Imaging the deep carbon stocks with complex electrical conductivity

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Abstract. ~~Due to the limited penetration depth of standard sampling methods, mapping~~Mapping of soil organic carbon (SOC) is usually restricted to the top 100 cm of soils~~. Hence,~~ due to the limited penetration depth of standard soil sampling methods. This has resulted in current models ~~underestimate~~underestimating SOC due to the unexplored deep carbon stocks. Moreover, standard methods only offer punctual data relying on interpolation to investigate extensive areas. We demonstrate here that subsurface 2D images of the complex electrical conductivity (CC) can delineate the presence and geometry of SOC reaching a depth of a few tens of meters below the surface. ~~In particular, we~~We show that an increase in the polarization effect at low frequencies (< 5 Hz) is linearly related to high concentrations of SOC. We present measurements from a catchment with silty loam soils, where the geometry of a deep carbon stock (between 4 and 6 m depth) was identified by CC images, and validated through laboratory analysis of soil samples.

1 Introduction

Soils are the largest terrestrial reservoir of organic carbon with the potential for long-term carbon storage (e.g., Panagos et al., 2013). Estimating soil organic carbon content (SOC) and inventories is therefore critically important for realistically evaluating the global C balance~~.~~ and changes in this budget due to human activities (Ganzenmüller et al., 2025). Current methods primarily estimate SOC for the topsoil (0 to 100 cm depth), as they contain the largest concentrations of SOC (e.g., Harrison et al. 2011; Yost and Hartemink, 2020). However, ~~top soils~~topsoils have limited potential to sequester further carbon, and it ~~it might~~can be ~~quickly lost~~rapidly processed and released to the atmosphere due to high rates of microbial respiration and soil disturbances (Button et al., 2022 and references therein). Mapping of SOC in deep soils (> 100 cm) has ~~only~~ been seldom addressed due to the enormous costs required for detailed ~~deeper~~deep drilling over large areas, and analysis of the large number of samples this implies (Harrison et al. 2011; Yost and Hartemink, 2020). ~~Furthermore, random drilling is ineffective for targeted sampling of deeper SOC layers, so~~Based on the analysis of boreholes reaching 37 m depth, Harper and Tibbett (2013) reported an increase in SOC storage at deep soils correlated with rainfall and following reforestation. Likewise, deep carbon stocks in permafrost

soils are poorly understood with estimations made from the interpolation of sparse data (e.g., Tarnocai et al., 2009; Strauss, et al., 2013; Walter Anthony, 2018); although the thawing of such soils has a direct impact on climate change. Random drilling is ineffective for sampling of deep SOC layers, especially when only a limited number of cores can be taken. Thus, ~~.~~ any investigation of deep carbon stocks requires prior information for designing survey sampling strategies.

Geophysical methods permit the ~~collecting~~collection of quasi-continuous information about subsurface properties in a non-invasive manner. Among them, electrical methods~~,~~ have proved their potential to resolve geological, hydraulic and chemical properties of the soil (see Kemna et al., 2012; Kessouri et al., 2019; Binley et al., 2015). Electrical methods, such as the electrical resistivity tomography (ERT) and associated complex conductivity (CC~~) has demonstrated the possibility of quantifying soil texture and hydraulic properties of the~~), resolve subsurface ~~(see Binley et al., 2015 for a review) and its potential to sense changes in pore space~~ electrical properties ~~associated with biogeochemical processes (Atekwana and Slater 2009). CC provides information about~~at low frequencies (< 1 kHz). The methods are based on an electrode pair used to inject a current into the ~~electrical~~ ground, while other electrode pairs measure the resulting electrical field (see Appendix 5.2 and references therein). Current flow in the soils takes place along the fluid filling the pores (electrolytic conduction) and at the electrical double layer (EDL) formed at the grain fluid interface (surface conductivity). Thus, it is controlled by porosity, saturation, the conductivity of the pore water as well as surface charge, soil surface area and cation exchange capacity (CEC) of the solid phase. Additionally, current flow causes the polarization of charges in the EDL, resulting in a secondary electrical field observed after switching off the current. The conductive and capacitive properties of ~~the subsurface,~~ soils can be expressed ~~in terms of its~~ by the complex conductivity (σ^*), consisting of a real (σ'~~) and~~σ', representing the conduction or energy loss) and an imaginary (σ''~~)~~$''$, representing the capacitance or energy storage) components. ~~The (real component) conductivity (σ') accounts for the migration of electrical charges along the electrolyte filling of the pore space and at the electrical double layer (EDL) formed at the grain-fluid interface; while the imaginary component (or polarization, σ'') accounts for the accumulation~~ The highest conduction and polarization ~~of charges at the EDL, which is also known as the induced polarization (IP)~~ effect~~.~~ ~~The~~ can be observed in presence of electronic conductors such as sulphide minerals; thus, rendering the CC method ~~was initially developed~~optimal for mining applications ~~due to the high σ'' observed in the presence of iron sulfides such as pyrite~~ (Seigel et al., 2017 for a review). ~~Laboratory~~Based on this, the CC has been used to monitor the precipitation of iron sulphides (FeS) accompanying the stimulation of iron reducing bacteria in laboratory experiments ~~have also demonstrated the sensitivity of the method to monitor the activity of iron reducers~~ (Williams et al., 2005; Ntarlagiannis et al., 2005~~). Field experiments have suggested the possibility to sense not only the activity of iron reducers, but also changes in the redox state of sediments accompanying the~~) and at the field-scale in the bioremediation of uranium ~~contaminant plumes~~-contaminated aquifer (Flores Orozco et al., 2011; 2013). ~~Extensive~~The CC measurements ~~revealed the potential of the CC method~~ have also been conducted at the floodplain-scale to map ~~the presence of~~ naturally reduced zones, ~~where~~ due to the stimulation of iron-reducing microbes taking place in areas with high concentrations of organic matter ~~at a few meters below the surface stimulated the activity of iron-reducing bacteria and resulted in the accumulation of iron sulfides~~in soils (Wainwright et al., 2015).

~~In the absence of metallic minerals, the use of the~~In absence of electronic conductors, the polarization of an alternating current injected into the soil (i.e., soil capacitance) is mainly controlled by the properties of the fluid-grain interface. Accordingly, CC ~~method to characterize~~has been largely used to delineate immiscible organic contaminants ~~has been well documented~~ (e.g., Flores Orozco et al., 2012a; Schwartz and Furman, 2012; Johansson et al., 2015). ~~Recently,~~Moreover, laboratory experiments have demonstrated the sensitivity of CC to the adsorption of organic matter (OM) to mineral grain surfaces (Schwartz et al., 2014; Mellage et al., 2022) due to the formation of organo-mineral complexes (Schwartz and Furman, 2014); while Strobel et al. (2023) reported high σ'' values (around 50 Hz) in samples taken from degraded peatlands. Pehstani et al. (2025) investigated the adsorption of pentaglycine onto ferrihydrite-coated sand and argue that the increase in both conductivity (σ') and polarization (σ'') is due to the interaction between the grain surface and organic functional groups (e.g., carboxyl and amine). These results demonstrate the possibility of the CC method to investigate the interaction between organic compounds and porous media.

To date only few studies have applied the CC method at the field scale to investigate changes in SOC. Flores Orozco et al. ~~(2020) demonstrated the possibility of the CC method to map areas with high rates of methanogenesis, i.e., biogeochemical hot spots in municipal solid~~ (2020) revealed anomalous regions characterized by high σ' and σ'' in waste ~~(MSW) landfill. The authors found that the polarization (σ'') response was related to~~ containing high concentrations of total organic carbon~~. Built on these results,~~ (TOC) measured in leachates; whereas surveys conducted in peatlands have also revealed an increase in the polarization response with increasing the SOC (McAnallen et al., 2018; Katona et al~~. (~~., 2021~~) used CC measurements to delineate the geometry of carbon turnover hotspots in peatlands. McAnallen et al. (2018) and Strobel et al. (2023) also revealed high σ'' values due to an increase of organic carbon in degraded peatlands, while~~); although Ponziani et al., (2012) reported a decrease in σ'' with increasing ~~the~~peat humification ~~of peatlands.~~ . However, to date, the CC has not been applied to investigate large scale variations in SOC in mineral soils.

~~To our knowledge, no study has so far addressed~~Deforestation, reforestation, land use and climate change have a direct impact on the ~~identification~~dynamics of SOC ~~in mineral soils using CC. This study aims at filling~~, yet the response of deep (>1 m) carbon pools remains poorly understood. To fill this knowledge gap~~. Our results demonstrate~~, this study aims at evaluating the potential of CC images for mapping ~~high~~anomalies in SOC concentrations ~~in deep loamy soils at the catchment scale. Measurements presented here were collected in the Hydrological Open Air Laboratory (HOAL), a 66 ha catchment dedicated to understand water flow (further details in A1).Our results evidence that the CC method can be used to map organic carbon pools~~ at varying depths~~; thus, permitting to design~~ in loamy soils. This study focusses on deep investigations (> 1 m), which are rarely investigated in soil ~~sampling campaigns towards~~surveys, yet may be critical for the computation of more realistic organic carbon budgets~~.~~ as suggested by Harper and Tibbett (2013) among others. All data sets were collected at the HOAL (se Appendix 5.3), located in Petzenkirchen (Austria), which is a 66 ha research catchment dedicated to understanding water-related flow and transport processes involving sediments, nutrients and microbes in small catchments (Blöschl et al., 2016).

2 Results

2.1 The electrical properties of the HOAL – imaging results at 1Hz

Figure 1 shows the CC imaging results obtained for the measurements along the exploration line E1~~, from which~~. Here two layers can be visually identified~~.~~: (1) ~~On~~on the top~~,~~ the silty loam ~~related~~corresponding to the lowest conductivity and polarization values, ~~while~~and (2) ~~on~~at the bottom ~~is found~~ a lignite layer ~~with~~corresponding to the highest conductivity ($\sigma' =$ ~~=~~ 60 mS/m) ~~and~~but low polarization ($\sigma'' <$ ~~<~~ 0.25 mS/m~~), corresponding to the underlying lignite. Figure 1 reveals that drilling cores from B1, G2 and G4 support the interpretation of the electrical images.~~) values. While no groundwater was observed during the drilling of B1 and B2, the recovered sediments were often close to saturation~~.~~ in the loamy soils (see Appendix 5.4). The high σ' values are interpreted as being caused by the contribution of both ~~interfacial~~surface and electrolytic conduction. Due to the fine texture of clays, polarization is mainly expected at ~~high~~ frequencies ~~(~~>above ≥ 10 Hz~~),~~, explaining the low σ'' values ~~resolved for~~at 1 Hz ~~data~~ (see e.g., Mendieta et al.,2021). The increase in both σ' and σ'' for the lignite at depths below 7 m is expected due to the high surface charge ~~in~~of organic soils, which contributes to interfacial conductivity and polarization (e.g., Shao et al., 2017; Gao et al., 2017; Katona et al., 2021). A clear anomaly is also revealed in the loamy soils associated to the highest polarization values (σ''> 0.5 mS/m) in the profile. The anomaly is located below 2m depth, so unlikely to be related to infrastructure, yet above the expected position of the lignite layer.

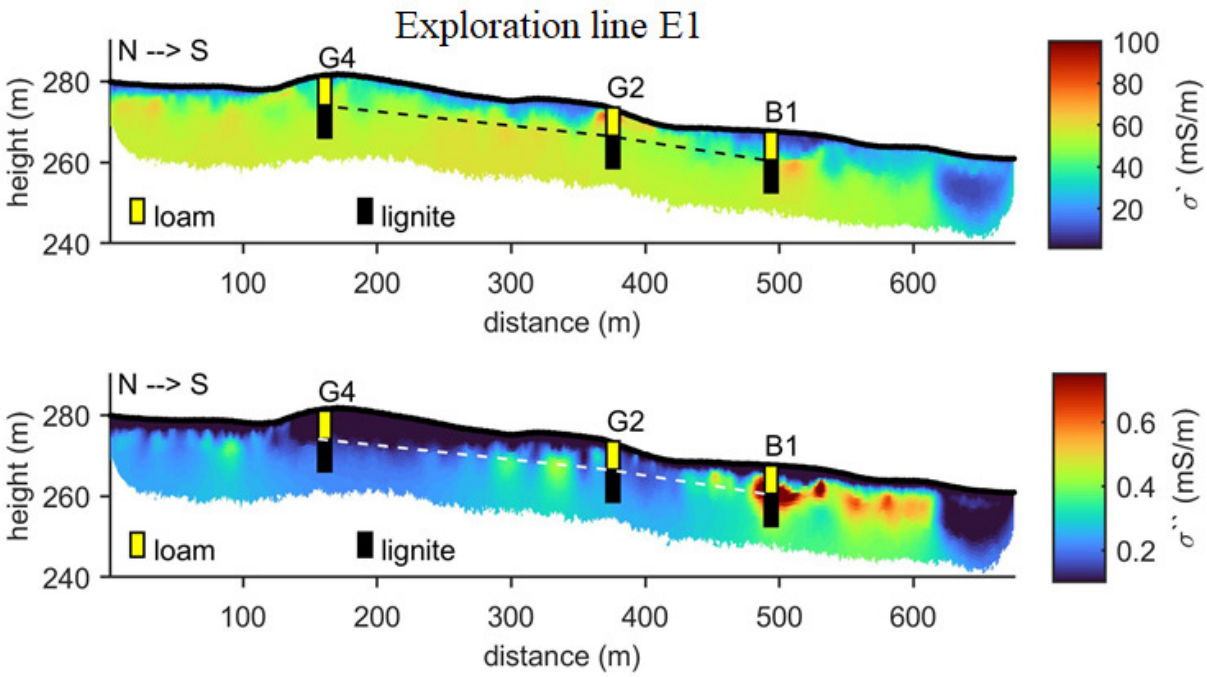

Figure 1: CC imaging results obtained for the Exploration line E1, expressed in terms of the conductivity (σ') and ~~induced~~ polarization (σ''). The information about lithological changes observed in soil samples extracted from existing boreholes G4 and G2,

as well as the drilled borehole for this study (B1), is imposed on the electrical images for comparison. The dashed line represents the depth to the lignite layer from the linear interpolation of the borehole data.

Figure 2 shows the imaging results for parallel line SIP1~~.~~ for data collected at different frequencies. Overall, the values are consistent to those in E1. The shape of the shallow polarizable anomaly is clearly resolved between 2 and 6 m depth at the middle of the SIP1 profile, with the highest polarization (σ'' ~ 1 mS/m) at low frequencies (0.5 and 1 Hz) and a negligible response at frequencies above 7.5 Hz. In contrast, the conductivity images reveal only a layered media and no variation at the position of the polarization anomaly. Figure 2 reveals vertical changes in σ' consistent with those observed in cores from B1 and B2, with lower values ~~.~~(~20 mS/m) for sandy loam~~, and higher (~50 mS/m) in~~ than for the clayey loam. Figure 2 also shows a shallow conductivity anomaly (between 10 and 20 m profile distance), which is only polarizable at frequencies above 10 Hz, ~~which is indicative of a clay-rich area~~likely indicating the presence of clay-rich sediments. The frequency at which the maximum polarization is observed is inversely proportional to grain size (see Bücker et al., 2019), and laboratory results have reported the maximum response in clays at frequencies between 10 - 100 Hz (see Mendieta et al., 2021 and references therein) supporting the interpretation of the conductive and polarizable shallow anomaly observed between 10 and 20 m along the SIP1 profile.

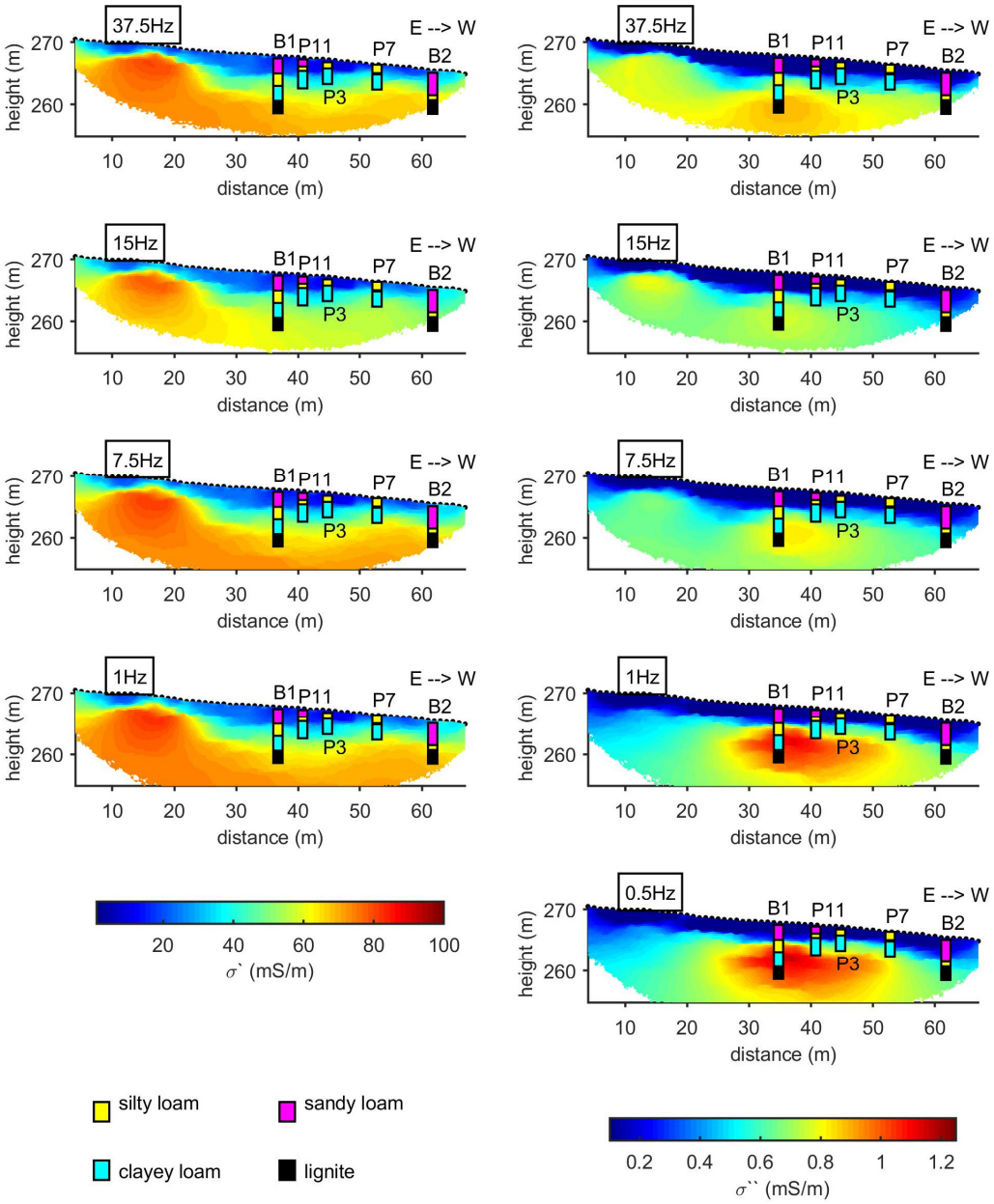

Figure 2: CC imaging results obtained for multi-frequency data collected at the line SIP1 expressed in terms of the conductivity (σ') and polarization (σ''). The information about lithological changes observed in soil samples extracted from existing piezometers (P11 and P7), as well as the drilled boreholes for this study (B1 and B1) is imposed on the electrical images for comparison.

2.2 The deep carbon stock: geochemical interpretation of the high electrical polarization anomaly

Figure 3 shows the ~~laboratory~~chemical and physical analysis of the soil samples from B1 and B2 and the vertical conductivity (σ') and ~~σ''~~ polarization (σ'') values extracted from the SIP1 ~~images~~data at the position of the boreholes. Such plots demonstrate ~~that~~ the ~~high~~highest σ'' values are resolved at 1 Hz in B1 between 2 and 6 m depth ~~cannot be explained by changes in the soil textural properties.~~. The σ'' values of B1 are almost twice those of B2, although the clay content is 50% lower~~.~~; thus, the polarization anomaly cannot be explained by changes in the textural properties of soil, especially at low frequencies. The surface charge, as indicated by the CEC, ~~also reveals~~is consistent ~~values of B1 and B2~~in both boreholes, with ~~a higher~~the lowest values in the loam soils and an abrupt increase ~~in CEC~~ at the position of the lignite layer ~~at a depth of 6 m in B1~~.

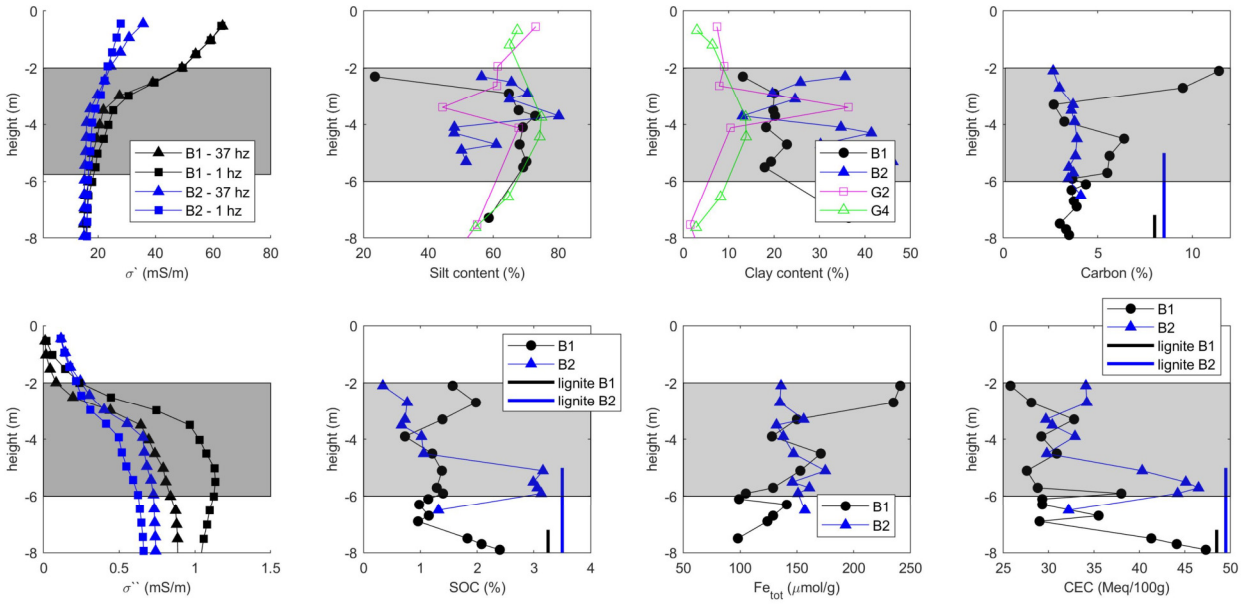

Figure 3: Comparison of the electrical (σ' and σ'') and geochemical parameters (Fe_{tot}, TOC, CEC) measured in the drilling cores (B1 and B2). Electrical parameters represent the mean values computed from pixels extracted from the inversion results of lines SIP1 at 1 Hz (solid triangles) and 37.5 Hz (solid circumferences). Textural properties in boreholes (B1 and B2) and piezometer~~s~~ samples are also presented for comparison. The depth to the lignite layer found at the position of B1 and B2 is indicated by the vertical lines in the plots of the SOC, Carbon and CEC data.

The polarizable anomaly (σ''~~) around~~> 1 mS/m) at B1 is ~~consistent~~collocated with the highest SOC (> 1%) and Fe_{tot} concentrations ~~measured~~. In comparison, geoelectrical and geochemical parameters are both much lower in B2. It might be argued that the increase in iron content enhances the electrode polarization observed in iron sulfides. However, XRD scans in our samples revealed negligible concentrations of sulfides, with the mineralogy being dominated by calcite and silicates. Hence, iron is mainly present as iron oxides, commonly related to negligible polarization at 1 Hz, with the exception of

Hematite (e.g., Hubbard et al., 2014; Abdel Aal, 2014), which was also not found ~~-~~in our samples neither in soils nor bound to organic matter.

The polarizable anomaly ~~($\sigma'' > 1$ mS/m)~~ is most likely related to two organic carbon ~~stocks~~rich layers: (1) the main one found between 2 and 3 m depth (> 2 % SOC), and (2) a deeper stock ~~found~~ between 4 and 6 m depth (ca 1.5 % SOC). This interpretation is supported by the geochemical analysis of sediments in B1. High σ'' and SOC in B2 at 5 m depth are due to the presence of the lignite layer, which is observed at 7.2 m depth in B1.

3 Discussions

Results presented above demonstrate that soil ~~texture~~textural properties of the HOAL vary enormously in space, ~~so achieving~~making a reliable characterization from a few discrete soil ~~probes is not possible.~~samples difficult. Moreover, CC imaging results for E1 and SIP1 reveal a distinctive polarizable anomaly ($\sigma'' >$ ~~>~~ 0.6~~-~~ mS/m) within 3 m and 6 m depth. At the HOAL, this is the only location at which such high polarization values have been observed. Analysis of samples collected in B1 and B2 demonstrate this anomaly is not due to buried infrastructure ~~or changes in clay content, and can only be explained by the variations in SOC.~~(pipes, cables etc) or changes in clay content, yet variations in σ'' are consistent with changes in SOC and Fe_{tot} concentrations supporting our interpretation of deep carbon stocks. The SOC concentrations observed in these deep carbon stocks are similar to the value (~2.1 %) in Austrian topsoils, as reported by Panagos et al. (2013).

Mineralization of C is higher in coarse-textured soils (e.g., Hassnik, 1992), with finer grains hindering the access of soil microbes and O_2 to the SOC. Additionally, clay and iron oxide surfaces adsorb C, forming soil aggregates that protect SOC from decomposition (Elliot, 1986). Hence, low permeable loams from the HOAL offer the best conditions to preserve SOC from O_2, which ~~can~~could trigger ~~the~~its decomposition ~~of SOC.~~. The carbon stocks found are ~~also favoured~~supported by the presence of iron oxides~~,~~ (as reported by high Fe_{tot} concentrations) which ~~also play a major role~~contribute ~~in~~to the sorption and stabilization of SOC (see Singh et al., 2018 and references therein).

~~Classical sampling of the top soil is limited to investigations with a maximum depth ~ 1 m; while the use of CC imaging, permitted us to map two deep carbon stocks at a high spatial resolution. However, it is still critical to use borehole data to improve the interpretation of the geophysical results. In this case, analysis of samples permitted to differentiate two separated carbon stocks from the anomaly detected with CC imaging. The deep carbon stocks found are relevant in C budgets, as these are close to the SOC average value (2.1 %) in top soils in Austria, as reported by Panagos et al. (2013).~~

~~The high polarization response at low frequencies in the presence of SOC observed here is consistent with the study of Katona et al. (2021) conducted~~Our results are consistent with those recently reported by Peshtani et al. (2025), who reported an increase in σ' and σ'' following the adsorption of pentaglycine into the surface of ferrihydrite-coated sand and ceramic beads. The increase in the polarization (σ'') is explained by electrostatic and chemical interactions between the reactive mineral surface and functional groups present in the organic matter such as amine and carboxyl.

Our results are also consistent with previous studies revealing an increase in the polarization with increasing carbon concentration in peatlands ~~and with Flores Orozco et al. (2020) for measurements~~(McAnallen et al., 2018; Katona et al., 2021;

Strobel et al., 2023) and in municipal solid waste landfills.(Flores Orozco et al., 2020). Gao et al. (2017; 2019) have also found evidence for the sensitivity of the method to organic carbon for measurements conducted in in biochar. Similarly, Ponziani et al. (2012), McAnalen et al. (2018) and Strobel et al. (2023) reported high polarization in the presence of organic matter in peatlands but the response changed for different degrees of decomposition leading to an inconclusive σ'' and SOC relationship in their study. Further analysis on the composition of the OC observed in our sample sis beyond the scope of this study. While measurements. Though further research is needed to fully understandquantitatively resolve SOC-CC associations or, as also pointed out by Peshtani et al. (2025), identify the fundamental physicochemical controlsnature of the polarization response in presence of SOC, this study highlights the capability oforgano-mineral complexes.

Our results demonstrate that the CC method may help to map deepovercome the limitations in SOC investigations based solely on a few soil samples. However, interpreting CC results still requires boreholes soil data as ground truthing. Hence, we believe that CC would be a useful tool when designing the soil sampling campaigns. For our study, chemical analysis of samples allowed us to differentiate between two separated carbon stocks with a spatial resolution not achievable with direct methodsrevealed by the polarizable anomaly in the CC images. Since the geochemical and geophysical measurements represent very different sampling volumes (a few grams in the soil analysis andvs. a few m^3 in the geophysical data), we refrained from a numerical comparison, focusing on highlighting the potential of the polarization images to map variations in SOC. However, quantitative estimation of SOC from σ'' values. Nonetheless, volume estimates of SOC can be obtained from 3D electrical models of geophysical data as presented in the Appendix A5.5 (Figure A2). Moreover, furtherFurther investigations should consider CC laboratory and field monitoring experiments to better understand the geophysical response due to theorganic carbon dynamics, such as sequestration and degradation of SOC.

4 Conclusions

We present a novel application of electrical geophysical methodmethods to resolve variations in soil organic caroncarbon (SOC) in an imaging framework. Our results demonstrate the potential of the complex conductivity imaging method to map carbon stocks in soils in a depth between 4 and 6 m. Electrical anomalies with high polarization (i.e., capacitive properties) at frequencies ≤ 1 Hz indicate high SOC, informationa feature not resolved inby the electrical conductivity, which is highly sensitive to lithological changes. A suitable interpretation of the electrical images requires ground truth. Nonetheless, CC imaging results are key for an adequate designvariations. While support of soil sampling, yet a few samples help for the analysis is necessary for a quantitative interpretation of polarization imaging results at depths not easily accessible for electrical properties, our study demonstrates the advantages of using the CC method to select the collectionposition of soil samples. In particular, the delineation ofdrilling for soil sampling. Hence, CC may provide a unique opportunity to investigate deep carbon pools is key towards obtaining reliable SOC estimates beyond the depth capabilities of current field based methods. Further research could focus on better understanding ofstorage, for instance in thawing arctic soils, as well as to understand the temporal dynamics of SOC through the application of CC monitoring.

5 Appendix

5.1 The Hydrological Open Air Laboratory (HOAL)

All data sets were collected at the HOAL, located in Petzenkirchen (Austria), which is a 66 ha observatory dedicated to understanding water-related flow and transport processes involving sediments, nutrients and microbes in small catchments (Blöschl et al., 2016). Soil cores recovered from eight boreholes distributed across the HOAL (G1 to G8 in Figure A1) reveal only silty loam soils underlain by a succession of consolidated and unconsolidated lignite. Topography variations (see Figure A1) are aligned with variations in the depth to the lignite layer between 6 m and 40 m. The silty loam soils exhibit low saturated hydraulic conductivity (< ~~10^{-7}~~ 10^{-7} m s^{-1}) and may give rise to discrete perched aquifers, while an artesian aquifer was found below the consolidated lignite. Further details about the site can be found in Blöschl et al. (2016).

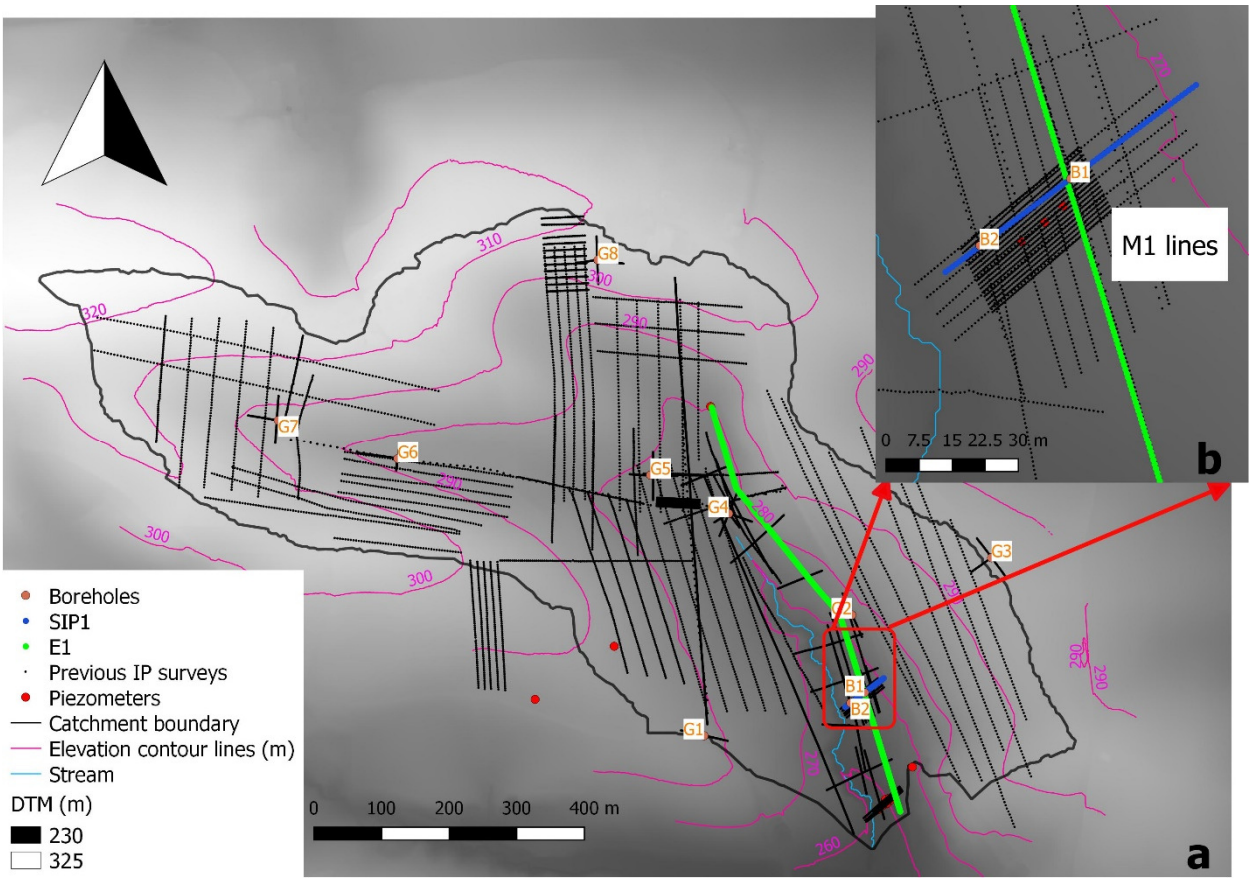

Figure A1: Existing surface and subsurface information at the HOAL: (1a) The topography changes are indicated in the grey tones and the isolines (pink lines), available CC measurements (black lines) and boreholes (G1 to G8). The embedded plot (1b) highlights the orientation of the CC lines presented in this study: exploration results (E1 with the green line), the multi-frequency measurements (SIP1 with the blue line) and mapping measurements (M1 indicated with the black lines) as well as the boreholes B1 and B2 drilled for sampling and geochemical analysis of soil samples in the electrical anomaly.

5.2 The Complex Conductivity Imaging method

The complex conductivity (CC) method is also known as complex resistivity (CR), electrical impedance tomography or induced polarization (IP). The method uses a pair of electrodes to impose an electrical field into the ground (i.e., related to current flow), while another pair of electrodes measures the resulting voltage. Imaging methods deploy tens to hundreds of electrodes, where thousands of measurements can be used to compute spatial changes in the electrical properties of the subsurface. The method operates at frequencies below 10 kHz, where the electrical properties of the soil are due to the movement of free charges in the pore water (electrolytic conduction), in the EDL formed at the grain-fluid interface (interfacial or surface conductivity) or through the solid particle of the soil (matrix conduction). In the absence of electronic conductors and semi-conductors, the matrix conduction is negligible; thus, the electrical conductivity of the soils is given by electrolytic (σ_{el}) and surface conductivity (σ_s). While σ_{el} is controlled by the saturation, porosity and conductivity of the fluid; the σ_s is mainly controlled by the surface area and surface charge in the EDL. Moreover, the application of an external field results in the polarization of charges in the EDL. Accordingly, the surface conductivity is represented as a complex value (σ^*) contributing to bulk conductivity (σ_s') and the so-called polarization effect (σ_s''). Hence, the low-frequency properties of the soil can be expressed by means of the complex conductivity, such as:

$$\sigma^* = \sigma' + i\sigma'' = (\sigma_{el} + \sigma_s') + i\sigma_s' \quad (1)$$

In Eq. 1, i represents the imaginary unit ($i^2 = -1$).

The CC can use direct-current (DC) or alternating-current (AC), with the former referred to as time-domain (TD) and the latter as frequency-domain (FD). In the FD, the polarization effect results in a phase-shift between the sinusoidal current imposed in the current dipole and the voltage measured; whereas in the TD, the polarization effect results in a decaying secondary electrical field observed after switching the current off. In the FD, it is common to use currents in the range between 0.1 mHz and 10 kHz; while in the TD it is common to use a square wave with a pulse-length varying between 0.2 and 8 s. For further details see Ward, 1980, Binley and Kemna (2005), Sumner (2012), Binley and Slater (2020).

The resolution of the CC method is controlled by the separation between the electrodes used for the voltage measurements; while the depth of investigation is defined by the maximum separation between the transmitting dipole (i.e., dipole used to inject current) and the voltage dipole. However, increasing the separation between current and voltage dipole also decreases the signal-to-noise ratio (S/N). To increase the S/N, it is necessary to increase the dipole length. Hence, geophysical surveys need to be carefully designed to achieve a high resolution (enhanced by decreasing the dipole lengths) and reach the required depth of investigation (enhanced by increasing the dipole length). It is well accepted that the maximal resolution in the CC imaging results is given by 1/3 of the dipole length, while the depth of investigation is approximately 1/3 of the maximum separation for the current and voltage dipole. However, the presence of highly conductive materials (e.g., clay-rich soils) close to the surface might channel current flow reducing the depth of investigation. We refer to Sasaki, 1992; Friedel, 2003; Okpoli, 2013.

Kemna (2000) demonstrated that the resolution of the CC imaging results can be evaluated by means of the cumulative sensitivity. In electrical imaging, sensitivity quantifies the effect that changes in the electrical properties at a given position of the imaging plane (i.e., model parameter) have on the measured voltages at the surface (Kemna, et al., 2002). Accordingly, high sensitivity is resolved for measurements with small separation between current and voltage dipoles (i.e., close to the surface) and it gradually decreases at depth. The sensitivity for each model parameter of the electrical image (i.e., volume for 3D measurements) is calculated within the inversion, whereas the cumulative sensitivity for each model parameter is the sum of the values calculated for each current injection in an imaging data set (i.e., 4-electrode arrays). The cumulative sensitivity is commonly expressed as a normalized value (i.e., divided by the highest sensitivity value found in a given imaging data set) on a logarithm scale. Accordingly, low cumulative sensitivity values can be used to exclude poorly resolved areas in the imaging plane (i.e., volume for 3D measurements). We refer to Kemna, 2000 and Weigand et al. (2017) for further details.

5.3 Collection and processing of the CC data presented in this study

The CC measurements presented here were carried out with the DAS-1 instrument (Multiphase Technology, MPT) using coaxial cables to reduce distortions in the data by electromagnetic (EM) coupling (Flores Orozco et al., 2021). More than 150 lines CC have been collected in the HOAL. In this study, we present only imaging results for three data sets: M1, E1, and SIP1. E1 refers to an exploration line collected at 1 Hz using a roll-along scheme for a total of 676 electrodes and 1 m spacing between them. The SIP1 line was collected perpendicular to E1, with 64 electrodes (1 m spacing) with 10 frequencies between 0.5 and 225 Hz to gain information about the frequency-dependence of the electrical properties. The mapping data M1 comprises 27 lines using 72 electrodes in each line (further details in Appendix A.5.5~~2~~). The position and orientation of the lines is indicated in Figure A1.

All CC measurements were collected using a dipole-dipole skip-0 configuration (i.e., the dipole length is the same as the electrode spacing) and all possible skip-0 dipoles. The configuration conducted voltage measurements always ahead of the current dipole to minimize contamination of the data due to enhanced redox reactions in the electrodes used to inject current (i.e., polarization of the electrodes). Measurements were collected as normal and reciprocals (i.e., interchanging the current and voltage dipoles). Erroneous measurements filtered in all data correspond to those quadrupoles associated to negative resistances and apparent resistivity readings (after modelling the numerical geometric factor for each quadrupole) as well as those measurements where normal and reciprocal pairs deviate over 75% their mean value. Normal and reciprocal misfit analysis was conducted in representative measurements to quantify data error (see Flores Orozco et al., 2012b, 2021; 2022). Moreover, for data collected at different frequencies, we deleted those measurements (i.e., 4-electrode arrays) not found in all frequencies under investigations. This ensures a consistent sensitivity in all CC imaging across the different frequencies. We used CRTomo (Kemna, 2000) for the inversion of the data. Inversion results are presented in terms of real and imaginary components of the complex conductivity.

The highest resolution in our SIP investigations (c.f., Figure 2 and Figure 3) is 0.35 cm, corresponding to 1/3 of the dipole length. Such resolution is found close to the surface, with numerical simulations revealing that a polarizable anomaly ($\sigma'' = 1$ mS/m, such as the one observed in Figure 2) can be resolved to a maximum depth 7 m but is not detected below such depth. The maximum separation between current and voltage dipoles is 29 m, corresponding to a nominal depth of investigation of 9.7 m. In the analysis of the CC inversion results, all model parameters with a logarithmic cumulative sensitivity below -3 were excluded. This has been demonstrated to be an appropriate threshold for identifying the reliable data in CC imaging results as shown by Weigand et al. (2017). Nonetheless, numerical simulations were performed in this study to validate the selected threshold.

5.~~4~~3. Ground truth: analysis of borehole sediments

During the field surveys, two boreholes (B1 and B2 in Figure A1) were drilled to a depth of 8 m for the collection of ~~sediment~~soil samples. ~~Sediments~~Soils were immediately packed in dry ice to avoid chemical transformations~~.~~ during transport and storage. Soil chemical analysis was performed after the samples were freeze-dried and milled ~~in~~using an agate ball mill. Total carbon was measured by combustion using a Thermo Quest CN element analyser at the Bayreuth Keylab for Experimental Biogeochemistry. Reactive iron (~~Fe~~Fe_{tot}) was ~~determined on~~ classified as the total Fe concentration in samples after extraction by 1M HCl~~.~~ after 24h on a horizontal shaker. The ~~solution~~extract was filtered (0.45 µm) and analysed for total Fe photometrically using the phenanthroline method (Wallmann et al., 1993; Tamura et al., 1974). The ~~cations~~cation exchange capacity (CEC) was determined with an ICP-OES after Matschonat and Matzner (1995)~~using standard methods~~, except that Fe and Mn were also included in the CEC calculation in addition to the base cations. The inorganic carbon content was measured using the method described by Horváth et al., (2005) with replicate RSDs of core samples ranging from 0.8 to 2 %. The SOC carbon content is the total carbon minus inorganic carbon content. Grain sizes of sediments obtained in B1 and B2, as well as from previously drilled boreholes G2, and G4, and from four piezometers (see Figure A1) were measured by sieve analysis. Groundwater electrical conductivity (EC) measured in the piezometers was about ~~400~~40 mS/m during the measurement campaign.

~~Here we present the geometry of the high polarizable anomaly resolved from time-domain induced polarization measurements along the 27 lines corresponding to the survey M1. Erroneous measurements filtered in all data correspond to those quadrupoles associated to negative resistances and apparent resistivity readings (after modelling the numerical geometric factor for each quadrupole). Reciprocal readings were collected in exemplary lines for statistical analysis of the misfit between normal and reciprocal to quantify data error using the approach by Flores Orozco et al., (2012b, 2021; 2022). We used CRTomo (Kemna, 2000) for the inversion of the data. Chargeability measurements were linearly converted to 1 Hz apparent phase values using~~

~~the approach described elsewhere (Kemna, 2000; Flores Orozco et al., 2021). Inversion results are presented in terms of the imaginary component of the complex conductivity (σ'').~~

340

5.5.2 The geometry of the deep carbon stock

Figure A2 shows the extension of the polarization (σ'') anomaly resolved at 4 m depth as obtained from the interpolation of the complex conductivity imaging results from the inversion of all mapping lines referred to as M1. The mapping M1 consists of 32 lines, namely: 5 long and 17 short lines parallel to the stream direction (roughly N-S), as well as 5 long and 5 short lines
345 perpendicular to them (roughly W-E). Long lines have a separation of 5 m between them and were carried out using 72 electrodes in each, with 1 m spacing between electrodes~~;~~, whereas short lines have 1 m separation between them, each with 72 electrodes and a spacing of 0.5 m. The data were inverted for each independent line using CRTomo using the same methodology as the one used for the processing and inversion of lines E1 an SIP1~~.~~ (see A5.3). Nonetheless, the 3D inversion of all M1 lines was also conducted with other inversion algorithms in actual 3D (data not shown) revealing consistent results
350 with the Figure A2 presented below. Considering that the data was collected ~~without measurements a using electrodes placed in different lines~~independently for each electrode line, we decided here to work only with 2D inversion.

The geometry of the carbon stock at 4 m depth presented in A2 corresponds to the high polarization values (σ~~→~~`> 900 μS/m) extracted from the inversion of the M1 data. These values are consistent to those observed in the E1 and SIP lines
355 (Figure 2 and 3). The map presented in Figure A2 reveals that the carbon stock extends towards the northwest from the drilled boreholes B1, where the high organic carbon content was measured in soil samples (Figure 4). The map presented in Figure A2 can be used to guide further drilling for the collection of soil samples.

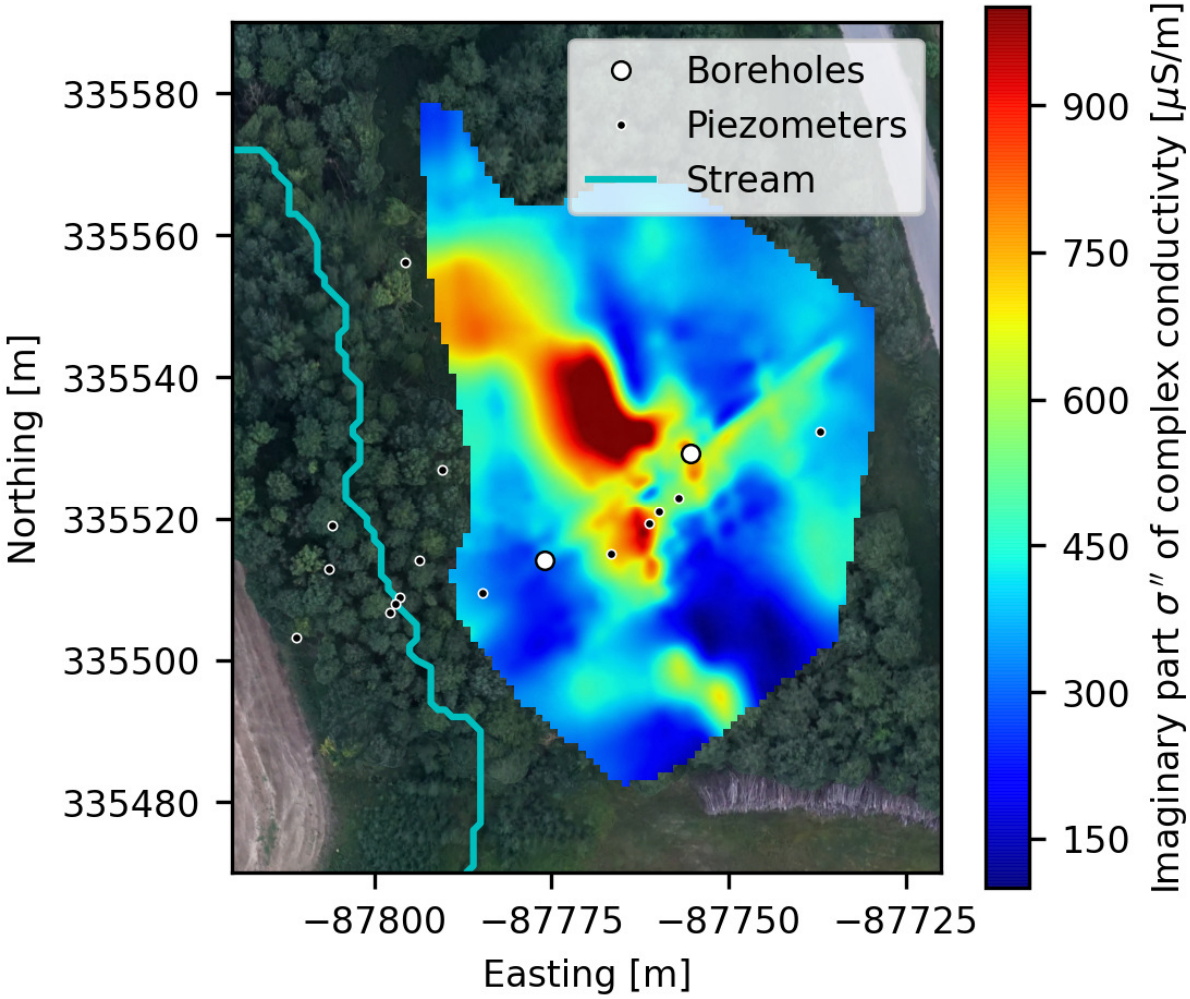

Figure A2. Geometry of the deep carbon stock (at 4 m depth) given by the anomalous high induced polarization values (σ'' > 1 mS/m)

6 Data availability

Data presented here are available at the repository of the TU Wien with the digital object identifier (DOI): https://doi.org/10.48436/5h7jb-26w42

7 Author contribution

AFO designed the experiments, while JG and TK carried out field data, with laboratory analysis of samples conducted by BG. AFO conducted the Data Curation, Formal Analysis, Methodology and Visualization. AFO, GB, PS and SF were in charge of Resources. AFO prepared the manuscript with contributions from all co-authors.

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