GS2024-17

Initial results from a long-period magnetotelluric survey in the Flin Flon, Snow Lake and The Pas area, west-central Manitoba (NTS 63F, G, J, K, parts of 63B, I, N)

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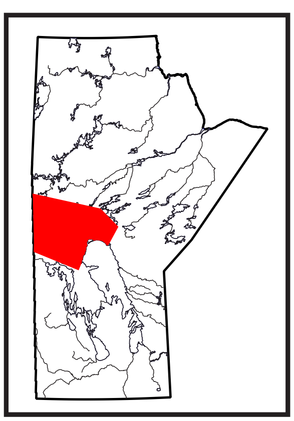
In Brief:
- Long-period magnetotelluric data was collected and will be used to produce a 3-D resistivity model of the lithosphere
- Conductive anomalies in the 3-D resistivity model will be interpreted using the mineral systems framework

Citation:
Chase, B.F.W., Marks, J., Williamson, A., Maki, A., Moshtaghian, K. and Unsworth, M.J. 2024: Initial results from a long-period magnetotelluric survey in the Flin Flon, Snow Lake and The Pas area, west-central Manitoba (NTS 63F, G, J, K, parts of 63B, I, N); *in* Report of Activities 2024, Manitoba Economic Development, Investment, Trade and Natural Resources, Manitoba Geological Survey, p. 145–152.



Summary

The Manitoba Geological Survey, in collaboration with the University of Alberta, is developing a model of the lithospheric structure beneath the province of Manitoba. Information about deep lithospheric structure cannot be obtained from drilling and requires deep sounding geophysical exploration. One of the most useful methods for this task is magnetotelluric exploration, which uses natural low-frequency electromagnetic signals to determine the electrical resistivity structure of the Earth to depths in excess of 200 km. A long-period magnetotelluric survey was conducted at 22 stations in June and July of 2024 in west-central Manitoba. The new data will be combined with long-period magnetotelluric data previously collected in Saskatchewan to produce a 3-D resistivity model of the lithosphere of the Trans-Hudson orogen beneath west-central Manitoba and central Saskatchewan. This 3-D resistivity model will improve the understanding of the factors that control the spatial distribution of mineralization and may also guide future exploration in the region.

Introduction

The crystalline basement rocks of Manitoba are part of the eastern margin of the Trans-Hudson orogen (THO) and include the boundary with the Superior craton (Figure GS2024-17-1). This part of Laurentia was assembled during the closure of the Manikewan Ocean in the Proterozoic, 1.9–1.8 Ga (Whitmeyer and Karlstrom, 2007). Lithotectonic units mapped in this region include the Flin Flon belt (FFB; part of the Flin Flon–Clearwater domain), the Kisseynew domain, the Superior boundary zone (SBZ) and several domains of the Superior province (i.e., Superior craton; Figure GS2024-17-1). The FFB is one of a series of volcano-sedimentary belts within the THO and includes a series of arc and oceanic-island basalts and successor-arc plutons (Lewry and Collerson, 1990; Conners et al., 1999; Syme et al., 1999; Whalen et al., 1999). It is commonly linked to the Glennie domain in Saskatchewan, and both are interpreted to have a similar tectonic origin (Clowes and Roy, 2021). The FFB is one of the most well-endowed volcanogenic massive-sulphide districts on Earth (Syme et al., 1999). The Kisseynew domain is the largest component of the THO in Saskatchewan and Manitoba and consists of metasedimentary and intrusive supracrustal units that are interpreted to have been deposited in a back-arc basin (Ansdell et al., 1995; Zwanzig et al., 2007). The Kisseynew domain formed over the FFB–Glennie domain crust, which was undergoing extension as a result of northward-directed subduction zone retreat (Clowes and Roy, 2021). The Kisseynew domain underwent tectonic collapse and thickening during accretion of the Sask and Superior cratons ca. 1.84 Ga (Ansdell et al., 1995; White et al., 2005). The SBZ is largely composed of supracrustal Paleoproterozoic continental rift margin rocks that first intruded through and were deposited on the attenuated edge of the Superior craton from 1.880 to 1.865 Ga, and these rocks were then later intruded by granitoids during terminal ocean closure, 1.836–1.726 Ga (Bleeker, 1990; Machado, 1990; Weber, 1990; Bleeker et al., 1995). The Thompson nickel belt is a prolific mining district located within the SBZ. The Superior province defines the eastern margin of the THO and is composed of a series of Archean blocks accreted together before ca. 2.6 Ga and separated by major structures or changes in metamorphic gradient (Percival et al., 2006, 2012).

The current understanding of the deep lithospheric structure of the THO is derived from geophysical studies that have used seismic, magnetotelluric (MT) and potential field exploration methods (e.g., Jones et al., 2005; White et al., 2005). In the THO, previous studies have been limited in their depth of exploration to within the crust, providing limited information about the lithospheric mantle. Another limitation of these studies is that they have generally used 2-D approaches to data analysis,

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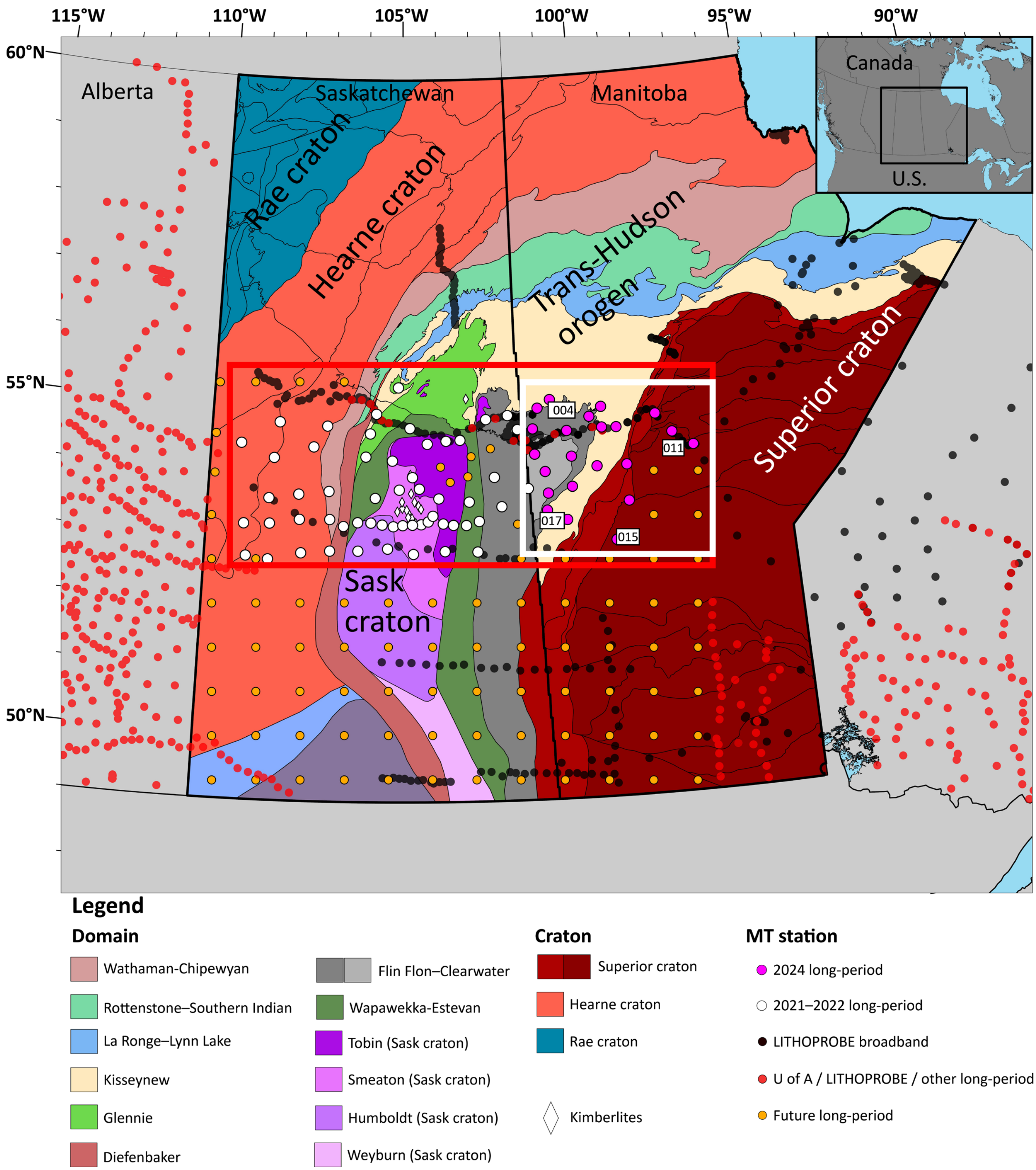

Figure GS2024-17-1: *Lithotectonic units of Manitoba and Saskatchewan. The Trans-Hudson orogen is composed of the various lithotectonic units between the Hearne and Superior cratons. Thin black lines indicate the boundaries of the domains within the Superior, Hearne and Rae cratons. Magnetotelluric (MT) data coverage is shown for the region (University of Alberta, unpublished data, 2024). Note that the LITHOPROBE or U of A long-period stations in Alberta represent stations where the data were collected for the LITHOPROBE program or by the University of Alberta (U of A), whereas in the rest of Canada, data were collected for the LITHOPROBE program or other programs. Data from the stations inside the red box will be used to create a 3-D resistivity model of the lithosphere of the Trans-Hudson orogen in this area. The white box defines the new long-period magnetotelluric (LMT) survey area shown in Figure GS2024-17-3. The numbered boxes correspond to the LMT stations displayed in Figure GS2024-17-4. Manitoba lithotectonic units modified after Manitoba Geological Survey (2022). Saskatchewan lithotectonic units modified after Saskatchewan Energy and Resources (2021).*

which provides limited information about the along-strike variability of the structure of the THO in Canada (e.g., White et al., 2002). In past studies, the structural complexity of the THO has led to differing interpretations of fundamental features, such as polarity of subduction (e.g., White et al., 2002). In the United States, the use of deep-imaging, whole-lithosphere–scale, geophysical methods in 3-D have helped improve the understanding of the structure of the southern THO (lat. 43–49°N). These data have highlighted that the structural complexity observed at shallow depths in the crust may have developed during late-stage deformation and may also overprint earlier structures at greater depth (e.g., Ye et al., 2019; Bedrosian and Finn, 2021). To improve the understanding of the THO in Canada, 3-D geophysical datasets that can produce images of the entire lithosphere are required.

The new long-period magnetotelluric (LMT) dataset described in this report addresses this goal and offers the ability to image the deep structure around regional mineral deposits and mining districts. The MT method is ideal for this task, given its sensitivity to common ore-related minerals and its ability to delineate regions altered by the passage of mineralizing fluids, which both often present as conductive anomalies (e.g., Heinson et al., 2018; Kirkby et al., 2022; Chase and Unsworth, 2024). Identified conductors can be interpreted within the mineral systems framework to efficiently select areas for continued mineral exploration (McCuaig et al., 2010; McCuaig and Hronsky, 2014).

There are two questions that the 2024 LMT dataset will address:

- What is the electrical resistivity structure of the eastern margin of the THO and adjacent area of the Superior craton?
- Are the low resistivity anomalies mapped with MT spatially associated with the occurrence of mineral deposits?

Previous studies

Geophysical studies of the deep lithospheric structure of the THO have taken place since the 1980s through the LITHOPROBE program (Clowes et al., 1999). The LITHOPROBE program collected multiple seismic reflection, seismic refraction and MT profiles across the THO (Figure GS2024-17-1). Critically, the seismic datasets were used to delineate terrane boundaries and determine the direction of subduction during closure of the Manikewan Ocean (e.g., Ansdell, 2005; White et al., 2005). The MT datasets were used in a similar manner and identified an extension of the North American Central Plains (NACP) conductor, a crustal anomaly that is related to the suture zone observed in the THO both in the United States and Canada (Jones et al., 2005; Bedrosian and Finn, 2021). The MT data also showed that the NACP conductor occurred beneath the La Ronge gold belt (central Saskatchewan), suggesting a connection between the conductor and mineral deposits (Jones et al., 2005). The LMT data collected in 2021–2022 (Figure GS2024-17-1), revealed a similar conductor beneath the Flin Flon region and suggested that regional-scale conductors were associated with a major conductor in the lithospheric mantle beneath the Sask craton (Chase and Unsworth, 2024).

Introduction to the magnetotelluric method

In mineral exploration, airborne or ground-based electromagnetic (EM) surveys are routinely used to locate electrically conductive anomalies related to mineralization (Simpson and Bahr, 2005). In these methods, the depth of investigation is limited by the skin depth, which is defined as

$$\delta = \frac{503}{\sqrt{\sigma f}} \qquad (1)$$

where δ is the skin depth (metres), is the electrical conductivity (the inverse of resistivity) of the Earth (siemens/metre), and is frequency (hertz) and the reciprocal of the period (seconds). These methods use a transmitter to generate the signals and the depth of investigation is typically limited to a few hundred metres.

For deeper imaging, it is most efficient to use natural low-frequency EM signals as they increase the depth of investigation (Equation 1), which is what is used during an MT survey. The MT method is similar to controlled-source EM methods but with some important distinctions. The first is that the MT method uses natural EM signals. At frequencies above 1 hertz (Hz), these signals come from global lightning activity, and below 1 Hz they are primarily generated by interactions between solar wind and the magnetosphere (Simpson and Bahr, 2005). The MT data are transformed during processing into the frequency domain to give apparent resistivity curves, which show the resistivity of the subsurface as a function of frequency. The frequencies collected in MT exploration are typically in the range of 10 000–0.0001 Hz (or 0.0001–10 000 seconds). In comparison, controlled-source EM methods use signals in the frequency range 100 000–100 Hz. This makes the MT method capable of imaging deeper structures than controlled-source EM methods. Magnetotelluric exploration uses three distinct frequency bands, depending on the target depth. The first is audio magnetotellurics (AMT), which has the frequency range of 10 000–1 Hz, and is useful for imaging the near surface, usually to depths of <1–2 km. The second is broadband magnetotellurics (BBMT), which has the frequency range of 1000–0.001 Hz, and is useful for imaging the crust and upper mantle. The final is LMT, which has a frequency range of 1–0.0001 Hz, and is capable of imaging the entire lithosphere. Long-period magnetotelluric data were collected for the 2024 study described in this report.

In the field, MT instruments record two orthogonal electric field components and three orthogonal magnetic field components as a function of time (Figure GS2024-17-2). In LMT systems, the magnetic fields are recorded with a single three-component sensor, whereas in BBMT and AMT systems they are recorded using three different sensors. The MT method is an ideal regional exploration tool that can be used to investigate mineral systems

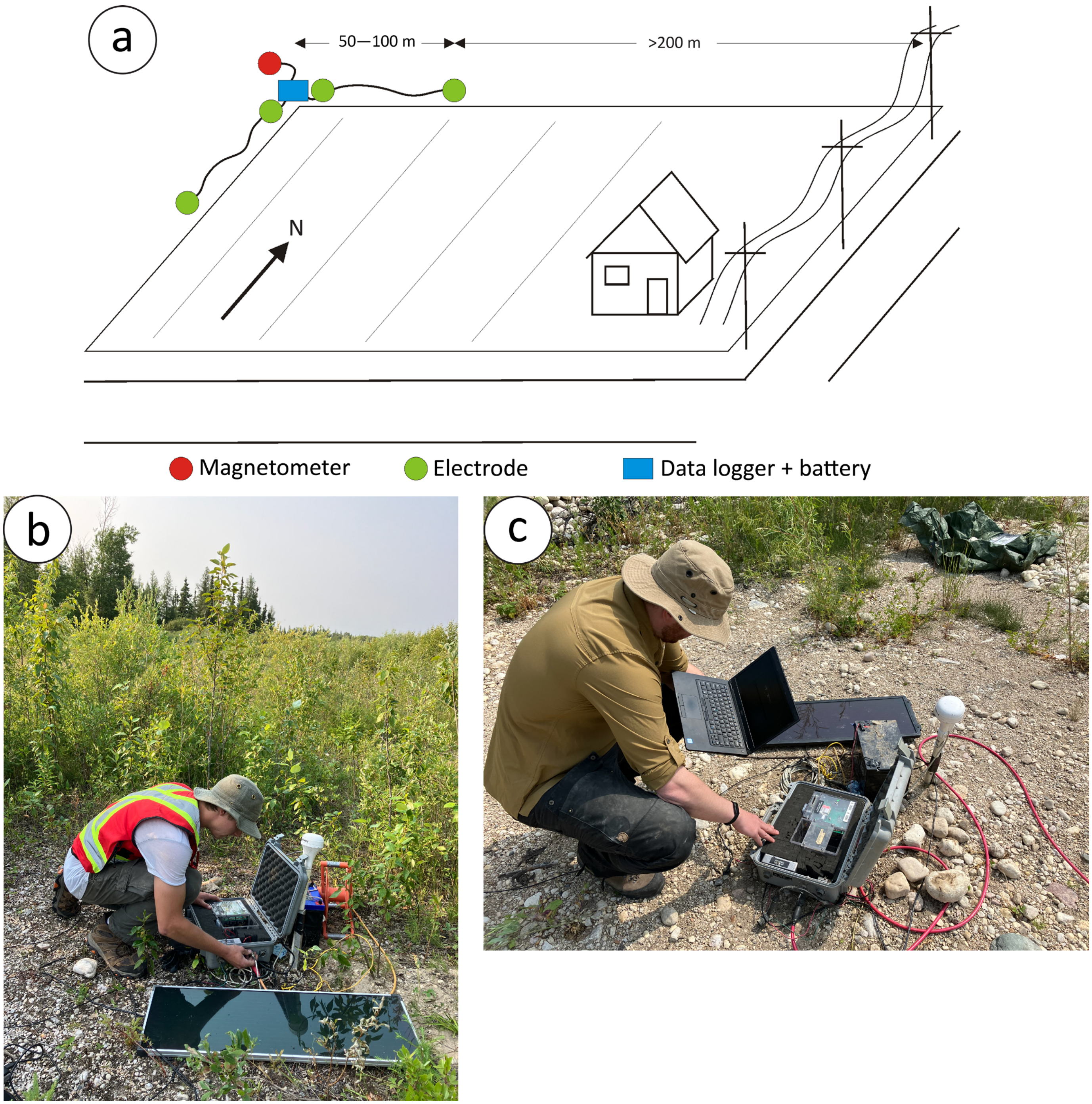

Figure GS2024-17-2: a) *Layout of a long-period magnetotelluric (LMT) station. Installation only requires digging 4–6 temporary holes in the ground to a depth of 30–40 cm. The station typically occupies an area that is up to 100 by 100 m in size;* ***b, c)*** *Examples of a LMT system (Narod Geophysics Ltd.'s Narod Intelligent Magnetotelluric System [NIMS]) being deployed in the field in Manitoba.*

on a range of spatial scales. This includes deposit- to lithospheric-scale studies that image the pathways taken by the fluids that formed a mineral deposit.

Magnetotelluric fieldwork

In the summer of 2024, LMT data were recorded at 22 stations in west-central Manitoba with an average station spacing of 50–70 km (Figure GS2024-17-3). At each location, the LMT station recorded data for 10–15 days. The data were recorded with Narod Geophysics Ltd.'s Narod Intelligent Magnetotelluric System (NIMS) LMT instruments. Following best practices for LMT data collection, the electrodes were buried 30–40 cm below the surface to avoid the effects of daily temperature variations and precipitation. Bentonite was placed in the electrode holes to improve electrical contact with the ground. Stations were time synchronized using GPS in order to allow for comparison of the time-series data and the removal of noise. Stations were installed at least 0.5–1 km away from major infrastructure to minimize

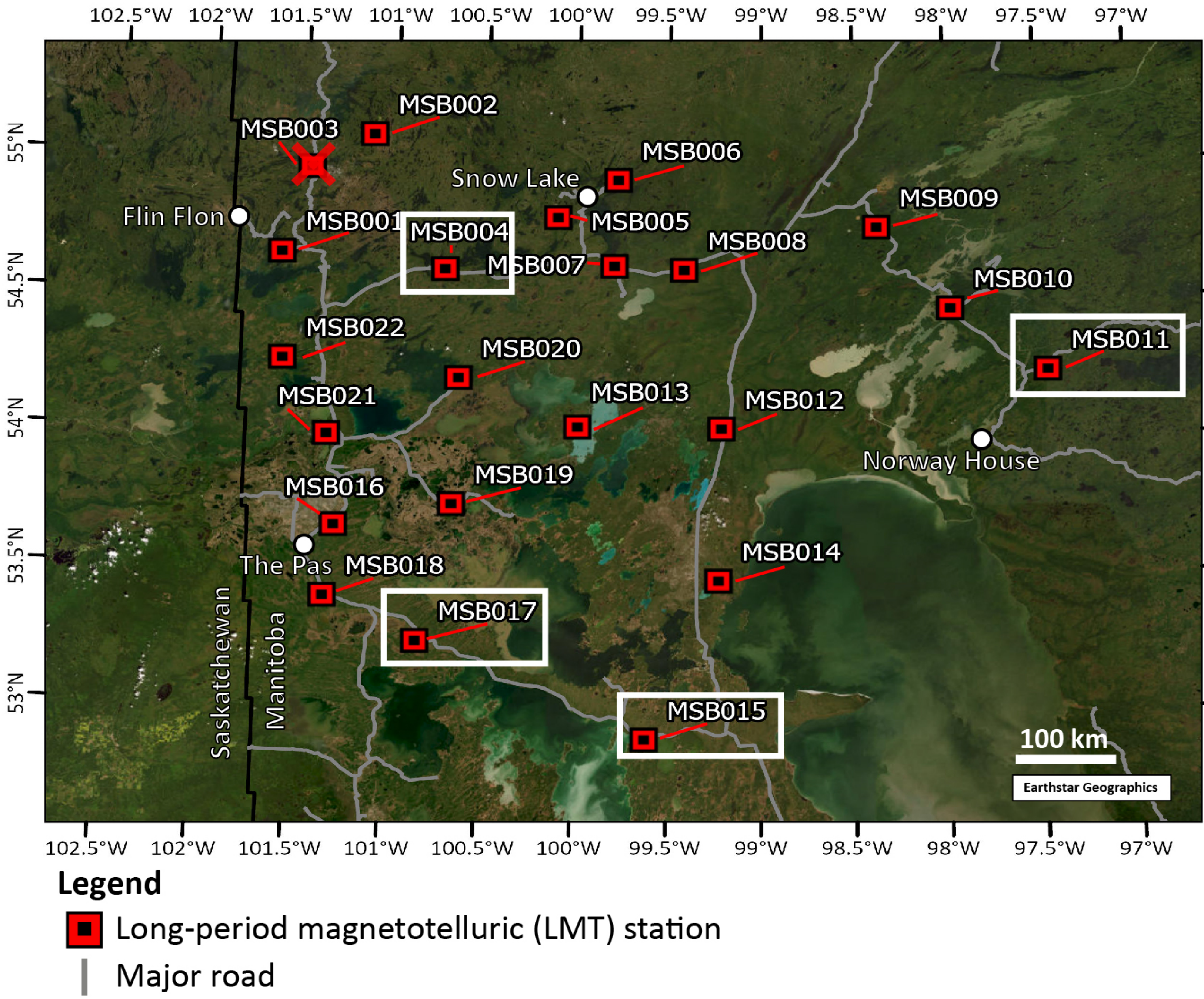

Figure GS2024-17-3: *Distribution of the long-period magnetotelluric (LMT) stations installed in 2024 in west-central Manitoba. The red X on station MSB003 indicates that it was excluded from the 3-D inversion process due to poor data quality. White boxes correspond to the LMT stations in Figure GS2024-17-4. Basemap was created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri software, please visit <https://esri.ca/>.*

cultural noise. Each station produced 100–220 Mb of time-series data.

Magnetotelluric data analysis

After data processing, reliable apparent resistivity curves were obtained in the period range 5–10 000 s. Data from one station (MSB003, Figure GS2024-17-3) were not used due to poor quality because of equipment failure. Figure GS2024-17-4 provides examples of data from the 2024 LMT survey. At each of these stations, the resistivity from the shallow data (high frequency) is in the range 100–10 000 ohm-metre (Ω•m; Figure GS2024-17-4), as expected in a shield environment with crystalline upper crustal rocks. Data from stations MSB004 and MSB011 show similar resistivity values but MSB004 has slightly lower values, likely reflecting a more conductive lithosphere within the THO (Figure GS2024-17-4a). Data from station MSB011, the farthest east, show the highest resistivity values, likely due to it being located on the Superior craton (Figure GS2024-17-4b). The decreasing resistivity values exhibited at longer periods are likely associated with conductive features in the region. Stations MSB015 and MSB017 are located along the southern margin of the survey area and the data show evidence of a conductor at mid-periods (Figure GS2024-17-4c, d). A 2-D or 3-D resistivity structure is indicated by the XY and YX curves diverging as a function of frequency. If the resistivity structure was 1-D, the curves would be coincident.

The LMT data were measured as a function of frequency and need to be converted into a resistivity model as a function

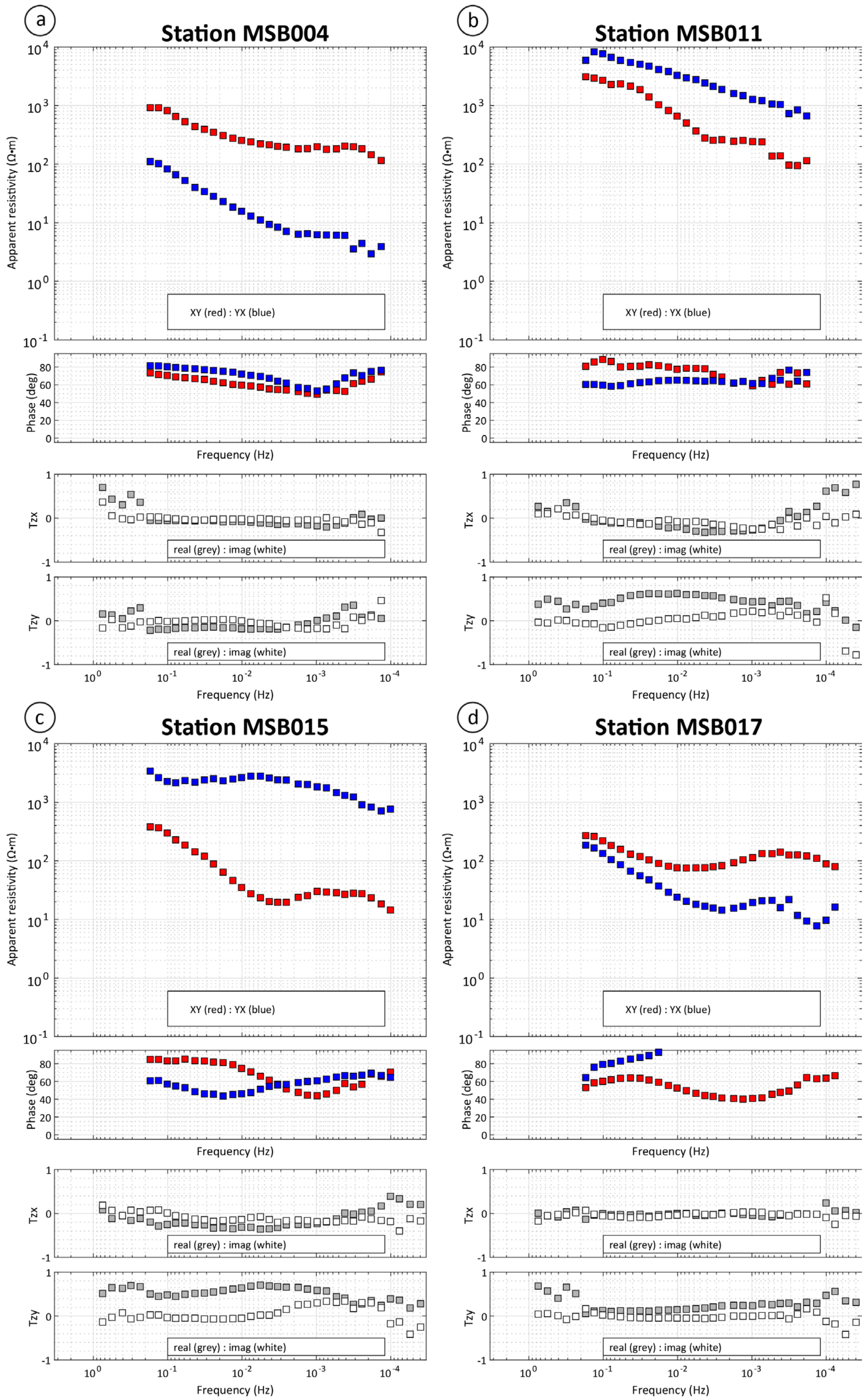

Figure GS2024-17-4: *Apparent resistivity and phase curves as a function of frequency for four long-period magnetotelluric (LMT) stations installed as part of this study:* ***a)*** *station MSB004;* ***b)*** *station MSB011;* ***c)*** *station MSB015;* ***d)*** *station MSB017. The apparent resistivity curves are obtained from the ratio of components of the electric and magnetic field measurements. The X and Y correspond to measurements of these fields in the north-south and east-west directions, respectively. Red curves are the traverse electric mode, which is highly sensitive to conductive features. Blue curves are the transverse magnetic mode, which is sensitive to both resistors and conductors, but the latter less so than the transverse electric mode. The functions labelled Tzy and Tzx are the components of the tipper (T) and are computed from the ratio of vertical (z) to horizontal (x and y) magnetic field components. The tipper is highly sensitive to conductive features. The real and imaginary (imag) components of the tipper are the in-phase and quadrature components, respectively. The locations of the stations chosen are shown in Figures GS2024-17-1 and -3. Abbreviations: Ω•m, ohm-metre; deg, degree; Hz, hertz.*

of depth and horizontal distance using a process called inversion. The LMT data collected in Manitoba show some 3-D characteristics (Figure GS2024-17-4) thus a 3-D inversion approach must be used. The 3-D inversion models are produced using the ModEM (Modular system for Electromagnetic inversion) algorithm of Kelbert et al. (2014). Computer resources are provided by the Digital Research Alliance of Canada. Some initial inversions have been completed and resulting models show that a number of crustal conductors are located in the central portion of the new data grid approximately 30–80 km east of The Pas. A major lithospheric conductor is also present beneath the Snow Lake mining district; it is similar to those observed by Chase and Unsworth (2024) beneath the mining districts around Flin Flon and La Ronge.

Future work

The inversion of the new LMT data collected in Manitoba is still in progress. The planned research will combine the 2024 LMT data with the LITHOPROBE (Jones et al., 2005) and Chase and Unsworth (2024) MT datasets. The integrated dataset will be inverted to produce a resistivity model that includes as much of the previously collected data as possible. The resulting 3-D resistivity model will be evaluated with a sensitivity analysis to determine which model features are required. This will be followed by a systematic interpretation of the 3-D resistivity model. Conductive anomalies in this model will be quantitatively interpreted to determine the cause. Anomalies present in the crust will be evaluated using data from regional geology maps and drillcore and geophysical data, allowing for a better understanding of the structural controls related to their formation and how they may relate to regional mineralization. The 3-D resistivity model will be interpreted within the mineral systems framework (e.g., McCuaig et al., 2010; McCuaig and Hronsky, 2014) to determine the factors that control the spatial distribution of mineralization. In the long term, it is planned to extend the LMT survey across southern Manitoba and Saskatchewan (Figure GS2024-17-1). This grid of LMT stations can then be combined with the EarthScope MT array in the contiguous United States (Murphy et al., 2023). This will produce a 3-D resistivity model of the lithosphere of the entire THO, which will improve tectonic evolution models for North America.

Economic considerations

The MT resistivity model developed by Chase and Unsworth (2024) for central Saskatchewan shows the presence of several major lithosphere conductors beneath Flin Flon and the La Ronge gold belt. These conductors are connected to an underlying conductive anomaly located in lithospheric mantle beneath the Sask craton. These conductors were interpreted to be due to the presence of sulphide minerals and graphite films deposited by past episodes of fluid flow in the lithosphere. These sulphide minerals may contain economically important base and precious metals (e.g., Tomkins and Evans, 2015; Walters et al., 2020). Ultimately, these conductors may explain why economic mineralization is concentrated beneath the La Ronge gold belt and Flin Flon. The new LMT data suggest that a conductor is present in the study area in Manitoba and appears to have a similar nature to the previously reported conductors in Saskatchewan. This may suggest there are regional whole-lithosphere controls on the distribution of mineralization in this region of the THO. Additional conductors were detected beneath the thin Phanerozoic sedimentary cover both east of The Pas and in Saskatchewan (Chase and Unsworth, 2024). These may indicate additional zones of mineralization that have not been previously investigated.

Acknowledgments

The authors thank the Manitoba Geological Survey for logistical support and K. Reid, T. Martins, T. Kennedy and G. Keller are acknowledged for logistical support, assistance in survey planning and communication with local communities about the survey. The authors thank T. Hodder, K. Reid and T. Martins for reviews of this report. C. Steffano is thanked for the layout of the report. C. Epp and P. Belanger are thanked for their assistance with vehicle and equipment maintenance. RnD Technical is thanked for technical editing assistance.

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