Towards the imaging of deep land ore deposits with ERT-IP method – first results from a demonstration survey in Finland

Vers l'imagerie de gisements minéraux terrestres profonds avec la méthode ERT-IP - premiers résultats d'une campagne démonstratrice en Finlande

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Abstract. In this study, we conducted a comprehensive geophysical survey near Kuusamo (Finland) to assess the potential of electrical resistivity methods in delineating mineral deposits at depths greater than 1 km. Preliminary investigations, including magnetic and gravity methods as well as drilling, revealed significant anomalous structures in the survey area. We employed multiple electrical and electromagnetic methods at the site, comprising controlled-source electromagnetic (CSEM), magnetotelluric (MT), electrical resistivity tomography (ERT), and induced polarization (IP). To obtain the geophysical data in very large-scale area, we used a total of 25 transmitter dipoles with 1km long using three distinct transmitter systems and recorded data at 119 receiver stations. In this paper, we present the acquisition and preliminary results from ERT-IP. Analysis of the resistivity and IP responses revealed notable IP signals at depths exceeding 1.5 km. Meanwhile, the resistivity data indicated generally very high values, around 10,000 ohm-m, with complex variations observed near the surface.

Résumé. Dans cette étude, nous avons mené une campagne géophysique de grande envergure dans la région de Kuusamo (Finlande) pour évaluer le potentiel des méthodes de résistivité électrique afin d'imager des dépôts minéraux à des profondeurs supérieures à 1 km. Des investigations préliminaires en 2022, incluant des méthodes magnétiques et gravimétriques ainsi que des forages, ont révélé des structures anormales significatives dans la zone d'étude. Nous avons alors employé plusieurs méthodes électriques et électromagnétiques sur le site, comprenant l'électromagnétique à source contrôlée (CSEM), la magnétotellurique (MT), la tomographie de résistivité électrique (ERT) et la polarisation provoquée (IP). Pour obtenir les données géophysiques dans une zone très vaste, nous avons utilisé un total de 25 dipôles émetteurs d'une longueur

de 1 km en utilisant trois systèmes émetteurs distincts et enregistré des données à 119 stations de réception. Dans cet article, nous présentons l'acquisition et les résultats préliminaires de l'ERT-IP. L'analyse des réponses de résistivité et IP a révélé des signaux IP notables à des profondeurs dépassant 1,5 km. De plus, les données de résistivité présentaient généralement des valeurs très élevées, autour de 10 000 ohm-m, avec de fortes hétérogénéités observées près de la surface.

1 Introduction

A geophysical survey was carried out over a layered mafic igneous complex in Finland, aimed at delineating possible host rocks of deposits holding Critical Raw Materials (CRM) at considerable depths (exceeding 1 km). Preliminary geophysical investigations (gravity, magnetics, Audio-MT) revealed significant geophysical anomalies, that are related to a deep-seated continuation of the mafic-ultramafic intrusions outcropping 20 km east and west from the survey site. An exploration hole has been drilled subsequently and showed some positive lithological evidence for the presence of deep-seated mafic intrusive rocks at more than 1.5 km depth. Data from this drillhole indeed revealed that the Archaean basement gneiss extends down to approximately 510 m, underlain by a granite dyke with interspersed thin layers of pyroxenite and peridotite. Notably, peridotite layers at about 1500 m depth exhibited distinct magnetic and IP responses in the petrophysical laboratory measurements.

This study presents the results of a ground-based electromagnetic (EM) survey aiming at pushing the depth of investigation of conventional EM exploration methods. We employed multiple electrical and electromagnetic methods at the site, including controlled-source electromagnetic (CSEM), (radio-)magnetotelluric (R/MT), time domain electromagnetic (TEM), electrical resistivity tomography (ERT), and induced polarization (IP). In this paper, after presenting the survey setup, we report on the results of the ERT-IP survey only.

2 Geophysical surveys for deep mineral exploration

Table 1. Summary of the field survey.

	Transmitter system	**Receiver system**
Instrument [No. station]	Zonge GGT3 Phoenix TXU-30 IRIS TIP6000	Metronix ADU07-e and ADU08-e [18] SERCEL RAU + BRGM adaptor [83] IRIS VFullwaver [18]
Dipole spacing	~1 km	50 m
Electrode	Steel	Non-polarizable / Steel (a few part)
Source frequency [Hz]	0.0625, 0.125, 0.5, 2, 8, 32, 128, 512	

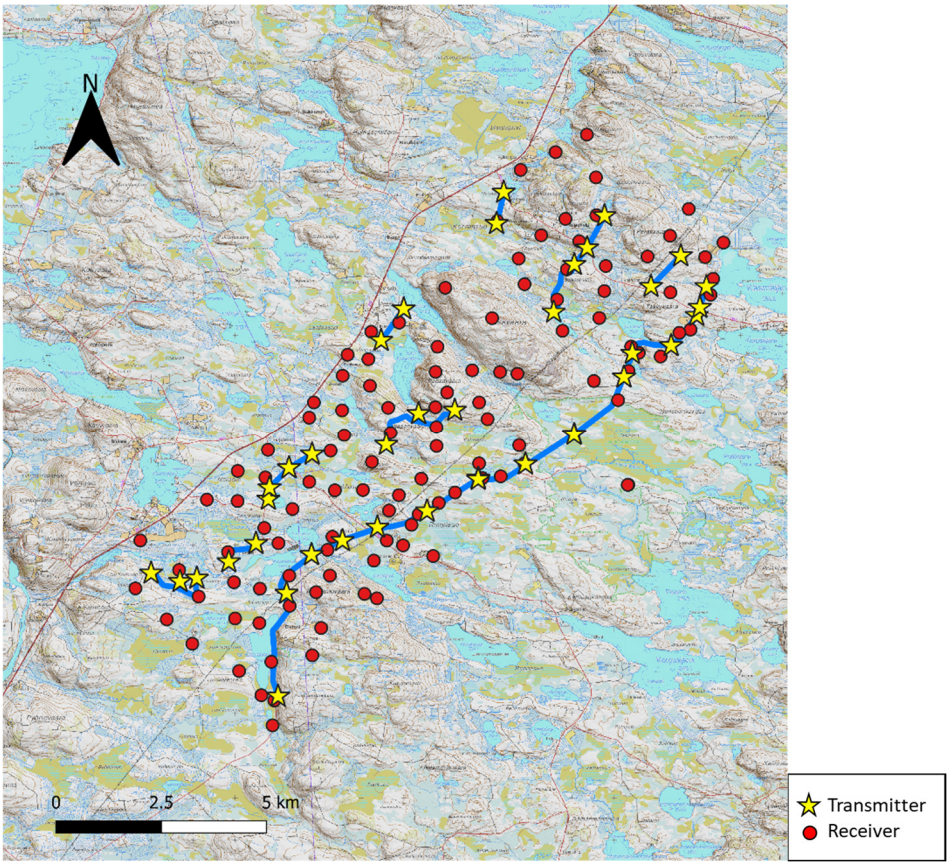


Fig. 1. The field site map. The yellow star represents transmission point and the red circle represents receiving point.

Fig. 1 shows the survey geometry with receiver locations (in red) and transmitter cable and electrode locations (in blue/yellow respectively). For CSEM and ERT-IP, 25 transmitters operated from August 25 to 29, 2023, employing three different transmitter instruments depicted in Fig. 2: GGT3 from Zonge, TXU-30 from Phoenix, and TIP6000 from IRIS. The average injection current amplitude was 3-4 A for the GGT3 and the TIP6000, and 7-8 A for the TXU-30. The dipole lengths averaged 1 km (see Fig. 1). For each grounding injection point depicted in Fig. 1, seven 1-meter-long stainless-steel electrodes were planted into the ground, spaced approximately 1.5 m apart, and connected to the main cable in parallel. Only one transmitter at a time, we injected a sequence of square waveforms in ascending order at frequencies of 0.0625, 0.125, 0.5, 2, 8, 32, 128, and 512 Hz, for a total duration of 1 hour. Notably, only 0.0625 Hz corresponded to a square waveform with a 50% off-duty cycle and the others used 100% off-duty cycle.

(a) (b) (c)

Fig. 2. Transmitter instruments: (a) GGT3 (Zonge), (b) TXU-30 (Phoenix), and (c) TIP6000 (IRIS).

Three distinct recording systems logged data continuously with different sampling frequencies: 18 ADUs (ADU07-e and ADU08-e from Metronix) at 4096 Hz, 83 RAUs (from Sercel+BRGM adapter) at 2000 Hz, and 18 VFullwavers (FWV from IRIS) at 100 Hz. Although the RAU system was originally designed for seismic data recording, it was adapted to record the electric field using a homemade preamplifier. FWVs were aligned along the main southern road, while RAUs and ADUs were set up in 3D geometries.

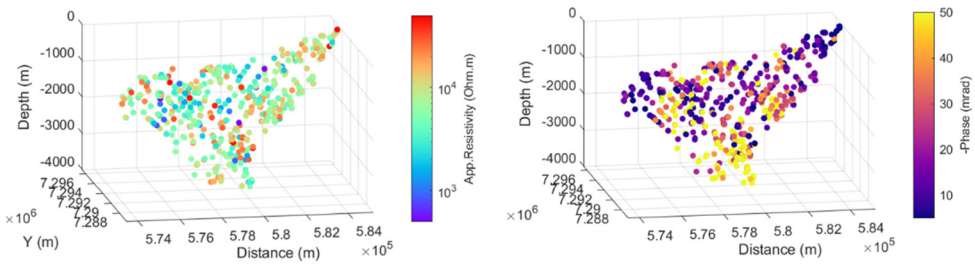
All 119 receivers recorded the two horizontal electric field components (Ex and Ey) using non-polarizable electrodes or stainless-steel electrodes in swamps. In addition, in order to compute MT transfer functions (impedance tensor and tipper), ADUs recorded the three magnetic field components (Hx, Hy, Hz) using induction coils. To minimize local noise in MT data, remote reference processing was applied using reference data.

3 Result

In the processing of ERT and IP data, we utilized full time-series data recorded across the four lowest main frequency of 0.0625 Hz to 8Hz to harness voltage data in a steady state. The ERT data processing was conducted using BRGM/IRIS software 'Jalien' [1]. Apparent resistivity data were derived from the stacked voltage data. IP data were initially extracted from the decay curves of these stacked voltage data and subsequently processed in the frequency domain.

An ERT dataset was extracted from the recorded signals, adopting an original principal component-based filtering approach for the time series. IP data was collected in the form of decaying curves from full time series data, using 50% duty cycle of source waveform and without-phasing. To interpret IP characteristic of the field site, we utilized phase data obtained from the processed time-series data in the frequency domain.

In this study, we firstly analyzed ERT-IP data from VFullwaver system with 8 s source waveform period. The apparent resistivity data generally indicated very high resistivity values, approximately 8000-10000 ohm-m. Data near the surface showed a complex mix of highly resistive and conductive values. In contrast, phase data revealed a distinct anomalous region with a maximum absolute value of 368 mrad, especially at depths greater than 2 km. Additionally, a reversed V-shape feature was observed in the middle of the profile, starting from the shallow depths.



(a) (b)

Fig. 3. 3D pseudo-sections of (a) apparent resistivity and (b) phase data.

The data were inverted using the open-source code 'pyGimLi' to obtain a 3D resistivity model. Datasets with negative apparent resistivity or very low voltage, under 0.1 mV, were excluded. The inversion, which included a maximum of 4 iterations, was performed using 594 filtered data and unstructured mesh comprising 294,864 cells, applying basic roughness constraints.

The recovered resistivity model generally displays high resistivity values near 10000 ohm-m (Fig. 4). Near-surface resistivity distribution appears complex, as evident in the pseudo-section. The depth of investigation extends to approximately 2.5 km. The 3D resistivity model was then compared with a synthetic geological model built on existing geophysical and geological data. This anticipated geological model features a dome-shaped mafic intrusion within a granite structure. We do not observe any clear correlation between the intrusion and resistivity anomalies. However, the IP anomaly seems to correlate well with the intrusion. Future studies will aim to refine this model by performing inversions that incorporate IP-data and constraints derived from the geological structures.

4 Conclusion

In this research, we carried out a comprehensive suite of geophysical surveys – including Controlled-Source Electromagnetic (CSEM), Magnetotelluric (MT), Electrical Resistivity Tomography (ERT), and Induced Polarization (IP) – to assess the potential of various electrical resistivity methods to map a mineral deposit located at more than 1 km beneath the surface near Kuusamo (Finland). For an extensive survey of the large field area, 25 transmitter stations, utilizing three different transmitter systems, were deployed, and data were recorded at 119 receiver stations.

The ERT dataset, extracted from the recorded signals, benefited from an innovative principal component-based filtering technique applied to the time series. IP data were gathered as decay curves from the complete time series dataset. The analysis of the resistivity and IP responses uncovered significant IP signals at depths greater than 1.5 km. Concurrently, the resistivity data generally displayed very high values, approximately 10000 ohm-m, alongside complex variations near the surface.

This study serves as a valuable case example demonstrating that ERT and IP methods can effectively delineate deep-seated mineral deposits, offering comparable results to CSEM and MT methods. Notably, the deep-depth IP responses were particularly striking. Future work will involve a comparative analysis of these findings with geological data obtained from borehole investigations.

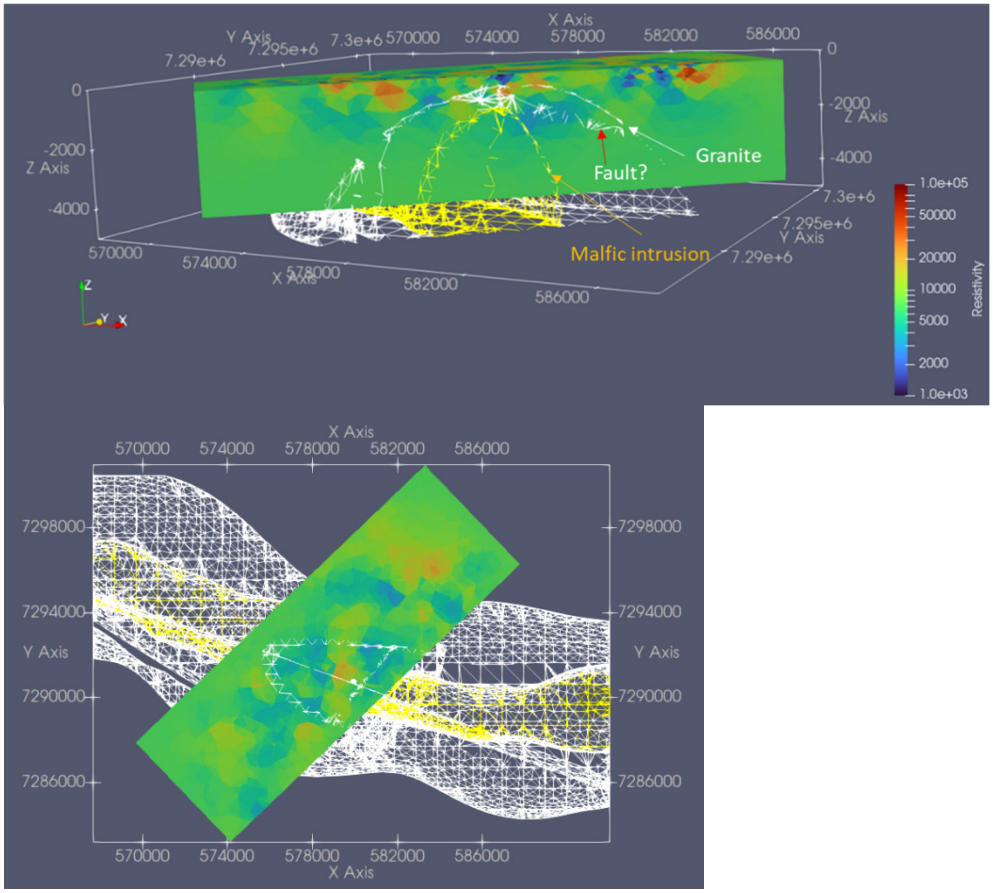


Fig. 4. Ross section near the profile of VFullwaver from the recovered 3D resistivity image and a depth slice at 1000 m. White mesh and yellow mesh represent granite and mafic intrusion models, respectively.

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