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GEOLOGICAL SURVEY OF CANADA
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Space Weather Hazard Assessment for Alberta

L. Trichtchenko, L. Nikitina, and P. Fernberg

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Executive Summary

Introduction

Geomagnetic disturbances produce electric fields that drive electric currents in the Earth and in power transmission networks at the Earth's surface. These geomagnetically induced currents (GIC) flow through transformer windings where they produce partial saturation of the transformer core leading to harmonic generation, increased VAR demand and transformer heating which can cause misoperation of protective relays, voltage sag and damage to equipment. In extreme cases, as in the March 13, 1989, magnetic storm, this can result in burnt-out transformers and system collapse.

Concern that a major geomagnetic storm could cause widespread problems on the North American power networks has prompted the North American Electric Reliability Corporation (NERC) to set up a Geomagnetic Disturbance Task Force. This is developing new rules that will require power utilities to undertake a geomagnetic hazard assessment and to take action to mitigate the risks if necessary.

The aim of this research is to understand and assess the possible geomagnetic effects on power systems, pipelines and other ground infrastructure in the province of Alberta.

The report consists of five chapters. Analysis of the geomagnetic activity based on long records of geomagnetic data at several observatories is described in Chapter 1. The geological settings and analysis of the resistivity structures based on an extensive literature review described in the Chapter 2 as well as the resulting ten earth resistivity models which cover the whole province of Alberta.

The theory on the modelling of the geoelectric fields which drives the electric currents in grounded networks is described in Chapter 3. It also presents the results of the statistical analysis of the calculated geoelectric field variations for 40 years as well as the 40-years maximum values for each particular resistivity zone of the province.

The estimated values can be used with power or pipeline network models to calculate the GIC in the power lines or pipe-to-soil potential variations for the pipelines.

Geomagnetic Climatology

Analysis of the geomagnetic activity in the Alberta area was made using data from several geomagnetic observatories which are part of the NRCan Canadian Magnetic Observatories Network (Figure 1). The geomagnetic activity is greatest in the auroral zone, where the most of the province is located, and it has also most spatial variability in this zone. There is only one geomagnetic observatory in Alberta, e.g. Meanook (MEA) and thus for some approximate evaluation of the spatial variability of the geomagnetic disturbances we use the data from the observatory available to the north of the provincial border (Yellowknife, YKC) and the closest observatory to the south (Gleanlea, GLN), later closed and replaced by Brandon observatory (BRD), recordings from Ottawa (OTT) observatory were used for comparison.

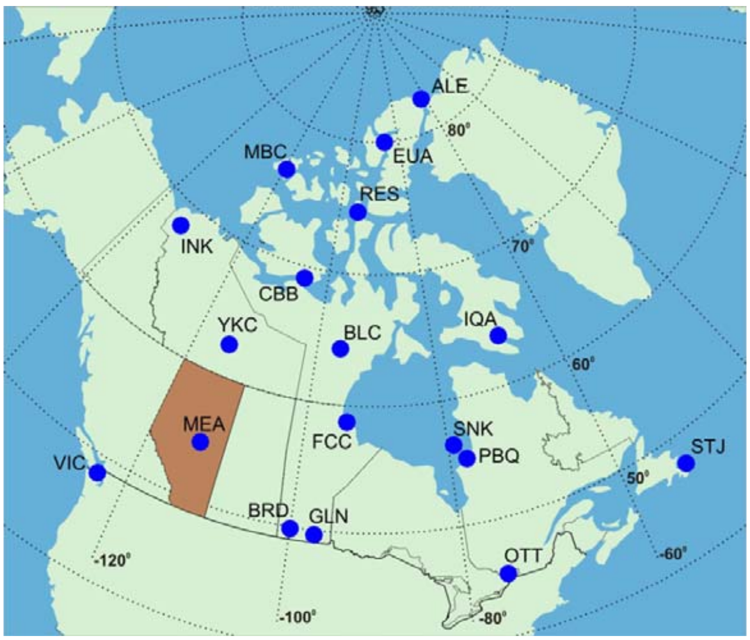

Figure 1. The map representing locations of the NRCan observatories.

The exact geographic and geomagnetic coordinates of observatories used in the assessment of the geomagnetic activity and years of data availability are presented in the Table 1, samples of annual variability of geomagnetic activity for year 1989 at MEA and OTT are presented in Figs. 2 and 3.

Table 1. Locations of Geomagnetic Observatories and data coverage period

Station	Code	Latitude (N)	Longitude (E)	Geomagnetic Latitude	Geomagnetic Longitude	Years of availability
Meanook	MEA	54.616 N	246.653 E	61.29 N	52.80 W	1973-2012
Yellowknife	YKC	62.480 N	245.518 E	68.71 N	59.37 W	1975-2012
Glenlea	GLN	49.645 N	262.880 E	58.28 N	31.37 W	1982-1996
Brandon	BRD	49.870 N	260.026 E	58.23 N	34.91 W	2007-2012
Ottawa	OTT	45.403 N	284.448 E	55.18 N	4.11 W	1973-2012

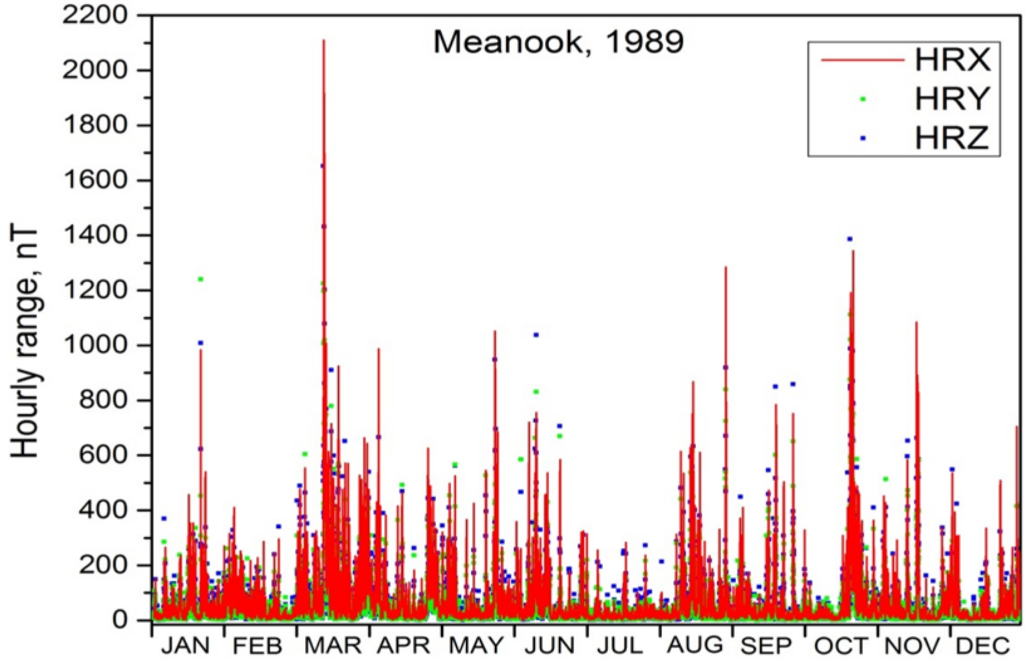

Figure 2. Variations of the geomagnetic field (hourly range index), Meanook observatory. The color-coded are different directions of magnetic field components, such as: red-Northward (X), Green-Eastward (Y) and blue-Downward (Z).

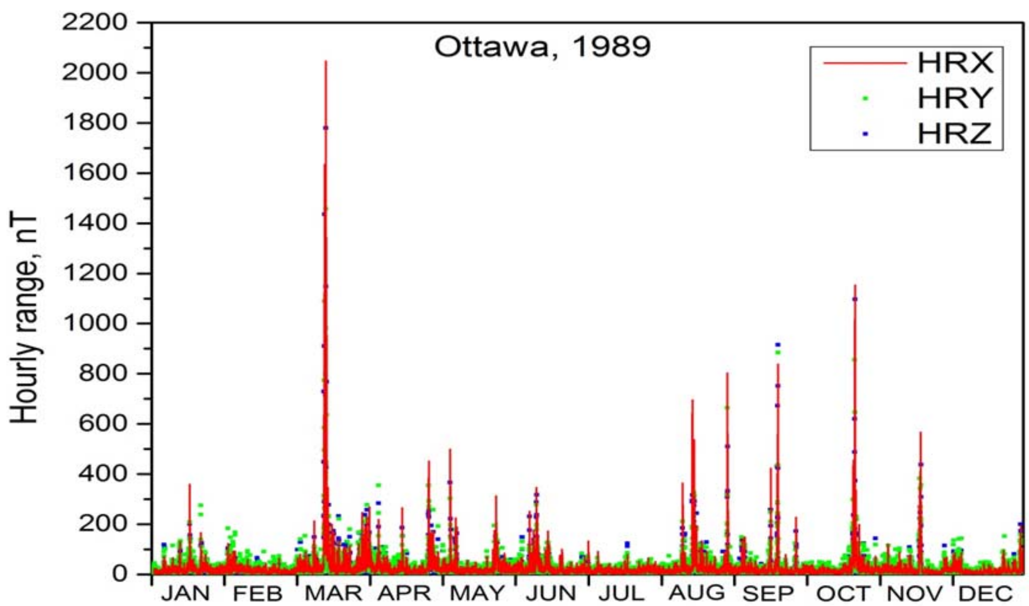

Figure 3. Variations of the geomagnetic field (hourly range index), Ottawa observatory.

Comparison of figures 2 and 3 gives clear evidence that geomagnetic variations (at least in 1989) in Meanook are larger than in Ottawa. More complete statistical results of the analysis of all available data from four observatories are presented in Figure 4.

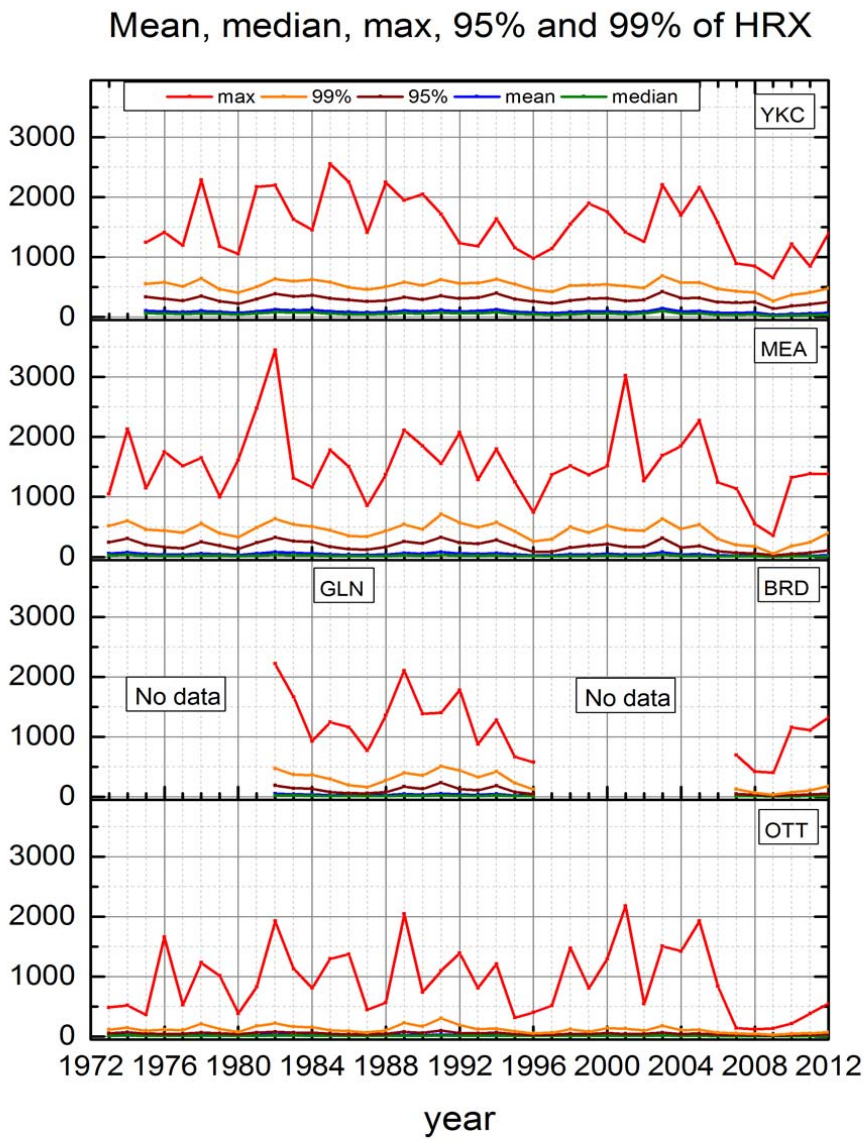

Figure 4. Annual changes of the statistical properties of the HRX Geomagnetic activity index variations, such as median, mean, 95%, 99% and maximum for several observatories.

It is shown, that the maximum activity levels in MEA can even exceed 3000 nT, while in OTT and YKC these are less than 2200 nT. Because of such high levels of geomagnetic activity, the detailed assessment of the possible geoelectric fields in the area is needed.

Earth Resistivity Models for Alberta

In order to model and assess the variations of the ground electric field in Alberta province, the resistivity structure of the underlying Earth needs to be determined.
A review of publically-available information was undertaken, such as government geological reports and maps including on-line resources, engineering studies and scientific research papers. This geological and geophysical information was used to prepare one-dimensional (1D) models of the Earth resistivity for further inputs into the modelling of the geoelectric field and subsequent applications for modelling of GIC in the network.

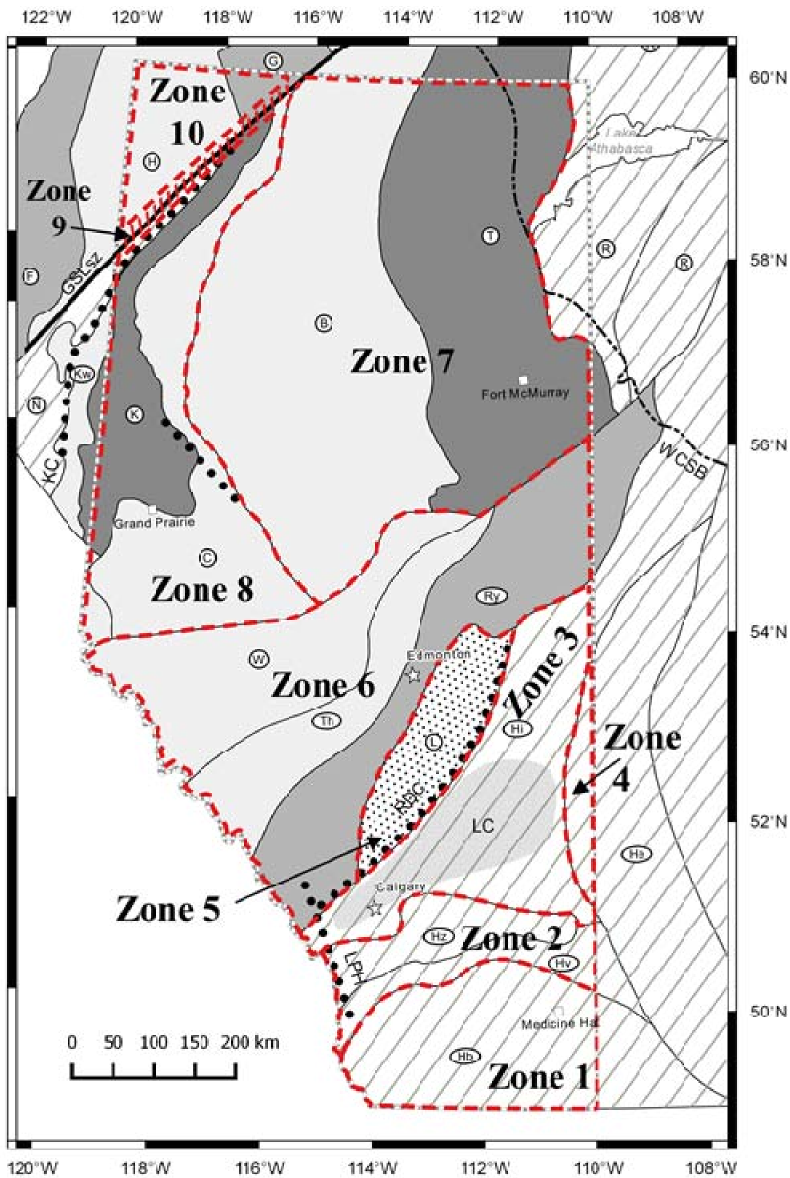

Figure 5. Locations of ten zones associated with different 1D layered Earth resistivity models. Also shown are underlying tectonic elements and conductive anomalies (general location, see Chapter 3 for more details).

The results of the study provide identification of the major Earth resistivity zones (Figure 5) with the details on the composition of the layers, i.e. their thicknesses and resistivities (Table 2).

Table 2, Earth resistivity models, Zones 1-6

Layer	Zone 1 (Medicine Hat Block)	Zone 2 (Vulcan Structure)	Zone 3 (Loverna Block)	Zone 4 (Eyehill Domain)	Zone 5 (Lacombe Domain)	Zone 6 (Rimbey, Thorsby & Wabamun Domains)
1 – Over burden	75 m thick 30 ohm.m *limits 10, 100*	50 m thick 30 ohm.m *limits 10, 100*	40 m thick 30 ohm.m *limits 10, 100*	50 m thick 50 ohm.m *limits 10, 100*	35 m thick 30 ohm.m *limits 10, 100*	65 m thick 50 ohm.m *limits 10, 100*
2 – Sediment.Basin	0-2.2 km 2.2 km thick 30 ohm.m *limits 3, 100*	0-2.4 km 2.4 km thick 25 ohm.m *limits 3, 200*	0-2.9 km 2.9 km thick 6 ohm.m *limits 3, 100*	0-2 km 2 km thick 10 ohm.m *limits 3, 30*	0-3.1 km 3.1 km thick 20 ohm.m *limits 3, 50*	0-2.7 km 2.7 km thick 15 ohm.m *limits 3, 50*
3 – Upper Crust	2.2-15 km 13 km thick 385 ohm.m *limits 350, 400*	2.4-24 km 21.6 km thick 3000 ohm.m *lower limits 500*	2.9-19 km ± 16 {16.1} km thick 2000 ohm.m *limits 3, 3000*	2-19 km 17 km thick 1900 ohm.m *limits 300, 3000*	3.1-19 km ~ 16 {15.9} km thick 440 ohm.m *limits 3, 3000*	2.7-12 km ~ 9 km thick 3000 ohm.m *limits 1000, 3000*
4 – Middle Crust	15-27.5 km 12.5 km thick 2500 ohm.m *limits 500, 3000*	24-37 km 13 km thick 2000 ohm.m *limits 300, 3000*	19-29 km 10 km thick 3000 ohm.m *limits 300, 3000*	19-29 km 10 km thick 1700 ohm.m *limits 300, 3000*	19-29 km 10 km thick 900 ohm.m *limits 500, 3000*	12-29 km 17 km thick 2300 ohm.m *limits 300, 3000*
5 – Lower Crust	27.5-45 km 17.5 km thick 2500 ohm.m *limits 1000,4000*	37-45 km 8 km thick 4000 ohm.m *limits 3000, 5000*	29-41 km 12 km thick 620 ohm.m *limits 3, 3000*	29-43 km 14 km thick 850 ohm.m *limits 100, 3000*	29-39 km 10 km thick 330 ohm.m *limits 3,1000*	29-39 km 10 km thick 2100 ohm.m *limits 30,3000*
6 – Upper Mantle	45-100 km 55 km thick 2250 ohm.m *limits 500, 4000*	45-100 km 55 km thick 2000 ohm.m *limits 300, 3000*	41-100 km 59 km thick 150 ohm.m *limits 3, 500*	43-100 km 57 km thick 500 ohm.m *limits 30, 3000*	39-100 km 61 km thick 950 ohm.m *limits 100, 3000*	39-100 km 61 km thick 1400 ohm.m *limits 30, 3000*
7 – Upper Mantle	100-250 km 150 km thick 550 ohm.m limits 250, 1700	100-250 km 150 km thick 260 ohm.m limits 80, 700	100-250 km 150 km thick 230 ohm.m limits 100, 360	100-250 km 150 km thick 530 ohm.m limits 100, 1000	100-250 km 150 km thick 160 ohm.m limits 25, 300	100-250 km 150 km thick 160 ohm.m limits 30, 300
8 – Upper Mantle	250-410 km 160 km thick 40 ohm.m limits 5, 75	250-410 km 160 km thick 70 ohm.m limits 50, 75	250-410 km 160 km thick 90 ohm.m limits 20, 200	250-410 km 160 km thick 90 ohm.m limits 20, 200	250-410 km 160 km thick 40 ohm.m limits 10, 75	250-410 km 160 km thick 50 ohm.m
9 – Transition Zone	410-520 km 110 km thick 8 ohm.m	410-520 km 110 km thick 8 ohm.m	410-520 km 110 km thick 8 ohm.m	410-520 km 110 km thick 8 ohm.m	410-520 km 110 km 20 ohm.m	410-520 km 110 km 20 ohm.m
10 –Transition Zone	520-670 150 km thick 2.4 ohm.m	520-670 150 km thick 2.4 ohm.m	520-670 150 km thick 2.4 ohm.m	520-670 150 km thick 2.4 ohm.m	520-670 150 km 5.6 ohm.m	520-670 150 km 5.6 ohm.m
11 – Lower Mantle	670-900 km 230 km thick 1.12(i) ohm.m upper limits 3 or 30	670-900 km 230 km thick 1.12(i) ohm.m upper limit 3	670-900 km 230 km thick 1.12(i) ohm.m upper limit 3	670-900 km 230 km thick 1.12(i) ohm.m upper limit 3	670-900 km 230 km thick 1.58(i) ohm.m upper limit 3	670-900 km 230 km thick 1.58(i) ohm.m upper limit 3
12 – Lower Mantle	900-1000 km 100 km thick 0.47 ohm.m	900-1000 km 100 km thick 0.47 ohm.m	900-1000 km 100 km thick 0.47 ohm.m	900-1000 km 100 km thick 0.47 ohm.m	900-1000 100 km 1.12 ohm.m	900-1000 100 km 1.12 ohm.m

Table 2, continued, Zones 7-10

Layer	Zone 7 (Buffalo Head, Taltson)	Zone 8 (Chinchaga, Ksituan, Kiskatinaw, Nova)	Zone 9 (Great Slave Lake shear zone)	Zone 10 (Great Bear, Hottah, Fort Simpson)
1 – Overburden	50 m thick 30 ohm.m *limits 10, 100*	25 m thick 30 ohm.m *limits 10, 100*	25 m thick 15 ohm.m *limits 5, 30*	175 m thick 30 ohm.m *limits 10, 100*
2 – Sedimentary Basin	0-1.4 km 1.4 km thick 10 ohm.m *limits 3, 125*	0-3.3 km 3.3 km thick 10 ohm.m *limits 3, 30*	0-1.9 km 1.9 km thick 10 ohm.m *limits 3, 30*	0-1.9 km 1.9 km thick 10 ohm.m *limits 3, 30*
3 – Upper Crust	1.4-13 km 11.6 km thick 3000 ohm.m *limits 500, 5000*	3.3-15 km 11.7 km thick 900 ohm.m *upper limit >1000*	1.9-12 km 10.1 km thick 4200 ohm.m *limits 1000, 7500*	1.9-8 km 6 km thick 1000 ohm.m *limits 250, >1000*
4 – Middle Crust	13-29 km 16 km thick 1750 ohm.m *limits 1000, 2500*	15-30 km 15 km thick 275 ohm.m *limits 10, 1000*	12-24 km 12 km thick 4500 ohm.m *limits 200, 10000*	8-18 km 10 km thick 1300 ohm.m *limits 100, 2500*
5 – Lower Crust	29-38 km 9 km thick 1200 ohm.m *limits 400,2500*	30-39 km 9 km thick 360 ohm.m *limits 40,1000*	24-40 km 16 km thick 4500 ohm.m *limits 100, 10000*	18-40 km 22 km thick 800 ohm.m *limits 30, 2500*
6 – Upper Mantle	38-100 km 62 km thick 1400 ohm.m *limits 300, 5000*	39-100 km 61 km thick 315 ohm.m *limits 100, 400*	40-100 km 60 km thick 1600 ohm.m *limits 40, 5000*	40-100 km 60 km thick 500 ohm.m *limits 30,1000*
7 – Upper Mantle	100-250 km 150 km thick 635 ohm.m (a) limits 800, 1000 (b) limits 10, 30	100-250 km 150 km thick 660 ohm.m (a) limits 200, 1000 (b) limits 10, 30	100-250 km 150 km thick 680 ohm.m (a) upper limit 1000 (b) limits 30, 100	100-250 km 150 km thick 625 ohm.m (a) limits 200, 1000 (b) limits 30, 80
8 – Upper Mantle	**250-410 km 160 km thick 50 ohm.m**	**250-410 km 160 km thick 50 ohm.m**	**250-410 km 160 km thick 50 ohm.m**	**250-410 km 160 km thick 50 ohm.m**
9 – Transition Zone	**410-520 km 110 km thick 20 ohm.m**	**410-520 km 110 km thick 20 ohm.m**	**410-520 km 110 km thick 20 ohm.m**	**410-520 km 110 km thick 20 ohm.m**
10 –Transition Zone	**520-670 150 km thick 5.62 ohm.m**	**520-670 150 km thick 5.62 ohm.m**	**520-670 150 km thick 5.62 ohm.m**	**520-670 150 km thick 5.62 ohm.m**
11 – Lower Mantle	**670-900 km 230 km thick 1.58(i) ohm.m upper limits 3, 30**	**670-900 km 230 km thick 1.58(i) ohm.m upper limits 3, 30**	**670-900 km 230 km thick 1.58(i) ohm.m upper limits 3, 30**	**670-900 km 230 km thick 1.58(i) ohm.m upper limits 3, 30**
12 – Lower Mantle	**900-1000 km 100 km thick 1.12 ohm.m**	**900-1000 km 100 km thick 1.12 ohm.m**	**900-1000 km 100 km thick 1.12 ohm.m**	**900-1000 km 100 km thick 1.12 ohm.m**

Analysis of the Geoelectric Field Variations

To obtain the geoelectric field at the Earth's surface from known geomagnetic field data, the following sequence of operations (Figure 6) was performed:

1. Conversion of the geomagnetic data from time domain into frequency domain [using Fast Fourier Transformation (FFT)].
2. Multiplication by the surface impedance, obtained from one-dimensional resistivity profile of particular area.
3. Inverse transform of the geoelectric values back into time domain by using inverse FFT

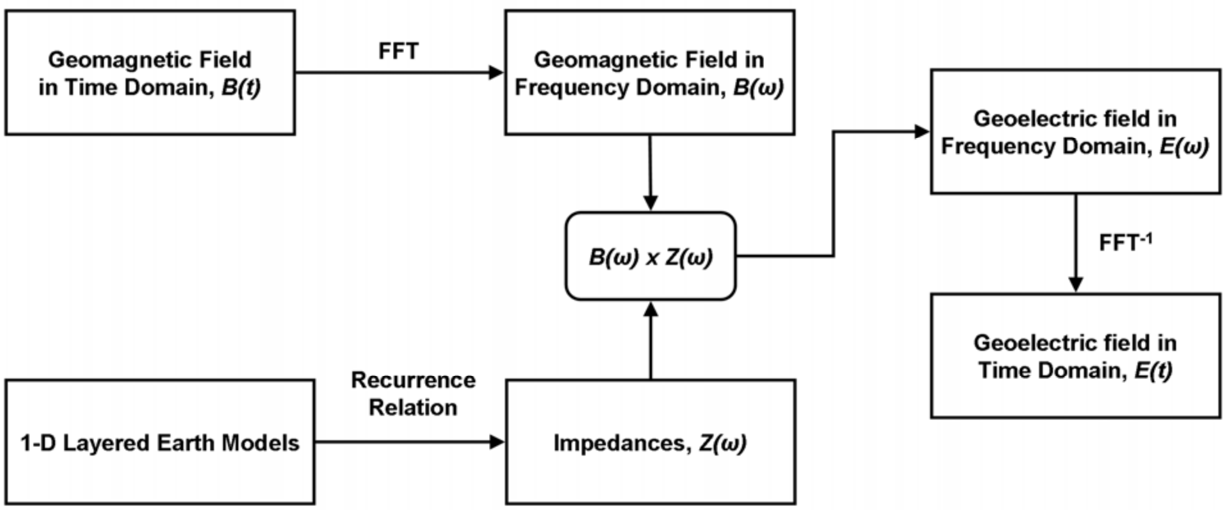

Figure 6. Sequence of steps used for calculations of the electric field from the geomagnetic field and layered earth model

In order to get a statistical description of the levels of geoelectric field variations, we establish the hourly index as the maximum amplitude of the X and Y-components of the geo-electric field in one hour (Hourly Maximum Amplitude). Geomagnetic data from 2 observatories which have produced data for 40 years (i.e. MEA and YKC) with respective zonal surface impedance models were used to calculate geoelectric field X (northward) and Y (eastward) components. Because the geomagnetic data from GLN and BRD were not available in the period comparable with 40 years, we did not include them in the presented analysis.

Annual changes of the eastward (Y-) component of the electric field hourly maximum are presented in Figure 7 (median value) and Figure 8 (annual largest value) for illustrative purposes. More details can be found in Chapter 4. As well, the Table 3 contains the exact values of the geoelectric field.

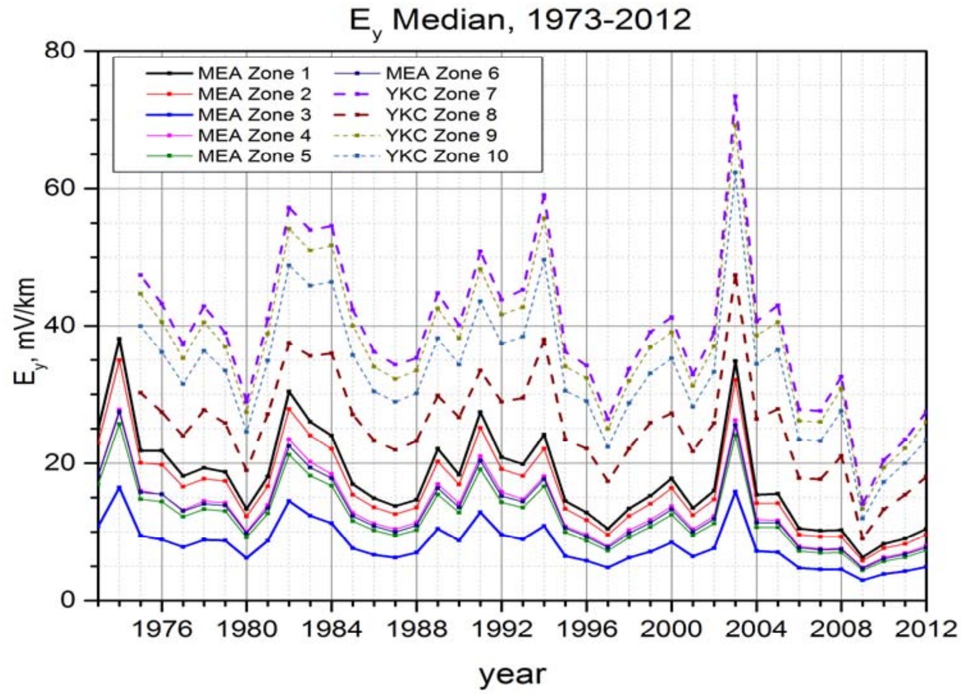

Figure 7. Annual changes of the median of the electric field hourly amplitude, Y- component

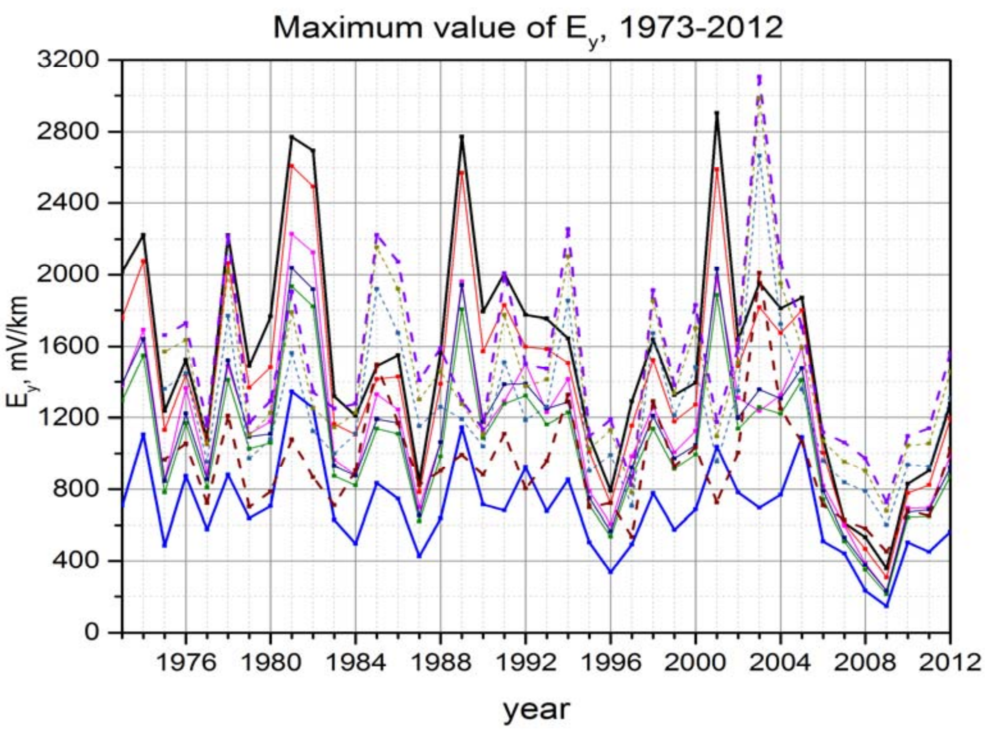

Figure 8. Annual changes of the annual maximum of the electric field hourly amplitude, Y- component

Table 3 Statistical properties of the modelled geoelectric field variations, 40 years

a) X-component

	Median mV/km	Mean mV/km	95% mV/km	99% mV/km	Max mV/km
MEA, ZONE 1	13.0	30.3	106.8	303.0	2208.0
MEA, ZONE 2	12.0	27.8	98.1	277.4	1987.3
MEA, ZONE 3	6.1	13.9	49.6	136.3	889.0
MEA, ZONE 4	9.9	23.0	81.4	229.1	1626.2
MEA, ZONE 5	9.1	20.9	73.4	208.9	1474.7
MEA, ZONE 6	9.7	22.2	78.1	220.2	1568.6
YKC, ZONE 7	27.6	52.7	185.1	372.0	2438.6
YKC, ZONE 8	17.3	32.6	113.4	228.0	1487.6
YKC, ZONE 9	25.9	49.4	173.2	348.6	2326.7
YKC, ZONE 10	23.1	43.8	153.2	308.7	2053.7

b) Y-component

	Median	Mean	95%	99%	Max
MEA, ZONE 1	16.3	38.7	146.0	361.0	2901.9
MEA, ZONE 2	14.9	35.6	134.7	332.6	2607.5
MEA, ZONE 3	7.4	18.0	70.0	174.3	1345.7
MEA, ZONE 4	12.2	29.4	112.3	280.9	2229.6
MEA, ZONE 5	11.2	26.7	101.7	253.4	1933.2
MEA, ZONE 6	11.9	28.4	108.0	268.3	2037.1
YKC, ZONE 7	38.1	69.0	237.8	468.5	3106.7
YKC, ZONE 8	24.8	43.9	147.3	292.1	2010.0
YKC, ZONE 9	36.0	65.0	221.4	439.1	2986.5
YKC, ZONE 10	32.3	58.0	196.7	390.0	2666.1

As inferred from the analysis, statistically the southern part of the province (MEA 1-6) is characterized by lower geoelectric field than northern part (YKC 7-10) and the north-south (X) component is usually lower than east-west (Y). At the same time, the maximum ("extreme") values for 40 years are comparable for both geographic areas of province, and the difference between components is less significant (20%).

These 40-years statistical values can be applied with the network model for evaluation of the different types of scenarios, from the assessment of the "most often" (using the median values) case to "worst in 40 years" (using the maximum values) scenarios. It should be noted, that statistical values do not correspond to the same moment in time, so it would not be correct to say that when the X component is at its maximum value, the Y-component is also at its maximum.

Conclusions

The 40 years of the geomagnetic data recordings from three geomagnetic observatories were used to derive the statistical and the maximum values of the geomagnetic activity and geoelectric field values. While the results for the Meanook and Yellowknife locations are directly relevant to the infrastructure of the Alberta due to their close proximity, the data for Ottawa were analyzed for setting some “background” geomagnetic activity values for comparison with some other, close to mid-latitudes, locations.

The geoelectric field has been modelled using the geomagnetic field data and earth resistivity models to derive the surface impedances at different locations.
It should be noted, that the geoelectric field results are very dependent on the surface impedance, so that the difference in these models can give extreme values up to three times larger (smaller).

The estimated values can be used with power or pipeline network models to derive the GIC in the power lines or pipe-to-soil potential variations for the pipelines.

Acknoledgements

We acknowledge Alberta power company AltaLink for support of this study, the members of Geomagnetic Laboratory, NRCan, for provision of geomagnetic data and Dr. David Boteler, NRCan, for his thorough review of this Open File.

Chapter 1. Geomagnetic Climatology

1.1. Introduction

Analysis of the geomagnetic activity in the Alberta area was made using data from several geomagnetic observatories which are part of the NRCan Canadian Magnetic Observatories Network (Figure 1.1). Geomagnetic activity is greatest in the auroral zone, where most of the province is located, and it has also the most spatial variability in this zone. There is only one geomagnetic observatory in Alberta, e.g. Meanook (MEA) and thus for some approximate evaluation of the spatial variability of the geomagnetic disturbances we use the data from the observatory available to the north of the provincial border (Yellowknife observatory, YKC) and the closest observatory to the south (Gleanlea, GLN), later closed and replaced by Brandon observatory (BRD).

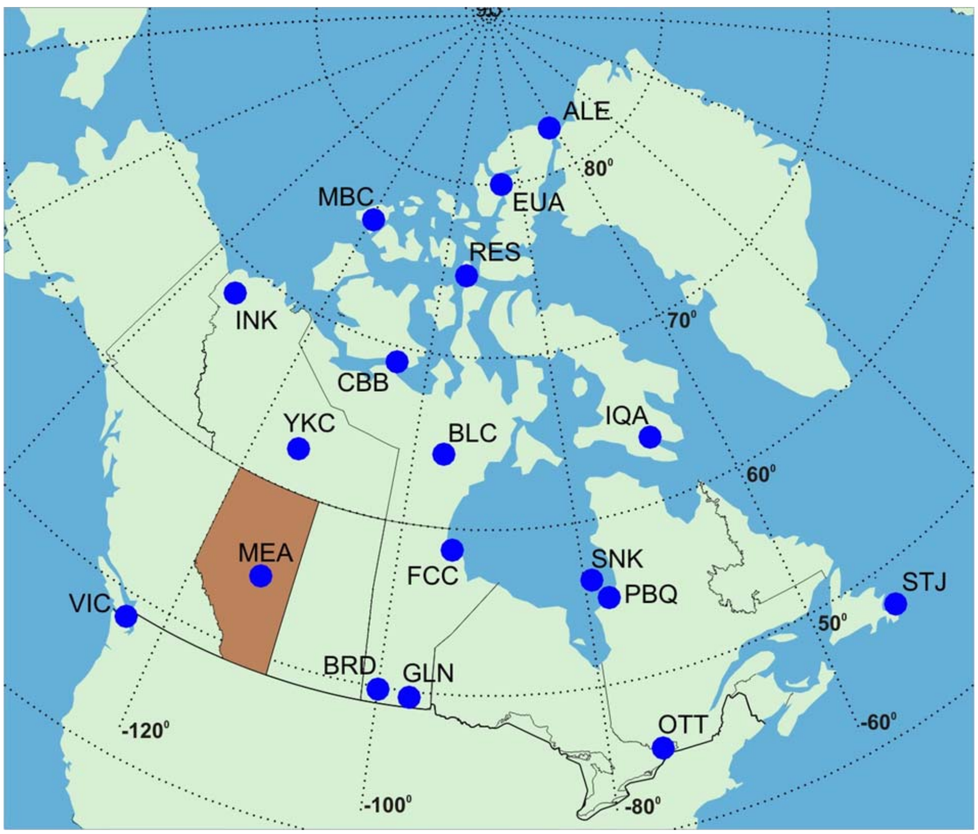

Figure 1.1. The map representing locations of the NRCan observatories.

Meanook data cover almost 40 years, from 1973 to 2012, Yellowknife data cover 38 years, from 1975 to 2012. Currently we have only 15 years of GLN data (from 1982 to 1996), with several years after 1996 to be available later. This station was closed in 2006 and replaced by Brandon geomagnetic observatory starting 2007.

Because the data from both Glenlea and Brandon observatories do not cover the period of time comparable with YKC and MEA data and also for comparison with geomagnetic activity in the lower latitudes, the recordings from Ottawa (OTT) observatory were also used.
The exact geographic and geomagnetic coordinates of observatories used in the assessment of the geomagnetic activity and years of data availability are presented in the Table 1.1 below.

Table 1.1. Locations of Geomagnetic Observatories and data coverage period

Station	Code	Latitude (N)	Longitude (E)	Geomagnetic Latitude	Geomagnetic Longitude	Years of availability
Meanook	MEA	54.616 N	246.653 E	61.29 N	52.80 W	1973-2012
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Brandon	BRD	49.870 N	260.026 E	58.23 N	34.91 W	2007-2012
Ottawa	OTT	45.403 N	284.448 E	55.18 N	4.11 W	1973-2012

A statistical study of these 40 years of geomagnetic data was made to evaluate the the statistical occurrences of the different activity levels for the geomagnetic "climate" in Alberta.

1.2. Geomagnetic Data Availability

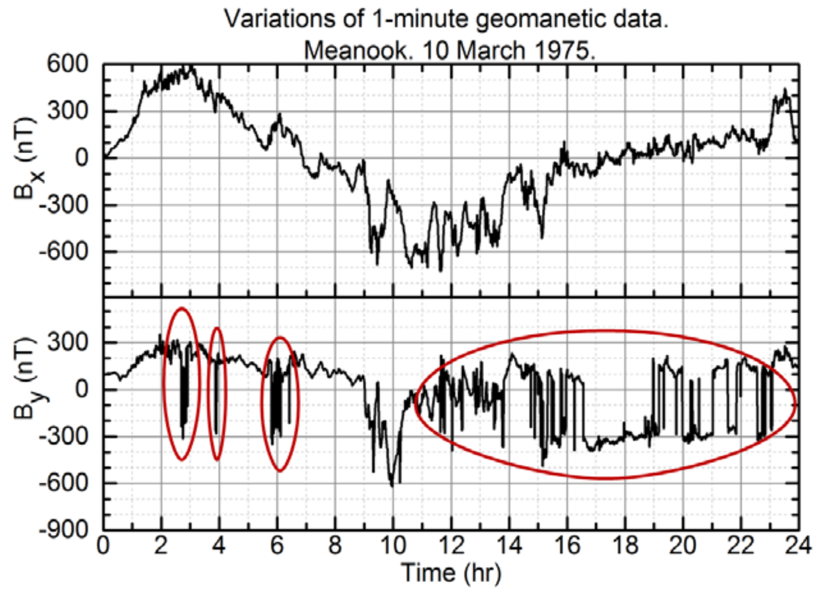
Data sampling rate was 1 minute, recordings consist of three components of the magnetic field, X (directed northward), Y (directed eastward) and Z (directed vertically down). Time is the hours of Universal Time (UT).

The data were processed to determine the maximum hourly range (i.e. the absolute difference between the lowest and highest 1-minute values within a particular hour) for both horizontal components for each hour of each day of each year. And these hourly range indices were then used for the statistical evaluation of the local geomagnetic activity, rather than minute-by-minute variations. The approach of utilizing indices is widely used in the research and applications related to the geomagnetic activity (Mayaud, 1980) and space weather, such as, for example, widely used 3-hour planetary Kp index which describes the geomagnetic activity at mid-latitudes.

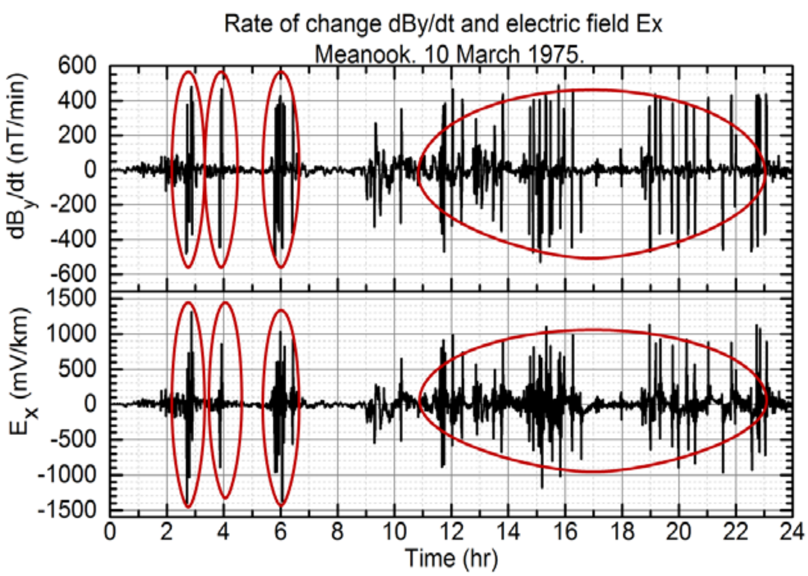
The Kp index (named global index of geomagnetic activity) has been widely accepted as "level" of geomagnetic storms (see, for example, NOAA scales of the space weather activity). This index is derived from geomagnetic variations of several stations around the globe, among which there are MEA and OTT. Although it seems that use of Kp index is reasonable for MEA and OTT areas, it will be shown later than the local activity in MEA and OTT are quite different, thus, it is better to use local geomagnetic indices for descriptions of the geomagnetic variations in the particular area for assessments of the impacts on the local infrastructure.

The hourly range indices in X and Y components, HRX and HRY, were examined to identify and remove those hours when: (1) no measurements being made due to various causes at the observatory, and (2) there were less than 48 minutes of good data available for a particular hour due to, for example, malfunctioning of magnetometers.

An example of corrupted data is shown on Fig.1.2, a, b. Spikes in the Y component of the minute variations of the geomagnetic field By (east-west) component (Fig. 1.2a, lower panel) and corresponding spikes in the rate of change variations and the modelled electric field variations (Fig. 1.2 b) are encircled in red. Spikes and DC-like offsets in the magnetic field achieve values of several hundreds of nT. They produce spikes in the electric field as large as 1500 mV/km.



a)



b)

Fig. 1.2. Example of corrupted data for Y component of the geomagnetic field in Meanook, March 10, 1975. a) Variations in the Bx and By components of the geomagnetic field. b) Rate of change dBy/dt and variations of the modelled electric field Ex. The corrupted data are encircled in red.

The analyses of day-by-day magnetic data revealed that the data from early years, especially in 1973-1978 years, were significantly corrupted. The detailed cleaning of the geomagnetic data for the years preceding INTEMAGNET (before 1991) was done in order to exclude them from further analysis and modelling. More on the importance to exclude corrupt data from statistical study is discussed in Part 1.4

It is widely accepted that variations of the geomagnetic activity (number of geomagnetic storms) are correlating to some extent with the variations in the sunspot number, usually referred as "solar activity cycle" approximately about 11 years, it was important to have several solar cycle of data. The percentage of the data available from year to year is shown in Figure 1.2 together with the variations of the solar cycle index, i.e. monthly sunspot number. As can be seen, the data availability covers entire three solar cycles, with the exception of the Glenlea/Brandon.

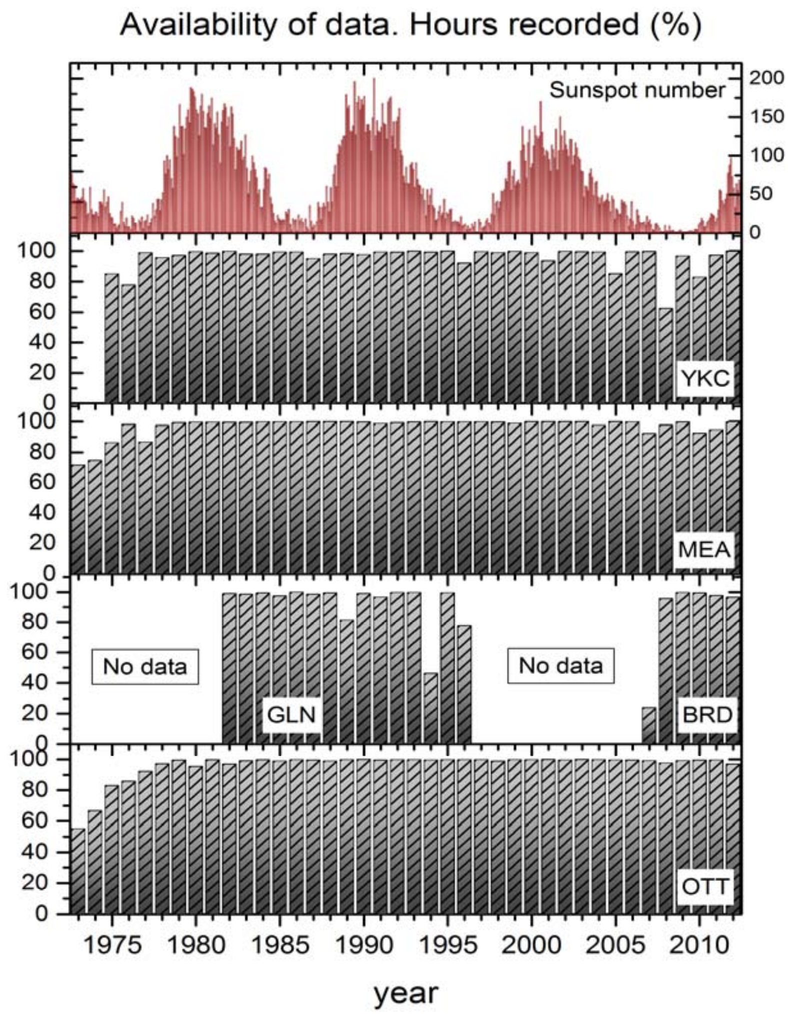


Figure 1.3. Solar Cycle variations (top-sunspot number, SSN) and their coverage by the availability of the geomagnetic data per observatory (top to bottom: Yellowknife, Meanook, Glenlea/ Brandon and Ottawa) for the period from 1973 to 2012.

1.3. Geomagnetic Variations in Alberta

For an initial examination of the geomagnetic activity in the area, a 1989 year was chosen because of the strong magnetic storm on March 13th which caused widespread power systems problems including the Quebec blackout. This year has good coverage of the data (very few missing hours). The evaluation of the geomagnetic activity was based on the hourly range of the minute variations in each of three components, i.e. HRX, HRY, HRZ. These variations for Yellowknife (YKC), Meanook (MEA), Glenlea (GLN) and Ottawa (OTT) are shown in Figures 1.4-1.7.

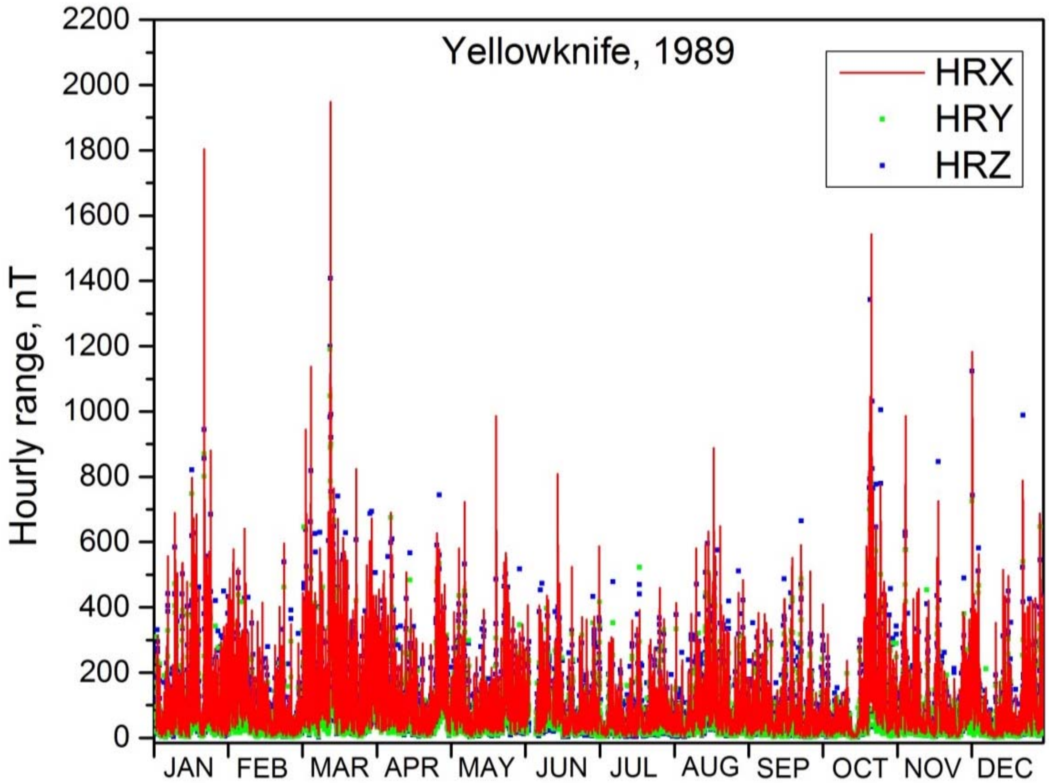


Figure 1.4. Variations of the geomagnetic field (hourly range index) at the Yellowknife observatory in 1989. The color-coded are different components, such as: red-X, Green-Y and blue-Z component.

Visual examination of the plots shows that the north of the province (represented by geomagnetic data from Yellowknife magnetic observatory) experiences the variations <800 nT most frequently, which is typical for auroral zone, while southward of it, in the central part of the province (MEA) and southern part (represented by GLN) the variations of such size become less frequent. Typical geomagnetic activity experienced by the power systems in mid-latitude is represented by the data from the Ottawa geomagnetic observatory (Fig.1.6) and are significantly lower (<400nT).

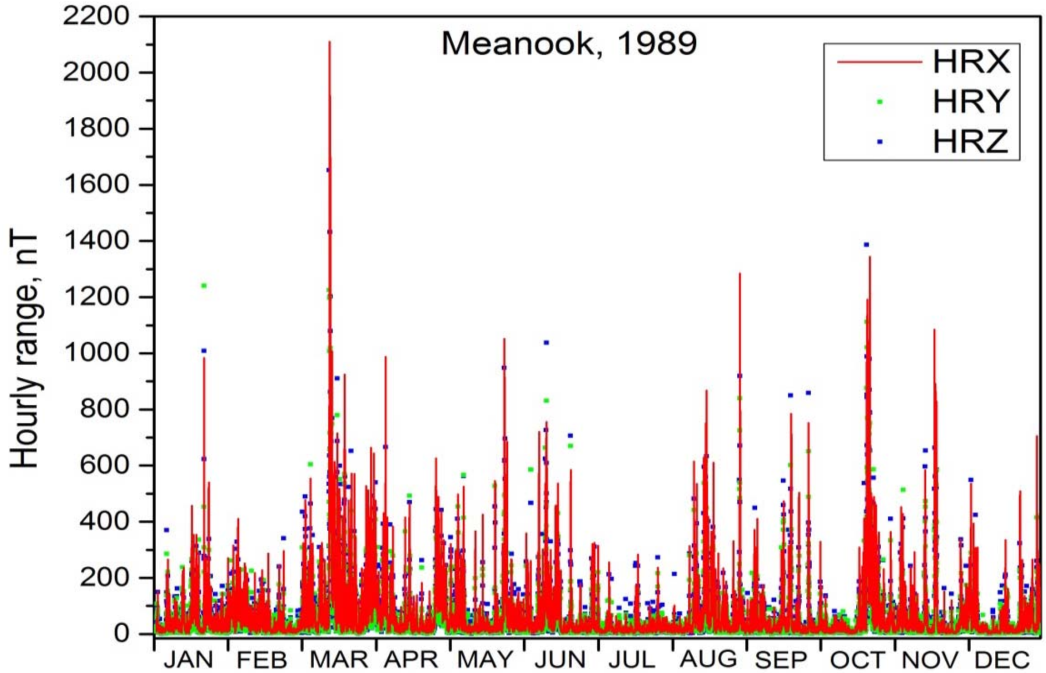


Figure 1.5. Variations of the geomagnetic field (hourly range index) at the Meanook observatory in 1989. The color-coded are different components, such as: red-X, Green-Y and blue-Z component.

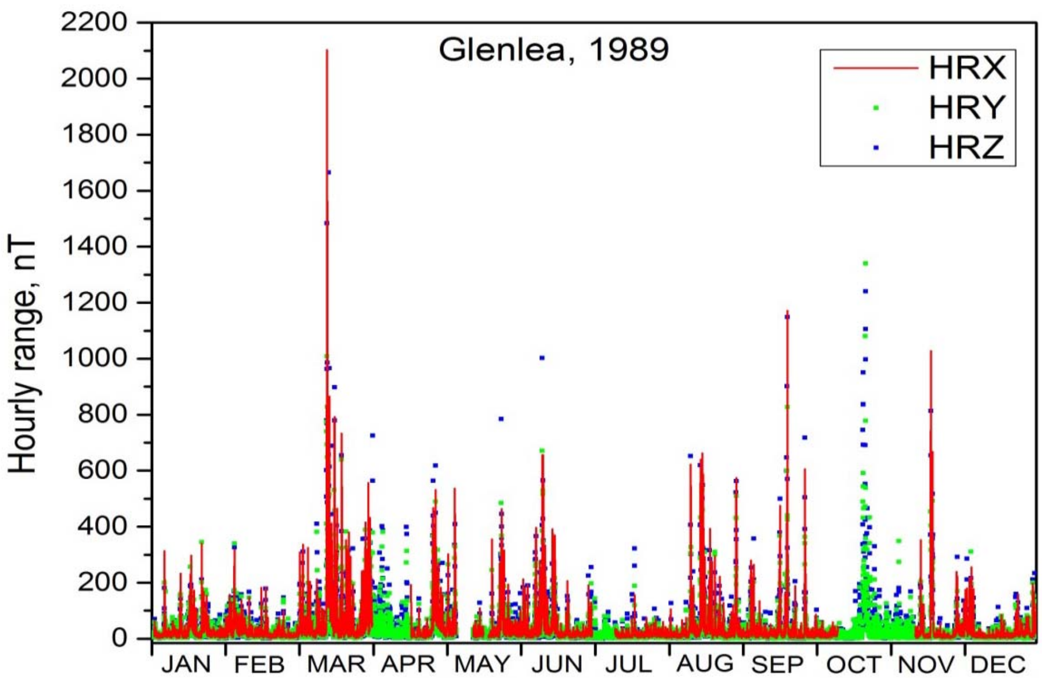


Figure 1.6. Variations of the geomagnetic field (hourly range index) at the Glenlea observatory in 1989. The color-coded are different components, such as: red-X, Green-Y and blue-Z component.

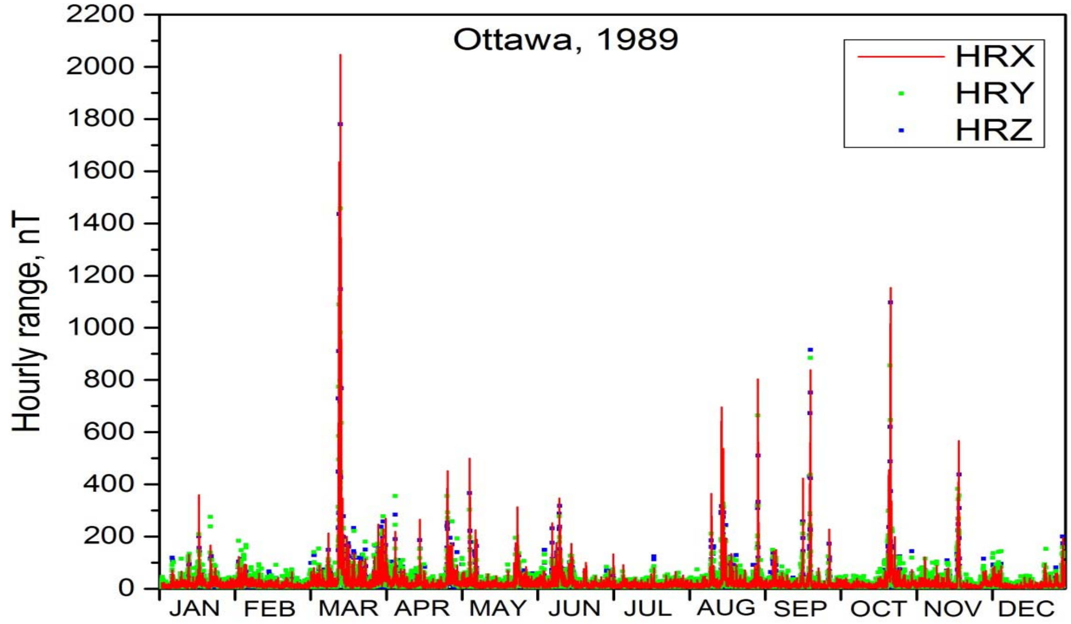


Figure 1.7. Variations of the geomagnetic field (hourly range index) at the Ottawa observatory in 1989. The color-coded are different components, such as: red-X, Green-Y and blue-Z component.

Regarding the highest “spikes” in the plots it can be noted, that their sizes are comparable for MEA and GLN. Specifically for the geomagnetic disturbance during March 13, 1989 storm, the geomagnetic activity has been equally large at all observatories except YKC, where it was a bit less than at lower latitudes. At the same time, the geomagnetic activity was quite high in the middle of January at YKC, less high at MEA, but not significant at GLN and OTT.

Two conclusions can be drawn based on the initial examination:

1. It is very important to have the local monitoring of the geomagnetic activity instead of reliance on average “global” indices.
2. The statistical analysis must be done to characterise the occurrences of different sizes of disturbances. This is described in the next paragraph.

1.4. Statistical Properties of the Geomagnetic Variations/annual

The occurrence of different statistical levels of geomagnetic activity was determined by counting the number of hourly ranges in bins 10 nT wide. Figs. 1.6 and 1.7 show the illustrative example for Meanook observatory, year 1989. The lower part of the figure shows the total number of counts for the year in each bin. The upper part of the figure shows the cumulative counts as a percentage of the total number of hours in the year.

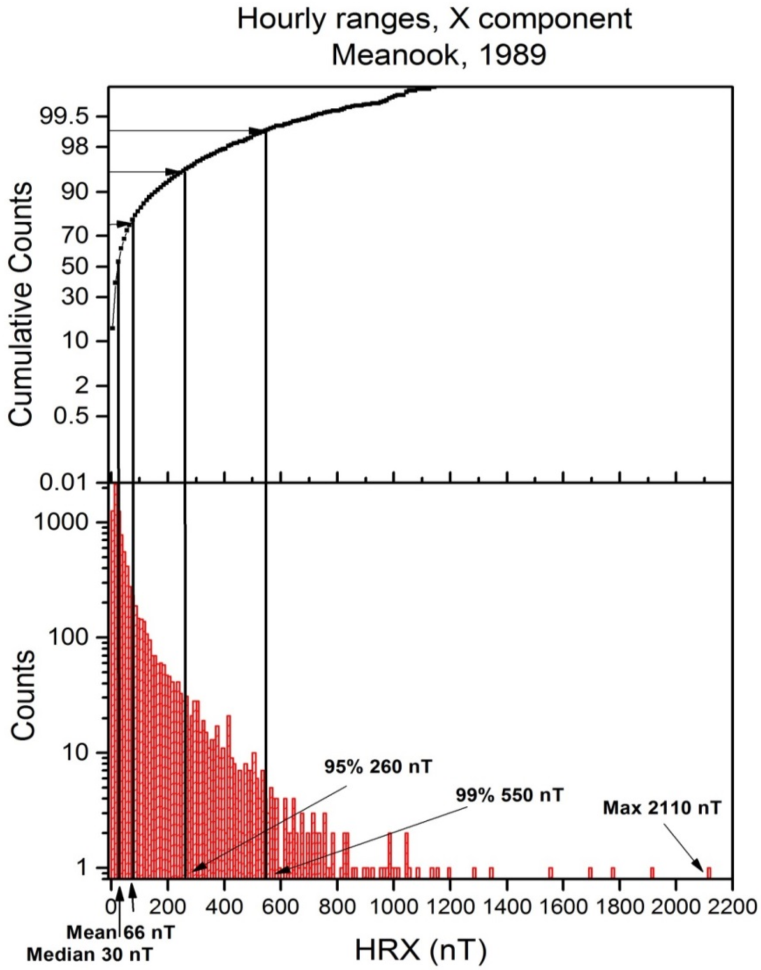


Figure 1.8. Statistical parameters of the hourly range variations of the geomagnetic field in MEA, year 1989.

Several statistical levels were chosen for description, such as median level (corresponding to the maximum of the curve in Figure 1.8), mean (average), the levels at the 95%, 99% annual occurrences and the annual maximum value. In the case of year 1989 (Fig.1.8) the median value (i.e. the value which happens most often) is 30 nT, mean value (average) is 66 nT, 95% occurrence value (i.e. 95% of the year the hourly range index is below this value) is 260 nT, 99% occurrence value is 550 nT and maximum in the year is 2110 nT.

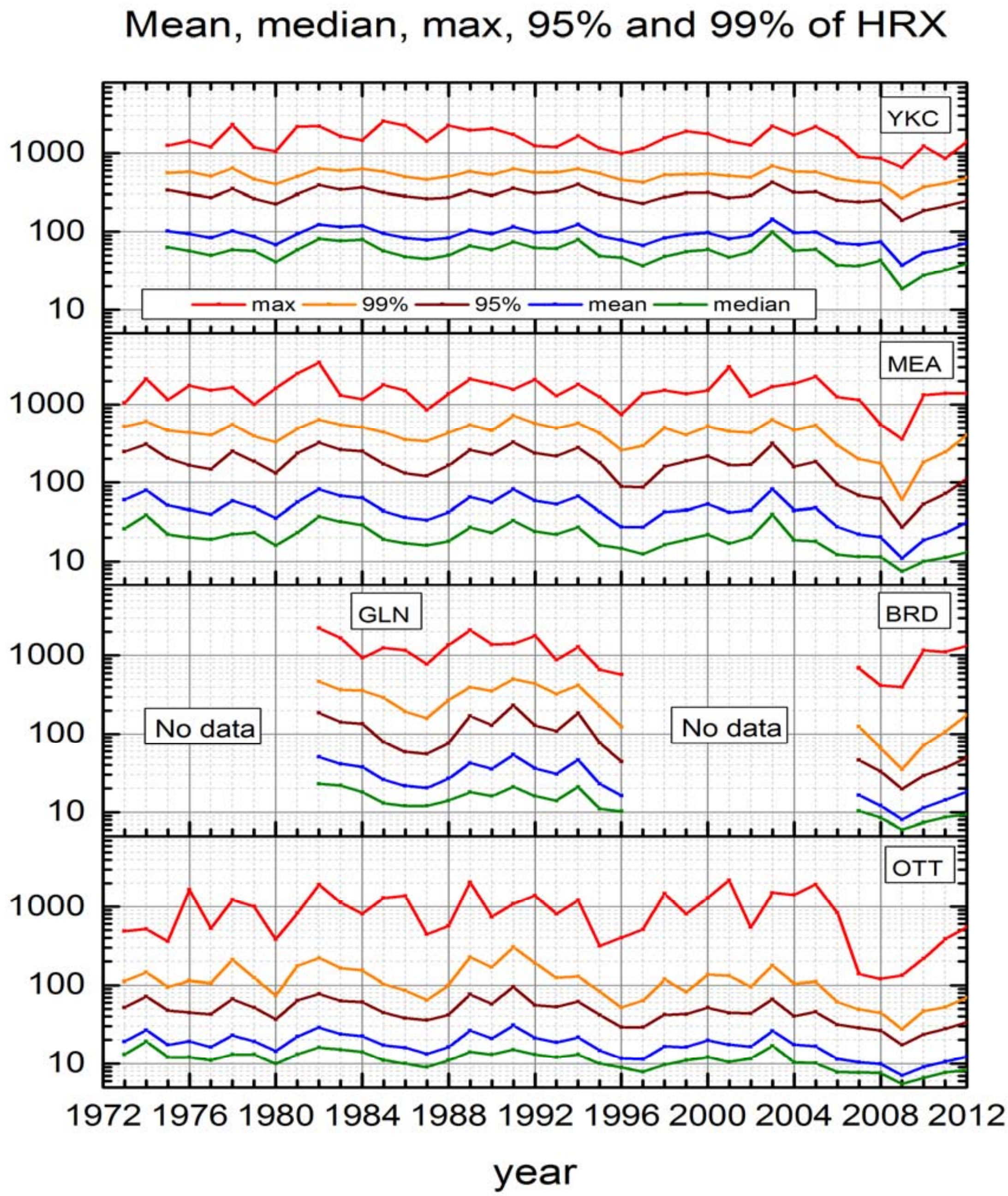


Figure 1.9. Annual changes of the statistical properties of the HRX Geomagnetic activity index variations, such as median, mean, 95%, 99% and maximum for several observatories (vertical scales are in log).

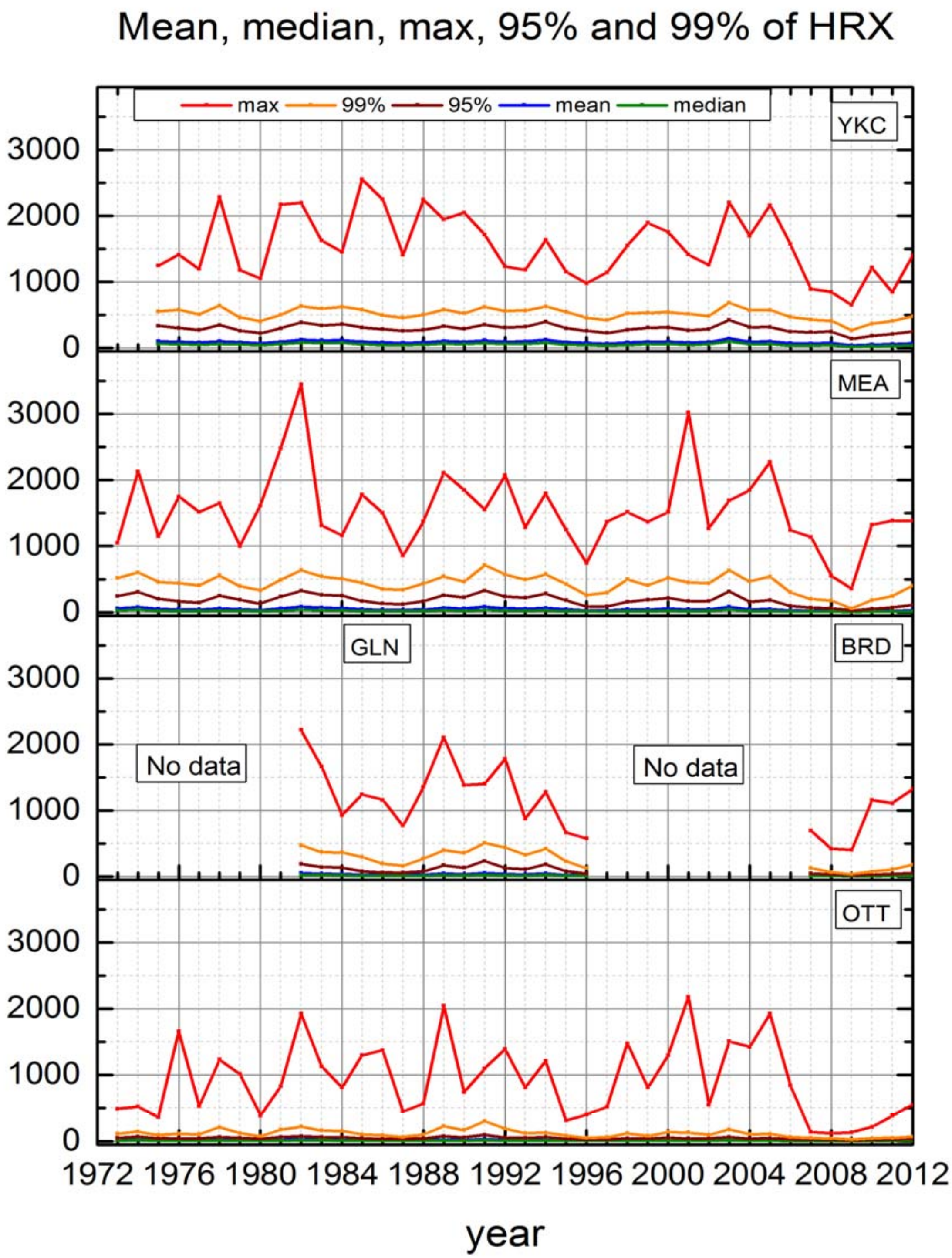


Figure 1.10. Annual changes of the statistical properties of the HRX Geomagnetic activity index variations, such as median, mean, 95%, 99% and maximum for several observatories (vertical scales are plain).

The variations of these levels of geomagnetic hourly ranges (X-component only) for each year from 1973 to 2012 are shown in logarithmic and linear scales in Figures 1.9 and 1.10 respectively for each observatory (including OTT for comparison).

Annual changes of the median, mean, 95% and 99% are better recognizable in the logarithmic plot (Figure 1.9). It is easy to conclude that, while typical for mid-latitudes (OTT) fluctuations of median and mean are below 30 nT level, for mid- and northern Alberta (MEA and YKC) the levels are mostly between 10 and 100 nT, i.e. 3 times higher.

The 95% and 99% occurrence levels for typical mid-latitude situation (OTT) is between 30 nT and 300 nT, while for Alberta these are between 100 and 1000 nT. It is also clear that in mid-Alberta (MEA) the variability is higher than for Northern part (YKC).
Maximum activity levels in OTT are not exceeding 2200 nT, while for MEA and YKC they are mostly between 900 nT and 3000 nT. In exceptional cases in MEA the highest value can even exceed the 3000 nT level (see Figure 1.9 for better resolution). As well, the highest geomagnetic activity levels in MEA do not obviously coincide with the ones at any other stations, such as, for example, the highest in 40 years values was recorded in 1982 and the second highest - in 2001.

Because the data from GLN and BRD are not covering the whole period, they are plotted but not analyzed until more data will be available in the future. It needs to be mentioned that, according to the data, the geomagnetic activity has been exceptionally low in the years 2007-2010 and tends to increase to normal levels after 2011.

The annual distribution in each year for MEA observatory is provided as Appendix A and for YKC can be found in (Trichtchenko L. and Fernberg P., 2012).

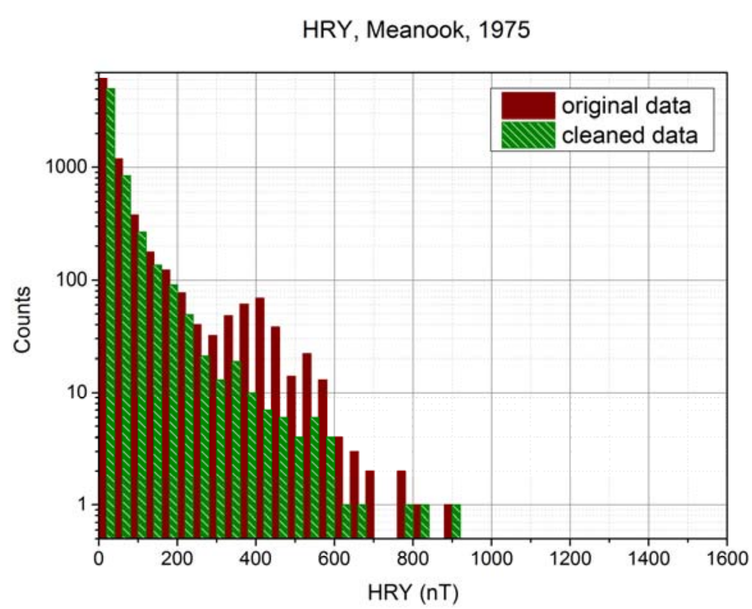


Fig. 1.11. The impact of corrupted data on the statistical distribution of the hourly range index (Y-component). Corrupted (brown) and cleaned (green) geomagnetic data for Meanook, 1975.

The spikes in the minute variations of the geomagnetic field significantly impact the shape of the annual distributions of the data, as illustrated in Figure 1.11. In this figure the annual distributions of the original corrupted data and the cleaned data for Meanook, 1975, are plotted. The comparison of these two histograms shows that the corrupted data provides a 'bump' in the histogram around 400 nT. It is the result of the corrupted magnetic variations similar to ones encircled on Figure 1.2a).

1.5. Statistical Properties of the Geomagnetic Variations/long-term

Further statistical analysis based on the data for longer periods, i.e. for 15 years (period of data availability from GLN observatory) and for the whole period of 40 years has been done on the properties of the distribution function for hourly range index at MEA observatory. The shape and the characteristics of the 40-year distribution as an example are presented in Figure 1.12. The median value is quite low at 19 nT, while average is 47 nT. The 95% and 99% are 190 nT and 460 nT respectively. The "extreme" (i.e. maximum in 40 years) geomagnetic activity hourly range index is very high at 3450 nT.

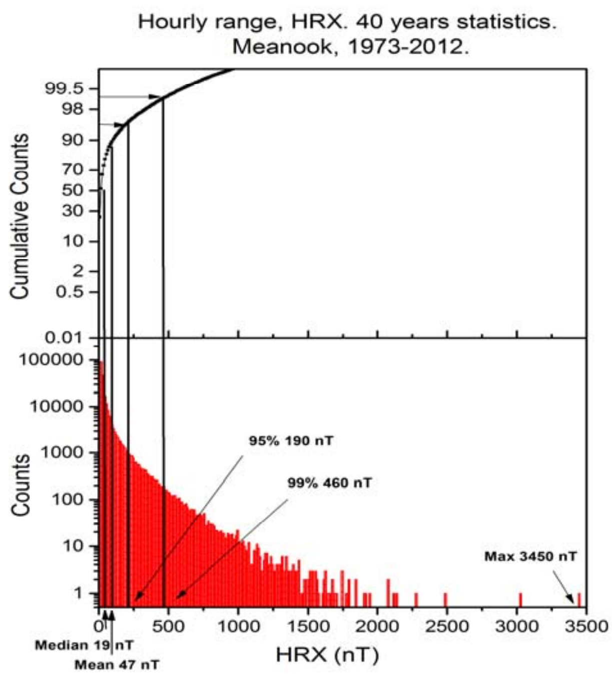
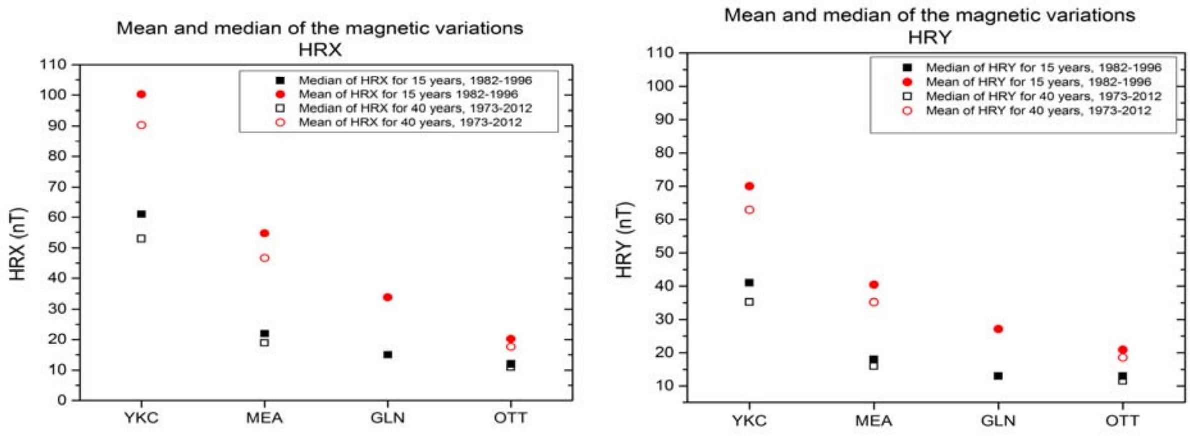
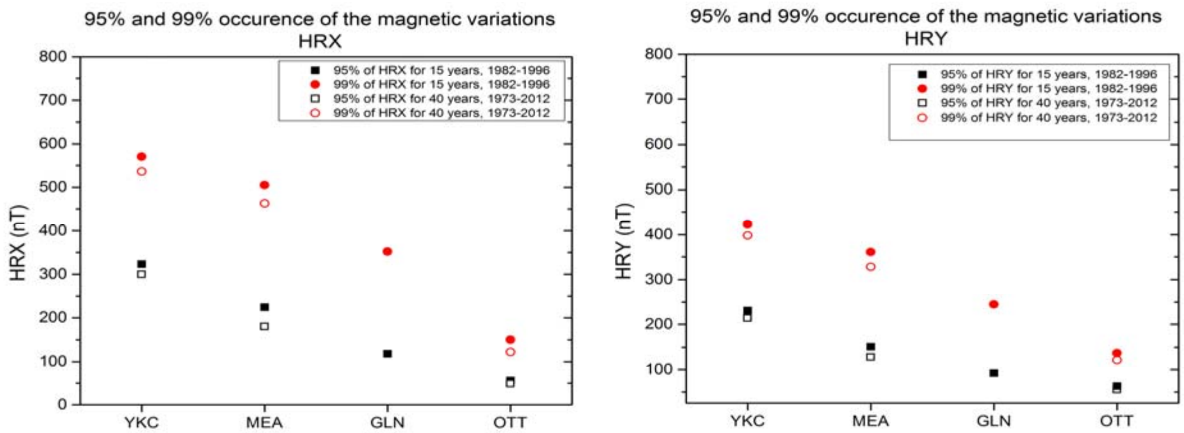


Figure 1.12. The parameters of the distribution function of hourly range variations of the X-component in MEA, 40 years of data.

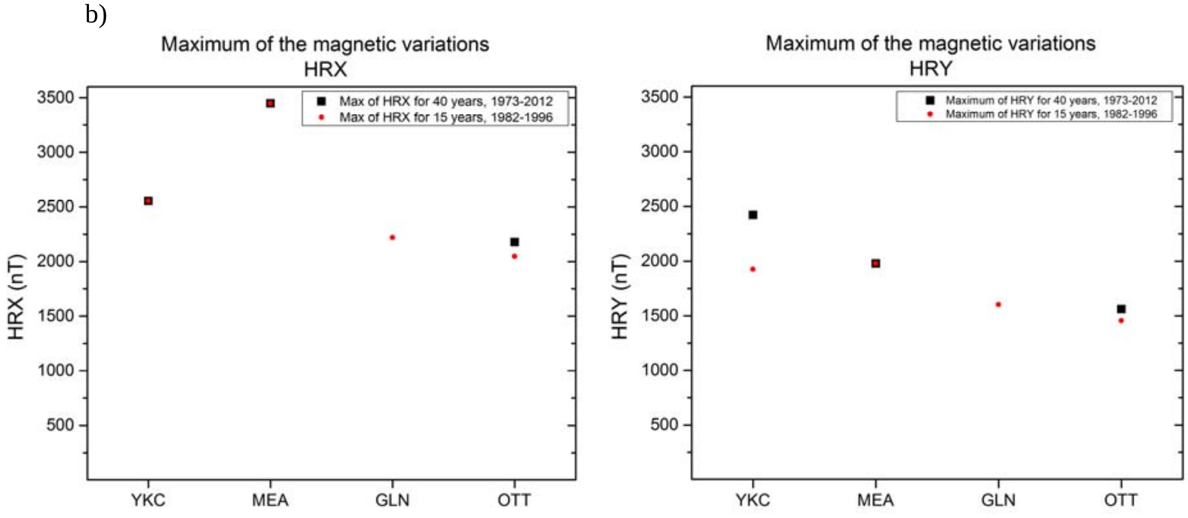
Because the GLN data were available for only 15 years, the statistical properties were calculated for two periods of time, 40 years (for YKC, MEA and OTT) and 15 years (for YKC, MEA, OTT and GLN). This gives us opportunity to include the limited coverage of GLN data recording and also to see how the duration of recordings impacts the statistical properties of the dataset.
Results for X- and Y-components are presented in Figures 1.13 (a-c) with solid circles for 15 years statistics and open circles for 40 years statistics.



a)



b)



c)

Figure 1.13. Statistical parameters for 40 years and 15 years of HRX and HRY indices of geomagnetic activity: a)-median and mean; b)- 95%, 99% and c)-maximum values.

The statistically most often occurring median and mean levels of the geomagnetic activity (Figure 1.13a) are decreasing from their values at high latitude observatories (YKC, MEA) down to lower latitude observatories (GLN, OTT), similarly in shape, with 40 years values less than 15 years values. The X-components are higher than Y-components for auroral stations and are practically the same for lower latitude (OTT).

The HRX and HRY values at 95 and 99 % levels are decreasing with moving from high latitudes to lower latitudes (Figure 1.13b). The 40 years duration of records gives smaller HRX and HRY values than 15 years duration recordings and the variations in Y (East-West) direction are smaller than in X-direction (North-South) in higher latitudes, but are practically the same in OTT.

The maximum values in 40-years (and 15 years) for each station are plotted in Figure 1.13c. These “extreme” values do not obviously follow the expected pattern (smaller at lower latitudes and higher at high latitudes), which means that extreme values are random and must be investigated separately. The analysis of the extreme values of the geomagnetic activity levels is described in (Nikitina and Trichtchenko, 2015).

References:

Mayaud, P.N., 1980, *Derivation, Meaning and Use of the Geomagnetic Indices*, Geophysical Monograph 22, AGU, Washington, DC, pp.40-52.

Trichtchenko L. and Fernberg P., *Assessment of Telluric Activity in McKenzie Valley Area*, 2012, Geological Survey of Canada, Open File 7143, doi:10.4095/291562

Nikitina, L. and Trichtchenko, L., *Extreme Values Statistical Assessment for Geomagnetic and Geoelectric Field Variations for Alberta.* 2015, Geological Survey of Canada, Open File 7605, doi:xxxxxx

Chapter 2. Earth Resistivity Models for Alberta

2.1 Introduction

In order to model and assess the variations of the geoelectric field in Alberta, the resistivity structure of the underlying Earth needs to be determined. This chapter describes how geological and geophysical information was used to prepare one-dimensional (1D) models of the Earth resistivity for further inputs into the modelling of the geoelectric field and subsequent applications for modelling of GIC in the network.

A review of publically-available information was undertaken, such as government geological reports and maps including on-line resources, engineering studies and scientific research papers. The focus was on the results of previous geophysical surveys, undertaken as part of crustal investigations, which provide information on the deep earth electrical resistivity and thickness of the crust. No re-calculation of available geophysical data was done.

Based on the review results, the province was divided into a series of zones that reflect significantly different geological realms which in turn would manifest themselves as zones of differing resistivity. The identification of a zone was based on the concept of geological terranes where a terrane represents a region of the Earth's crust characterized by a distinctive assemblage of rock that is different from its neighbours. Terranes are typically fault bounded. For each zone we produced an Earth model in which the resistivity changed in only one direction: vertically.

Each 1D model is comprised of a series of layers, showing the thickness and resistivity, extending from Earth's surface through the crust and into the mantle. Determination of resistivity into 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.

These one-dimensional (1D) models do not include lateral changes of resistivity within each zone. However lateral resistivity changes are taken into account by the changes in the resistivity models from zone to zone.

This chapter first provides a background of Earth's internal structure and how variable the electrical resistivity of Earth materials can be, as well as how resistivity is measured. Secondly, the geological areas of the province are briefly described. Finally, a description is provided on how 1D models were developed for the ten different resistivity zones, the sources of information that were used, ending with a presentation of the 10 developed 1D models. Appendix 1 provides tables detailing the information sources and justifications for resistivity values and thickness for layers shown in each of the models.

2.2. Interior Structure of Earth

The Earth's electrical resistivity varies with depth as a function of temperature and pressure, changes to abundance and distribution of conductive minerals, and pore volume and fluid composition For the purpose of modelling the geoelectric field, Earth can be divided into large and small scale structures in which the electrical resistivity is affected by different factors.

On the large scale, Earth's interior structure is divisible into four main layers: crust, mantle, outer core, and inner core (Figure 2.1). 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.

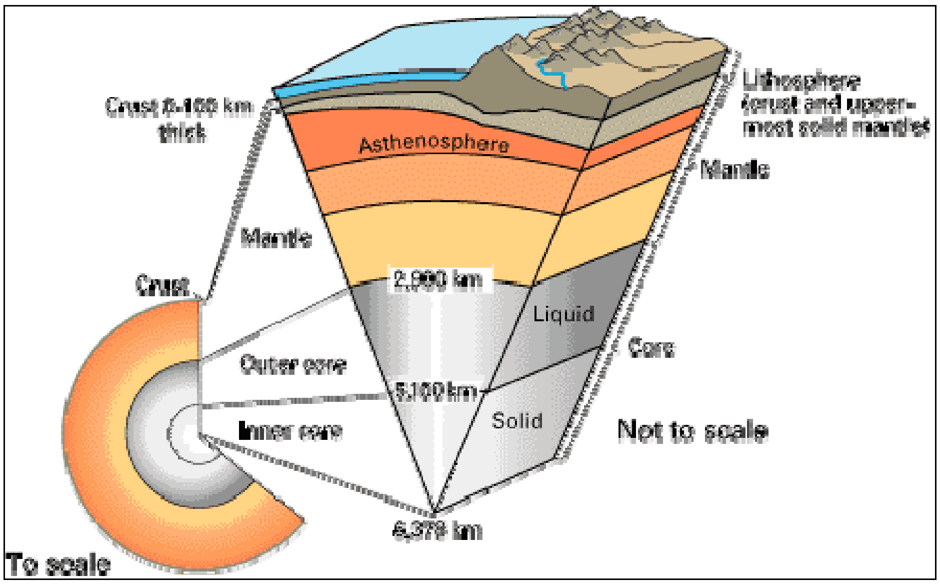


Figure 2.1. Earth's internal layers (http://pubs.usgs.gov/gip/dynamic/inside.html)

Layers within the crust (upper, middle and lower) and mantle (upper and lower) are defined by transitional boundaries where increasing pressure and temperature changes the physical and electric properties of minerals with ever increasing depth. Starting at the depth of about 100-km is the Low-Velocity Zone where partial melting of the uppermost portion of the mantle starts to occur. A discontinuity in resistivity at the depth of 400 km occurs because of a mineral phase change where the dominant minerals (olivine and pyroxene) comprising the mantle at this depth transform to a more compact form (Mussett and Khan, 2000). At a depth of about 600 km, the boundary between upper and lower mantle, a mineral phase change occurs as minerals become evermore dense. These changes influence the electrical resistivity and result in the mantle having a much lower resistivity than the overlying crust.

2.3. Electrical Resistivity of Earth Materials

The resistivity of Earth materials varies widely, as shown in Figure 2.2, with a considerable overlap of their 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 2.1 and 2.2. Geologic age of the rock, particularly for sedimentary rocks, also has an effect on resistivity values as shown in Table 2.2, whereby compaction associated with increasing thickness of overlying rock reduces pore space and amount of inter-pore water thereby increasing the rock resistivity. World-wide surveys have shown that near-surface sedimentary rock has a much lower resistivity than underlying crystalline and metamorphic and igneous rock (Ferguson and Odwar, 1997). 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. Local variations, such as presence of inter-connected sulphide minerals and graphite, are always a possibility that can further modify the resistivity values.

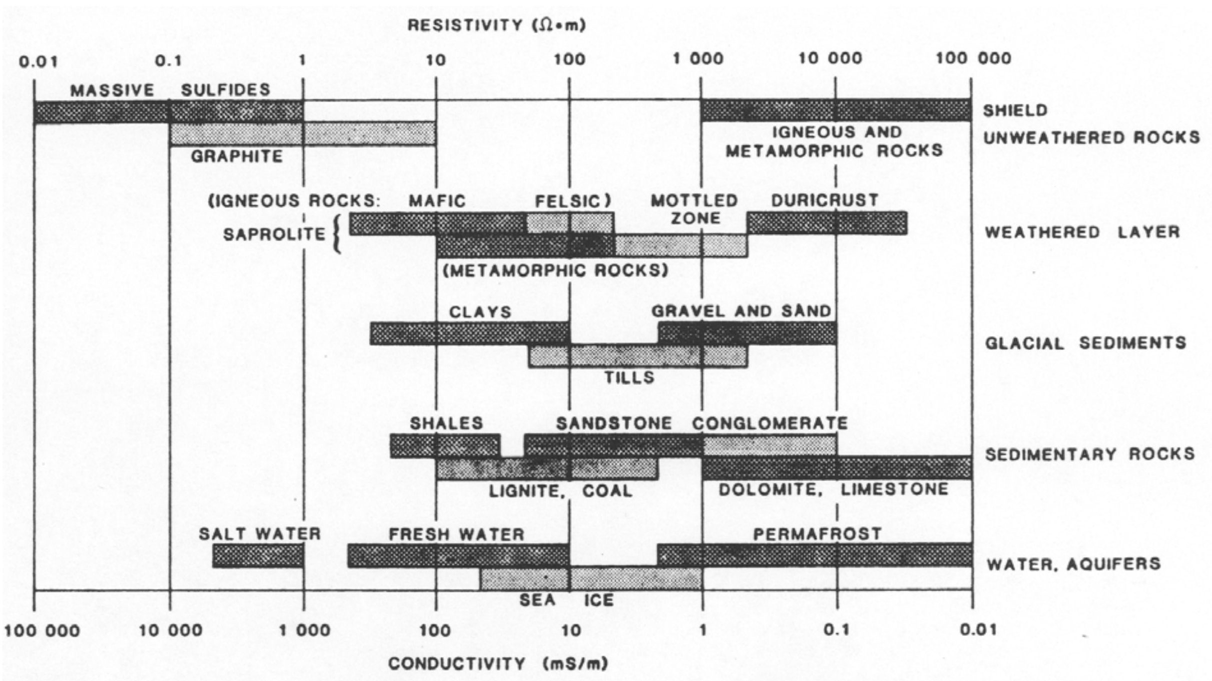


Figure 2.2. Range of resistivities for common Earth materials (from Sheriff, 2002).

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.

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 2.1. Resistivity values for some common rocks (modified from Palacky, 1988)

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

Table 2.2. Resistivity values for water-bearing rocks of various types
(from Dobrin and Savit, 1988)

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 (Jones, 1992).

Mechanisms that can alter 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 (Wu et al, 2005, Plover, 1996).

Overburden also exhibits a wide resistivity range from < 10 Ω.m to about 10,000 Ω.m, depending on the porosity, groundwater conductivity, and clay content (Ferguson and Odwar, 1997). For glacially deposited sediments resistivity values are lowest in clays, mid-range for till, and highest in gravel and sand (Palacky, 1988). In permafrost terrain, the resistivity of ice-bearing soils and rock is a function of the unfrozen water content. Ice has a higher resistivity than water and if present in sufficient quantity it will increase the resistivity of an otherwise unfrozen material. When frozen, the resistivity generally doubles in fine sized sediments such as clay and silt, and increases by a half an order of magnitude for coarser sands and gravels. Frozen rock exhibits a varying resistivity depending on its water content, porosity, salinity of the pore water, and grain size of the rock (Parkhomenko and Keller, 1967). At -12^{o}C, the resistivity of a rock is about 10 to 100 times larger than when measured at 18^{o}C (Mackay, 1979). However, if the rock is relatively impermeable to water, then the resistivity when frozen may not differ significantly from the unfrozen condition. Table 2.3 provides a compilation showing the difference in resistivity between unfrozen and frozen overburden in northern Canada.

Soil Materials	**Apparent Resistivity** (ohm-m)
<u>Thawed</u>	
Fine lake bottom sediments	2 – 20
Saturated peat	4 – 10
Sandy or gravely, silt	4 – 60
Sand and gravel beach	15 – 80
Moist gravel	80 – 200
Ice muddy silt	120 – 300
Moist peat	800 – 1000
<u>Frozen</u>	
Silt	1000 – 1200
Old high level beach gravel	900 – 1500
Icy Peat	3300 – 6100
Fine cross-bedded sands with thin beds of peat	3600 – 4000
Muddy gravel	4500 – 6000
Segregated ice	6000 +
Sand, silt and gravel mix with ice lenses, pipes and dikes	9500 +
Silty peat	13000 +
Sand with gravel lenses	15000 – 20000
Gravel and sand ridge	20000 – 22000

Table 2.3. Apparent resistivity of thawed and frozen materials (Mackay, 1970)

2.4. Measuring Earth Resistivity

Geophysical surveys using electromagnetic (EM) methods are typically used to measure variations of the Earth resistivity. Most ground and airborne EM survey systems use an electrical generator to transmit a magnetic field to induce a current into the subsurface and then measure the response. Such techniques are limited to detecting resistivity changes between tens to a few hundred metres deep because of the higher frequencies that are produced by the relatively low-powered transmitter.

The magnetotelluric (MT) method is the only geophysical technique with the ability to provide an image of the Earth's electrical structure over a depth range from near surface to the deep mantle because it utilizes powerful naturally induced currents that globally penetrate Earth. 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 apparent resistivity at various depths.

The depth to which resistivity structures can be imaged depends on the depth of penetration of the EM fields. This is dependent on the presence of local near-surface structures of low-resistivity (that can impede penetration by EM fields) and the periodicity and intensity of the EM wave. Commonly to other EM methods, 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 in oil and gas exploration wells is accomplished by the use of probes lowered into a well, often to a depth of thousands of meters. An induction tool, similar to a surface EM method, measures resistivity up to 5m or more from the borehole and provides a good representation of resistivity through the surrounding rock (Mussett and Kahn, 2000). Comparison of petroleum-well induction logs has shown a very good match with resistivity derived from MT soundings (Boerner et al, 2000).

2.5. Identification of the different zones based on geological structure

The maps of geological provinces of Canada (Figure 2.3) and the major rock types (Figure 2.4) demonstrate that all of Alberta is covered by sedimentary rock of the Western Canada Sedimentary Basin (WCSB), a component of the Interior Platform that covers much of the Canadian Prairies. Beneath the WCSB is a crystalline basement comprised mainly of granitic and gneissic rock, which has been subdivided into differing terranes on the basis of geophysical information (seismic, aeromagnetic, gravity, and in some areas magnetotelluric surveys) and drill core because bedrock exposure is limited. Ancient plate tectonics has resulted in the accretion and amalgamation of numerous, small, crustal fragments and magmatic arcs[1] of varying geological age, onto larger pre-existing Archean crust, forming the present-day mosaic of terranes. The terranes are distinguished by their particular aeromagnetic and gravity expression (orientation, pattern, magnitude).

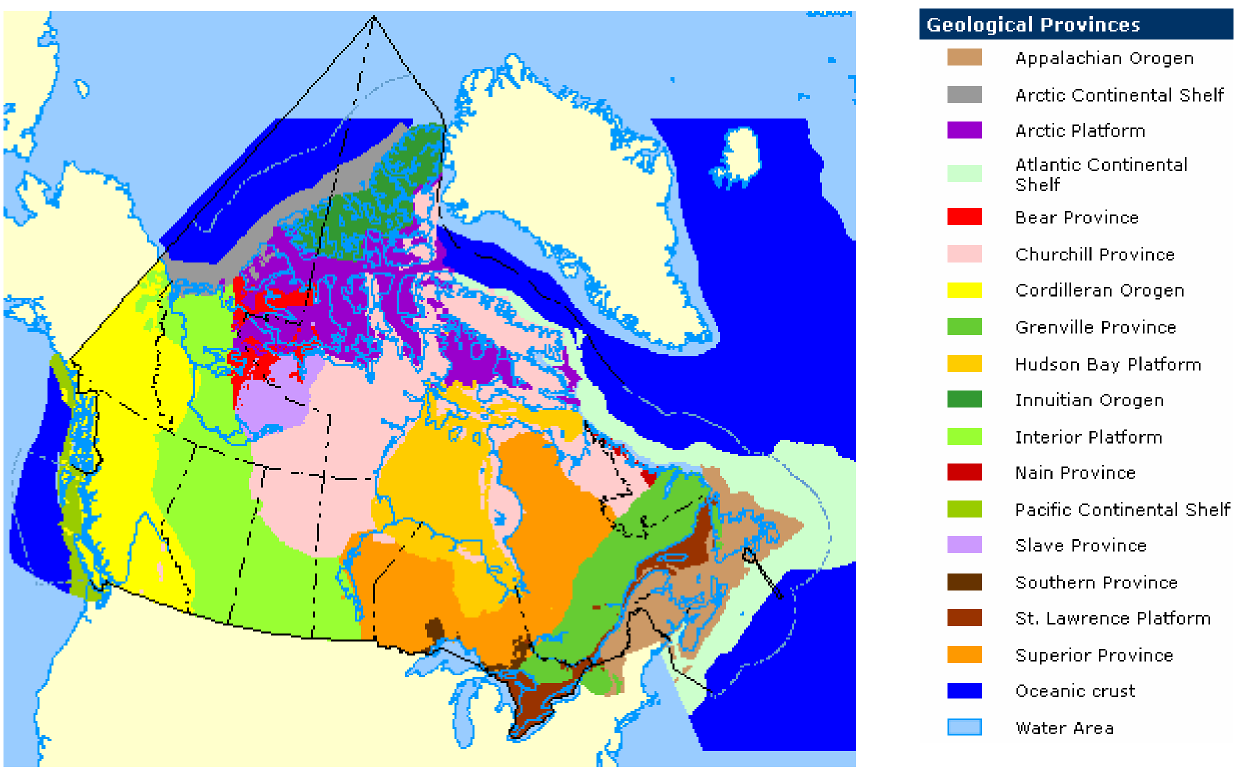


Figure 2.3. Geological Provinces of Canada, (NRCan 2012a)

[1] An arcuate range of volcanoes and intrusive bodies (plutons) parallel to a subduction zone, occurring on ocean or continental tectonic plates.

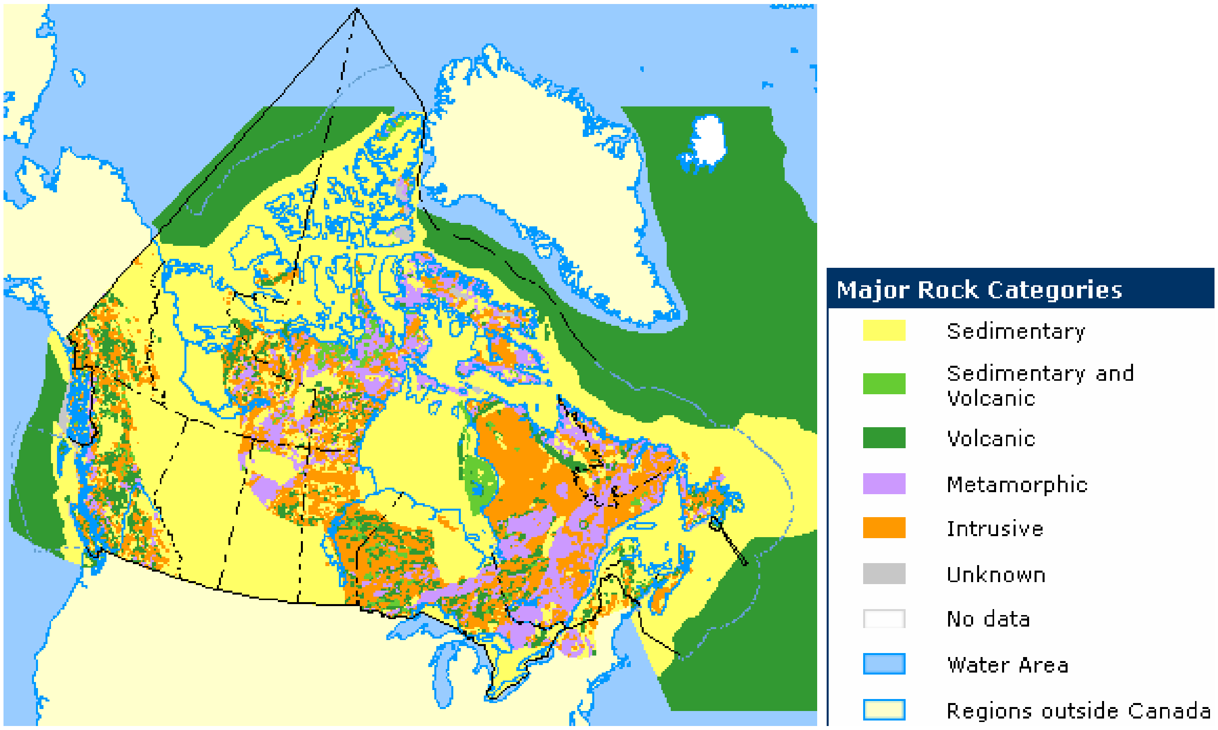


Figure 2.4. Major Rock Types in Canada, (NRCan 2012b)

In details, the geological settings of the Alberta province can be described as follows.
The top layer (overburden) is mostly a glacial till blanket, with areas of glaciolacustrine deposits of clay and silt, and lesser amount of sand and gravel. Thickness of the overburden is highly variable, up to 300 m deep in some pre-glacial bedrock valleys, but generally > 50m thick north of Edmonton and < 30 m thick south of Edmonton.

Sedimentary strata of the WCSB of Paleozoic to Tertiary age has variable thicknesses, in general increases in thickness southwestward from < 200 m at the Alberta / Saskatchewan boundary to > 5500 m at the base of the foothills of the Cordillera mountain ranges where the sedimentary strata steepen considerably. Paleozoic strata, comprised mainly of carbonates, makes up 30 to 60 % of the basin. Mesozoic-Tertiary strata are predominately clastic sediments, and include the highly carbonaceous shale of the Mannville Group up to 700 m thick.

Buried beneath the WCSB is a collage of various crustal domains (e.g. Medicine Hat Block, Buffalo Head) of Archean (early Precambrian) and Proterozoic (late Precambrian) age, as well as major tectonic features (e.g. Kiskatinaw magnetic low, Vulcan Structure) identified by regional patterns in magnetic, gravity and EM differences (Figure 2). Descriptions of and crustal evolution of the Precambrian basement are provided in Villeneuve et al. (1993), Boerner et al. (2000), Clowes et al. (2002), Gorman et al. (2002), Hope and Eaton (2002), Lemieux et al. (2000), Ross (2002), and Pana (2003).

The geological Archean Provinces, Hearne Domain and Rae Domain underlie the southeastern part and northeastern parts of Alberta, respectively. Tectonic elements (Figure 2.5) within the Hearne Domain include the Medicine Hat and Loverna Blocks. Separating the two blocks is the

Vulcan Structure (also known as the Vulcan Low), a 350-km long, more electrically resistive, prominent east-trending gravity and magnetic anomaly low, which possibly represents an ancient subduction zone (Nieuwenhuis, 2011).

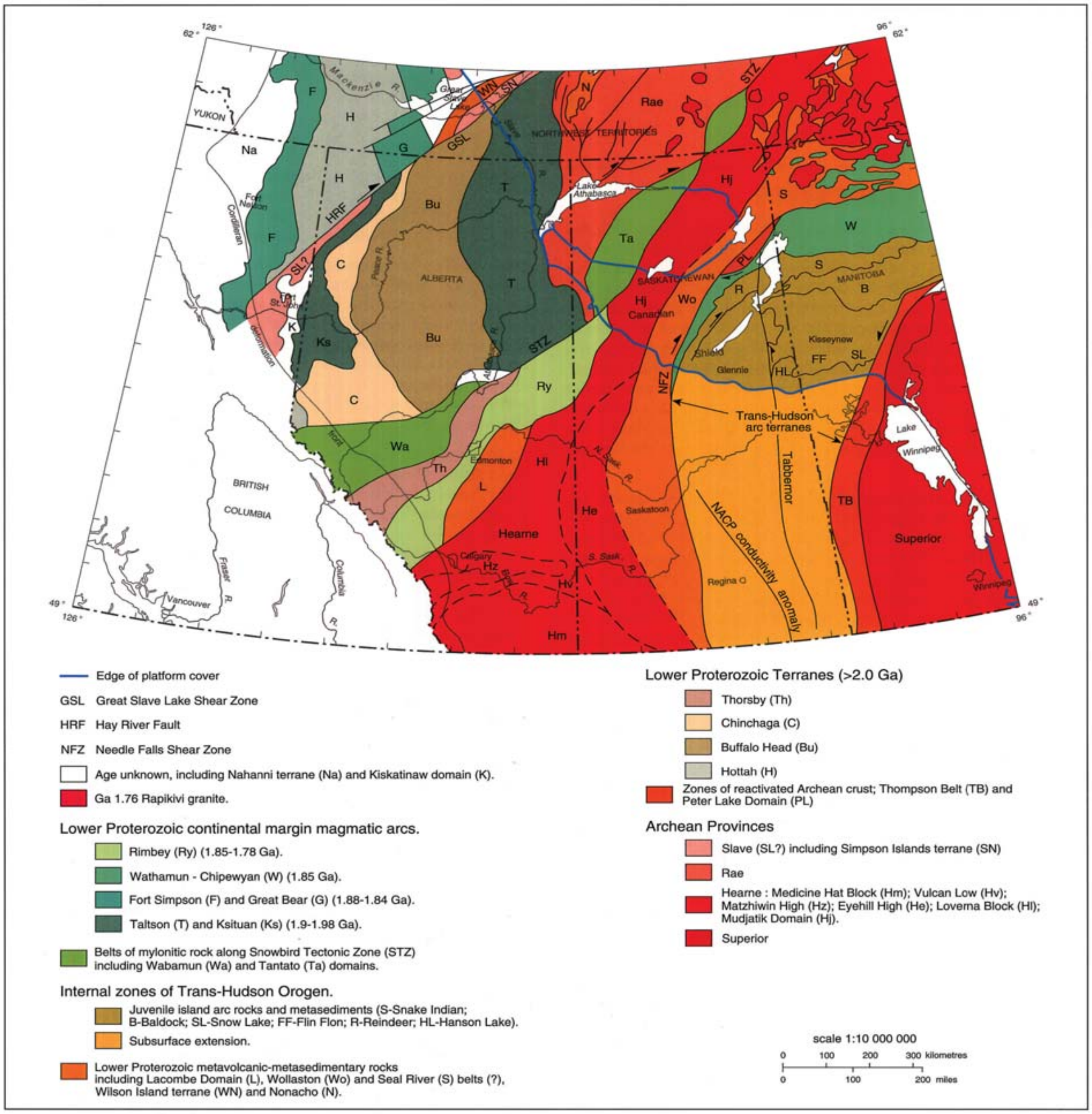


Figure 2.5. Tectonic domains underlying the Western Canada Sedimentary Basin. Trace of NACP conductivity anomaly, as shown, has been modified by subsequent research. Note blue line delineating eastern zero-edge of sedimentary cover rock. (Ross et al., 1994, their Fig. 4.1).

A number of domains, of younger Paleoproteozoic time, were accreted against the Hearne and Rae Domains and underlie the rest of Alberta (Figure 2.5). Subduction of small crustal components resulted in generation of magmatic belts (e.g. granites) that welded together the collage of crustal pieces.

Regional shear zones include the Snowbird Tectonic Zone (STZ) which separates the Hearne and Rae Domains (in Saskatchewan), would appear to continue into northern, and possibly southern Alberta. In northwestern Alberta, the Great Slave Lake Shear Zone (GSLsz) is a 25 km wide belt of mylonite, an intensely deformed rock, and electrically resistive.

Conductive and Resistive Anomalies in Crust and Upper Mantle

From north to south the following conductive and resistive anomalies (Figure 2.6) have been identified (see cited references for details):

i) Loverna Conductor (LC) is a regional low resistivity feature in the upper mantle (~40-100 km) below the western part of the Loverna Block, exhibiting 3-30 ohm.m range, and broadly dipping southeasterly (Nieuwenhuis et al., 2014). The eastern portion of the Loverna Block is resistive, >3000 ohm.m, above 20 km depth. At shallower depths (17-37 km), the LC anomaly appears to merge partially with the RDC anomaly near the southwest boundary of the Lacombe Domain and Loverna Block, but to the northeast along the boundary the LC and RDC anomalies diverge. Graphite films and/or sulphides developed on mineral grains through introduction of carbon and/or metasomatic fluids, during subduction along the Vulcan structure, have been proposed as a cause of the high pervasive conductivity (Nieuwenhuis et al., 2014).
ii) Red Deer Conductor (RDC), a shallow linear conductor (3 - 30 ohm.m) within Precambrian basement rock just below the WCSB cover, possibly extending to a depth <10 km as imaged on MT profiles. The RDC follows the northeast trending boundary between the Proterozoic Lacombe Domain and the Archean Loverna Domain (Figure 3). It also coincides with a high magnetic anomaly (Boerner et al., 2000) called the Red Deer High, which suggests an association with banded iron formation as a possible cause of the high conductivity (Boerner et al, 2000).
iii) Linear Foothills Anomaly (LFH) is a north-south trending linear conductor (<10 ohm.m), imaged at 2 - 3 km depth, spatially associated with the thickening of the southwest margin of the WCSB (in the Rocky Mountain Foothills) against the more resistive (>1000 ohm.m) Cordillera fold and thrust belt to the west (Nieuwenhuis, 2011; Nieuwenhuis et al., 2014). Fracturing of the Precambrian basement caused by thrusting of the Cordillera terranes over the basement may have allowed migration of interconnecting saline fluids into surrounding rock which could lower the resistivity (Nieuwenhuis, 2011).
iv) Kiskatinaw conductor (KC), a southeast dipping conductor (~ 10 ohm.m) imaged between 20 and 50 km depth, which may represent a fossil subduction zone. Its conductivity is postulated to be due to graphic derived from subducted organic material (Turkoglu et al., 2007). The KC follows the trend of the Kiskatinaw magnetic low.
v) Upper mantle conductor (50-150 ohm.m) situated between the Ksituan and Chinchaga Domains at a depth of 50 – 100 km, striking northwest. Part of this conductor merges with the KC feature.
vi) Great Slave Lake shear zone is a near-vertical, crustal-scale, resistive anomaly (> 4000 ohm.m) bounded by more conductive crust on either side. This 25 km wide zone of mylonitic rock is coincident with a magnetic low. The high resistivity is interpreted to be due to the resistive nature of the granitic protolith of the mylonite (Wu et al., 2002).

2.6. Zonal Earth resistivity models

As a first approximation to determine the Earth resistivity structure, a one dimensional (1D) representation (i.e. layered structures) was chosen as it contains the least complication of geological structure and is the simplest way to broadly assign resistivity values to any particular depth. From the surface downward the layers of a 1D model are as follows: overburden; sedimentary rocks accumulated in a depositional basin (not always present); basement complex (sedimentary, volcanic and intrusive igneous, and metamorphosed rocks) that is considered to be the upper crust; middle and lower crust (sometimes combined into a single layer); and, mantle divisions based on changes of its seismic velocity.

The developed 1D models are presented in Figures 2.7-2.16, representing differences in crust and upper mantle resistivities between southern and northern Alberta Accompanying Table 2.4 provides a comparison of layer depth and resistivity values for all ten 1D models. Appendix B has more detailed summary tables which present individual layer depths, thickness, and resistivity/conductivity for each 1D model, as well as sources of depth and resistivity values and summarised justification for their selection.

<u>Sources of Information</u>

The dominant type of <u>overburden and sedimentary</u> rock were determined from generalized maps of Canadian surficial geology (Fulton, 1995) and descriptions from the 1994 *Geological Atlas of the Western Canada Sedimentary Basin*. Information about resistivity values for overburden specific to Alberta was found to be limited to recent airborne electromagnetic (EM) survey results (Slattery and Andriashek, 2012). The airborne EM results were assessed against resistivity values for similar overburden elsewhere in western Canada, and a resulting composite resistivity value was applied to overburden for Alberta. Resistivity for the WCSB was obtained from descriptions of past and recent MT transects.

A two-step process was then used to delineate areas (i.e. zones) of the different deep conductivity Earth models (below overburden and sedimentary), used in GIC modelling.

First, continent-scale maps of lithospheric bulk-resistivity (at depths of 20, 40, 100 and 200 km), prepared by Jones et al. (2014, their figs. 8 and 11) were examined to identify gross differences that coincide with major tectonic domains (Figure 2.5) underlying the Province of Alberta.

Second, to construct the 1D model for tectonic domain(s), the resistivity values for crust and uppermost mantle were obtained from the results of two recent magnetotelluric (MT) surveys which also incorporated data from the Lithoprobe Alberta Basement Transect (ABT) undertaken in the mid-1990s (Figure 2.6). A total of 320 MT soundings, as well as seismic recordings, were made during the ABT deployment. In northern Alberta (north of 55 degrees north latitude) Turkoglu et al. (2009) completed 23 MT soundings during 2004-2006, combined it with data from some 80 ABT stations and prepared both 2D and 3D resistivity models. For southern Alberta, 2D and 3D resistivity models were prepared by Nieuwenhuis et al. (2014) and Nieuwenhuis (2011), using data from 67 MT soundings completed 2008-2010 and combined with data from some 300 MT stations previously collected during the ABT deployment.

It is important to recognize that resistivity values assigned to the crust (Layers 3 to 5) could have been underestimated. Earlier MT interpretation by Boerner et al. (2000) and more recently in northern Alberta by Turkoglu et al. (2009) have on the MT inversion profiles a resistivity scale up to 1000 ohm.m. In contrast, newly done interpretation by Nieuwenhuis et al, (2014) has a resistivity scale up to 10,000 ohm.m but on the small-sized profiles the scale bar does not provide fine resolution between 1000 to 10,000 ohm.m. For the northern most part of Alberta, resistivity values for continuation of same terranes into Northwest Territories was obtained from Wu et al. (2002, 2005) who prepared 2D inversion models for the Lithoprobe SNORCLE transect Corridors 1 and 1a.

General depths of the upper and middle crust were measured off the Lithoprobe's trans-Canada seismic transect for the Alberta section (Hammer et al., 2010). Within Alberta detailed depths to the crust / mantle boundary (Mohorovicic discontinuity) was obtained from an isopach map prepared by Bouzidi et al., (2002, Fig. 8). Additional seismic profiles, prepared by Clowes et al. (2002), Gorman et al. (2002), Hope and Eaton (2002), and Lemieux et al. (2002).

Depths and resistivity for the middle and lower divisions of the upper mantle, transition zones, and lower mantle – Layers 7 to 12 – between 100 and 1000 km were based on the regional conductivities determined by Kelbert et al. (2009).

Due to the presence of the Loverna Conductor, the uppermost mantle (~41~100 km) under the Archean crust (Loverna Block) in southern Alberta is substantially less resistive than the upper mantle immediately to the south (Medicine Hat Block) and to the north (Lacombe Domain, Rimbey Domain). In contrast, upper mantle resistivities below the Archean Rae/Hearne Domain in northern Manitoba and eastern Nunavut, and western Superior Province in Ontario have a range of 2500-8000 ohm.m.

Also, the presence of the Red Deer Conductor has reduced upper crust resistivity in the Lacombe Domain compared to adjacent terranes. As well, the Kiskatinaw Conductor has influenced, by lowering, crust and uppermost mantle resistivity.

The areas of the resulting ten earth resistivity models are presented in Figure 2.6, and the details of the layers (depths, thicknesses, mean and range of resistivities for each layer) are presented in Figures 2.7-2.16. and are summarised in the Table 2.4

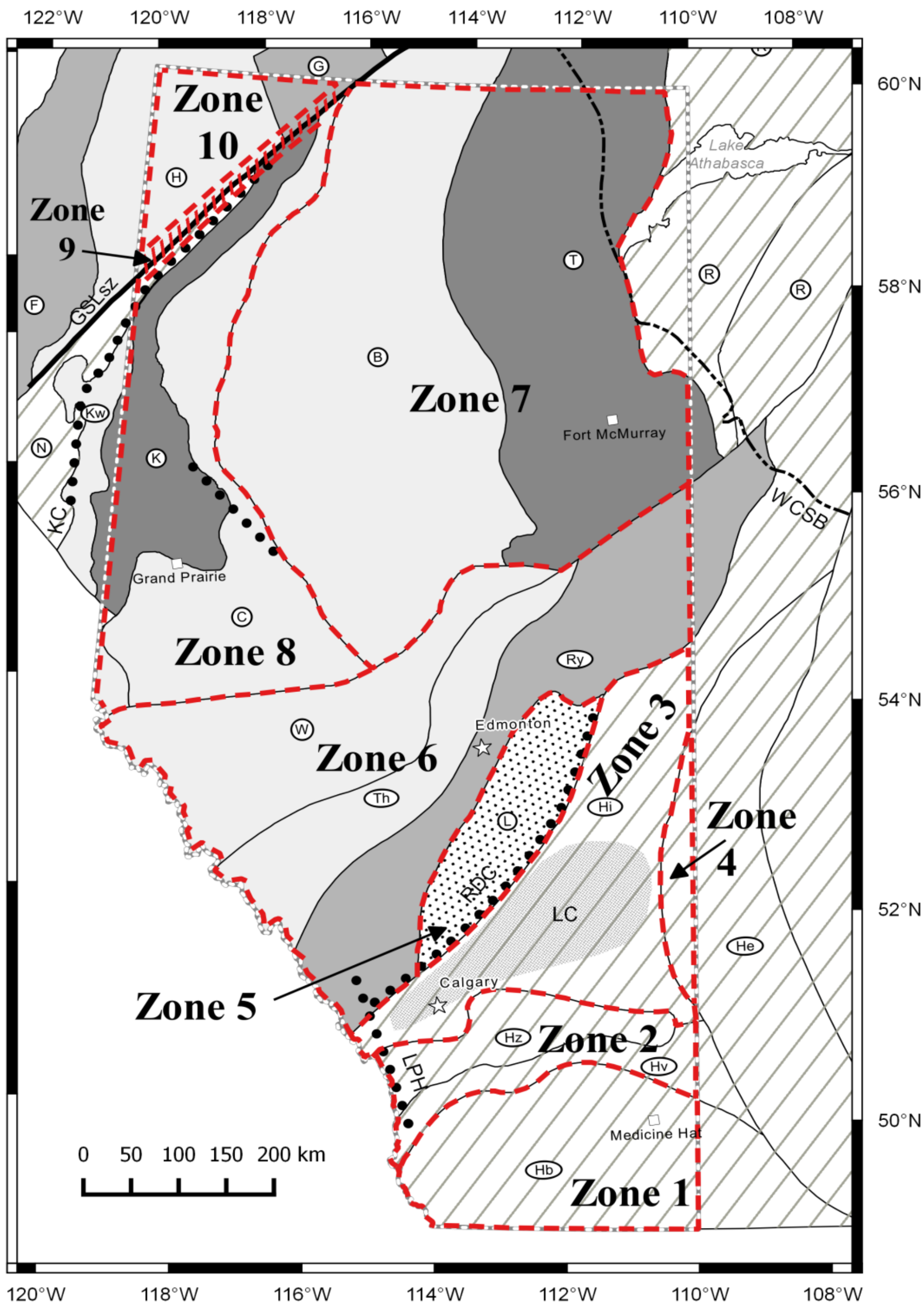


Figure 2.6. Coverage areas of ten proposed layered earth models (separated by the blue dashed lines) with respect to the conductive anomalies and tectonic elements, of Precambrian age, underlying Alberta (*modified from* Boerner et al., 2002, their Fig. 2). Small circles represent locations of the 320 magnetotelluric stations of Alberta Basement Transect Experiment. *Abbreviations*: GFTZ, Great Falls tectonic zone; GLSsz, Great Slave Lake shear zone; LC, Loverna Conductor; KC, Kiskatinaw Conductor; LFH, Linear Foothills Anomaly; RDC, Red Deer Conductor, after (Nieuwenhuis, 2011; Turkoglu et al., 2009).

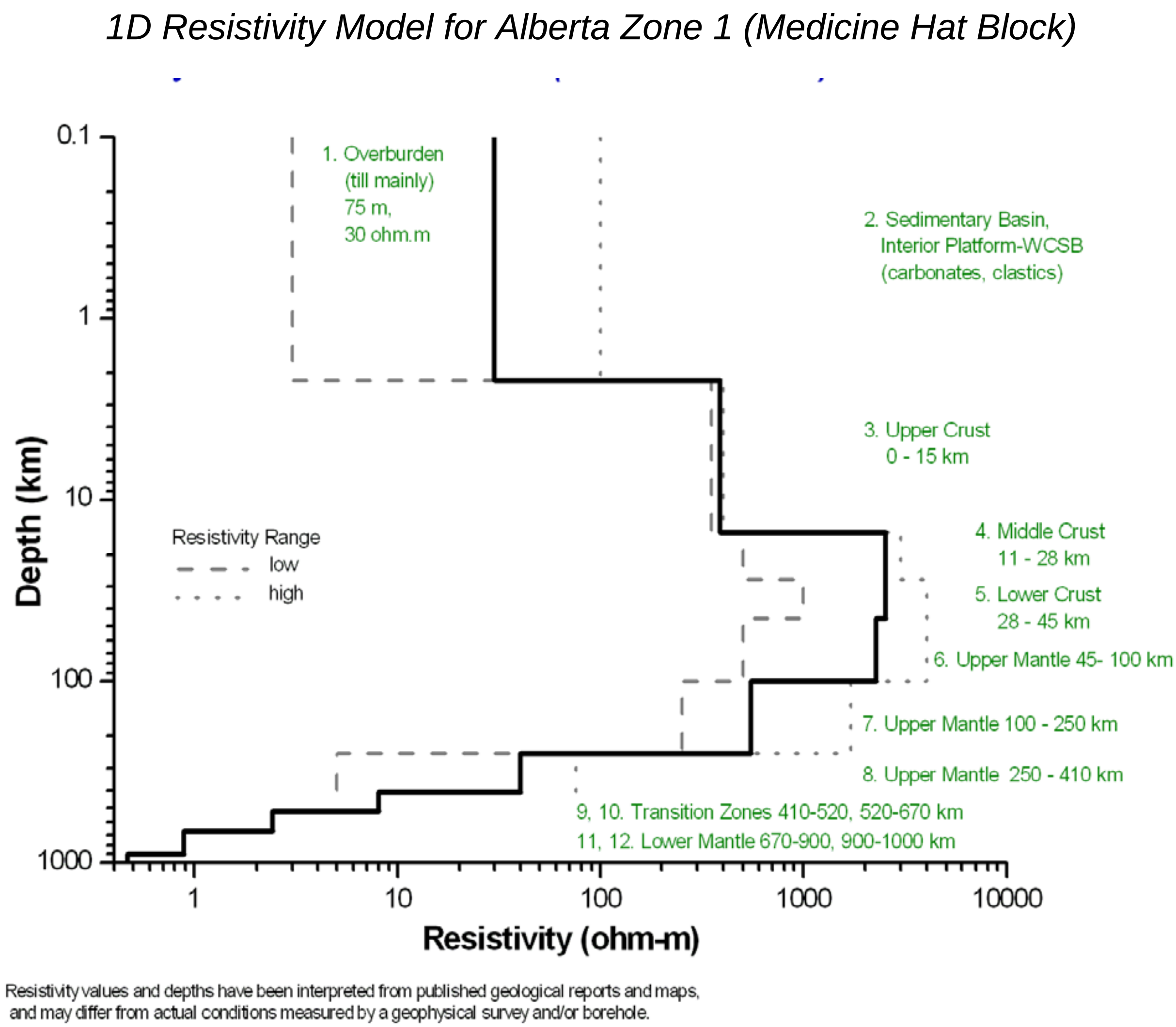


Figure 2.7. 1D Earth resistivity model for Zone 1 (Medicine Hat Block), covering part of southern Alberta. Refer to Appendix B for additional details.

1D Resistivity Model for Alberta Zone 2 (Vulcan Structure)

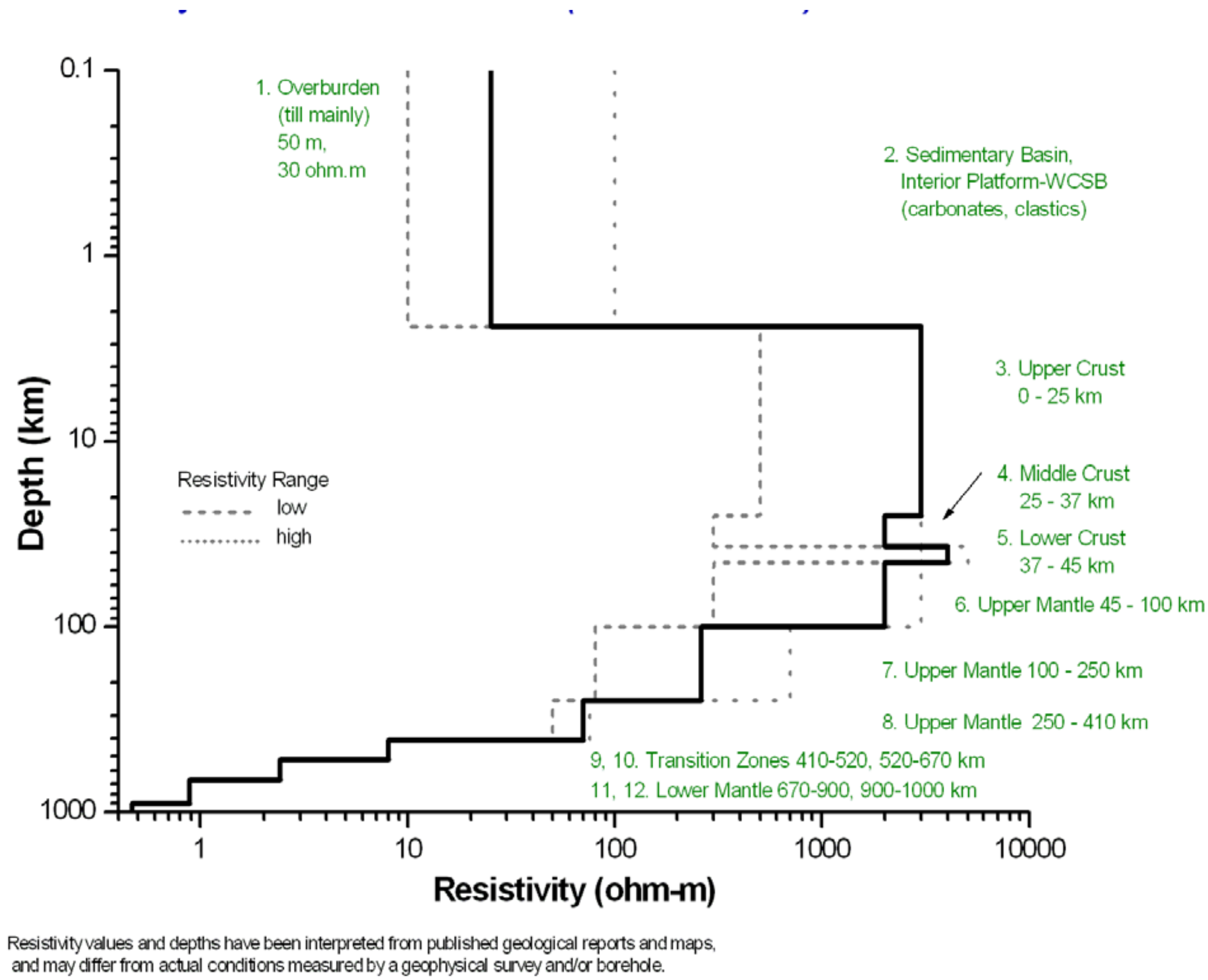


Figure 2.8. 1D Earth resistivity model for Zone 2 (Vulcan Structure), covering part of southern Alberta. Refer to Appendix B for additional details.

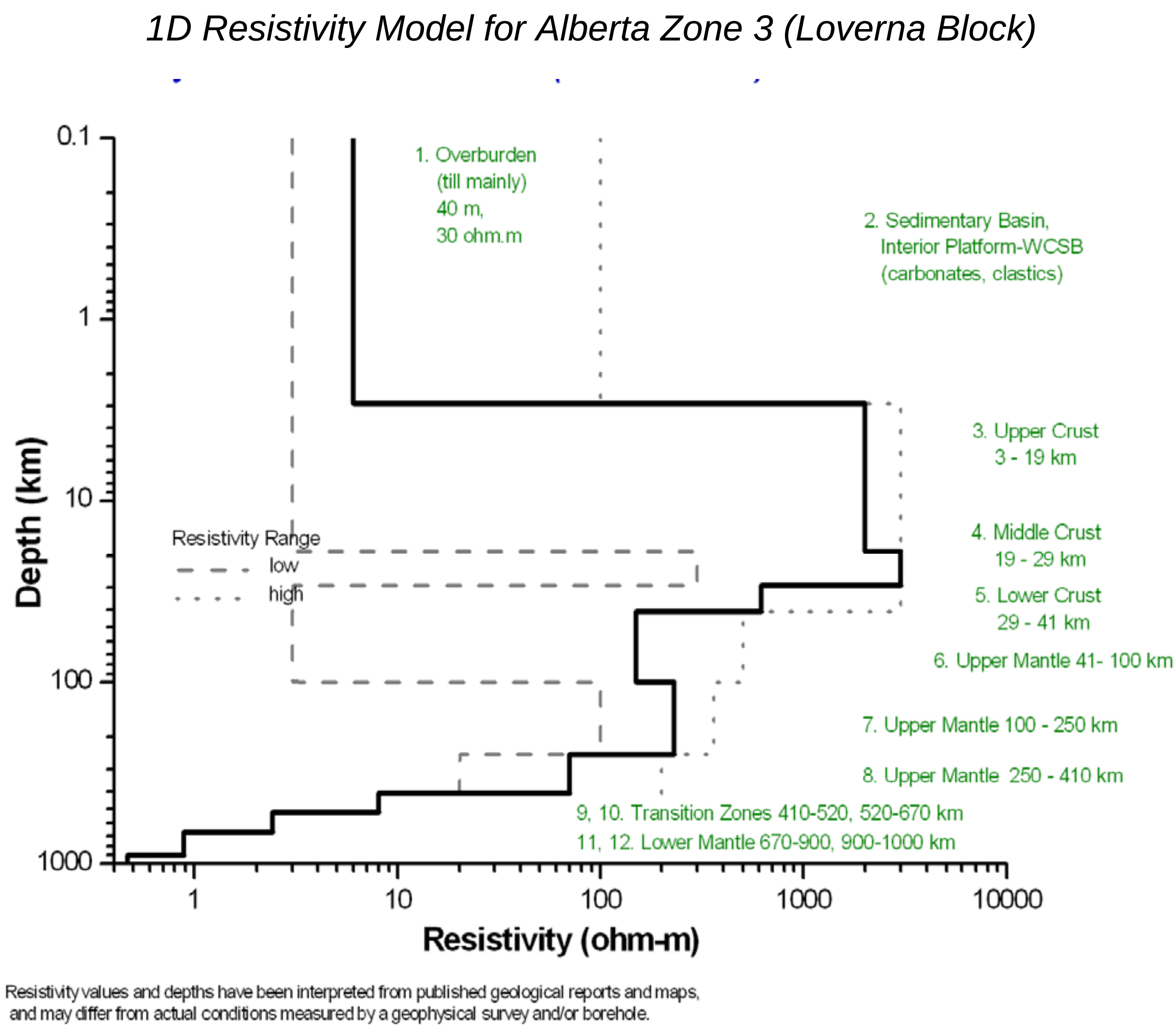


Figure 2.9. 1D Earth resistivity model for Zone 3 (Loverna Block), covering part of southern Alberta. Refer to Appendix B for additional details.

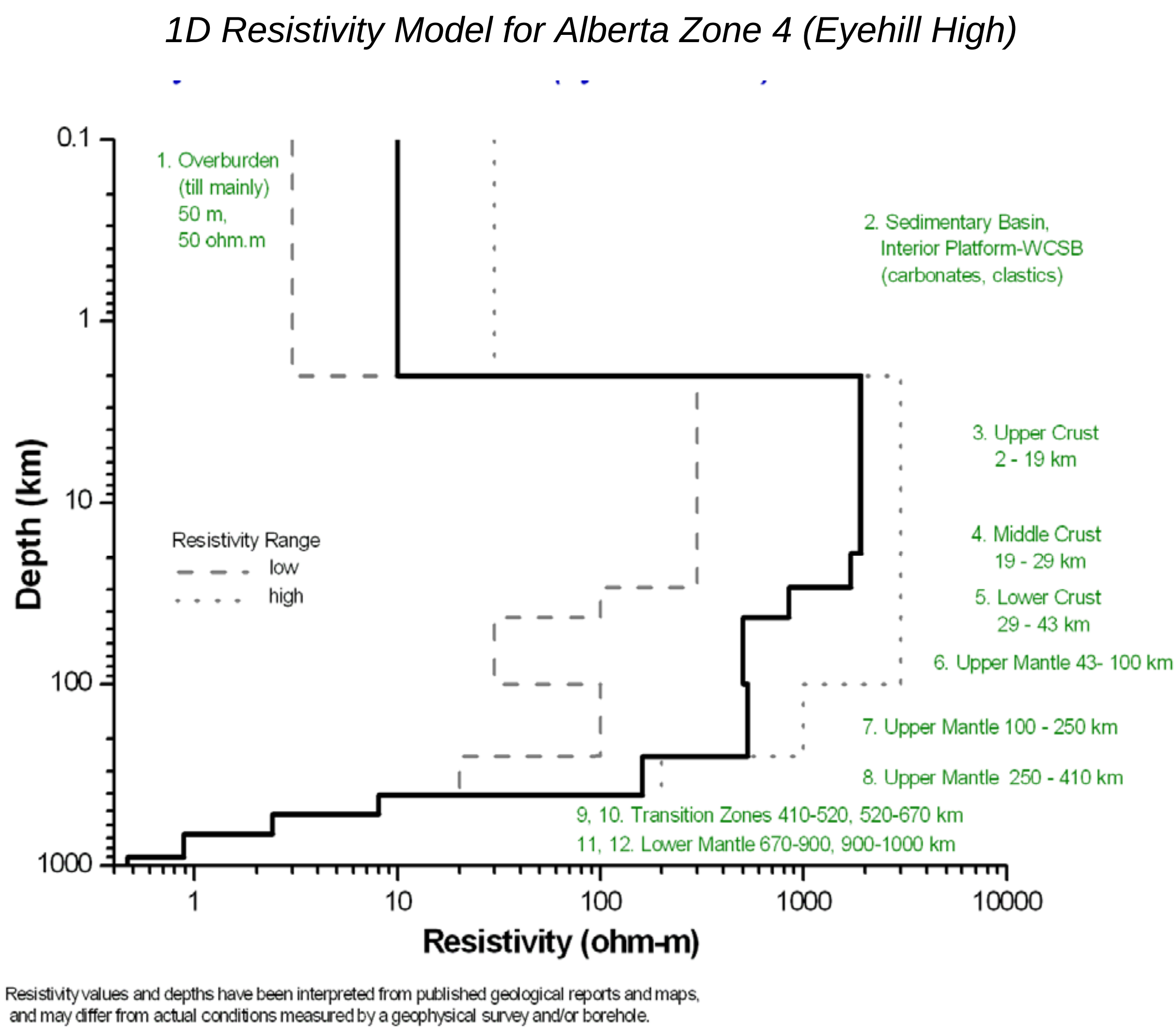


Figure 2.10. 1D Earth resistivity model for Zone 4 (Eyehill High), covering part of southern Alberta. Refer to Appendix B for additional details.

1D Resistivity Model for Alberta Zone 5 (Lacombe Domain)

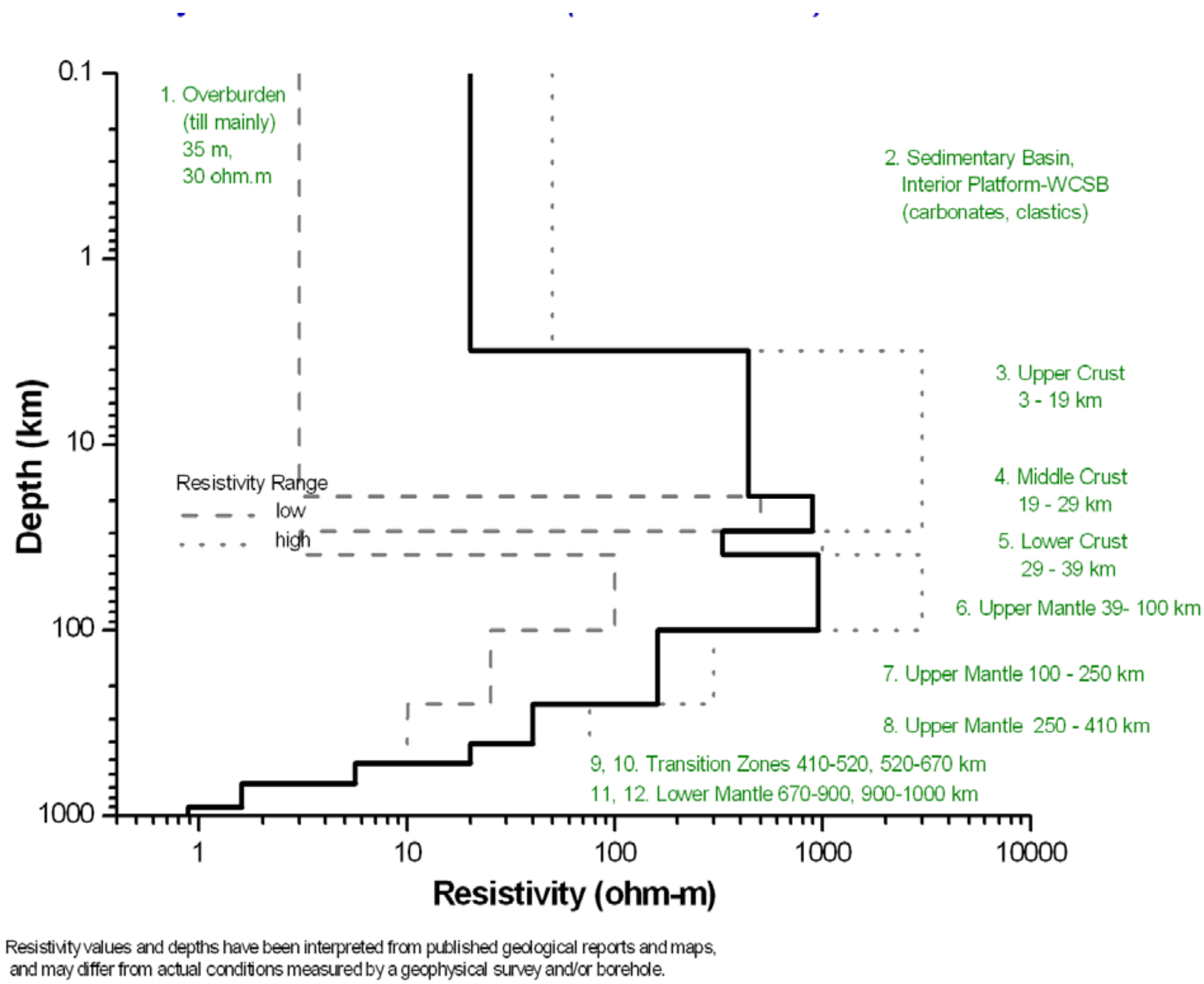


Figure 2.11. 1D Earth resistivity model for Zone 5 (Lacombe Domain), covering part of southern Alberta. Refer to Appendix B for additional details.

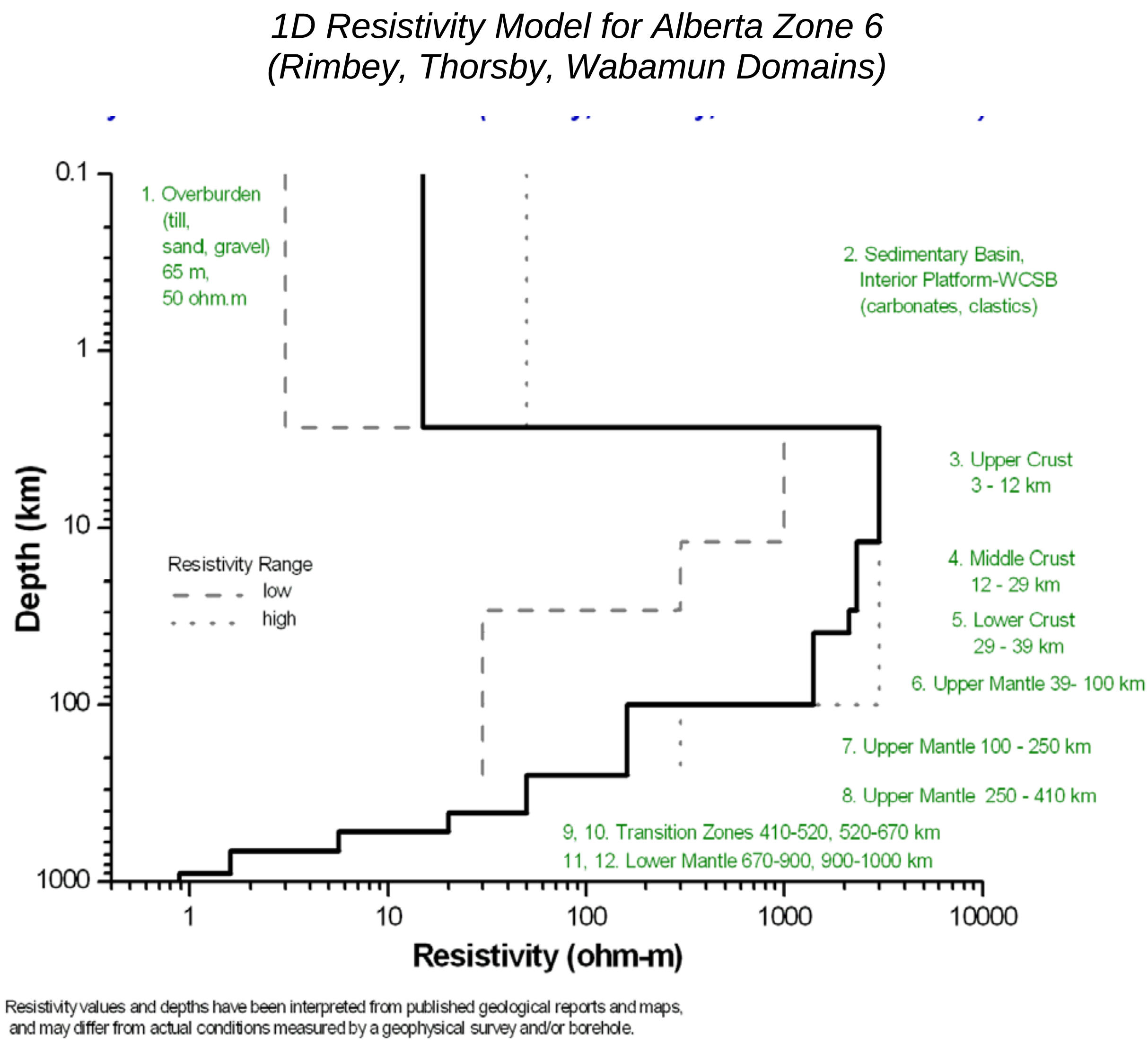
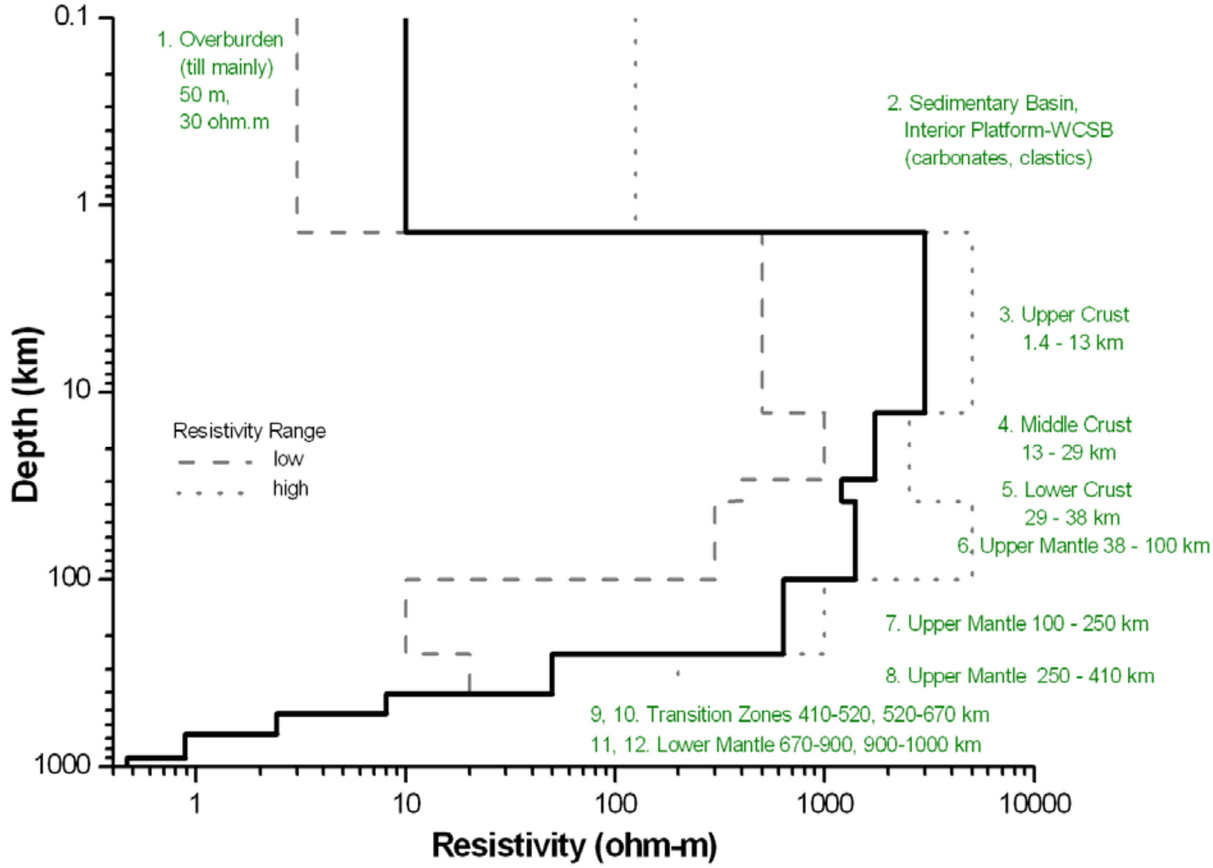


Figure 2.12. 1D Earth resistivity model for Zone 6 (Rimbey, Thorsby, Wabamun Domains), covering part of southern Alberta. Refer to Appendix B for additional details.

1D Resistivity Model for Alberta Zone 7 (Buffalo Head, Taltson Domains)



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 2.13. 1D Earth resistivity model for Zone 7 (Buffalo Head, Taltson Domains), covering part of northern Alberta. Refer to Appendix B for additional details.

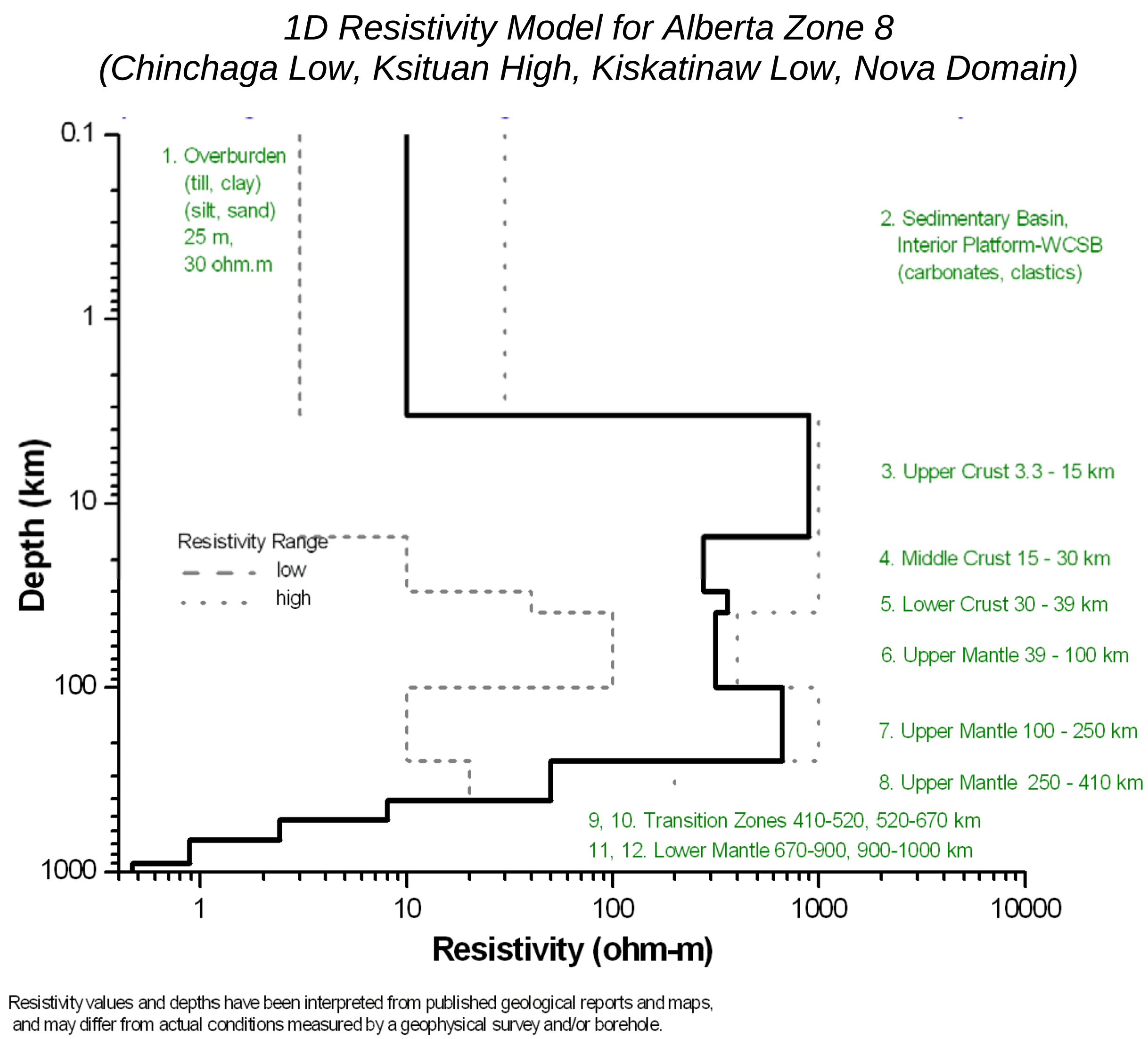


Figure 2.14. 1D Earth resistivity model for Zone 8 (Chinchaga Low, Ksituan High, Kiskatinaw Low, Nova Domain), covering part of northern Alberta. Refer to Appendix B for additional details.

1D Resistivity Model for Alberta Zone 9 (Great Slave Lake shear zone)

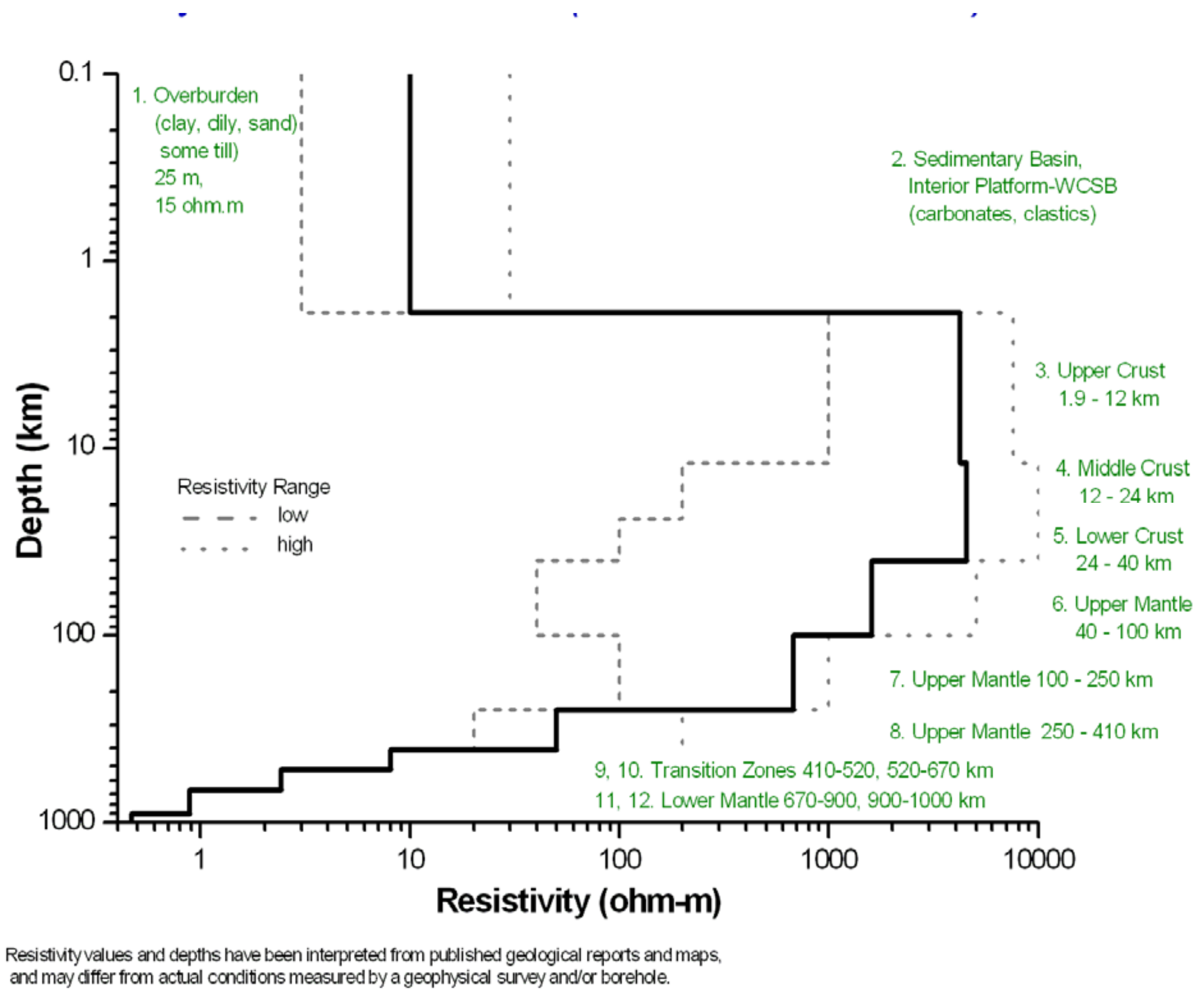


Figure 2.15. 1D Earth resistivity model for Zone 9 (Great Slave Lake shear zone), covering part of northern Alberta. Refer to Appendix B for additional details.

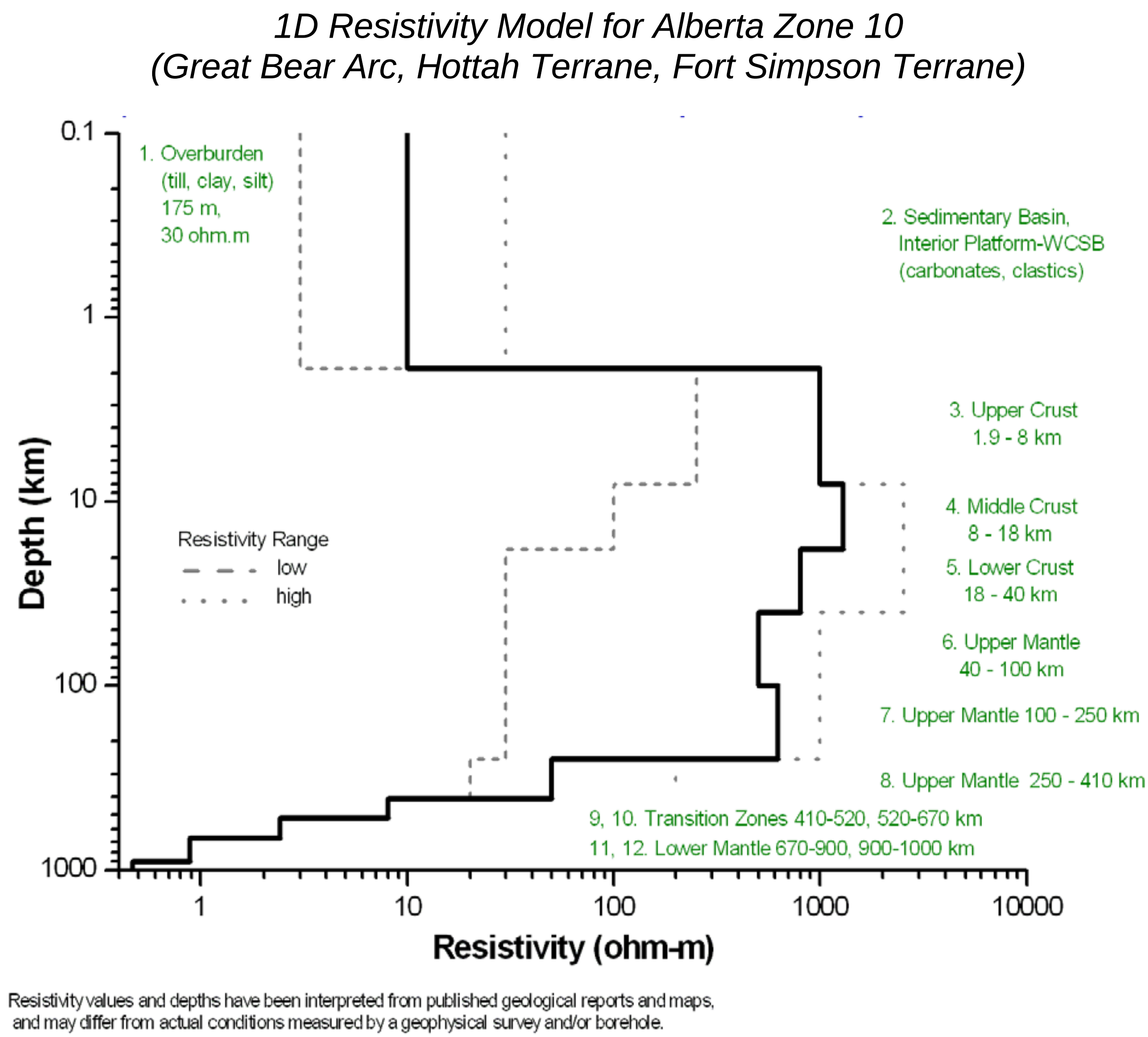


Figure 2.16. 1D Earth resistivity model for Zone 10 (great Bear Arc, Hottah Terrane, Fort Simpson Terrane), covering part of northern Alberta. Refer to Appendix B for additional details.

Table 2.4
Summary Comparison of 1D Earth Resistivity Models for Province of Alberta

Layer	Zone 1 (Medicine Hat Block)	Zone 2 (Vulcan Structure)	Zone 3 (Loverna Block)	Zone 4 (Eyehill Domain)	Zone 5 (Lacombe Domain)	Zone 6 (Rimbey, Thorsby & Wabamun Domains)
1 – Over burden	75 m thick 30 ohm.m *limits 10, 100*	50 m thick 30 ohm.m *limits 10, 100*	40 m thick 30 ohm.m *limits 10, 100*	50 m thick 50 ohm.m *limits 10, 100*	35 m thick 30 ohm.m *limits 10, 100*	65 m thick 50 ohm.m *limits 10, 100*
2 – Sediment.Basin	0-2.2 km 2.2 km thick 30 ohm.m *limits 3, 100*	0-2.4 km 2.4 km thick 25 ohm.m *limits 3, 200*	0-2.9 km 2.9 km thick 6 ohm.m *limits 3, 100*	0-2 km 2 km thick 10 ohm.m *limits 3, 30*	0-3.1 km 3.1 km thick 20 ohm.m *limits 3, 50*	0-2.7 km 2.7 km thick 15 ohm.m *limits 3, 50*
3 – Upper Crust	2.2-15 km 13 km thick 385 ohm.m *limits 350, 400*	2.4-24 km 21.6 km thick 3000 ohm.m *lower limits 500*	2.9-19 km ± 16 {16.1} km thick 2000 ohm.m *limits 3, 3000*	2-19 km 17 km thick 1900 ohm.m *limits 300, 3000*	3.1-19 km ~ 16 {15.9} km thick 440 ohm.m *limits 3, 3000*	2.7-12 km ~ 9 km thick 3000 ohm.m *limits 1000, 3000*
4 – Middle Crust	15-27.5 km 12.5 km thick 2500 ohm.m *limits 500, 3000*	24-37 km 13 km thick 2000 ohm.m *limits 300, 3000*	19-29 km 10 km thick 3000 ohm.m *limits 300, 3000*	19-29 km 10 km thick 1700 ohm.m *limits 300, 3000*	19-29 km 10 km thick 900 ohm.m *limits 500, 3000*	12-29 km 17 km thick 2300 ohm.m *limits 300, 3000*
5 – Lower Crust	27.5-45 km 17.5 km thick 2500 ohm.m *limits 1000,4000*	37-45 km 8 km thick 4000 ohm.m *limits 3000, 5000*	29-41 km 12 km thick 620 ohm.m *limits 3, 3000*	29-43 km 14 km thick 850 ohm.m *limits 100, 3000*	29-39 km 10 km thick 330 ohm.m *limits 3,1000*	29-39 km 10 km thick 2100 ohm.m *limits 30,3000*
6 – Upper Mantle	45-100 km 55 km thick 2250 ohm.m *limits 500, 4000*	45-100 km 55 km thick 2000 ohm.m *limits 300, 3000*	41-100 km 59 km thick 150 ohm.m *limits 3, 500*	43-100 km 57 km thick 500 ohm.m *limits 30, 3000*	39-100 km 61 km thick 950 ohm.m *limits 100, 3000*	39-100 km 61 km thick 1400 ohm.m *limits 30, 3000*

Table 2.4 (continued)
Summary Comparison of 1D Earth Resistivity Models for Province of Alberta

Layer	Zone 1 (Medicine Hat Block)	Zone 2 (Vulcan Structure)	Zone 3 (Loverna Block)	Zone 4 (Eyehill Domain)	Zone 5 (Lacombe Domain)	Zone 6 (Rimbey, Thorsby & Wabamun Domains)
7 – Upper Mantle	100-250 km 150 km thick 550 ohm.m *limits 250, 1700*	100-250 km 150 km thick 260 ohm.m *limits 80, 700*	100-250 km 150 km thick 230 ohm.m *limits 100, 360*	100-250 km 150 km thick 530 ohm.m *limits 100, 1000*	100-250 km 150 km thick 160 ohm.m *limits 25, 300*	100-250 km 150 km thick 160 ohm.m *limits 30, 300*
8 – Upper Mantle	250-410 km 160 km thick 40 ohm.m *limits 5, 75*	250-410 km 160 km thick 70 ohm.m *limits 50, 75*	250-410 km 160 km thick 90 ohm.m *limits 20, 200*	250-410 km 160 km thick 90 ohm.m *limits 20, 200*	250-410 km 160 km thick 40 ohm.m *limits 10, 75*	250-410 km 160 km thick 50 ohm.m
9 – Transition Zone	410-520 km 110 km thick 8 ohm.m	410-520 km 110 km thick 8 ohm.m	410-520 km 110 km thick 8 ohm.m	410-520 km 110 km thick 8 ohm.m	410-520 km 110 km 20 ohm.m	410-520 km 110 km 20 ohm.m
10 – Transition Zone	520-670 150 km thick 2.4 ohm.m	520-670 150 km thick 2.4 ohm.m	520-670 150 km thick 2.4 ohm.m	520-670 150 km thick 2.4 ohm.m	520-670 150 km 5.6 ohm.m	520-670 150 km 5.6 ohm.m
11 – Lower Mantle	670-900 km 230 km thick 0.89(i) ohm.m *upper limits 3 or 30*	670-900 km 230 km thick 0.89(i) ohm.m *upper limit 3*	670-900 km 230 km thick 0.89(i) ohm.m *upper limit 3*	670-900 km 230 km thick 0.89(i) ohm.m *upper limit 3*	670-900 km 230 km thick 1.58(i) ohm.m *upper limit 3*	670-900 km 230 km thick 1.58(i) ohm.m *upper limit 3*
12 – Lower Mantle	900-1000 km 100 km thick 0.47 ohm.m	900-1000 km 100 km thick 0.47 ohm.m	900-1000 km 100 km thick 0.47 ohm.m	900-1000 km 100 km thick 0.47 ohm.m	900-1000 100 km 0.89 ohm.m	900-1000 100 km 1.12 ohm.m

Table 2.4 (continued)
Summary Comparison of 1D Earth Resistivity Models for Province of Alberta

Layer	Zone 7 (Buffalo Head, Taltson)	Zone 8 (Chinchaga, Ksituan, Kiskatinaw, Nova)	Zone 9 (Great Slave Lake shear zone)	Zone 10 (Great Bear, Hottah, Fort Simpson)
1 – Overburden	50 m thick 30 ohm.m *limits 10, 100*	25 m thick 30 ohm.m *limits 10, 100*	25 m thick 15 ohm.m *limits 5, 30*	175 m thick 30 ohm.m *limits 10, 100*
2 – Sedimentary Basin	0-1.4 km 1.4 km thick 10 ohm.m *limits 3, 125*	0-3.3 km 3.3 km thick 10 ohm.m *limits 3, 30*	0-1.9 km 1.9 km thick 10 ohm.m *limits 3, 30*	0-1.9 km 1.9 km thick 10 ohm.m *limits 3, 30*
3 – Upper Crust	1.4-13 km 11.6 km thick 3000 ohm.m *limits 500, 5000*	3.3-15 km 11.7 km thick 900 ohm.m *upper limit >1000*	1.9-12 km 10.1 km thick 4200 ohm.m *limits 1000, 7500*	1.9-8 km 6 km thick 1000 ohm.m *limits 250, >1000*
4 – Middle Crust	13-29 km 16 km thick 1750 ohm.m *limits 1000, 2500*	15-30 km 15 km thick 275 ohm.m *limits 10, 1000*	12-24 km 12 km thick 4500 ohm.m *limits 200, 10000*	8-18 km 10 km thick 1300 ohm.m *limits 100, 2500*
5 – Lower Crust	29-38 km 9 km thick 1200 ohm.m *limits 400,2500*	30-39 km 9 km thick 360 ohm.m *limits 40,1000*	24-40 km 16 km thick 4500 ohm.m *limits 100, 10000*	18-40 km 22 km thick 800 ohm.m *limits 30, 2500*
6 – Upper Mantle	38-100 km 62 km thick 1400 ohm.m *limits 300, 5000*	39-100 km 61 km thick 315 ohm.m *limits 100, 400*	40-100 km 60 km thick 1600 ohm.m *limits 40, 5000*	40-100 km 60 km thick 500 ohm.m *limits 30,1000*

Table 2.4 (continued)
Summary Comparison of 1D Earth Resistivity Models for Province of Alberta

Layer	Zone 7 (Buffalo Head, Taltson)	Zone 8 (Chinchaga, Ksituan, Kiskatinaw, Nova)	Zone 9 (Great Slave Lake shear zone)	Zone 10 (Great Bear, Hottah, Fort Simpson)
7 – Upper Mantle	100-250 km 150 km thick 635 ohm.m *(a) limits 800, 1000* *(b) limits 10, 30*	100-250 km 150 km thick 660 ohm.m *(a) limits 200, 1000* *(b) limits 10, 30*	100-250 km 150 km thick 680 ohm.m *(a) upper limit 1000* *(b) limits 30, 100*	100-250 km 150 km thick 625 ohm.m *(a) limits 200, 1000* *(b) limits 30, 80*
8 – Upper Mantle	250-410 km 160 km thick 50 ohm.m	250-410 km 160 km thick 50 ohm.m	250-410 km 160 km thick 50 ohm.m	250-410 km 160 km thick 50 ohm.m
9 – Transition Zone	410-520 km 110 km thick 20 ohm.m	410-520 km 110 km thick 20 ohm.m	410-520 km 110 km thick 20 ohm.m	410-520 km 110 km thick 20 ohm.m
10 –Transition Zone	520-670 150 km thick 5.62 ohm.m	520-670 150 km thick 5.62 ohm.m	520-670 150 km thick 5.62 ohm.m	520-670 150 km thick 5.62 ohm.m
11 – Lower Mantle	670-900 km 230 km thick 1.58(i) ohm.m *upper limits 3, 30*	670-900 km 230 km thick 1.58(i) ohm.m *upper limits 3, 30*	670-900 km 230 km thick 1.58(i) ohm.m *upper limits 3, 30*	670-900 km 230 km thick 1.58(i) ohm.m *upper limits 3, 30*
12 – Lower Mantle	900-1000 km 100 km thick 1.12 ohm.m	900-1000 km 100 km thick 1.12 ohm.m	900-1000 km 100 km thick 1.12 ohm.m	900-1000 km 100 km thick 1.12 ohm.m

NOTES

* Layer depth (km), thickness (km), resistivity (ohm.m) and upper/lower limits of resistivity shown for each tectonic zone.

* Zones 7 to 10, for Layer 7, (a) limits for depth 100 – 200 km, and (b) limits for depth 200-250 km.

* Zones 1 to 4, for Layers 9– 12 shaded grey, the generalized depths and resistivities are determined by Kelbert et al. (2009) for Canada regional model, based on data from Ottawa magnetic observatory situated on Archean craton.

* Zones 5 to 7, for Layers 8 or 9– 12 shaded grey with diagonal pattern, the generalized depths and resistivities are determined by Kelbert et al. (2009) for North American regional model, based on data from Tucson magnetic observatory situated on Proterozoic craton.

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Chapter 3. Analysis of Geoelectric Field Variations

3.1. Introduction

The geomagnetic field fluctuations are accompanied by the geo-electric field and currents at the surface of the Earth and in the power lines. This chapter contains a description of geoelectric activity in Alberta.

Two factors affect variations of the geoelectric field in the particular area, one is the geomagnetic field variations and the other is the deep ground resistivity structure. The simplified theory of the relations between geomagnetic field and geoelectric field is presented in Part 3. 2. This theory allows us to find the geo-electric (telluric) field at the Earth surface if the geomagnetic field and the Earth resistivity profile are known.

In order to calculate geo-electric (telluric) field variations in the study area, magnetic data from several Geomagnetic Observatories (Chapter 1) were used with surface impedances for the ten different zones, derived from one-dimensional Earth resistivity models created on the basis of the geological surveys (Chapter 2).

Frequency characteristics of the surface impedance, as well as its influence on the geoelectric field, are discussed in Part 3.3.

The examples of daily variations of the calculated geoelectric fields for the March 13, 1989 storm are discussed in Part 3.4.

In Part 3.5 we analyze the results of the statistical analysis of the annual variations of geoelectric field modelled with Meanook and Yellowknife geomagnetic field and ten different Earth resistivity models described in Chapter 2.

The 40 years statistical characteristics (median, mean, 95% and 99% occurences) together with the 40 years "extreme" values of the modelled geoelectric field are presented in Part 3.6.

3.2. Theoretical Background

The electric fields produced by geomagnetic disturbances drive electric currents within the earth. These induced currents have the effect of shielding the interior of the earth from the geomagnetic disturbances. The decrease of the magnetic and electric fields within the earth is dependent both on frequency and the resistivity structure of the earth. At the frequencies of the geomagnetic field variations, the skin depths within the earth extend to hundreds of kilometers, and the resistivity of the earth down to these depths has to be taken into account in calculating the relationship between the electric and magnetic fields at the surface.

The variation of resistivity with depth within the earth can be modeled using multiple horizontal layers with different uniform conductivities as shown in Chapter 2, with the last layer as a uniform half-space. For the calculation of the geo-electric field an assumption also needs to be made about the spatial structure of the source of geomagnetic fluctuations. Here we assume the simplest case of a plane wave (a wave uniform in both the x and y directions) propagating down into the Earth.

We use the geomagnetic coordinate system with axis *x* north, *y* east, and *z* vertically downwards. For the frequency range of 1 sec - 24 hours and earth resistivities of 1 - 1000 Ohm-m, displacement currents are small and can be neglected. Therefore, electric (*E*) and magnetic (*H*) fields in the frequency domain (ω) can be given by diffusion equations.

$$\frac{d^2E}{dz^2} = i\omega\mu\sigma E \tag{3.1}$$

$$\frac{d^2H}{dz^2} = i\omega\mu\sigma H \tag{3.2}$$

where z is the depth into the earth, σ is the conductivity and μ is the constant of permeability of free space ($4\pi\cdot10^{-7}$ H/m).

Solutions for each layer have the form

$$E = A(e^{-kz} + Re^{kz}) \tag{3.3}$$

$$H = A(\frac{e^{-kz}}{Z_0} - R\frac{e^{kz}}{Z_0}) \tag{3.4}$$

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 medium).

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

$$E_s = Z_s H_s \tag{3.5}$$

where Z_s is the surface impedance of the 1^{st} layer and E_s and H_s are surface geo-electric and geomagnetic fields.

The impedance at any layer can be found by applying the recursion relation for the impedance of an n-layered half-space (Weaver, 1994).

$$Z_n = i\omega\mu\left(\frac{1 - r_n e^{-2k_n l_n}}{k_n(1 + r_n e^{-2k_n l_n})}\right) \tag{3.6}$$

Where l_n and k_n are thickness and propagation constant of layer n,

$$r_n = \frac{1 - k_n \dfrac{Z_{n+1}}{i\omega\mu}}{1 + k_n \dfrac{Z_{n+1}}{i\omega\mu}} \tag{3.7}$$

and for the last layer

$$Z_N = \frac{i\omega\mu}{k_N} \tag{3.8}$$

To obtain geo-electric field at the earth's surface from known geomagnetic field data, the following sequence of operations (Figure 3.1) was performed:

1. Conversion of the geomagnetic data from time domain into frequency domain [using Fast Fourier Transformation (FFT)].

2. Multiplication by the surface impedance, obtained from one-dimensional resistivity profile of particular area.
3. Inverse transform of calculated geoelectric spectrum back into time domain by using inverse FFT.

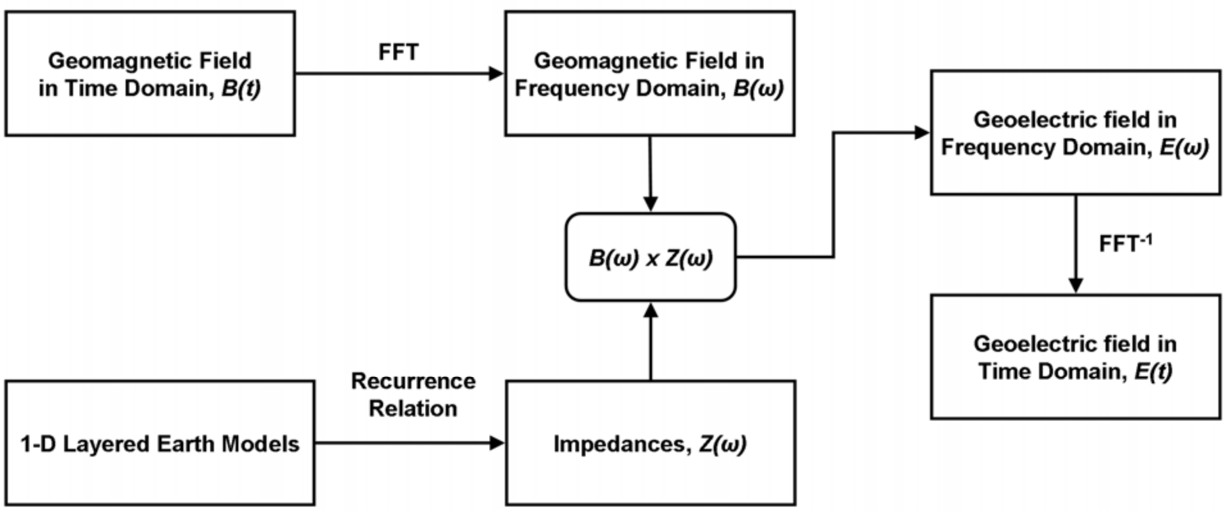


Figure 3.1. Sequence of steps used for calculations of the electric field from the geomagnetic field and layered earth model

The Fast Fourier Transform routine is available as built-in procedures in ORIGIN 6 and IDL, and available as FORTRAN code in *Numerical Recipes in Fortran 77* (Press et al, 1992).

3.3. Surface Impedance Models

The earth resistivity profiles for the different zones, described in Chapter 3, were used as input to the recursion relation (3.6) to produce surface impedance values for the ten zones. Table 3.1 below contains values of thicknesses and resistivities for each layer in each zone. It should be noted that extra bottom layer with the same resistivity of 1 Ohm·m has been added to represent the half-space, to be used in formula (3.8).

Table 3.1. Thickness **d** (meters) and resistivity **R** (Ohm·m) of each layer for 10 earth models

Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
d	**R**	**d**	**R**	**d**	**R**	**d**	**R**	**d**	**R**
75	30.	50.	30.	40.	30.	50.	50.	35.	30.
2125	30.	2350.	25.	2860.	6.	1950.	10.	3065.	20.
12800	385.	21600.	3000.	16100.	2000.	17000.	1900.	15900.	440.
12500	500.	13000	2000.	10000.	3000.	10000.	1700.	10000.	900.
17500	2500.	8000	4000.	12000	620.	14000.	850.	10000.	330.
55000	2250.	55000	2000.	59000	150.	57000.	500.	61000.	950.
150000	550.0	150000	260.	150000	230.	150000.	530.	150000.	160.
160000	40.0	160000	70.	160000	90.	160000.	90.	160000.	40.
110000	8.0	110000	8.	110000	8.	110000.	8.	110000.	20.
150000	2.4	150000	2.4	150000	2.4	150000.	2.4	150000.	5.6
230000	1.12	230000	1.12	230000	1.12	230000.	1.12	230000.	1.58
100000	0.47	100000	0.47	100000	0.47	100000.	0.47	100000.	1.12
1000000	1.	1000000	1.0	1000000	1.	1000000	1.	1000000	1.0

Zone 6		Zone 7		Zone 8		Zone 9		Zone 10	
d	R	d	R	d	R	d	R	d	R
65	50.0	50	30.0	25	30.0	25	15.0	175.0	30.0
2635.00	15.0	1350.00	10.0	3275.00	10.0	1875.0	10.0	1725.0	10.0
9300.00	3000.0	11600.0	3000.0	11700.0	900.0	10100.0	4200.0	6100.0	1000.0
17000.0	2300.0	16000.0	1750.0	15000.0	275.0	12000.0	4500.0	10000.0	1300.0
10000.0	2100.0	9000.00	1200.0	9000.00	360.0	16000.0	4500.0	22000.0	800.0
61000.0	1400.0	62000.0	1400.0	61000.0	315.0	60000.0	1600.0	60000.0	500.0
150000.	160.0	150000.	635.0	150000.	680.0	150000.	680.0	150000.	625.0
160000.	50.0	160000.	50.0	160000.	50.0	160000.	50.0	160000.	50.0
110000.	20.0	110000.	20.0	110000.	20.0	110000.	20.0	110000.	20.0
150000.	5.6	150000.	5.62	150000.	5.62	150000.	5.62	150000.	5.62
230000.	1.58	230000.	1.58	230000.	1.58	230000.	1.58	230000.	1.58
100000.	1.12	100000.	1.12	100000.	1.12	100000.	1.12	100000.	1.12
1000000	1.0	1000000	1.0	1000000	1.0	1000000	1.0	1000000	1.0

The calculated surface impedance used as the transfer function between geomagnetic variations and geo-electric (telluric) field at the Earth's surface, as $E(\omega) = Z(\omega) \times B(\omega)$.

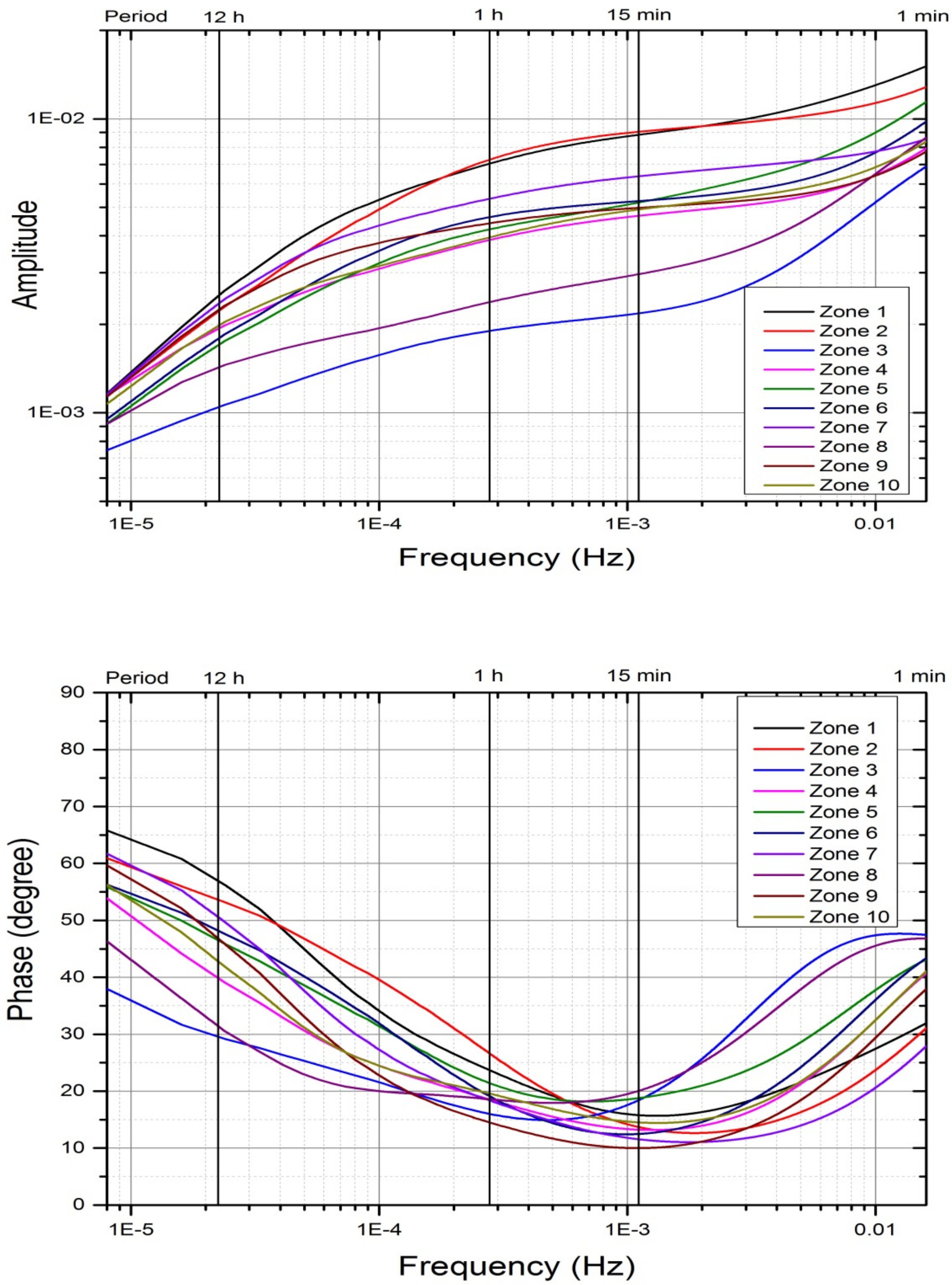


Figure 3.2. Surface impedances (amplitude and phase) for the layered earth resistivity models.

As shown in Figure 3.2, the surface impedances (amplitude and phase) vary for the different zones, depending upon frequency as well as the resistivity of the different layers. This dependence can be explained in terms of the “skin depth” of conductors with respect to the electromagnetic waves. When electromagnetic waves propagate down through the Earth, they partially penetrate through and partially reflect from the different layers, decaying at the different depths, depending on their frequency (i.e wavelength) and the particular resistivity of the layer. In our study we are using 1 minute data, which defines the highest frequency as ~0.015 Hz.

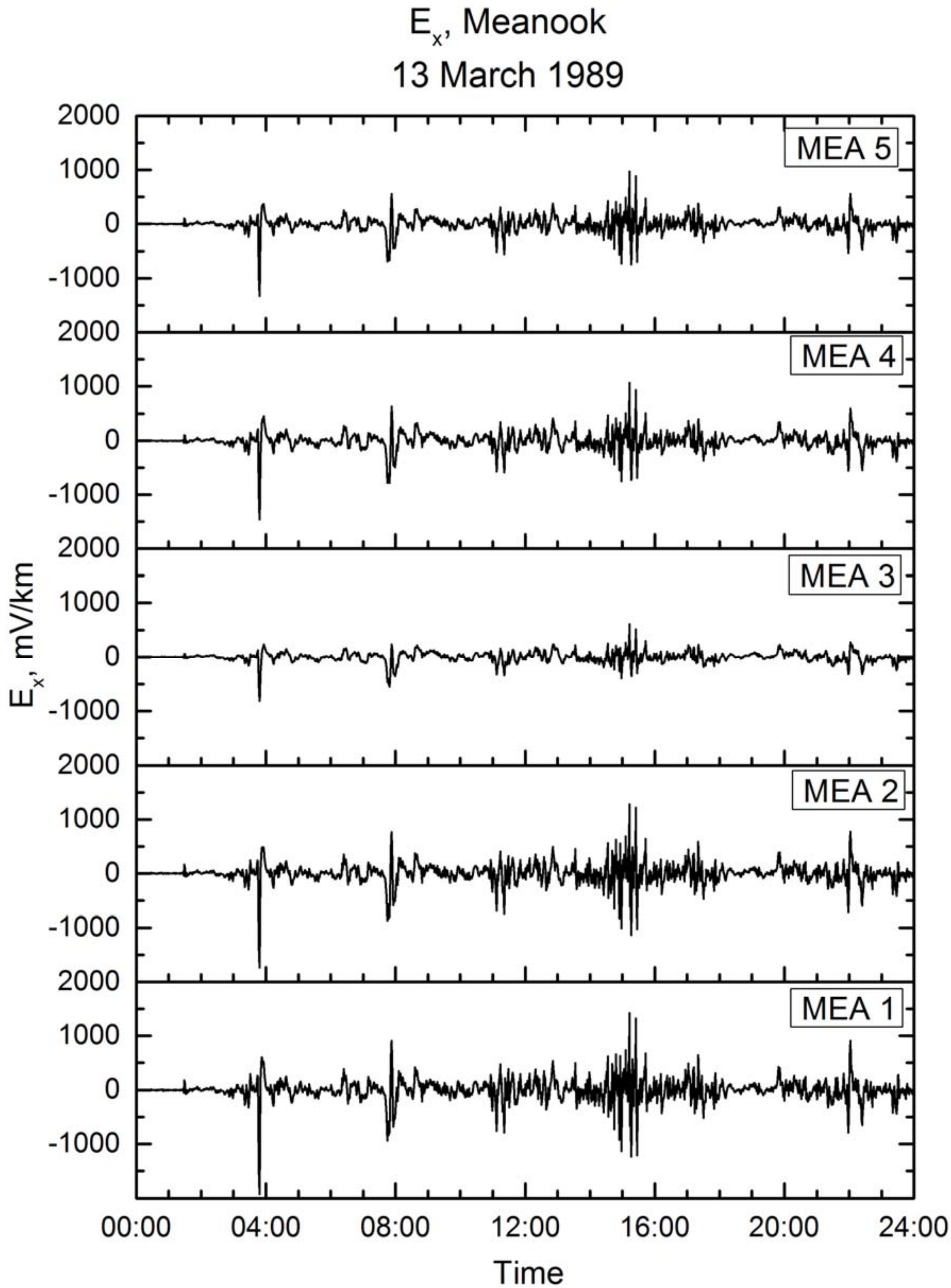
Variations with more than 12 hours period or about 0.01 mHz, characterize the lower part of studied frequency spectrum. Natural electromagnetic waves of this frequency range (0.01 Hz-0.01 mHz) penetrate deep into the Earth and are not affected by the surficial geology. Thus, changes in the resistivity of a topmost layer, such as those due to permafrost (which penetrates to a maximum depth of approximately half a kilometer) or surficial geology, do not affect the surface impedance at the frequencies we are concerned with.

The largest difference between the surface impedances can be seen in the amplitudes of Zone 3 and Zone 8 having the lowest amplitude and second low, and Zone 1. Zone 3 has the so-called Loverna Conductor (LC), which is a regional low resistivity feature in the upper mantle (~40-100 km) below the western part of the Loverna Block, exhibiting 3-30 Ohm·m range, and broadly dipping southeasterly, while Zone 8 contains the Kiskatinaw conductor (KC), a southeast dipping conductor (~ 10 Ohm·m) imaged between 20 and 50 km depth, which may represent a fossil subduction zone (see Chapter 2 for details).

The lower amplitude of these impedances will result in attenuated geo-electric field variations compared with the other zones. This will translate into different geoelectric fields produced by geomagnetic variations in this frequency range and as a result different values of the geoelectric fields.

3.4. Daily Variations of the Geoelectric Field

The effect of different impedances can best be illustrated by calculating geo-electric field values from a sample of geomagnetic data using different earth resistivity parameters and comparing the results. The same geomagnetic field minute values (Meanook, March 13, 1989) were used in the electric field calculations with all ten different Earth models, as presented in Figures 3.3 (Zones 1-5) and Figure 3.4 (Zones 6-10) below.



E$_x$, Meanook
13 March 1989
MEA 5
MEA 4
MEA 3
MEA 2
MEA 1
E$_x$, mV/km
2000
1000
0
-1000
00:00
04:00
08:00
12:00
16:00
20:00
24:00
Time

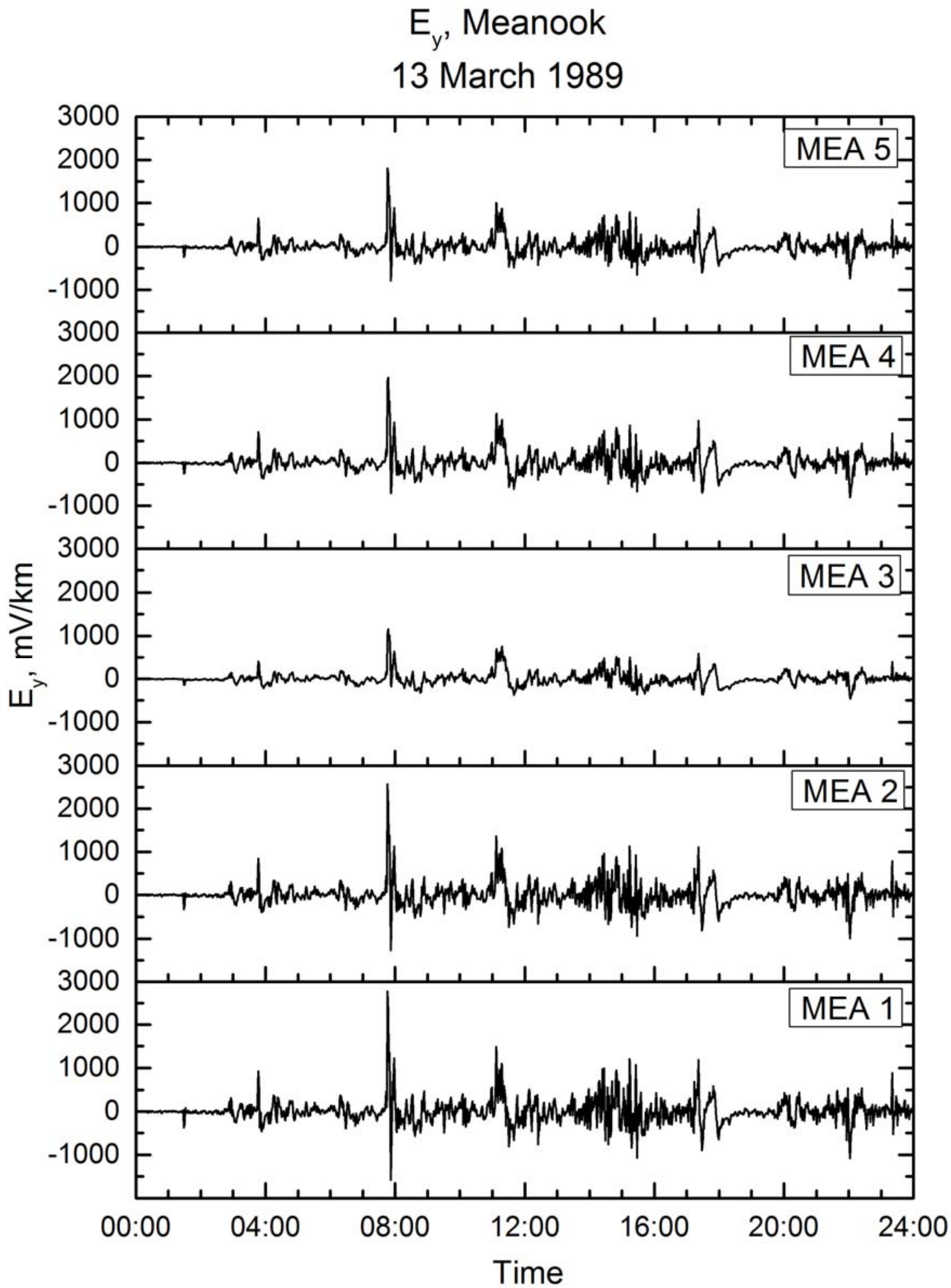
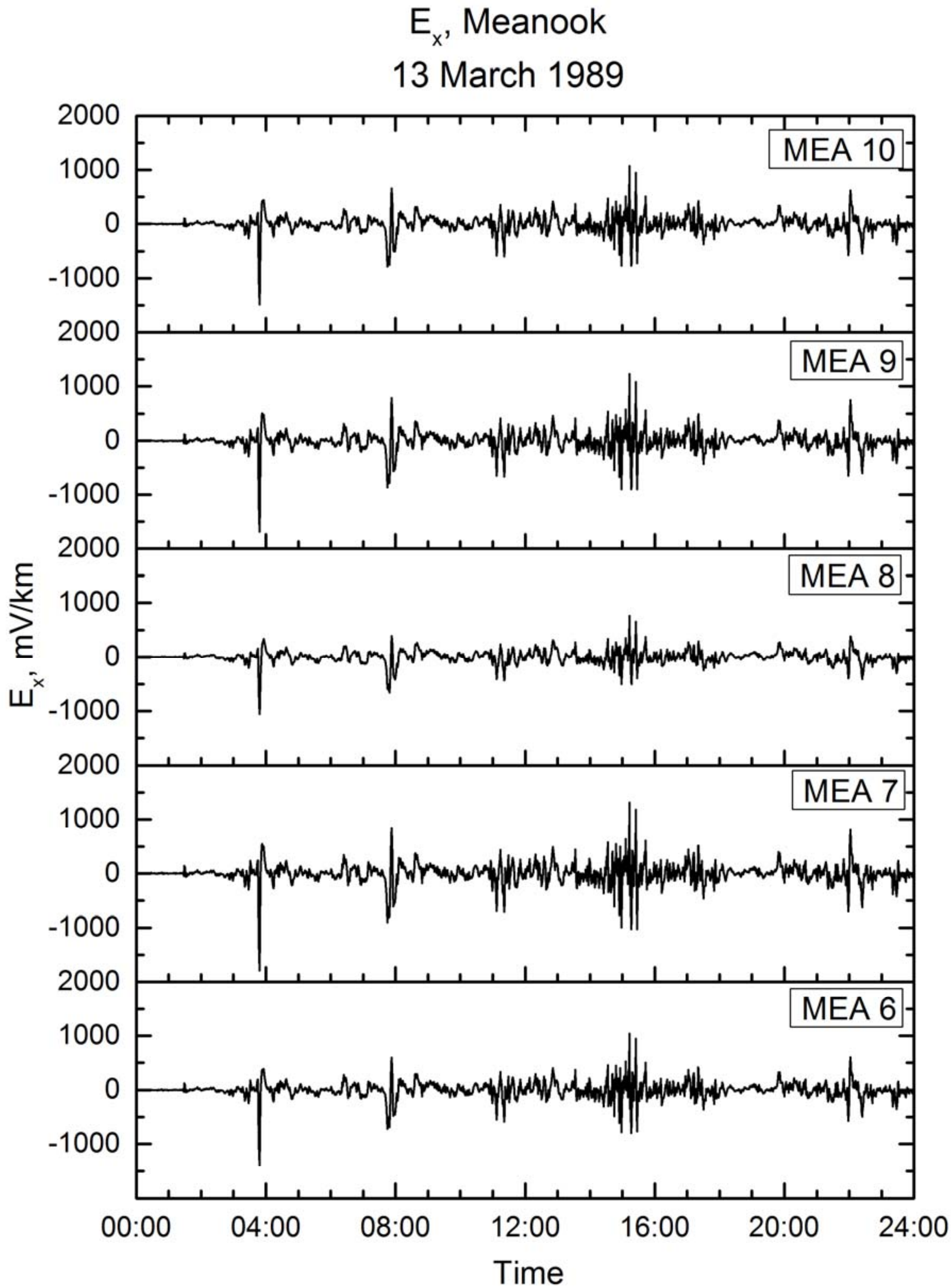


Figure 3.3. Geoelectric field variations during March 13, 1989, X and Y components, calculations done with the use MEA observatory data and earth resistivity models for Zones 1-5.


E_x, Meanook
13 March 1989
MEA 10
MEA 9
MEA 8
MEA 7
MEA 6
E_x, mV/km
2000
1000
0
-1000
00:00
04:00
08:00
12:00
16:00
20:00
24:00
Time

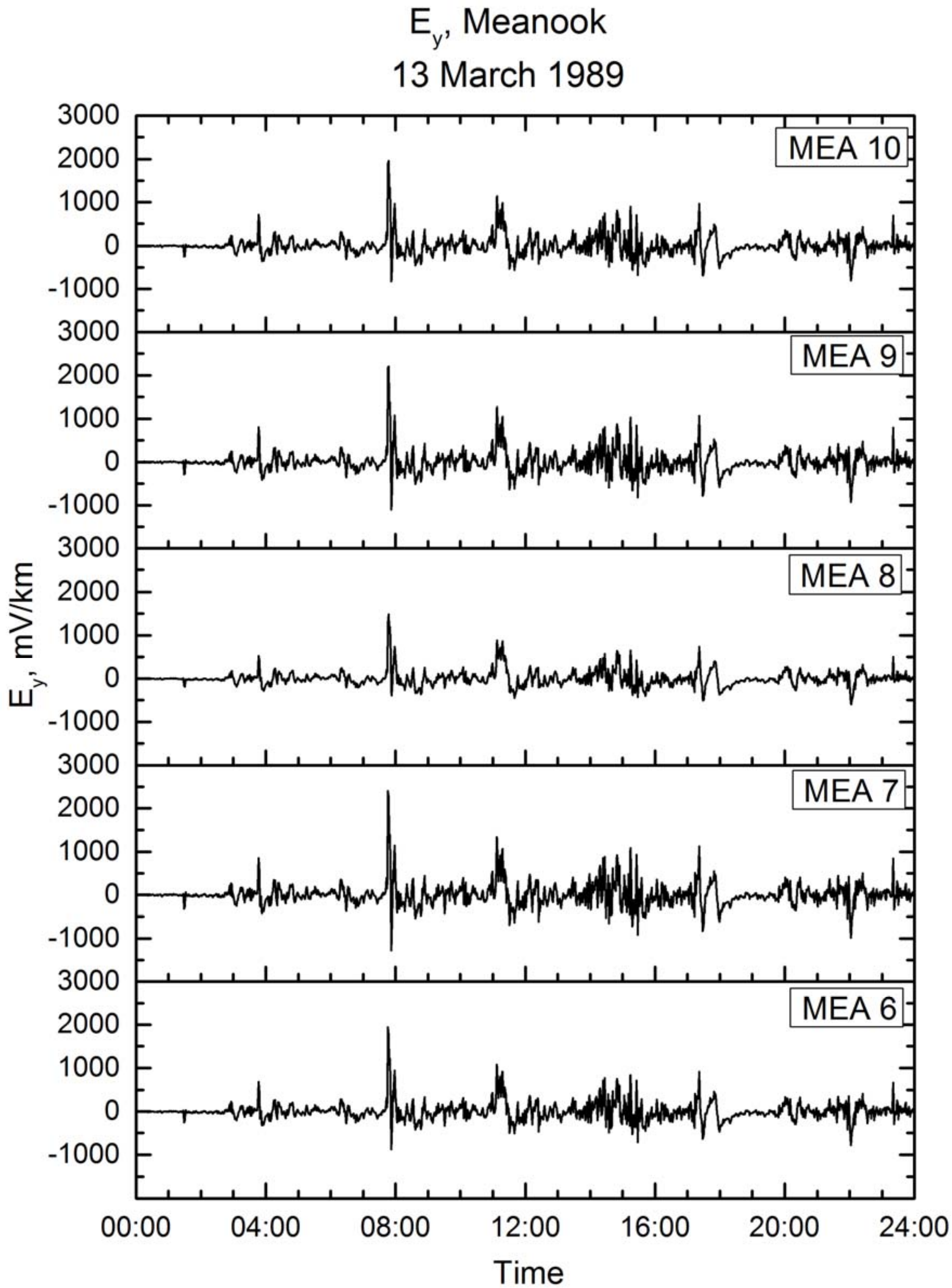


Figure 3.4. Geoelectric field variations during March 13, 1989, X and Y components, calculations done with the use MEA observatory and the earth resistivity models for Zones 6-10.

As can be inferred from the Figures 3.3 and 3.4, the differences in variations of X- and Y-components are significant for UT times of 04:00 (large spike in X-component) and 08:00 (large spike in Y-component), thus both directions of the electric field can make a significant input into the resulting GIC in power lines. It is also evident that lower amplitudes of the geoelectric field are in Zones 3 and 8, which is due to the lower amplitude of the surface impedance, while the highest are in Zones 1 and 2, and zones 4-7, 9 and 10 are experiencing the same sizes of the geoelectric field fluctuations due to the similarities in their surface impedance (Fig. 3.2).

3.5. Statistical Properties of the Geoelectric Field Variations/annual

In order to get a statistical description of the levels of geoelectric field variations, we establish the hourly index as the maximum amplitude of the X and Y-components of the geo-electric field in one hour (Hourly Maximum Amplitude).

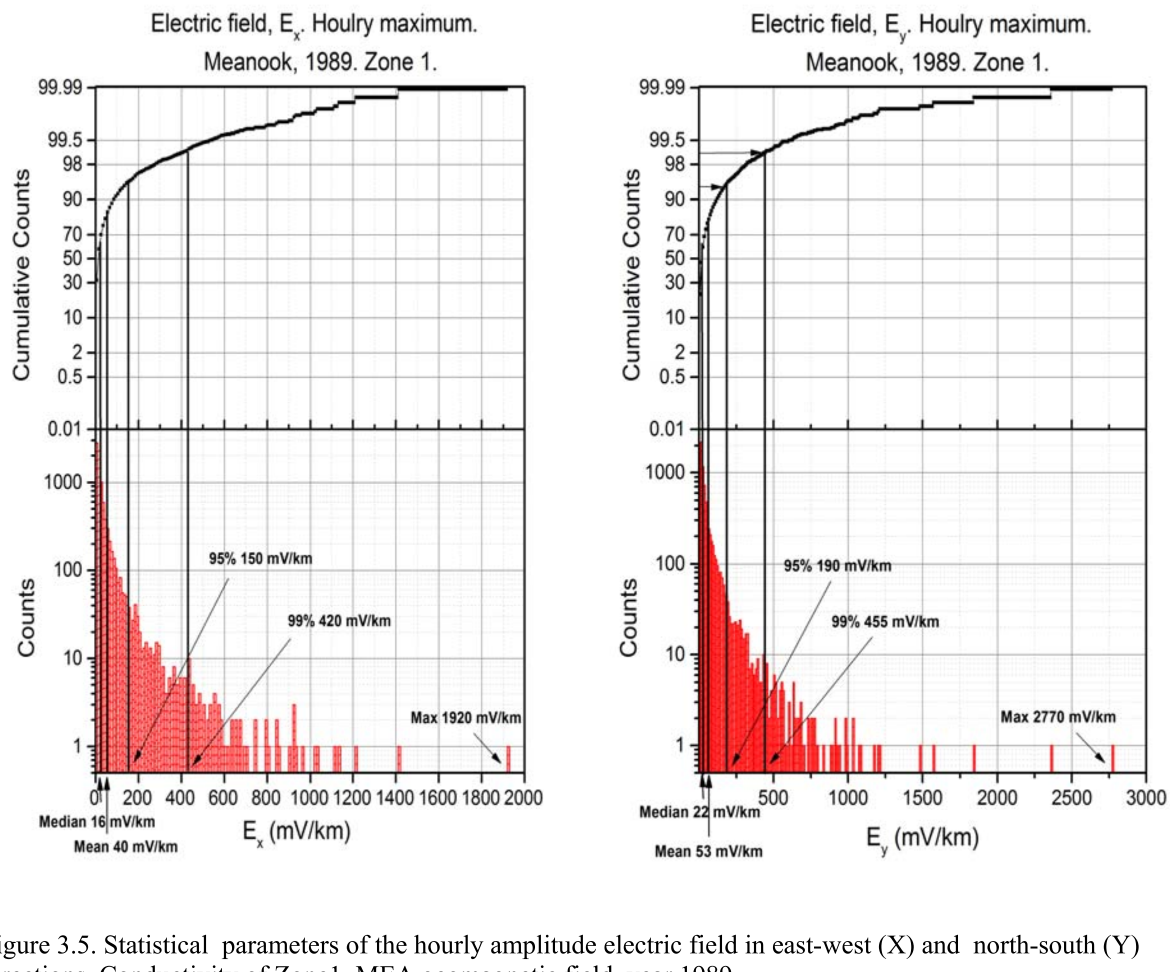


Figure 3.5. Statistical parameters of the hourly amplitude electric field in east-west (X) and north-south (Y) directions, Conductivity of Zone1, MEA geomagnetic field, year 1989.

As it was done for geomagnetic activity in Chapter 1, we examine the distribution function to obtain the statistical characteristics such as median, mean, 95% and 99% levels and the maximum values for each year. Examples of the distribution functions for hourly maximum index (X- and Y-components) for the year of 1989 calculated for Zone 1 layered earth model are presented in Figure 3.5. Eastward component of the geoelectric field (Y-component) has larger values of each statistical parameter as well as the maximum value.

Geomagnetic data from 2 observatories, which have produced data for 40 years (i.e. MEA and YKC) with respective Layered Earth zonal models, were used to calculate geo-electric field X (northward) and Y (eastward) components. Because the geomagnetic data from GLN and BRD were not available in the period comparable with 40 years, we did not include them in the presented analysis. If the data from GLN observatory is recovered and available, these will be also used in calculations (zones 1 and 2).

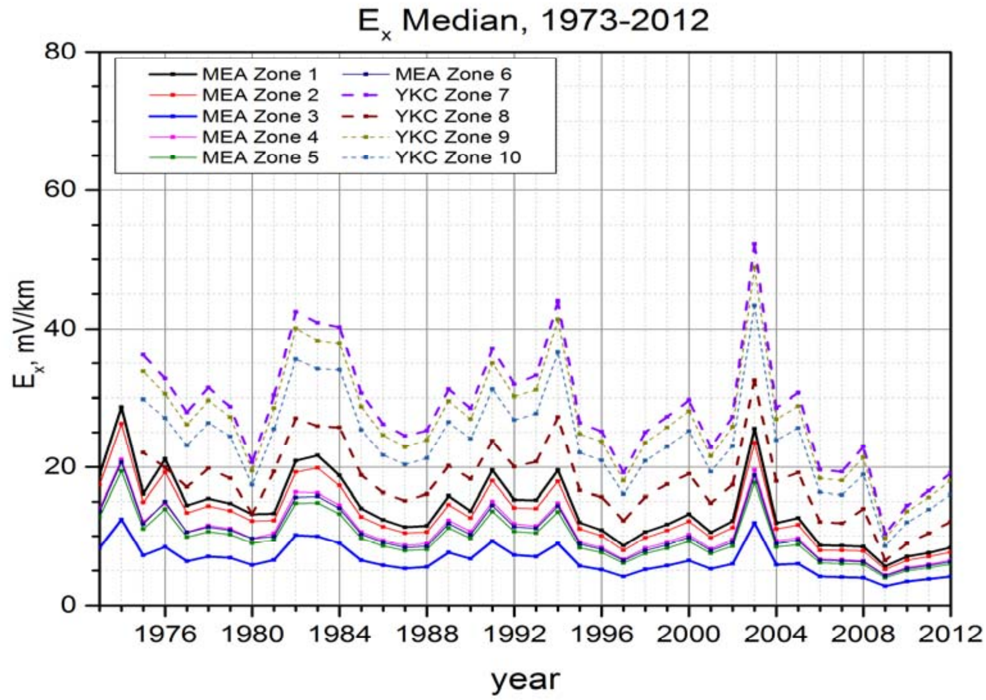
The ten zones and the corresponding geomagnetic data are listed in Table 3.1.

Layered Earth Zonal model	**Geomagnetic Data Source**
1	Meanook (Glenlea)
2	Meanook (Glenlea)
3	Meanook
4	Meanook
5	Meanook
6	Meanook
7	Yellowknife
8	Yellowknife
9	Yellowknife
10	Yellowknife

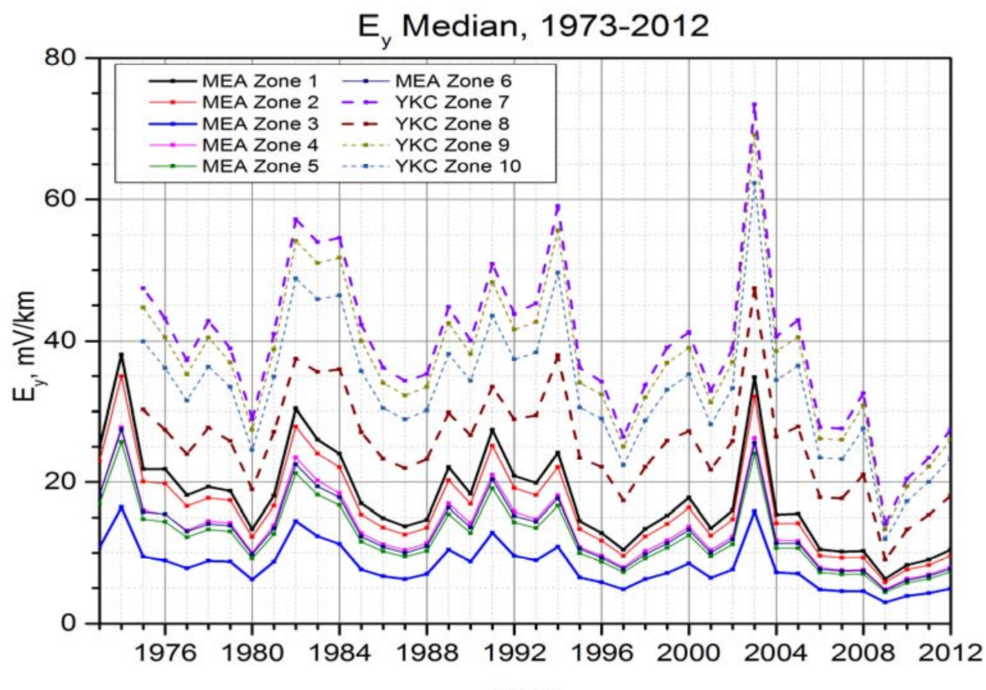
Table 3.1. Summary of resistivity models and respective geomagnetic data used in geoelectric field calculations

Geomagnetic data from YKC observatory were used for Zones 7-10 (Northern part of Alberta) and geomagnetic data from MEA observatory were used for Zones 1-6, i.e. southern part of Alberta.

Annual changes of the northward (X-) and eastward (Y-) components of the electric field hourly maximum are presented in Figure 3.6 a,b) for median, Figure 3.7 a,b) for mean, Figure 3.8 a,b) for 95%, Figure 3.9 a,b) for 99% and Figure 3.10 for annual largest values.

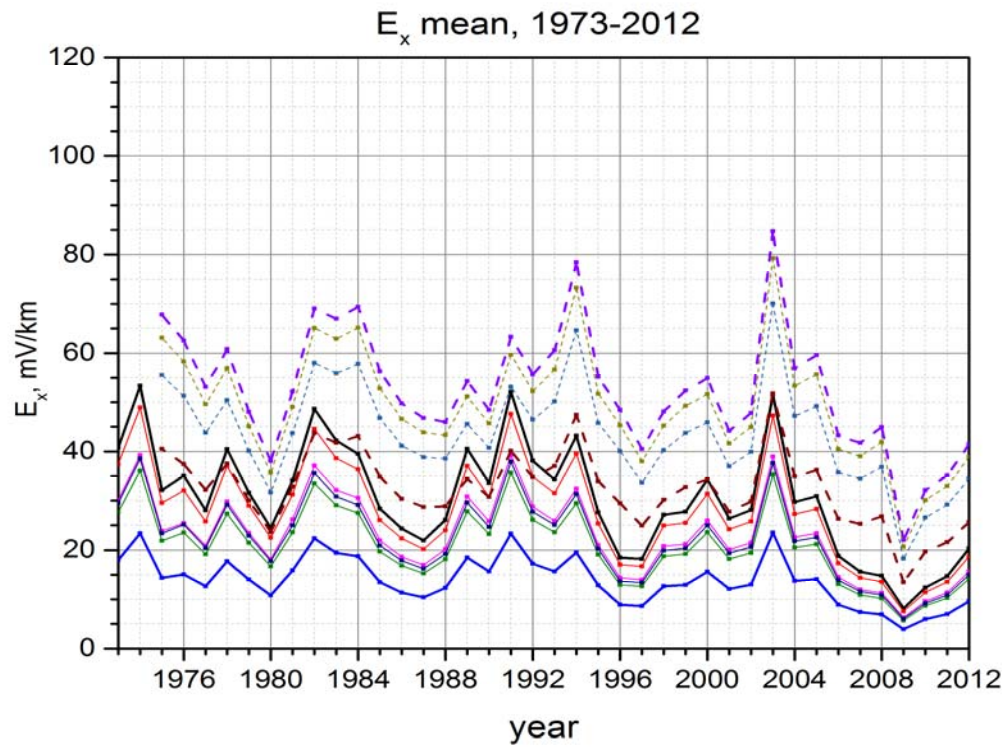


a)

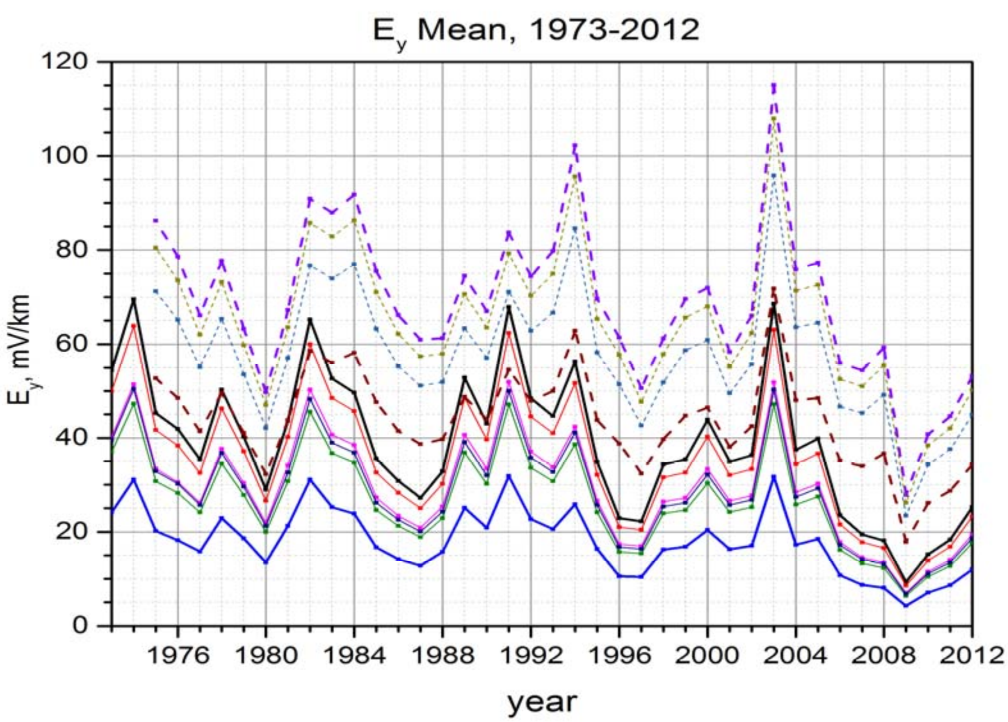


b)

Figure 3.6 Annual changes of the median of the electric field hourly maximum: a)-X, b)-Y components

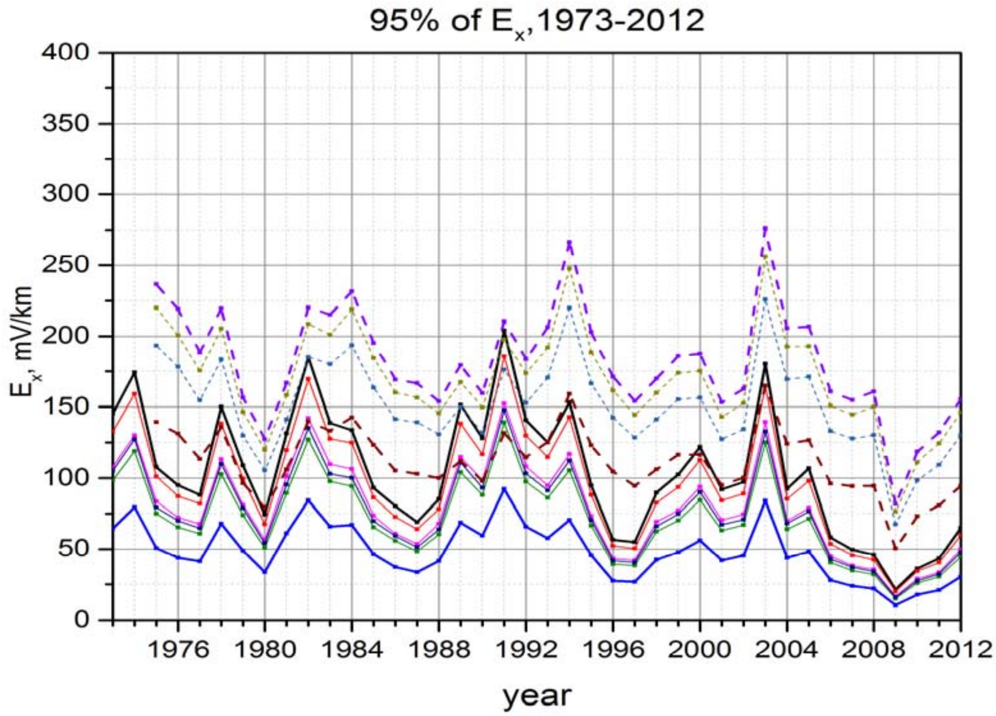


a)

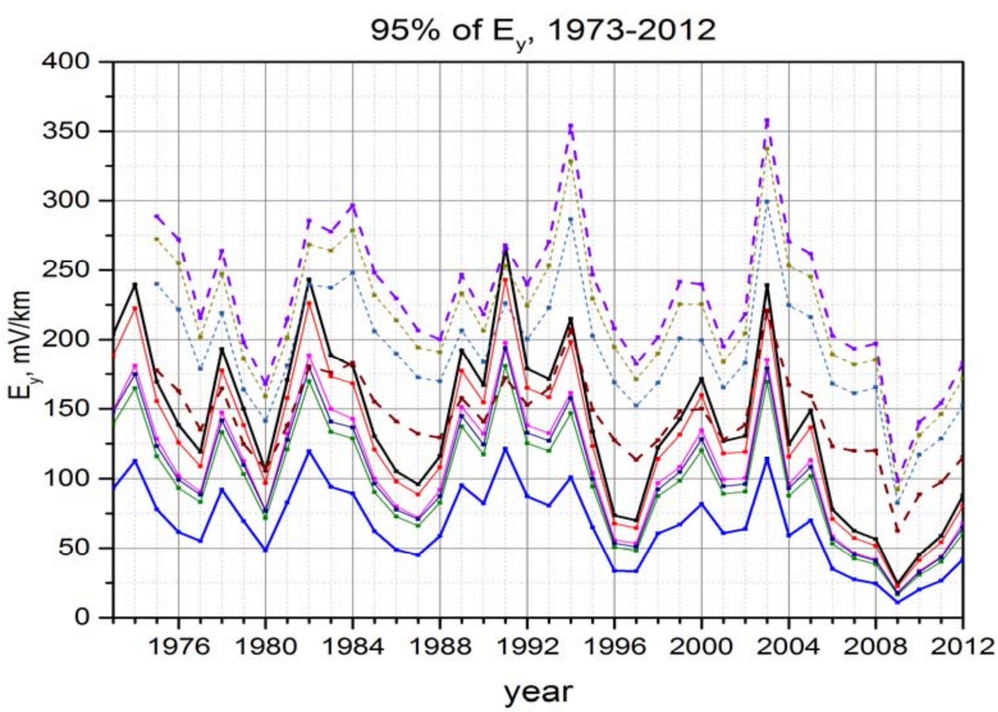


b)

Figure 3.7 Annual changes of the mean of the electric field hourly maximum: a)-X, b)-Y components

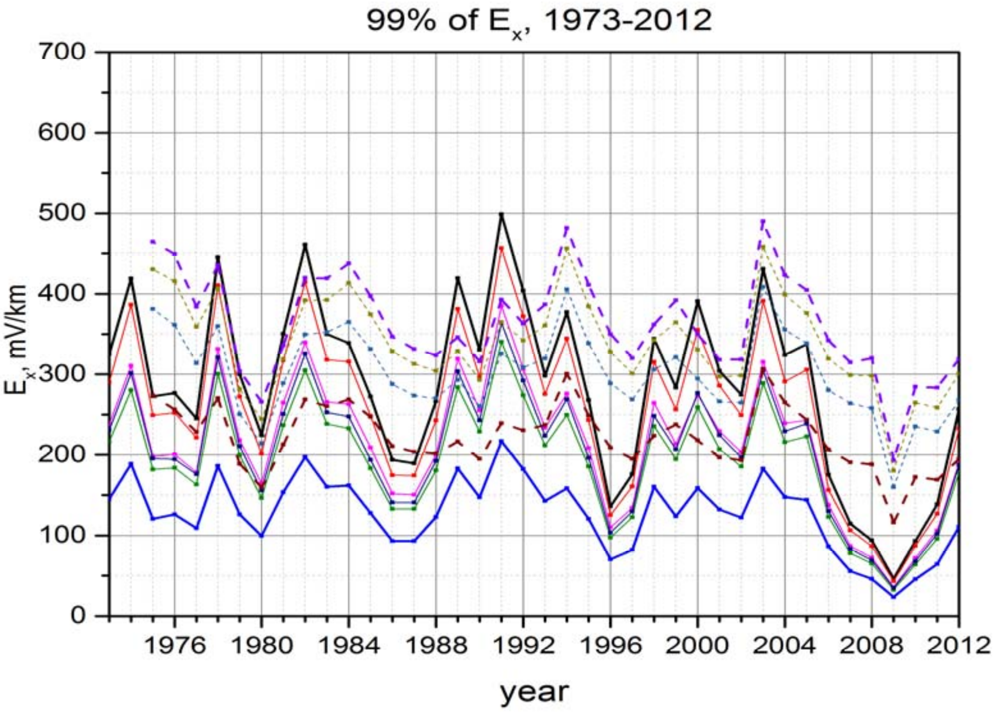


a)

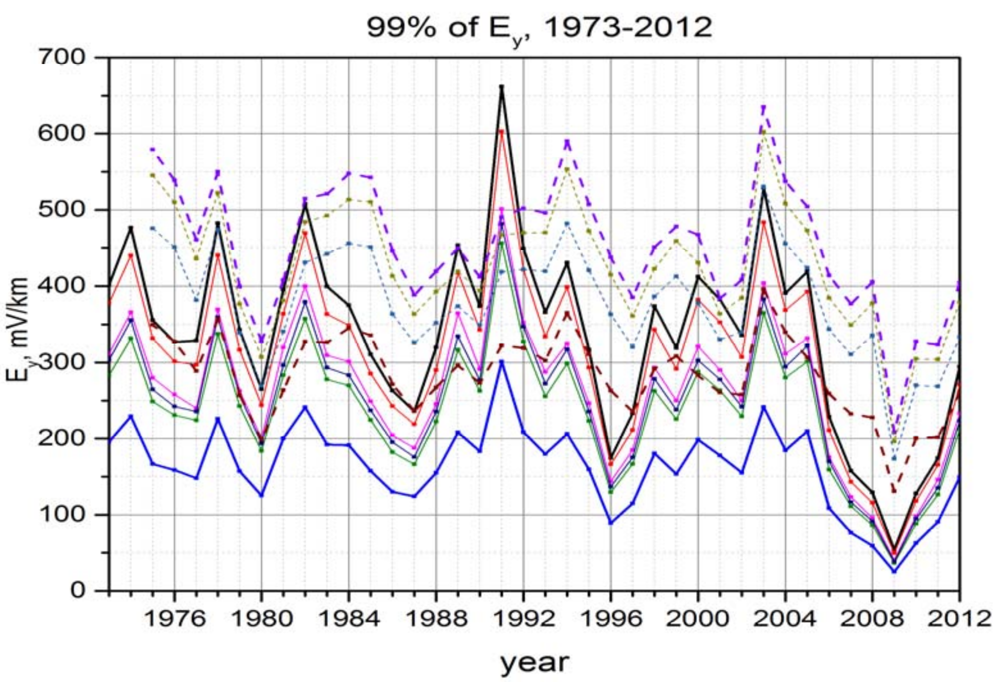


b)

Figure 3.8 Annual changes of the 95% of the electric field hourly maximum: a)-X, b)-Y components

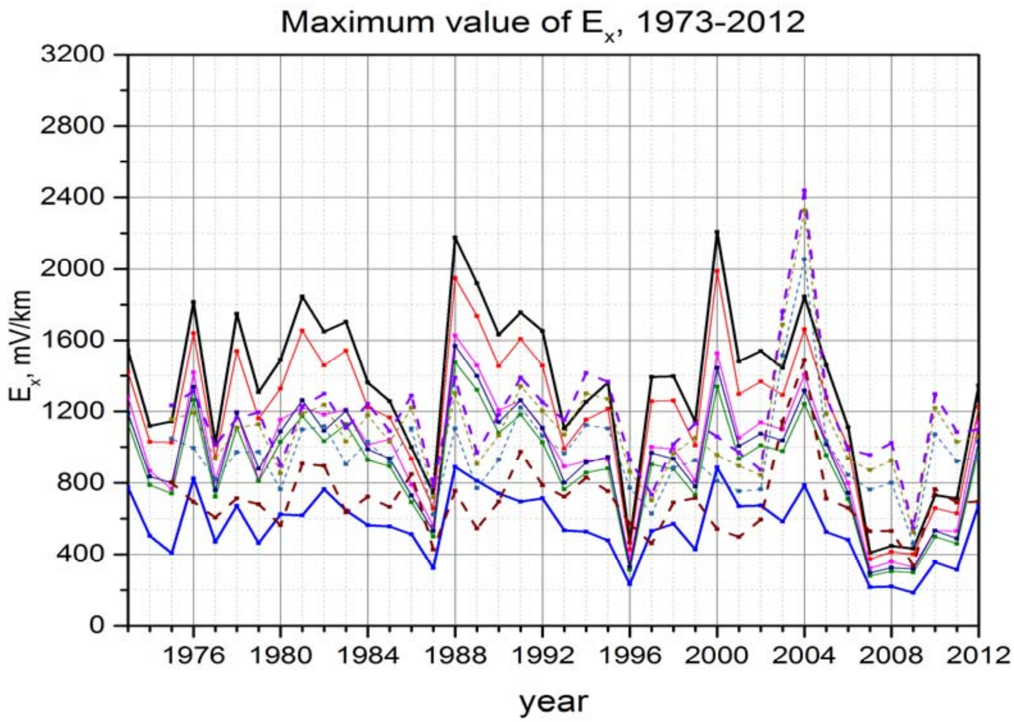


a)

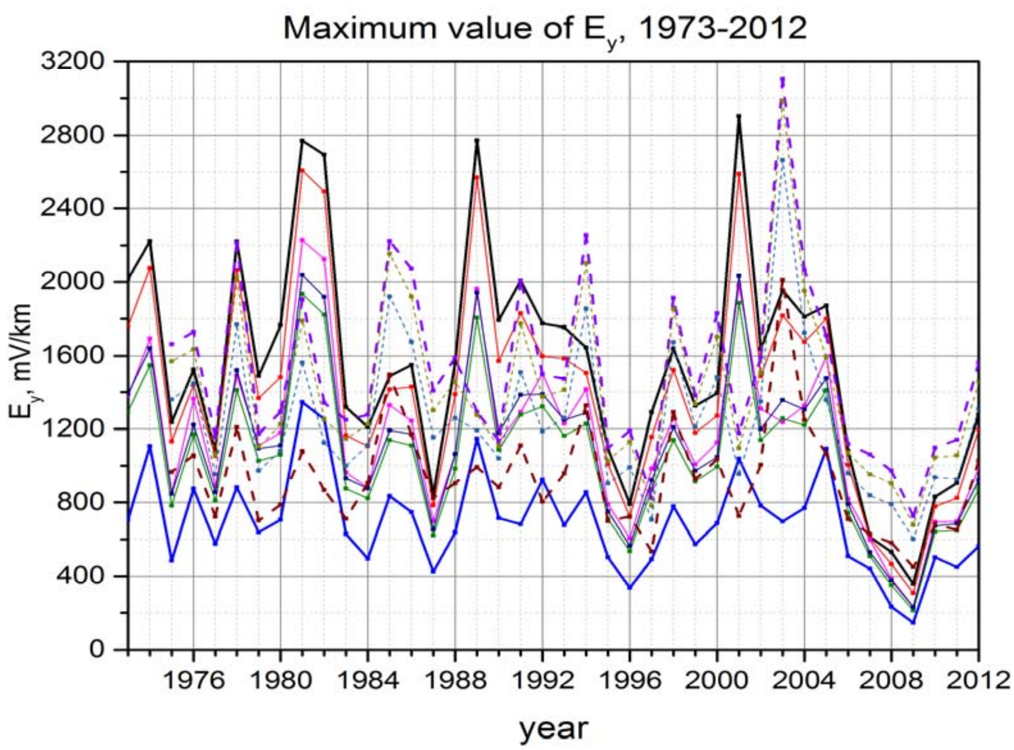


b)

Figure 3.9 Annual changes of the 99% of the electric field hourly maximum: a)-X, b)-Y components



a)



b)

Figure 3.10. Annual changes of the annual maximum values of electric field for (X-) and Y- components

The following points can be made based on the analysis of these plots:

1. Overall, the statistical characteristics (median, mean, 95% and 99%) of the geoelectric fields in northern parts of Alberta are experiencing higher geoelectric fields than southern parts due to the higher geomagnetic activity. This behavior just slightly changes at the 99% level due to the high geomagnetic activity in 1991. The extreme values (annual maximums) do not demonstrate this separation, thus, during geomagnetic storms the geoelectric fields in southern Alberta can be as large as in northern Alberta.

2. Median values (most often occurring) in X-component are below 55 mV/km, with peak value in 2003, when the geomagnetic activity is also higher than normal (see Fig. 1.8 Chapter 1). Eastward component of the median electric field index is only slightly higher and in general less than 60 nT with the exception of 2003, when the highest value is ~ 75 mV/km.

3. Mean values of the electric field are < 80 mV/km in northward direction and < 100 mV/km in eastward. The respective values in year 2003 are ~ 85 mV/km and ~115 mV/km respectively.

4. At the 95% level the electric field hourly maximum is below 280 mV/km and 350 mV/km for northward and eastward components respectively. Here the impacts of geomagnetic storms starts to be seen as the values of the geoelectric field at southern part can be the same as for the northern part (for example in 1989).

5. The level of occurrence of 99% is already including the effects of geomagnetic storms, making the values of geoelectric field in northern and southern parts similar in value. Nevertheless, the eastward component is larger than the northward component.

6. The top several annual maximum values are of the orders of 2200-2400 mV/km for northward component and 2800 mV/km for eastward component with the majority of them below 1700 mV/km and below 2400 mV/km respectively. It should be noted, that not always both components are the highest for the same geomagnetic storm. As well, the geoelectric field is smaller in Zone 3 and higher in Zone 5 for southern part (when use of the same MEA magnetic data) and for the northern part it is lower for Zone 8-higher for Zone 7 (when use the same YKC magnetic field data). Thus, the extreme values of the geoelectric field are dependent not only on geomagnetic variations, but also on the layered earth models.

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3.5. Statistical Properties of the Geoelectric Field Variations/long-term

Further statistical analysis based on the data for 40 years has been done for hourly maximum of the modelled electric field variations. The specific examples for Zone 1 (south-most zone of Alberta) are presented in Figure 3.11 for Northward (X) and eastward (Y) components.

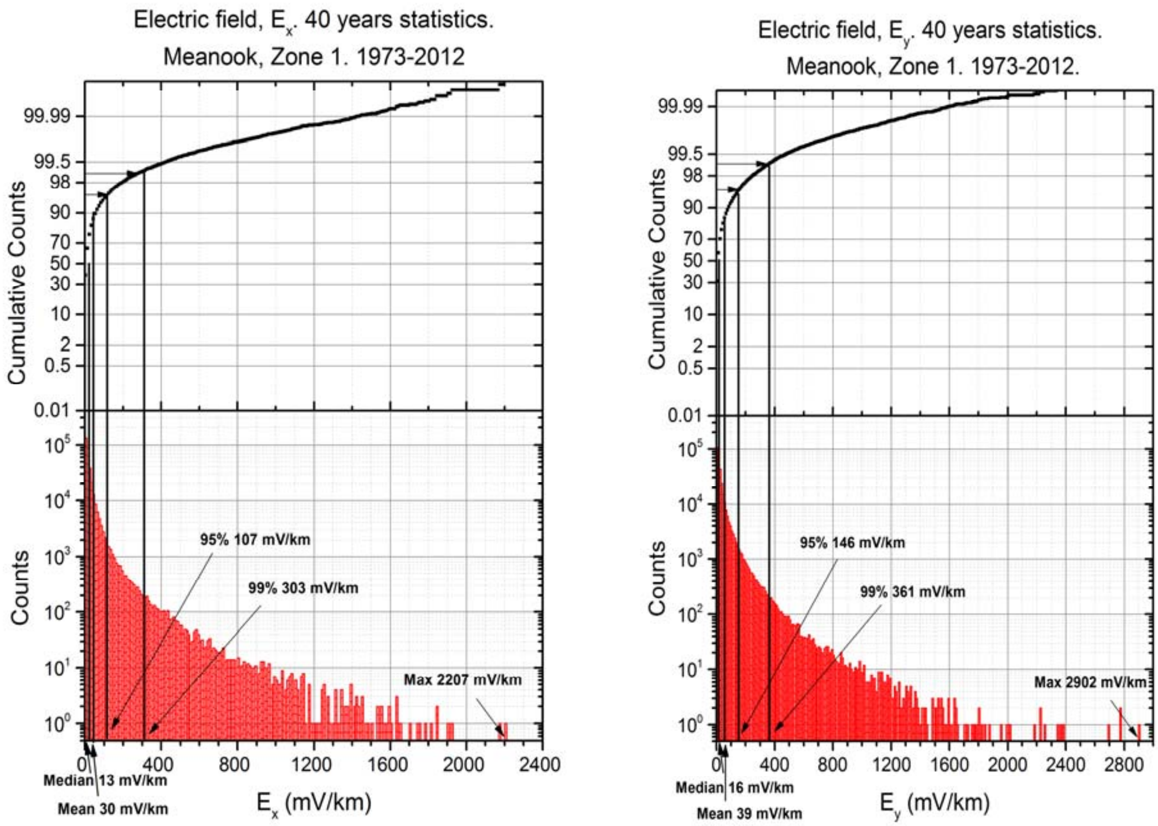
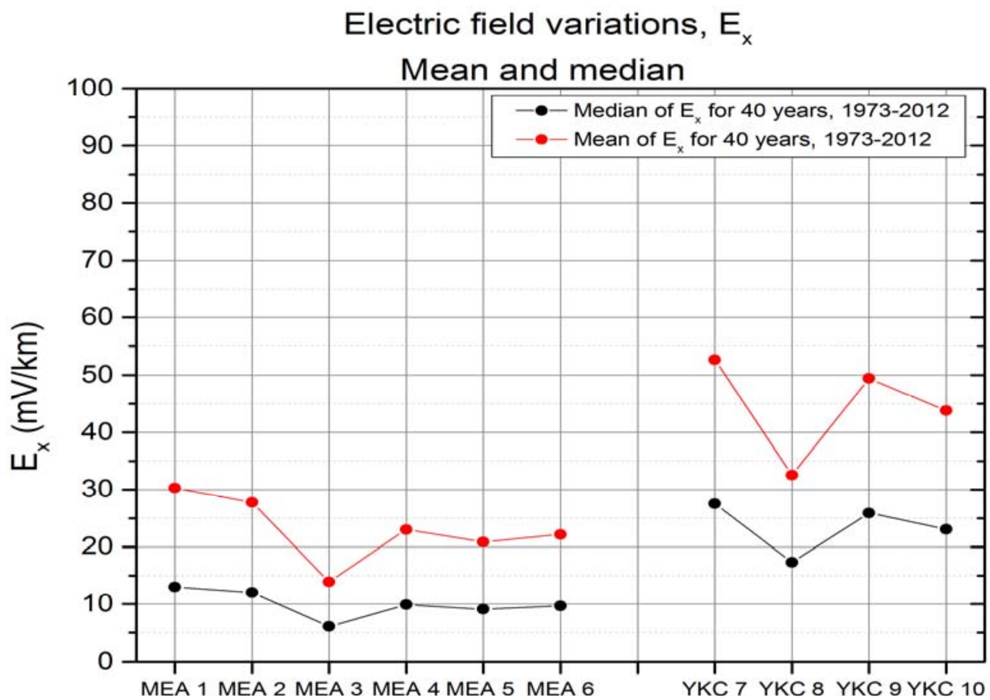


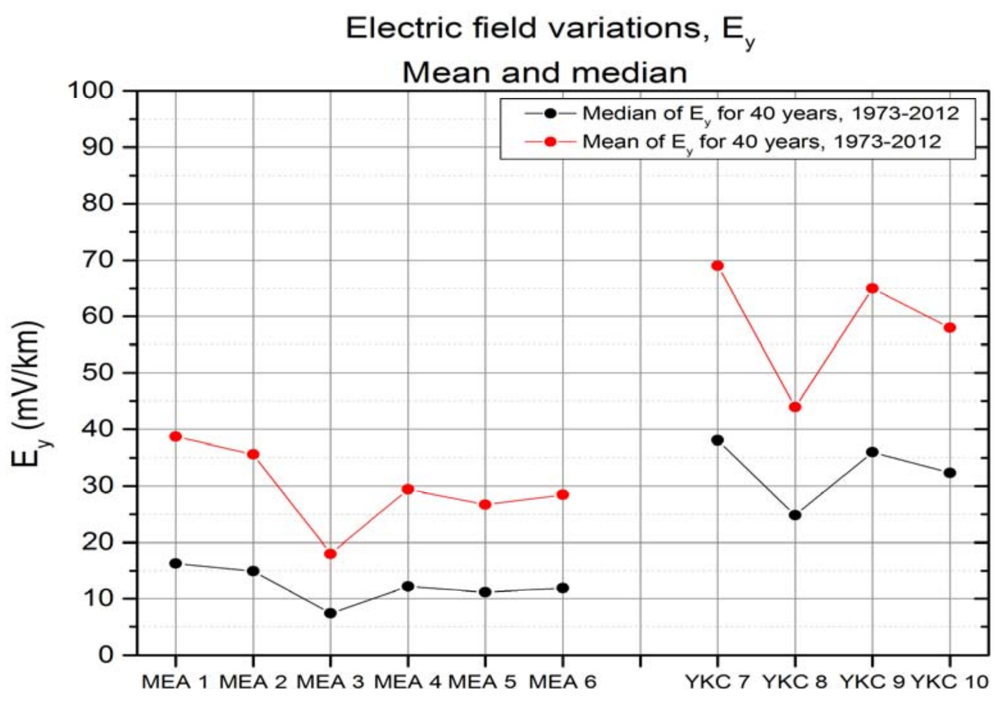
Figure 3.11 Statistical properties for modelled hourly maximum geoelectric field (Zone 1, 40 years of geomagnetic records, MEA observatory).

The median value (occurring most often) is quite low, i.e. 13 mV/km (X-component) and 16 mV/km (Y-component), while average is 30 mV/km (X) and 39 mV/km (Y). The 95% and 99% are 107mV/km and 303mV/km for X-component, and 146 mV/km and 361 mV/km for Y-component respectively. The “extreme” (i.e. maximum in 40 years) geoelectric field values are very high at 2207mV/km for electric field in X (northward) direction and 2902 mV/km for electric field in Y (eastward) direction.

The complete set of these characteristics for all 10 zones of the province is presented in Figures 3.12-3.14.

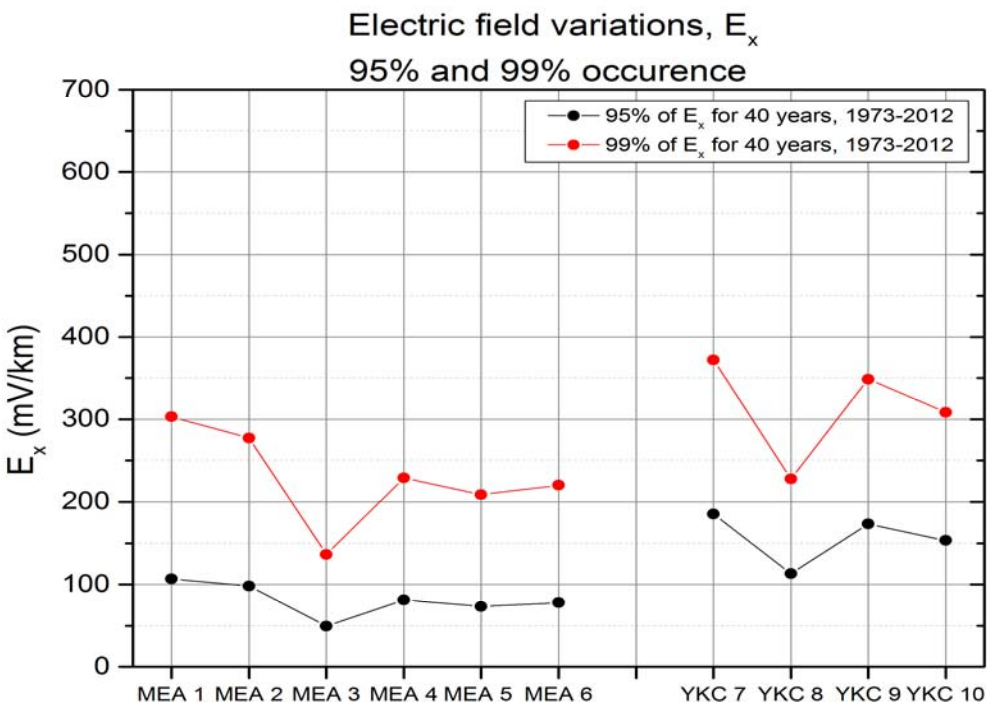


a)

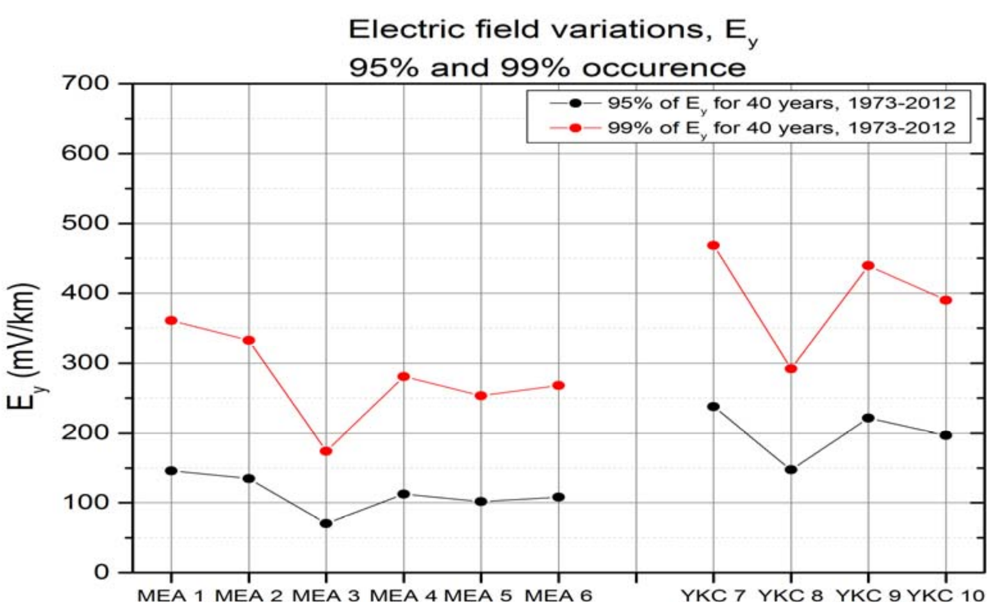


b)

Figure 3.12 Geoelectric field median and mean, all zones. a) X-component, b) Y-component

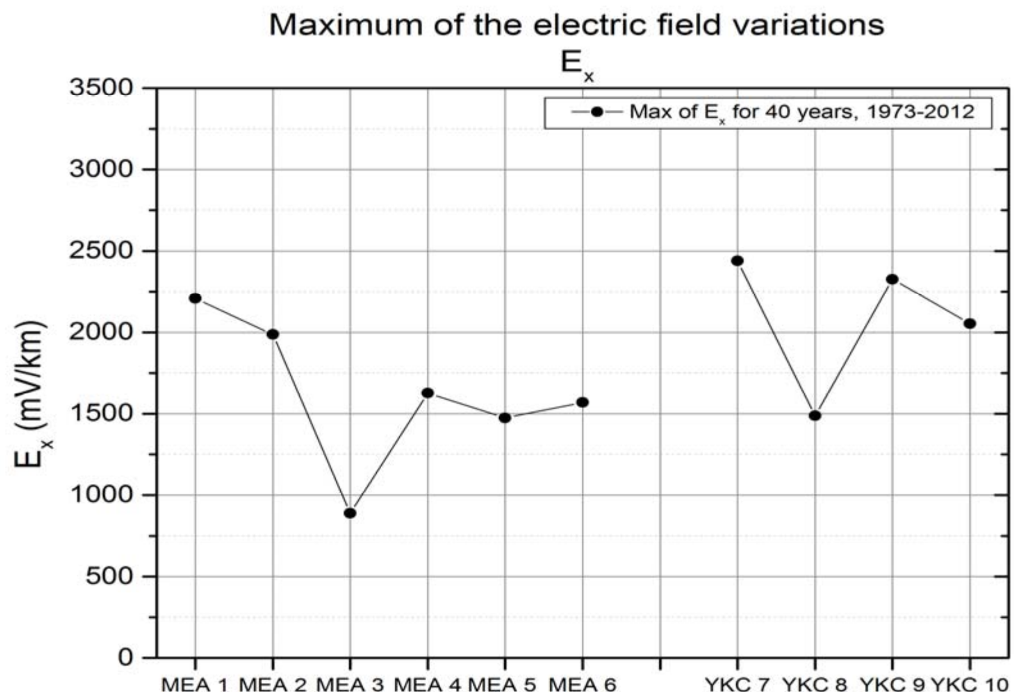


a)

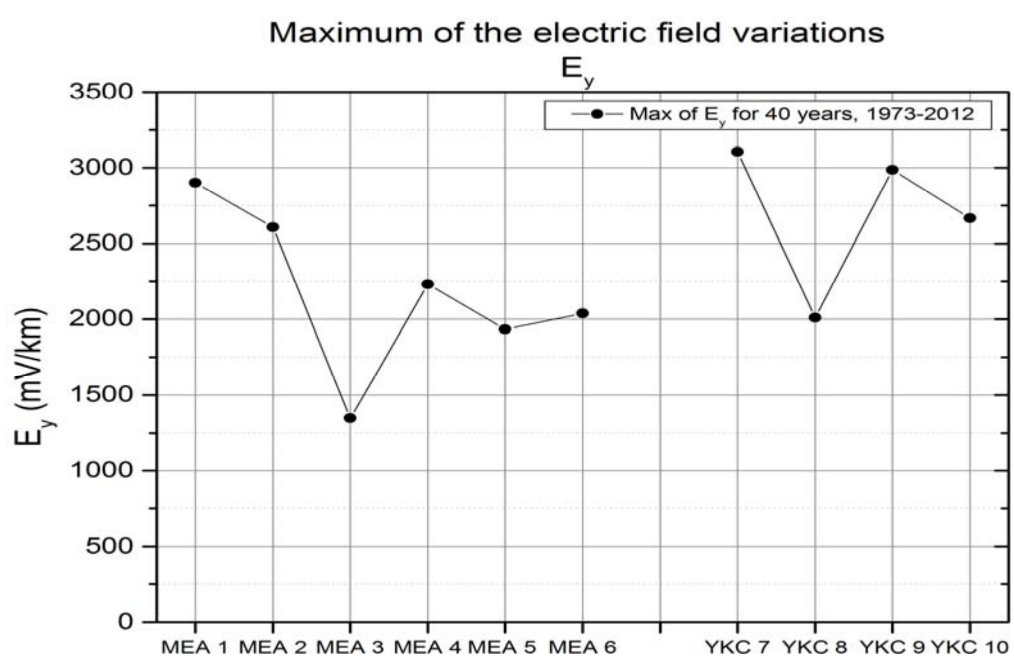


b)

Figure 3.13 Geoelectric field, 95% and 99%, occurrence, all zones. a) X-component, b) Y-component



a)



b)

Figure 3.14 Geoelectric field, maximum in 40 years, all zones. a) X-component, b) Y-component

As can be inferred from the analysis, statistically the southern part of the province (MEA 1-6) is characterized by lower geoelectric field than northern part (YKC 7-10) and the north-south (X) component is usually lower than east-west (Y). At the same time, the maximum values for 40 years are comparable for both geographic areas of province, and the difference between components is less significant (20%).

These 40-years statistical values can be applied with the network model for evaluation of the different types of scenarios, from the assessment of the “most often” case to “worst in 40 years” scenario. For convenience, the exact numbers are placed in the Table 3.2 a)-X-component, b)-Y-component. It should be noted, that two components do not coincide at any moment of time.

Table 3.2 Statistical properties of the modelled geoelectric field variations, 40 years

	Median mV/km	Mean mV/km	95% mV/km	99% mV/km	Max mV/km
MEA, ZONE 1	13.0	30.3	106.8	303.0	2208.0
MEA, ZONE 2	12.0	27.8	98.1	277.4	1987.3
MEA, ZONE 3	6.1	13.9	49.6	136.3	889.0
MEA, ZONE 4	9.9	23.0	81.4	229.1	1626.2
MEA, ZONE 5	9.1	20.9	73.4	208.9	1474.7
MEA, ZONE 6	9.7	22.2	78.1	220.2	1568.6
YKC, ZONE 7	27.6	52.7	185.1	372.0	2438.6
YKC, ZONE 8	17.3	32.6	113.4	228.0	1487.6
YKC, ZONE 9	25.9	49.4	173.2	348.6	2326.7
YKC, ZONE 10	23.1	43.8	153.2	308.7	2053.7

a) X-component

	Median	Mean	95%	99%	Max
MEA, ZONE 1	16.3	38.7	146.0	361.0	2901.9
MEA, ZONE 2	14.9	35.6	134.7	332.6	2607.5
MEA, ZONE 3	7.4	18.0	70.0	174.3	1345.7
MEA, ZONE 4	12.2	29.4	112.3	280.9	2229.6
MEA, ZONE 5	11.2	26.7	101.7	253.4	1933.2
MEA, ZONE 6	11.9	28.4	108.0	268.3	2037.1
YKC, ZONE 7	38.1	69.0	237.8	468.5	3106.7
YKC, ZONE 8	24.8	43.9	147.3	292.1	2010.0
YKC, ZONE 9	36.0	65.0	221.4	439.1	2986.5
YKC, ZONE 10	32.3	58.0	196.7	390.0	2666.1

b) Y-component

Conclusions

The 40 years of the geomagnetic data recordings from three geomagnetic observatories were used to derive the geoelectric field values. The geoelectric field has been modelled using the geomagnetic field data and set of surface impedance models which cover the whole province.

These modelled geoelectric field variations were analyzed to obtain the set of statistical values (mean, median, 95% occurrence rate and 99% occurrence rates) and the 40-year maximum values of the geoelectric activity. While the results for the Meanook and Yellowknife locations are directly relevant to the infrastructure of the Alberta due to their close proximity, the data for Ottawa were analyzed for setting some "background" climatology of the more populated mid-latitude regions which has more dense coverage of ground networks.

The estimated values can be used with power or pipeline network models to derive the GIC in the power lines or pipe-to-soil potential variations for the pipelines.

It should be noted, however, that the geoelectric field results are very dependent on the surface impedance models, so that the difference in these models can give extreme values up to three times larger (smaller). Thus, the obtained results (Table 3.2) can only be valid in the areas where the input models are applicable (in Alberta).

References:

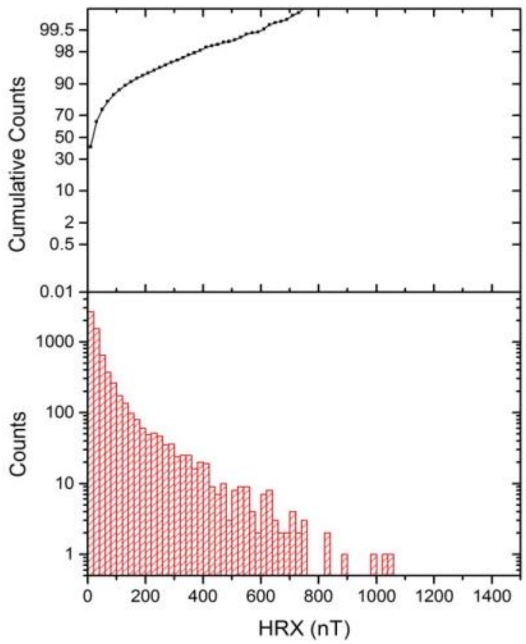
Press, W.H., Vetterling, W.T., Teukolsky, S.A., & Flannery B.P. (1992). *Numerical Recipes in Fortran 77: The Art of Scientific Computing (2nd ed.).* New York: Cambridge University Press.

Weaver, J.T., (1994). *Mathematical Methods for Geo-electromagnetic Induction.* Toronto: John Wiley & Sons Inc.

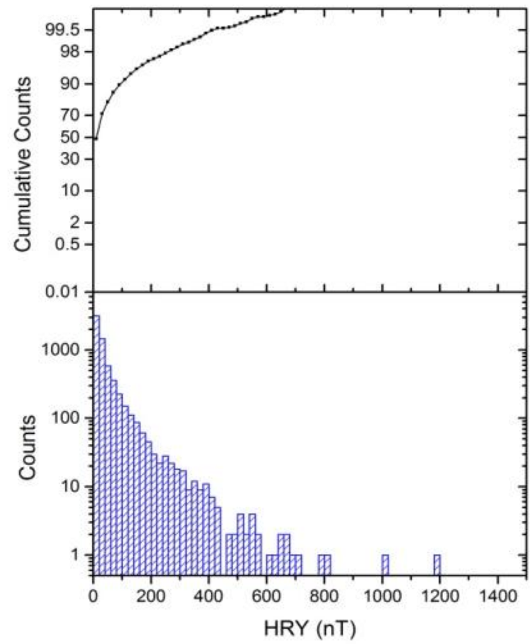
Appendix A

Histograms for the geomagnetic hourly range variations. Meanook, 1973-2012

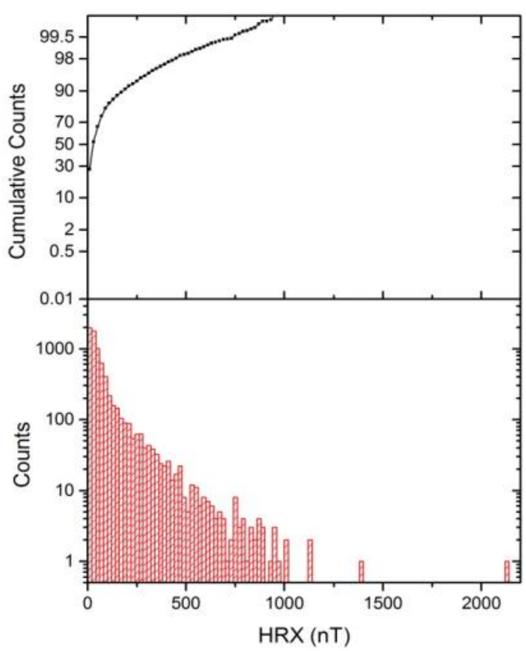
HRX, Meanook, 1973



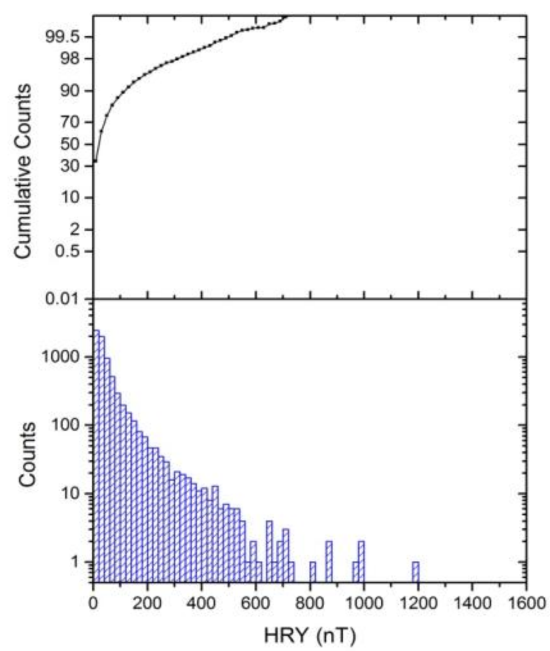
HRY, Meanook, 1973

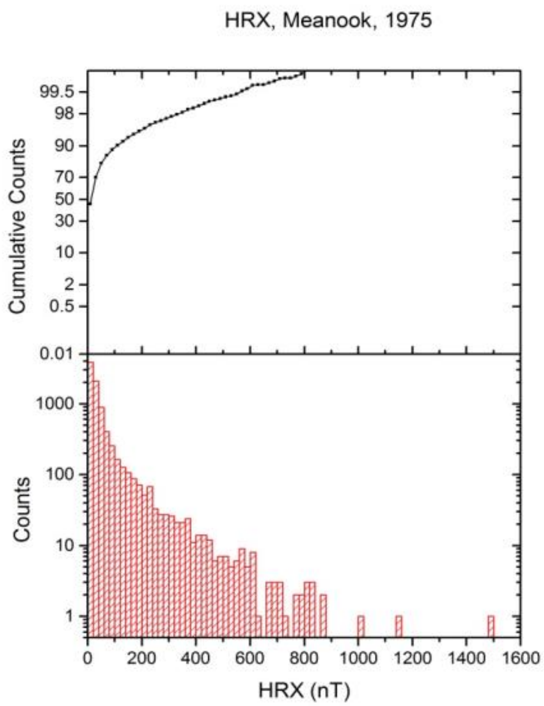


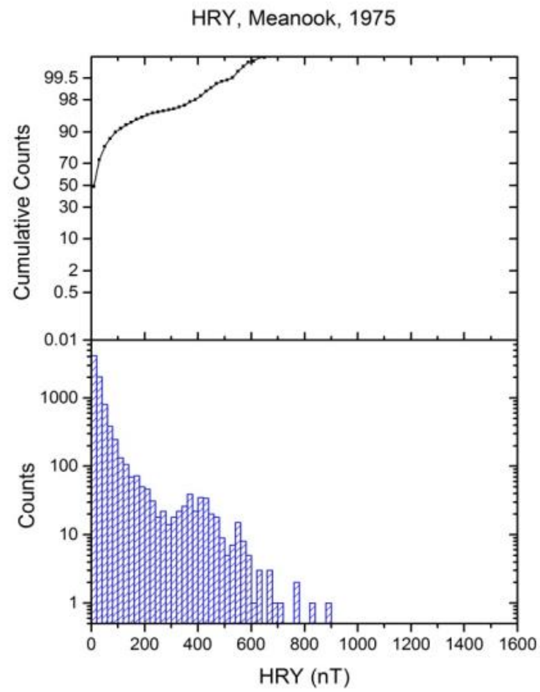
HRX, Meanook, 1974

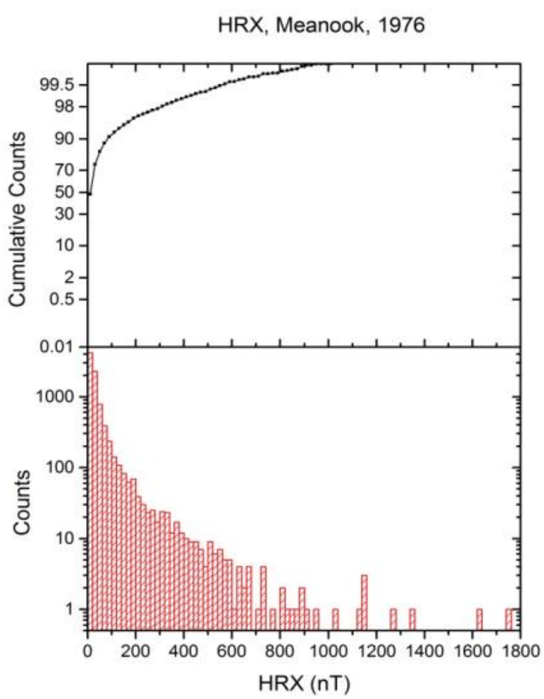


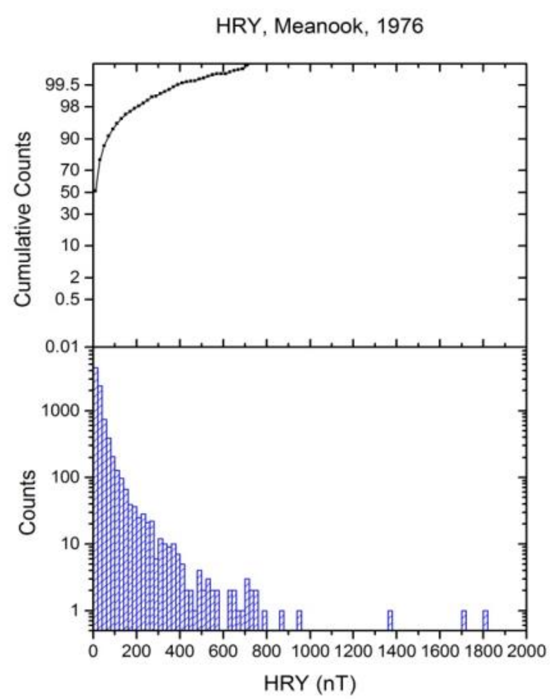
HRY, Meanook, 1974

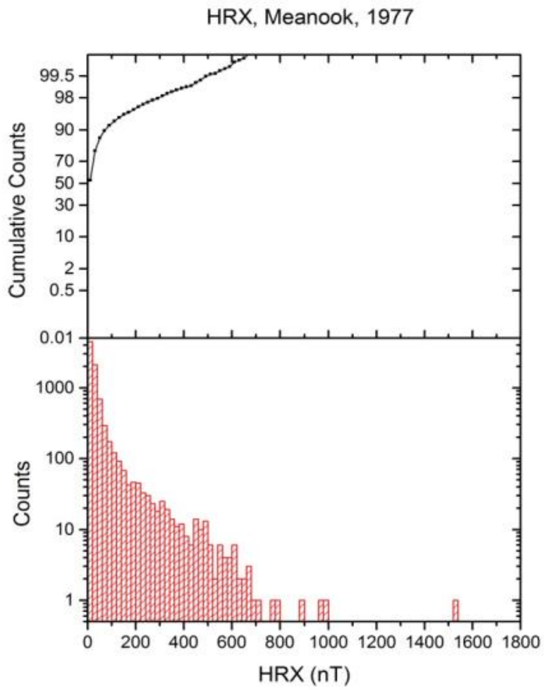


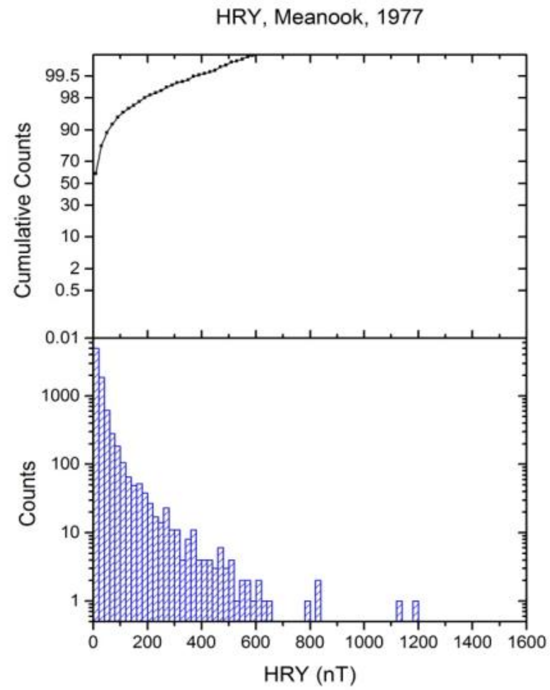

HRX, Meanook, 1975
Cumulative Counts
Counts
HRX (nT)

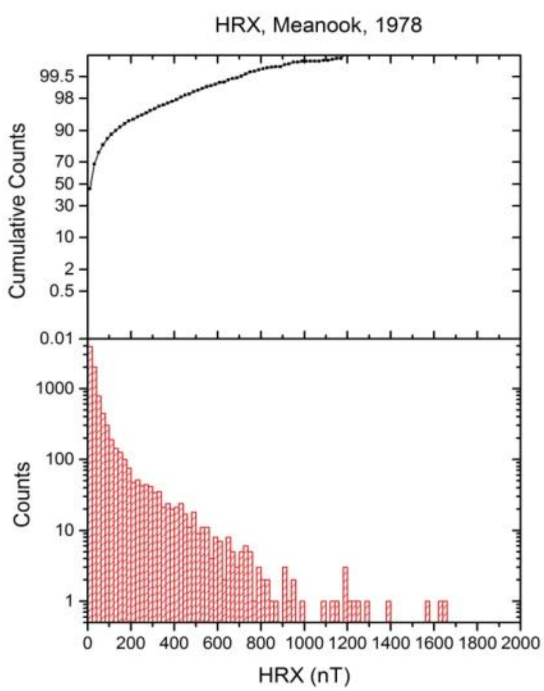

HRY, Meanook, 1975
Cumulative Counts
Counts
HRY (nT)

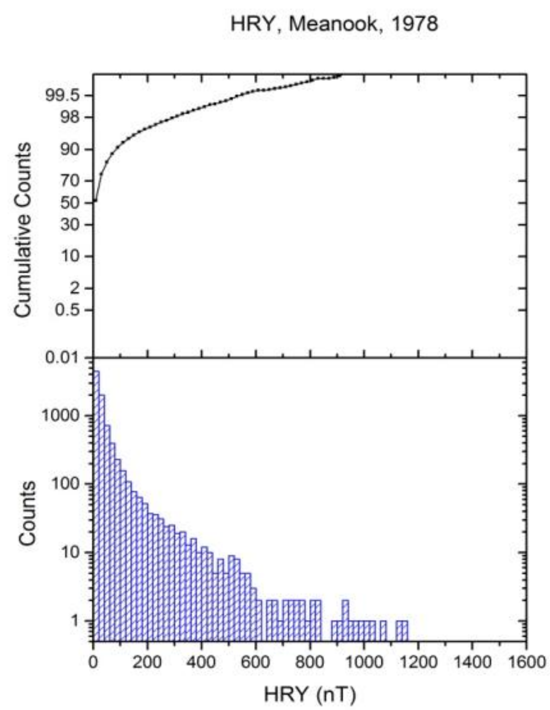

HRX, Meanook, 1976
Cumulative Counts
Counts
HRX (nT)


HRY, Meanook, 1976
Cumulative Counts
Counts
HRY (nT)


HRX, Meanook, 1977
Cumulative Counts
99.5
98
90
70
50
30
10
2
0.5
0.01
Counts
1000
100
10
1
0 200 400 600 800 1000 1200 1400 1600 1800
HRX (nT)


HRY, Meanook, 1977
Cumulative Counts
99.5
98
90
70
50
30
10
2
0.5
0.01
Counts
1000
100
10
1
0 200 400 600 800 1000 1200 1400 1600
HRY (nT)


HRX, Meanook, 1978
Cumulative Counts
99.5
98
90
70
50
30
10
2
0.5
0.01
Counts
1000
100
10
1
0 200 400 600 800 1000 1200 1400 1600 1800 2000
HRX (nT)


HRY, Meanook, 1978
Cumulative Counts
99.5
98
90
70
50
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2
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0.01
Counts
1000
100
10
1
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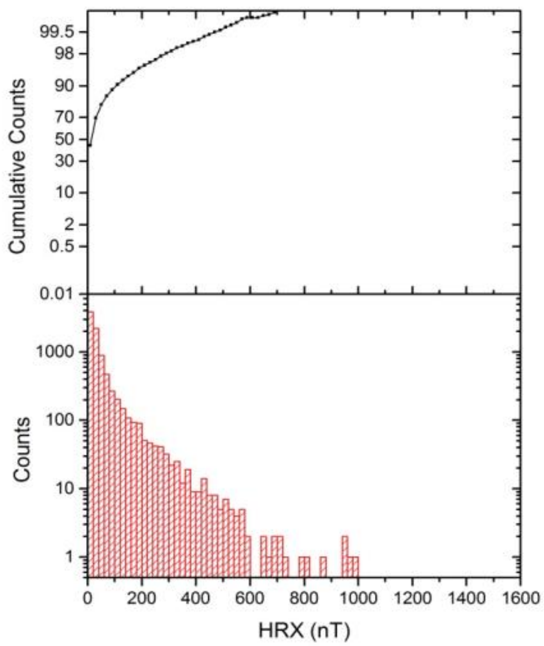
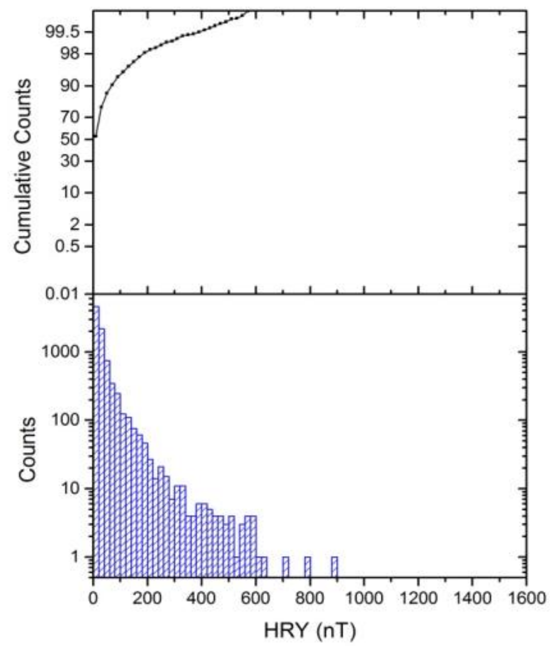
HRY (nT)

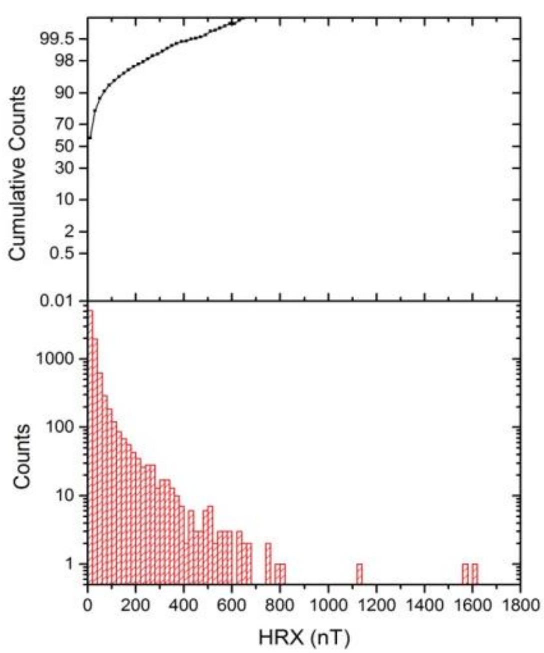
HRX, Meanook, 1979



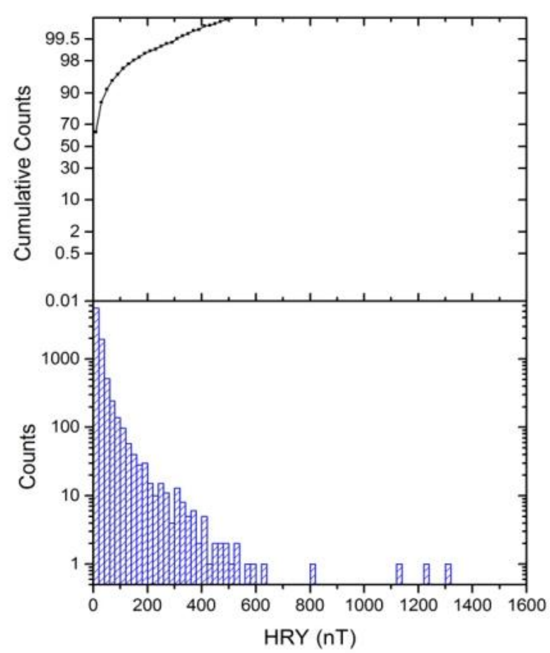
HRY, Meanook, 1979



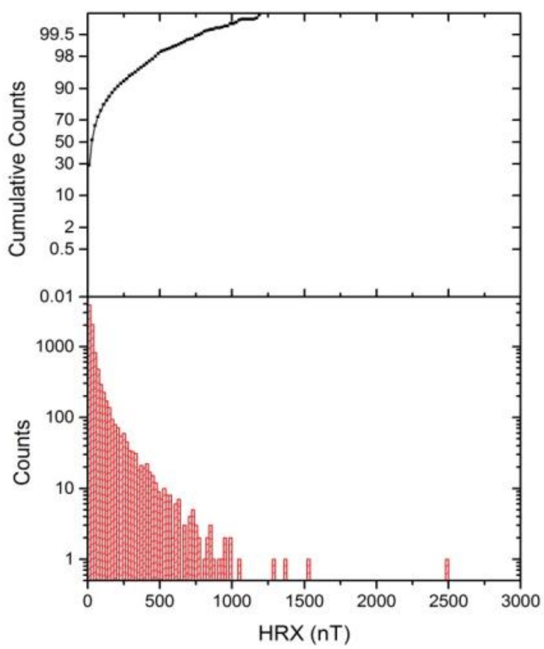
HRX, Meanook, 1980



HRY, Meanook, 1980



HRX, Meanook, 1981



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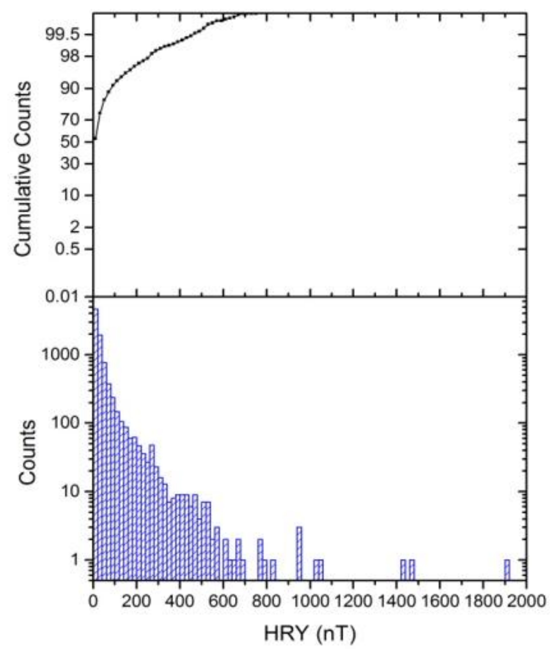
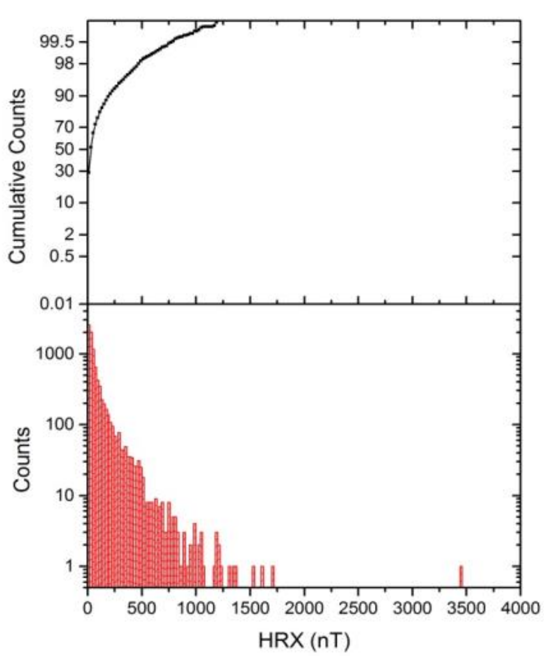
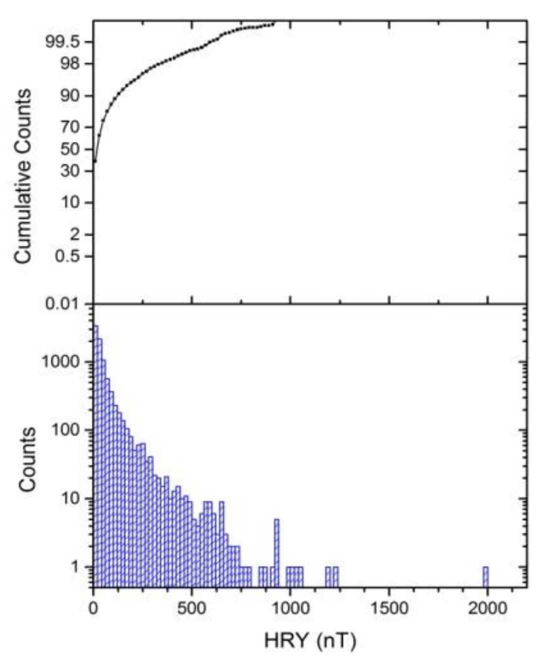


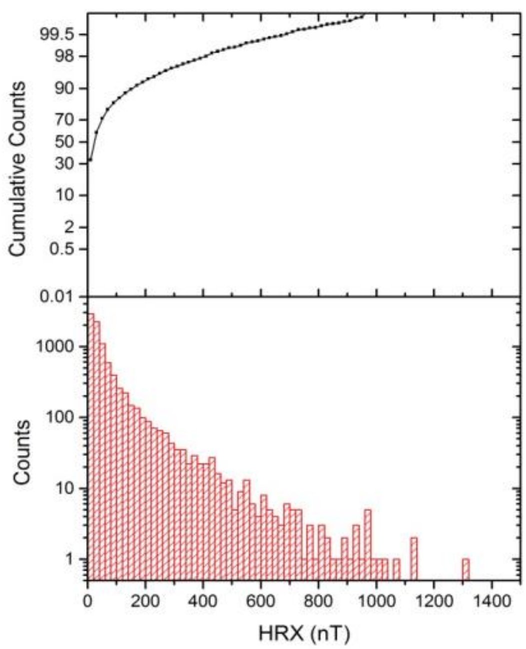
HRX, Meanook, 1982



HRY, Meanook, 1982



HRX, Meanook, 1983



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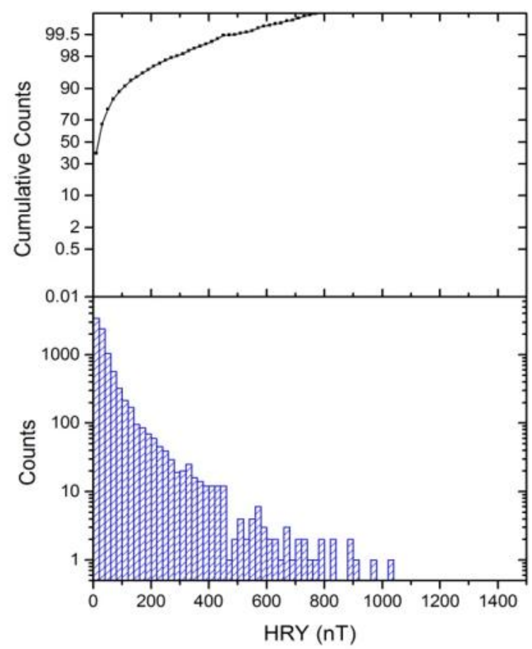

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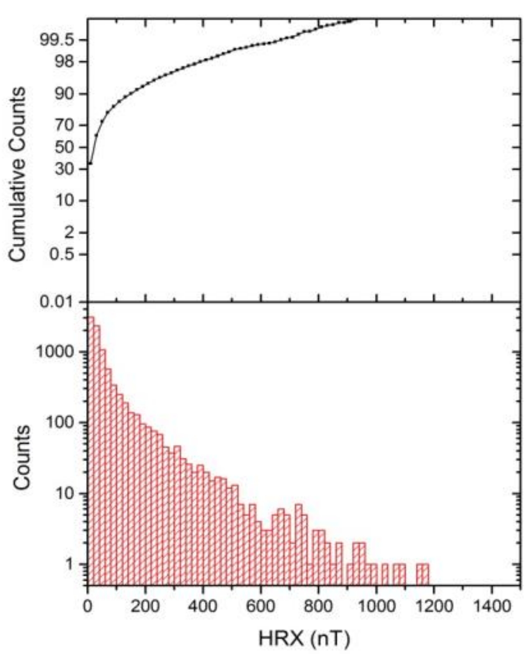

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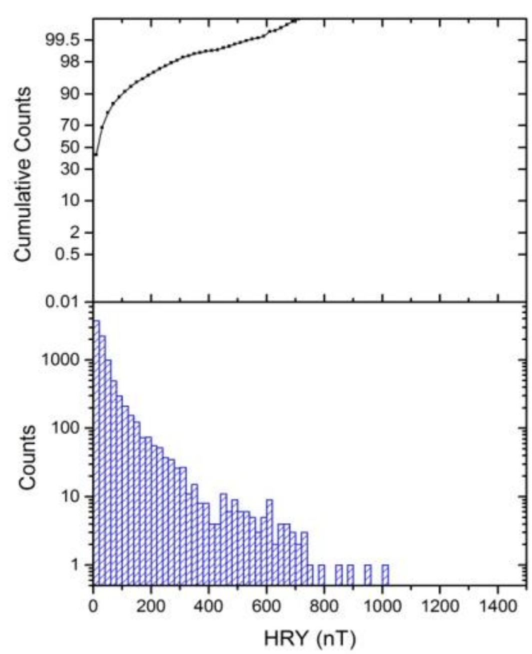
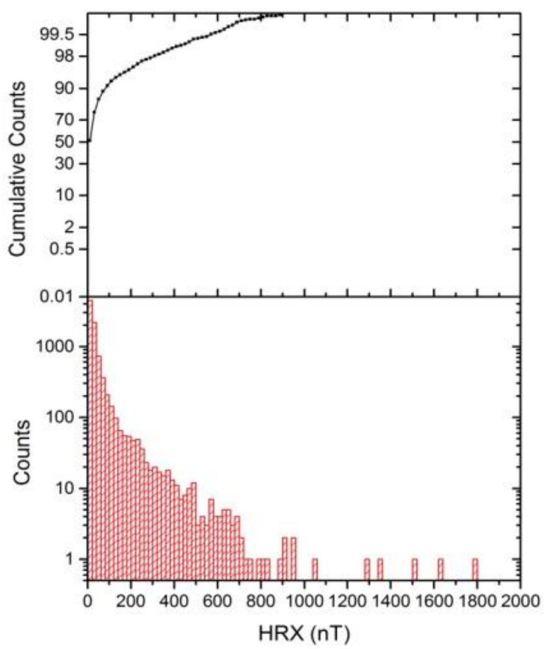


HRX, Meanook, 1985



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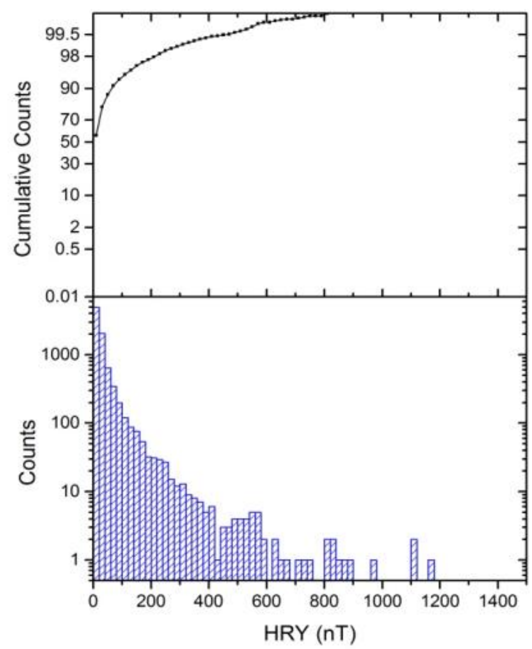
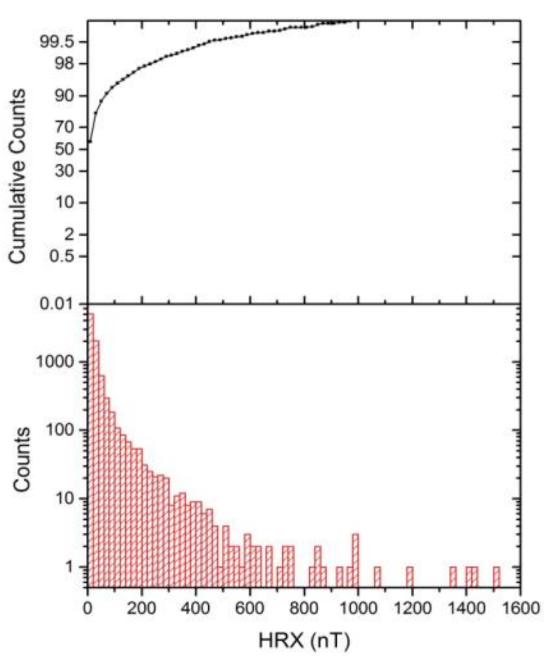


HRX, Meanook, 1986



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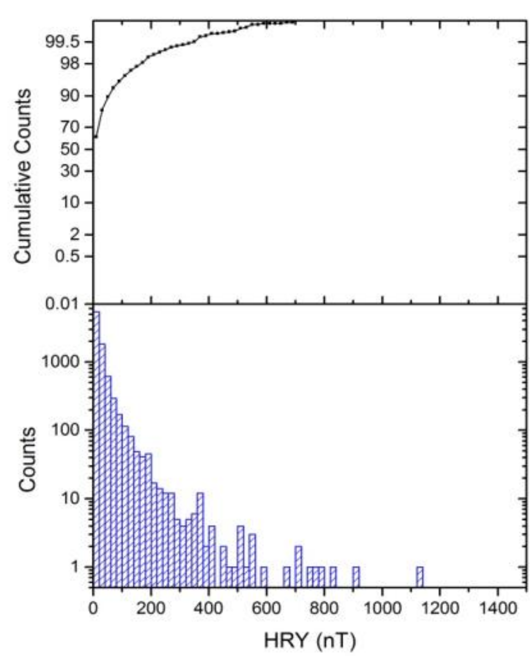

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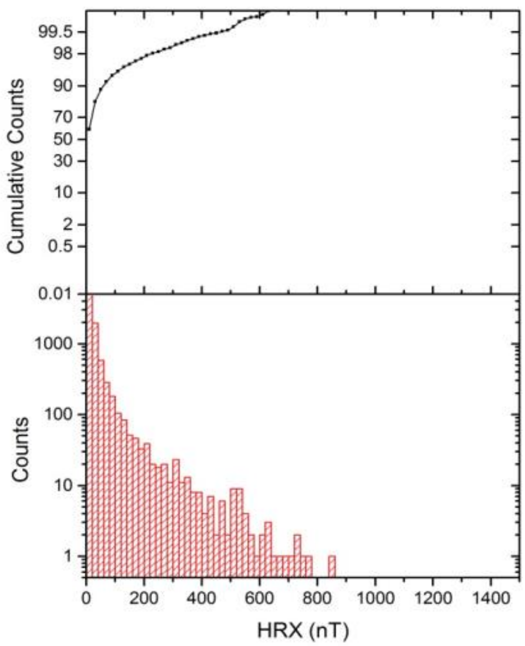

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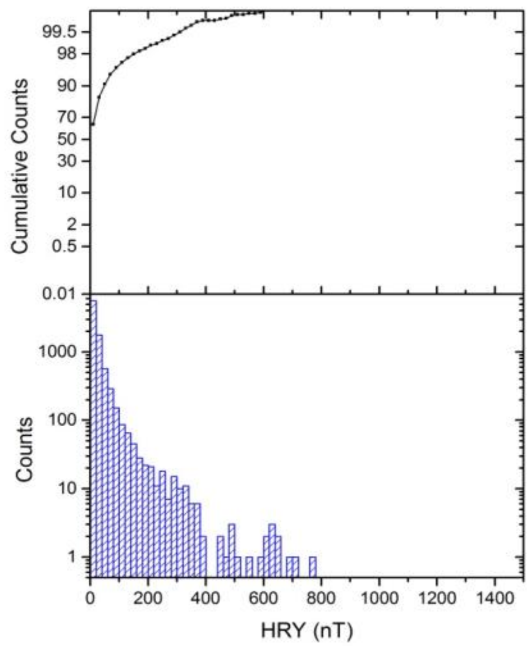
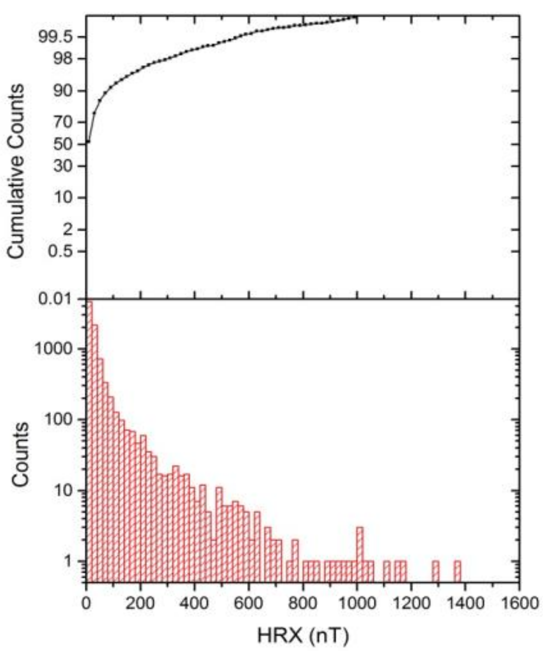


HRX, Meanook, 1988



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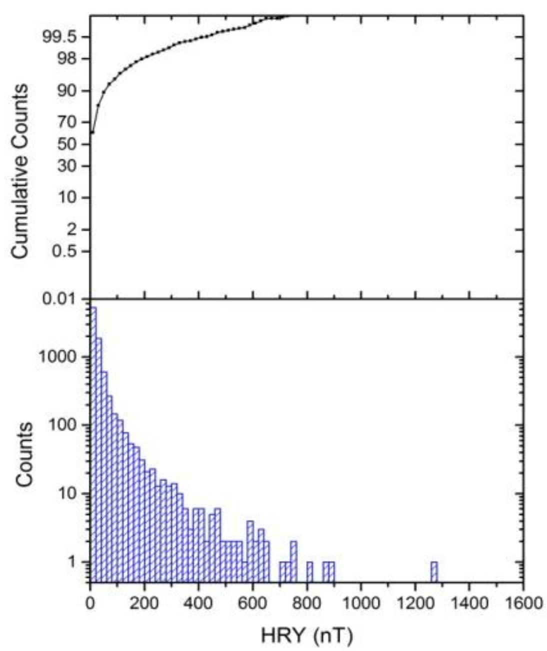
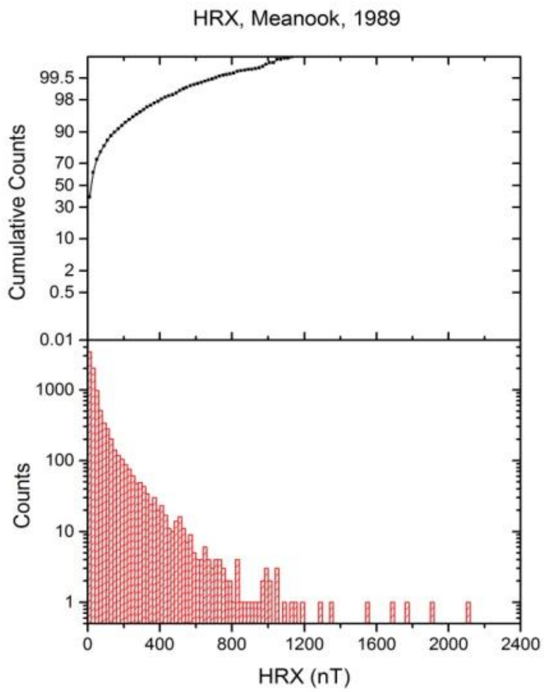
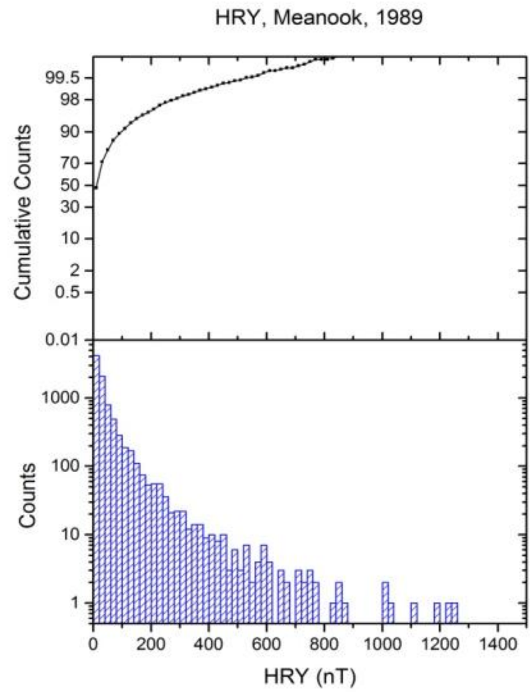



HRX, Meanook, 1989
Cumulative Counts
Counts
HRX (nT)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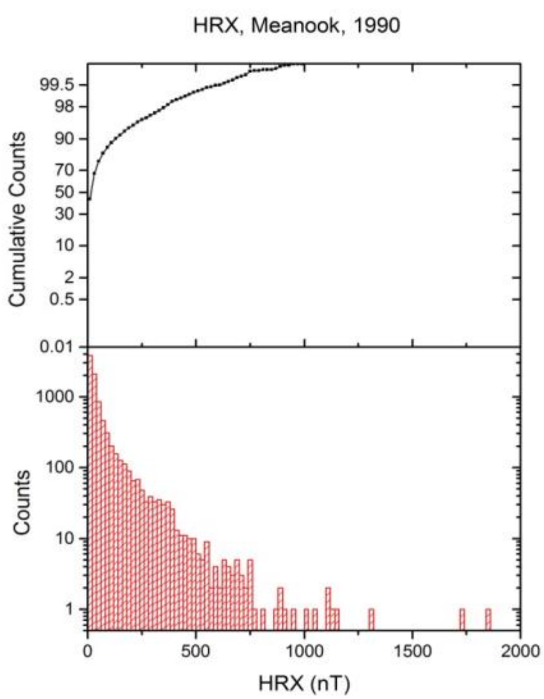
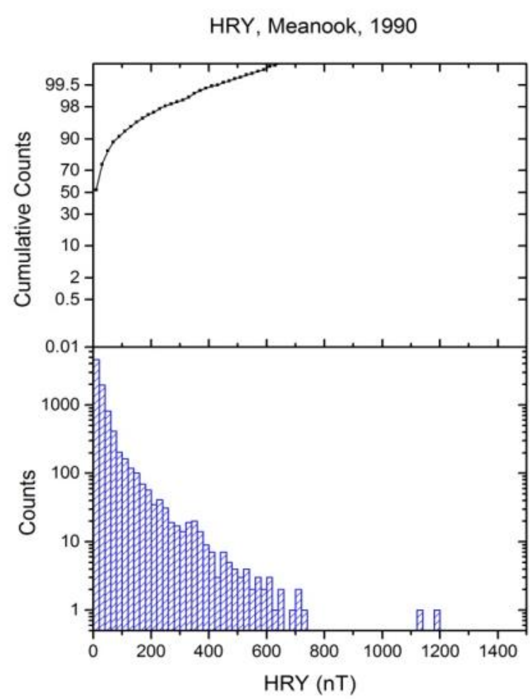
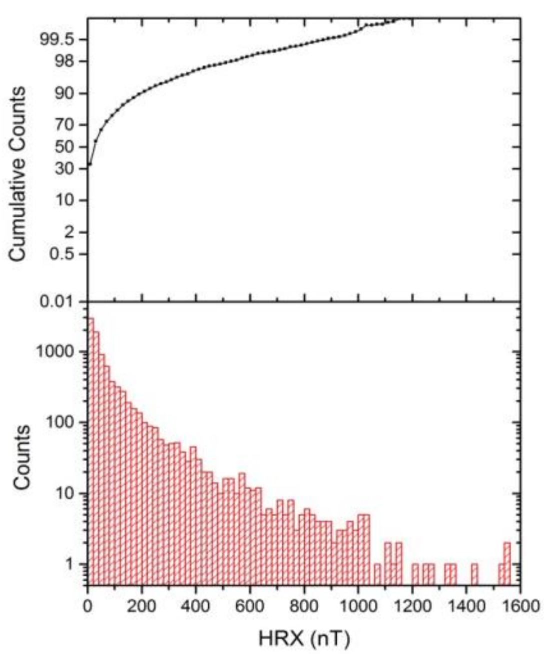
Cumulative Counts
Counts
HRY (nT)

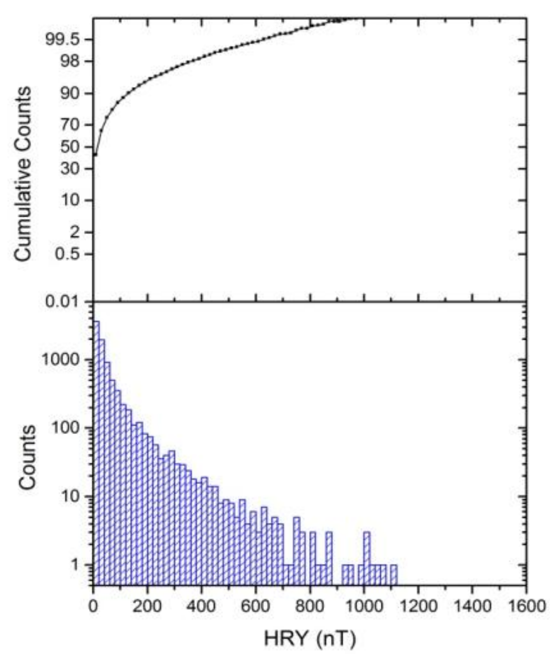

HRX, Meanook, 1990
Cumulative Counts
Counts
HRX (nT)


HRY, Meanook, 1990
Cumulative Counts
Counts
HRY (nT)

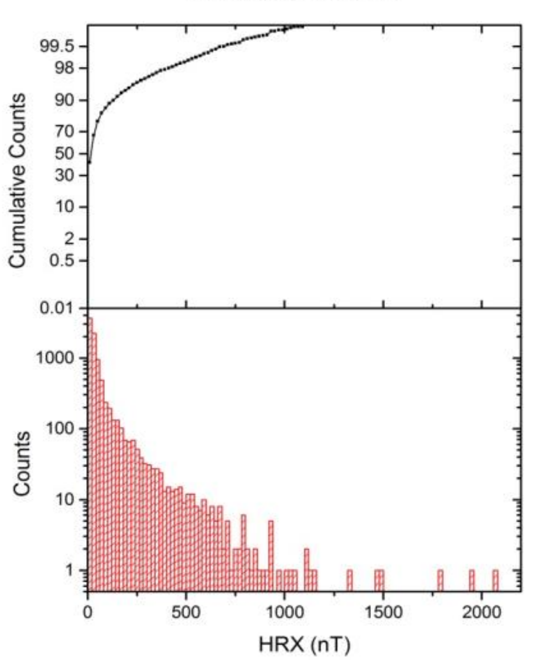
HRX, Meanook, 1991



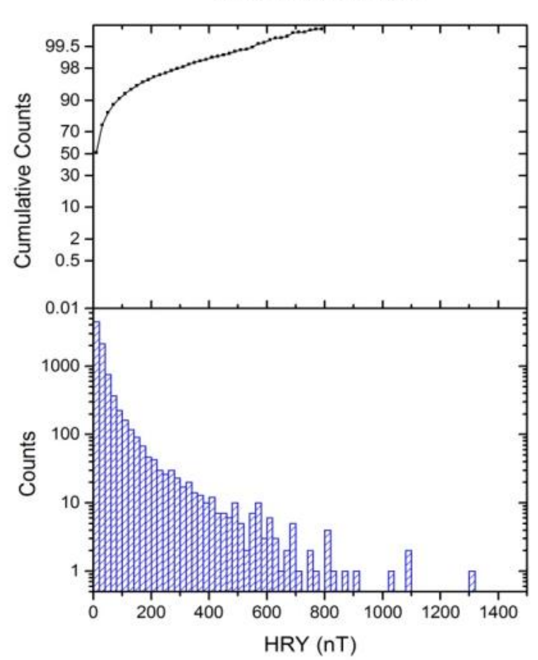
HRY, Meanook, 1991



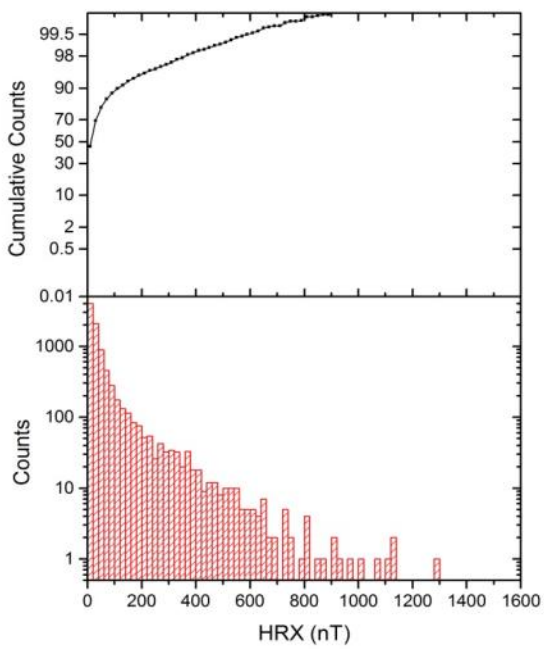
HRX, Meanook, 1992



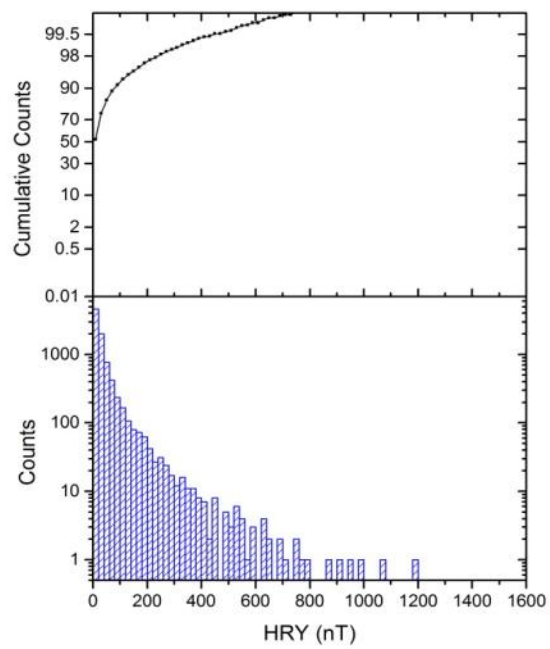
HRY, Meanook, 1992



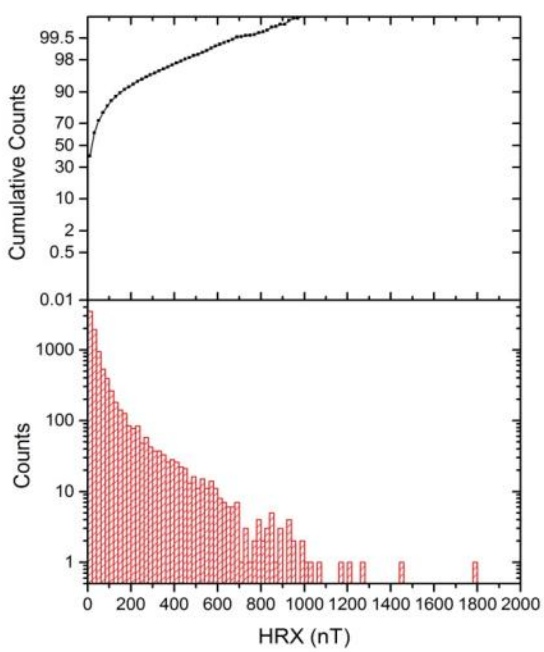
HRX, Meanook, 1993



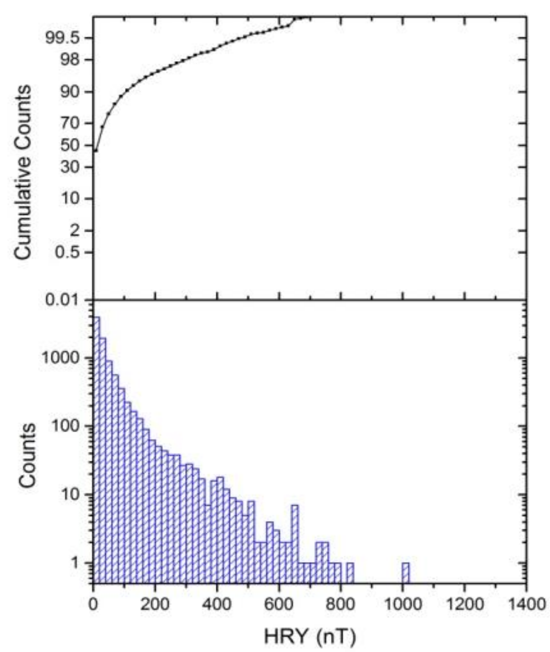
HRY, Meanook, 1993



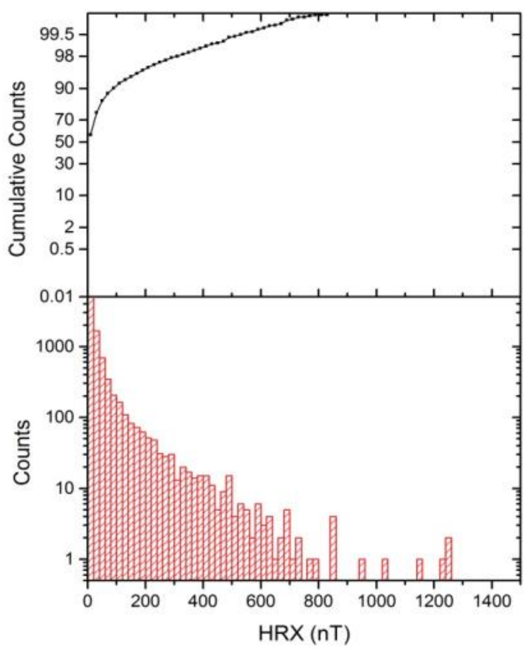
HRX, Meanook, 1994



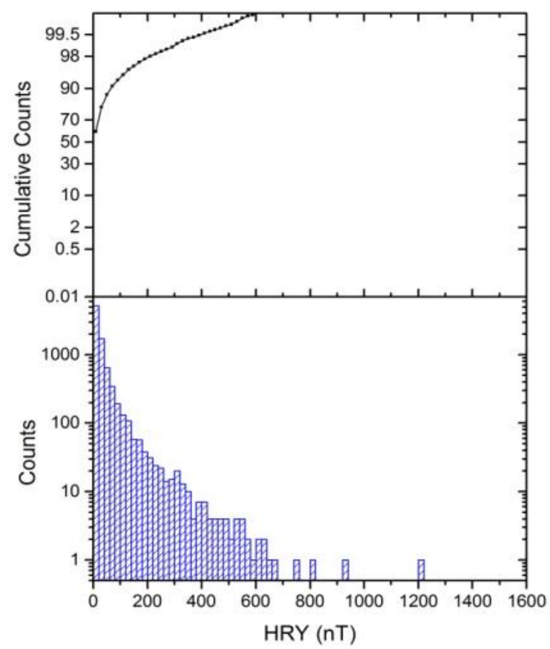
HRY, Meanook, 1994



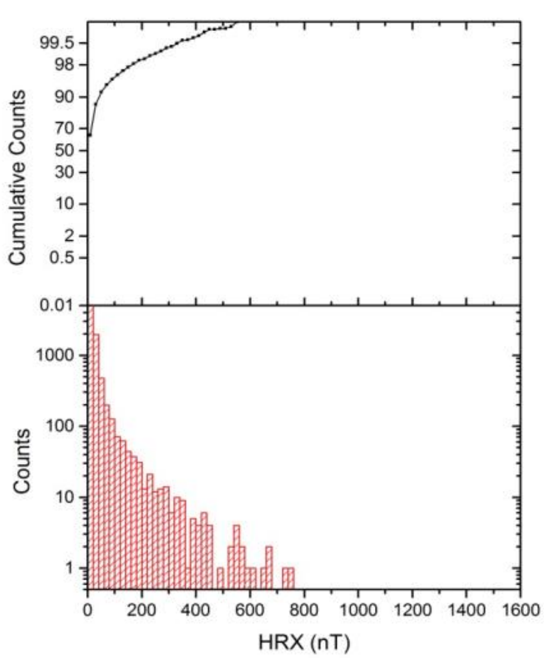
HRX, Meanook, 1995



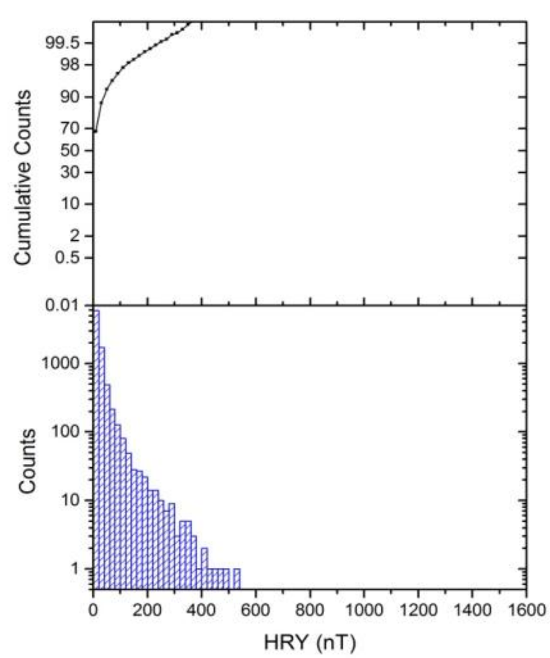
HRY, Meanook, 1995



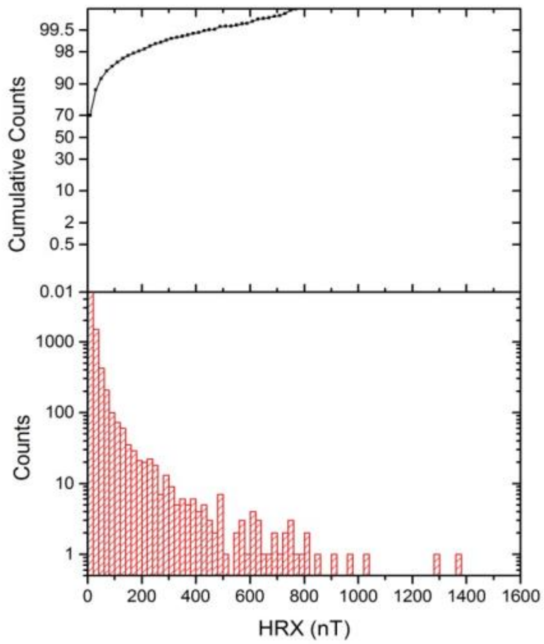
HRX, Meanook, 1996



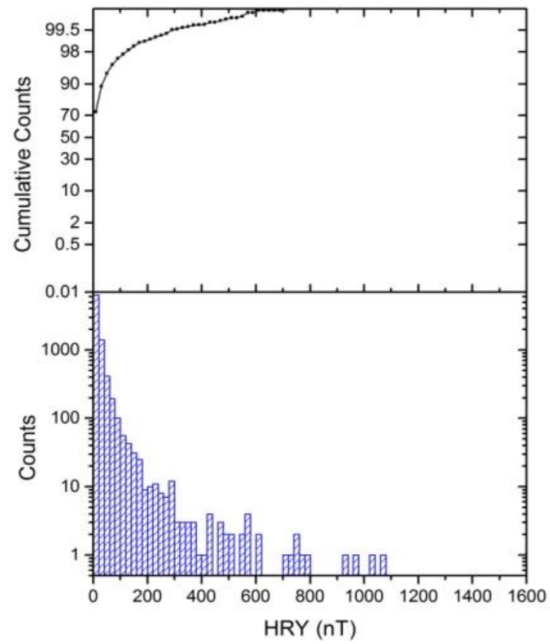
HRY, Meanook, 1996



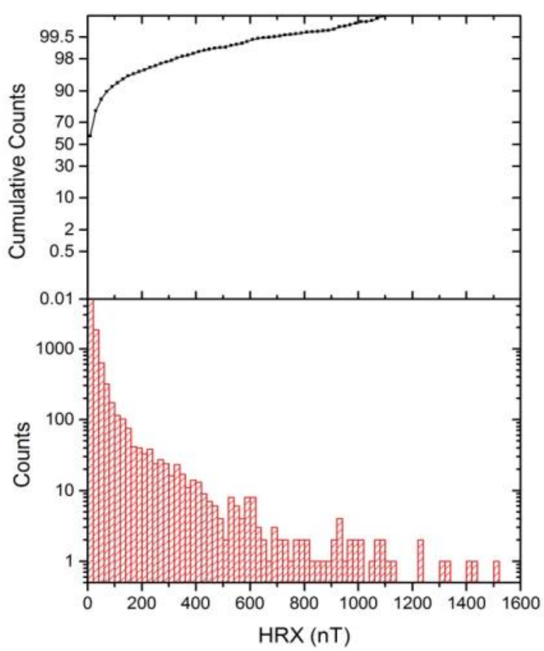
HRX, Meanook, 1997



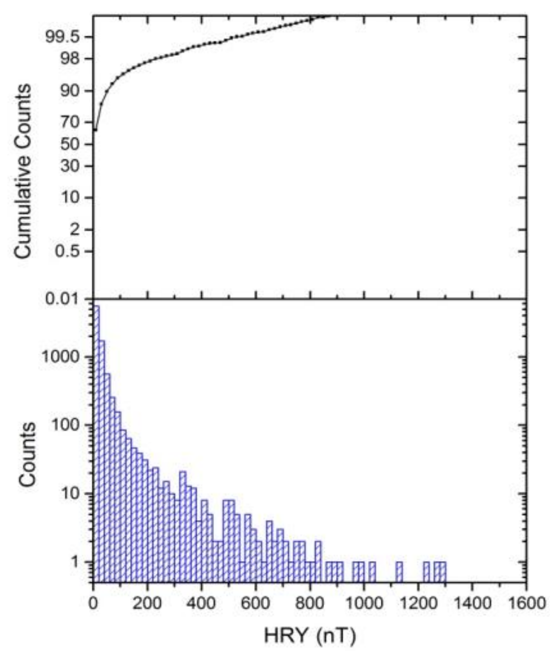
HRY, Meanook, 1997



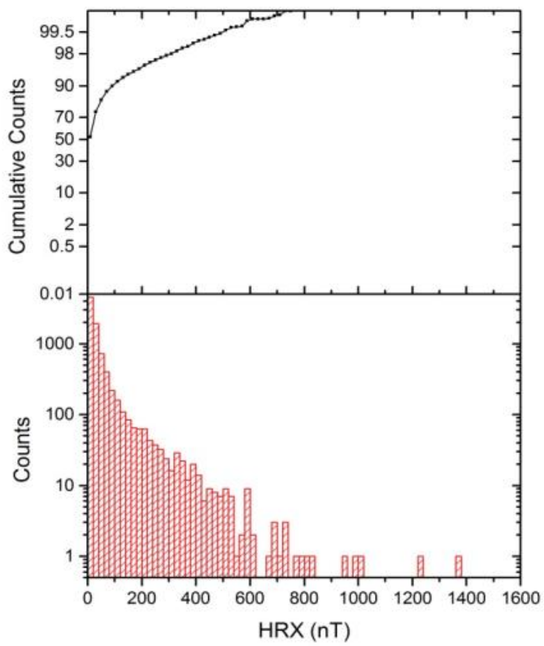
HRX, Meanook, 1998



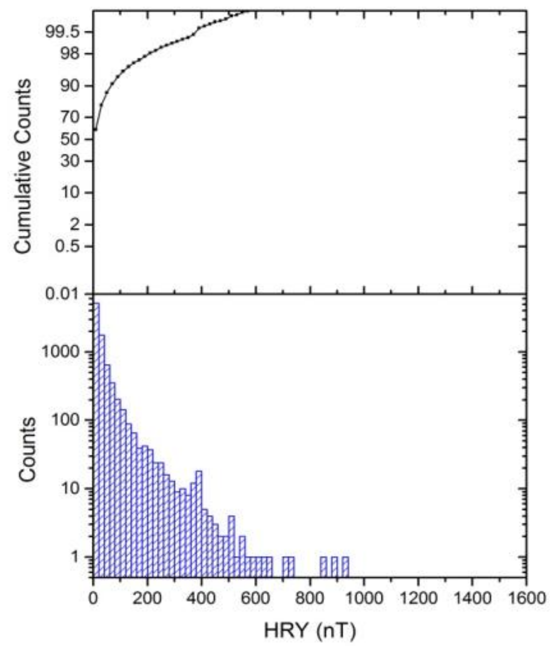
HRY, Meanook, 1998



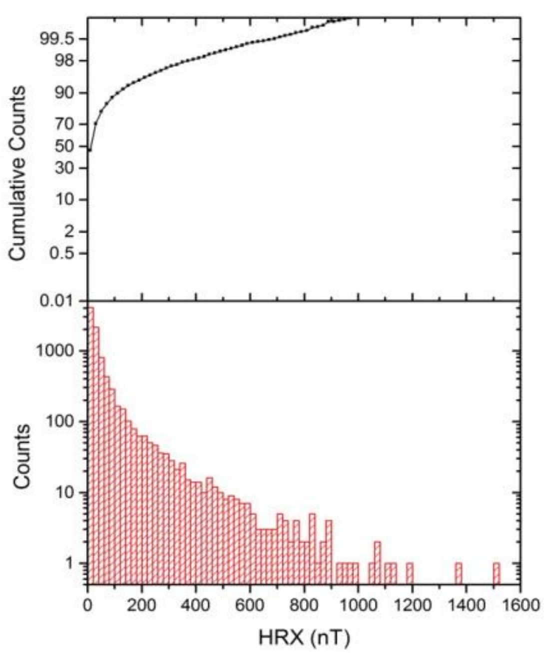
HRX, Meanook, 1999



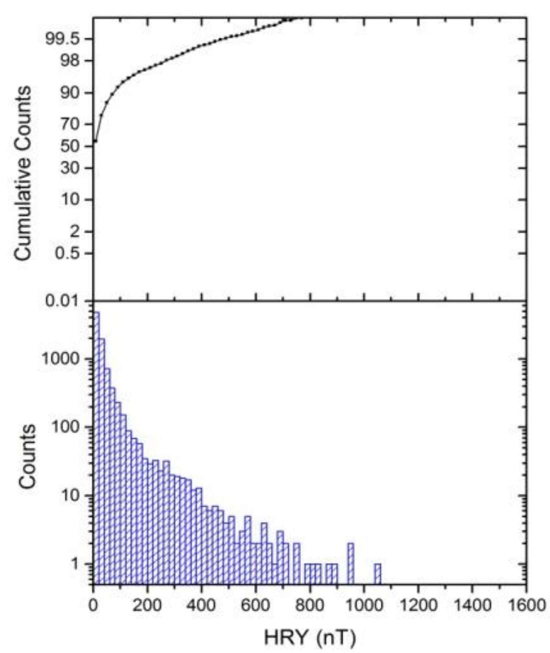
HRY, Meanook, 1999

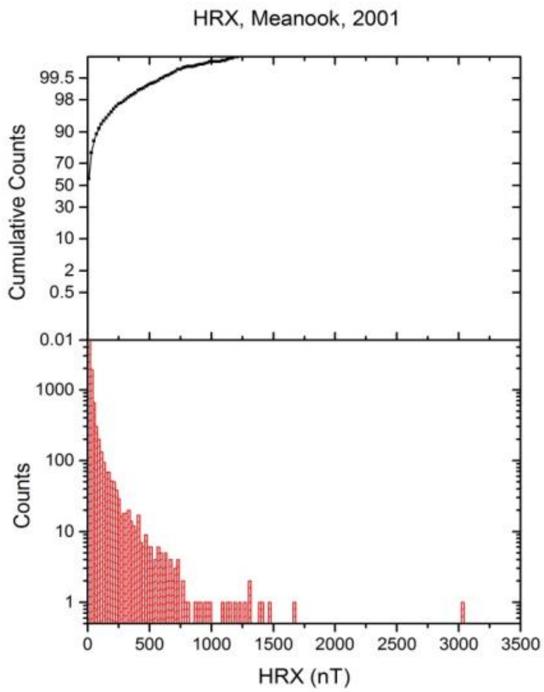


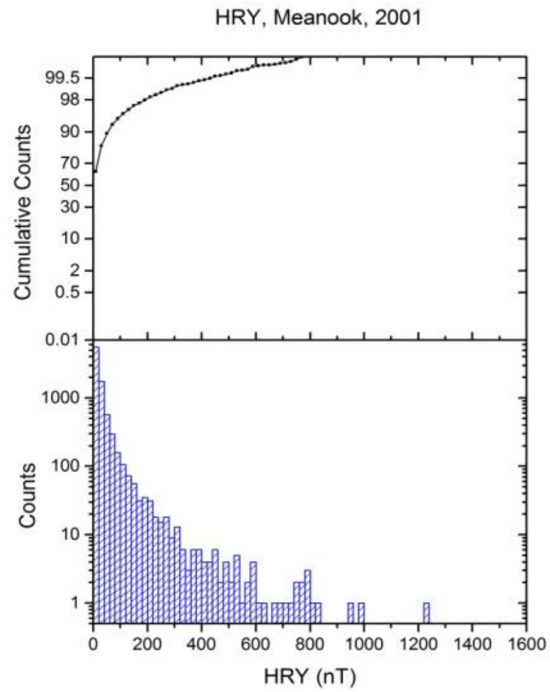
HRX, Meanook, 2000

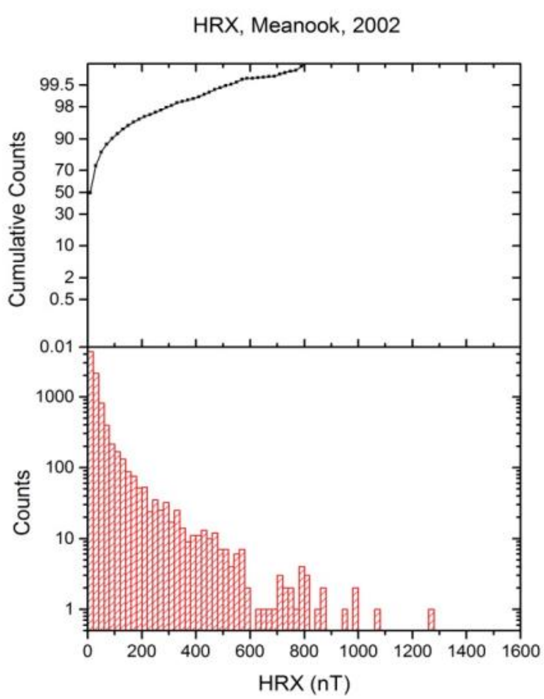


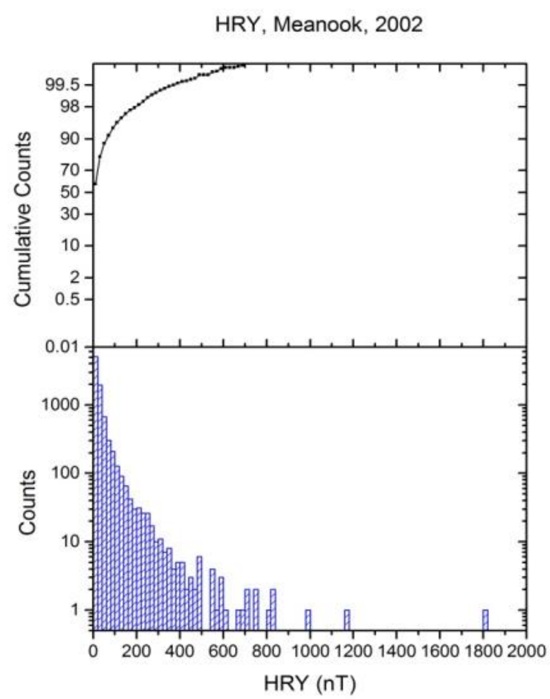
HRY, Meanook, 2000

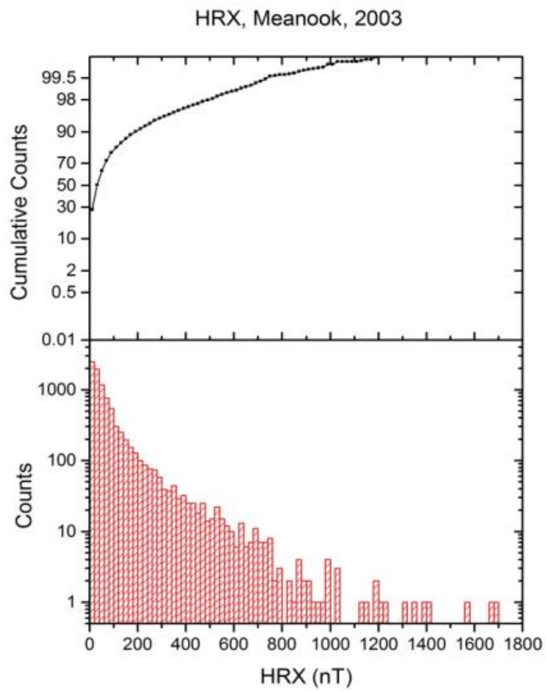


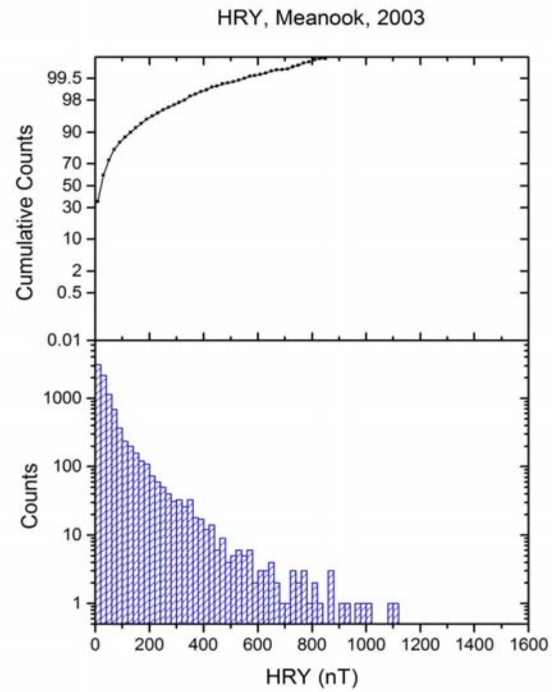

HRX, Meanook, 2001
Cumulative Counts
Counts
HRX (nT)

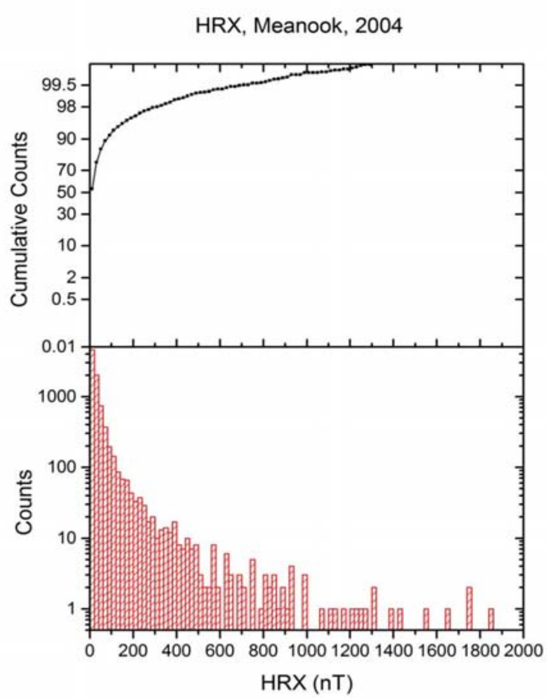

HRY, Meanook, 2001
Cumulative Counts
Counts
HRY (nT)

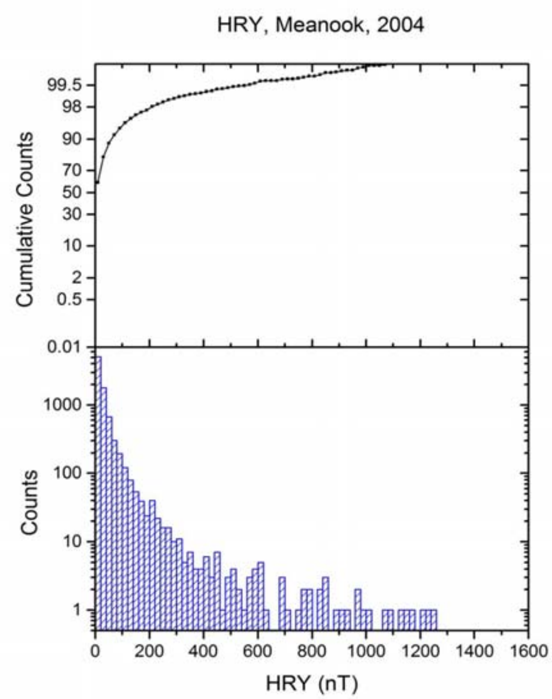

HRX, Meanook, 2002
Cumulative Counts
Counts
HRX (nT)

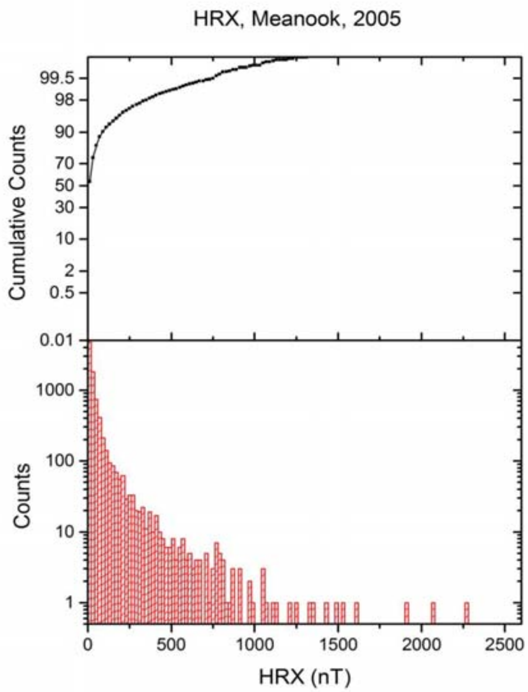

HRY, Meanook, 2002
Cumulative Counts
Counts
HRY (nT)

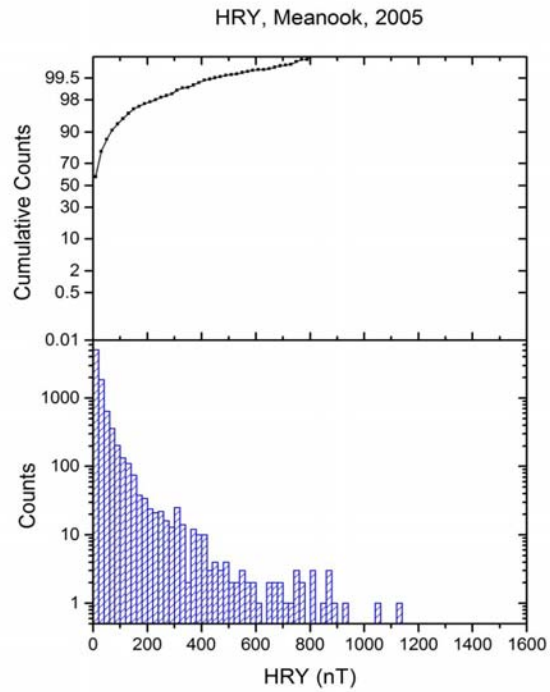

HRX, Meanook, 2003
Cumulative Counts
Counts
HRX (nT)


HRY, Meanook, 2003
Cumulative Counts
Counts
HRY (nT)


HRX, Meanook, 2004
Cumulative Counts
Counts
HRX (nT)


HRY, Meanook, 2004
Cumulative Counts
Counts
HRY (nT)


HRX, Meanook, 2005
Cumulative Counts
99.5
98
90
70
50
30
10
2
0.5
0.01
Counts
1000
100
10
1
0
500
1000
1500
2000
2500
HRX (nT)


HRY, Meanook, 2005
Cumulative Counts
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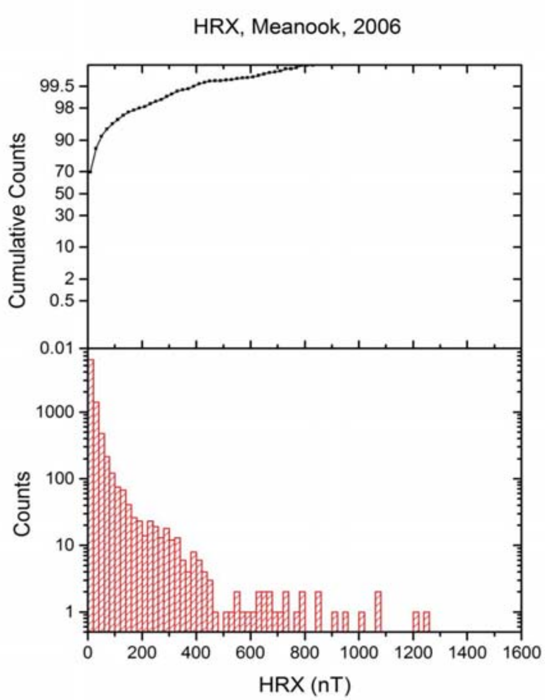
90
70
50
30
10
2
0.5
0.01
Counts
1000
100
10
1
0
200
400
600
800
1000
1200
1400
1600
HRY (nT)


HRX, Meanook, 2006
Cumulative Counts
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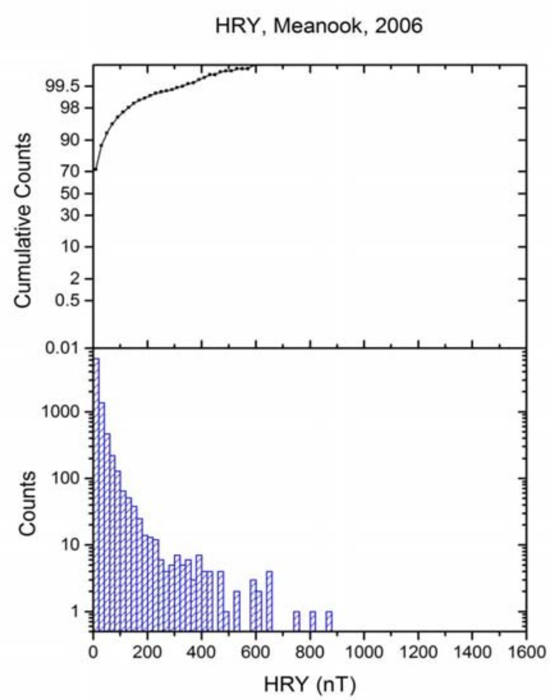
70
50
30
10
2
0.5
0.01
Counts
1000
100
10
1
0
200
400
600
800
1000
1200
1400
1600
HRX (nT)


HRY, Meanook, 2006
Cumulative Counts
99.5
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70
50
30
10
2
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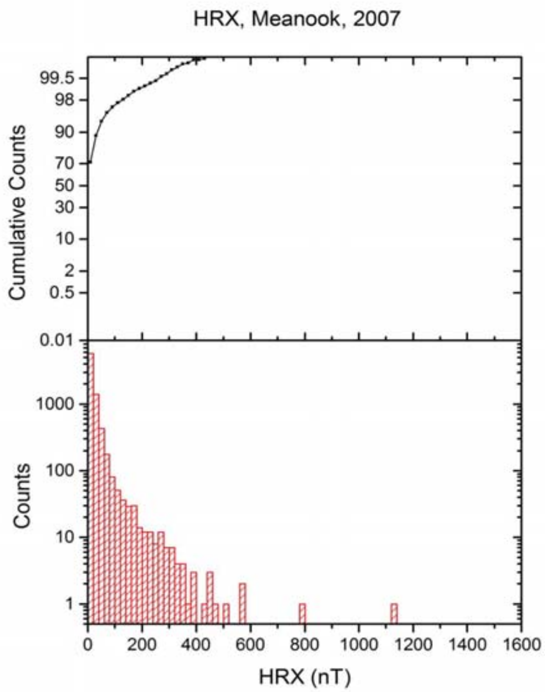
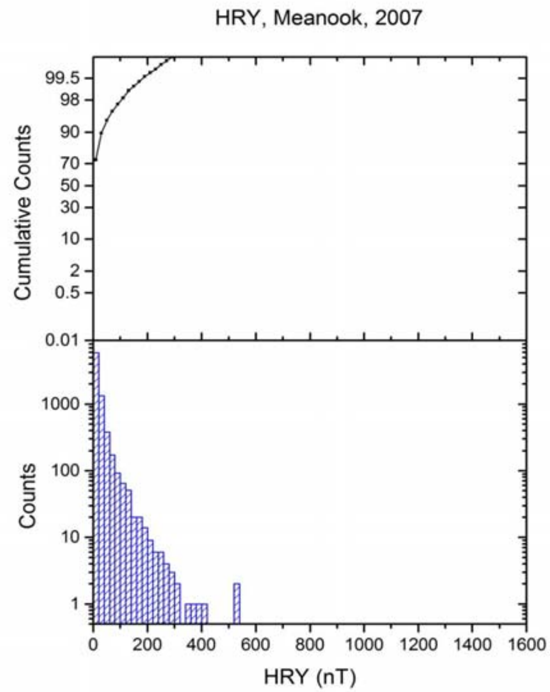
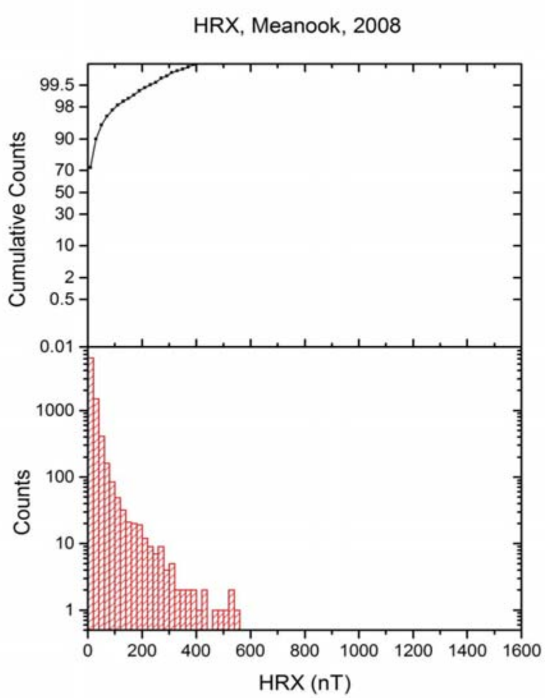
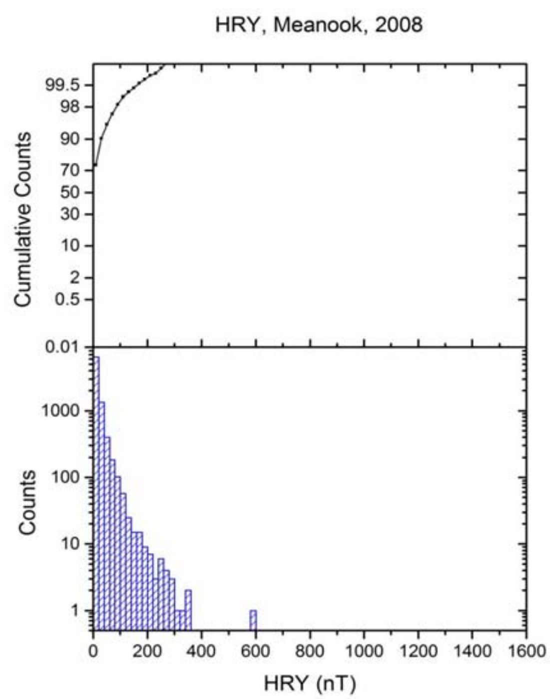
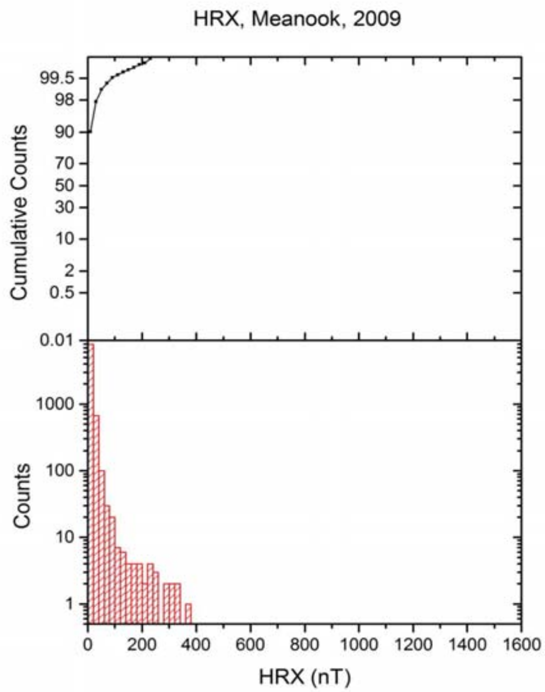
0.01
Counts
1000
100
10
1
0
200
400
600
800
1000
1200
1400
1600
HRY (nT)


HRX, Meanook, 2007
Cumulative Counts
Counts
HRX (nT)


HRY, Meanook, 2007
Cumulative Counts
Counts
HRY (nT)


HRX, Meanook, 2008
Cumulative Counts
Counts
HRX (nT)


HRY, Meanook, 2008
Cumulative Counts
Counts
HRY (nT)


HRX, Meanook, 2009
Cumulative Counts
99.5
98
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50
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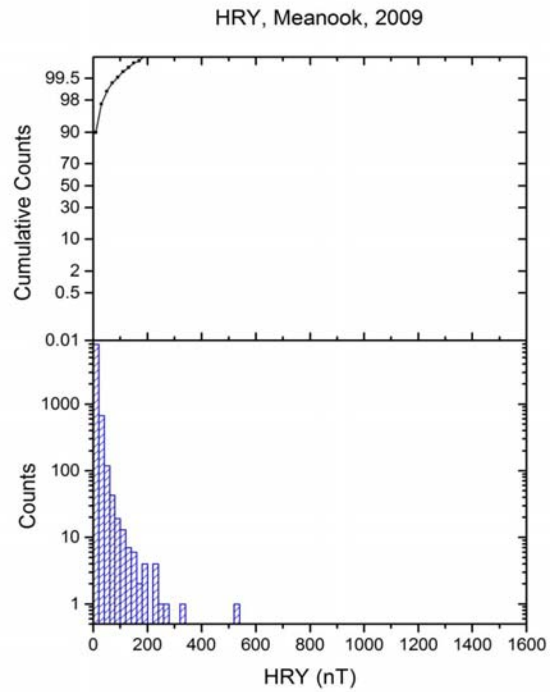
10
2
0.5
0.01
Counts
1000
100
10
1
0 200 400 600 800 1000 1200 1400 1600
HRX (nT)


HRY, Meanook, 2009
Cumulative Counts
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2
0.5
0.01
Counts
1000
100
10
1
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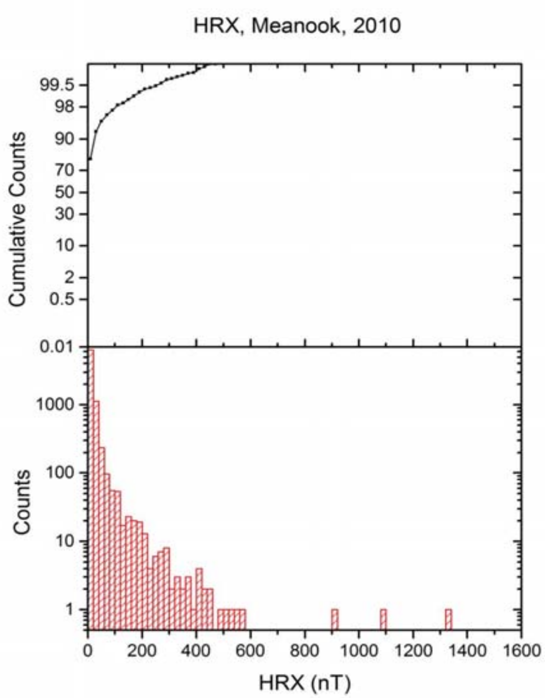
HRY (nT)


HRX, Meanook, 2010
Cumulative Counts
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2
0.5
0.01
Counts
1000
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10
1
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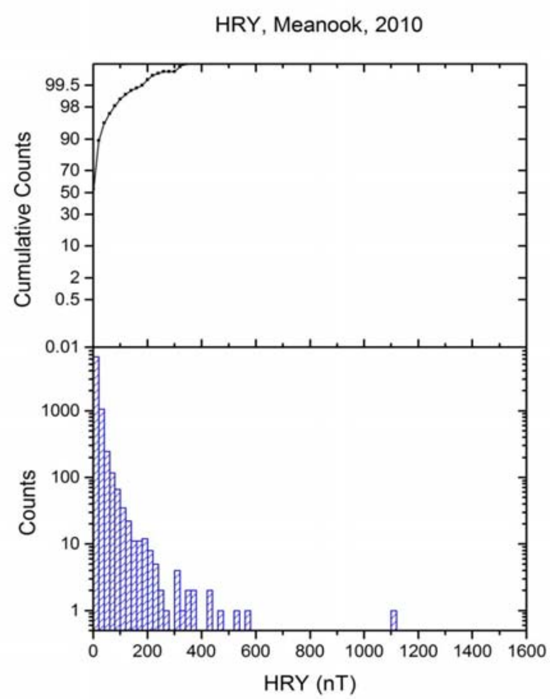
HRX (nT)


HRY, Meanook, 2010
Cumulative Counts
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2
0.5
0.01
Counts
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10
1
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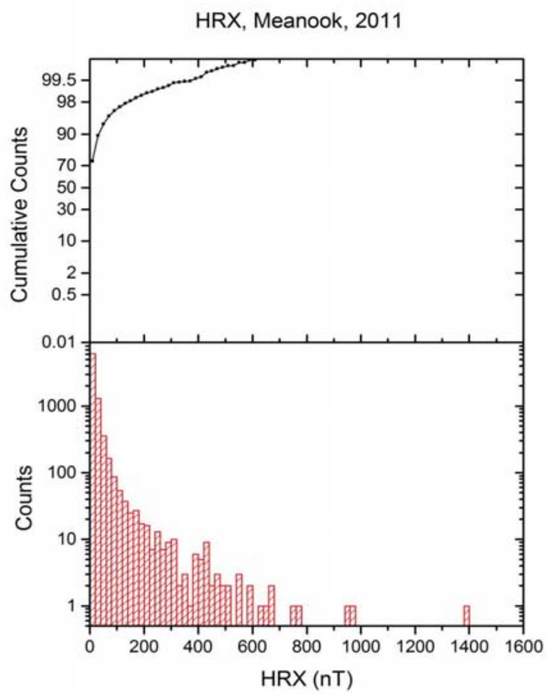
HRY (nT)


HRX, Meanook, 2011
Cumulative Counts
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2
0.5
0.01
Counts
1000
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10
1
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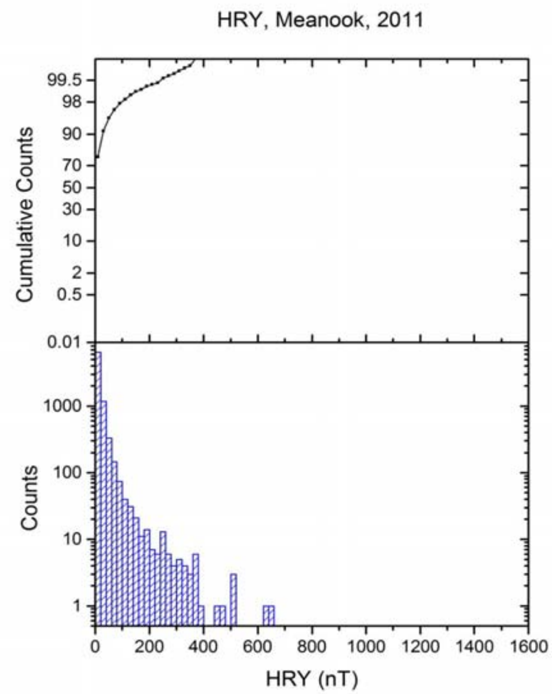
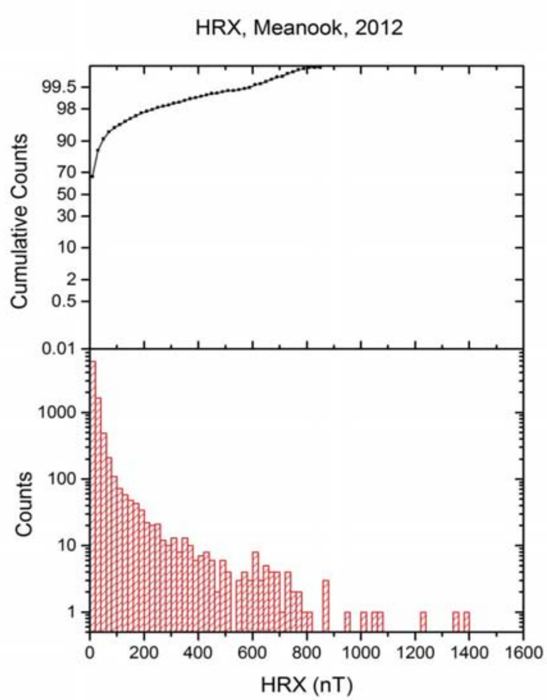
HRX (nT)


HRY, Meanook, 2011
Cumulative Counts
99.5
98
90
70
50
30
10
2
0.5
0.01
Counts
1000
100
10
1
0 200 400 600 800 1000 1200 1400 1600
HRY (nT)


HRX, Meanook, 2012
Cumulative Counts
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2
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0.01
Counts
1000
100
10
1
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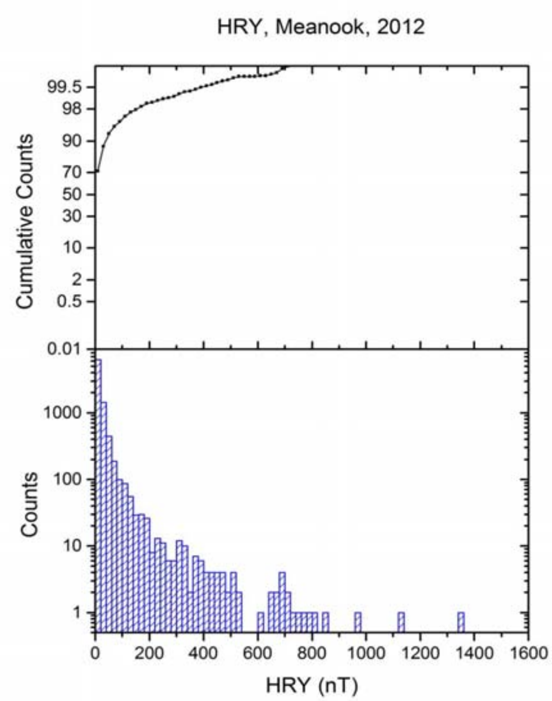
HRX (nT)


HRY, Meanook, 2012
Cumulative Counts
99.5
98
90
70
50
30
10
2
0.5
0.01
Counts
1000
100
10
1
0 200 400 600 800 1000 1200 1400 1600
HRY (nT)

Appendix B

Detailed Description of the Earth Resistivity Models for Alberta

Table A3.1
1D Earth Resistivity Model for Alberta Zone 1 (Medicine Hat Block)

Layer	Depth* [Certainty**]	Thickness	Resistivity (ohm-m) [Certainty**]	Conductivity (S/m) [Certainty**]	Comments
1. Overburden	0 – 75 m [I] [II]	75 m	30 [5, 3, 32, 6, 33] [III]	0.03333 [24]	Till is predominant, mostly as thicker blanket [4]. Large patchy areas of fine-grained (clay, silt) glaciolacustrine deposits and smaller areas with coarse-grained (silt, sand, gravel) glaciolacustrine deposits commonly along / nearby rivers [4]. Overburden typically <50m with areas 50-100 m thick, up to 150 m thick in Medicine Hat area [1]. Assigned midpoint thickness of 75 m. Airborne resistivity survey profiles over central Alberta indicate ~20 ohm.m, plan view maps show 10-20 ohm.m at 20m depth [5]. Borehole logs of Manitoba overburden show 40-50 ohm.m for till and 70-200 ohm.m for sand and gravel [3]. Resistivities for tills range 20-100 ohm.m [32]. MT survey in SE Manitoba indicates 5-30 ohm for mix of till, clay, silt and sand [6]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [33] Assigned midpoint of resistivity range 10-50 ohm.m for tills.

Table A3.1 (continued)
1D Earth Resistivity Model for Alberta Zone 1 (Medicine Hat Block)

Layer	Depth* Certainty**	Thickness	Resistivity (ohm-m) Certainty**	Conductivity (S/m) Certainty**	Comments
2. Sedimentary Basin	< 3 km [7] [II]	2.2 km	30 [12b] [I]	0.03333 [24]	*WCSB*: Upper strata consist of Mesozoic sandstone, siltstone and shale. Lower strata consist of Paleozoic carbonate and subordinate shale [11] WCSB of Interior Platform mainly ranges 2000-2400m thick, increasing to 3000m at western end of MHB alongside the Rocky Mountain foothills, shallows to 2000 m at Cdn/USA border [7] Assign prevailing average thickness MT 3D inversion model indicates 5-10 ohm.m range over entire thickness of WCSB [12a] 0.6-0.8 km depth resistivity map [12b] shows range 3-25 ohm.m. Chose 15 ohm.m weighted average ((3 x 0.5)+(25 x 0.5)) 1.8-2.1 km depth resistivity map [12b] shows range 10-100 ohm.m. Selected approx. 40 ohm.m weighted average based on area occupied by dominant value ((10 x 0.20)+(50 x 0.80)) Assign 30 ohm.m, midpoint value of weighted averages (15, 40 ohm.m)
3. Upper Crust	2.2 - 15 km [14, 15] [I , II]	13 km	385 [12c, d] [I]	0.00259 [24]	*Medicine Hat Block*: plutonic (granitic) and gneissic rock [12h] Lower depth scaled from trans-continental seismic transect compilation (11-12 km) across southern Alberta [13] and seismic profiles; 20 km [15], 15 km [14] Assign averaged lower depth (11, 20, 15 km) MT 3D inversion profile slices show predominately 400 ohm.m [12c]; profile shows range 100-600 ohm.m, midpoint 350 ohm. [12d] Assign 385 ohm.m, average of values (400, 350 ohm.m). Limits 350, 400 ohm.m

Table A3.1 (continued)
1D Earth Resistivity Model for Alberta Zone 1 (Medicine Hat Block)

Layer	Depth* Certainty**	Thickness	Resistivity (ohm-m) Certainty**	Conductivity (S/m) Certainty**	Comments
4. Middle Crust	15 – 27.5 km [16, 15, 14] [I]	12.5 km	2500 [12b, d] [I]	0.0004 [24]	Thickness scaled from seismic profiles across southern Alberta; 18 km [16], 12.8 km [15], 6.9 km [14] Assign 12.5 km, averaged thickness MT profiles show average of 2000 ohm becoming 3000 ohm.m approaching northern margin of MHB. [12d] 17-20 km depth resistivity map ranges 500-3000 ohm.m predominately at higher end of range [12b] Assigned 2500 ohm.m to reflect slightly more conductive nature than underlying layers [12b]. Limits 500, 3000 ohm.m
5. Lower Crust	27.5 – 45 km [18a] [I]	17.5 km	2250 [12d] [I]	0.00044 [24]	Lower depth, to Moho, averaged from seismic depth determinations and scaled off seismic profiles Moho depth contour map shows typical range 43-49, thickening westward to Cordillera mountains at BC/Alberta boundary, thins to 37 km beneath Medicine Hat city; Moho ranges 47-50 km on seismic profile [19c]; range 47-60 km, average 54 km, on seismic profile [15] Assign 45 km determined from seismic picks [18a] MT profiles show an upper range >3000 ohm.m [12c]; range 1000-4000 ohm.m, becoming more resistive approaching northern margin of MHB [12d] 20.6 km depth resistivity map shows dominantly >3000 ohm.m [12b] Assign 2500 ohm.m midpoint of range. Limits 1000, 4000 ohm.m

Table A3.1 (continued)

1D Earth Resistivity Model for Alberta Zone 1 (Medicine Hat Block)

Layer	Depth Certainty**	Thickness	Resistivity (ohm-m) Certainty**	Conductivity (S/m) Certainty**	Comments
6. Upper Mantle	45 - 100 km [23] [III]	55 km	2250 [12d] [I]	0.00044 [24]	Used generalized lower depth [23]. MT profiles show: * range 500 >3000 ohm.m with decreasing resistivity going SW direction [12d]. Chose >2000 to reflect more dominant higher resistivity * range 1000-4000, more resistive approaching northern margin of MHB [12d]. Chose average 2500 ohm.m 48-57 km depth resistivity map shows dominantly >3000 ohm.m [12b] 63-74 km depth resistivity map shows dominantly>3000 ohm.m [12b] Assign 2250 ohm.m average of above selected values (2000, 2500 ohm.m). Limits 500, 4000 ohm.m
7. Upper Mantle	100 - 250 km [23] [III]	150 km	100-130km 1550 [12c] [I] 130-250km 275 [12c] [I]	100-200km 0.00064 [24] 200-250km 0.00363 [24]	Used generalized lower depth [23]. MT profiles [12c] show distinct resistivity change at 130 km depth MT 3D [12c] profiles show: * 100-130 km depth, range 500-3000 ohm.m. Chose midpoint 1700 ohm.m * 130-250 km depth, range 200-400 ohm.m, dominantly 300 ohm.m * Select approx. 600 ohm.m weighted average ((1700 x 0.2)+(300 x 0.8)) based on percentage of depth occupied by dominant resistivity value

Table A3.1 (continued)
1D Earth Resistivity Model for Alberta Zone 1 (Medicine Hat Block)

Layer	Depth Certainty**	Thickness	Resistivity (ohm-m) Certainty**	Conductivity (S/m) Certainty**	Comments
7. Upper Mantle - continued			100-250 km 550 [12c] [I]	100-250 km 0.00181 [24]	MT 2D profiles [12b] show: * 100-130 km depth, range 800-2000 ohm.m. Chose midpoint 1400 ohm.m * 130-250 km depth, range 80-400 ohm.m, dominantly 250 ohm.m * Select 475 ohm.m weighted average ((1400 x 0.2)+(250 x 0.8)) based on percentage of depth occupied by dominant resistivity value Assign: * 100-130 km depth, 1550 ohm.m, average of midpoints (1700, 1400 ohm.m) * 130-250 km depth, 275 ohm.m, average of values (300, 250 ohm.m) * 100-250 km depth, 550 ohm.m, average of weighted averages (600, 475 ohm.m). Limits 250, 1700 ohm.m
8. Upper Mantle	250–410 km [23] [III]	160 km	40 [35b, 12f] [I]	0.025 [24]	Used generalized lower depth [23]. MT 2Dprofiles show 10 ohm.m between 225-300 km depth [35b]; and an averaged resistivity of 75 ohm.m for southern Alberta [12f] Assign 40 ohm.m, average of values (10, 75 ohm.m). Limits 5, 75 ohm.m.
9. Transition Zone	410–520 km [23] [III]	110 km	8 [25]	0.1258 [23] [III]	Utilized Canada regional model [23], based on Ottawa magnetic observatory data, situated, for all depths and resistivities below 410 km For southern Alberta averaged resistivity 50 ohm.m over entire 3D model [12g] ranges 410-500 ohm.m. Hence, an alternative resistivity for layer 9 is 50 ohm.m

Table A3.1 (continued)
1D Earth Resistivity Model for Alberta Zone 1 (Medicine Hat Block)

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Certaunty		Certainty	Certainty	
10. Transition Zone	520–670 km [23]	150 km	2.4 [25]	0.4168 [23]	Assign Canada regional model
	[III]			[III]	
11. Lower Mantle	670–900 km [23]	230 km	0.89 [25]	1.1220 [23]	Assign Canada regional model. Upper limit 15 ohm.m 620-780 km depth resistivity map [12c] shows east half of MHB is 3 ohm.m and west half is 30 ohm.m Hence, alternative resistivity is 15 ohm.m, midpoint of range (3-30) ohm.m) for Layer 11. Upper limits 3 or 30 ohm.m
	[III]			[III]	
12. Lower Mantle	900–1000 km [23]	100 km	0.47 [25]	2.0892 [23]	Assign Canada regional model
	[III]			[III]	

See end of Table 10 for abbreviations and notes

Table A3.2
1D Earth Resistivity Model for Alberta Zone 2 (Vulcan Structure)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
1. Overburden	0 – 50 m [1] [II]	50 m	30 [5, 3, 32, 6, 33] [III]	0.03333 [24]	Till is predominant, mostly as thicker blanket [4]. Large patchy areas of fine-grained (clay, silt) glaciolacustrine deposits and smaller areas with coarse-grained (silt, sand, gravel) glaciolacustrine deposits commonly along / nearby rivers [4] Overburden typically <50m, minor areas 50-100 m, localized 100-150 m thick at west end of zone in vicinity of Ft. McLeod[1] Assigned midpoint thickness of 50 m Airborne resistivity survey profiles over central Alberta indicate ~20 ohm.m, plan view maps show 10-20 ohm.m at 20m depth [5]. Borehole logs of Manitoba overburden show 40-50 ohm.m for till and 70-200 ohm.m for sand and gravel [3]. Resistivities for tills range 20-100 ohm.m [32]. MT survey in SE Manitoba indicates 5-30 ohm for mix of till, clay, silt and sand [6]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [33]. Assigned 30 ohm.m midpoint of resistivity range 10-50 ohm.m for tills

Table A3.2 (continued)

1D Earth Resistivity Model for Alberta Zone 2 (Vulcan Structure)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
2. Sedimentary Basin	0 – 2.4 km [7] [II]	2.4 km	20 [12b,c] [I]	0.05 [24]	*WCSB*: Upper strata consist of Mesozoic sandstone, siltstone and shale. Lower strata consist of Paleozoic carbonate and subordinate shale [11] WCSB of Interior Platform mainly ranges 2200-2400m thick, ranging 2400-4300 in foothills approaching the Cordillera deformation front [7] Assign average 2400m, covering majority of populated area MT 3D inversion model indicates 5-10 ohm.m range over entire thickness of WCSB [12a] 0.6-0.8 km depth resistivity map [12b] shows predominately 3 ohm.m with narrow band of increasing resistivity, from 30 to 3000 ohm.m, where foothills meet Cordillera 1.8-2.1 km depth resistivity map shows range 10-200 ohm.m, predominantly 50 ohm.m, with 10 ohm.m localized along west edge of VS where Cordillera mountains begin [12c] Assign 25 ohm.m, based on average of predominant values (3, 50 ohm.m). Limits 3, 200 ohm.m. Conceivably overall resistivity for entire thickness could be 7 ohm.m, on basis of 5-10 ohm.m range stated by [12a]
3. Upper Crust	2.4 - 24 km [16, 15, 14] [I]	21.6 km	3000 [12c, d] [I]	0.00033 [24]	Lower depth scaled from seismic profiles; maximum 26.5 km [16]; maximum 24 km [15]; 18-22 km [14] Assign 24 km, averaged lower depth maximums (26.5, 24, 22 km) MT 3D inversion profile slices show upper range possibly 3000 ohm.m [12c] MT profile shows range of 500-3000 ohm.m with resistivity increasing with depth [12d] 17-20 km depth resistivity map shows predominance of approx 3000 ohm.m [12b] Assign 3000 ohm.m. Lower limit 500 ohm.m

Table A3.2 (continued)
1D Earth Resistivity Model for Alberta Zone 2 (Vulcan Structure)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
4. Middle Crust	24 – 37 km [15, 14] [I]	13 km	2000 [12c, d] [I]	0.0005 [24]	Thickness scaled from seismic profiles across southern Alberta; 14 km [15], 10.5 km [14], 13 km averaged 33-37 km depth resistivity map shows range 300-3000 ohm.m, with a 300-400 ohm.m band subparallel to northern margin and west flank of VS and 3000 ohm.m along central-south margin and east flank of VS [12c,d] Assigned 2000 ohm.m weighted average based on areal distribution of dominant resistivity value ((3000 x 0.6) + (300 x 0.4)). Limits 300, 3000 ohm.m
5. Lower Crust	37 – 45 km [18a] [I]	8 km	4000 [12b] [I]	0.00025 [24]	Moho depth contour map shows typical range 43-47, thickening westward to Cordillera mountains at BC/Alberta boundary, deepest NW of Medicine Hat city; average 44 km on seismic profile [19c]; 47 km on seismic profile [15] Assign 45 km, average determined from seismic picks [18a] MT profiles show an upper range >3000 ohm.m [12c]; range 3000-5000, more resistive approaching northern margin of MHB [12d] 33-37 km depth resistivity map shows range 300 to >3000 ohm.m. [12b], diminishing resistivity along northern boundary of VS Assign 40000 ohm.m, midpoint of range. Limits 3000, 5000 ohm.m

Table A3.2 (continued)
1D Earth Resistivity Model for Alberta Zone 2 (Vulcan Structure)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
6. Upper Mantle	45 - 100 km [23] [III]	55 km	2000 [12b, d] [I]	0.0005 [24]	Used generalized lower depth [23]. MT profiles show predominately 3000 ohm.m with northern margin having much lower resistivity of 300-400 ohm.m [12d]. Chose 2600 ohm.m weighted average based on areal distribution of dominant / midpoint resistivity values ((3000 x 0.85)+(350 x 0.15}) 48-57 km and 63-74 km depth resistivity maps shows show range 300-3000 ohm.m with low resistivity along north margin and west flank of VS and higher resistivity (3000 ohm,m) along part central-south margin and east flank [12b]. Overall lowering of resistivity. Chose approx. 1400 ohm.m weighted average based on areal distribution ((3000 x 0.40)+(300 x 0.60)) Assign 2000 ohm.m ohm.m, midpoint of weighted averages (2600, 1400 ohm.m). Limits 300, 3000 ohm.m
7. Upper Mantle	100 - 250 km [23] [III]	150 km	100-130km 700 [12c, d] [I] 130-250km 300 [12c, d] [I] 100-250 km 260 [12c, d] [I]	100-200km 0.00142 [24] 200-250km 0.00333 [24] 100-250 km 0.00384 [24]	Used generalized lower depth [23]. MT profiles [12d] show distinct resistivity change at 130 km depth MT 3D averaged profile [12g] shows 225 ohm.m average resistivity MT profiles [12c, d] show: * 100-130 km depth, averaging 700 ohm.m * 130-250 km depth, range 80-300 ohm.m, * chose 300 ohm.m weighted average ((700 x 0.2) + (200 x 0.8)) Assign approx. 260 ohm.m, average of resistivity values (225, 300 ohm.m). Limits 80, 700 ohm.m

Table A3.2 (continued)
1D Earth Resistivity Model for Alberta Zone 2 (Vulcan Structure)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
8. Upper Mantle	250–410 km [23] [III]	160 km	70 [35b, 12g] [I]	0.01428 [24]	Used generalized lower depth [23]. MT profiles shows; range 50-80 ohm.m, chose midpoint 65 ohm.m, between 225-300 km depth [35b], and averaged resistivity of 75 ohm.m for southern Alberta [12g] Assign 70 ohm.m, average of values (65, 75 ohm.m). Limits 50, 80 ohm.m.
9. Transition Zone	410–520 km [23] [III]	110 km	8 [25]	0.1258 [23] [III]	Utilized Canada regional model [23], based on Ottawa magnetic observatory data, for all depths and resistivities below 410 km For southern Alberta averaged resistivity 50 ohm.m over entire 3D model [12g] ranges 410-500 ohm.m. Hence, an alternative resistivity for layer 9 is 50 ohm.m
10. Transition Zone	520–670 km [23] [III]	150 km	2.4 [25]	0.4168 [23] [III]	Assign Canada regional model
11. Lower Mantle	670–900 km [23] [III]	230 km	0.89 [25]	1.1220 [23] [III]	Assign Canada regional model. Upper limit 3 ohm.m 620-780 km depth resistivity map [12c] shows dominantly 3 ohm.m except at western margin (near Cordillera) where resistivity increases to 20, 300 and 3000 ohm.m Hence, alternative resistivity approx 2 ohm.m, average of values (3, 0.89 ohm.m) for Layer 11
12. Lower Mantle	900–1000 km [23] [III]	100 km	0.47 [25]	2.0892 [23] [III]	Assign Canada regional model

See end of Table 10 for abbreviations and note

Table A3.3
1D Earth Resistivity Model for Alberta Zone 3 (Loverna Block)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
1. Overburden	0 – 40 m [1] [II]	40 m	30 [5, 3, 32, 6, 33] [III]	0.03333 [24]	Till is predominant, mostly as thicker blanket [4]. Large patchy areas of fine-grained (clay, silt) glaciolacustrine deposits and smaller areas with coarse-grained (silt, sand, gravel) glaciolacustrine deposits commonly along / nearby rivers [4] Overburden typically <50m [1] overall, western half of zone typically < 35 m [2], <20m beneath Calgary, 50-100 m thick in the Brooks – Empress area[1] Assign midpoint depth of range 35-50m Airborne resistivity survey profiles over central Alberta indicate ~20 ohm.m, plan view maps show 10-20 ohm.m at 20m depth [5]. Borehole logs of Manitoba overburden show 40-50 ohm.m for till and 70-200 ohm.m for sand and gravel [3]. Resistivities for tills range 20-100 ohm.m [32]. MT survey in SE Manitoba indicates 5-30 ohm for mix of till, clay, silt and sand [6]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [33] Assigned midpoint of resistivity range 10-50 ohm.m for tills. Limits 10, 100 ohm.m

Table A3.3 (continued)
1D Earth Resistivity Model for Alberta Zone 3 (Loverna Block)

Layer	Depth / Certainty	Thickness	Resistivity (ohm-m) / Certainty	Conductivity (S/m) / Certainty	Comments
2. Sedimentary Basin	0 – 2.9 km [7] [II]	2.9 km	6 [12b] [I]	0.16666 [24]	*WCSB*: Upper strata consist of Mesozoic sandstone, siltstone and shale. Lower strata consist of Paleozoic carbonate and subordinate shale [11] WCSB of Interior Platform ranges 1800-4000 m thick, maximum in foothills, 3500 m at Calgary [7] Assign 2900m average thickness MT 3D inversion model indicates 5-10 ohm.m range over entire thickness of WCSB [12a] 0.6-0.8 km depth resistivity map [12b] shows predominately 3 ohm.m with narrow band of increasing resistivity, from 20 to 3000 ohm.m, where foothills meet Cordillera mountain range 1.8-2.1 km depth resistivity map [12b] shows range 3-100 ohm.m, predominantly 10 ohm.m Assign 6 ohm.m average of dominant values (3, 10 ohm.m). Limits 3, 100 ohm.m
3. Upper Crust	2.9 - 19 km [15, 14] [I]	16 km	2000 [12b] [I]	0.0005 [24]	*Loverna Block*: granite and granitic gneiss Lower depth scaled from seismic profiles across southern Alberta; 18 km [15], 20 km [14] Assign averaged lower depth MT profile shows range of 80-3000 ohm.m, predominantly 3000 ohm.m [12d] 17-20 km depth resistivity map [12b] shows predominance of approx. 3000 ohm.m, except narrow zone 3-300 ohm.m (midpoint 150 ohm.m) coincident with trend of RDC, core of conductive anomaly is 3 ohm.m Assigned approx. 2000 ohm.m, weighted average based on area occupied by dominant / midpoint values ((3000*0.66)+(150*0.34)). Limits 3, 3000 ohm.m

Table A3.3 (continued)
1D Earth Resistivity Model for Alberta Zone 3 (Loverna Block)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
4. Middle Crust	19 – 29 km [15, 14] [I]	10 km	3000 [12d] [I]	0.00033 [24]	Thickness scaled from seismic profiles across southern Alberta; 11.4 km [15], 8.6 km [14]. Lower depth scaled from seismic profile; 30 km [19a] Assign 10 km, averaged thickness MT profile shows predominantly 3000 ohm.m [12d], assigned. Limits 300, 3000 ohm.m
5. Lower Crust	29 – 41 km [18b] [I]	12 km	620 [12b] [I]	0.00161 [24]	Lower depth, to Moho, from seismic depth determinations [18a, b] and scaled off seismic profiles Moho depth contour map [18b] shows range 37-45, deepening westward to Cordillera mountains at BC/Alberta boundary. Seismic profiles show lower depth range 37-46 km, average 41 km [15]; average thickness 12.8 km [14] Assign 41 km, midpoint of range depicted on depth contour map MT profiles show predominant range 25-300 ohm.m, flanked by 3000 ohm.m [12d] 33-37 km depth resistivity map shows range of 3-3000 ohm.m, east and central areas occupied by LC anomaly 3-100 ohm.m (50 ohm.m midpoint), with 3 ohm.m core of LC occupying 40% of Loverna Block [12b] Assign 620 ohm.m, weighted average based on area occupied by dominant / midpoint values ((3000 x 0.2) + (50 x 0.4) + (3 x 0.4)). Limits 3, 3000 ohm.m.

Table A3.3 (continued)
1D Earth Resistivity Model for Alberta Zone 3 (Loverna Block)

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Certainty		Certainty	Certainty	
6. Upper Mantle	41 - 100 km [23] [III]	59 km	150 [12f] [I]	0.00666 [24]	Used generalized lower depth [23]. MT profile shows predominant range of 25-125 ohm.m [12d] MT resistivity-depth curve [12f] shows range 35-260 ohm.m, averaging 150 ohm.m, between depth 40-100 km beneath LB 48-57 km and 63-74 km depth resistivity maps show range of 3-500 ohm.m overall (250 ohm.m midpoint), east and central areas occupied by LC anomaly 3-300 ohm.m, with 3 ohm.m core of LC occupying 30% of LB, and up to 30 ohm.m occupying 50% of LB [12b] Assign 150 ohm.m, based on average resistivity from resistivity depth curve. Limits 3, 500 ohm.m
7. Upper Mantle	100 - 250 km [23] [III]	150 km	230 [12d, f] [I]	0.00434 [24]	Used generalized lower depth [23] MT profiles show range 80-400, dominantly 100 ohm.m [12d] MT resistivity-depth curve [12f] shows average 360 ohm.m, between 100-150 km depth beneath LB Assign 230 ohm.m midpoint of resistivity values (100, 360 ohm.m). Limits 100, 360 ohm.m
8. Upper Mantle	250–410 km [23] [III]	160 km	90 [35b, 12g] [I]	0.01111 [24]	Used generalized lower depth [23]. MT profile shows range 20-200 ohm.m (110 ohm.m midpoint) between 225-300 km depth [35b]; and an averaged resistivity of 75 ohm.m for southern Alberta [12g] Assign approx. 90 ohm.m, average of values (110, 75 ohm.m). Limits 20, 200 ohm.m.

Table A3.3 (continued)
1D Earth Resistivity Model for Alberta Zone 3 (Loverna Block)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
9. Transition Zone	410–520 km [23] [III]	110 km	8 [25]	0.1258 [23] [III]	Utilized Canada regional model [23], based on Ottawa magnetic observatory datafor all depths and resistivities below 410 km For southern Alberta, between 410-500 km, averaged resistivity is 50 ohm.m over entire 3D model [12g]. Hence, an alternative resistivity for Layer 9 is 50 ohm.m
10. Transition Zone	520–670 km [23] [III]	150 km	2.4 [25]	0.4168 [23] [III]	Assign Canada regional model
11. Lower Mantle	670–900 km [23] [III]	L230 km	1.12 [25]	0.89 [23] [III]	Assign Canada regional model. Upper limit 3 ohm.m 620-780 km depth resistivity map [12c] shows dominantly 3 ohm.m except at western margin (near Cordillera) where resistivity increases to 20, 300 and 3000 ohm.m Hence, alternative resistivity approx 2 ohm.m, average of values (3, 0.89 ohm.m) for Layer 11
12. Lower Mantle	900–1000 km [23] [III]	100 km	0.47 [25]	2.0892 [23] [III]	Assign Canada regional model

See end of Table 10 for abbreviations and notes

Table A3.4
1D Earth Resistivity Model for Alberta Zone 4 (Eyehill High)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
1. Overburden	0 – 50 m [1] [II]	50 m	50 [5, 3, 32, 6, 33] [III]	0.02 [24]	Till blanket and coarse-grained (silt, sand, gravel) glaciolacustrine deposits, approx. half of each type overburden [4]. Overburden typically <50m, 50-100m along major river valley [1] Assign maximum overall depth 50m Airborne resistivity survey profiles over central Alberta indicate ~20 ohm.m, plan view maps show 10-20 ohm.m at 20m depth [5]. Borehole logs of Manitoba overburden show 40-50 ohm.m for till and 70-200 ohm.m for sand and gravel [3]. Resistivities for tills range 20-100 ohm.m [32]. MT survey in SE Manitoba indicates 5-30 ohm for mix of till, clay, silt and sand [6]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [33] Assigned midpoint of resistivity range (10-100 ohm.m) for combination of tills and sand/gravel. Limits 10, 100 ohm.m

Table A3.4 (continued)
1D Earth Resistivity Model for Alberta Zone 4 (Eyehill High)

Layer	Depth / Certainty	Thickness	Resistivity (ohm-m) / Certainty	Conductivity (S/m) / Certainty	Comments
2. Sedimentary Basin	0 - 2 km [7] / [II]	2 km	10 [12b] / [I]	0.1 [24]	*WCSB*: Upper strata consist of Mesozoic sandstone, siltstone and shale. Lower strata consist of Paleozoic carbonate and subordinate shale [11] WCSB of Interior Platform mainly ranges 1700-2200m thick, thickening southwestward [7] Assign 2000m midpoint depth MT 3D inversion model indicates 5>10 ohm.m range over entire thickness of WCSB [12a] Limited number of MT sounding sites on resistivity maps, inversion model results potentially influenced by edge effect 0.6-0.8 km depth resistivity map [12b] shows range 3>30 ohm.m (15 ohm.m midpoint) 1.8-2.1 km depth resistivity map [12b] shows dominantly 3 ohm.m Assign approx. 10 ohm.m, average of dominant / midpoint values (15, 3 ohm.m). Limits 3, 30 ohm.m
3. Upper Crust	2 - 19 km [15, 14] / [I]	17 km	1900 [12b] / [I]	0.00052 [24]	*Eyehill High*: metaplutonic gneiss and amphibolite gneiss comprise the Eyehill domain [20]. Lower depth scaled from seismic profiles across southern Alberta; 18 km [15], 20 km [14] Assign averaged lower depth 17-20 km depth resistivity map [12b] shows range 300-3000 ohm.m Assign 1900 ohm.m weighted average based on areal extent of individual resistivity ranges ((300 x 0.4) + (3000 x 0.6)). Limits 300, 3000 ohm.m

Table A3.4 (continued)
1D Earth Resistivity Model for Alberta Zone 4 (Eyehill High)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
4. Middle Crust	19 – 29 km [15, 14, 19a] [I]	10 km	1700 [12c] [I]	0.00058 [24]	Thickness scaled from seismic profiles across southern Alberta; 11.4 km [15], 8.6 km [14]. Lower depth scaled from seismic profile; 30 km [19a] Assign 10 km, averaged thickness MT profiles show a very approximate range 300-3000 ohm.m [12c]. Limited resolution of profile prevents finer selection of resistivity Assign 1700 ohm.m, midpoint of range. Limits 300, 3000 ohm.m
5. Lower Crust	29 – 43 km [18a] [I]	14 km	850 [12b] [I]	0.00117 [24]	Lower depth, to Moho, determined from seismic depth determinations [18a], showing range 39-46 km Assign 43 km, average of depth range 33-37 km depth resistivity map shows range of 100-3000 ohm.m, some influence from LC anomaly [12b] Assign 850 ohm.m weighted average based on areal extent of dominant resistivity ((150 x 0.75) + (3000 x 0.25)). Limits 100, 3000 ohm.m
6. Upper Mantle	43 - 100 km [23] [III]	57 km	500 [12b] [I]	0.002 [24]	Used generalized lower depth [23]. 48-57 km and 63-74 km depth resistivity maps [12b] show range of 30-3000 ohm.m Assign 500 ohm.m weighted average based on areal extent of dominant resistivity ((30 x 0.7)+(300 x 0.15) +(3000 x 0.15)). Limits 30, 3000 ohm.m
7. Upper Mantle	100 - 250 km [23] [III]	150 km	530 [12c] [I]	0.00188 [24]	Used generalized lower depth [23] MT profile shows range 100-1000, dominantly at lower end of range [12c] Assign 530 ohm.m weighted average based on areal extent of dominant resistivity ((300 x 0.63)+(1000 x 0.34)). Limits 100, 1000 ohm.m

Table A3.4 (continued)
1D Earth Resistivity Model for Alberta Zone 4 (Eyehill High)

Layer	Depth / Certainty	Thickness	Resistivity (ohm-m) / Certainty	Conductivity (S/m) / Certainty	Comments
8. Upper Mantle	250–410 km [23]	160 km	90 [35b, 12g]	0.01111 [24]	Used generalized lower depth [23]. MT profile shows range 20-200 ohm.m (110 ohm.m midpoint) between 225-300 km depth [35b]; and an averaged resistivity of 75 ohm.m for southern Alberta [12g] Assign 90 ohm.m, average of resistivity value / midpoint value (110, 75 ohm.m). Limits 20, 200 ohm.m.
	[III]		[I]		
9. Transition Zone	410–520 km [23]	110 km	8 [25]	0.1258 [23]	Utilized Canada regional model [23], based on Ottawa magnetic observatory data for all depths and resistivities below 410 km
	[III]			[III]	
10. Transition Zone	520–670 km [23]	150 km	2.4 [25]	0.4168 [23]	Assign Canada regional model
	[III]			[III]	
11. Lower Mantle	670–900 km [23]	230 km	1.12 [25]	0.89 [23]	Assign Canada regional model. Upper limit 3 ohm.m 620-780 km depth resistivity map [12c] shows range 3-30 ohm.m, half of area is 3 ohm.m, possible overestimate of higher end of range due edge effects of inversion process
	[III]			[III]	
12. Lower Mantle	900–1000 km [23]	100 km	0.47 [25]	2.0892 [23]	Assign Canada regional model
	[III]			[III]	

See end of Table 10 for abbreviations and notes

Table A3.5

1D Earth Resistivity Model for Alberta Zone 5 (Lacombe Domain)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
1. Overburden	0 – 35 m [1] [II]	35 m	30 [5, 3, 32, 6, 33] [III]	0.03333 [24]	Till is predominant, mostly as thicker blanket [4]. Large patchy areas of fine-grained (clay, silt) glaciolacustrine deposits and smaller areas with coarse-grained (silt, sand, gravel) glaciolacustrine deposits commonly along / nearby rivers [4]. Overburden typically <50m [1] overall, western half of zone typically < 20 m [2], 35-50m beneath Red Deer city and river [2]. Assign midpoint depth of range (20-50m) Airborne resistivity survey profiles over central Alberta indicate ~20 ohm.m, plan view maps show 10-20 ohm.m at 20m depth [5]. Borehole logs of Manitoba overburden show 40-50 ohm.m for till and 70-200 ohm.m for sand and gravel [3]. Resistivities for tills range 20-100 ohm.m [32]. MT survey in SE Manitoba indicates 5-30 ohm for mix of till, clay, silt and sand [6]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [33] Assigned midpoint of resistivity range 10-50 ohm.m for tills. Limits 10, 100 ohm.m

Table A3.5 (continued)
1D Earth Resistivity Model for Alberta Zone 5 (Lacombe Domain)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
2. Sedimentary Basin	0 - 3.1 km [7] [II]	3.1 km	20 [12b] [I]	0.05 [24]	*WCSB*: Upper strata consist of Mesozoic sandstone, siltstone and shale. Lower strata consist of Paleozoic carbonate and subordinate shale [11] WCSB of Interior Platform mainly ranges 1800-4500m, maximum at west margin adjacent to Cordillera deformation front, 2400-2800m south of Edmonton [7] Assign 3100m average thickness MT 3D inversion model [12b] indicates 5-10 ohm.m range over entire thickness of WCSB [12b] Average resistivity at Red Deer approx. 5 ohm.m [10] 0.6-0.8 km depth resistivity map [nie2014f9] shows dominantly 3 ohm.m 1.8-2.1 km depth resistivity map [12b] shows range 25-50 ohm.m (35 ohm.m midpoint) Assign 20 ohm.m, average of dominant / midpoint resistivity values (3, 35 ohm.m). Limits 3, 50 ohm.m
3. Upper Crust	3.1 - 19 km [15, 14] [I]	16 km	440 [35a, 12b] [I]	0.00227 [24]	*Lacombe Domain*: low-grade felsic metavolcanic and metasedimentary rocks Lower depth scaled from seismic profiles across southern Alberta; 18 km [15], 20 km [14] Assign averaged lower depth MT profiles show approx. 500 ohm.m [35a]; 3000 ohm.m [35b]. Limited resolution of profile prevents finer selection of resistivity. 17-20 km depth resistivity map [12b] shows range 3-3000 ohm.m, RDC anomaly is 3-30 ohm.m with core of 3 ohm.m. Chose 385 ohm.m weighted average based on areal extent of individual resistivity ranges ((15 x 0.75) + (1500 x 0.25)) Assign 440 ohm.m, average of dominant / midpoint values (385, 500 ohm.m). Limits 3, 3000

Table A3.5 (continued)
1D Earth Resistivity Model for Alberta Zone 5 (Lacombe Domain)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
4. Middle Crust	19 – 29 km [15, 14, 19a] [I]	10 km	900 [35a, b] [I]	0.00101 [24]	Thickness scaled from seismic profiles across southern Alberta; 11.4 km [15], 8.6 km [14]. Lower depth scaled from seismic profile; 30 km [19a] Assign 10 km, averaged thickness MT profiles show range 500-3000 ohm.m [35a] or 10-1000 [35b]. Limited resolution of profile prevents finer selection of resistivity Assign approx. 900 ohm.m, average of midpoint values of ranges (1450, 500 ohm.m)
5. Lower Crust	29 – 39 km [18b] [I]	10 km	330 [35b, 12b] [I]	0.00303 [24]	Moho depth contour map [18b] shows range 37-42, deepening southwestward and southward, approx. 37 km beneath Red Deer city Assigned 39 km depth, midpoint of range MT profiles show approx. 3000 ohm.m [35a] or 10-1000 [35b]. Limited resolution of profile prevents finer selection of resistivity 33-37 km depth resistivity map [12b] shows range of 3-1000 ohm.m, RDC anomaly much diminished in size and exhibits 30-100 ohm.m. Chose 160 ohm.m midpoint value of range 30-300 which has largest areal extent. Assign 330 ohm.m average of midpoint values of ranges (500, 160 ohm.m). Limits 3, 1000 ohm.m
6. Upper Mantle	39 - 100 km [23] [III]	61 km	950 [35b, 12b] [I]	0.00105 [24]	Used generalized lower depth [23]. MT profile shows range 500-3000 ohm.m [35b] (midpoint 1700 ohm.m) 48-57 km and 63-74 km depth resistivity maps show range of 100-300 ohm.m [12b] (midpoint 200 ohm.m) Assign 950 ohm.m average of midpoint values of ranges (200, 1700 ohm.m). Limits 100, 3000 ohm.m

Table A3.5 (continued)
1D Earth Resistivity Model for Alberta Zone 5 (Lacombe Domain)

Layer	Depth / Certainty	Thickness	Resistivity (ohm-m) / Certainty	Conductivity (S/m) / Certainty	Comments
7. Upper Mantle	100 - 250 km [23] [III]	150 km	160 [35b, 12c] [I]	0.00625 [24]	Used generalized lower depth [23] MT profiles show shows range 25-300 ohm.m resistivity [35b,12c], (midpoint 160 ohm.m); Assign 160 ohm.m, midpoint of ranges
8. Upper Mantle	250–410 km [23] [III]	160 km	40 [35b, 12g] [I]	0.025 [24]	Used generalized lower depth [23]. MT profile shows 10 ohm.m between 225-300 km depth [35b]; and an averaged resistivity of 75 ohm.m for southern Alberta [12g] Assign 40 ohm.m, average of values (10, 75 ohm.m). Limits 10, 75 ohm.m
9. Transition Zone	410–520 km [23] [III]	110 km	20 [25]	0.050118 [23] [III]	Utilized North American regional model [23], based on Tucson magnetic observatory data for all depths and resistivities below 410 km
10. Transition Zone	520–670 km [23] [III]	150 km	5.62 [25]	0.177827 [23] [III]	Assign North American regional model
11. Lower Mantle	670–900 km [23] [III]	230 km	1.58 [25]	0.630957 [23] [III]	Assign North American regional model. Upper limit 3 ohm.m 620-780 km depth resistivity map [12c] shows dominantly 3 ohm.m except at western margin (near Cordillera deformation front) where resistivity increases to 20, 300 and 3000 ohm.m
12. Lower Mantle	900–1000 km [23] [III]	100 km	1.12 [25]	0.89 [23] [III]	Assign North American regional model

See end of Table 10 for abbreviations and notes

Table A3.6
1D Earth Resistivity Model for Alberta Zone 6 (Rimbey, Thorsby & Wabamun Domains)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
1. Overburden	0 – 65 m [1] [II]	65 m	50 [5, 3, 32, 6, 33] [III]	0.02 [24]	Till is predominant, mostly as thicker blanket [4]. Narrow areas of fine-grained (clay, silt) glaciolacustrine deposits and coarse-grained (silt, sand, gravel) glaciolacustrine deposits commonly major rivers, including beneath Edmonton [2] Overburden typically <50m thick for 2/3 of zone, eastern 1/3 of zone ranges 50-200m (average 125m) in Cold Lake – Lac La Biche area [1], usually <35m beneath Edmonton [2] Assign 65m, weighted average of areal coverage of dominant depth ((35 x 0.66) + (125 x 0.34)) Airborne resistivity survey profiles over central Alberta indicate ~20 ohm.m, plan view maps show 10-20 ohm.m at 20m depth [5]. Borehole logs of Manitoba overburden show 40-50 ohm.m for till and 70-200 ohm.m for sand and gravel [3]. Resistivities for tills range 20-100 ohm.m [32]. MT survey in SE Manitoba indicates 5-30 ohm for mix of till, clay, silt and sand [6]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [33] Assign midpoint of resistivity range 10-100 ohm.m for combination of tills and sand/gravel.

Table A3.6 (continued)
1D Earth Resistivity Model for Alberta Zone 6 (Rimbey, Thorsby & Wabamun Domains)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
2. Sedimentary Basin	0 – 2.7 km [7] [II]	2.7 km	15 [11, 12b] [I]	0.06666 [24]	*WCSB*: Upper strata consist of Mesozoic sandstone, siltstone and shale. Lower strata consist of Paleozoic carbonate and subordinate shale [11] WCSB of Interior Platform (all 3 domains) ranges 900-4500 thick (midpoint 2700m) [7] *Rimbey Domain*: ranges 900-4500m (midpoint 2700m) *Thorsby Domain*: ranges 1700 ohm (midpoint 3100m) *Wabamun Domain*: ranges 2000-4500m (midpoint 3250m) Assign 2700m, midpoint of overall range MT survey [11] across Rocky Mountain foothills and adjacent WCSB determined an upper 20-50 ohm.m resistivity layer to depth of 2 km, and underlying 10 ohm.m layer at depth of 2-4 km, within zone 6 Limited number of MT sounding sites on resistivity maps, inversion model results potentially influenced by edge effect *Rimbey Domain* * 0.6-0.8 km depth resistivity map [12b] shows range 3-30 ohm.m (midpoint 15 ohm.m) * 1.8-2.1 km depth resistivity map shows predominantly 10 ohm.m * chose 10 ohm.m, approx. midpoint of range (15, 10 ohm.m) *Thorsby & Wabamun Domains* * Chose approx. 20 ohm.m, weighted average ((35 x 0.5) + (10 x 0.5)) based on MT survey [11] passing through Rocky Mountain House area Assign overall 15 ohm.m, average of midpoint / weighted average values (10, 20 ohm.m). Limits 3, 50 ohm.m

Table A3.6 (continued)
1D Earth Resistivity Model for Alberta Zone 6 (Rimbey, Thorsby & Wabamun Domains)

Layer	Depth / Certainty	Thickness	Resistivity (ohm-m) / Certainty	Conductivity (S/m) / Certainty	Comments
3. Upper Crust	2.7 - 12 km [13] [II]	12 km	3000 [12e, 35a] [I]	0.00033 [24]	Rimbey, *Thorsby & Wabamun Domains*: plutonic (lecuogranite, quartz diorite, tonolite) rocks [20] Overall lower depth scaled from trans-continental seismic transect (11-12 km) across southern Alberta [13]. Same depth assigned to individual Rimbey, Thorsby and Wabamun Domains. Limited seismic profile information for better resolution. Noticeable resistivity change on 2D inversion profiles at 10-15 km depth [35].
			Rimbey Domain * MT profiles show approx. range 1000-3000 ohm.m [12e], >3000 ohm.m [35a]. Limited resolution of resistivity differences on figures. *Thorsby & Wabamun Domains* * MT profile shows >3000 ohm.m [35a]. Limited resolution of resistivity differences on figure. Assign overall minimum 3000 ohm.m. Lower limit 1000 ohm.m		
4. Middle Crust	12 – 29 km [19b] [I]	17 km	2300 [12b, 35a] [I]	0.00043 [24]	Depth to layer bottom scaled from seismic profile [19b] *Rimbey Domain*: 26 km to layer bottom *Thorsby Domain*: 31 km to layer bottom *Wabamun Domain*: 31 km to layer bottom Assign 29 km, average of depths from 3 domains
			Rimbey Domain: * 17-29 km depth resistivity map [12b] shows range of 300-3000 ohm.m due influence of RDC anomaly; 1000-3000 ohm.m occupies 75% of Zone 6, 300 ohm.m occupies 25 % of Zone 6 * chose 1575 ohm.m weighted average of midpoint / dominant value ((2000 x 0.75)+(300 x 0.25)) *Thorsby & Wabamun Domains* * 2D inversion profile depicts general > 3000 ohm.m [35a]; Limited resolution of profile prevents finer selection of resistivity Assign overall 2300 ohm.m. average of weighted average / dominant value (1575, 3000 ohm.m). Limits 300, 3000 ohm.m		

Table A3.6 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 6 (Rimbey, Thorsby & Wabamun Domains)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
5. Lower Crust	29 – 39 km [18a]	10 km	2100 [12b, 35a]	0.00047 [24]	Lower depth, to Moho, averaged from seismic depth determinations [18a] and scaled off seismic profiles
	[I]		[I]		
		Rimbey Domain * 26 km depth to top of layer, 36 km to bottom (Moho) [19b] * 37 km to Moho, midpoint 37 km [18b] * 36.5 km average of estimated depths to Moho from seismic picks [18c] * chose 37 km to bottom of layer *Thorsby Domain* * 31 km depth to top of layer, 42 km to bottom (Moho) [19b] * 35-43 km to Moho, midpoint 39 km [18b] * maximum 45 km estimated depth to Moho from seismic picks [18c] * chose 44 km estimated depth to Moho *Wabamun Domain* * 31 km depth to top of layer, 38 km to bottom (Moho) [19b] * 35-39 km to Moho, midpoint 37 km [18b] * 36 km average of estimated depths to Moho from seismic picks [18c] * chose 36 km to bottom of layer Assign overall depth averages, 29 km to top of layer, 39 km to bottom *Rimbey Domain* * 33-37 km depth resistivity map [12b] shows range of 3-1000 ohm.m due influence of RDC and LC anomalies; 1000-3000 ohm.m occupies 50% of RD, 3-300 ohm.m occupies 50 % of Rimbey Domain * chose 1150 ohm.m weighted average based on areal extent of midpoint resistivity value ((2000 x 0.5)+(150 x 0.5)) *Thorsby & Wabamun Domain* * MT profile depicts range 30 to > 3000 ohm.m [35a]; low range of resistivity due presence of conductive anomaly at 60-100 km depth, unknown if conductor is a processing artifact. Limited resolution of profile prevents finer selection of resistivity * chose 3000 ohm.m for Thorsby and Wabamun domains Assign overall 2100 ohm.m, average of resistivity values (1150, 3000 ohm.m). Limits 30, 3000 ohm.m			

Table A3.6 (continued)
1D Earth Resistivity Model for Alberta Zone 6 (Rimbey, Thorsby & Wabamun Domains)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
6. Upper Mantle	39 - 100 km [23] [III]	61 km	1400 [12b, 35a] [I]	0.00071 [24]	Used generalized lower depth [23] *Rimbey Domain* * 48-57 km and 63-74 depth resistivity maps [12b] show range of 10-1000 ohm.m due influence of combining RDC and LC anomalies; 300-1000 ohm.m occupies 75% of RD, 3-300 ohm.m occupies 25 % of RD * chose 550 ohm.m weighted average ((650 x 0.75)+(150 x 0.25)) *Thorsby & Wabamun Domains* * MT profile depicts range 30 > 3000 ohm.m [35a]; low range of resistivity due presence of conductive anomaly at 60-100 km depth, unknown if conductor is a processing artifact * chose 3000 ohm.m for Thorsby and Wabamun domains. Limited resolution of profile prevents finer selection of resistivity * chose 2250 ohm.m weighted average ((30 x 0.25)+(3000 x 0.75)) Assign overall 1400 ohm.m, average of dominant / weighted average resistivity values (550, 2250 ohm.m). Limits 30, 3000 ohm.m
7. Upper Mantle	100 - 250 km [23] [III]	150 km	160 [12e] [I]	0.00625 [24]	Used generalized lower depth [23] MT profile shows overall range 30-300 ohm.m, dominantly 100 ohm.m [12e] Assign 160 ohm.m midpoint of range. Limits 30, 300 ohm.m
8. Upper Mantle	250–410 km [23] [III]	160 km	50 [25] [III]	0.019952 [23]	Utilized North American regional model [23], based on Tucson magnetic observatory data, for all depths and resistivities below 250 km.

Table A3.6 (continued)
1D Earth Resistivity Model for Alberta Zone 6 (Rimbey, Thorsby & Wabamun Domains)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
9. Transition Zone	410–520 km [23] [III]	110 km	20 [25]	0.050118 [23] [III]	Assign North American regional model
10. Transition Zone	520–670 km [23] [III]	150 km	5.62 [25]	0.177827 [23] [III]	Assign North American regional model
11. Lower Mantle	670–900 km [23] [III]	230 km	1.58 [25]	0.630957 [23] [III]	Assign North American regional model. Upper limit 3 ohm.m 620-780 km depth resistivity map [12c] shows average 10 ohm; higher resistivity possible due limited data points Alternative resistivity is approx. 5 ohm.m, average of values (10, 1.58 ohm.m) for Layer 11. Upper limit 10 ohm.m
12. Lower Mantle	900–1000 km [23] [III]	100 km	0.89 [25]	1.122018 [23] [III]	Assign North American regional model

See end of Table 10 for abbreviations and notes

Table A3.7
1D Earth Resistivity Model Proximal for Alberta Zone 7 (Taltson Domain, Buffalo Head Domain)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
1. Overburden	0 – 50 m [1] [II]	50 m	30 [5, 3, 32, 6, 33] [III]	0.03333 [24]	Variety glacial deposits; till blanket being dominant, followed by fine-grained glaciolacustrine (clay, silt), localized organic and eolioan (windblown silt & sand) deposits [4] Depth ranges 0-200m, thicker in central portion where ranges 50-250m deep [1] Assign 50m thickness, weighted average based on areal extent of dominant thicknesses ((0.75 x 25m)+(0.25 x 125m)) Airborne resistivity survey profiles over central Alberta indicate ~20 ohm.m, plan view maps show 10-20 ohm.m at 20m depth [5]. Borehole logs of Manitoba overburden show 40-50 ohm.m for till and 70-200 ohm.m for sand and gravel [3]. Resistivities for tills range 20-100 ohm.m [32]. MT survey in SE Manitoba indicates 5-30 ohm for mix of till, clay, silt and sand [6]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [33] Assigned midpoint of resistivity range 10-50 ohm.m for tills, the dominant overburden in Zones 7, 8 and 10. Lower and upper limits, 10 and 100 ohm.m respectively, applicable to glacial deposits ranging from till to glaciolacustrine
2. Sedimentary Basin	0 – 1.4 km [7] [II]	1.4 km	10 [9] [I]	0.1 [24]	WCSB of Interior Platform overlies area, deepening southwestward. Lower strata consist of Paleozoic carbonate, shale and evaporite. Upper strata consist of Mesozoic marine shales, and alternating sandstone and shales [8] Depth ranges 0-2800m, assign midpoint 1400m [7] 1.7 km depth resistivity map shows overall ~10 ohm.m with localized areas up to 30 ohm.m [9]. Low resistivity attributed to presence of pore fluids in sedimentary rock [8]. MT profile shows aprox. 8 ohm.m [10b] Profile shows range 50-200 ohm.m [34], midpoint 125 ohm.m, in nearby NWT Assign approx. 10 ohm.m, based on MT survey over northern Alberta [9]. Limits 3, 125 ohm.m

Table A3.7 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 7 (Taltson Domain, Buffalo Head Domain)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
3. Upper Crust	1.4 - 13 km [36] [I]	11.6 km	3000 [9, 10b, 34] [I, II]	0.00033 [24]	*Taltson Domain*: highly deformed gneiss and granitic rocks, and moderately deformed plutonic rocks [20]. *Buffalo Head Domain*: mainly metaplutonic rocks subordinate metavolcanic and high-grade gneissic rocks [39] Lower depth scaled off seismic profile [36] MT profiles show 500 >1000 ohm.m [9], dominantly 1000 ohm.m; >1000 ohm.m [10b], limited resolution; range 1000-5000 ohm.m [34], midpoint 3000 ohm.m, in nearby NWT Assign 3000 ohm.m midpoint based on range 1000-5000 ohm.m in adjacent NWT. Limits 500-5000 ohm.m
4. Middle Crust	13 - 29 km [36] [I]	16 km	1750 [9, 10b, 34] [I, II]	0.00057 [24]	Lower depth scaled off seismic profile [36] MT profiles show 400 >1000 ohm.m [9], dominantly 1000 ohm.m; >1000 ohm.m [10b], limited resolution; range 1000-2500 ohm.m [34], midpoint 1750 ohm.m, in nearby NWT Assign 1750 ohm.m midpoint based on range 1000-2500 ohm.m in adjacent NW. Limits 1000-2500 ohm.m
5. Lower Crust	29 – 38 km [18b, 36] [I]	9 km	1200 [9, 10b, 34] [I, II]	0.00083 [24]	Lower depth scaled of seismic profiles. Moho ranges 35-43 km deep, chose midpoint 39 km, deepest immediately north of Peace River 41-43 km & NW of Edmonton 41 km [18b]; depth 29-44 km, chose midpoint 37 km [36] Assign 38 km, average of midpoint depths MT profiles show 400 >1000 ohm.m [9], dominantly 1000 ohm.m; >1000 ohm.m [10b], limited resolution; range 800-2500 ohm.m [34], midpoint 1650 ohm.m, in nearby NWT 41 km depth resistivity map shows range 400 >1000 ohm. [9]. Select 700 ohm.m midpoint of range Assign approx. 1200 ohm.m, average of midpoints 700 and 1650 ohm.m. Limits 400, 2500 ohm.m

Table A3.7 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 7 (Taltson Domain, Buffalo Head Domain)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
6. Upper Mantle	38 - 100 km [23] [III]	62 km	1400 [9, 34] [I, II]	0.00071 [24]	Used generalized lower depth [23]. MT profiles show 300-800 ohm.m [9], chose 550 ohm.m midpoint; range 800-5000 ohm.m [34], midpoint 3000 ohm.m, in adjacent NWT 65 km depth resistivity map [9] shows range 500 >1000 ohm covering 90% of zone, and 100-300 ohm.m range covering 10% of zone along boundary with Zone 8, part of dipping KC anomaly. Chose 675 ohm.m weighted average ((midpoint 750 x 0.9)+(midpoint 200 x 0.1)) Assign 1400 ohm.m, average of midpoints 550, 675, 3000 ohm.m incorporating same terranes found in adjacent NWT. Limits 300, 5000 ohm.m
7. Upper Mantle	100 - 250 km [23] [III]	150 km	100-200km 950 [9] [I] 200-250km 20 [9] [I] 100-250 km 635 [9] [I]	100-200km 0.00105 [24] 200-250km 0.05 [24] 100-250 km 0.00157 [24]	Used generalized lower depth [23]. MT profiles [9] show distinct resistivity change at 200 km depth. MT profiles [9] show at: *100-200 km depth, range 800>1000 ohm.m. Chose 950 ohm.m weighted average ((1000 x 0.75)+(800 x 0.25)). * 200-250 km depth, range 10-30 ohm.m (midpoint 20 ohm.m) Assign 635 ohm.m weighted average ((midpoint 950 x 0.66)+(midpoint 20 x 0.34)) for entire layer. Limits 800, 1000 between 100-200 km and 10, 30 between 200-250 km
8. Upper Mantle	250–410 km [23] [III]	160 km	50 [25]	0.019952 [23] [III]	Utilized North American regional model [23], based on Tucson magnetic observatory data for all depths and resistivities below 250 km

Table A3.7 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 7 (Taltson Domain, Buffalo Head Domain)

Layer	Depth	Thickness	Resistivity (ohm-m)	Conductivity (S/m)	Comments
	Certainty		Certainty	Certainty	
9. Transition Zone	410–520 km [23]	110 km	20 [25]	0.050118 [23]	---
	[III]			[III]	
10. Transition Zone	520–670 km [23]	150 km	5.62 [25]	0.177827 [23]	---
	[III]			[III]	
11. Lower Mantle	670–900 km [23]	230 km	1.58 [25]	0.630957 [23]	---
	[III]			[III]	
12. Lower Mantle	900–1000 km [23]	100 km	1.12 [25]	0.89 [23]	---
	[III]			[III]	

See end of Table 10 for abbreviations and notes

Table A3.8
1D Earth Resistivity Model Proximal for Alberta Zone 8 (Chinachga, Ksituan, Kiskatinaw, Nova Domains)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
1. Overburden	0 – 25 m [1] [II]	25 m	30 [5, 3, 32, 6, 33] [III]	0.03333 [24]	Glacial deposits consisting of till blanket and fine-grained glaciolacustrine, with localized areas of coarse-grained (sand, gravel) glaciolacustrine deposits [4] Depth ranges 0-50m [1] Assign 25m, midpoint of range Airborne resistivity survey profiles over central Alberta indicate ~20 ohm.m, plan view maps show 10-20 ohm.m at 20m depth [5]. Borehole logs of Manitoba overburden show 40-50 ohm.m for till and 70-200 ohm.m for sand and gravel [3]. Resistivities for tills range 20-100 ohm.m [32]. MT survey in SE Manitoba indicates 5-30 ohm for mix of till, clay, silt and sand [6]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [33] Assigned midpoint of resistivity range 10-50 ohm.m for tills, the dominant overburden in Zones 7, 8 and 10. Lower and upper limits, 10 and 100 ohm.m respectively, applicable to glacial deposits ranging from till to glaciolacustrine
2. Sedimentary Basin	0 – 3.3 km [7] [II]	3.3 km	10 [9] [I]	0.1 [24]	WCSB of Interior Platform overlies area, deepening southwestward. Lower strata consist of Paleozoic carbonate, shale and evaporite. Upper strata consist of Mesozoic marine shales, and alternating sandstone and shales [8] Depth ranges 1200-5500m, assign midpoint 3300m [7] 1.7 km depth resistivity map shows overall ~10 ohm.m with localized areas up to 30 ohm.m [9]. Low resistivity attributed to presence of pore fluids in sedimentary rock [8]. MT profiles show range aprox. 1-8 ohm.m [10b] Profile shows range 3-30 ohm.m [34], midpoint 15 ohm.m, in nearby NWT Assign approx. 10 ohm.m, based on MT survey over northern Alberta [9]. Limits 3, 30 ohm.m

Table A3.8 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 8 (Chinchaga, Ksituan, Kiskatinaw, Nova Domains)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
3. Upper Crust	3.3 – 15 km [36] [I]	11.7 km	900 [10b] [I]	0.00111 [24]	*Chinchaga Domain*: metasedimentary and metaplutonic rock [20]. *Ksituan Domain*: metaplutonic (granitic gneiss) [20, 39] *Kiskatinaw Low*: granitic gneiss [20] *Nova Domain*: mylonitic mafic gneiss [20] Lower depth from averaged values from regional seismic profile [36] MT profiles show >1000 ohm.m [9], limited resolution; >1000 ohm.m [10b], with two 5 ohm.m conductive anomalies Assign 900 ohm.m weighted average ((1000 x 0.9)+(5 x 0.1)) based on distribution of resistivity on profile by [10b]. Upper limit >1000 ohm.m
4. Middle Crust	15 – 30 km [36] [I]	15 km	275 [9] [I]	0.00363 [24]	Lower depth from averaged values from seismic profile [36] MT profiles show 100 >1000 ohm.m [9], limited resolution; >1000 ohm.m [10b], with two 40-60 conductive anomalies being continuation of same anomalies located in upper crust 20.6 km depth resistivity map [9] shows range 10-200 ohm.m (midpoint 100 ohm.m) covering 75% of, and 800 ohm.m covering 25% of Zone 8. Chose 275 ohm.m weighted average ((100*0.75) + (800*0.25)) Assign 275 ohm.m weighted average. Limits 10, 1000 ohm.m

Table A3.8 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 8 (Chinchaga, Ksituan, Kiskatinaw, Nova Domains)

Layer	Depth / Certainty	Thickness	Resistivity (ohm-m) / Certainty	Conductivity (S/m) / Certainty	Comments
5. Lower Crust	30 – 39 km [18b, 36] [I]	9 km	360 [9, 10b] [I]	0.00277 [24]	Lower depth scaled off seismic profiles Moho ranges 37-49 km (midpoint 43 km), shallowest SW of Grande Prairie 37 km, depth increases rapidly southwestward in front of Cordillera 41-49 km [18b]; Moho is transitional between 35-42 km (midpoint 39 km) in Ft. Nelson BC area [37]; Moho averages 40 km, as scaled [36]; Moho depth ranges 30-40 km, thickness 10 km [36b] Assign 39 km, average of midpoint depths MT profiles shows range 40-200 ohm.m [9]; 100>1000 ohm.m [10b], dominantly > 1000 ohm.m, with large conductive 1-10 ohm.m anomaly underlying Chinchaga magnetic low; range 100>1000 ohm.m [10b]; chose 550 ohm.m weighted average ((100 x 0.5) + (1000 x 0.5)) 41 km depth resistivity map shows range 100-300 ohm.m [9], predominately 40-300 ohm.m. Chose 175 ohm.m midpoint of predominate range Assign approx. 360 ohm.m, average of midpoints 175 and 550 ohm.m. Limits 40, 1000 ohm.m
6. Upper Mantle	40 – 100 km [23] [III]	60 km	315 [9] [I]	0.00317 [24]	Used generalized lower depth [23] MT profiles show 300-400 ohm.m [9], chose 250 ohm.m midpoint 65 km depth resistivity map [9] shows range 100-300 ohm.m covering 80% of zone, and 400-800 ohm.m remaining 20%. Chose 380 ohm.m weighted average ((midpoint 200 x 0.8)+(midpoint 600 x 0.2)) Assign 315 ohm.m average of midpoint values 250, 380 ohm.m. Limits 100, 400 ohm.m

Table A3.8 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 8 (Chinchaga, Ksituan, Kiskatinaw, Nova Domains)

Layer	Depth / Certainty	Thickness	Resistivity (ohm-m) / Certainty	Conductivity (S/m) / Certainty	Comments
7. Upper Mantle	100 – 250 km [23]	150 km	100-200km 985 [9] [I]	100-200km 0.00101 [24]	Used generalized lower depth [23]. MT profiles [9] show distinct resistivity change at 200 km depth. MT profiles [9] show at: *100-200 km depth, range 300>1000 ohm.m, influence of KC anomaly (300-550 ohm.m) between 100-125 km depth, predominately >1000 ohm.m overall elsewhere. Choose 985 ohm.m weighted average ((1000 x 0.9)+(midpoint 425 x 0.20)) * 200-250 km depth, range 10-30 ohm.m (midpoint 20 ohm.m) Assign 660 ohm.m weighted average ((midpoint 985 x 0.66)+(midpoint 20 x 0.34)) based on areal coverage with respect to depth. Limits 200, 1000 between 100-200 km and 10, 30 between 200-250 km
	[III]		200-250km 20 [9] [I]	200-250km 0.05 [24]	
			100-250 km 660 [9] [I]	100-250 km 0.00151 [24]	
8. Upper Mantle	250 – 410 km [23]	160 km	50 [25]	0.019952 [23]	Utilized North American regional model [23], based on Tucson magnetic observatory data for all depths and resistivities below 250 km
	[III]			[III]	
9. Transition Zone	410 – 520 km [23]	110 km	20 [25]	0.050118 [23]	---
	[III]			[III]	
10. Transition Zone	520 – 670 km [23]	150 km	5.62 [25]	0.177827 [23]	---
	[III]			[III]	

Table A3.8 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 8 (Chinchaga, Ksituan, Kiskatinaw, Nova Domains)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
11. Lower Mantle	670 – 900 km [23] [III]	230 km	1.58 [25]	0.630957 [23] [III]	---
12. Lower Mantle	900 – 1000 km [23] [III]	100 km	1.12 [25]	0.89 [23] [III]	---

See end of Table 80 for abbreviations and notes

Table A3.9
1D Earth Resistivity Model Proximal for Alberta Zone 9 (Great Slave Lake Shear Zone)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
1. Overburden	0 – 25 m [1] [II]	25 m	15 [5, 3, 32, 6, 33] [III]	0.06666 [24]	Glacial deposits, mostly fine-grained glaciolacustrine with lesser amount of till blanket [4] Depth ranges 0-50m [1] Assign 25m midpoint of range Airborne resistivity survey profiles over central Alberta indicate ~20 ohm.m, plan view maps show 10-20 ohm.m at 20m depth [5]. Borehole logs of Manitoba overburden show 40-50 ohm.m for till and 70-200 ohm.m for sand and gravel [3]. Resistivities for tills range 20-100 ohm.m [32]. MT survey in SE Manitoba indicates 5-30 ohm for mix of till, clay, silt and sand [6]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [33] Assign 15 ohm.m midpoint of range 5-30 ohm.m for mix of till and glaciolacustrine deposits, reflects greater predominance of fine-grained glaciolacustrine deposits for Zone 9
2. Sedimentary Basin	0 – 1.9 km [7] [II]	1.9 km	10 [9] [I]	0.1 [24]	WCSB of Interior Platform overlies area, deepening southwestward Depth ranges 1000-2800m, assign midpoint 1900m [7] 1.7 km depth resistivity map shows overall ~10 ohm.m with localized areas up to 30 ohm.m [9]. Low resistivity attributed to presence of pore fluids in sedimentary rock [8] MT profiles show aprox. 5-8 ohm.m [10b]; range 3-30 ohm.m [35], midpoint 15 ohm.m, in nearby NWT Assign approx. 10 ohm.m, based on MT survey over northern Alberta [9]. Limits 3, 30 ohm.m

Table A3.9 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 9 (Great Slave Lake Shear Zone)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
3. Upper Crust	1.9 – 12 km [36] [I]	10.1 km	4200 [34] [II]	0.00023 [24]	*Great Slave Lake shear zone*: mylonitic rock (granitic protolith) [40] Lower depth scaled off seismic profile [36] Assigned 12 km bottom depth, average of Zones 8 and 10 MT profiles show 500 >1000 ohm.m [9], limited resolution; >1000 ohm.m [10b], limited resolution; range 1000-7500 ohm.m [34], midpoint 4200 ohm.m, in nearby NWT, top of resistive anomaly in upper crust Assign 4200 ohm.m midpoint based on range 1000-7500 ohm.m in adjacent NWT. Limits 1000, 7500 ohm.m
4. Middle Crust	12 - 24 km [36] [I]	12 km	4500 [9, 10b, 34] [I, II]	0.00022 [24]	Lower depth scaled of regional seismic profile [36] Assigned 24 km bottom depth, average of Zones 8 and 10 MT profiles show >1000 ohm.m [10b], limited resolution; range 7500-10000 ohm.m [34], midpoint 8800 ohm.m, in nearby NWT 20.6 km depth resistivity map shows dominantly 200 ohm.m [9], influence of western edge of KC conductive anomaly in lower crust Assign 4500 ohm.m, midpoint of range 200-8800 ohm.m, which accounts for presence of KC anomaly. Limits 1000, 2500 ohm.m
5. Lower Crust	24 – 40 km [18b] [I]	16 km	4500 [9, 34] [I, II]	0.00022 [24]	Moho ranges 39-40 km deep [18b] MT profiles show 40 >1000 ohm.m [9]; range 7500-10000 ohm.m [34], midpoint 8850 ohm.m, in adjacent NWT 41 km depth resistivity map shows range 10-200 (midpoint 100 ohm.m) ohm.m covering 90% of, and >1000 ohm.m covering 10% of Zone 9. Chose 200 ohm.m weighted average ((100*0.90) + (1000*0.10)) Assign 4500 ohm.m, average of midpoints 200 and 8800 ohm.m. Limits 100, 10000 ohm.m

Table A3.9 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 9 (Great Slave Lake Shear Zone)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
6. Upper Mantle	40 - 100 km [23] [III]	60 km	1600 [9, 34] [I, II]	0.00062 [24]	Used generalized lower depth [23] MT profiles show 100-400 ohm.m [9], chose 250 ohm.m midpoint; range 800-5000 ohm.m [34] midpoint 3000 ohm.m, in adjacent NWT 65 km depth resistivity map [9] shows range 40-400 ohm. Chose 220 ohm.m midpoint of range Assign 1600 ohm.m average of midpoints 220, 3000 ohm.m incorporating continuation of GSLsz into adjacent NWT. Limits 40, 5000 ohm.m
7. Upper Mantle	100 - 250 km [23] [III]	150 km	100-200km 1000 [9] [I] 200-250km 60 [9] [I] 100-250 km 680 [9] [I]	100-200km 0.001 [24] 200-250km 0.01666 [24] 100-250 km 0.00147 [24]	Used generalized lower depth [23]. MT profiles [9] show distinct resistivity change at 200 km depth MT profiles [9] show at: *100-200 km depth, >1000 ohm.m * 200-250 km depth, range 30-100 ohm.m (midpoint 60 ohm.m) Assign 680 ohm.m weighted average ((1000 x 0.66)+(midpoint 60 x 0.34)) based on areal coverage with respect to depth. Upper limit 1000 ohm.m between 100-200 km. Limits 30, 100 ohm.m between 200-250 km
8. Upper Mantle	250–410 km [23] [III]	160 km	50 [25]	0.019952 [23] [III]	Utilized North American regional model [23], based on Tucson magnetic observatory data, for all depths and resistivities below 250 km

Table A3.9 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 9 (Great Slave Lake Shear Zone)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
9. Transition Zone	410–520 km [23] [III]	110 km	20 [25]	0.050118 [23] [III]	---
10. Transition Zone	520–670 km [23] [III]	150 km	5.62 [25]	0.177827 [23] [III]	---
11. Lower Mantle	670–900 km [23] [III]	230 km	1.58 [25]	0.630957 [23] [III]	---
12. Lower Mantle	900–1000 km [23] [III]	100 km	1.12 [25]	0.89 [23] [III]	---

See end of Table 90 for abbreviations and notes

Table A3.10
1D Earth Resistivity Model Proximal for Alberta Zone 10 (Great Bear, Hottah, Fort Simpson)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
1. Overburden	0 – 175 m [1] [II]	175 m	30 [5, 3, 32, 6, 33] [III]	0.03333 [24]	Variety glacial deposits; till blanket and fine-grained glaciolacustrine (clay, silt), localized organic deposits [4] Depth ranges 0-300m [1] Assign 175m midpoint depth of predominant range 50-300m Airborne resistivity survey profiles over central Alberta indicate ~20 ohm.m, plan view maps show 10-20 ohm.m at 20m depth [5]. Borehole logs of Manitoba overburden show 40-50 ohm.m for till and 70-200 ohm.m for sand and gravel [3]. Resistivities for tills range 20-100 ohm.m [32]. MT survey in SE Manitoba indicates 5-30 ohm for mix of till, clay, silt and sand [6]. Glaciolacustrine clays average 30 ohm.m in northeastern Ontario [33] Assigned midpoint of resistivity range 10-50 ohm.m for tills, the dominant overburden in Zones 7, 8 and 10. Lower and upper limits, 10 and 100 ohm.m respectively, applicable to glacial deposits ranging from till to glaciolacustrine.
2. Sedimentary Basin	0 – 1.9 km [7] [I]	1.9 km	10 [9] [I]	0.1 [24]	WCSB of Interior Platform overlies area, deepening southwestward. WCSB of Interior Platform overlies area, deepening southwestward. Lower strata consist of Paleozoic carbonate, Depth ranges 1000-2800m, assign midpoint 1900m [7] 1.7 km depth resistivity map shows overall ~10 ohm.m with localized areas up to 30 ohm.m [9]. Low resistivity attributed to presence of pore fluids in sedimentary rock [8] MT profiles show aprox. 5-8 ohm.m [10b]; range 3-30 ohm.m [34], midpoint 15 ohm.m, in nearby NWT Assign approx. 10 ohm.m, based on MT survey over northern Alberta [9]. Limits 3, 30 ohm.m

Table A3.10 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 10 (Great Bear, Hottah, Fort Simpson)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
3. Upper Crust	1.9 - 8 km [37] [II]	6 km	1000 [9, 10b, 34] [I, II]	0.001 [24]	*Great Bear Domain*: plutonic (granitic) and volcano-sedimentary rock [34c]. *Hottah Domain*: plutonic and gneissic rock [20] *Fort Simpson Domain*: plutonic [20] and metasedimentary rock [34c]. Terrane lies immediately outside of west boundary of province. Lower depth scaled off regional seismic profile, for Ft. Nelson area in adjacent British Columbia [37] MT profiles show >1000 ohm.m [9], limited resolution; >1000 ohm.m [10b], with two 5 ohm.m conductive anomalies; in nearby NWT range 250-1000 ohm.m [34], dominantly 1000 ohm.m Assign 1000 ohm.m based on predominance. Limits 250, 1000 ohm.m
4. Middle Crust	8 - 18 km [37] [II]	10 km	1300 [9, 10b, 34] [I, II]	0.00076 [24]	Lower depth scaled off regional seismic profile, for Ft. Nelson area in adjacent British Columbia [37] MT profiles show 200 >1000 ohm.m [9], dominantly 1000 ohm.m, start of a lower crust conductor at bottom of layer 4; >1000 ohm.m [10b], with two 40-60 ohm.m conductive anomalies; range 100-2500 ohm.m [34], midpoint 1300 ohm.m, exclusive of conductive anomalies ranging 10-100 ohm.m, in nearby NWT. Conductor E is 10 ohm.m in middle crust, and its influence extends to 100 km depth where anomaly becomes 100 ohm.m, and occurs at boundary between Hottah and Great Bear terranes. 20.6 km depth resistivity map shows dominantly >1000 ohm. [9] Assign 1300 ohm.m midpoint of range 100-2500 based on nearby survey in NWT. Limits 100, 2500 ohm.m

Table A3.10 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 10 (Great Bear, Hottah, Fort Simpson)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
5. Lower Crust	18 – 40 km [34b, 37] [II]	22 km	800 [9, 10b, 34] [I, II]	0.00125 [24]	Lower depth scaled off seismic profiles. Moho possibly at 39 km [18b]; approx. 40 km depth beneath Hottah terrane and Great Bear magmatic arc [34]; at Ft. Nelson area (Ft. Simpson magmatic belt) Moho is transitional between 41-45 km [37]; in NWT adjacent northern Alberta ranges 37-40 km deepening eastward, midpoint 38.5 km [34b] Assign 40 km, average of midpoint depths MT profiles show 200 >1000 ohm.m [9], dominantly 1000 ohm.m; 100>1000 ohm.m [10b], lower resistivity due influence of upper crustal conductors. Chose 325 ohm.m weighted average ((100 x 0.75) + (1000 x 0.25)); range 100-2500 ohm.m [34], midpoint 1300 ohm.m, exclusive of conductive anomalies (C, D, E, F) ranging 10-100 ohm.m, in nearby NWT 41 km depth resistivity map shows 30-200 (midpoint 115 ohm.m) ohm.m covering 20% of, and >1000 ohm.m covering 80% of Zone. Chose 825 ohm.m weighted average ((115*0.20) + (1000*0.80)) Assign approx. 800 ohm.m, average of midpoints 825, 325 and 1300 ohm.m. Limits 30, 2500 ohm.m
6. Upper Mantle	40 - 100 km [23] [III]	60 km	500 [9, 34] [I, II]	0.002 [24]	Used generalized lower depth [23]. MT profiles show 250-800 ohm.m [9], dominantly 800 ohm.m; range 60-400 ohm.m [34] and includes conductive anomalies H and I at 80-100 km depth. Chose midpoint 230 ohm.m of range 65 km depth resistivity map [9] shows range 30-300 ohm.m (conductive anomaly) covering 25% of zone, and 400>1000 ohm.m remaining 75%. Chose approx. 800 ohm.m weighted average ((midpoint 160 ohm.m x 0.25) + (mainly 1000 x 0.75)) Assign approx. 500 ohm.m, average of midpoints 800, 230 ohm.m incorporating same terranes found in adjacent NWT. Limits 30, 1000 ohm.m

Table A3.10 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 10 (Great Bear, Hottah, Fort Simpson)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
7. Upper Mantle	100 - 250 km [23] [III]	150 km	100-200km 920 [9] [I] 200-250km 50 [9] [I] 100-250 km 625 [9] [I]	100-200km 0.00108 [24] 200-250km 0.02 [24] 100-250 km 0.0016 [24]	Used generalized lower depth [23]. MT profiles [9] show distinct resistivity change at 200 km depth MT profiles [9] show at: *100-200 km depth, range 200>1000 ohm.m, influence of KC anomaly (200 ohm.m) between 100-125 km depth, predominately >1000 ohm.m overall elsewhere. Choose 920 ohm.m weighted average ((1000 x 0.9)+(200 x 0.10)) * 200-250 km depth, range 30-80 ohm.m (midpoint 50 ohm.m) Assign 625 ohm.m weighted average ((920 x 0.66)+(midpoint 50 x 0.34)) based on areal coverage with respect to depth. Limits 100, 1000 ohm.m between 100-200 km and 30, 80 ohm.m between 200-250 km
8. Upper Mantle	250–410 km [23] [III]	160 km	50 [25]	0.019952 [23] [III]	Utilized North American regional model [23], based on Tucson magnetic observatory data, for all depths and resistivities below 250 km
9. Transition Zone	410–520 km [23] [III]	110 km	20 [25]	0.050118 [23] [III]	---
10. Transition Zone	520–670 km [23] [III]	150 km	5.62 [25]	0.177827 [23] [III]	---

Table A3.10 (continued)
1D Earth Resistivity Model Proximal for Alberta Zone 10 (Great Bear, Hottah, Fort Simpson)

Layer	Depth Certainty	Thickness	Resistivity (ohm-m) Certainty	Conductivity (S/m) Certainty	Comments
11. Lower Mantle	670–900 km [23] [III]	230 km	1.58 [25]	0.630957 [23] [III]	---
12. Lower Mantle	900–1000 km [23] [III]	100 km	1.12 [25]	0.89 [23] [III]	---

BC	British Columbia
GSLsz	Great Slave Lake shear zone
KC	Kiskatinaw Conductor
LC	Loverna Conductor
MHB	Medicine Hat Block
moho	Mohorovicic Discontinuity
MT	magnetotelluric
NE	northeast
NW	northwest
NWT	Northwest Territories
SE	southeast
SW	southwest
VS	Vulcan Structure
WCSB	Western Canada Sedimentary Basin
2D	two-dimensional
3D	three-dimensional

Table A3.10 (continued)

1D Earth Resistivity Model Proximal for Alberta Zone 10 (Great Bear, Hottah, Fort Simpson)

[1] Fenton et al. (1994), Fig. 26.3-Surface to Bedrock Isopach drift thickness

[2] Barker et al (2011), p.27, Figs. 3.1, 3.2

[3] Oldenborger et al. (2010), p.3

[4] Fulton (1995), map, surficial materials

[5] Slattery and Andriashek (2012), stratigraphic and resistivity cross-sections

[6] Gowan et al. (2009), Figs. 7, 8

[7] Wright et al. (1994), Fig. 3.2 isopach map

[8] Turkoglu et al. (2007), Figs. 14 and 15

[9] Turkoglu et al. (2009), Figs. 7, 8.

[10a] Boerner et al. (2000), Fig. 9

[11] Xiao (2006), p.329

[12a] Nieuwenhuis (2014), p.851

[12b] Nieuwenhuis (2014), Fig. 9

[12c] Nieuwenhuis (2014), Fig. 10

[12d] Nieuwenhuis (2014), Fig. 12

[12e] Nieuwenhuis (2014), Fig. 7

[12f] Nieuwenhuis (2014), Fig. 14

[12g] Nieuwenhuis (2014), Fig. 13

[12h] Nieuwenhuis (2014), p. 4

[18a] Bouzidi et al. (2002), Table 4

[18b] Bouzidi et al. (2002), Fig. 8

[18c] Bouzidi et al. (2002), Table 2

[19a] Hope and Eaton (2002), Fig. 13

[19b] Hope and Eaton (2002), Fig. 7

[19c] Hope and Eaton (2002), Fig. 17

[20] Villeneuve et al. (1993)

[23] Kelbert et al. (2009), Figure 2, global and regional conductivity profile, Canada or North America regional conductivity chosen

[24] Converted from resistivity obtained from listed reference source

[25] Converted from conductivity obtained from listed reference source

[32] Palacky (1988)

[33] Palacky (1992)

[34] Wu et al. (2005), Fig. 10

[34b] Wu et al. (2005), Fig. 13

[34c] Wu et al. (2005)

[35a] Nieuwenhuis (2011), Figs. 5.8

[35b] Nieuwenhuis (2011), Figs. 6.3

[36] Zelt (1989), Fig. 4.10

[36b] Zelt (1989), Fig. 4.34

Table A3.10 (continued)

1D Earth Resistivity Model Proximal for Alberta Zone 10 (Great Bear, Hottah, Fort Simpson)

[13] Hammer et al. (2011), lithospheric cross-section

[14] Lemieux et al. (2002) Fig. 13

[15] Gorman et al. (2002), Fig. 10

[16] Clowes et al., (2002), Fig. 8

[37] Welford et al (2001), Figs. 4, 11

[38] Eaton et al. (2000)

[39] Pana (2003)

[40] Wu et al. (2002)

NOTES:

* Depth Certainty

I = best representation

* overburden: geological report/map coverage of local area.

* crust: seismic/gravity transects crossing local area, within 10 km.

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 geophysical electromagnetic methods, including MT.

* crust: value obtained by regional MT survey.

III = possibly representative (measurements from general compilations).