# Pseudo-3D Electrical Resistivity Imaging for Improved Site Characterization

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Reflection on Resources

ABSTRACT
Reclamation and remediation are important steps to ensure that the ground we use is restored to its previous state. An important part of a successful reclamation is to ensure that the Site is properly assessed, which involves adequate soil sampling, volume estimation, and site characterization. Geophysical methods can greatly enhance the accuracy of these typical ground methods and improve initial site characterization as a whole.
This paper highlights two areas where a combination of historical site assessments, electromagnetic surveys, and a multi-line pseudo-3D resistivity method was employed to significantly enhance the assessment of a remediation site. It will be shown how pseudo-3D resistivity imaging can greatly improve the characterization of a site without any ground disturbance, and how using geophysical methods in areas of complex terrain can aid remediation planning in areas where typical borehole sampling/drilling is too challenging or impossible to obtain adequate results. While these results are based on remediation sites, these geophysical methods can be applied to contaminant mapping, void detection, volume estimation, and bedrock delineation.

RÉSUMÉ
La remise en état et l'assainissement sont des étapes importantes pour s'assurer que le sol que nous utilisons est restauré dans son état antérieur. Une partie importante d'une remise en état réussie consiste à s'assurer que le site est correctement évalué, ce qui implique un échantillonnage adéquat du sol, une estimation du volume et une caractérisation du site. Les méthodes géophysiques peuvent grandement améliorer la précision de ces méthodes au sol typiques et améliorer la caractérisation initiale du site dans son ensemble.
Cet article met en évidence deux domaines où une combinaison d'évaluations de sites historiques, de levés électromagnétiques et d'une méthode de résistivité pseudo-3D multiligne a été utilisée pour améliorer considérablement l'évaluation d'un site d'assainissement. Il sera montré comment l'imagerie de résistivité pseudo-3D peut grandement améliorer la caractérisation d'un site sans aucune perturbation du sol, et comment l'utilisation de méthodes géophysiques dans des zones de terrain complexe peut faciliter la planification de l'assainissement dans des zones où l'échantillonnage typique est trop difficile ou impossible pour obtenir des résultats adéquats. Bien que ces résultats soient basés sur des sites d'assainissement, ces méthodes géophysiques peuvent être appliquées à la cartographie des contaminants, à la détection des vides, à l'estimation du volume et à la délimitation du substratum rocheux.

## 1 INTRODUCTION

The remediation and reclamation of decommissioned oil and gas sites is an ongoing and ubiquitous endeavor throughout the provinces of Canada, particularly in Alberta. Before remediation strategies are implemented, an adequate assessment of the site must be performed in terms of historical spills, the extent of contamination, if any, and the desired end-use of the land with the main goal of reclaiming the land to its original state. If spills or contamination have occurred on the site, geophysical electromagnetic surveys are often employed to get an idea of the lateral extent of contamination without having to disturb the soil. Following up with soil sampling and drilling (i.e. ground-truthing) is always required to confirm the properties of the contaminated soil, and to refine the utility of the geophysics. However geophysical investigations can be a powerful tool to explore and delineate these physical properties of the subsurface to get a better idea of the site before ground-truthing. In the planning stage of remediation and reclamation, geophysics provides valuable guidance for borehole location, soil sampling, and impacted soil delineation. Electromagnetic (EM) surveys are the most widely used preliminary geophysical methods to explore terrain conductivity at a site of interest, but it has its limitations. Other methods such as multi-line pseudo-3D resistivity imaging, or rapid conductivity volumes (RCV's) can provide high-value horizontal *and* vertical delineation at much greater depths, without many of the drawbacks and limitations of standard EM surveys. Such pseudo-3D resistivity imaging has been employed for geotechnical studies (Sauvin et al., 2011), sinkhole investigations (Kidanu et al. 2020), groundwater studies (Chen et al., 2022), fault mapping (Vanneste et al., 2007), and more.

This particular study focuses on two historical oil and gas sites located in southern Alberta, where the integration of geophysics and soil/borehole sampling were used to inform a Supplementary Phase II Environmental Site Assessment (ESA). Two sites are highlighted in this paper: one site with complex topography that relied heavily on geophysics for delineation of salt impact, and a second site that illustrates how pseudo-3D resistivity imaging greatly enhances delineation efforts in a 3-dimensional space, beyond the capabilities of a standard electromagnetic survey.

This project demonstrates strong collaboration between multiple consulting firms. Phase II borehole samples collected from Stantec Consulting Limited and Envirosearch Limited are compared with the most recent geophysical results to identify contours of conductivity that suggest environmental significance for remediation planning.

### 1.1 Site Overview

The two sites described in this investigation are located in Southern Alberta, just south of the South Saskatchewan River (Fig. 1). The first site, which we will call "Well Site #1," is located to the west in Fig. 1 and is located next to abundant cropland, indicating its importance for potential use as additional cropland and/or to ensure that contamination on site does not spread to the surrounding areas. The second site to the east in Figure 1 is located in an area of complex topography, with steep gullies/coulees that make ground sampling at the site very challenging or impossible, which also poses challenging hydrogeological conditions.

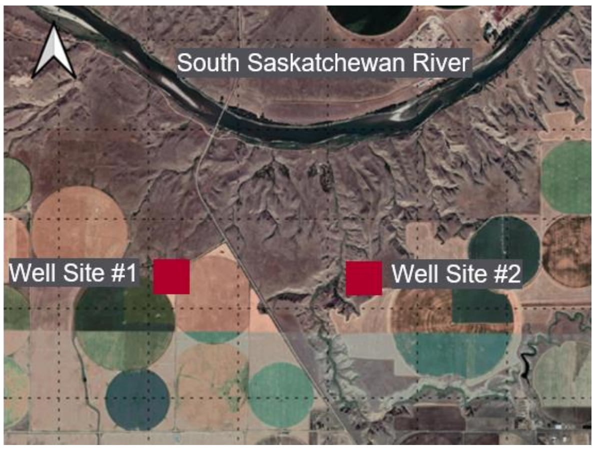


**Fig. 1**. Aerial overview of the two study areas called "Well Site #1" and "Well Site #2."

Fig. 2 provides an overview of Well Site #1, where the original site plan showing historical facilities is provided in the black outline, and its position within the investigation area is shown relative to the yellow lines. The yellow lines are the individual electrical resistivity lines that were acquired to effectively cover the area, while the multi-coloured overlay is an electromagnetic survey (EM31) that was acquired to provide preliminary delineations of terrain conductivity at the site prior to this investigation. However, such types of surveys do not provide vertical delineation and are prone to interference from buried and on-surface infrastructures such as metal, vehicles, powerlines, and pipelines. Note the proximity of an irrigation lagoon that was installed on this site as a potential ecological receptor to site contaminants; this has significant implications in regard to site closure.

Fig. 3 demonstrates the topographical complexities encountered at Well Site #2, which makes ground-truthing and drilling for samples very challenging or impossible. The aerial satellite imagery provides the approximate location of historical facilities relative to the area of investigation (outlined in black), while the yellow lines denote each of the ERI lines that were used to build the rapid conductivity volume (RCV) model of the subsurface for contaminant delineation. Also shown are photographs of the site that further illustrate the complexities of the terrain at this site. Note from Fig. 1 that the coulees all flow towards the South Saskatchewan River, a potentially important pathway for contaminant migration.

Both sites represent the unique challenges that many decommissioned oil and gas sites face, and thus may require an elegant approach that perhaps only geophysics can provide.

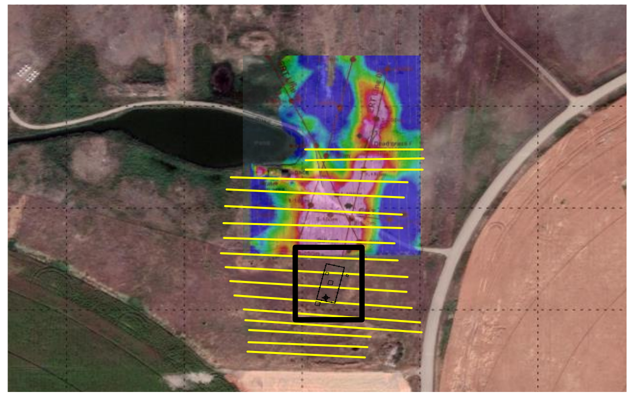

**Fig. 2:** Satellite overview of study site. Yellow lines indicate ERI lines used to build the pseudo-3D volume. A previous EM31 survey is overlain to illustrate the shape of the conductive anomaly (pink = high conductivity, blue = low conductivity). Black lines indicate the historical location of facilities.

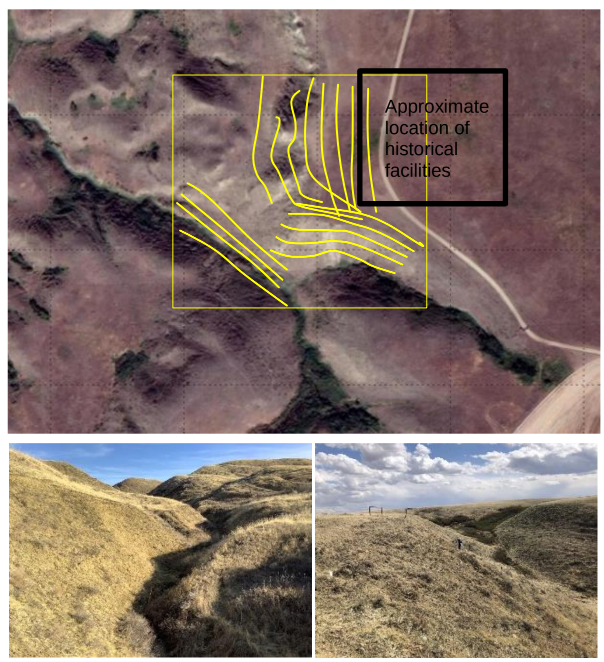


**Fig. 3**. Aerial view of investigation area, where yellow lines illustrate the locations of ERI lines used to build the conductivity model. The bottom photographs demonstrate the topographic complexities encountered at this site.
type of array being targeted.

## 2 GEOPHYSICAL METHODOLOGY

2.1 Electrical Resistivity Imaging (ERI)

Electrical resistivity imaging (ERI) employs basic physical principles to measure the electrical properties of the subsurface (Hermann, 2001). Generally, ERI surveys use an array of 4 electrodes per measurement, and measures hundreds to thousands of points in the subsurface depending on the length of the total array (i.e. number of total electrodes used and limitations of equipment being used). For a single resistivity measurement, 4 electrodes are used; two electrodes are used to inject current into the subsurface (via the “C” electrodes), while two other electrodes are used to measure the electrical potential difference, or voltage, (the “P” electrodes) at some distance away from the two “C” electrodes. Many different types of arrays can be used, such as the Wenner Array (Fig. 4), Dipole-Dipole Array, and Gradient Array, where the choice of the array depends on the type of target to be imaged.

The foundation of this electrical method incorporates Ohm’s Law, where the resistance of a material can be measured experimentally when controlling a known amount of current, and measuring the voltage in the subsurface due to that current. In the context of electrodes, this must be related to the specific geometry of an electrode array and to the subsurface, which results in the general formulation:

$$\rho_{app} = \frac{V}{I}K \qquad [1]$$

Where $\rho_{app}$ is *apparent* resistivity, *V* is the measured voltage between the “P” electrodes, *I* is the injected current to the “C” electrodes, and the value of K is a geometric factor that is dependent on the specified electrode array.

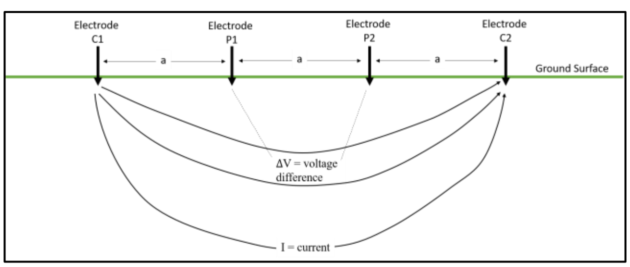


Fig. 4 Typical 4-electrode ‘Wenner’ array deployed on the surface.

Once an array of electrodes is planted on the surface with equal spacing (designated as “a” in Fig. 4), a computer system controls the injection/measurement of current /voltage, respectively, and builds a cross-section of data points. The larger the spacing between electrodes, the greater the depth penetration of each measurement. With a cross-section of measurement points, we can then invert the section using RES2DINV (an industry-standard software by Geometrics). Using a rapid ERI acquisition method we can acquire multiple lines of resistivity to effectively cover our region of interest. These lines can then be combined and interpolated to obtain a rapid conductivity volume (RCV) model of the subsurface, which provides us with an improved understanding of the site’s subsurface.

2.2 Pseudo-3D Model Visualization

In order for a model to be considered truly 3-Dimensional, it should have equal spacing in the X, Y, and Z directions, or at most 4x times the electrode spacing between each 2D line (Kidanu et al., 2020). In our case, we have acquired and inverted individual 2-dimensional lines and then applied an Inverse Distance weighting interpolation (Bartier and Keller, 1996) to the data between them – as such, we describe the resulting model as pseudo-3D, since it does not satisfy the requirement of equal-sized data distribution in both X and Y directions. It should be noted that in this method, we are introducing a 2-dimensional bias to our data; under the assumption that the measurements we acquire are due only to effects in the plane of the 2D acquisition line. However, for our investigations, we have found the method to produce adequate and accurate results given the scope of investigation, as found in similar studies (agiusa.com, 2021; Yang and Lagmonson, 2006). The 3D models presented in this investigation were produced using Voxler, an industry-standard 3D geologic and scientific modeling software by Golden Software. 2D inversions of resistivity were obtained using RES2DINV, another industry standard inversion program used for resistivity data (Arrhus GeoSoftware, Denmark, 2022). Inversion results from RES2DINV were imported to Voxler, and then gridded. The gridded interpolation then provides a volume model that can be used to visualize a specified isosurface, a coloured block model, a face render model, etc.

Voxler requires that certain gridding parameters are specified to produce satisfactory interpolation results. The key parameters include:

- The search ellipse, which describes how much of the data is to be included for the interpolation calculation
- The geometry and resolution of the grid spacing
- The gridding method (i.e. inverse distance)
- The level of anisotropy (anisotropy ellipse vs. isotropic sphere)

Note that the parameters chosen should be specific to the data and methodology/parameters of the acquisition.

3 RESULTS

The 3D models provided in this investigation are shown as conductivity isosurfaces (contours of equal conductivity across the interpolated volume model). The gridding parameters were applied with a search ellipse of 20 meters in all directions, and an anisotropy ellipse of 5 meters in the X direction, 15 meters in the Y direction, and 2 meters in the Z direction, to account for the sparsity of data density between lines in the Y direction, and the higher data density in the X and Z direction These parameters are designed to address the 2D bias we incorporate by interpolating between individual 2D inversions, thus making it a pseudo-3D volume.

3.1 Site #1

The results of the RCV survey at Site #1 are shown in Fig. 5. A very good qualitative correlation was found between the previously acquired EM31 survey and the 2021 RCV results, shown in Fig. 5 when comparing the grey isosurface (120 mS/m) and the pink anomaly in the EM31. Boreholes containing geochemical information are also shown as coloured cylinders, where chloride concentrations are coloured red for any concentrations greater than 100 mg/kg, indicating site-impacted soil as per Alberta guidelines (AEP, 2019).

Geophysical results were compared with the chloride concentrations, where high conductivities (>120 mS/m) were indicative of site-impacted sediment according to its correlation with the geochemistry. The isosurface was chosen based on the result that best encapsulated the chloride concentrations exceeding remediation guidelines (i.e. the isosurface that encompasses all the boreholes shown in red, indicating concentrations > 100 mg/kg). The geophysical anomalies also clearly identified two main source areas of contamination, based on location and anomaly geometry: deep contamination from the calcium chloride sump, and shallower contamination from the surface casing vent pipe (Fig. 5). These interpretations were largely informed by the historical overview of the site. Figure 6 provides a side-profile view of the anomalies, which extends to a total depth of ~30m, and illustrates the improved delineation of salt impact at depth as compared to a typical EM31 survey.

The generated geophysical model was used by Envirosearch Ltd. to guide their borehole sampling program that occurred in late-2021. This provided an excellent opportunity to refine the geophysics with the acquired samples after collection to determine how well the geophysical anomalies delineated the actual contaminated soil. In Fig. 7, there are two boreholes (circled in red) from the 2021 sampling program that shows the geophysical anomaly both above and below an unimpacted lens of soil, which was supported by the chloride concentrations there. Such information can be used going forward to greatly improve volume estimation during remediation.

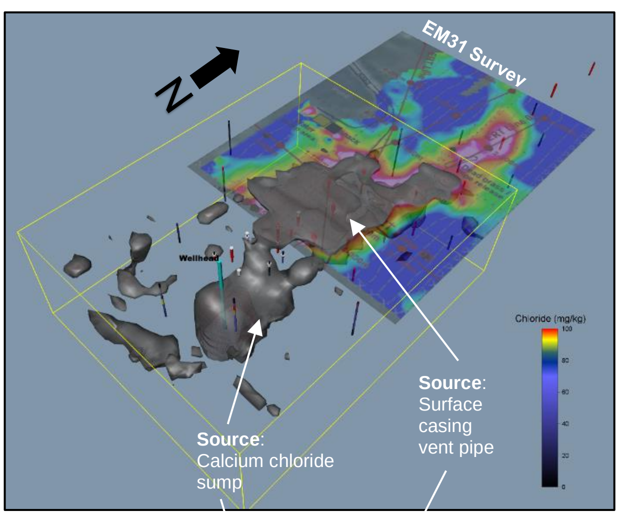


Fig. 5: Looking from the SE corner of the site: A gray isosurface was mapped at 120 mS/m. Note that two main conductive bodies were identified, which are assumed to be sourced from the calcium chloride sump and the surface casing vent pipe.

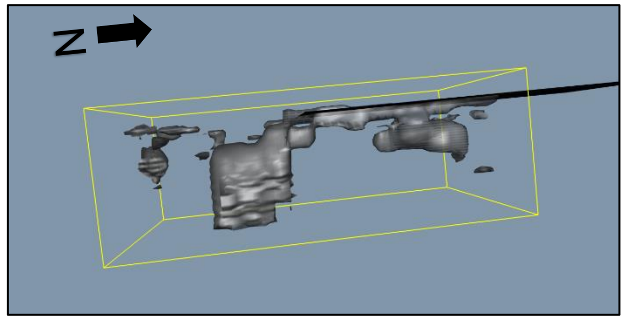


Fig. 6. Side view of the 3D conductivity model shows the delineated conductive anomaly extending to depth below the EM31, below the historical location of the calcium chloride sump. The total depth of the model is 30 meters.

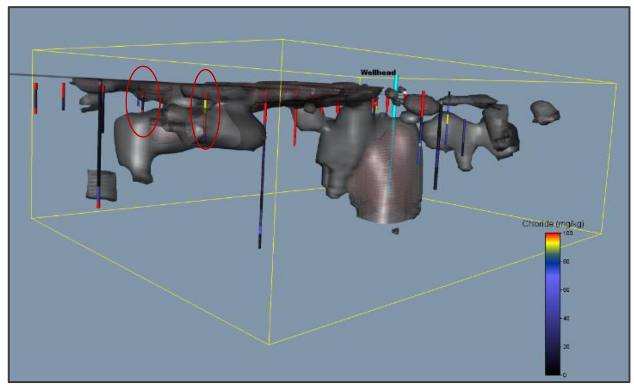


Fig. 7 Perspective view looking from the NW corner of the site: Note the isosurface is widespread at the surface, and steps down to depth below the EM31 surveyed area. Circled in red shows two boreholes that indicate chloride impact at the surface, and at depth with an unimpacted lens of soil in between. The geophysical anomaly matches very well to these geochemical results.

The combined results of geophysics and soil/borehole sampling demonstrate that the path to closure can be well delineated, and gave rise to the following concerns:

- The extent of impact should be delineated into the lagoon as a potential ecological receptor.
- Extent of impact down-gradient to the north towards a possible human receptor (a domestic water well within 1km of the area) and the South Saskatchewan River, as well as the deeper impacts that were correlated with the historical calcium chloride sump potentially affecting groundwater.

These concerns are illustrated in Fig. 8, showing the conductive anomaly underlain a satellite image of the site, and arrows that demonstrate possible hydraulic pathways toward receptors of importance.

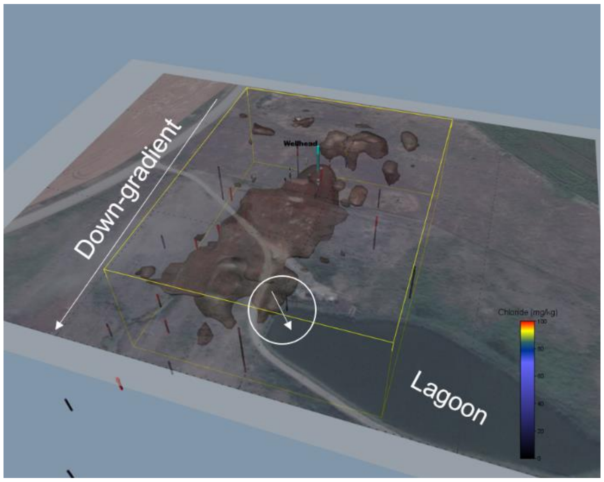


Fig. 8 Perspective view looking from the NW corner of the site. White arrows indicate potential hydraulic pathways for contaminants to flow; down-gradient towards the South Saskatchewan River, and towards the irrigation lagoon.

3.2 Well Site #2

Results from the second site are shown in Fig. 9. Yellow lines (Fig. 9a) indicate the locations of the RCV lines, which also demonstrate the complex/steep environment based on their undulations. The complex terrain made subsurface sampling very challenging, so the results of the geophysical RCV survey were relied on heavily for soil impact delineation as no other method can obtain depth information at the bottom of the coulee.

Other complicating factors on this site include sensitive native prairie vegetation, sensitive wildlife that limits when and where drilling can occur, and pre-contact stone circles that limit any ground disturbance whatsoever due to their heritage value.

RCV results (Fig. 9b) show conductive anomalies at the crest of the hill where historical infrastructure was located (Fig. 3), and down the ravine to the south of the hill crest where a surface casing vent pipe was known to be leaking fluids into the coulee. Vertical delineation of this anomaly was achieved down to ~13 metres below ground surface at the bottom of the ravine, whereas geochemical information was only available in the top metre of soil.

Fig. 9b also shows previously sampled borehole locations that are coloured according to measured chloride concentrations, where red cylinders indicate chloride concentrations that are approximately equal to, and greater than 100 mg/kg, suggesting site-impacted soil. Note the lack of samples along the slope of the hill, and where they do exist are extremely shallow due to the lack of a drilling rig capable of sampling in these areas.

Based on these RCV results, planned boreholes for 2022 are shown in cyan. Using the geophysical model, the planned boreholes were chosen and strategically placed to target areas of concern and interest, and avoid areas that are less likely to contain contaminated soil thereby reducing drilling and sampling costs.

Similar to Site #1, the geophysical model allowed the delineation of two main impact sources: the calcium chloride sump at the top of the hill; and the surface casing

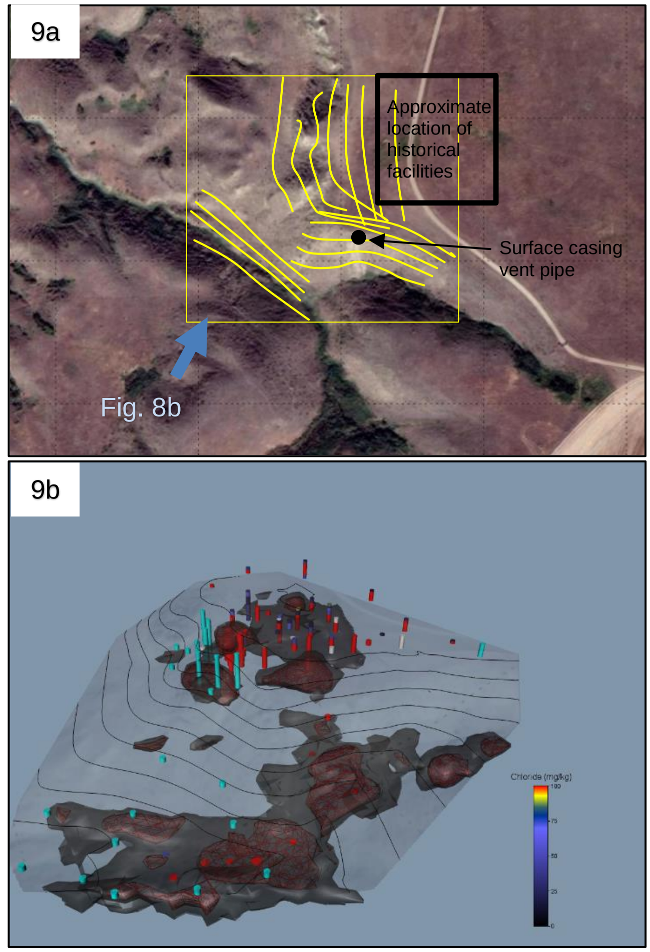


Fig. 9 a) Overview of lease site and lines (yellow) showing rapid ERT lines. b) Pseudo-3D volume showing 120 mS/m isosurface in gray and 150 mS/m isosurface in red. Previously sampled boreholes (pre-2021) are coloured according to chloride concentration (mg/kg). Planned boreholes (2022) informed by RCV results are shown in cyan.

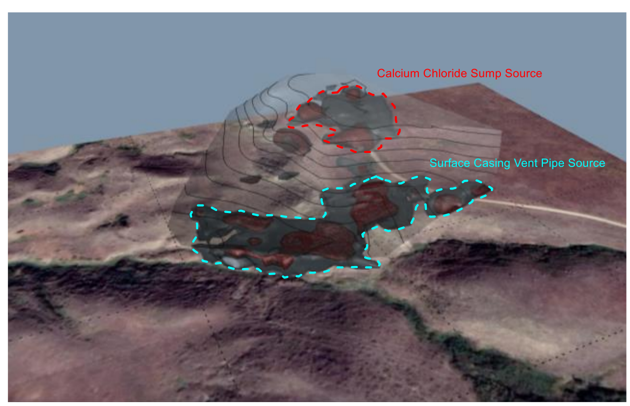


Fig. 10 Interpreted anomalies based on their sources of contamination. Contamination at the top of the hill is interpreted to be sourced from the calcium chloride sump, while down into the coulee is interpreted to be sourced from the leaking surface casing vent pipe.

vent pipe that spills over the side of the hill and into the bottom of the coulee (Fig. 10). Such interpretations greatly improve the understanding and characterizations of the site, ultimately improving the path to closure and remediation.

## 4 CONCLUSIONS

Comparing geophysical results with geochemical information showed that the geophysics was able to delineate anomalies that coincided with site contamination at two decommissioned oil and gas sites. In areas of complex terrain/topography, geophysical surveys can be used where traditional ground sampling is difficult or even impossible. Having a pseudo-3D model allowed for the better planning of borehole strategies and placement, particularly in areas of sensitive vegetation, wildlife, and challenging field conditions which ultimately improves efficiency and lowers overall costs, and promotes a better path to closure in remediation and reclamation.

The success of the results presented here are a direct consequence of the collaboration between DMT Geosciences Ltd, Stantec Consulting Ltd, Envirosearch Ltd, and ATCO, in the interest of improved site characterization and remediation planning. Paths to closure rely on the effective collaboration and coordination of sampling and surveying to fully understand these sites, and ensure that the desired end land-use is achieved.

## 5. ACKNOWLEDGEMENTS

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