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SUCCESSES AND PITFALLS OF GEOPHYSICAL SURVEY FOR VERIFYING THE PRESENCE OF UNDERGROUND STRUCTURES IN THE AREA OF FORMER FOUNDRIES (CASE STUDY)

ÚSPECHY A ÚSKALIA GEOFYZIKÁLNEHO PRIESKUMU PRI OVEROVANÍ PRÍTOMNOSTI PODZEMNÝCH STAVIEB V PRIESTORE BÝVALÝCH ZLIEVARNÍ (PRÍPADOVÁ ŠTÚDIA)

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Abstract

The environment in which a geophysical survey is conducted is one of the determining factors in the choice of proper applied methods. This study presents the results of a comprehensive geophysical survey aimed at verifying the presence of remnants of underground structures, foundations, and tanks across the former foundries in Krnov (Czech Republic). The site constitutes an extensive area in which, as the survey progressed, it became clear that the near-surface layer contained a large quantity of heterogeneous metallic material from the former foundry. Magnetic field measurements, selected for the initial areal mapping, together with supporting ground-penetrating radar (GPR) measurements, were therefore supplemented by dipole electromagnetic profiling (DEMP) due to the strong interference. Despite pronounced noise and a large number of shallow anomalies, by appropriate processing and display of the individual datasets we were ultimately able to build a coherent picture of the spatial distribution of anomalous responses of the measured fields within the study area. Delineated anomalies can indicate the presence of underground constructions or voids. Excavation works verifying the recorded anomalies confirmed most of the interpreted features.

Abstrakt

Prostredie, do ktorého je zasadený geofyzikálny prieskum je jedným z určujúcich faktorov pre výber metódy. Táto štúdia prezentuje výsledky komplexného geofyzikálneho prieskumu zameraného na overenie prítomnosti zbytkov podzemných konštrukcií, základov a nádrží na ploche areálu bývalých zlievarní v Krnove (ČR). Jedná sa o rozsiahly areál, na ktorom, ako sa v priebehu prieskumu ukázalo, sa v pripovrchovej vrstve nachádza veľké množstvo rôznorodého kovového materiálu zo zaniknutej stavby zlievarne. Meranie magnetického poľa zvolené pre prvotné plošné mapovanie a doplnkový georadarový prieskum boli z dôvodu veľkého rušenia doplnené o dipólové elektromagnetické profilovanie. Napriek výraznému rušeniu a veľkému množstvu pripovrchových anomálií sa spracovaním a správnym zobrazením výsledkov z jednotlivých meraní, nakoniec podarilo vytvoriť komplexný obraz rozloženia anomálnych prejavov meraných polí v skúmanom areáli. Boli vymapované anomálie, ktoré potencionálne predstavujú prítomnosť podzemných konštrukcií, antropogénnych prvkov alebo dutín. Overenie anomálií výkopovými prácami prinieslo spätnú väzbu a potvrdilo prítomnosť zbytkov podzemných konštrukcií u väčšiny interpretovaných anomálií.

Keywords

Geophysical survey, underground spaces and foundations, magnetometry, electromagnetic induction, ground-penetrating radar (GPR)

Kľúčová slova

Geofyzikálny prieskum, podzemné priestory a základy, magnetometria, elektromagnetická indukcia (EMI), georadar (GPR)

1. Introduction

Geophysical survey has become a commonly used tool within engineering geological investigations, whether for assessing landslide areas, designing remediation measures, foundation engineering, and related tasks (Bláha, 2017; Ľahučká et al., 2024; Brixová et al., 2022; Al-Heety et al., 2016; Pasierb et al., 2019). Depending on the objectives and the selected method, geophysics provides useful information about the subsurface. However, the choice of a suitable geophysical method is often constrained by the parameters and the nature of the environment. The surrounding environment posed a particular challenge in the survey presented here. Its goal was to verify the presence of underground structures, spaces, and tanks within the area of the former foundries in Krnov. The area of the former foundries in Krnov (Czech Republic) is situated in the SW part of the town near the railway station (see location figure). In 2013–2014, the obsolete foundry buildings were demolished and, following removal of the structures and disposal of construction waste, a plot with a total area of approximately 4.3 ha was created (Fig. 1), where the survey was to be conducted.

Geophysical methods suitable for surveys focused on verifying underground foundations, spaces, and cavities are primarily those that allow areal measurements in a continuous mode. Such methods include GPR, magnetometry, and electromagnetic induction surveys (Daniels, 2004; Jol, 2009; Reynolds, 2011; Hinze et al., 2013; Jabrane et al., 2021; Putiška et al., 2024; Peng et al., 2025). Mapping anomalies of the local geomagnetic field, caused by local variations in the magnetic properties of the environment, is frequently used to detect archaeological objects and also to detect unexploded ordnance, steel pipelines, reinforced concrete objects, etc. In sparsely populated areas this is a very effective method, with the major benefit of with the benefit of fast and easy data collection. A potential problem for magnetometric surveys in built-up urban environments is interference from magnetic noise sources (buildings, utilities, traffic…). Similar magnetometric surveys on construction sites—where remnants of reinforced-concrete slabs were clearly expressed—have nonetheless been carried out successfully. Given the size of the area of interest and based on the available information on its condition, we therefore proposed areal magnetic surveying in Krnov to achieve the objective, followed by verification of anomalies using GPR. The actual state of the terrain, however, did not allow magnetic surveying to be carried out across the entire area. After terrain maintenance (removal of shrubs and levelling of parts of the area), a second stage of the survey was planned. Based on the initial magnetometric results, both the choice of geophysical methods and the workflow were reconsidered. The presence of large amounts of iron debris in the near-surface layers—most likely originating from the demolished foundry buildings—produced strong interference and hindered interpretation of the magnetometry. In some parts of the area, sufficient terrain preparation for magnetic measurements could not be completed. Therefore, in the second stage, dipole electromagnetic profiling (DEMP) was employed for areal mapping. In DEMP, the response to a vertically transmitted electromagnetic pulse at a given frequency is measured, using inductive effects to generate artificial electromagnetic fields in the geological medium. DEMP enables determination of the apparent conductivity (or apparent resistivity) of the subsurface in the shallow zone. Alongside conductivity, the "In-phase" component is measured, which reflects the magnetic susceptibility of the induced field and allows detection of buried metallic objects such as tanks, reinforced-concrete structures, and pipelines. The method is particularly suitable for initial mapping and for establishing a spatial scheme of the investigated environment. The areal DEMP and magnetometric measurements were further supplemented with GPR. GPR employs electromagnetic waves transmitted by an antenna that penetrate the medium; when such a wave encounters an interface between layers with contrasting dielectric properties, part of the energy is reflected back while the remainder continues to propagate. If it encounters an isolated object, diffraction may occur. The reflected and diffracted energy is recorded at the surface and displayed as a radargram, in which

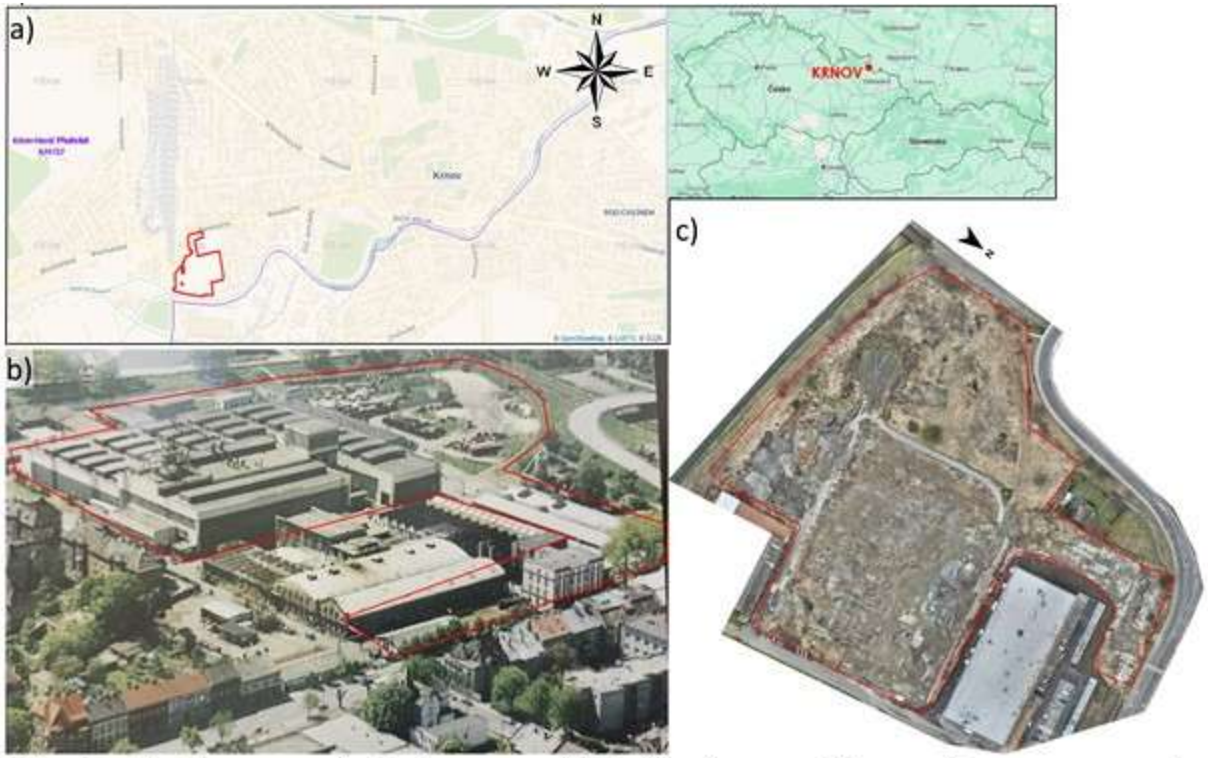

***Fig. 1:** Study area: a) study area within the town of Krnov (base source ...), b) historical photograph of the former Krnov foundries with the study area indicated, c) study area – condition at the time of the 2024 investigation.*

amplitudes and two-way travel times across individual layers (or objects) can be seen. The depth of penetration and resolution of a GPR system largely depend on the central frequency of the antenna used; the actual depth of penetration, however, depends on the site-specific conditions. The GPR survey in Krnov focused on verifying anomalies detected by areal magnetometry and DEMP and on surveying the part of the area where, based on historical materials and photographs, underground tanks and/or remnants of underground constructions and voids were expected.

This paper presents the linkage of results from the individual geophysical methods used and the subsequent integrated evaluation of both stages of the survey. A significant benefit was the verification of the interpreted anomalies by excavation works.

2. Survey methodology

In the first stage of the survey, highly precise areal measurements of the Earth's magnetic field were conducted using a SENSYS MAGNETO MXPDA system with five fluxgate probes (FGM650/3) arranged at 0.5 m spacing. An area of approximately 1.5 ha was surveyed (Fig. 2). In the second stage, areal measurements over the remaining area were supplemented with dipole electromagnetic profiling using a CMD-Explorer (G.F. Instruments, Brno), which allows measurements of apparent conductivity and the "In-phase" component at three depth levels simultaneously (2.2 m, 4.2 m, and 6.7 m) by varying transmitter–receiver coil spacing. Four areas, CMD1 to CMD4 (Fig. 2), were measured with a total area of about 1.9 ha. In addition, both profile-based and areal GPR surveys were carried out. For both survey modes a MALA GroundExplorer (GX) GPR was used together with an HDR (High Dynamic Range) antenna, with central frequencies of 160 MHz and 450 MHz. In the first stage, 13 profiles PF1–PF13 (Fig. 2) were measured with the 160 MHz antenna. Profiles were positioned to provide GPR images from each measurable part of the site. In the second stage, 11 profiles pf1–pf11 (Fig. 2) were measured using the 450 MHz antenna—primarily in the vicinity of uncovered holes leading to partially backfilled underground spaces. The profile measurements in both stages were aimed at determining whether GPR could provide an interpretable image of the environment of the demolished foundry. In the second stage, an areal GPR survey (Fig. 2) was also conducted over a pronounced anomaly detected by DEMP in the area where a chemical storage facility had been located according to historical sources. Approximately 900 m^2 were surveyed in a local coordinate system along 60 parallel lines with 0.5 m spacing. For improved depth coverage, the area was surveyed with both antennas (160 MHz and 450 MHz).

Accurate geodetic positioning during the areal magnetometry and DEMP surveys was ensured using a GNSS receiver (Trimble R8s) with real-time corrections via the CZEPOS service, integrated with the measuring equipment; measurements were performed in continuous mode with recording of the position of every measured point. For the GPR survey, the origin of the local coordinate system and the points delineating the surveyed area were measured, as well as the start and end points of all GPR profiles and the positions of the aforementioned holes.

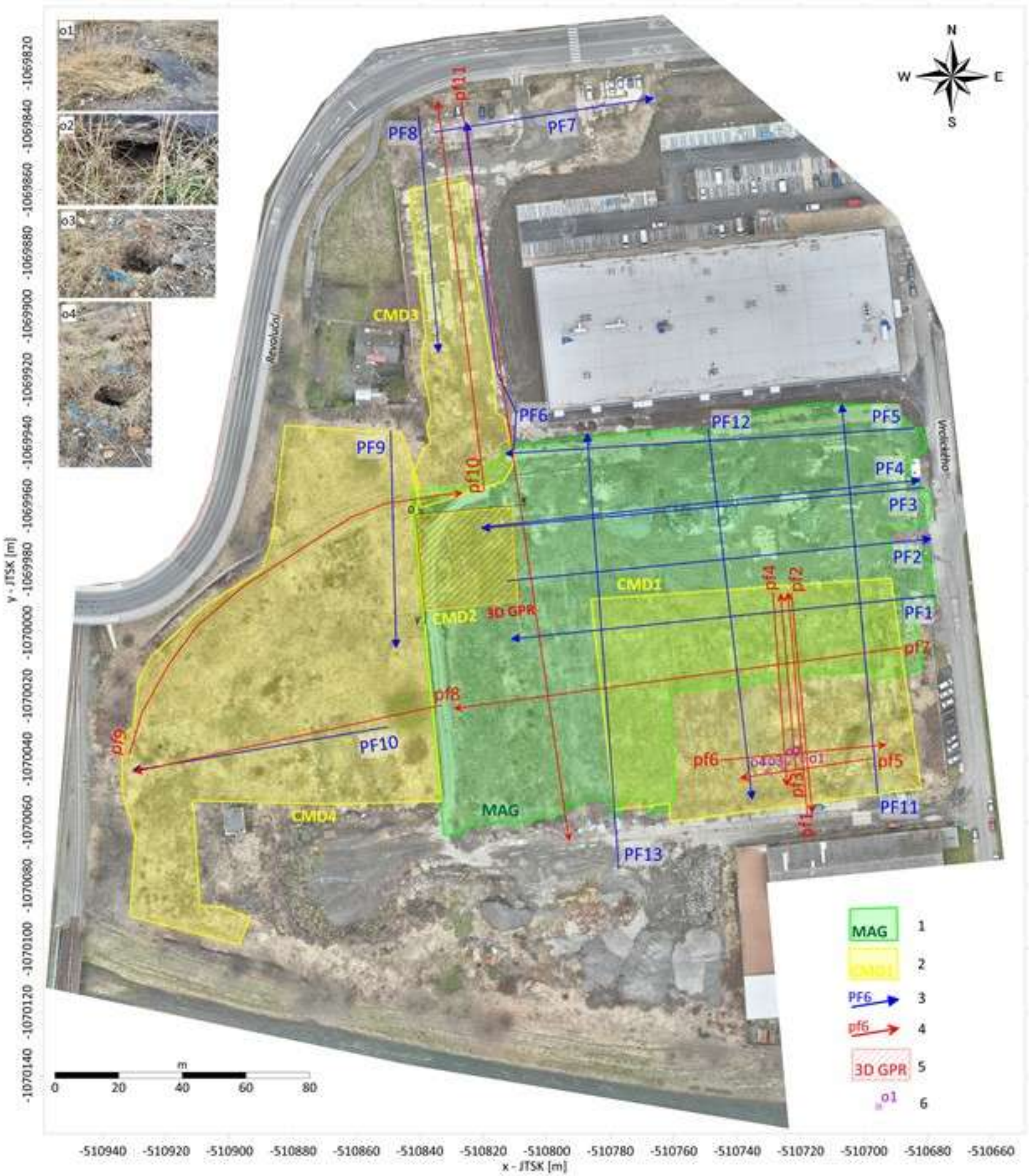

***Fig. 2:** Layout of geophysical surveys of the former Krnov foundries with photographic record of subsurface holes: 1) magnetometer survey area (stage 1), 2) DEMP survey areas (stage 2), 3) GPR profile survey with 160 MHz antenna (stage 1), 4) GPR profile survey with 450 MHz antenna (stage 2), 5) GPR areal survey (stage 2), 6) uncovered holes to subsurface spaces identified during field reconnaissance.*

3. Results

In the first stage, processing of the magnetic survey included application of a correction to each series of measurements to remove level offsets between individual sensors. The data were subsequently interpolated to a 0.2 × 0.2 m grid to produce an areal map of the anomalous magnetic field. However, the presence of large quantities of iron material—most likely originating from the demolished foundry buildings—caused the anomalous magnetic field over the surveyed area to exhibit severe distortions, reaching extreme values of several thousand nanotesla. Consequently, the analytic signal field was computed from the grid (Fig. 3), which suppressed the dipolar character of the field and made the anomalous image more readable. By identifying local maxima of the analytic signal occurring above the centers of detected objects, it was at least partially possible to interpret the outlines of underground objects. These appeared on the interpreted map as linear anomalies in shades of grey to black. In addition, local patches of approximately rectangular shapes appeared that exhibited minima of the analytic signal and were interpreted as relatively homogeneous areas without a high concentration of iron objects. Despite the adjustments and gap-filling of unsurveyed data, the resulting image remained difficult to interpret in more detail.

In the second stage, processing of the DEMP measurements involved converting the measured apparent conductivity values to apparent resistivity. The outputs were areal maps of apparent resistivity and In-phase maps for each depth level (Fig. 4). Given the character of the former foundry environment, interpretation focused on anomalies characterised by pronounced contrasts relative to the surroundings. On the apparent-resistivity maps, these appear as areas of very low resistivity, while on the In-phase maps they appear with elevated values. For clarity, maps displaying only anomalous In-

Fig. 3: Map of the analytical magnetometric response across the area of the former foundries with an example measurement using the SENSYS MAGNETO MXPDA device with five fluxgate probes.

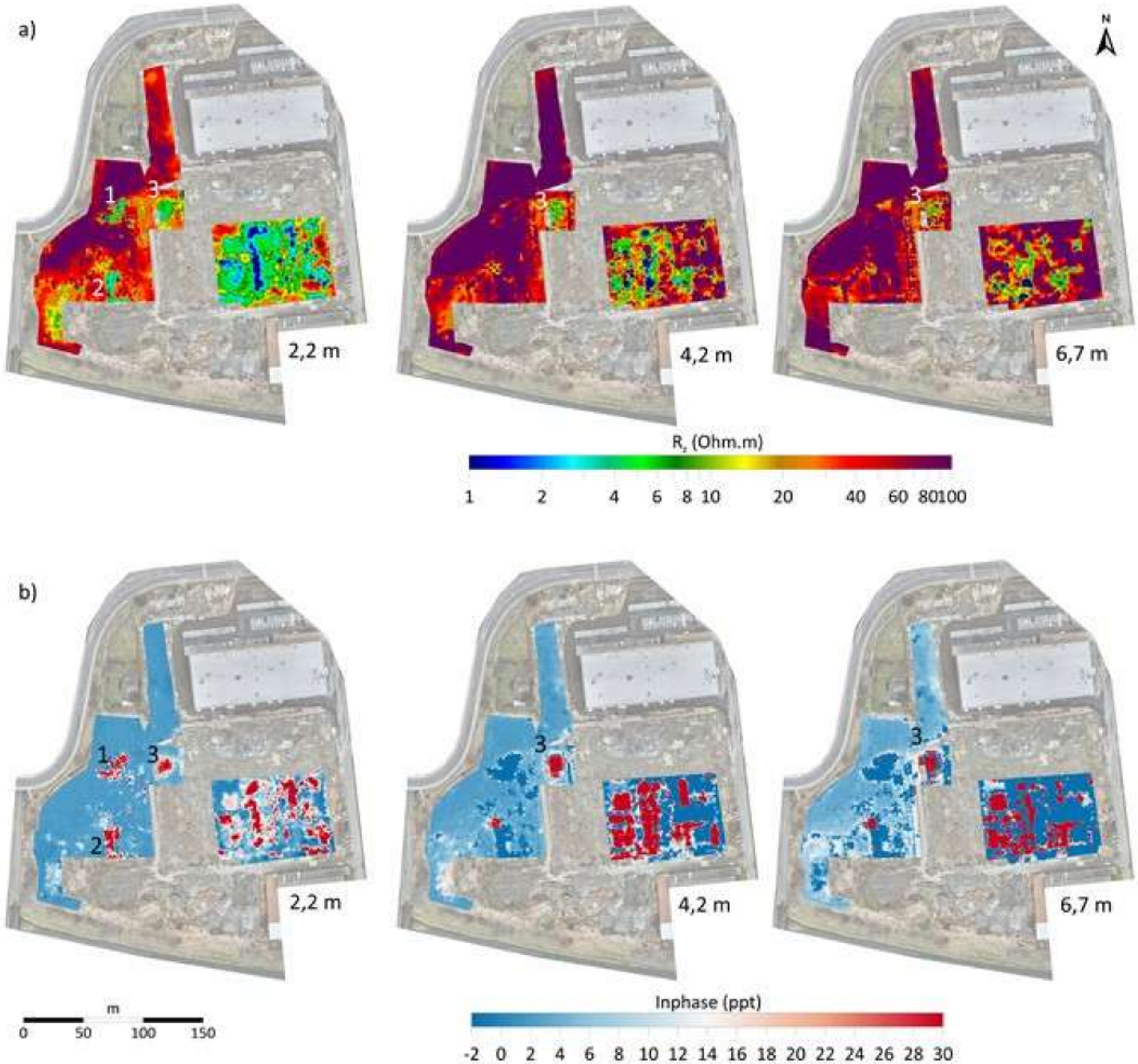

***Fig. 4:** Results of the DEMP survey for the investigated depth level: a) plan-view maps of apparent resistivity; b) plan-view maps of In-phase. Numbers 1,2,3 mark significant anomalies.*

phase values were also produced for the 2.2 m and 4.2 m depth levels (Fig. 5). The anomalies highlighted in these areas may correspond to remnants of metallic or reinforced-concrete structures. Interestingly, anomalies labelled 1 and 2 are present on both the apparent resistivity and In-phase maps only for the 2.2 m depth level; their expression disappears at greater depths, which would indicate that their sources are shallowly buried. Anomaly 3 occurs in the area where, according to historical materials, a chemical storage facility had been located. This anomaly was confirmed and refined by the areal GPR survey (Fig. 6). On the areal radargrams (Fig. 6a), despite significant noise, the outlines of remnants of a subsurface building can be seen. On the 2D vertical radargrams (Fig. 6b), the presence of remnants of iron structures is expressed by strong multiple reflections.

The profile-based GPR surveys from both stages, as anticipated, exhibit heavy interference, and the multitude of anomalies precludes identification of the causes of environmental changes in many cases. Numerous diffraction hyperbolae and multiples originate close to the surface and may be caused by construction debris (iron fragments, rebars, reinforced-concrete pieces, etc.). These shallow anomalies mask the signals of potentially deeper objects. Only a

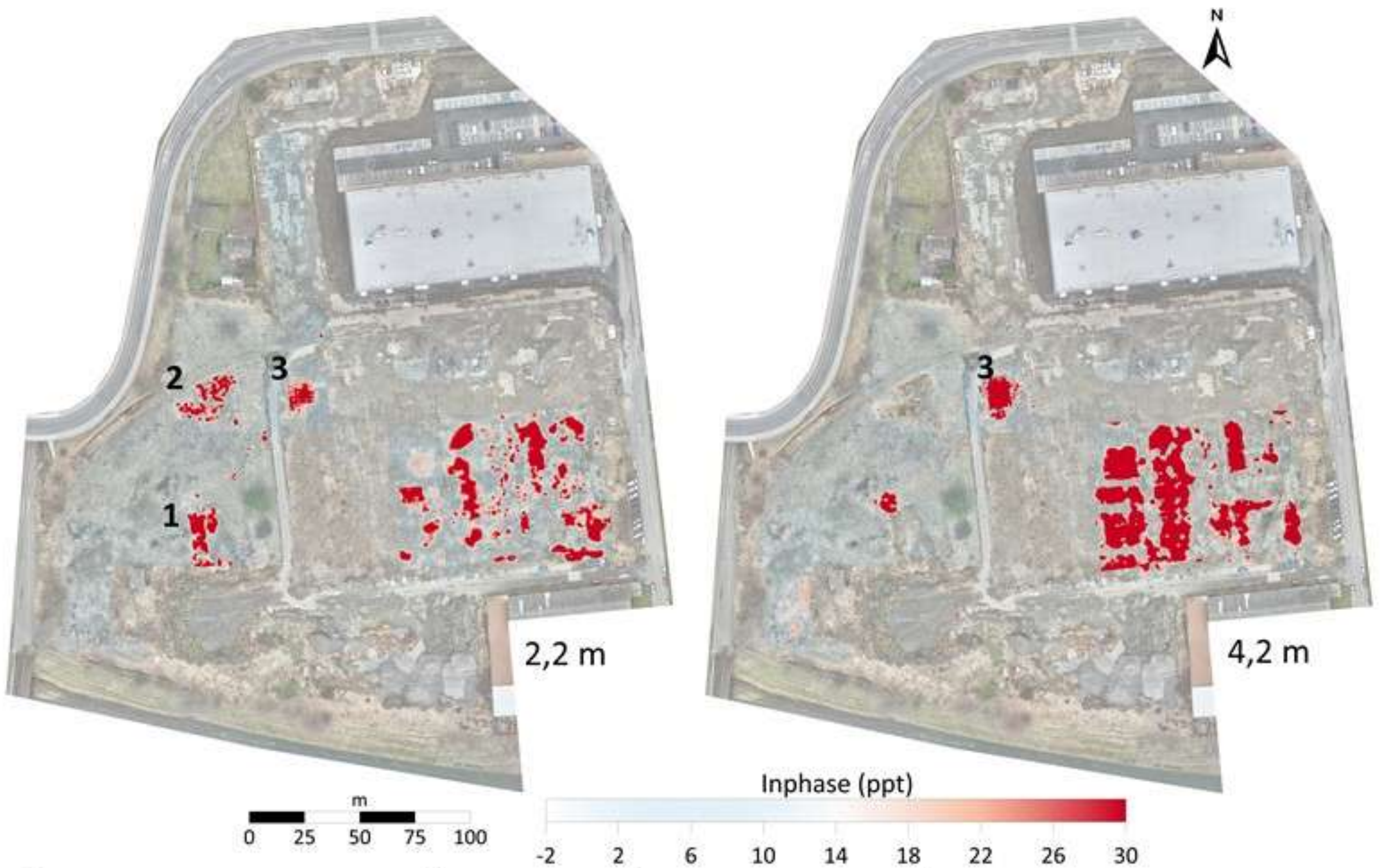

Fig. 5: DEMP results – plan-view maps showing only anomalous in-phase responses at depth levels of 2.2 m and 4.2 m. Numbers 1,2,3 mark significant anomalies.

few responses could be identified (Fig. 7), including for example:

- the presence of reinforced-concrete panels in the parking area (profile PF7 with the 160 MHz antenna; profiles pf10 and pf11 with the 450 MHz antenna);
- the presence of sleepers from an old railway track (profile pf9, 450 MHz antenna), expressed as regularly recurring hyperbolae;
- the response of a reinforced-concrete slab and voids (pf1 to pf6, 450 MHz) in the area of openings into the underground.

By linking the results of both stages, primarily magnetometry supplemented by DEMP, it was possible to build an integrated image of the distribution of anomalous responses of the measured fields within the site. A map of the analytic magnetic signal was produced together with the areal distribution of in-phase anomalies at depths of 2.2 m and 4.2 m (Fig. 8a). Anomalies that could represent underground constructions or voids were delineated. The outcome of the survey is therefore a comprehensive map of interpreted anomalies proposed for verification (Fig. 8b), marked as rectangular polygons so that they could be staked out in the field. The entire study area was divided into two subareas. In the subarea that had been occupied by foundry buildings during operation, anomalies A4 to A18 were delineated. In the subarea comprising loading areas and the railway, anomalies A1 to A3 were identified. Based on experience from other surveys, verification was proposed along the contacts of contrasting values of the measured parameters.

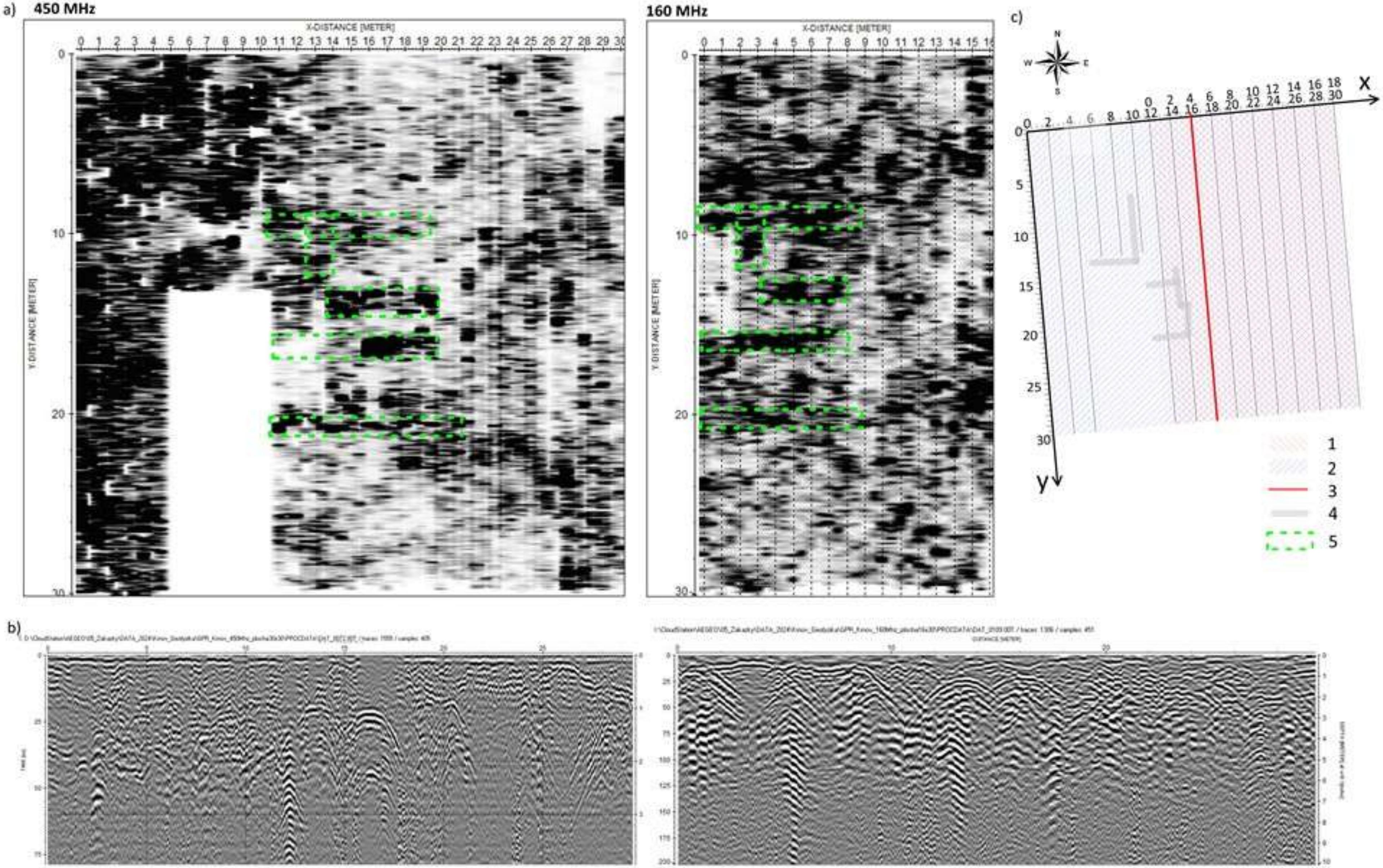

***Fig. 6:** Results of areal GPR survey with 450 MHz and 160 MHz antennas: a) plan-view radargram at a depth of 1.04 m; b) example of a vertical 2D radargram from a selected profile; c) survey layout. 1) areal survey with 160 MHz antenna, 2) areal survey with 450 MHz antenna, 3) displayed 2D profile, 4) remains of foundations reaching the surface, 5) interpreted anomalies.*

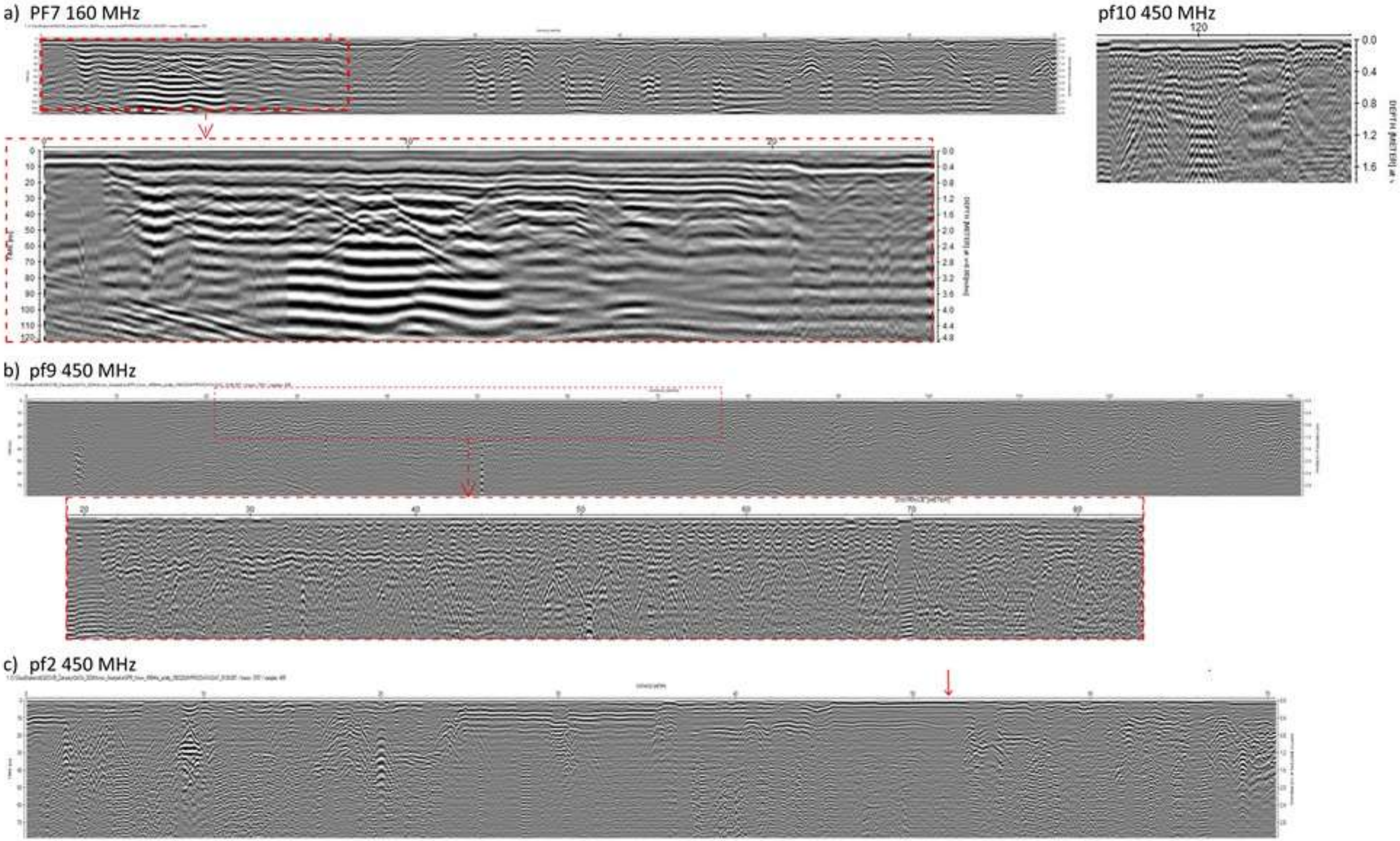

***Fig. 7:** Results of GPR profile surveys with 450 MHz and 160 MHz antennas: a) response of reinforced concrete parking panels in profile PF7 with detail radargram (bordered by a red dashed line) and detail radargram from profile pf10; b) response of sleepers of the former railway track in profile Pf9 with detail radargram (bordered by a red dashed line); c) response of a reinforced concrete slab above hole 1 (indicated by arrow) in profile Pf2.*

Conclusions

This case study illustrates a comprehensive geophysical survey in the complex environment of former foundries. The large quantity of metallic debris in the near-surface layer and the extent of the area of interest complicated both the selection of appropriate methods and the interpretation of the measured data. Profile-based GPR proved non-interpretable in this setting. Interpretation of the magnetic data was also challenging; however, after supplementing the dataset with DEMP—particularly maps of anomalous in-phase values—it became possible to delineate zones with a higher likelihood of remnants of foundations, underground constructions, and unfilled voided spaces. Areal GPR provided a more detailed image in one such anomalous area. More than elsewhere, this survey confirmed the maxim "one geophysical method—no method." It also highlighted the importance of proper processing as well as the choice of colour scale and display options so that the essential information emerges from the measured image. Interpretation would not have been possible without information gained from the study of historical documents and photographs, and useful information was also obtained from former employees. The combined effort ultimately yielded a map of anomalies, which were verified by excavation works. Interestingly, in the areas of anomalies A1 to A3, trenches to depths of 0.5–0.7 m intersected only dark clayey rubble with industrial contamination overlying natural sand-and-gravel sediments (Fig. 9c). Realized excavation works confirmed the detected anomalies as concrete surfaces beneath construction debris at depths of 0.2–1.6 m (A5, A7, and A10–A18; Fig. 9a) and as remnants of reinforced-concrete building foundations covered by construction debris (A4, A6; Fig. 9b); in the case of anomaly A4, circular tanks filled with water with a sewage odour were also encountered. The survey results substantially

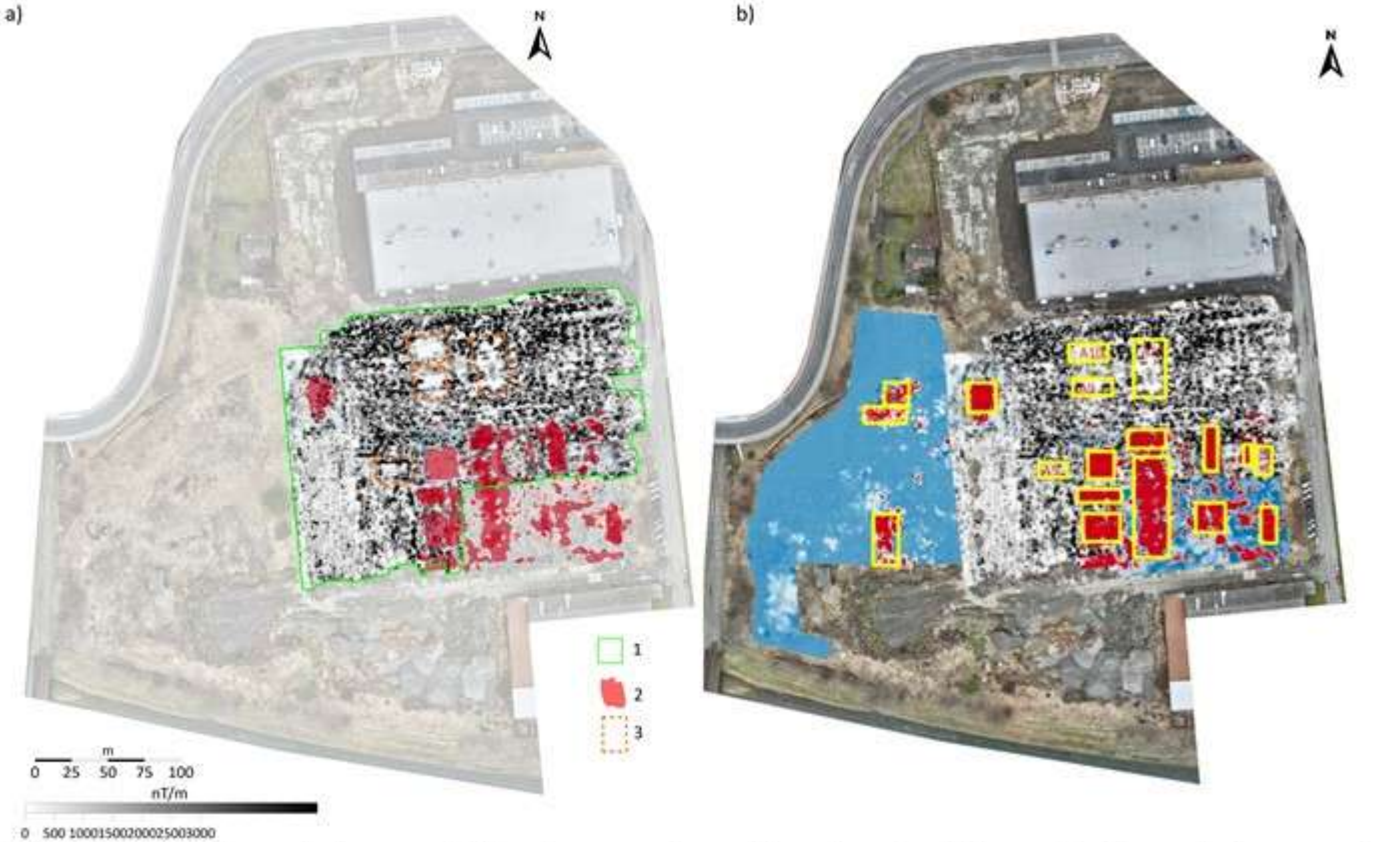

***Fig. 8:** a) Map of the analytical magnetometric signal with a display of the areal distribution of In-phase anomalies at depths of 2.2 m and 4.2 m: 1) map of the analytical magnetometric signal, 2) areal distribution of in-phase anomalies at depths of 2.2 m and 4.2 m, 3) areal distribution of analytical magnetometric response anomalies; b) map of the distribution of interpreted anomalies*

contributed to the assessment of the area of the former foundries prior to new development. Verification of the measured anomalies by excavation confirmed the interpretations and, at the same time, provided interesting insights into how specific objects/contamination manifest in geophysical fields and into the capabilities of the methods used.

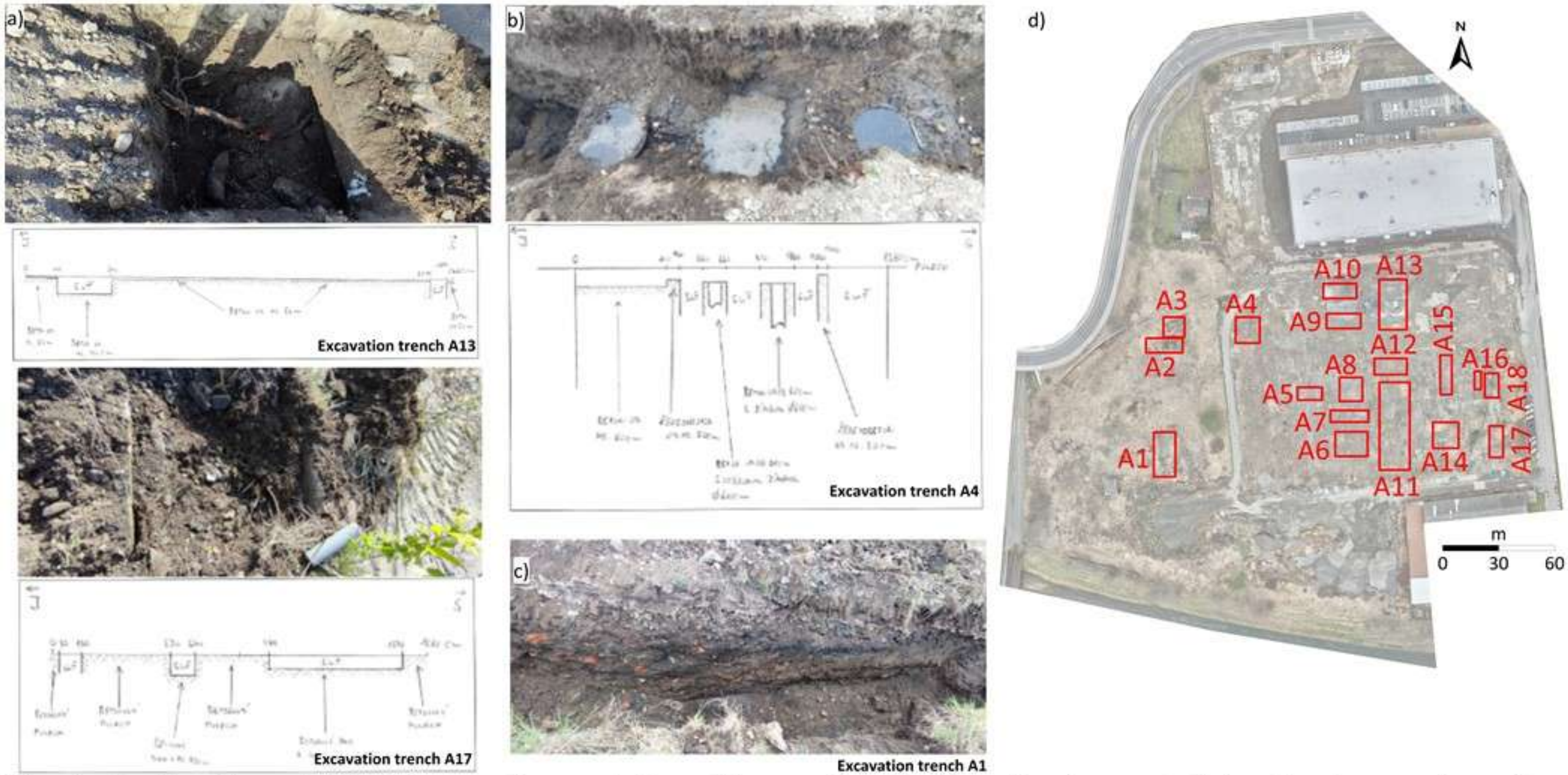

Fig. 9: Confirmation of detected anomalies – photographic record and schematic of excavated trench: a) concrete surfaces, b) reinforced concrete foundations and cylindrical pits, c) dark clay-rich debris with industrial contamination, d) map indicating anomalies.

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