

Multi-source 3D imaging of a graphite deposit combining drone-based semi-airborne and ground-based electromagnetics

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SUMMARY

The transition towards renewable energies demands secure supply with critical raw material and requires efficient non-invasive methods for deep earth resources exploration. The novel DESMEX (Deep electromagnetic sounding for mineral exploration) semi-airborne electromagnetic (semi-AEM) concept aims at efficient exploration of resources down to roughly 1 km depth. Here we present an exploration study combining ground-based controlled source electromagnetics (CSEM) with drone-based semi-AEM in a graphite mining district in eastern Bavaria, Germany.

On the ground, several horizontal electrical dipole transmitters were deployed, utilizing a rectangular current function with a base frequency between 1 Hz and 12 Hz. Drone-based magnetic field sensors measure the EM field on flight-lines with dense spacing and within several overlapping flight areas, providing a fast data acquisition and a high spatial coverage. As sensors, a three-component induction coil triple and a total-field magnetometer was utilized. In addition, multi-component magnetic as well as electric field measurements on a 3D grid were conducted on the ground, adding complementary information to the drone-based data set. Here, we present the concept and obtained results from the conducted survey, including an overview over the obtained transfer functions and preliminary 3D inversion results. We compare the overall performance and resolution of ground-based and drone-based semi-AEM data. Imaged shallow high conductivity structures can be correlated with graphite-rich zones and match well with existing helicopter-borne EM results.

Keywords: DESMEX, drone-based semi-airborne CSEM, 3D Inversion, Graphite

INTRODUCTION

Electromagnetic (EM) methods are sensitive to the electrical conductivity of the subsurface and, therefore, play an essential role in the characterization of mineral deposits. Graphite exhibits high conductivities and is therefore a suitable target for EM exploration. To combine the advantage of high signal strength and high penetration depth using grounded transmitters with fast areal data coverage of helicopter- and drone-towed receiver systems, the semi-airborne electromagnetic (semi-AEM) method was developed (Seigel, 1971; Elliott, 1998; Mogi et al, 2009; Wu et al, 2019). Within the project DESMEX (Deep electromagnetic sounding for mineral exploration) methods are de-

veloped, which aim for exploration depth down to 1 km. Recent demonstrations of the feasibility of the DESMEX system comprise studies by e.g. Becken et al (2020), Kotowski et al (2022), Mörbe et al (2024) and Thiede et al (2024).

The survey area is located in the western part of the graphite deposit Kropfmühl in the Bavarian forest, Germany. Mörbe et al (2024) investigated the eastern extend of the graphite deposit using helicopter-borne semi-AEM measurements within a large survey area of 15x8 km². Anomaly structures which correlate with the occurrence of graphite exhibit low conductivities below several Ωm . The extension of the western continuation of the deposit is unknown. For the investigation of the depth and lateral extend

of the deposit, drone-based measurements on a local scale are a fast and cost-efficient alternative to dense ground-based or helicopter-borne measurements.

FIELD SURVEY

We performed drone-based semi-AEM and ground-based CSEM measurements in an area of approximately $1.8 \times 2.5 \text{ km}^2$ (cp. Figure 1). Four dipole transmitters with length between 800-1600 m and currents between 5-16 Ampere were realized.

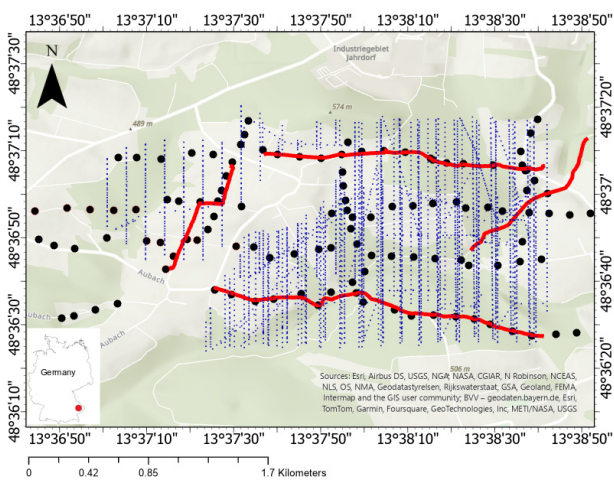


Figure 1: Overview over the semi-AEM field survey. The four grounded dipole transmitters are displayed in red. Drone-based data was spatial averaged over approx. 35 m and resulting stations are displayed in blue. Flight areas from different transmitters overlap. Additional 5-component ground-based CSEM stations are displayed in black.

As source signal, a rectangular current function with base frequencies between 1 Hz and 12 Hz was used. As drone-based field sensors we used an induction coil-triple for frequencies between 35 Hz and several kHz and a scalar magnetometer for lower frequencies between 1 Hz and approx. 100 Hz. To obtain a high data coverage, flight areas for different transmitters overlap. In addition, we measured three magnetic and both horizontal electric field components at the ground in a sparse 3D distribution. The obtained electric field data contains complementary information about the 3D conductivity distribution. Ground-based high quality data

for frequencies down to 1 Hz and the realization of larger transmitter-receiver offsets deliver additional constraints for the deep subsurface down to approx. 1 km depth.

DATA OVERVIEW

We calculated uni-variate, frequency-dependent transfer functions between the measured field components and the transmitted current function in a range between 1 Hz and several kHz. Processing steps include the calibration with the system response of the sensors and the rotation to an earth-fixed coordinate system. For further details about semi-AEM processing, we refer to Becken *et al* (2020).

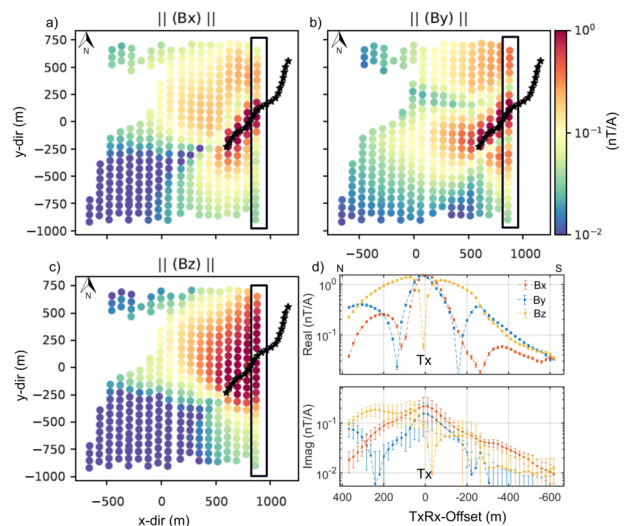


Figure 2: a)-c) Color-coded amplitudes of the drone-based induction coil data for all three magnetic field components and a frequency of 762 Hz. The location of the flight-line, for which transfer functions are displayed in d) is marked with a black box. d) Transfer functions for 762 Hz crossing the transmitter are displayed exemplarily for one flight-line.

In Figure 2 a-c, the amplitudes of the calculated transfer functions for the drone-based induction-coil data is exemplarily displayed for the easternmost transmitter dipole and an evaluation frequency of 762 Hz. The color coded B-field amplitudes show mainly the typical field geometry and decaying behavior of the primary field. The flight-line data displayed along profile in Figure 2d exhibit a high data

quality also for large offsets. The amplitudes of the imaginary part are smaller and more distorted by noise.

The overall obtained data quality is high for vector and scalar magnetometer data. However, due to the limited sensitivity of the utilized induction coil sensor for frequencies < 100 Hz and therefore an increased noise content in the low frequency range, we propose a joint inversion of scalar and vector magnetic field data. In addition, we include ground measurements of the electric field and high quality long offset magnetic field data.

RESULTS AND DISCUSSION

Due to the large footprint of the extended dipole transmitters and the expected 3D conductivity distribution of the subsurface, a 3D inversion is conducted. The obtained 3D data set was inverted with the open-source frameworks *custEM/pyGimli* (Rochlitz *et al.*, 2023; Rücker *et al.*, 2017). Within *custEM*, topography and an accurate source geometry is taken into account.

To gain insight into the resolution characteristics of the individual data sets, inversions were performed with drone-based vector and scalar magnetic field data and ground-based CSEM data individually as well as jointly. To incorporate the frequency dependent sensitivities of the sensors, we used a frequency dependent error model for inversion. The error floor was set to an absolute value of 2 nT/A and a relative error of 5 %. In Figure 3a, we show a shallow x-y model slice at 440 m.a.s.l of a preliminary 3D inversion model incorporating ground-based and drone-based vector magnetic field data jointly. In total, around 45000 data points using four transmitters were used for inversion. In Figure 3b, the error weighted misfit between observed and modeled data of the final iteration is displayed for an exemplary frequency of 269 Hz and one transmitter. Overall misfits are low, however they are slightly deteriorated in the area of strong conductivity contrasts visible in the subsurface model. The overall error weighted RMS converged to 2.4.

The derived conductivity model exhibits a zone of increased shallow subsurface conductivities in the northern part of the survey area at around $y = 500$ m. Here, conductivities drop down below $10 \Omega\text{m}$. The E-W running zone of increased conductivities matches well with existing helicopter-

borne EM measurements and might be correlated to zones of graphite enrichment. In order to investigate the depth extension and resolution of the conductivity anomaly, further resolution studies will be realized.

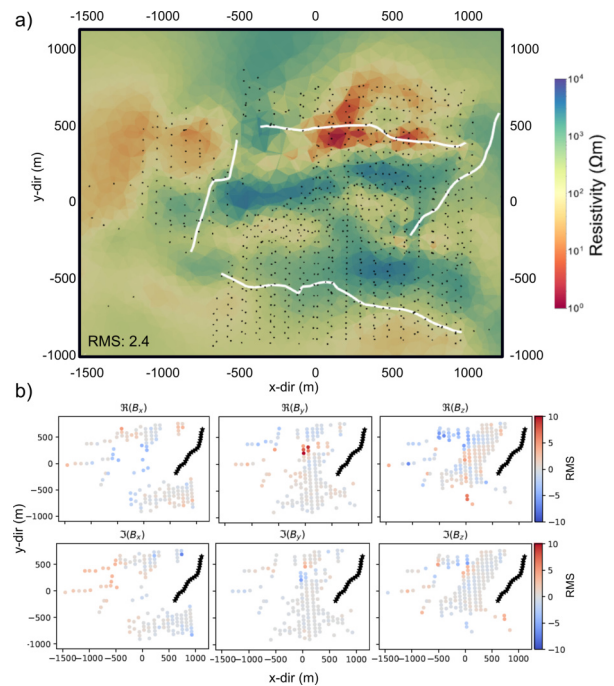


Figure 3: a) Depth slice of the derived 3D model at 400 m.a.s.l including three-component drone-based and ground-based coil data. Local topography varies between 430 m.a.s.l and 560 m.a.s.l. Transmitters are marked in white, receiver stations are indicated with black dots. b) Error-weighted RMS exemplarily shown for one transmitter (black line) and a frequency of 269 Hz. Data is overall well fitted. However, the misfit increases around the location of the conductivity contrast.

CONCLUSION

We investigated a graphite deposit in southern Germany with drone-based semi-AEM and complimentary CSEM ground stations. Hence, we combine the advantages of a fast data acquisition and dense area coverage of an airborne receiver system with the high signal strength of a grounded transmitter. The usage of two different magnetic field sensors broadens the usable frequency range. Combining drone-based and ground-based data delivers additional resolution especially for deep targets and

adds complementary information due to the measurement of the electric field. The preliminary derived 3D inversion model shows a high conductive structure, which correlates well with existing airborne EM measurements. Further resolution studies will highlight the resolution characteristics of the different obtained data sets and a combined inversion will constrain uncertainties regarding the depth extension and lateral extend of the anomaly. The incorporation of existing geological information as well as borelog data, including resistivity and induced polarization logs is planned.

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