – 40 km [4,32,33]	15 km	160 (midpoint) [1,2]	0.00625	Variable lower depth based on teleseismic studies. Crust/mantle boundary depth decreases northward, 46-43km at southern end Baffin (within Meta Incognita microcontinent block) to 37-39km in central Baffin [32, 33]. At Iqaluit 43km. At Cape Dorset and westward 35-37km. At Hall Peninsula 39km. At Cumberland Peninsula 30 or 36km. At Pond Inlet 34 km. Central Baffin 43km [4]. Assigned same resistivity values as Layer 4-Middle Crust due no significant resistivity change.
	[I]		[I]		
6. Upper Mantle	40 – 100 km [30]	60 km	1600 (midpoint) [1,2]	0.000625	Used generalized lower depth [30]. *Rae Domain*: > 3000 ohm.m [1,2], resistive mantle dips southerly *THO*: ~300 ohm.m [1,2] Layer 6 assigned midpoint value. To the southwest,mantle below entire Melville Peninsula ranges 100-5000 and at Southhampton Island 100-300 ohm.m. [24,27,34].
	[III]		[I]		
7. Upper Mantle	100 - 250 km [31]	150 km	210 [31]	0.0048	Utilized Canada regional model [31] for all depths and resistivities below 100 km.
	[III]			[III]	
8. Upper Mantle	250–410 km [31]	160 km	50 [31]	0.02	---
	[III]			[III]	

Table A2.5.1 (continued)
1D Earth Resistivity Model Proximal to the Iqaluit (Nunavut) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
9. Transition Zone	410–520 km [31]	110 km	20 [31]	0.05	---
	[III]			[III]	
10. Transition Zone	520–670 km [31]	150 km	5.6 [31]	0.178	---
	[III]			[III]	
11. Lower Mantle	670–900 km [31]	230 km	1.58 [31]	0.63	---
	[III]			[III]	
12. Lower Mantle	900–1000 km [31]	100 km	1.12 [31]	0.89	---
	[III]			[III]	

Table A2.5. 1 (continued)

1D Earth Resistivity Model Proximal to the Iqaluit (Nunavut) magnetic observatory

CNSC	Churchill Natural Studies Centre
NACP	North Americal Central Plains
NWT	Northwest Territories
SE	Southeast
THO	Trans-Hudson Orogen
WCSB	Western Canada Sedimentary Basin

NOTES:

Depth Confidence

- I = best representation
    - * overburden: geological report/map coverage of local area.
    - * crust: seismic/gravity transects crossing local area, within 10 km.
- II = likely representative
    - * crust/upper mantle: geological and/or seismic transect of a regional nature.
- III = possibly representative (measurements from general compilations).

Resistivity/Conductivity Confidence

- I = best representation (measurements from site or nearby).
    - * overburden: resistivity measurement by surface geophysical method and/or borehole in local area.
    - * crust: resistivity measurement from resistivity survey, MT survey and/or borehole in local area.
- II = likely representative (resistivity values extrapolated from measurements taken at some distance from the site, typically greater than 100 km).
    - * overburden: resistivity value obtained by geophysical measurement, including borehole logs.
    - * sedimentary basin: value obtained by geophysical survey using variety of geophysical electromagnetic methods, including MT.
    - * crust: value obtained by regional MT survey.
- III = possibly representative (measurements from general compilations).

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A2.6. Meanook magnetic observatory, Alberta

The model area is located in the western half of the Western Canada Sedimentary Basin (WCSB), see Figure A2.6.1. Assembly of the resistivity values for crust and uppermost mantle relied on the results of magnetotelluric (MT) surveys such as the Lithoprobe Alberta Basement Transect (ABT) undertaken in the mid-1990s. A total of 320 MT soundings, as well as seismic recordings, were made during the ABT deployment. In northern Alberta, 23 MT soundings were completed in 2004-2006 [1,2] while in southern Alberta 67 MT soundings were done in 2008-2010 (see [3,4]). The following conductive anomalies (Fig A2.6.1) have been identified [1,2,4,5]: Kiskatinaw conductor (KC), ~10 ohm.m, located between 20 and 50 km; Red Deer Conductor (RDC), <10 ohm.m, depth <10km; Loverna Block Conductor (LB), <50 ohm, dominantly ~5-10 ohm.m, extended at ~40-100 km; Linear Foothills Anomaly (LFH), conductor (<10 ohm.m) at 2 km depth.

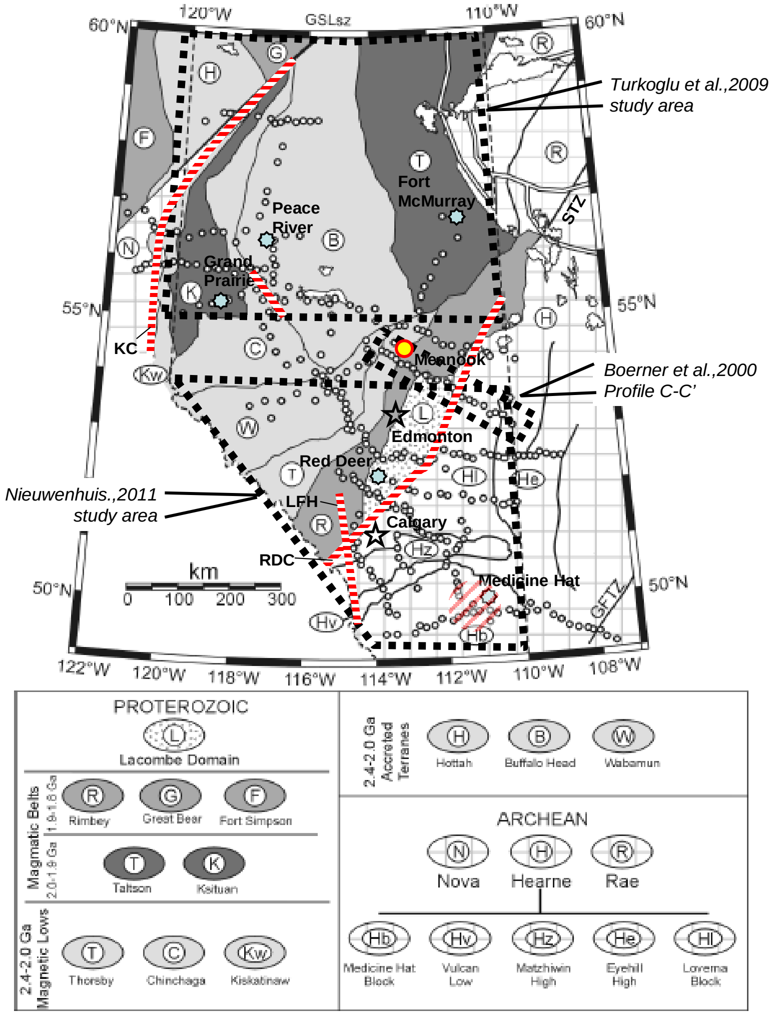
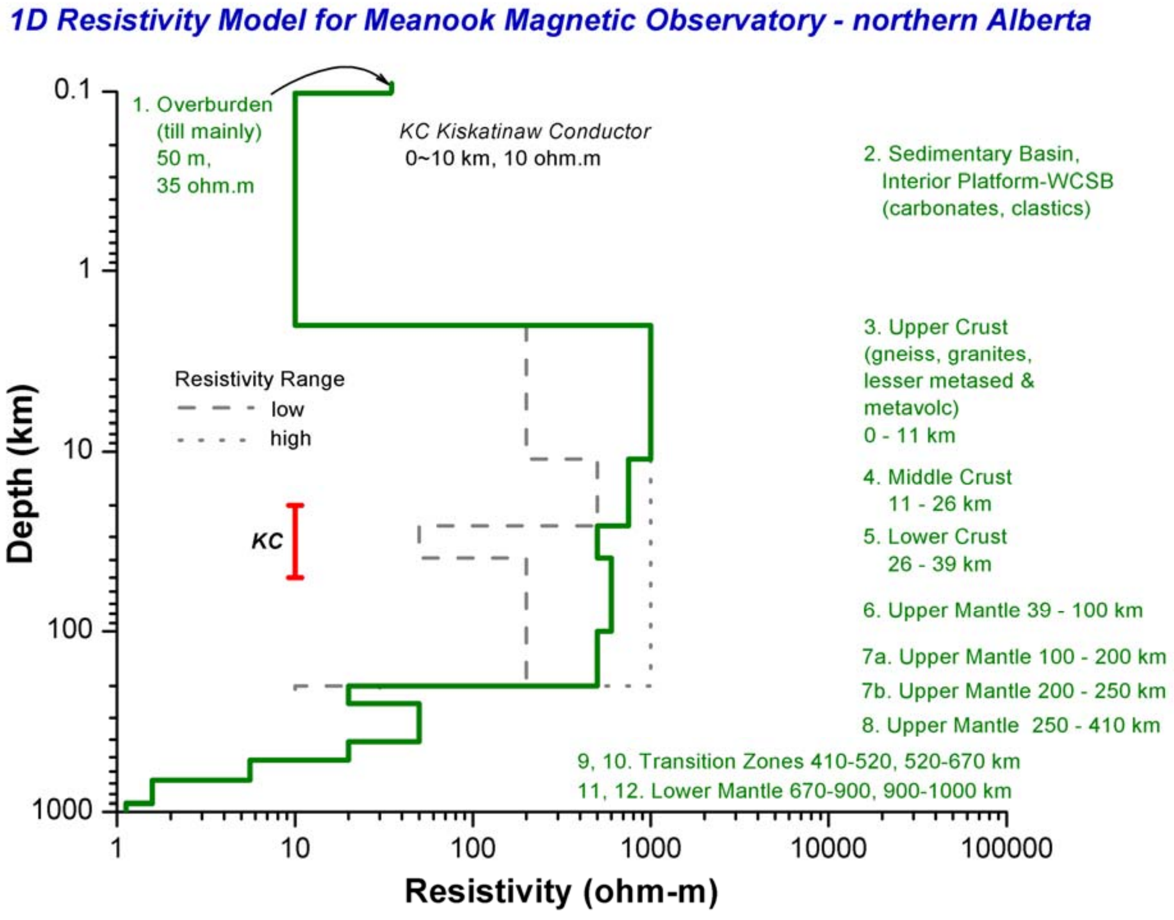


Figure A2.6.1. Map of conductive anomalies and tectonic elements of Alberta. General location of linear conductors is shown as thick red lines and a circle. Small circles represent locations of the 320 magnetotelluric stations occupied between 1993 and 1996 for the Alberta Basement Transect Experiment. GFTZ, Great Falls tectonic zone; GLSsz, Great Slave Lake shear zone; KC, Kiskatinaw Conductor; LFH, Linear Foothills Anomaly; RDC, Red Deer Conductor; STZ, Snowbird tectonic zone (*modified from* [6]). Meanook geomagnetic observatory (MEA) is shown as yellow circle.

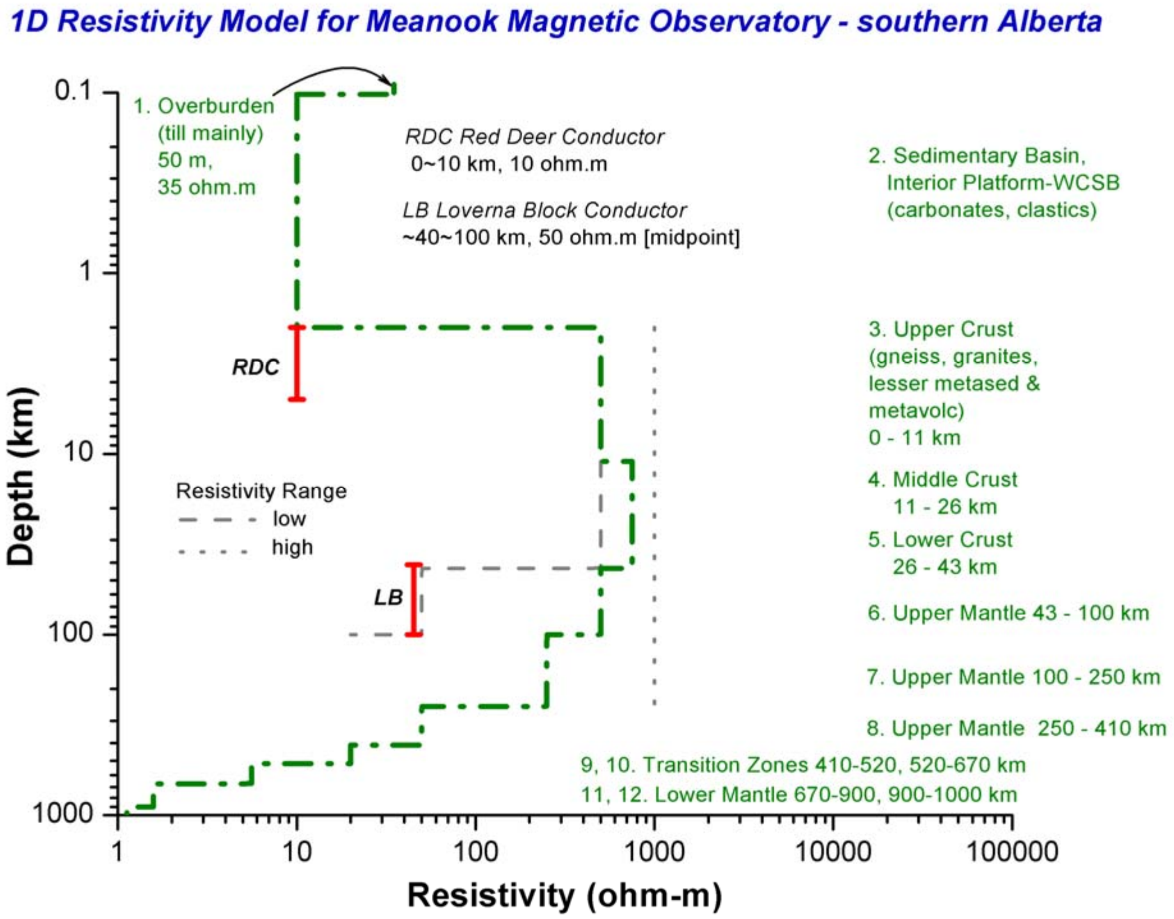
Geological Setting

Presented are two separate 1D block models (Figures A2.6.2, A2.6.3) and joint one (Figure A2.6.4), representing the vertical variance of electrical resistivity in northern and southern Alberta proximal to the Meanook magnetic observatory. Accompanying Table A2.6.1 summarizes individual layer depths, thickness, and resistivity/conductivity for both models.


1D Resistivity Model for Meanook Magnetic Observatory - northern Alberta

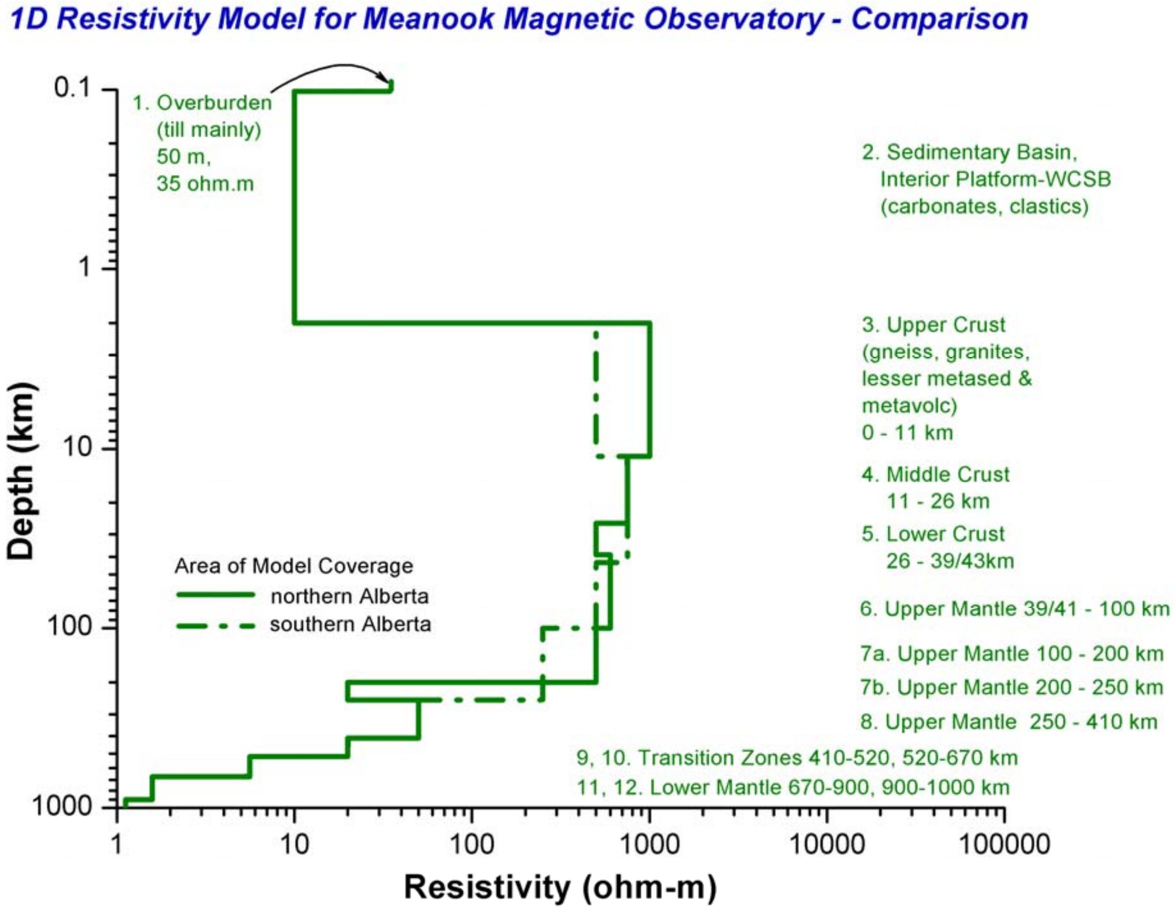
Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure A2.6.2. 1D Earth resistivity model proximal to the Meanook magnetic observatory within northern half of Alberta. Refer to Table A2.6.1 for additional details.



Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure A2.6.3. 1D Earth resistivity model proximal to the Meanook magnetic observatory within southern half of Alberta. Refer to Table A2.6.1 for additional details.



1D Resistivity Model for Meanook Magnetic Observatory - Comparison

Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure A2.6.4. Comparison of the northern and southern Alberta 1D Earth resistivity models proximal to the Meanook magnetic observatory. Refer to Table A2.6.1 for additional details.

Table A2.6.1
1D Earth Resistivity Model Proximal to the Meanook (Alberta) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
1. Overburden	0 – 50 m [7,8]	50 m	35 [8,9,10]	0.028	Till is predominant, mostly as thicker blanket, with patchy areas of fine-grained (clay, silt) glaciolacustrine deposits and smaller areas with coarse-grained (silt, sand, gravel) glaciolacustrine deposits [11]. Overburden typically <50m [7] but variable and thicker in pre-glacial bedrock channels. Meanook < 50m. NE of Edmonton commonly 60-300m. NW corner Alberta 250-300m [7]. Rock Mountain Foothills and western upland regions usually <5m [8]. Edmonton region >50m, south of Edmonton to USA <30m [8]. Assigned overall thickness of 50m. Airborne resistivity survey profiles over central Alberta indicate ~20 ohm.m, plan view maps show 10-20 ohm.m at 20m depth [12]. Borehole logs of Manitoba overburden show 40-50 ohm.m for till and 70-200 ohm.m for sand and gravel [10]. Resistivities for tills range 20-100 ohm.m [9]. MT survey in SE Manitoba indicates 5-30 ohm for mix of till, clay, silt and sand [13]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [14]. Assigned midpoint of resistivity range 20-50 ohm.m.
	[I]		[I, II]		

Table A2.6.1 (continued)

1D Earth Resistivity Model Proximal to the Meanook (Alberta) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
2. Sedimentary Basin	< 5.5 km [15] [I]	2 km (midpoint)	10.0 [1,2, 4,16, 17] [I]	0.1	WCSB of Interior Platform overlies much of model area, generally <3 km thick, deepening southwestward Thickens to 5.5 km trough in front of Cordillera mountain ranges [15]. Northern Alberta (north of 55 degree north): 2 km thick at Peace River and Meanook, 2.5 km at Edmonton, 4 km at Grande Prairie [15]. Lower strata consist of Paleozoic carbonate, shale and evaporite. Upper strata consist of Mesozoic marine shales, and alternating sandstone and shales [1] Basin resistivity ~10 ohm.m [1], at 1.7 km depth overall ~10 ohm.m (9). Low resistivity attributed to presence of pore fluids in sedimentary rock [15] Southern Alberta (south of 55 degree north): 2.2 km thick at Medicine Hat, 4 km thick at Calgary [15] Basin resistivity (north and south Alberta) ~5 [16]. Low resistivity attributed to presence of marine carbonaceous shales (up to 700 m thick) [16]. MT survey shows upper strata (0-2 km deep) of Mesozoic sandstone, siltstone and shale exhibits ~10 ohm.m, with lower strata (2-4 km deep) of Paleozoic carbonate with lesser shale and evaporite exhibiting 50-100 ohm [17]. MT profiles show 5-10 ohm.m [4] Layer 2: Assigned 10 ohm.m representing upper end of resistivity determinations.

Table A2.6.1 (continued)

1D Earth Resistivity Model Proximal to the Meanook (Alberta) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
3. Upper Crust	0 ~ 11 km [18]	11 km	North Alberta 1000 [2, 16]	North Alberta 0.001	Upper crust made up of Proterozoic age crustal fragments accreted to older Archean Rae and Hearne Domains. Crystalline basement rock comprised metamorphic gneisses, supracrustal rocks and intrusives. Lower depth scaled from trans-continental seismic transect (11-12 km) across southern Alberta [18], southern Alberta seismic transect (10-11 km) [19]. MT survey shows resistivity change at 10-15 km depth [4]. Applied ~11 km depth to entire area.
	[I]		[I]		
			South Alberta 500 [4,16]	South Alberta 0.002	<u>Northern Alberta</u>: Comprises granitoids, metasedimentary gneisses, granitic basement gneisses, and amphibolites and minor amount metasediments and metavolcanics [20,21,22] 2D/3D profiles show 200-1000 ohm.m range, predominantly 1000 ohm.m, with Kiskatinaw Conductor exhibiting 10 ohm.m [2].
			[I]		
			All Alberta 750	All Alberta 0.0013	Lithoprobe MT surveys show overall >1000 ohm.m with conductive (5-50 ohm.m) pods and dipping zones [16]. Proximal to Meanook, overall > 1000 ohm.m [16]
		<u>Southern Alberta</u>: Granites form the Proterozoic *Rimbey Domain*. Low-grade metamorphosed supracrustal rocks (metasediments and felsic metavolcanics) comprise the Proterozoic *Lacombe Domain* Granite and granitic gneiss makes up the Archean *Loverna Block*. Gneiss is predominant in the *Medicine Hat Block* [16, 22] *Rimbey Domain* and *Lacombe Domain*, predominantly 500 ohm.m. *Loverna Block*, predominantly 500 ohm.m with conductive (<10 ohm.m) pods. *Vulcan Structure* and *Medicine Hat Block* predominantly 500 ohm.m [4]. Lithoprobe MT surveys show overall >1000 ohm.m with conductive (1-25 ohm.m) pods and dipping zones [16]. 3D model profiles show crustal resistivity of 5000-10000 ohm.m with Red Deer Conductor exhibiting <10 ohm.m [4]. <u>Layer 3</u>: Northern Alberta assigned 1000 ohm.m based on its predominant resistivity value, excluding upper crust KC. Southern Alberta assigned 500 ohm.m based on its predominant resistivity value, excluding upper crust conductors.			

Table A2.6.1 (continued)

1D Earth Resistivity Model Proximal to the Meanook (Alberta) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
4. Middle Crust	11 ~ 26 [18,19]	15 km	North Alberta 750 [2]	North Alberta 0.0013	Lower depth scaled from trans-continental seismic transect (26-34 km) across southern Alberta [18], provincial transect (26 km) [23] and southern Alberta transect (20-30 km [19]. Applied ~26 km depth to entire model area. Northern Alberta: 2D/3D profiles show 200-1000 ohm.m range, predominantly 1000 ohm.m, with conductive (50-150 ohm.m) zone underlying axis of Kiskatinaw Conductor [2]. 3D depth slice at 20 km shows 500-1000 ohm.m away from Kiskatinaw Conductor [2]. Lithoprobe MT surveys show overall >1000 ohm.m with conductive (5-50 ohm.m) pods and dipping zones, same as Layer 3 [16]. Proximal to Meanook, overall > 1000 ohm.m, same as Layer 3 [16] Southern Alberta: *Rimbey Domain* and *Lacombe Domain*, >1000 ohm.m except dipping narrow conductor (<10 ohm.m) below Rimbey Domain. *Loverna Block*, range 500-1000 ohm.m, predominantly 500 ohm.m with conductive (<10 ohm.m) pods. *Vulcan Structure*, 500 ohm.m with dipping conductor (<5 ohm.m). *Medicine Hat Block* predominantly 500 ohm.m [4]. Lithoprobe MT surveys show overall >1000 ohm.m with conductive (1-25 ohm.m) dipping zones [16]. Layer 4: Northern Alberta assigned midpoint 750 ohm.m based on range 500-1000 ohm.m, excluding conductivity halo of the KC feature. Southern Alberta assigned midpoint 750 ohm.m based on range 500-1000 ohm.m, excluding discrete middle crust conductors.
	[I]		[I]		
			South Alberta 750 [4]	South Alberta 0.0013	
			[I]		
			All Alberta 750	All Alberta 0.0013	

Table A2.6.1 (continued)

1D Earth Resistivity Model Proximal to the Meanook (Alberta) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
5. Lower Crust	26 – 41 km [6]	15 km	North Alberta 500 [2]	North Alberta 0.002	Variable lower depth, 35-48 km [6] with mantle high and low areas. Depth increases southwestward and southward, ~35 km at Fort McMurray, 40 km at Meanook, and 43 km at Calgary. Northern and northeastern Alberta has thinner crust < 39 km. Southwestern and southern part of Alberta has thicker crust ~43 km. Assigned midpoint ~41 km based on 35-47 km range Northern Alberta: 2D/3D profiles show 200-1000 ohm.m range, predominantly 1000 ohm.m, with conductive (75-150 ohm.m) zone underlying axis of Kiskatinaw Conductor [2]. 3D depth slice at 41 km shows 50-1000 ohm.m, with greater amount of conductivity spreading out from KC feature [2]. Southern Alberta: Domains and Blocks and Vulcan Structure exhibit same resistivity values and distribution as Layer 4. Lithoprobe MR survey profiles end at 30 km depth [16]. Layer 5: Northern Alberta assigned midpoint 500 ohm.m based pm range 50-1000 ohm.m, incorporating greater spread of conductivity. Southern Alberta assigned midpoint 750 ohm.m based on range 500-1000 ohm.m, excluding discrete middle crust conductors (no significant difference compared to Layer 4)
	[I]		[I]		
			South Alberta 750 [4]	South Alberta 0.0013	
			[I]		
			All Alberta 625	All Alberta 0.0016	

Table A2.6.1 (continued)

1D Earth Resistivity Model Proximal to the Meanook (Alberta) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
6. Upper Mantle	41 - 100 km [25]	61 km	North Alberta 600 [2]	North Alberta 0.00167	Used generalized lower depth [25]. Northern Alberta: 2D/3D profiles show 200-1000 ohm.m range, predominantly 1000 ohm.m [2] 3D depth slice at 65 km shows 200-1000 ohm.m extending away from Kiskatinaw Conductor [2]. Southern Alberta: Proterozoic *Rimbey Domain* and *Lacombe Domain*, 1000 ohm.m. Archean *Loverna Block*, 5-100 ohm.m range, with a large conductive zone of 5 ohm.m known as the Loverna Conductor; assigned midpoint 50 ohm.m to account for a very conductive zone surrounded by halo of ever increasing resistivity. Archean *Vulcan Structure, Medicine Hat Block*, range 500-1000 ohm, midpoint 750 ohm.m [4]. Layer 6: Northern Alberta: assigned midpoint 600 ohm.m based on range of 200-1000 ohm.m. Southern Alberta: assigned midpoint ~500 ohm.m based on range of 50-1000 ohm.m. Note significant resistivity difference between Archean upper mantle below the *Loverna Block*, 50 ohm.m, and (a) Proterozoic upper mantle, 1000 ohm.m, situated to the north and (b)remainder of Archean upper mantle below *Vulcan Structure* and *Medicine Hat Block*, 500-1000 ohm.m situated south of *Loverna Block*.
	[III]		[I]		
			South Alberta 500 [4]	South Alberta 0.002	
			[I]		
			All Alberta 550	All Alberta 0.0018	

Table A2.6.1 (continued)

1D Earth Resistivity Model Proximal to the Meanook (Alberta) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
7. Upper Mantle	100 - 250 km [25] [III]	150 km	North Alberta {100-200km} 500 [2] North Alberta {200-250km} 20 [2] [I] South Alberta 250 [4] [I] All Alberta 375	North Alberta {100-200km} 0.002 North Alberta {200-250km} 0.05 South Alberta 0.004 All Alberta 0.00267	Used generalized lower depth [25]. Northern Alberta: 2D profiles show rapid gradation 200-1000 to 10-25 ohm.m to depth of 200 km, then mainly 10-25 ohm.m at depth of 200-250 km [2]. 3D profiles show consistent 500-1000 ohm.m to depth of 200 km, then 10-30 ohm.m at depth of 200-250 km [2]. Southern Alberta: *Rimbey Domain* and *Lacombe Domain*, 20-500 ohm.m. *Loverna Block* becomes conductive overall,10-75, 10-500, 10-50 and 5-25 ohm.m range as progress southwestward. *Vulcan Structure* images as a 500-1000 ohm.m north dipping resistor. *Medicine Hat Block*, range 50-500 ohm.m, assigned midpoint 275 ohm.m [4]. MT survey shows below *Loverna Block* a decrease of 5000 to 250 ohm across depth of 100-150 km, and 3000 to 250 ohm.m across depth of 150-250 km [24] Layer 7: Northern Alberta: assigned midpoint 500 ohm.m for depth 100-200 km, and 20 ohm.m for depth 200-250 km. Southern Alberta: assigned midpoint ~250 ohm.m based on range of 20-500 ohm.m for depth 100-250 km.
8. Upper Mantle	250–410 km [25] [III]	160 km	50 [25]	0.019952	Utilized Canada regional model [25] for all depths and resistivities below 250 km.

Table A2.6.1 (continued)
1D Earth Resistivity Model Proximal to the Meanook (Alberta) magnetic observatory

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference, Confidence		
9. Transition Zone	410–520 km [25]	110 km	20 [25]	0.050	---
	[III]				
10. Transition Zone	520–670 km [25]	150 km	5.6 [25]	0.178	---
	[III]				
11. Lower Mantle	670–900 km [25]	230 km	1.58 [25]	0.63	---
	[III]				
12. Lower Mantle	900–1000 km [25]	100 km	1.12 [25]	0.89	---
	[III]				

NE	northeast
KC	Kiskatinaw Conductor
SW	southwest
WCSB	Western Canada Sedimentary Basin

Table A2.6.1 (continued)

1D Earth Resistivity Model Proximal to the Meanook (Alberta) magnetic observatory

NOTES:

Depth Confidence

- I = best representation
  - * overburden: geological report/map coverage of local area.
  - * crust: seismic/gravity transects crossing local area, within 10 km.
- II = likely representative
  - * crust/upper mantle: geological and/or seismic transect of a regional nature.
- III = possibly representative (measurements from general compilations).

Resistivity/Conductivity Confidence

- I = best representation (measurements from site or nearby).
  - * overburden: resistivity measurement by surface geophysical method and/or borehole in local area.
  - * crust: resistivity measurement from resistivity survey, MT survey and/or borehole in local area.
- II = likely representative (resistivity values extrapolated from measurements taken at some distance from the site, typically greater than 100 km).
  - * overburden: resistivity value obtained by geophysical measurement, including borehole logs.
  - * sedimentary basin: value obtained by geophysical survey using variety of geophysical electromagnetic methods, including MT.
  - * crust: value obtained by regional MT survey.
- III = possibly representative (measurements from general compilations).

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A2.7. Ottawa magnetic observatory, Ontario

General

Presented is a one-dimensional (1D) Earth model representing the vertical variance of electrical resistivity for Southern Ontario at the location of the Ottawa Geomagnetic observatory, as shown in Figure A2.7.1.

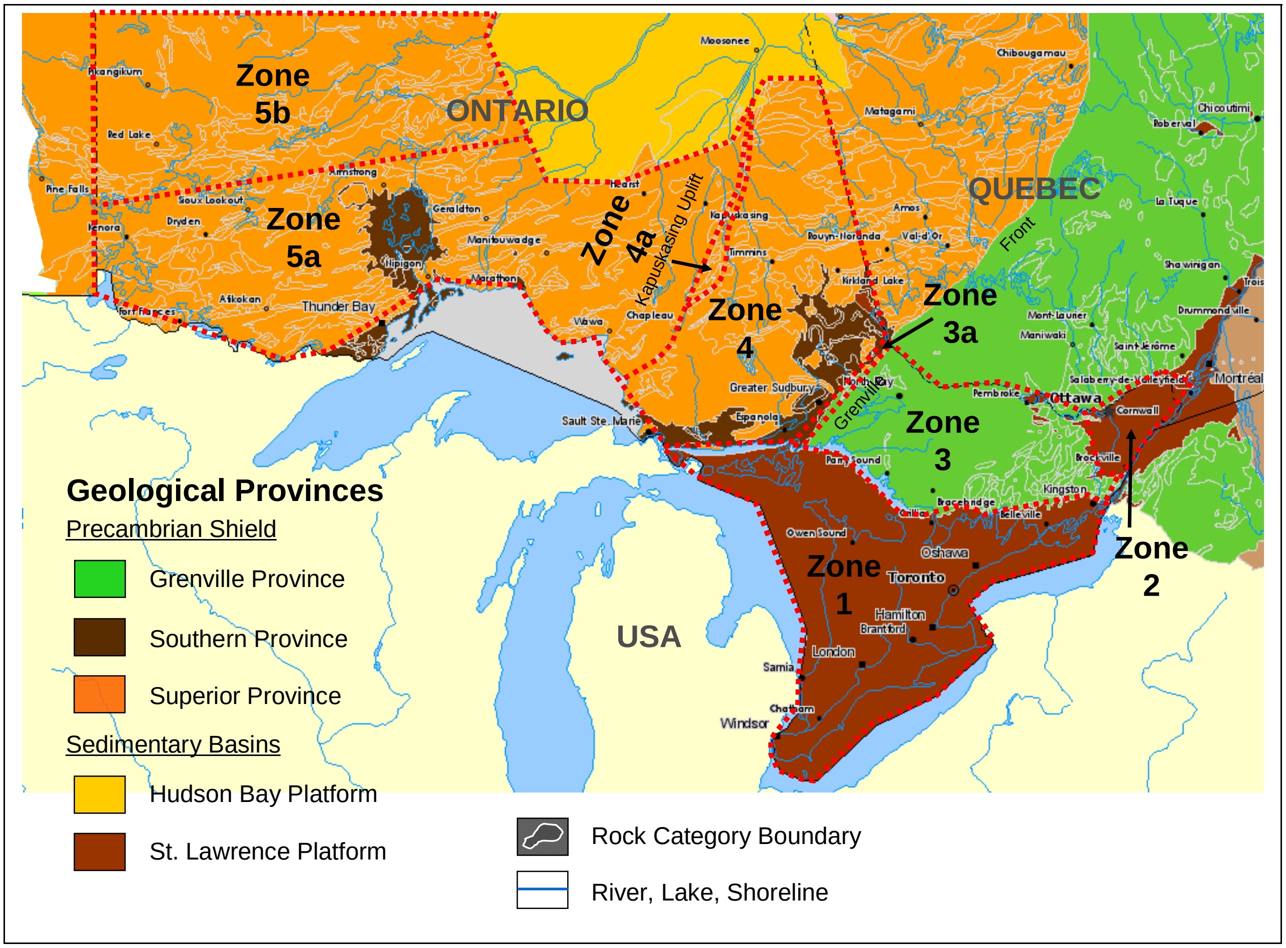

Figure A2.7.1. Location of several 1D Earth resistivity zones in Ontario (separated by the red dotted lines). Ottawa Magnetic Observatory is located within Zone 2, Central St. Lawrence Platform/Lowland.

Geological Setting

The 1D layered-Earth model corresponding to Ottawa observatory location (Zone2-Central St Lawrence Platform) is presented in Figure A2.7.2. Accompanying Table A2.7.1 summarizes the individual layer depths, thickness, and resistivity/conductivity for Ottawa 1D model, as well as sources of depth and resistivity values and justification for selection.

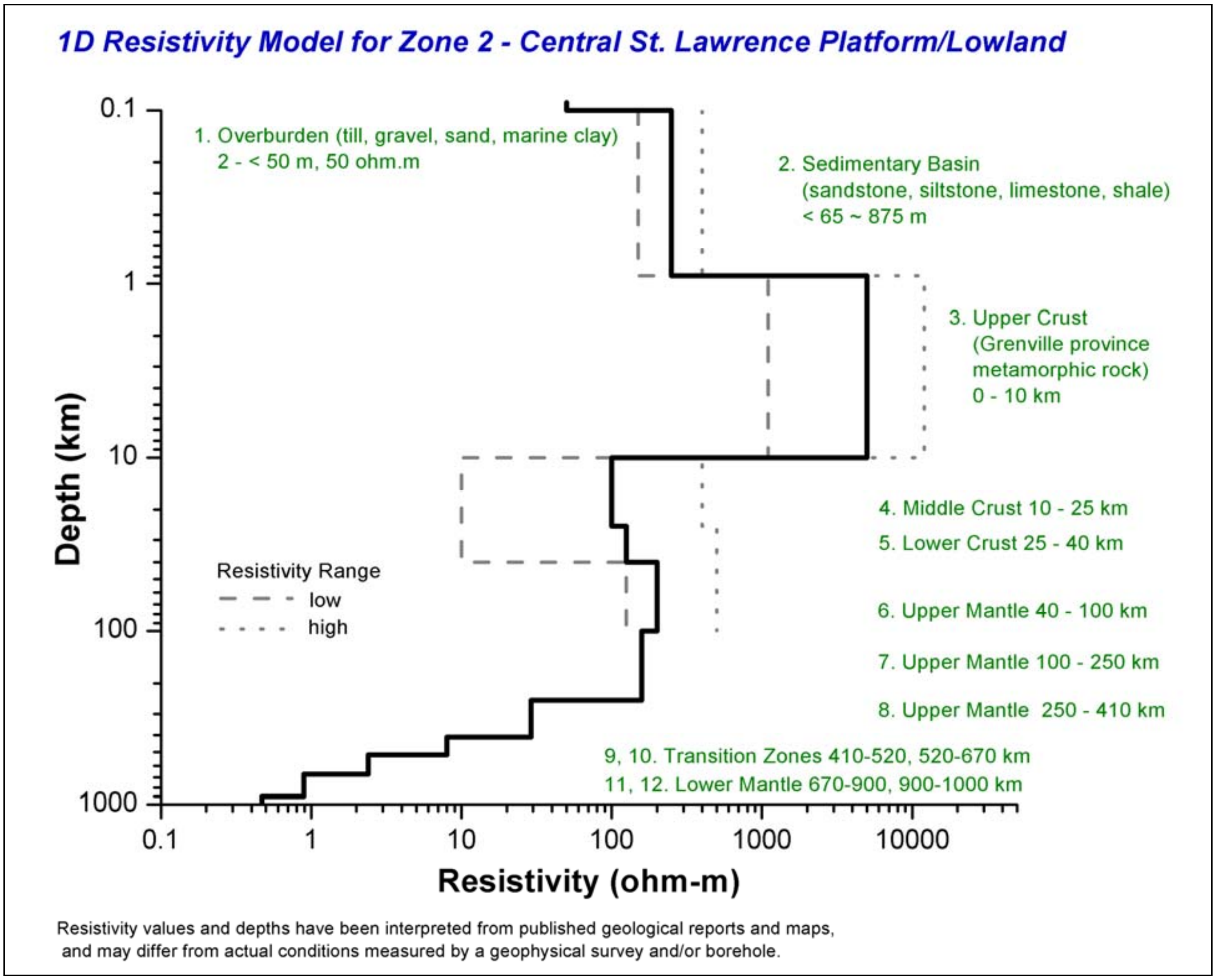

Figure A2.7.2. 1D Earth resistivity model, Zone-2, for the area encompassing the Central St. Lawrence Lowland (including Ottawa area). Refer to Table A2.7.1 for additional details.

Table A2.7.1

1D Earth Resistivity Model for Ottawa (Central St. Lawrence Platform / Lowland)

Layer	Depth	Thickness	Resistivity (ohm·m)	Conductivity (S/m)	Comments
	Reference [Confidence]		Reference [Confidence]		
1. Overburden	< 50 m [1, 2, 3] [II]	25 m	50 [4, 5] [II]	0.02	Glacial deposits (silt, sand, till), overlain by glaciomarine (Leda Clay) sediments mostly in northern and western 2/3 of platform. Variable depths, 2-50 m, typically <25 m, assigned midpoint depth. Leda Clay is conductive ranging 1-4 [4] or 1–20 ohm·m, 20-80 ohm.m [5]. Sand and till typically 100 ohm.m. Assigned midpoint value. Consider < 20 ohm.m where Leda Clay is extensive and thick.
2. Sedimentary Basin	< 65 – 875 m [1, 6] [II]	0.9 km	250 [5, 6, 7] [II]	0.004	Maximum thickness ~ 0.9 km at basin centre Depth from stratigraphic cross-sections. Variable resistivity based on lithology. Ottawa area sandstone and dolo/limestone ranges 250-400 ohm.m [6] or 2000-5000 [7], Ottawa Valley MT profile indicates < 150 ohm.m [5]. Dominant lithology influences overall resistivity, 250 ohm.m chosen to reflect predominance of more resistive sandstone, dolostone / limestone.

Table A2.7.1 (continued)
1D Earth Resistivity Model (Zone 2) for Central St. Lawrence Platform / Lowland

Layer	Depth	Thickness	Resistivity (ohm·m)	Conductivity (S/m)	Comments
	Reference [Confidence]		Reference [Confidence]		
3. Upper Crust	0 – 10 km [8] [II]	9.1 km	5000 [8] [II]	0.0002	Metamorphic rocks (gneisses, quartzite, marble) and intrusives (granite, syenite, gabbro) of the Grenville geological province Depth based on visual change of resistivity on Polaris Array transect [8] located 150 km west. Variable resistivity ranges determined by MT; 125-10000 [8], 1100-6000 ohm.m [5]. Assigned 5000 ohm.m to reflect a more conductive upper crust compared to more resistive Grenville province upper crust situated north of Zone 2.
4. Middle Crust	10 – 25 km [III]	15 km	100 [5, 8] [I, II]	0.01	No bottom depth distinction on [8]. Used generalized depth for middle crust \. Chose visually dominant resistivity on Polaris Array transect, TM mode. Ranges <10-125 on Polaris Array and 150-400 on Ottawa Valley MT transect.
5. Lower Crust	25 – 40 km [9] [I]	15 km	125 [8] [I, II]	0.005	Bottom depth varies 38-42 km [9], midpoint 40 km. Variable resistivity depending on transect and mode. Ottawa Valley TM mode has 250 ohm.m, Polaris array TM mode shows 125 ohm.m, and joint TE-TM mode range is <10-500 ohm.m. Assigned TM mode value of 125 ohm.m
6. Upper Mantle	40–100 km [10, 11] [III]	60 km	200 [8] [II]	0.004	Used generalized bottom depth [10, 11]. Variable resistivity depending on mode. 125-225 ohm.m for TM mode, 125-500 ohm.m for joint TM and TE mode on Polaris Array transect. Used midpoint of the two mode's range.

Table A2.7.1 (continued)

1D Earth Resistivity Model (Zone 2) for Central St. Lawrence Platform / Lowland

Layer	Depth Reference [Confidence]	Thickness	Resistivity (ohm·m) Reference [Confidence]	Conductivity (S/m)	Comments
7. Upper Mantle	100–250 km [11] [III]	100 km	158 [11] [III]	0.0063	Utilize Canada regional model [g] for all depths and resistivities below 100 km. Canada model based on data from Ottawa Magnetic Observatory located in Zone 2
8. Upper Mantle	250–410 km [11] [III]	160 km	29 [11] [III]	0.0346	---
9. Transition Zone	410–520 km [11] [III]	110 km	8 [11]	0.1258	---
10. Transition Zone	520–670 km [11] [III]	150 km	2.4 [11] [III]	0.4168	---
11. Lower Mantle	670–900 km [11] [III]	230 km	1.1220 [11] [III]	0.89	---
12. Lower Mantle	900–1000 km [11] [III]	100 km	0.47 [11] [III]	2.0892	---

Notes:

Depth Confidence
I = best representation
* overburden: geological report/map coverage of local area.
* crust: seismic/gravity transects crossing local area, within 10 km.
II = likely representative
* crust/upper mantle: geological and/or seismic transect of a regional nature.
III = possibly representative (measurements from general compilations).
Resistivity/Conductivity Confidence
I = best representation (measurements from site or nearby).
* overburden: resistivity measurement by surface geophysical method and/or borehole in local area.
* crust: resistivity measurement from resistivity survey, MT survey and/or borehole in local area.
II = likely representative (resistivity values extrapolated from measurements taken at some distance from the site,
typically greater than 100 km).
* overburden: resistivity value obtained by geophysical measurement, including borehole logs.
* sedimentary basin: value obtained by geophysical survey using variety of geophysical electromagnetic methods, including MT.
* crust: value obtained by regional MT survey.
III = possibly representative (measurements from general compilations

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A2.8. St. John’s magnetic observatory, Newfoundland

General

Presented is a one-dimensional (1D) Earth model representing the vertical variance of electrical resistivity for Newfoundland at the location of the St. John’s Geomagnetic observatory, as shown in Figure A2.8.1.

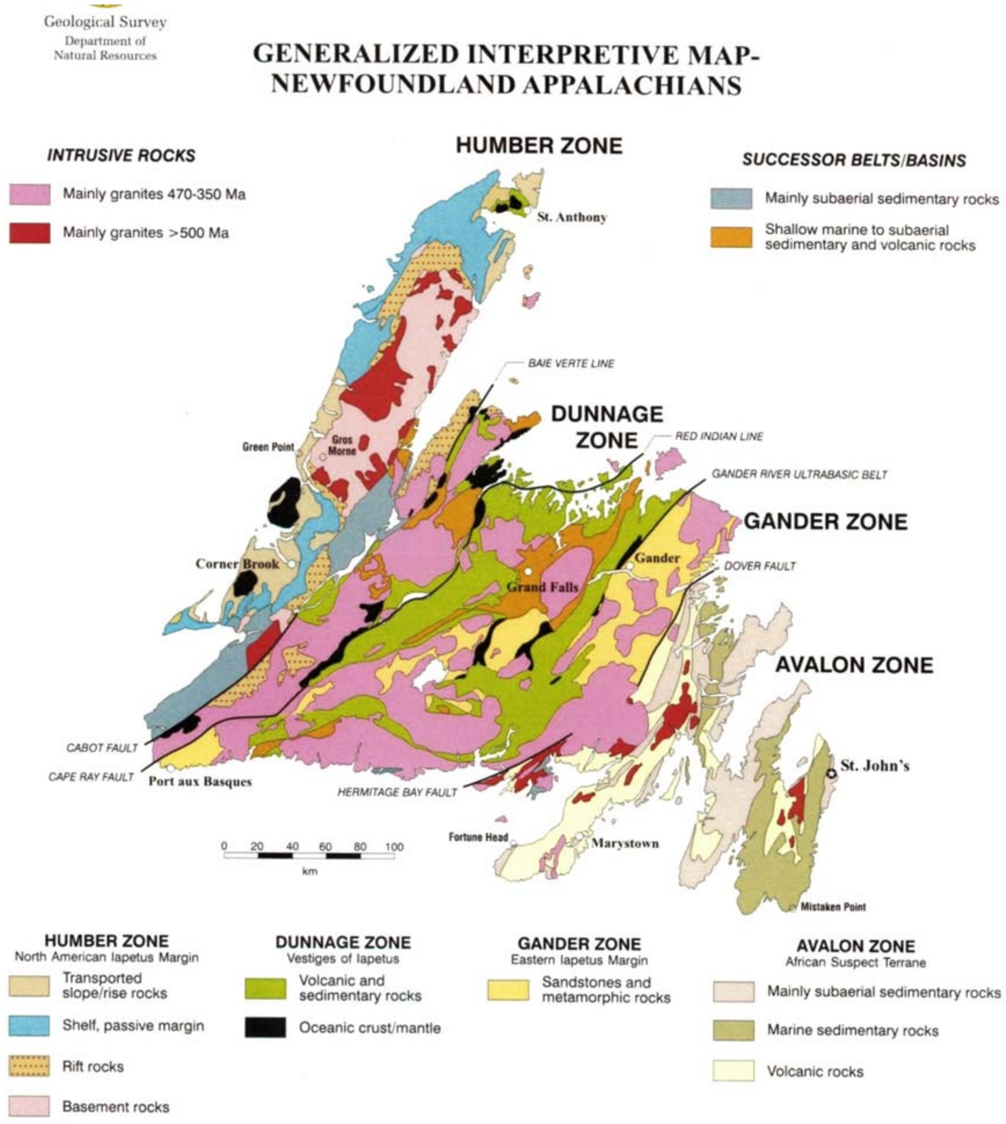
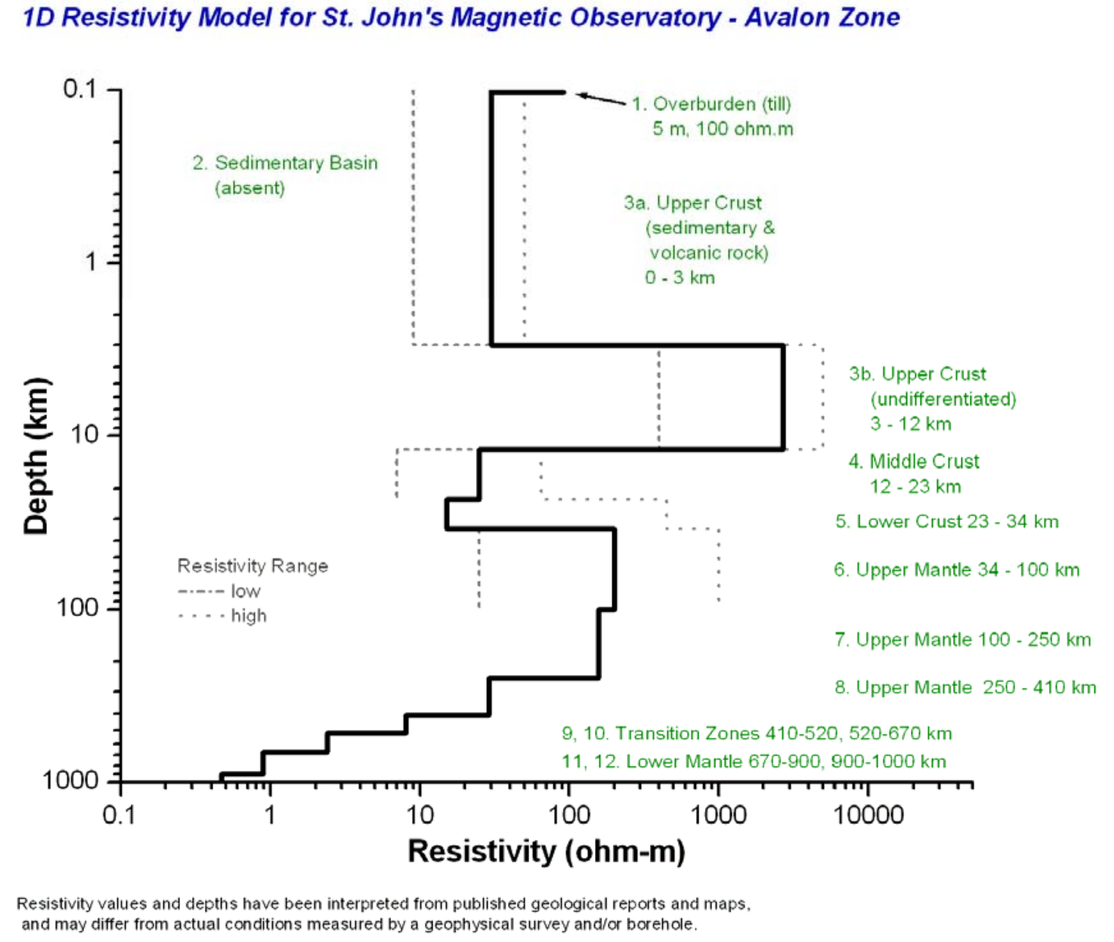


Figure A2.8.1. Major rock types and tectonic terranes (zones) underlying island of Newfoundland ([1]). Magnetic observatory located at St. John’s, i.e. within Avalon Zone.

Geological Settings

The 1D layered-Earth model corresponding to St. John's observatory location (Avalon Zone) is presented in Figure A2.8.2. Accompanying Table A2.8.1 summarizes the individual layer depths, thickness, and resistivity/conductivity for St. John's 1D model, as well as sources of depth and resistivity values and justification for selection.



Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure A2.8.2. 1D Earth resistivity model for the Avalon Zone on the Island of Newfoundland. Refer to Table A2.8.1 for the additional details and to Figure A2.8.1 for location of the St. John's magnetic observatory.

Table A2.8.1
1D Earth Resistivity Model for the St.John’s Magnetic Observatory – Avalon Zone

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	[reference]		[reference]		
1. Overburden	1.5 – 20 m [2]	8 m	100 [3]	0.01	Till is stoney, extensive and continuous except in higher ground where becomes discontinuous, varying thickness, ranges 1.5-6m [4] usually < 1.5m thick in northern half of peninsula [5]. Central part of peninsula dominated by thicker till blanket > 2m [6], may also range 2-15m and up to 20m thick where occur as till ridges. Glaciofluvial gravel and sand in valleys and outwash plains, 2-80m thick.
	Confidence [I]		Confidence [III]	Assigned overall 8m average thickness based on 1.5-15m range for tills being dominant. Assigned high-end of resistivity range for tills and presence of higher resistivity glaciofluvial material.	
2. Sedimentary Basin	absent	---	---	---	---

Table A2.8.1 (continued)

1D Earth Resistivity Model for the St. John’s Magnetic 0bservatory – Avalon Zone

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	reference		reference		
3a. Upper Crust	*Upper Sublayer* 0 – 5 km [7, 8]	*Upper Sublayer* 3 km	*Upper Sublayer* 30 [9]	*Upper Sublayer* 0.033	Late Precambrian igneous and sedimentary marine and subaerial clastic rocks overlain in places by Paleozoic shallow marine and terrestrial clastic sedimentary rocks with minor volcanic rock. Scattered, large, granitic intrusions, Late Precambrian-Cambrian and Devonian-Carboniferous age [11]. Upper crust divided into two sub-layers based on Lithoprobe transect MT profile [9]. A more conductive upper sublayer overlying a much resistive lower sublayer imaged in Bonavista peninsula area and which may extend eastward to St. John’s area. Bottom depth of Layer 3 scaled from a NW-SE seismic transect. Thickness of uppermost sublayer interpreted from MT results. <u>*Upper Sublayer*</u> Lithoprobe transect resistivity: Alternating, thin, more conductive (sediments) layers (5-50 ohm.m) at 0-2 km and 5 km depths in Bonavista peninsula area [9]. Other resistivity values: (i) on PEI within continuation of Avalon Zone, resistivity is 9 ohm.m to depth of 4 km, and in NB it’s 15 ohm.m to depth of 2 km [7]; (ii) 9 ohm.m to 3 km depth [12] Assigned midpoint value for depth based on range 2-5 km. Assigned midpoint value for resistivity based on range 9-50 ohm.m.
	Lower Sublayer 3 - 12 km [10]	*Lower Sublayer* 9 km	*Lower Sublayer* 2700 [9]	*Lower Sublayer* 0.00037	
	Confidence [I]		Confidence [I]		

Table A2.8.1 (continued)

1D Earth Resistivity Model for the St. John's Magnetic Observatory – Avalon Zone

Layer	Depth Reference,[Confidence	Thickness	Resistivity (ohm-m) Reference, Confidence	Conductivity (S/m)	Comments
3b. Upper Crust	3 - 12 km [10] [I]	9 km	2700 [9] [I]	0.00037	*Lower Sublayer* Lithoprobe transect resistivity: dominantly ranges 400-5000 ohm.m [9]. Assigned midpoint value. Other resistivity values: Eastern Piedmont terrane (Avalon Zone equivalent) in southern Appalachians, 800 ohm.m for depth of 0~15 km [o].
4. Middle Crust	12 - 23 km [10] [I]	11 km	25 [9] [I]	0.04	Depth scaled from seismic transect. Lithoprobe transect resistivity: distinct low resistivity ranges 7-65 ohm.m [9]. Isolated 7 ohm.m body near west margin of zone, 15-23 km deep. Assigned weighted average value. Other resistivity values: (i) On PEI and NB within continuation of Avalon Zone, resistivity ranges 50-500 ohm at depth 4-44 km, and 1000 ohm at depth 1-44 km [7]; (ii) Eastern Piedmont terrane (Avalon Zone equivalent) in southern Appalachians, 1000-10000 ohm.m for depth of ~15-20 km [13].
5. Lower Crust	23 - 34 km [10] [I]	11 km	15 [9] [I]	0.067	Depth scaled from a NW-SE seismic transect. Lithoprobe transect resistivity: dominantly 15 ohm.m [9]. Other resistivity values: (i) Eastern Piedmont terrane (Avalon Zone equivalent) in southern Appalachians, 45-450 ohm.m for depth of 20-45 km [o]; (ii) 1000 ohm.m for depth 3~35 km [13] Assigned upper end of range for Layer 4 is 450 ohm.m.

Table A2.8.1 (continued)

1D Earth Resistivity Model for the St. John’s Magnetic Observatory – Avalon Zone

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Confidence		Reference Confidence		
6. Upper Mantle	34 - 100 km [8, 10]	66 km	200 [7]	0.005	Upper depth scaled from a NW-SE seismic transect. Crust-mantle boundary figure depicted general depth of 38 km beneath island, reported to range 35-40 km [14]. Used generalized lower depth of 100 km [8]. Lithoprobe transect resistivity: Depicted resistivity extends to depth of approx. 45 km., showing continuation of 15 ohm.m [9].
	[I, II]		[III]		Other resistivity values: (i) On PEI and NB within continuation of Avalon Zone, 50-500 ohm.m at 4-44km, 10-200 ohm.m at 44-94 km, 1000 ohm.m at 1-44 km, and 50 ohm.m at 44-94 km or 100 ohm.m for 30-95 km depth [7], for approx. average 200 ohm.m; (ii) 300 ohm for Atlantic Canada [15], with range <20 to > 300 ohm.m; (iii) 244 ohm at depth of 0-100 ohm.m. for Canada regional model [8]; (iv) Eastern Piedmont terrane (Avalon Zone equivalent) in southern Appalachians, 1000-4000 ohm.m at 45-100 km [13]; (v) 100 ohm.m for depth ~35 –100 km depth for area beneath PEI [12] Assigned average of the midpoint s of the resistivity range values for PEI and NB. Assigned resitivity range for Layer 6 is 25-1000 ohm.m.

Table A2.8.1 (continued)
1D Earth Resistivity Model for the St. John's Magnetic Observatory – Avalon Zone

Layer	Depth Reference, Confidence	Thickness	Resistivity (ohm-m) Reference, Confidence	Conductivity (S/m)	Comments
7. Upper Mantle	100 - 250 km [8] [III]	150 km	158 [8]	0.0063	Applied Canada regional model [8] for all depths and resistivities below 100 km. Other resistivity values: Eastern Piedmont (Avalon zone equivalent) in southern Appalachians, 1000-7000 ohm.m for depth of 100-150 km, then 30-250 ohm.m for 150-200 km [13].
8. Upper Mantle	250–410 km [8] [III]	160 km	29 [8]	0.035	---
9. Transition Zone	410–520 km [8] [III]	110 km	8 [8]	0.125	---
10. Transition Zone	520–670 km [8] [III]	150 km	2.4 [8]	0.417	---
11. Lower Mantle	670–900 km [8] [III]	230 km	1.1220 [8]	0.89	---
12. Lower Mantle	900–1000 km [8] [III]	100 km	0.47 [8]	2.09	---

Notes:

Depth Confidence
I = best representation
* overburden: geological report/map coverage of local area.
* crust: seismic/gravity transects crossing local area, within 100 km.
II = likely representative
* crust/upper mantle: geological and/or seismic transect of a regional nature.
III = possibly representative (measurements from general compilations).

Resistivity/Conductivity Confidence
I = best representation (measurements from site or nearby).
* overburden: resistivity measurement by surface geophysical method and/or borehole in local area.
* crust: resistivity measurement from resistivity survey, MT survey and/or borehole in local area.
II = likely representative (resistivity values extrapolated from measurements taken at some distance from the site, typically greater than 100 km).
* overburden: resistivity value obtained by geophysical measurement, including borehole logs.
* sedimentary basin: value obtained by geophysical survey using variety of geophysical electromagnetic methods, including MT.
* crust: value obtained by regional MT survey.
III = possibly representative (measurements from general compilations

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A2.9. Victoria magnetic observatory, British Columbia

General

Presented is one-dimensional (1D) layered model representing the vertical variance of electrical resistivity in the crust and mantle underlying the Province of British Columbia near Victoria Magnetic Observatory. Altogether there were 12 models provide coverage of the British Columbia (Figure A2.9.1).

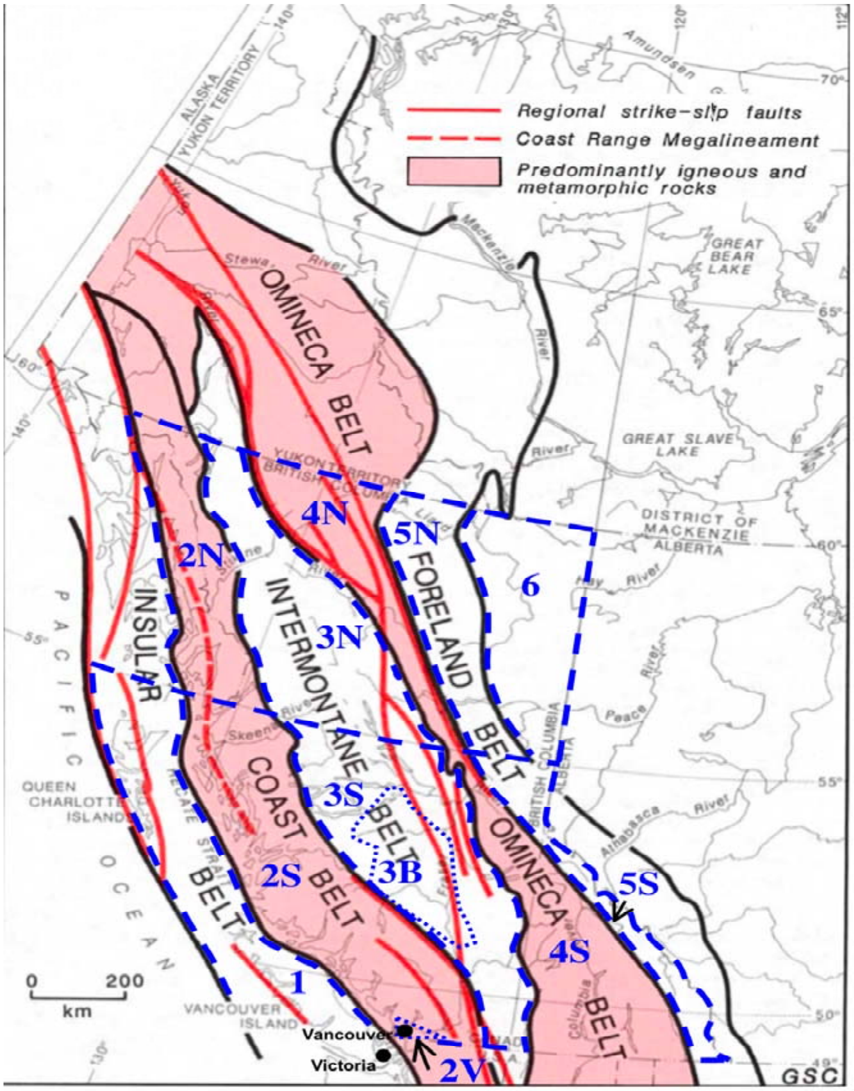
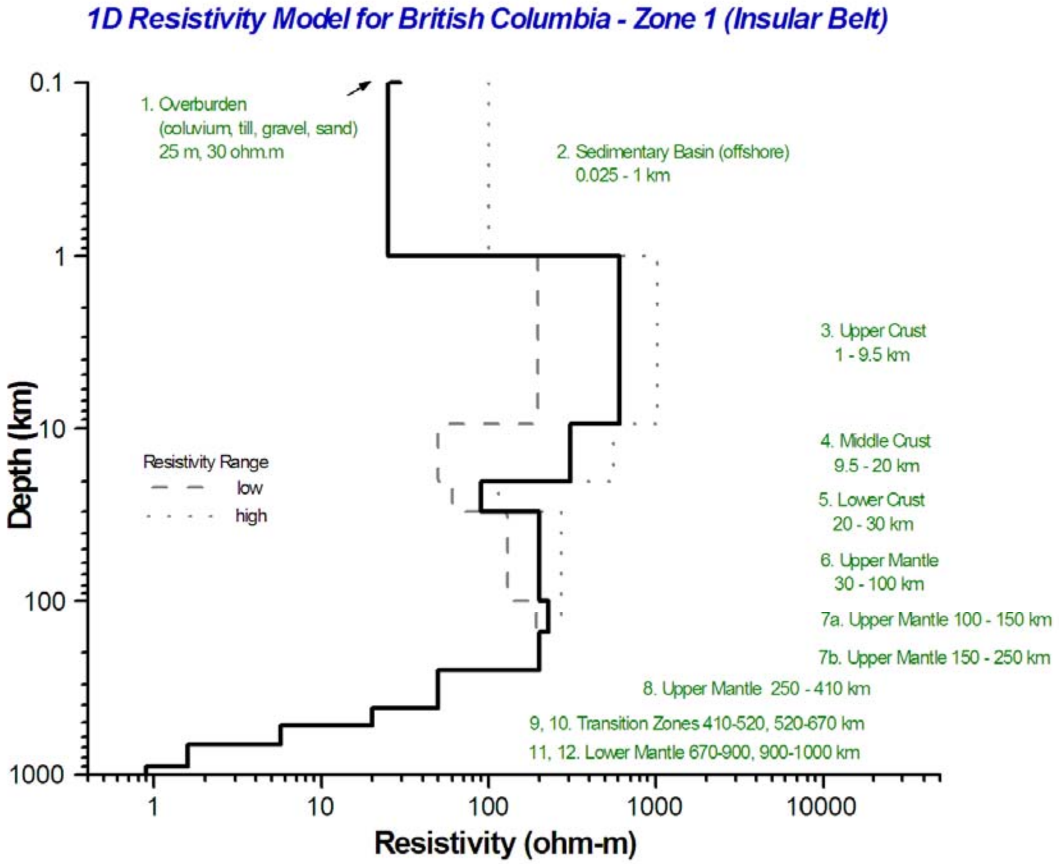


Figure A2.9.1. Geomorphological belts of the Canadian Cordillera (after [1a,1b]). Coverage area of 1D resistivity models labeled “1 to 6”.

The 1D layered-Earth model corresponding to Zone 1 (Z1) is presented in Figure A2.9.2. Accompanying Table A2.9.1 summarizes the individual layer depths, thickness, and resistivity/conductivity for Victoria 1D model, as well as sources of depth and resistivity values and justification for selection.



Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure A2.9.2. 1D Earth resistivity model for Zone 1, covering the Insular Belt within Canada, including Vancouver island. Layer 2 occurs only within the Strait of Georgia, and hence, is lacking below Vancouver Island itself. Refer to Table A2.9.1 for additional details.

Table A2.9.1
1D Earth Resistivity Model for Victoria Observatory (Insular Belt)

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Certainty		Reference, Certainty		
	Insular Belt represents a set of exotic terranes that accreted onto North America [2]. The belt includes the mountain ranges of Vancouver Island, Queen Charlotte Islands and Alexander Archipelago in Alaska Panhandle, in addition to submerged regions of continental margin. Comprised of volcanic and sedimentary rock with intrusions of granitic rock. Most rocks within southern Insular Belt are of mid-Paleozoic and early Mesozoic time (350-180 Ma). Sandstones on east Vancouver Island and submerged around island are Late Cretaceous and Early Tertiary age (85-40 Ma). Present-day detrital sediments accumulating in Strait of Georgia and Fraser Delta in Vancouver region [3]. *Zone 1 includes a Layer 2, the Georgia Basin, situated between Vancouver Island and the BC mainland. Layer 2 appears as a distinct resistivity layer on MT inversion profile. For a layered Earth model of only Vancouver Island, then Layer 2 has to be excluded.* *Zone 1 is limited to extent of Insular Belt in Canada, mainly south of 55 degrees latitude.*				
1. Overburden	0 – 25 m [4]	25 m	30 [5, 6, 7, 8a,b, 9]	0.033	Alpine Complexes (broken rock, colluvium, till pockets) predominant on higher ground. Patchy occurrences of a mix of till veneer / blanket, glaciofluvial (sands, gravels), glaciomarine to marine (clayey silt, sand and gravel) along coast of Vancouver Island [10,11]. In Greater Victoria area, typically clay overlies sand / gravel or till. Till has silty sand matrix.
	[I]		[III]		
			Surficial materials thickness varies from < 1 to > 1 m on Vancouver Island [11]. Variable thickness in Greater Victoria and Saanich Peninsula area, ranging approx. 2 m on steep slopes to 55 m in lowland areas, infrequently 100 m [4]. Assign 25 m thickness, midpoint of range determined for Greater Victoria and Saanich areas. Borehole logs of overburden in Saskatchewan, Manitoba and NE Ontario show: * till, 40-50 ohm.m, 20-100 ohm.m [6,7] * clayey and sandy till, 15-40 ohm.m range [9] * clayey till, 25 ohm.m; silty till, 50 ohm.m; sandy till, 115 ohm.m [8a,b] * glaciolacustrine clay, 5-10 ohm.m, 30 ohm.m; silt, 10-20 ohm.m, 45 ohm.m; sand, 40-60 ohm.m, 80 ohm [8a,b,9] * mix of till, clay, silt and sand, 5-30 ohm.m [5] Assign 30 ohm.m overall, an average value on basis of glaciofluvial sands/silts and glaciomarine clays being predominant with possible range 5-60 ohm.m.		

Table A2.9.1 (continued)

1D Earth Resistivity Model for Victoria Observatory (Insular Belt)

<table>
<tr><th rowspan="2">Layer</th><th>Depth</th><th rowspan="2">Thickness</th><th>Resistivity (ohm-m)</th><th>Conductivity (S/m)</th><th rowspan="2">Comments</th></tr>
<tr><th>Reference, Certainty</th><th>Reference, Certainty</th><th></th></tr>
<tr><td rowspan="3">2. Sedimentary Basin (offshore)</td><td>0 – 1 km
[12]</td><td rowspan="3">1 km</td><td>25
[13]</td><td rowspan="2">0.04</td><td rowspan="2">Layer 2 applicable only to Georgia Strait, situated offshore between Vancouver Island and BC mainland.
Layer 2 incorporates the Georgia Basin, a remnant forearc / strike-slip basin. It includes unconsolidated present-day detrital sediments (clay, silt, minor sand) accumulating in Strait of Georgia and Fraser Delta that overly Pleistocene glacial deposits (interlayers of till, sand, clay), all which rest on late Cretaceous – early Tertiary basin fill clastic sedimentary rock (sandstone, siltstone, mudstone, conglomerate [3,12,14]. Tertiary strata has gentle dips, overly the more deformed, faulted and folded, Cretaceous rock [15].</td></tr>
<tr><td rowspan="2">[I]</td><td>[I]</td></tr>
<tr><td colspan="3">Thickness approximately 2.5 km based on resistivity contrast on MT profile [13]. Seismic models [6] suggest maximum thickness 2 km (approx. 0.4 km unconsolidated sediments / glacial deposits; approx. 1.6 km clastic sedimentary rock). Depth to bedrock contour map illustrates maximum of 700 m unconsolidated sediments / glacial deposits [16].
Assign 1 km average thickness, midpoint of seismic determined depths. Depth 0 refers to sea-level.
Well log in City of Richmond through Fraser Delta unconsolidated sediments reveal 90-100 ohm.m to 120 m depth [14]. MT profile Line ABC-N [13] across southern BC shows approximately 25 ohm.m overall crossing Strait of Georgia, and Line ABC-S shows approx. 25 ohm.m in area of Fraser Delta (continuation of Georgia Basin into Vancouver area Lower Mainland).
Assign 25 ohm.m, on basis of MT profiles. Upper limit 100 ohm.m.</td></tr>
</table>

Table A2.9.1 (continued)
1D Earth Resistivity Model for Victoria Observatory (Insular Belt)

<table>
<tr><th rowspan="2">Layer</th><th>Depth</th><th rowspan="2">Thickness</th><th>Resistivity (ohm-m)</th><th>Conductivity (S/m)</th><th rowspan="2">Comments</th></tr>
<tr><th>Reference, Certainty</th><th>Reference, Certainty</th><th></th></tr>
<tr><td rowspan="3">3. Upper Crust</td><td>1 – 9.5 km
[17, 18, 19]</td><td rowspan="3">8.5 km</td><td>610
[13]</td><td rowspan="2">0.0016</td><td rowspan="2">Thick assemblage of middle Paleozoic to Jurassic volcanic, plutonic, and sedimentary rocks [12].
Depth scaled from regional seismic profile(s) across southern BC, approx. range 8-11.5 km [17, 18, 19]. Assign 9.5 km (below centre Vancouver Island), average of values.</td></tr>
<tr><td>[I]</td><td>[I]</td></tr>
<tr><td></td><td colspan="3">MT profiles [13] across southern BC show for:
* Line ABC-N, dominantly 1030 ohm.m
* Line ABC-S, weighted average approx. 195 ohm.m (see Note 1)
* chose approx. 610 ohm.m, average of above lines
5-km depth resistivity map [13] shows overall 4250 ohm.m (see Note 2).
10-km depth resistivity map [13] shows overall 350 ohm.m.
Assign 610 ohm.m, based on weighted averages of 2D inversion profiles. Limits 195, 1030 ohm.m.</td></tr>
<tr><td rowspan="3">4. Middle Crust</td><td>9.5 – 20 km
[18, 19]</td><td rowspan="3">10.5 km</td><td>310
[13]</td><td rowspan="2">0.0032</td><td rowspan="2">Depth scaled from regional seismic profile(s) across southern BC, approx. range 18.5-21.5 km [18,19]. Assign 20 km (below centre Vancouver Island), average of values.</td></tr>
<tr><td>[I]</td><td>[I]</td></tr>
<tr><td></td><td colspan="3">MT profiles [13] across southern BC show for:
* Line ABC-N, dominantly 560 ohm.m
* Line ABC-S, weighted average approx. 50 ohm.m (see Note 1)
* chose approx. 310 ohm.m, average of above lines
20-km depth resistivity map [13] shows overall 250 ohm.m (see Note 2).
Assign 310 ohm.m, based on weighted averages of 2D inversion profiles. Limits 50, 560 ohm.m.</td></tr>
</table>

Table A2.9.1 (continued)
1D Earth Resistivity Model for Victoria Observatory (Insular Belt)

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Certainty		Reference, Certainty		
5. Lower Crust	20 – 30 km [17]	10 km	90 [13]	0.0057	Depth scaled from regional seismic profile across southern BC [17]. Assign 30 km (below centre Vancouver Island).
	[I]		[I]		
					MT profiles [13] across southern BC show for: * Line ABC-N, dominantly 115 ohm.m * Line ABC-S, weighted average approx. 60 ohm.m (see Note 1) * chose approx. 175 ohm.m, average of above lines 30-km depth resistivity map [13] shows overall 200 ohm.m (see Note 2). Assign approx. 90 ohm.m, based on weighted averages of 2D inversion profiles. Limits 60, 115 ohm.m.
6. Upper Mantle	30 – 100 km [20]	70 km	200 [13]	0.005	Used generalized lower depth [20].
	[III]		[I]		
					MT profiles [13] across southern BC show for: * Line ABC-N, dominantly 270 ohm.m * Line ABC-S, weighted average approx. 130 ohm.m (see Note 1) Assign 200 ohm.m, based on weighted averages of 2D inversion profiles. Limits 130, 270 ohm.m

Table A2.9.1 (continued)
1D Earth Resistivity Model for Victoria Observatory (Insular Belt)

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Certainty		Reference, Certainty		
7. Upper Mantle	100 - 250 km [20]	150 km	100-150km 230 [13]	100-150km 0.0043	Layer 7 divisible into upper and lower segments. MT profiles [13] provide regional resistivity values between 100-150 km depth. Applied average of North American and Japan regional models for resistivity values between 150-250 km. <u>100-150 km depth</u>: MT profiles [13] across coast Belt in southern BC show for: * Line ABC-N, weighted average 270 ohm.m [see Note 1] * Line ABC-S, weighted average 190 ohm.m * chose approx. 230 ohm.m, average of above lines Assign 230 ohm.m, based on weighted averages of 2D inversion profiles. Limits 190, 270 ohm.m. <u>150-250 km depth</u>: Generalized depth [20] for base of lower segment. North American regional model [20], based on Tucson magnetic observatory data, situated on Proterozoic crust (late Precambrian time) indicates 210 ohm.m for 100-250 km. Japan regional model [20], situated on Phanerozoic subducting crust, indicates 190 ohm.m for 100-250 km. Assign approx. 200 ohm.m, average of North American and Japan models.
	[III]		[I]		
			150-250km 200 [20]	150-250km 0.0050	
			[III]		

Table A2.9.1 (continued)

1D Earth Resistivity Model for Victoria Observatory (Insular Belt)

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Reference, Certainty		Reference, Certainty		
8. Upper Mantle	250–410 km [20]	160 km	40 [20]	0.025	Utilized average of North American regional model [20], based on Tucson magnetic observatory data, situated on Proterozoic crust (late Precambrian time) and Japan model situated on Phanerozoic subducting crust for all depths and resistivities below 250 km (see Note 3).
	[III]		[III]		
9. Transition Zone	410–520 km [20]	110 km	11 [20]	0.088	Assign average of North American regional and Japan models.
	[III]		[III]		
10. Transition Zone	520–670 km [20]	150 km	2 [20]	0.5	Assign average of North American regional and Japan models.
	[III]		[III]		
11. Lower Mantle	670–900 km [20]	230 km	1.22 [20]	0.82	Assign average of North American regional and Japan models.
	[III]		[III]		
12. Lower Mantle	900–1000 km [20]	100 km	0.77 [20]	1.28	Assign average of North American regional and Japan models.
	[III]		[III]		

Table A2.9.1 (continued)

1D Earth Resistivity Model for Victoria Magnetic Observatory (Insular Belt)

NOTE 1: Calculation of Weighted Average for Layers 3 to 7, from 2D inversion profiles [13].

For each layer, percentage areal extent of dominant / midpoint resistivity value was determined by measurement (e.g. 25 % of layer is 150 ohm.m, thus 0.25 x 150). Resistivity estimated by visual comparison against provided resistivity scale. Results below are rounded.

<u>Layer 3, Upper Crust</u>
Line ABC-N: ((0.35 x 150, midpoint of range 100-200) + (0.65 x 1500)) = approx. 1030 ohm.m
Line ABC-S: ((0.23 x 25, midpoint 10-40) + (0.71 x 140, midpoint 75-200) + (0.06 x 1500) = approx. 195 ohm.m

<u>Layer 4, Middle Crust</u>
Line ABC-N: ((0.18 x 45, midpoint of range 20-75) + (0.46 x 300, midpoint of range 100-500) + (0.28 x 1500)) = approx. 565 ohm.m
Line ABC-S: ((0.64 x 25, midpoint 10-40) + (0.36 x 90, midpoint 75-100))= approx. 50 ohm.m

<u>Layer 5, Lower Crust</u>
Line ABC-N: ((0.33 x 35 midpoint of range 30-40) + (0.08 x 75) + (0.44 x 100) + (0.15 x 350, midpoint of range 200-500)) = approx. 115 ohm.m
Line ABC-S: ((0.3 x 25, midpoint 10-40) + (0.14 x 35, midpoint 30-40) + (0.36 x 75) + (0.2 x 100) = approx. 60 ohm.m

<u>Layer 6, Upper Mantle (Moho – 100 km)</u>
Line ABC-N: ((0.04 x 35, midpoint of 30-40) + (0.06 x 75) + (0.04 x 100) + (0.08 x 150) + (0.44 x 200) + (0.24 x 400) + (0.1 x 650) = approx. 270 ohm.m
Line ABC-S: ((0.12 x 100) + (0.22 x 150) + (0.66 x 200)) = approx. 130 ohm.m

<u>Layer 7, Upper Mantle (100- 150 km)</u>
Line ABC-N: ((400 x 0.27) + (0.13 x 150) + (0.55 x 200) + ((0.05 x 650)) = approx. 270 ohm.m
Line ABC-S: ((0.06 x 150) + (0.94 x 200)) = approx. 190 ohm.m

NOTE 2: Determination of overall resistivity for specific depths, from depth resistivity maps [13], by (i) visual estimation of percentage areal extent of dominant / midpoint resistivity value (e.g. 50 % of area is 75 ohm.m, thus 0.5 x 75), and (ii) visual comparison against provided resistivity scale.

Results below are rounded to nearest 5 or 10.

<u>5-km depth</u>
((0.6 x 6500) + (0.4 x 875, midpoint of range 750-1000)) = approx. 4250 ohm.m

<u>10-km depth</u>
((0.2 x 6500) + (0.8 x 875, midpoint of range 750-1000)) = approx. 2000 ohm.m

<u>20-km depth</u>
((0.1 x 750) + (0.85 x 200) + (0.05 x 75)) = approx. 250 ohm.m

<u>30-km depth</u>
((0.1 x 750) + (0.9 x 140, midpoint of range 75-200)) = approx. 200 ohm.m

Note 3, Depth Certainty

- I = best representation
  - * overburden: geological report/map coverage of local area.
  - * crust: seismic/gravity transects crossing local area
- II = likely representative
  - * overburden: geological report/map coverage of region
  - * crust/upper mantle: geological and/or seismic transect of a regional nature.
- III = possibly representative (measurements from general compilations).

Resistivity/Conductivity Certainty

- I = best representation (measurements from site or nearby).
  - * overburden: resistivity measurement by surface geophysical method and/or borehole in local area.
  - * crust: resistivity measurement from resistivity survey, MT survey and/or borehole in local area.
- II = likely representative (resistivity values extrapolated from measurements taken at some distance from the site, typically greater than 100 km).
  - * overburden: resistivity value obtained by geophysical measurement, including borehole logs.
  - * sedimentary basin: value obtained by geophysical survey using variety of methods, including MT.
  - * crust: value obtained by regional MT survey.
- III = possibly representative (measurements from general compilations).

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