GTK Open File Work Report 97/2018

17.12.2018

Geophysical surveys in the vicinity of the Kotalahti mine tailings landfill

Jouni Lerssi

Taija Huotari

GEOLOGICAL SURVEY OF FINLAND Applied Geophysics	GTK Open File Work Report 97/2018
	17.12.2018

GEOLOGICAL SURVEY OF FINLAND	**Description letter**
	2018-12-17

Authors Jouni Lerssi and Taija Huotari		Type of report Open file work report Commissioned by Finnish Mine Water Competence Network	
Title of report Geophysical surveys in the vicinity of the Kotalahti mine tailings landfill			
Abstract The purpose of this investigation was to find out and map seepage paths from Kotalahti mine tailings landfill southward to Lake Valkeinen. The used geophysical methods in this research were resistivity pitchfork (model Puranen), electromagnetic planewave VLF-R and frequency domain GEM-2 and as the main method multielectrode Electrical Resistivity Tomography (ERT). Near surface seepage was clearly observed by electromagnetic GEM-2 measurements. The near surface seepage and possible deeper parts of the seepage were extracted and mapped by VLF-R measurements. Further, conductive zone at the edge of gabbro was detected by VLF-R and ERT measurements. The near surface seepage and possible deeper parts of the seepage were extracted and mapped by ERT measurements. Despite of complex bedrock geology, on the grounds of research results it was possible to detect significant seepage of conductive waters from tailings landfill area into the Lake Valkeinen. These have remarkable impact on the contamination of this small (20 hectares) lake.			
Keywords Mine tailings landfill, Seepage water paths, Contamination, Geophysical measurements, Electromagnetic methods, Electrical resistivity tomography			
Geographical area Leppävirta, Kotalahti			
Map sheet N5223			
Report serial GTK Open File Work Report		Archive code 97/2018	
Total pages 26	Language English	Price 0 €	Confidentiality Public
Unit Applied Geophysics		Project code 50403-30024	
Signature/name Heikki Vanhala		Signature/name Jouni Lerssi	Taija Huotari

Contents

Table of Contents

1 INTRODUCTION

1.1 Introduction and background

This research is part of EAKR project Mine Water Excellence Network. The purpose of investigations was to find out and map seepage paths from Kotalahti mine tailings landfill towards to south to Lake Valkeinen. Lake Valkeinen is contaminated in the pore and overlying waters and is permanently stratified (Kauppila et. al, 2017).

Kotalahti nickel mine, located few kilometers to north-west from the investigation area, operated during the years 1959 – 1987. Outokumpu company owned the mine and in addition to nickel it produced copper. After operation the metal content of mine waters spreading to site environment, especially nickel, has stayed at high level.

Previous geophysical research in the investigation area and its surround include the standard low elevation airborne mapping (GTK, 1992) and ground magnetic and electromagnetic slingram measurements made by Outokumpu company in 1969. MaxMin frequency domain measurement in the tailings landfill area was done in 2013 (Pasanen et. al, 2013). Geological and environmental investigations include: Aatos et. al, 2004 and Järvinen, 2013. The area is now claimed by Boliden company, which has active exploration in the area.

The used geophysical methods in this research were resistivity pitchfork (model Puranen), electromagnetic planewave VLF-R and frequency domain GEM-2 and as the main method multielectrode Electrical Resistivity Tomography (ERT).

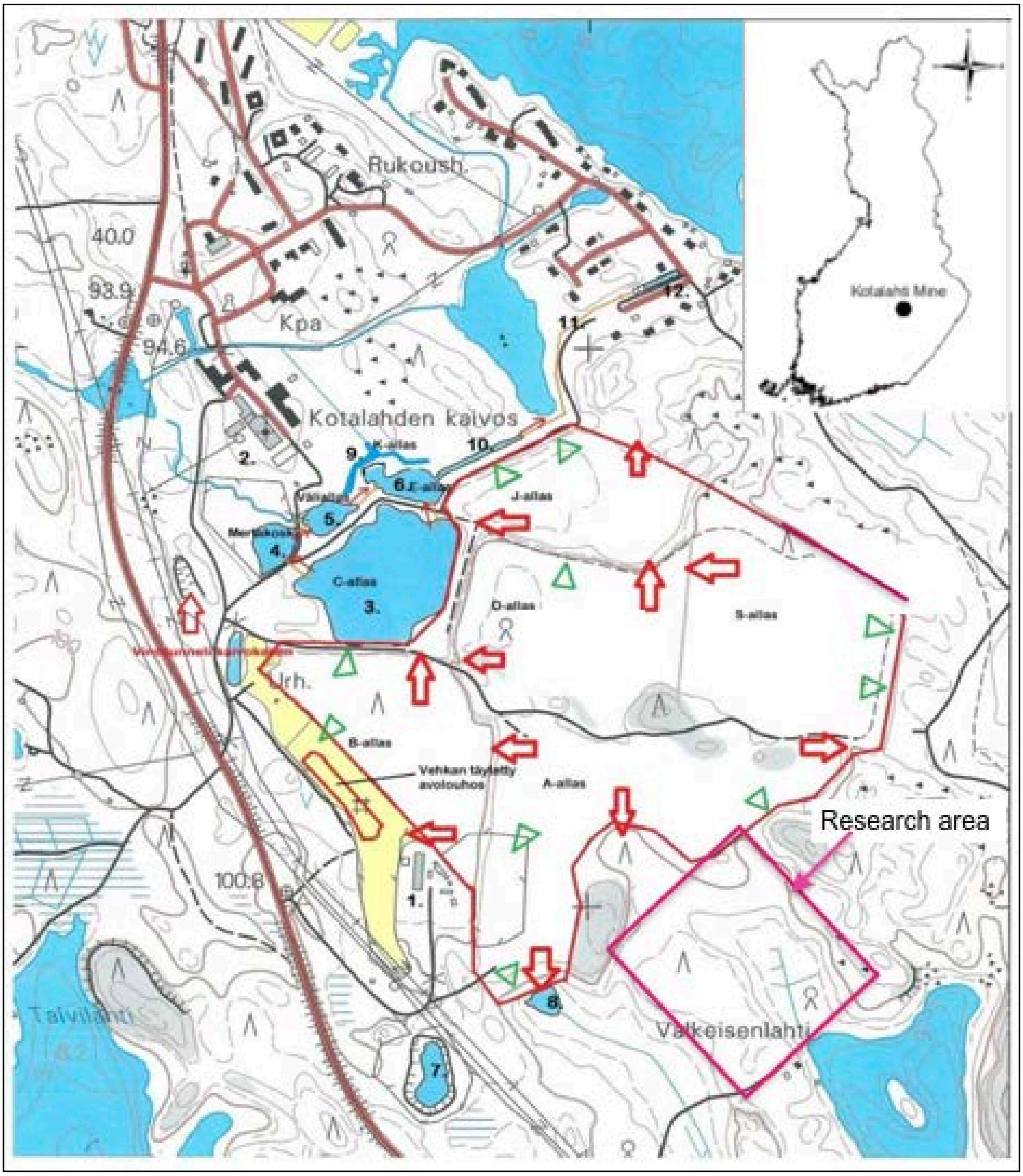

Figure 1. Research area and modified picture from the degree work by Timo Järvinen, showing the spread directions of mine waters from the tailings landfill. Green triangles indicate subterranean seepage directions and red arrows surface seepage directions.

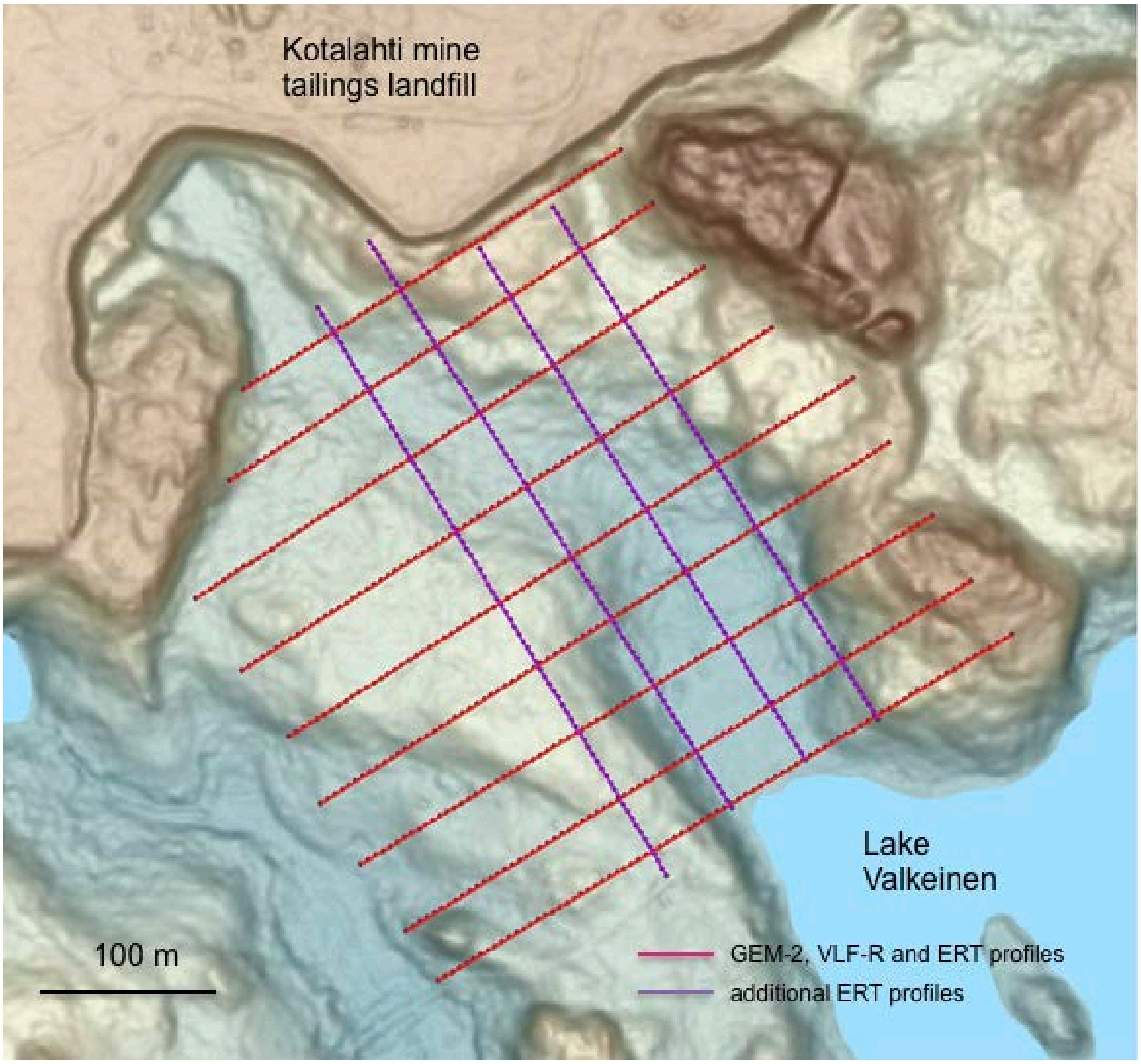

Figure 2. Research area and measured VLF-R, GEM-2 and ERT profiles. Basemap: LiDAR data © National Land Survey of Finland 2016.

1.2 Geology of Kotalahti area

The Kotalahti area is characterized by the Kotalahti Dome which is composed of Archaean gneiss surrounded by a Palaeoproterozoic craton-margin supracrustal sequence of quartzites, limestones, calc-silicate rocks, black schists and banded diopside amphibolites.

Metamorphism reached the amphibolite facies, causing gneissose and migmatitic textures in the supracrustal rocks. Several nickel deposits have been found in the Kotalahti area and in its close vicinity. The Kotalahti and Rytky nickel deposits are hosted by gabbro-peridotite intrusions in the contact zone of the Archaean gneiss and Palaeoproterozoic rocks. The main host rocks for the nickel ore are peridotites and metapyroxenites (Makkonen, 2017).

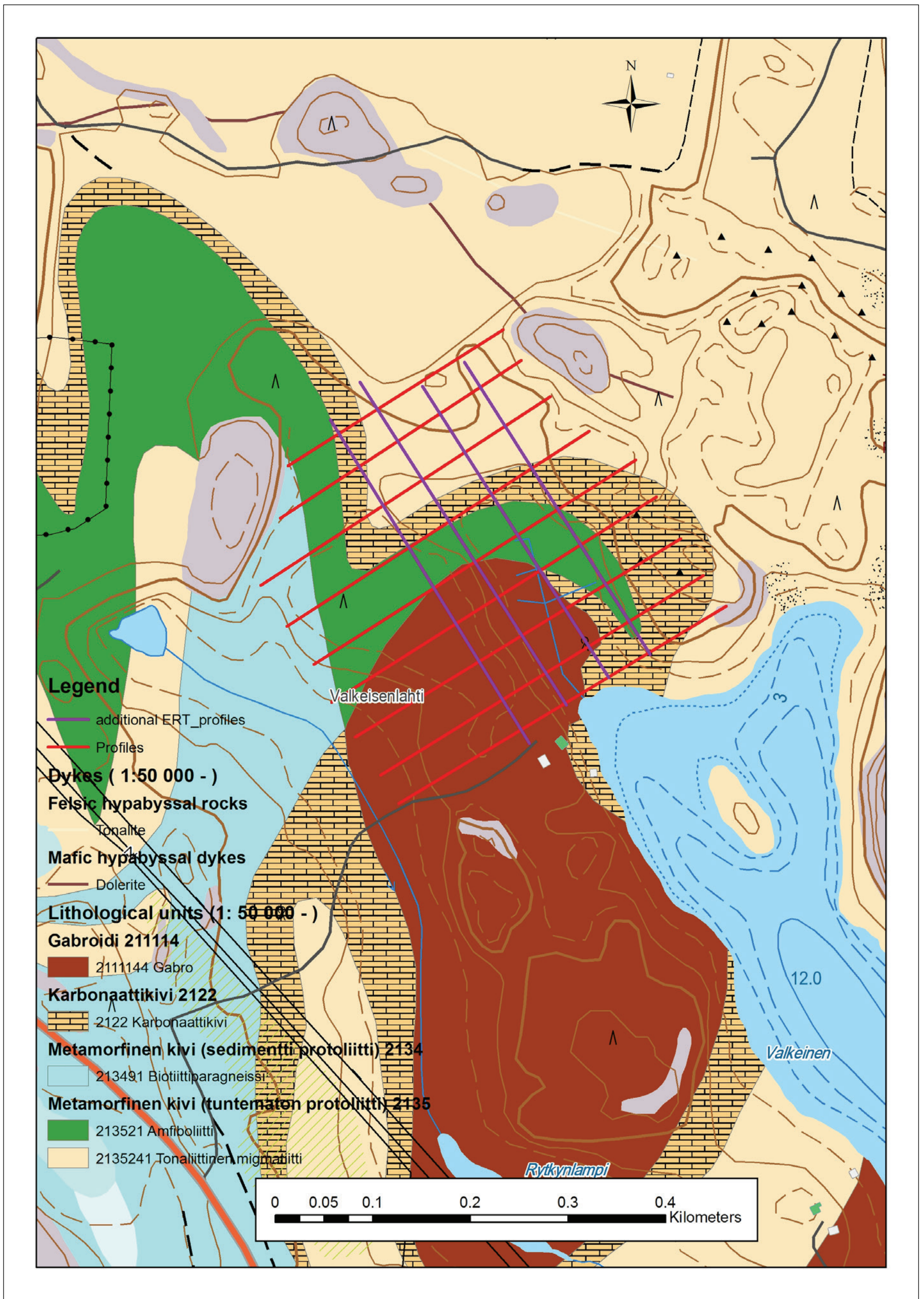

Figure 3. Geology of the research area and the measured profiles (Bedrock of Finland – DigiKP 2018).

1.3 Technical specifications of used geophysical methods

<u>Resistivity fork</u>

The resistivity fork is formed by a Wenner electrode array (48 cm long) and its electrode spikes are 11 cm long (Fig. 4). Resistivity fork gives resistivity estimate for the uppermost, layer of the overburden, mainly for a depth range of 0 - 30 cm. The most reliable measurement range of apparatus is from 5 to 5000 ohmm (Puranen et al., 1999).

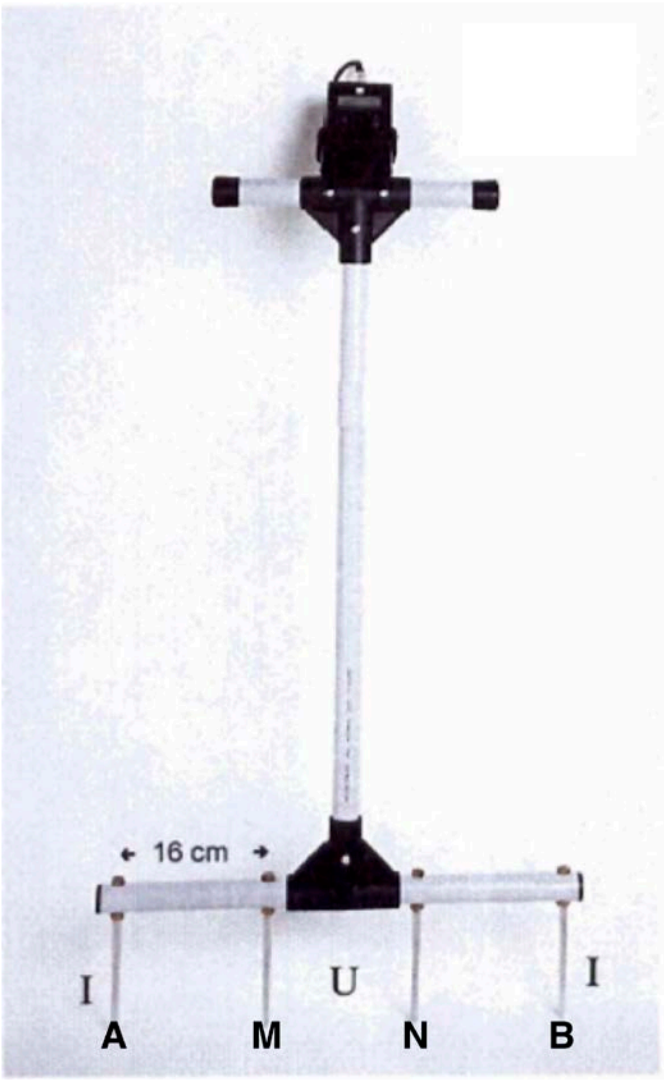

Fig 4. Resistivity fork.

GEM-2

The used equipment was terrain conductivity meter GEM-2, which is a lightweight frequency domain electromagnetic system using the frequency band of 300 - 96000 Hz. Three to 10 frequencies can be measured at the same time. The equipment was introduced in 1996 (Won, et.al, 1996). Detailed brochures of the equipment can be found in Geophex (2016) and the field example in Lerssi, et.al (2016). GEM-2 was used for mapping the electrical conductivity of uppermost ground surface. It is very suitable especially for fast mapping, for example to map the contaminated water paths and plumes.

The unit uses the pulse-width modulation technique to transmit and receive any digitally-synthesized waveform (Won et. al, 1996, Witten et. al, 1997, Huang et. al, 2003, Geophex Ltd., 2016). GEM-2 has the separation of 1.66 m between the transmitter and receiver. Depth of exploration is about 10 m depending on ground conductivity, target volume and ambient electromagnetic noise. At normal walking speed station spacing along the line is about 10 cm. Sensor is controlled and readings are stored into the handheld socket mobile computer (Somo 655) using bluetooth connection. GPS information is received from bluetooth GPS using serial to bluetooth adapter. So no cables are needed during the survey. Readings are exported to csv- files, from which they can easily be imported to processing and interpretation softwares (e.g. Oasis Montaj etc.). The equipment is especially suitable for environmental mapping and detecting of contamination plumes.

In this research 4 frequencies (1475, 5825, 22225 and 75525 Hz) were used for mapping the electrical conductivity of uppermost ground surface at 9 profiles (fig. 2).

VLF-R

The VLF resistivity (VLF-R) method uses the plane wave originating from distant radio transmitters (15 – 25 kHz) as the source field. Method is very suitable for mapping weak conductors and fracture zones in resistive environment. The depth extent of the method is also good (in favorable situations up to 300 m). All VLF-R measurements have been made with the Canadian GEONICS EM 16-R system using station DHO38 (23.4 kHz), located in north Germany, as the source field. A two-layer inversion is routinely employed in interpreting the data in addition to traditional resistivity and phase contour maps. In this research 9 profiles were measured in summer 2016 (fig. 2).

Electrical resistivity tomography:

In the Electrical Resistivity Tomography (ERT) measurements was used 12-channel ABEM Terrameter LS with Lund Imaging cable system. The used electrode array was multiple gradient electrode array (sort of combination of Schlumberger and pole-dipole array, see Fig. 3). The basic positioning of the profiles was made by high accuracy GPS and hand held GPS. The minimum electrode spacing in the measurements was 5 meters. The total length of one spreading of the cables with 5 meters electrode spacing is 400 meters (4 cables with 81 electrodes) and further, the maximum theoretical measurement depth is about 50-70 meters. It should be noticed that the resolution of the method degrades fast with the increasing depth. Only the layers thick enough can be detected from the results. When the minimum electrode distance decreases the resolution of the measurements increases, but due to the smaller profile length the depth penetration decreases.

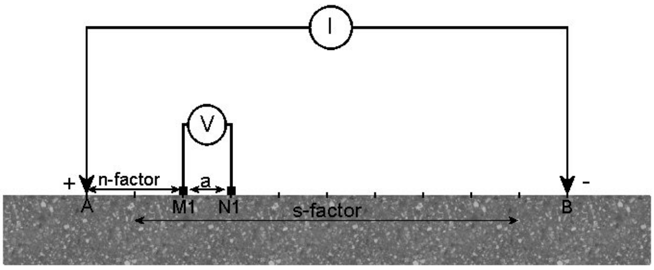

Figure 5. Multiple gradient array

Electrical resistivity measurement is a direct current (DC) method. The purpose of the resistivity measurements is to define the conductivity distribution of the earth. The real conductivity of the earth can be estimated on the basis of the resistivity measurements. The automatic ERT measuring procedure along the profile proceeds by feeding current into the ground through current electrodes A and B, and measuring the resulting potential difference in the ground using potential electrodes M_i and N_j. The potential difference between the electrodes is affected by electrical properties of the subsurface and measurement geometry. The field measurement result is called apparent resistivity ρ_a [Ωm] when result is received from heterogeneous ground. The resistivity is reciprocity of the conductivity σ [S·m^{-1}]. The ABEM Terrameter LS can also measure Induced Polarization (IP) that was not measured in this survey.

Totally 13 profiles were measured at the site. The minimum electrode spacing at profiles was 5 meters. The location of the ERT profiles is illustrated in the Figure 2.

2 RESULTS

2.1 Resistivity fork and GEM-2 results

Resistivity fork gives resistivity estimate for the uppermost, layer of the overburden, for a depth range of 0 - 30 cm. Results from the coarse regular measurement grid of resistivity fork measurements are presented in figure 6. Conductive surface seepage (Fig 7) was observed in several measuring points (red circles).

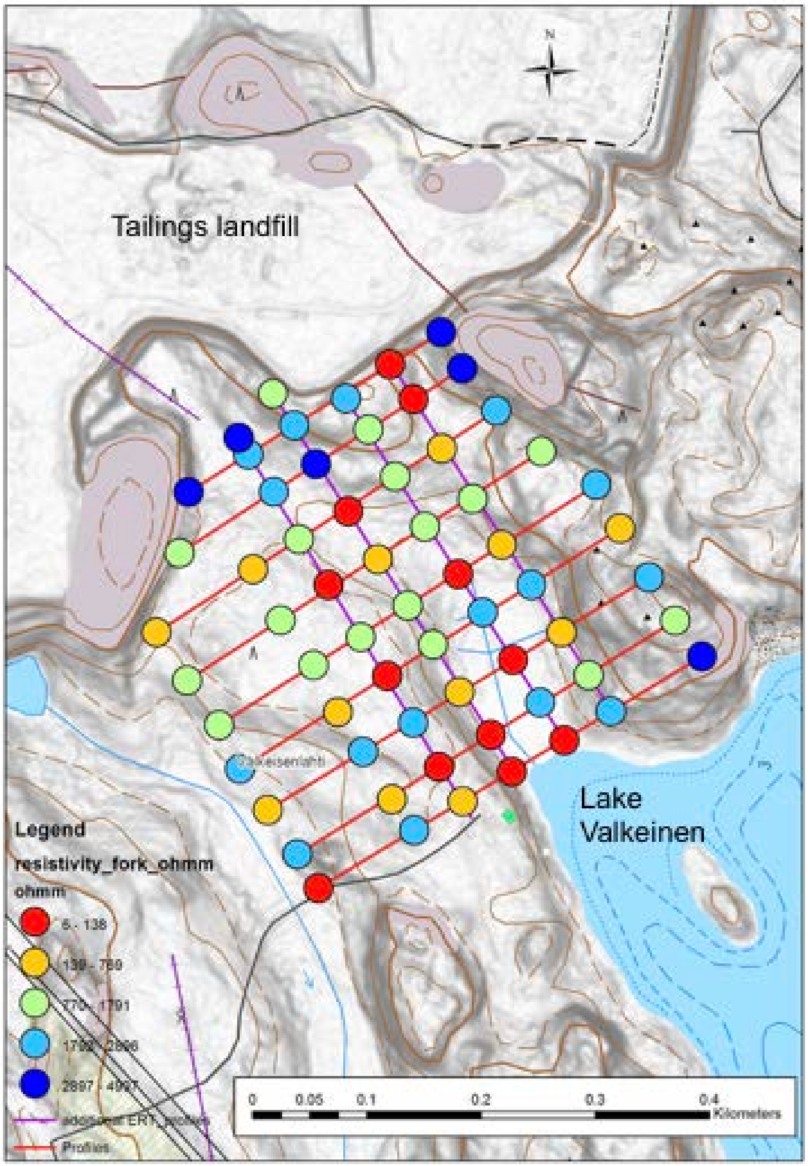

Figure 6. Results of the resistivity fork measurements.

From GEM-2 results apparent conductivity was calculated from the responses of the four different frequencies (Huang, et.al, 2003). Conductive near surface seepage was clearly observed and defined by electromagnetic GEM-2 measurements. Apparent conductivity map and interpretation is presented in figure 7.

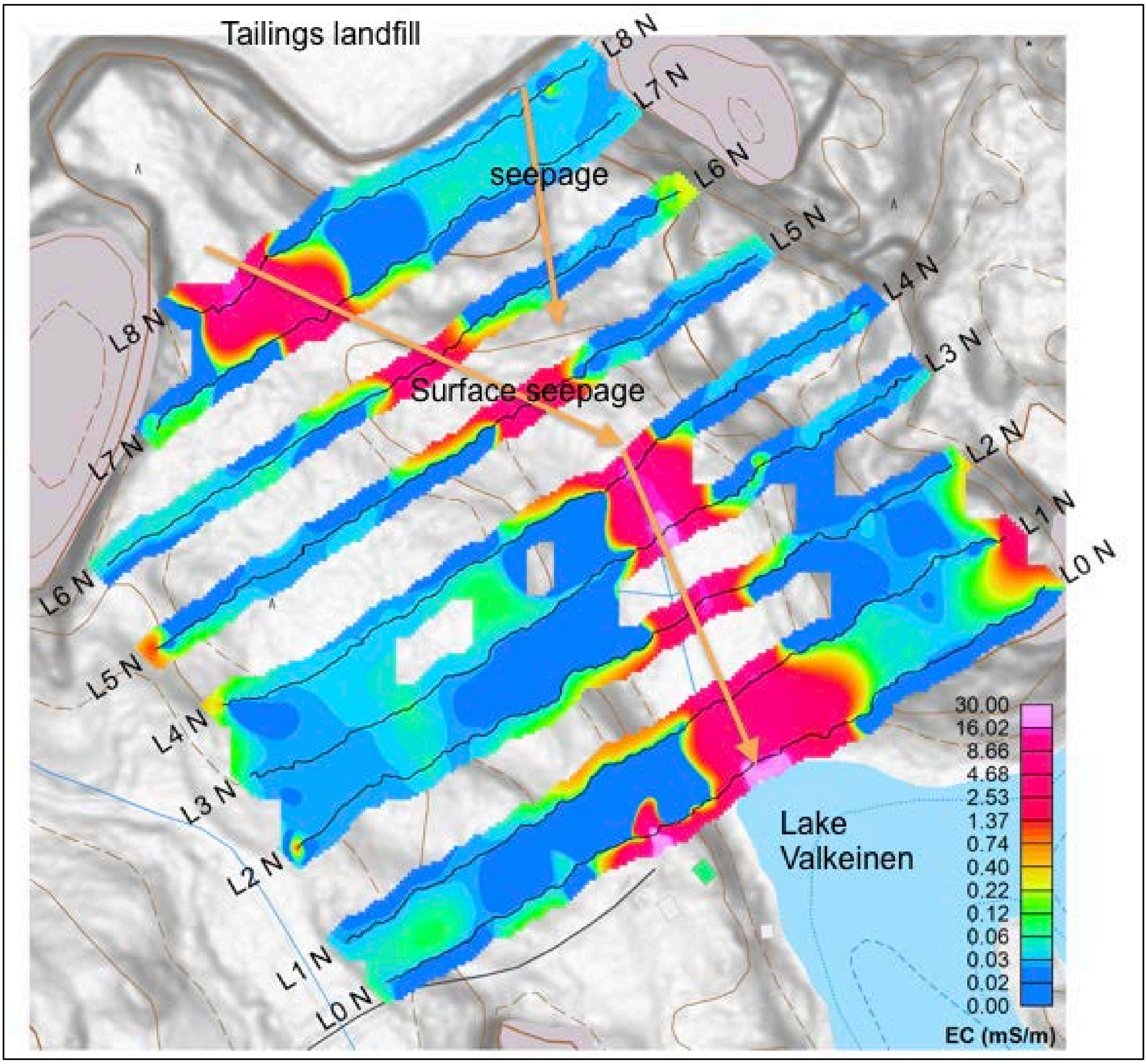

Figure 7. Apparent conductivity map and interpretation from GEM-2 results

2.2 VLF-R results

VLF-R measurements were executed to map fracture zones and conductors in the research area. Totally 9 profiles were measured. Measured profiles as well as interpretation results are presented in figures 8 (apparent resistivity) and 9 (phase angle). In addition to surface seepage, quite shallow conductivity anomaly in the eastern edge of gabbro formation was obtained. Also deep conductivity anomaly was found at the western edge of the gabbro at profiles 2, 3 and 4. Results matched excellent with those interpreted from ERT measurements. 2-layer inversion result examples with interpretation are presented in figures 10, 11 and 12.

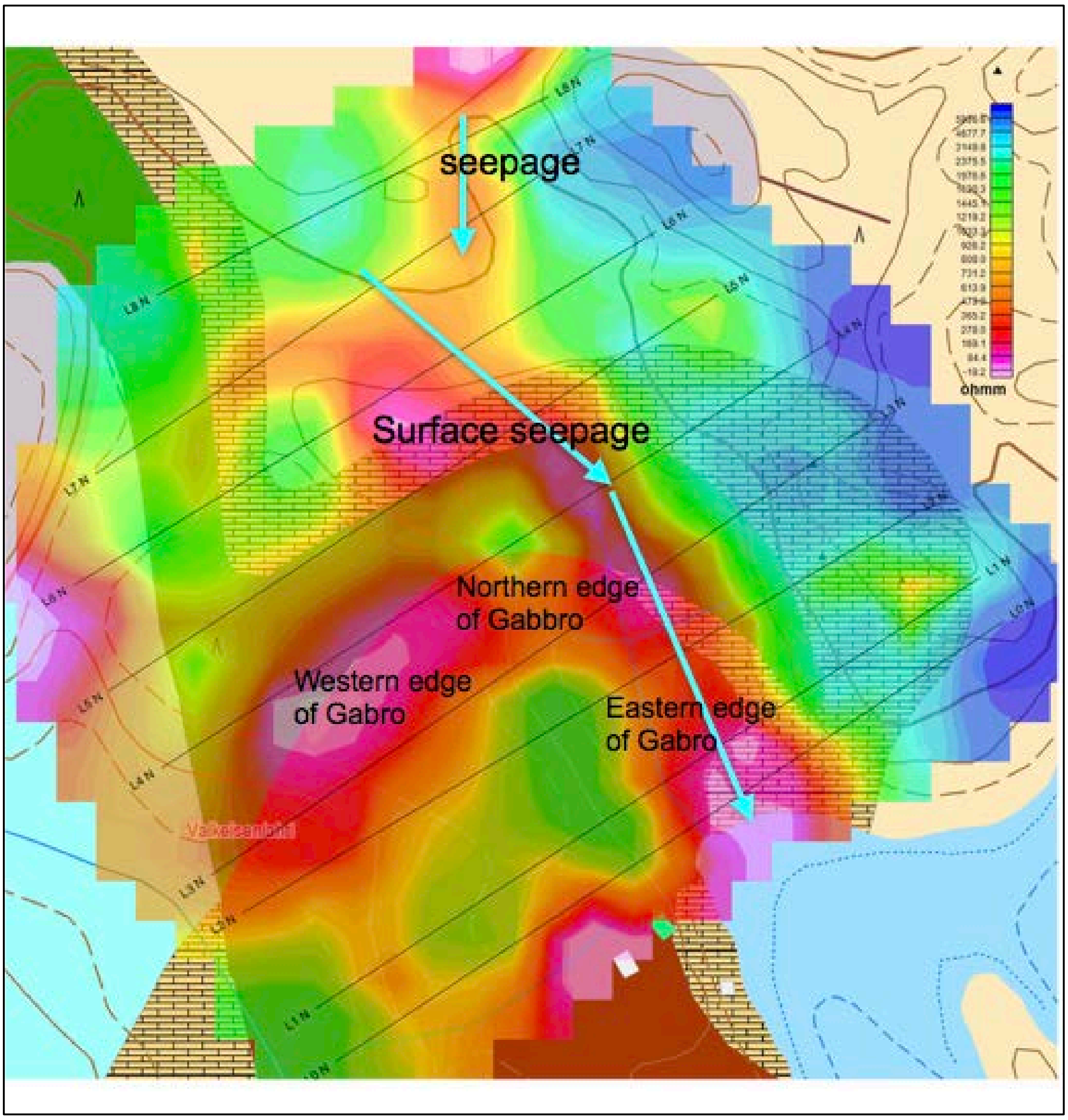

Figure 8. Apparent resistivity map and interpretation from VLF-R results.

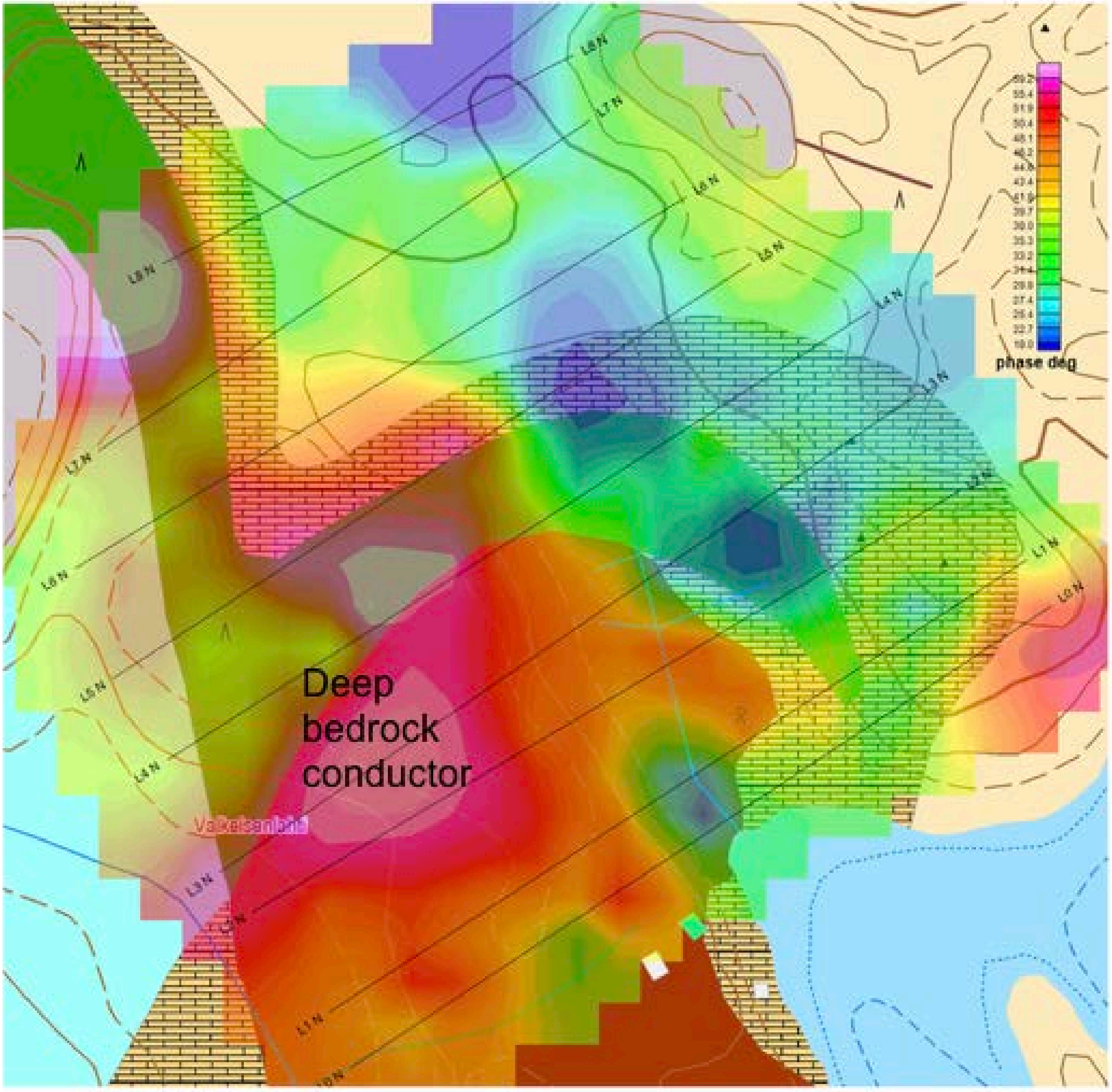

Figure 9. Phase angle map and interpretation from VLF-R results.

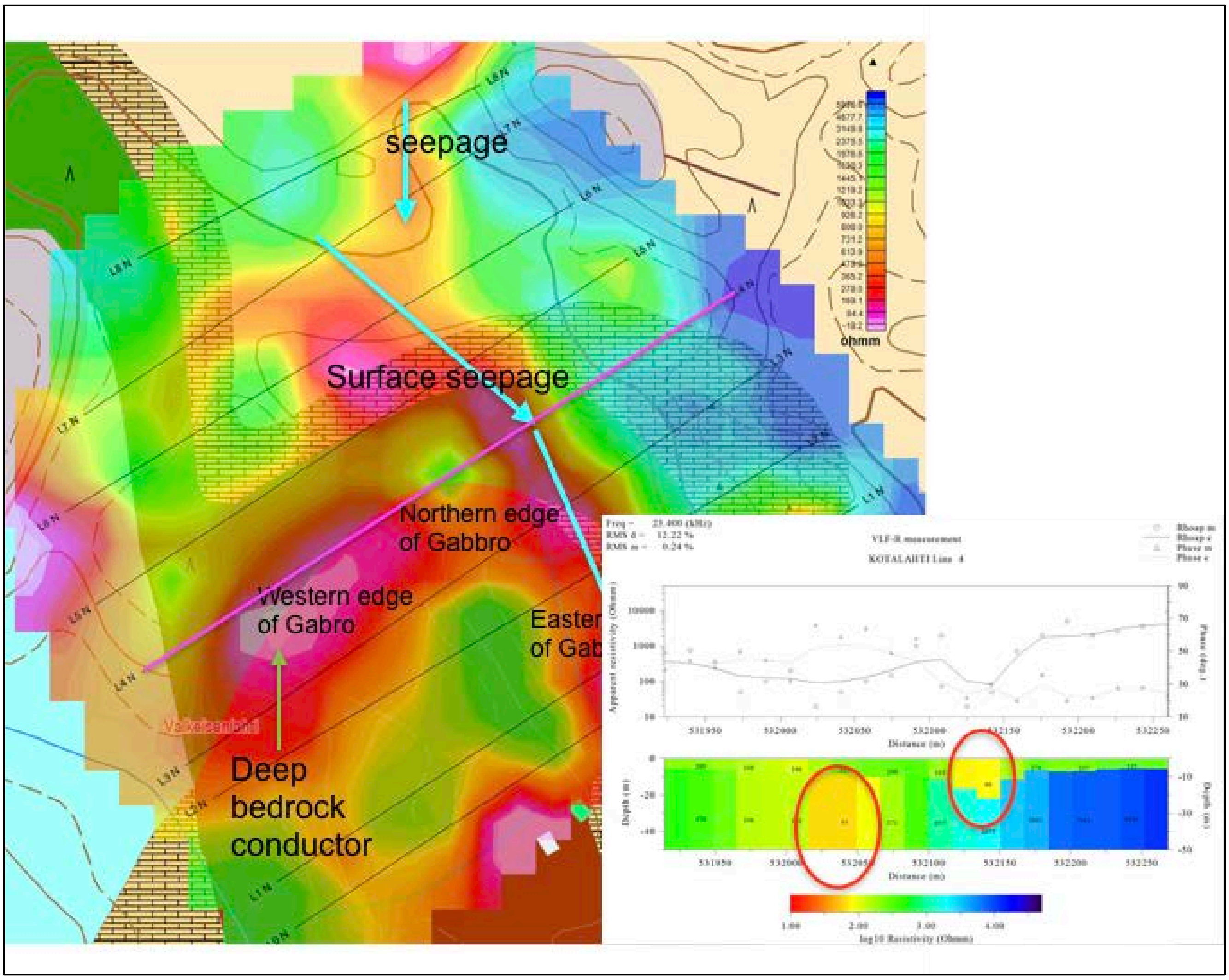

Figure 10. Apparent resistivity map and 2-layer inversion result from the profile 4.

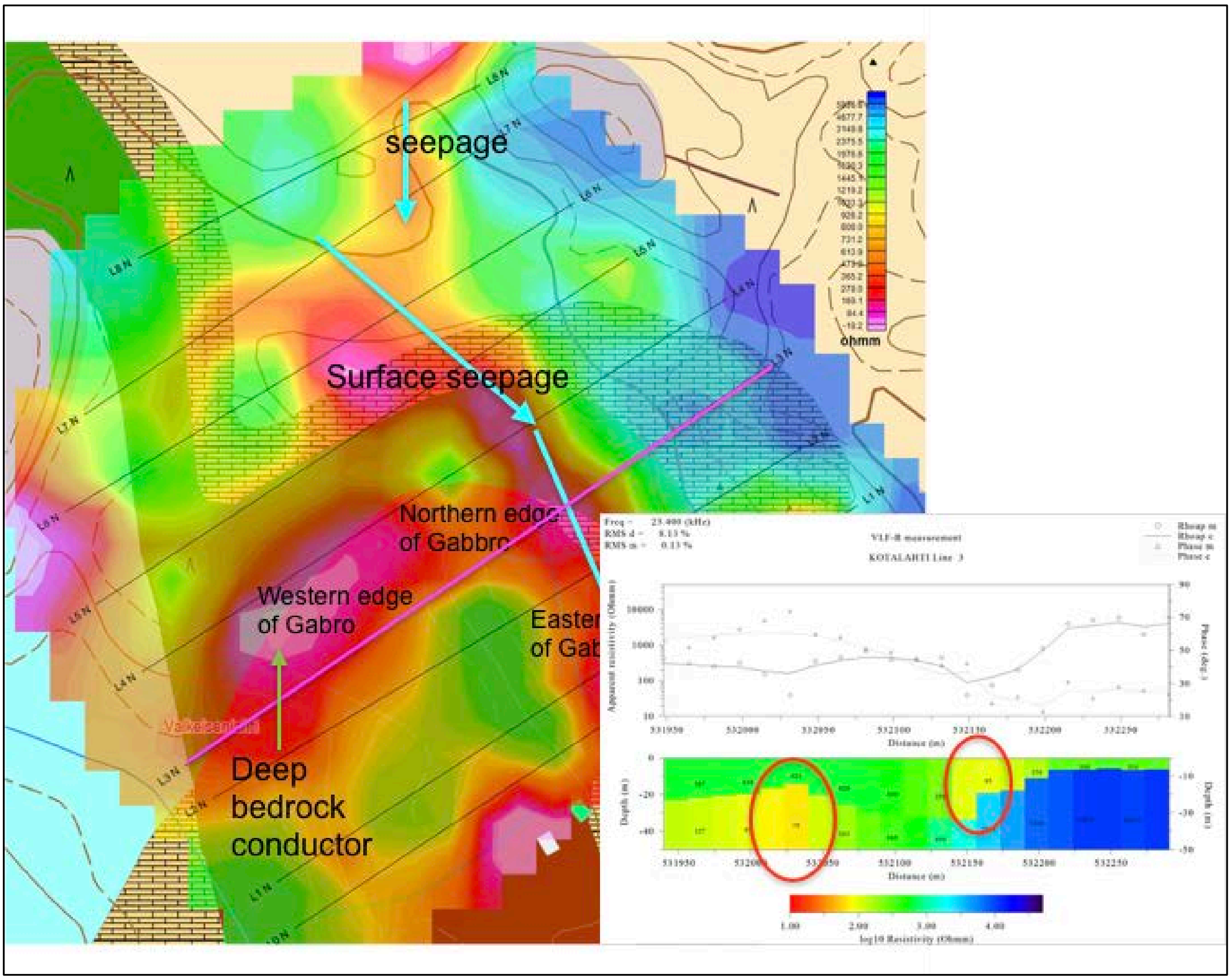

Figure 11. Apparent resistivity map and 2-layer inversion result from the profile 3.

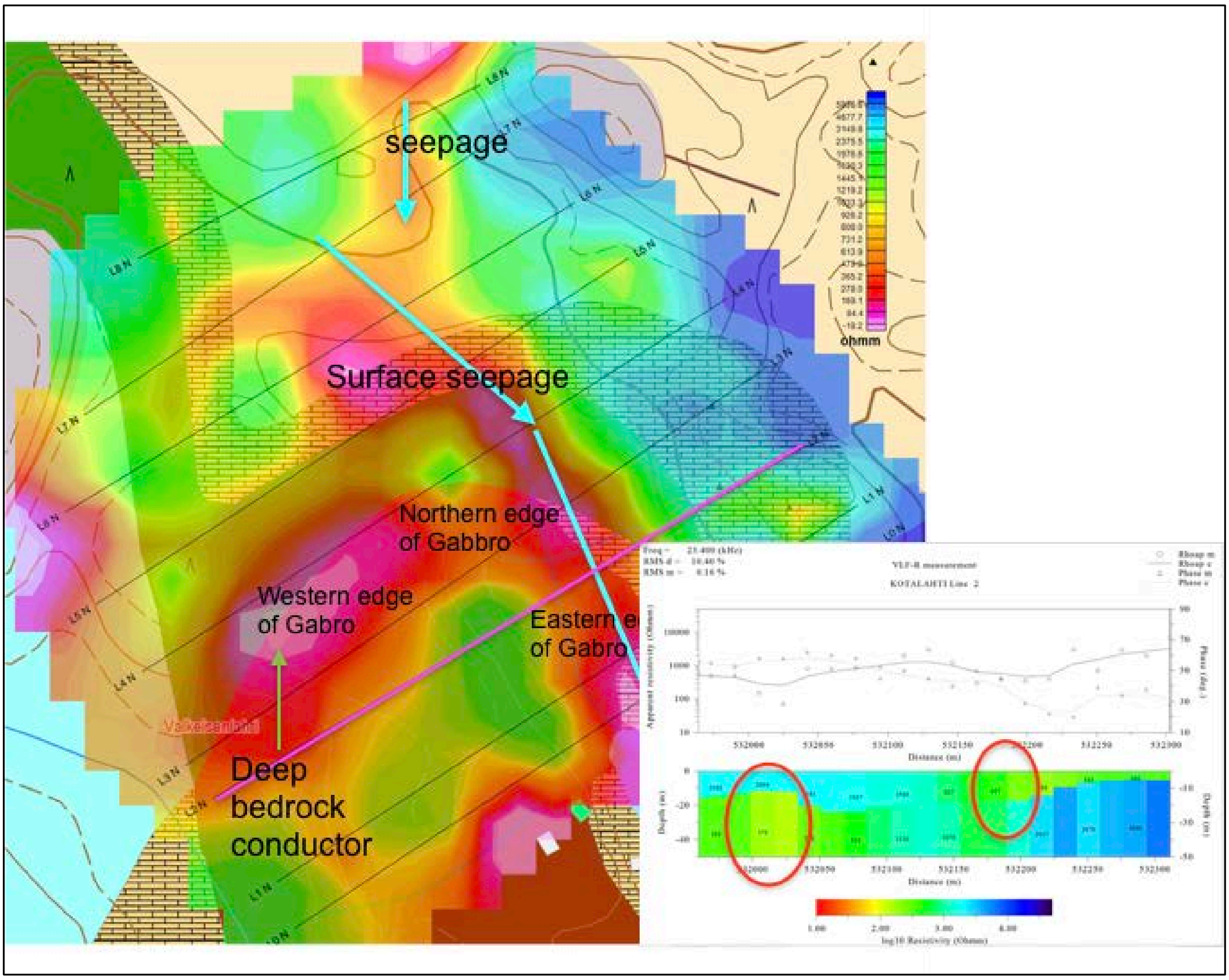

Figure 12. Apparent resistivity map and 2-layer inversion result from the profile 2.

2.3 ERT results

The interpretation of the results was made by Res2DInv program (Loke and Barker 1996), where also the topography of the ground can be taken into account. The interpretation of the measurement data (2D inversion) is based on the assumption of the 2D geological structures (the structures that are on the measurement line continue perpendicular to the line). The 2D inversion results were visualized in 2D and 3D using Geosoft Oasis Montaj software.

The visualized 2D-interpretation results are presented in the figures 13 - 25. 3D-visualization of the ERT results together with LiDAR topography is illustrated in the figure 26a and with geological map in figure 26b. In figure 27 is illustrated together the ERT results, LiDAR topography and GEM-2 conductivity. 3D-visualization of ERT results is illustrated together with the seepage routes and highly conductive edge of the Gabbro in the figure 28.

From the ERT results we can clearly see that the surface seepage is prevailing in area between the tailings impoundment and Lake Valkeinen. Further, the highly conductive zone in the edge of the Gabbro is dominating in the results in the deeper parts of the sections on profiles 0 - 4 and 9 - 11 (see Figures 13 - 17 and 22 - 24).

In illustration where ERT results are presented together with LiDAR topography (Fig 26a) we can see that the highest surface seepage is located naturally on the lowest topographical feature between the tailings impoundment and Lake Valkeinen. Yet, there is also some seepage under the surface near the tailings impoundment from north to south (see Fig 20 - 22, 14 - 25 and 28). In figure 26a there is a topographic low also on that same place where the seepage is occurring underground, nevertheless there is not visible seepage on the surface in the ERT results in that place. Further, GEM-2 is showing neither surface seepage in that same location (see fig 6), instead of that there are some evidences of very surficial seepage in the conductivity fork results (see Fig 5). On the other hand In VLF-R results we can see the evidence of seepage from north to south in that area, which is also detectable in the ERT results.

The geological map together with ERT results in figure 26b show that the highly conductive zone deeper in the ERT is located into the edge of Gabbro. On that location there is not existing any drilling data, but it is possible that there is some ore mineralization or some other conductor like black schist in the bedrock on that area.

The figure 27 emphasize even more clearly the natural correspondence of topographic low and surface seepage between that tailings impoundment and Lake Valkeinen. GEM-2 results together with ERT interpretation highlights the surface seepage route very clearly.

The deeper seepage from tailings impoundment towards the south is detectable in figure 28 visualizing the ERT results in 3D. Further, the surface seepage is observable as well as conductive edge of Gabbro in that same illustration.

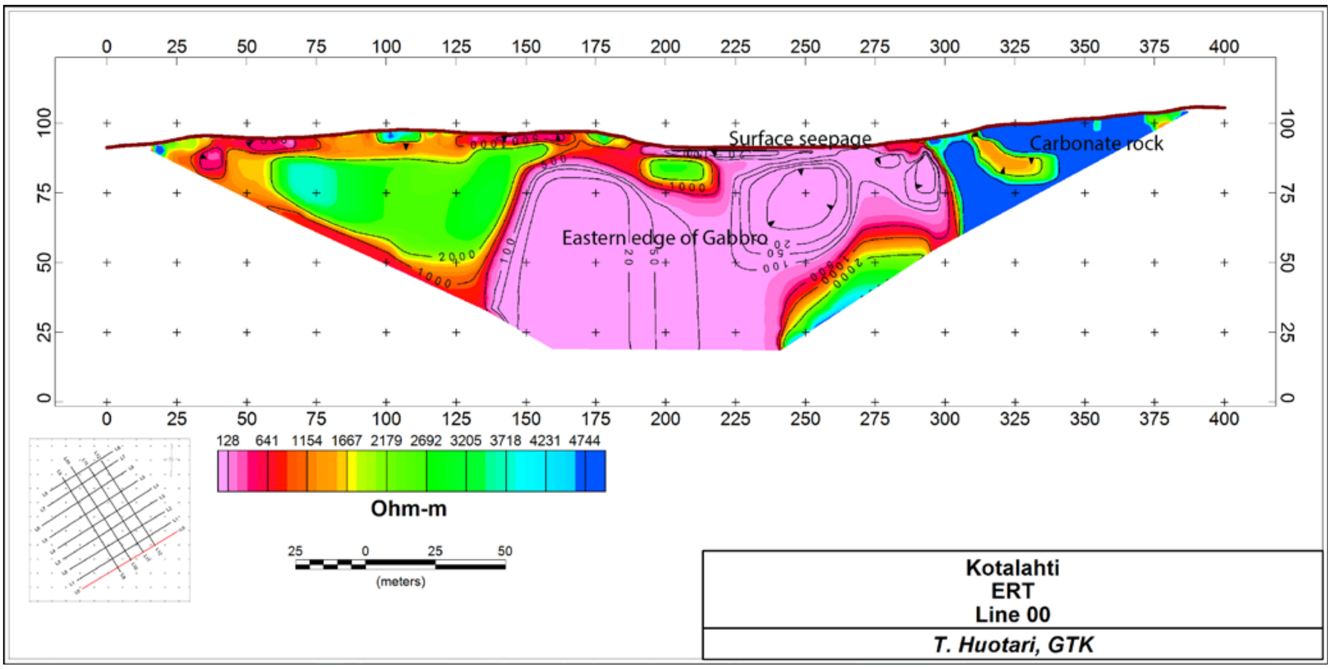

Figure 13. Interpretation of ERT line 00.

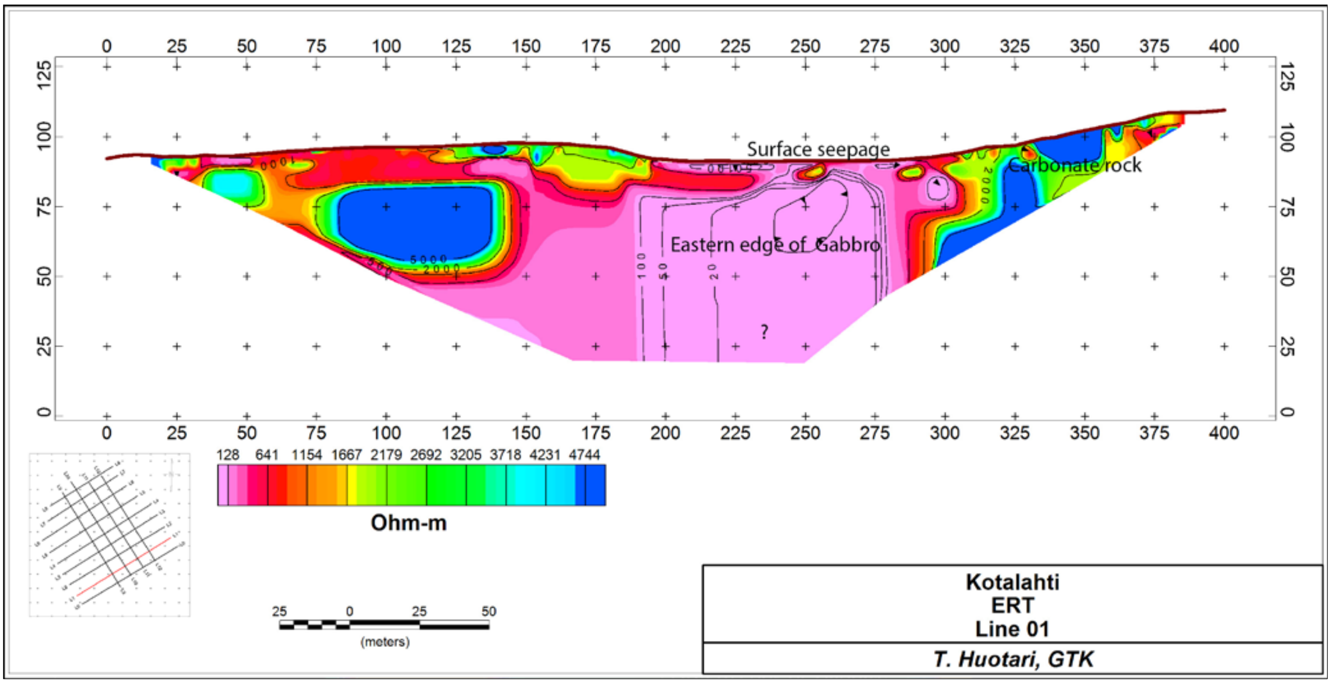

Figure 14. Interpretation of ERT line 01.

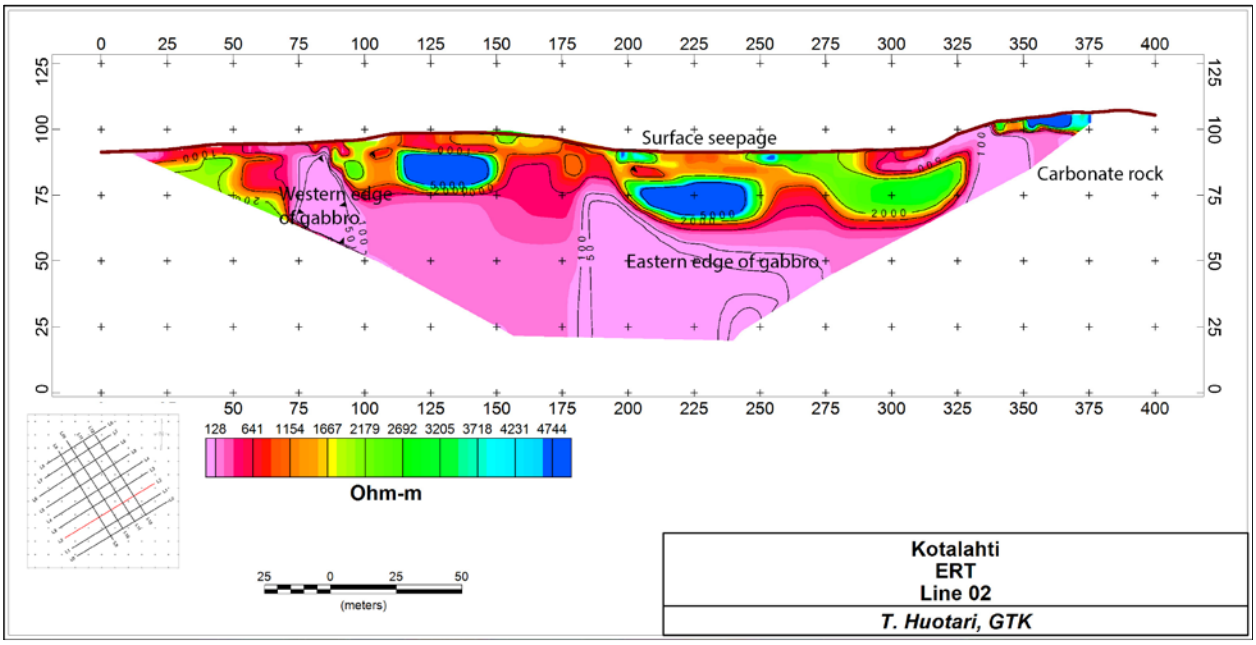

Figure 15. Interpretation of ERT line 02.

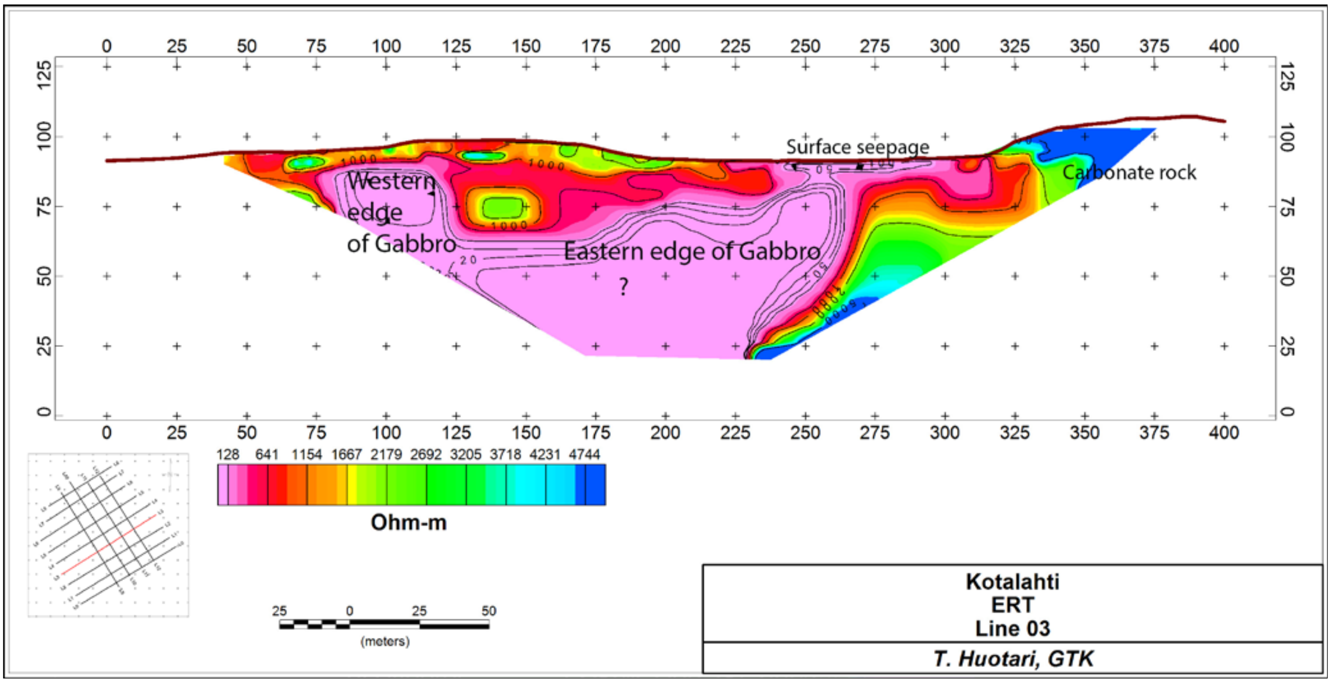

Figure 16. Interpretation of ERT line 03.

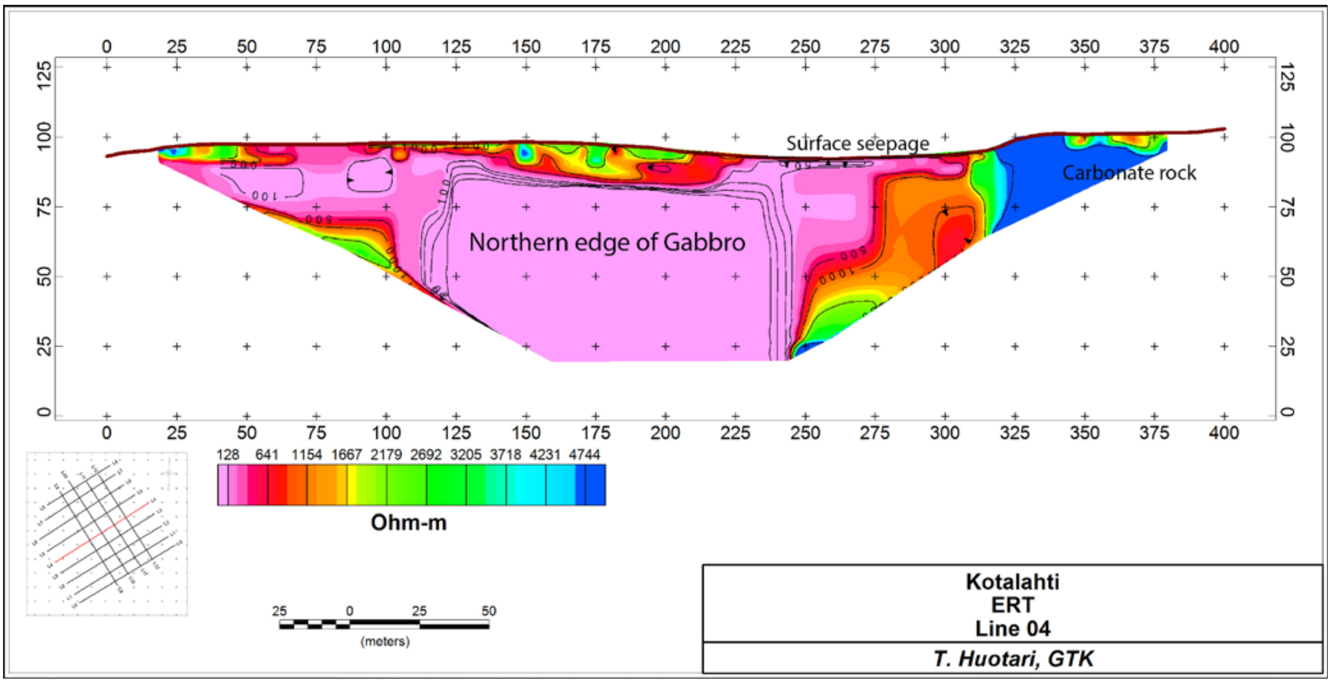

Figure 17. Interpretation of ERT line 04.

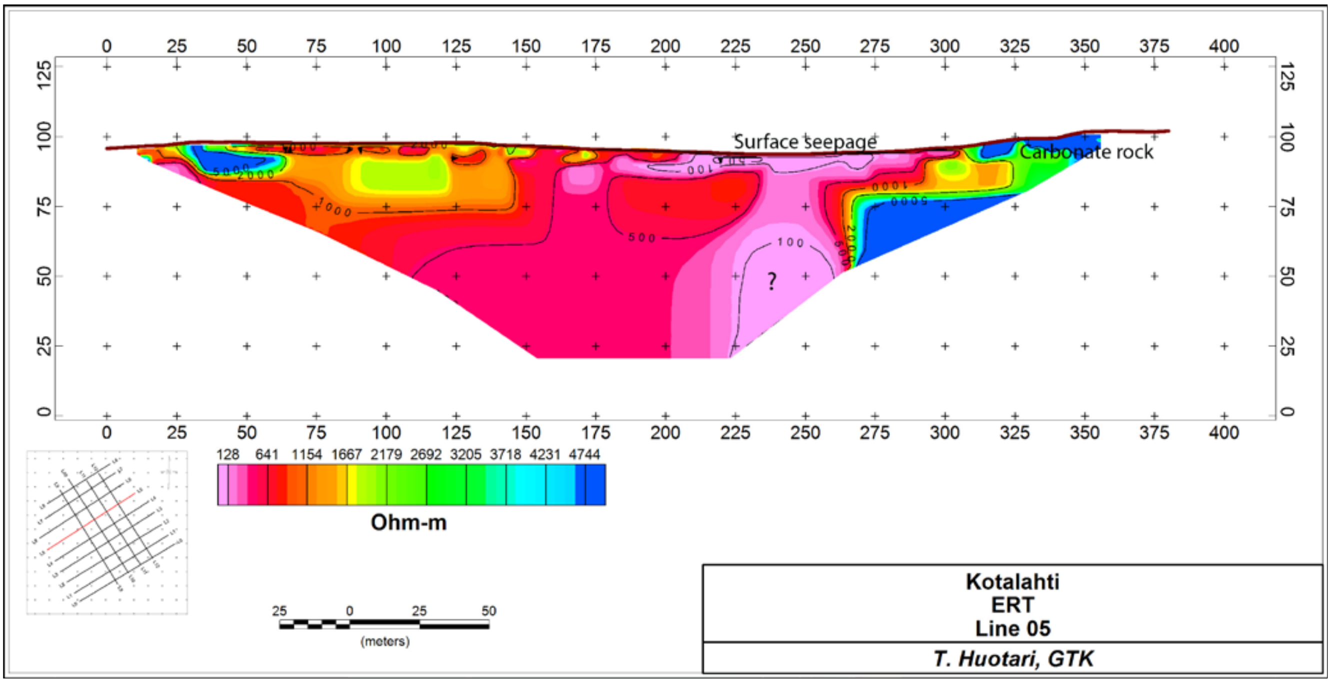

Figure 18. Interpretation of ERT line 05.

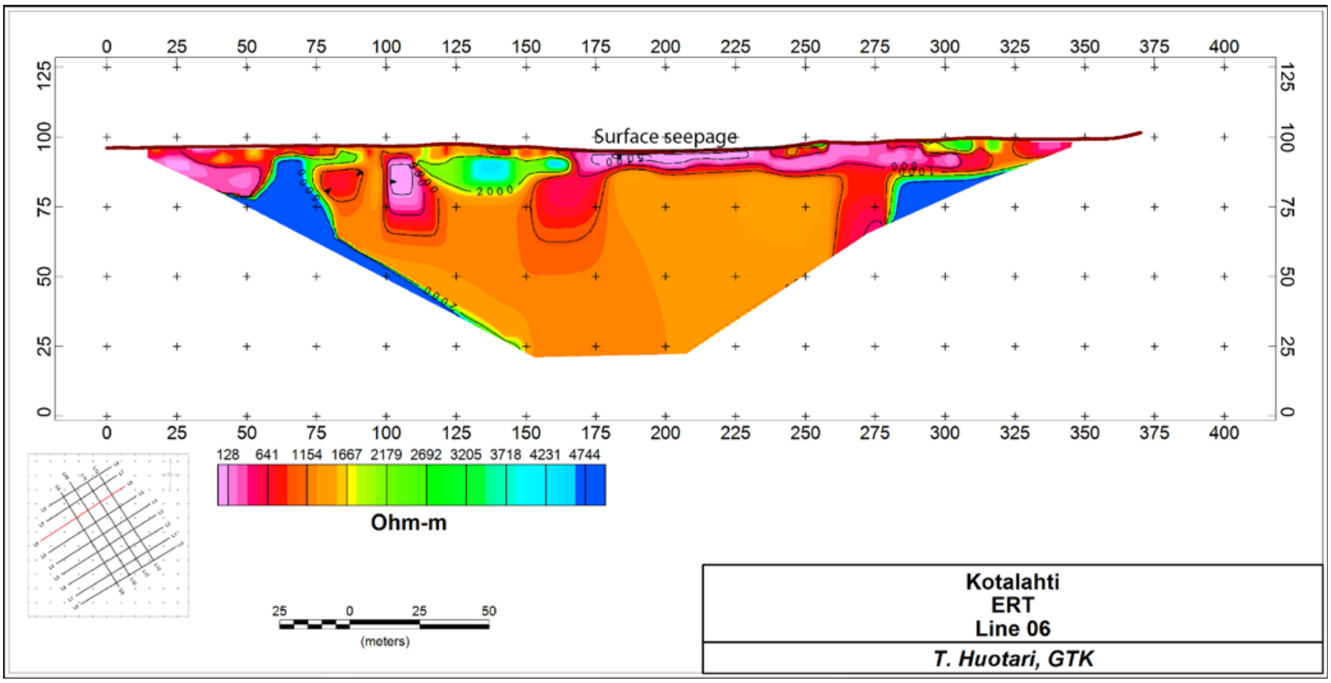

Figure 19. Interpretation of ERT line 06.

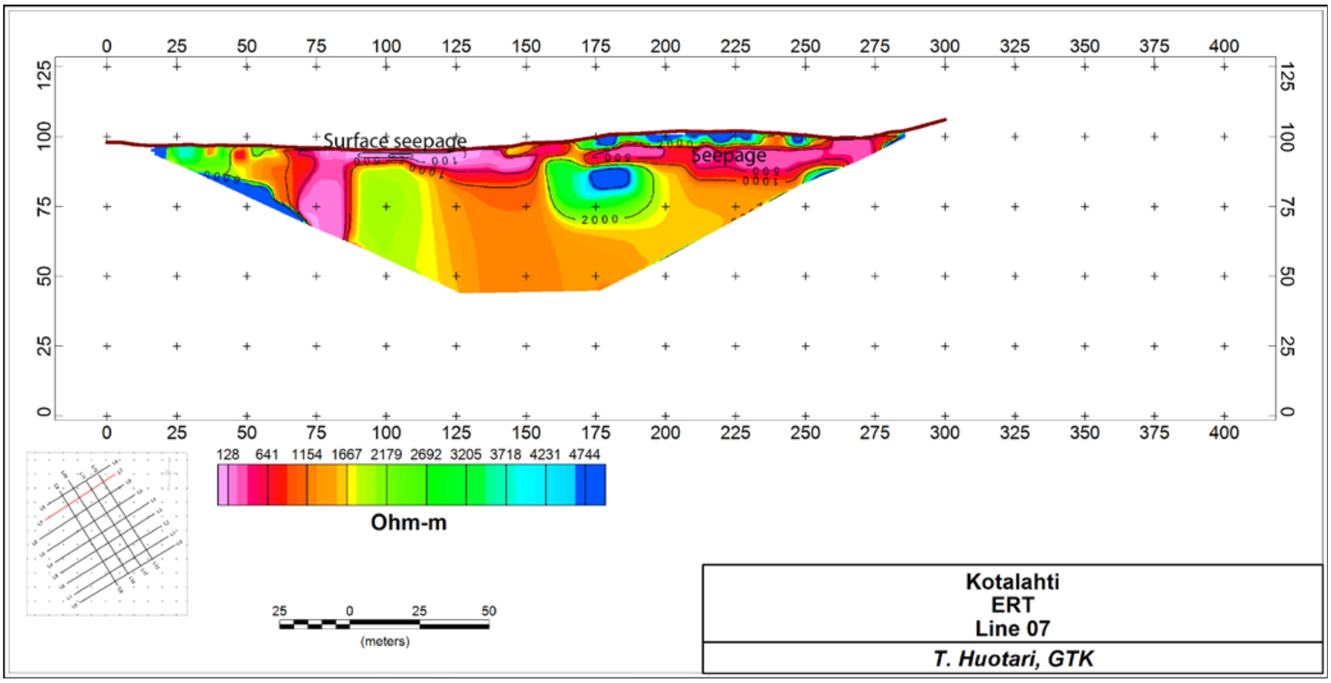

Figure 20. Interpretation of ERT line 07.

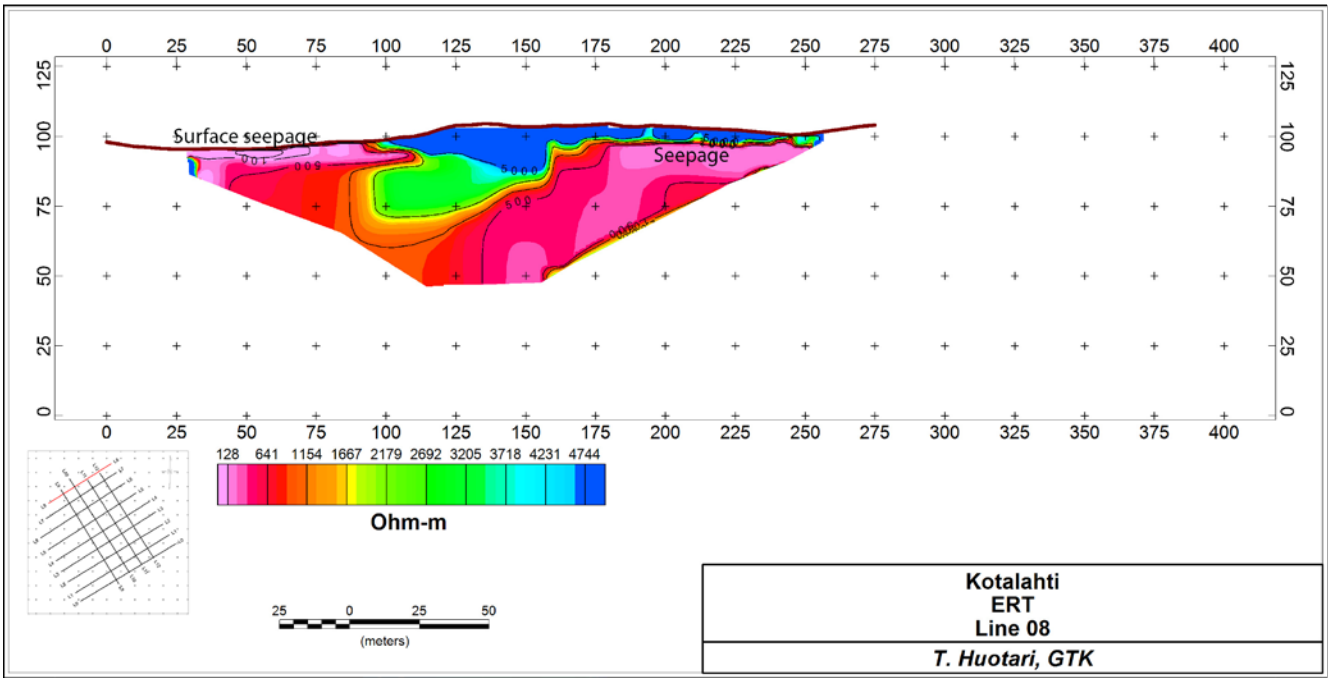

Figure 21. Interpretation of ERT line 08.

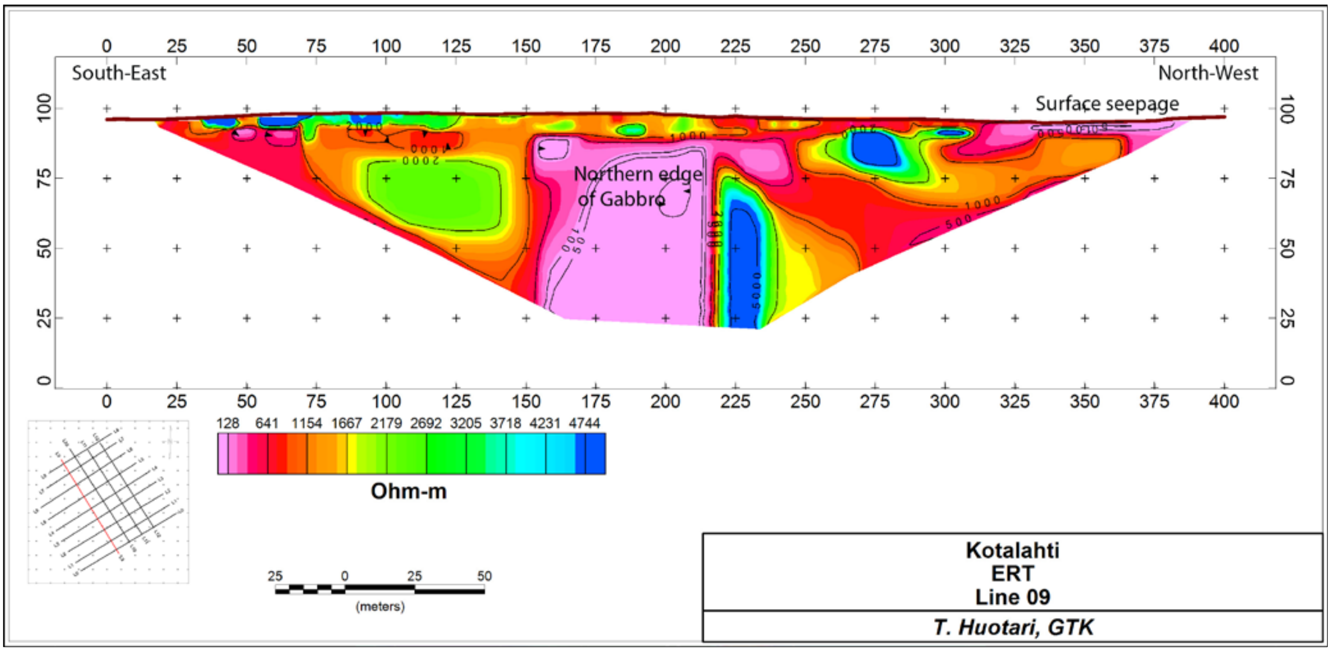

Figure 22. Interpretation of ERT line 09.

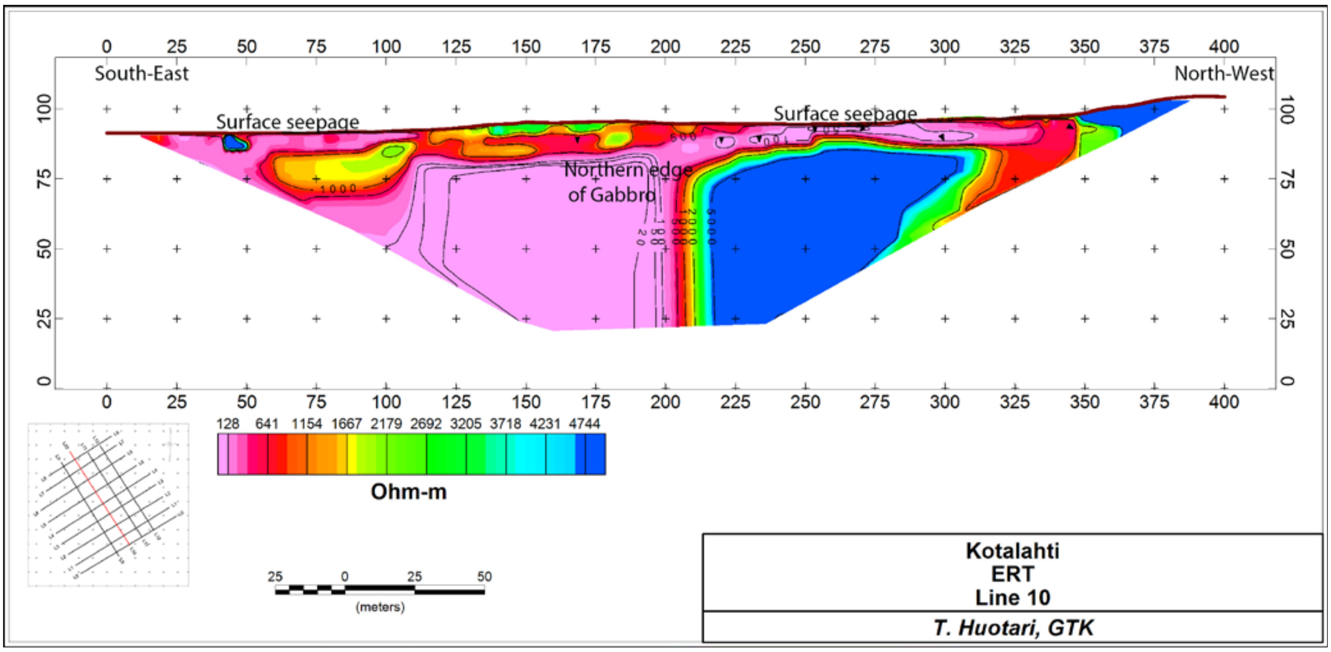

Figure 23. Interpretation of ERT line 10.

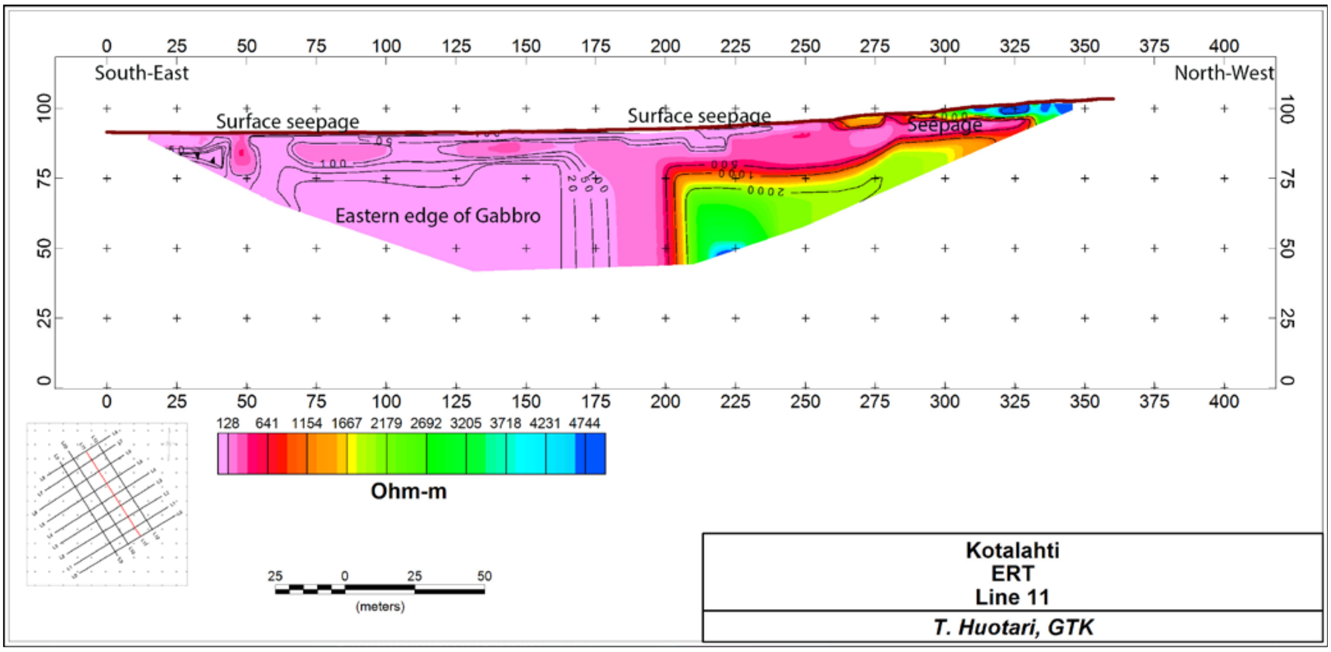

Figure 24. Interpretation of ERT line 11.

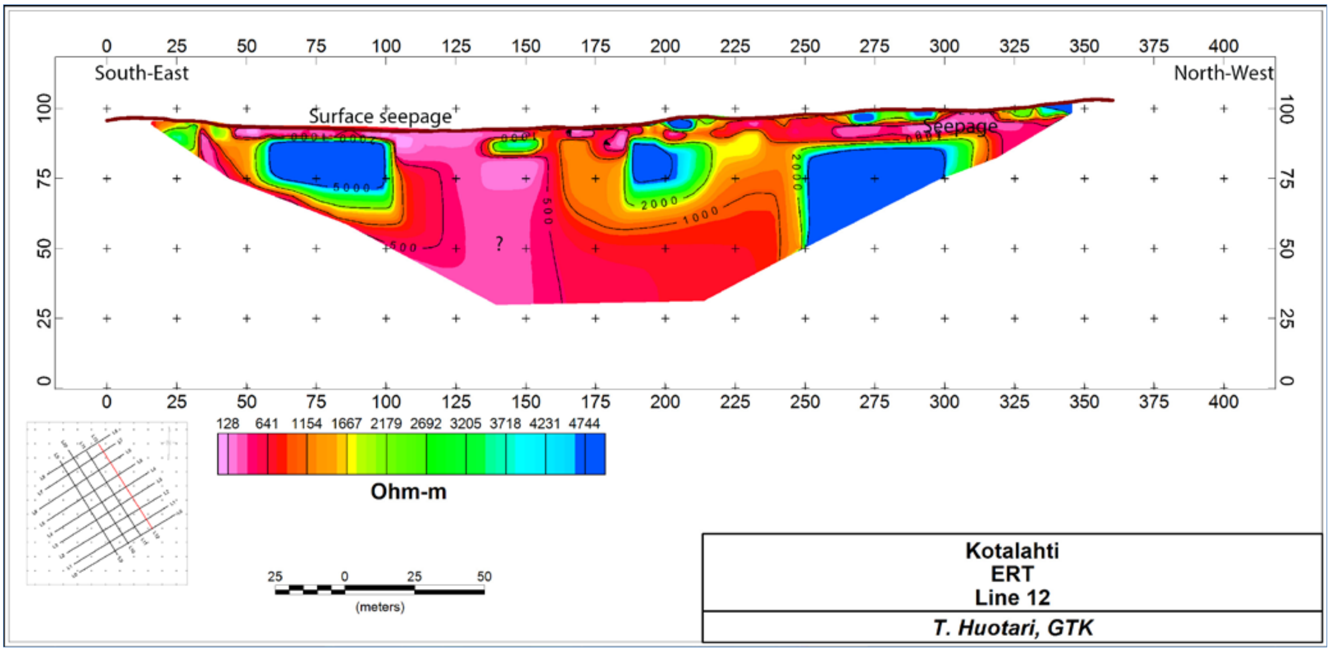

Figure 25. Interpretation of ERT line 12.

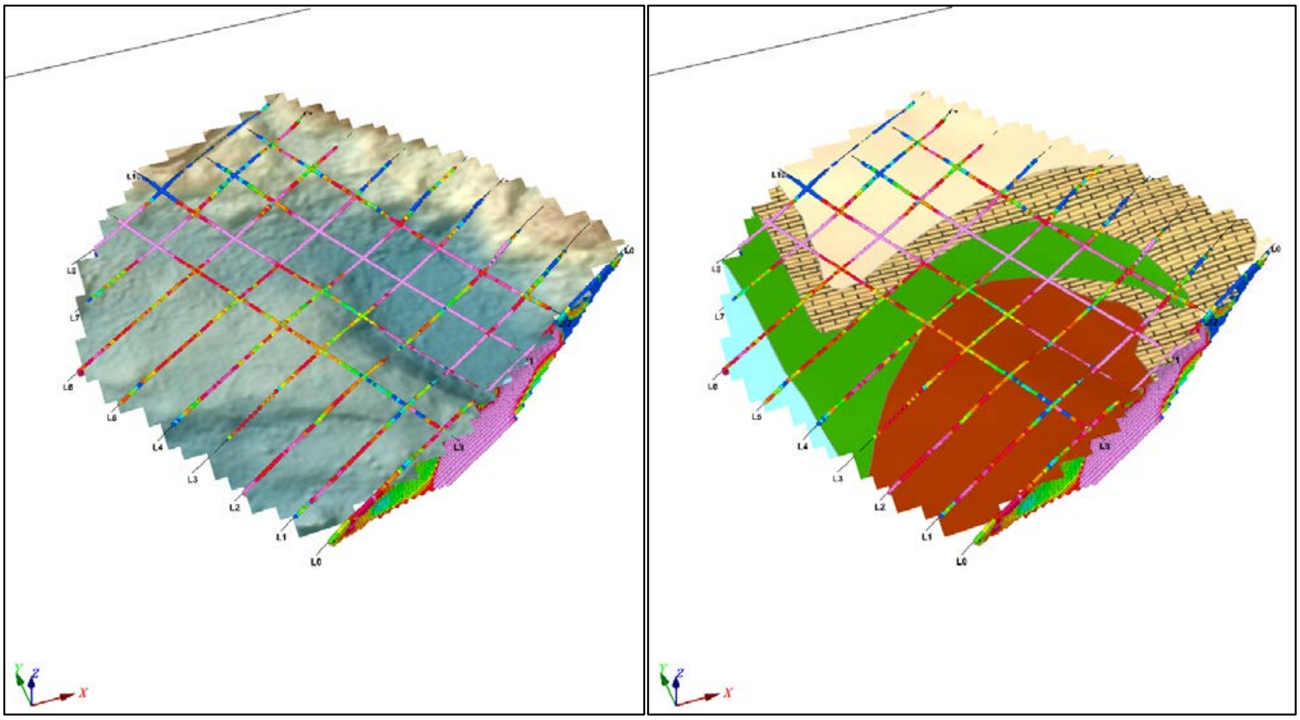

Figure 26. 3D-view of ERT results with LiDAR topography (left) and geological map (right). Color scale of ERT results is the same as in figures 13-25. Basemap: LiDAR data © National Land Survey of Finland 2016 and Bedrock of Finland – DigiKP 2018.

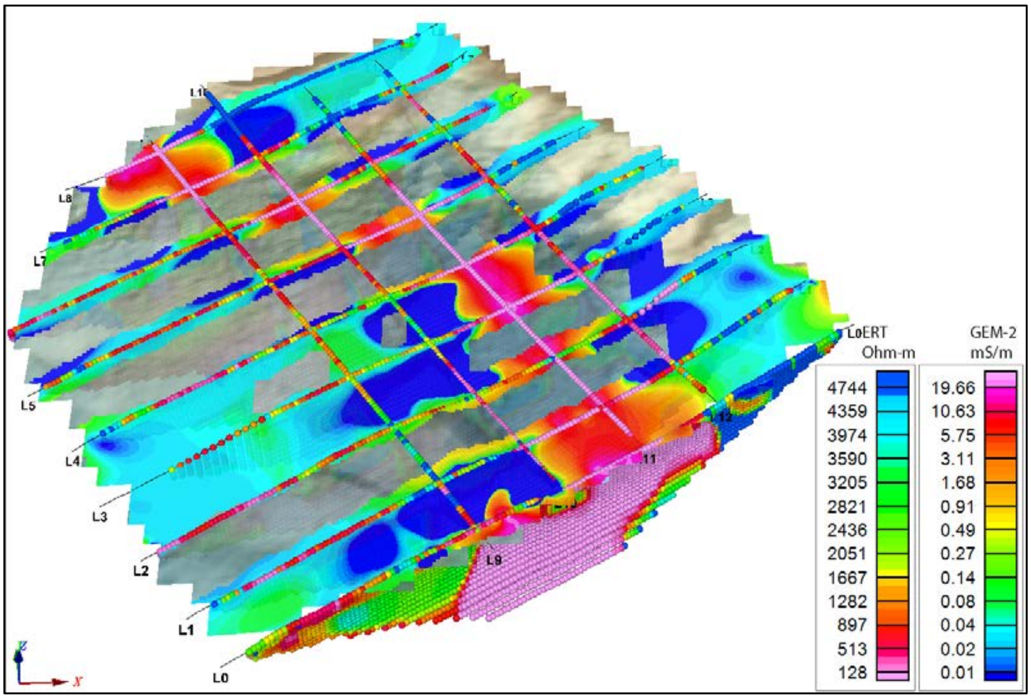

Figure 27. 3D-visualization of ERT results, LiDAR topography and GEM-2 conductivity. Basemap: LiDAR data © National Land Survey of Finland 2016.

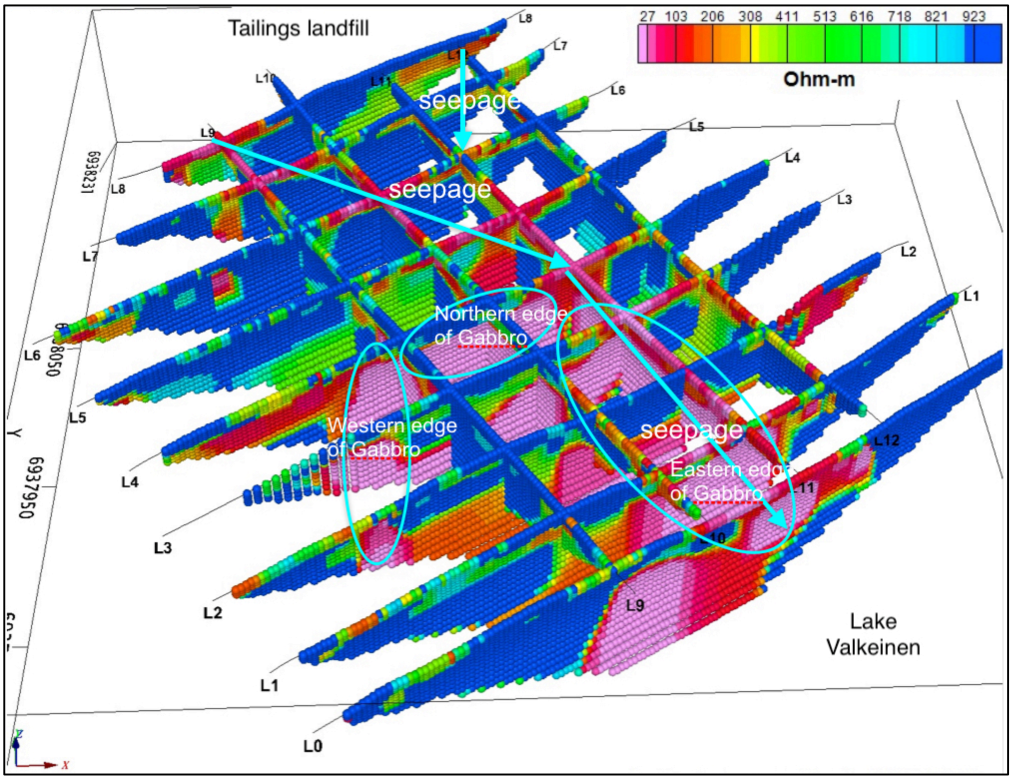

Figure 28. 3D-visualization of ERT results and interpretation.

3 CONCLUSIONS

Near surface seepage was clearly observed by electromagnetic GEM-2 measurements. The near surface seepage and possible deeper parts of the seepage were extracted and mapped by VLF-R measurements. Further, conductive zone at the edge of gabbro was detected by VLF-R and ERT measurements.

The near surface seepage and possible deeper parts of the seepage were extracted and mapped by ERT measurements. From the ERT inversion results the bottom of the conductor was not detectable on lines 0 - 4 and 9 - 11 at the southern part of the investigation area. The reason for that may be complex bedrock geology that may include unknown conductors. These conductors may be originated from mineralization, black shales or unknown fractures. The theoretical depth extend of ERT -measurements at the used configuration is about 50 - 70 m. Besides the limited depth extent, concentration of currents could be the reason for not to penetrate the good conductor. Very steep change from resistive to conductive surround is observed in profiles 10 and 11, which reflects bedrock contact between gabbro and amphibolite.

Despite of complex bedrock geology, on the grounds of research results it was possible to detect significant seepage of conductive waters from tailings landfill area into the Lake Valkeinen. These have remarkable impact on the contamination of this small (20 hectares) lake.

4 REFERENCES

Aatos, S., Saarelainen, J., Räisänen, M-L., Nikkarinen, M., Kiiskinen, A., 2004. Kotalahden suljetun kaivoksen rikastushiekka-alueen suoto- ja pintavesikartoitus. Geologian tutkimuskeskus, Kuopion yksikkö. Unpublished report. 35 p. In finnish.

Bedrock of Finland - DigiKP. Digital map database [Electronic resource]. Espoo: Geological Survey of Finland [referred 16.04.2018]. Version 2.1.

Cagniard, L.,1953. Basic theory of the magnetotelluric method of geophysical prospecting. Geophysics 18, 605-635p.

Geophex Ltd. ,2016. GEM-2, hand-held, digital, multifrequency broadband electromagnetic sensor (© Geophex Ltd.); GEM-2 Brochure, GEM-2 manual, documents in <http://www.geophex.com(/Publications.htm)>.

Hayles, J.G. and Sinha, A. K., 1986. A portable local loop VLF transmitter for geological fracture mapping. Geophysical Prospecting, 34, 873-896 p.

Hjelt, S-E., Heikka, J.V., Pernu, T.K. and Sandgren, E.I.O., 1990. Examples of the application of the VLF-R method to prospecting bedrock structures. Geological Survey of Finland. Report 95. 87-99 pp.

Huang, H., Won, I.J., 2003. Real-time resistivity sounding using a hand-held broadband electromagnetic sensor, Geophysics, vol. 68, no. 4. p. 1224-1231.

Hunkeler, P., Hendrics, S., Hoppmann, M., Paul, S., Gerdes, R., 2015. Towards an estimation of sub-sea-ice platelet-layer volume with multi-frequency electromagnetic induction sounding, Annals of Glaciology 56(69), 2015.

Järvinen, Timo, 2013. Valumavesien käsittely suljetulla kaivosalueella, Opinnäytetyö, Savonia-ammattikorkeakoulu, 27.5.2013, 49 s. In finnish.

Kauppila, Tommi; Mäkinen, Jari; Solismaa, Lauri , 2017. Sediment And Pore Water Properties Across The Chemocline Of A Mine Water-Impacted Boreal Lake During Winter Stagnation And Autumn Overturn. – In: Wolkersdorfer, C.; Sartz, L.; Sillanpää, M. & Häkkinen, A.: *Mine Water & Circular Economy* (Vol I). – p. 167 – 175; Lappeenranta, Finland (Lappeenranta University of Technology).

Lerssi, J., Niemi, S. and Suppala, I., 2016. GEM-2 – new generation electromagnetic sensor for near surface mapping. Extended abstract in Near Surface 2016, 22nd European meeting of Environmental and Engineering Geophysics, Barcelona, Spain. 4 p.

Lindsberg, E., 2008. Seismic Refraction Method and VLF and VLF-R methods in the Estimation of Ground Water. Master's thesis, University of Oulu, Faculty of Science, Department of Physical Sciences. 123 pp. [in Finnish, abstract in English].

Loke, M. and Barker, R., 1996. Rapid least-squares inversion of apparent resistivity pseudo sections by a quasi-Newton method. Geophysical Prospecting 44:131-162.

Makkonen, H., 2017. Personal communication.

Mursu, J., 1991. VLF-ja VLF-R-mittaukset käyttäen siirrettävää VLF-lähetintä. Report. University of Oulu, Department of Geophysics. 97 pp. [in Finnish]

Müllern, C-F. and Eriksson, L. 1982. Möjligheter till analys av VLF-anomalier vid prospektering efter grundvatten i berg. SGU Rapport 80-4151. Geological Survey of Sweden. 24 pp. [in Swedish]

Pasanen, A., Lerssi, J., Forss , H., 2013. Kotalahden kaivoksen rikastushiekka-altaan MaxMin-mittaus. Tutkimusraportti, M77K2013, 13 p. In Finnish.

Puranen, R., Sulkanen, K., Nissinen, R. & Simelius, P. ,1999. Ominaisvastusluotaimet ja vastustalikot. Geologian tutkimuskeskus, arkistoraportti Q15/27/4/99/2. 10 s. In finnish.

Tilsley, J.E., 1976. Very low frequency electromagnetic measurements using a portable signal generator. Transactions of the Institution of Mining and Metallurgy 85, 74-77 p.

Turunen, P., 2008. VLF-R and magnetic surveys at the Asentolampi and Isokangas targets, Portimojärvi, Ranua. Work report. Geological Survey of Finland. 5 p.

Witten, A., Won, I.J., Norton, S., 1997. Imaging underground structures using broadband electromagnetic induction, JEEG, Volume 2, issue 2, 1997, p. 105-114.

Won, I.J., Keiswetter, D.A., Fields, G.R.A., Sutton, L.C., 1996. GEM-2: A new Multifrequency Electromagnetic Sensor. JEEG, Volume 1, Issue 2, August 1996, p. 129-137.