



Resistivity Survey and Soil Flux Measurements in an Area with Natural CO₂ Emissions

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Abstract

In monitoring CO₂ storage sites, it is assumed that detectable variations in electrical resistivity exist in the monitoring area, as CO₂ has a significantly higher resistivity compared to the fluids in the reservoir's pores. Geophysical methods, particularly geoelectric ones, have been successfully applied to obtain detailed images of a wide range of geological structures, including the heterogeneity of aquifer lithology, aquifer layer thickness, the presence of shale lenses, the position of the hydrostatic level, the identification of fractures and cracks, as well as the characteristics of contamination plumes with inorganic and organic compounds. In this context, vertical electrical sounding (VES) is a near-surface geophysical method, aiming to determine the resistivity distribution with depth and at the surface. Complementary to the monitoring methods for the Băile Lăzărești site (Romania), electrical resistivity measurements – electrometry – were carried out to highlight water bodies near the surface, their regional extent, local geological characteristics, and potential gas migration pathways to the surface, by outlining resistivity anomalies. The method implemented was vertical electrical sounding (VES) – Schlumberger device (MiniSting R1) on 12 profiles (6 profiles from the 12 in the high CO₂ emission area in the northern part of the Lăzărești site, and 6 profiles in the low CO₂ emission area in the southern part of the site). For each of the 6 profiles measured in the high CO₂ emission area, 6 VES measurements were made, with 9 measurements each (a total of 54 resistivity values acquired for each profile). The distance between the current electrodes (AB) was 4, 6, 8, 10, 12, 14, 16, 18, and 20 meters, while the MN distance remained constant at 2 meters. Due to the physical-chemical properties of the soil (alternating shale, marl, and sandstone from the Cretaceous flysch), the maximum penetration depth was calculated at 4.20 meters. The length of the 6 profiles is 30 meters. The geoelectrical investigation revealed that the presence of shale content tends to reduce the increase in resistivity caused by the replacement of water with less conductive CO₂. The obtained results represent one important step to demonstrate the feasibility of using resistivity surveys for monitoring CO₂ geological storage sites.

Keywords: CO₂ geological storage monitoring, resistivity surveys, vertical electrical sounding, natural laboratory for CO₂ storage, soil flux surveys

1. Introduction

Carbon capture and storage (CCS) is perceived as a key technology to mitigate climate change [1] by providing the needed drastic reduction of industrial CO₂ emissions [2],[3]. Within the CCS chain, the geological storage part, especially onshore, is the one that faced the strongest public opposition. Since storage readiness level is low at global level [4], storage has become a major obstacle on the pathway of CCS large-scale deployment.

In this context it is very important to increase the public trust in the concept of geological storage and one way to achieve that is by designing and perfecting environmental monitoring solutions, especially onshore. One of the most common environmental monitoring solutions is represented by soil flux surveys, which can highlight leakage of CO₂ in the soil if the natural CO₂ background levels and seasonal variability of fluxes is determined [5]. Environmental monitoring of CO₂ geological storage sites can also include near-surface geophysical methods, such as geoelectric and ground penetrating radar (GPR). Geoelectric methods have been successfully applied for monitoring in order to determine near-surface fractures and fissures that could facilitate the movement of CO₂ toward the surface, to determine the contamination with CO₂ of shallow aquifers and highlight near-surface accumulation of CO₂. One of the most common used geoelectrical methods is represented by vertical electrical sounding (VES) which can provide a clear image regarding resistivity distribution with depth and therefore can highlight bodies of different resistivity compared with the surrounding environment [6].

Soil flux surveys and resistivity surveys (VES) have been implemented in Romania for testing their ability to detect leakage in the case

of onshore CO₂ geological storage. In the absence of an actual CO₂ storage project, testing of monitoring methodologies and methods have been done using natural analogues and natural laboratories for CO₂ geological storage. One of this natural testing sites from Romania is represented by Băile Lăzărești (Harghita County), near Tușnad, an important touristic city. Băile Lăzărești, also called Lăzărești, is in fact a good analogue for CO₂ leakage from an anthropic reservoir into the near environment [7]. This site was assessed starting with 2019 and was intensely explored and surveyed in 2022. From the point of view of CO₂ emissions, the site can be divided into two perimeters, a northern perimeter with high emissions where several wet and dry mofettes can be found and one southern perimeter with much lower emissions where just one wet mofette and one dry gas vent were identified. In the summer of 2022 testing of several monitoring methods has been done, including soil flux and resistivity surveys, alongside ground penetrating radar, soil gas measurements and soil sampling.

2. Materials and methods

2.1 Study area

The Gurghiu-Harghita post-eruptive chain represents the most intense post-volcanic activity in the Eastern Carpathians (Romania) (Fig.1), characterized by a significant release of gases. The ascent of volcanic gases to the surface is facilitated by deep-seated tectonic structures, through a complex system of crustal, regional, and local fractures — with regional and local fractures exhibiting varying degrees of present-day mobility [8].

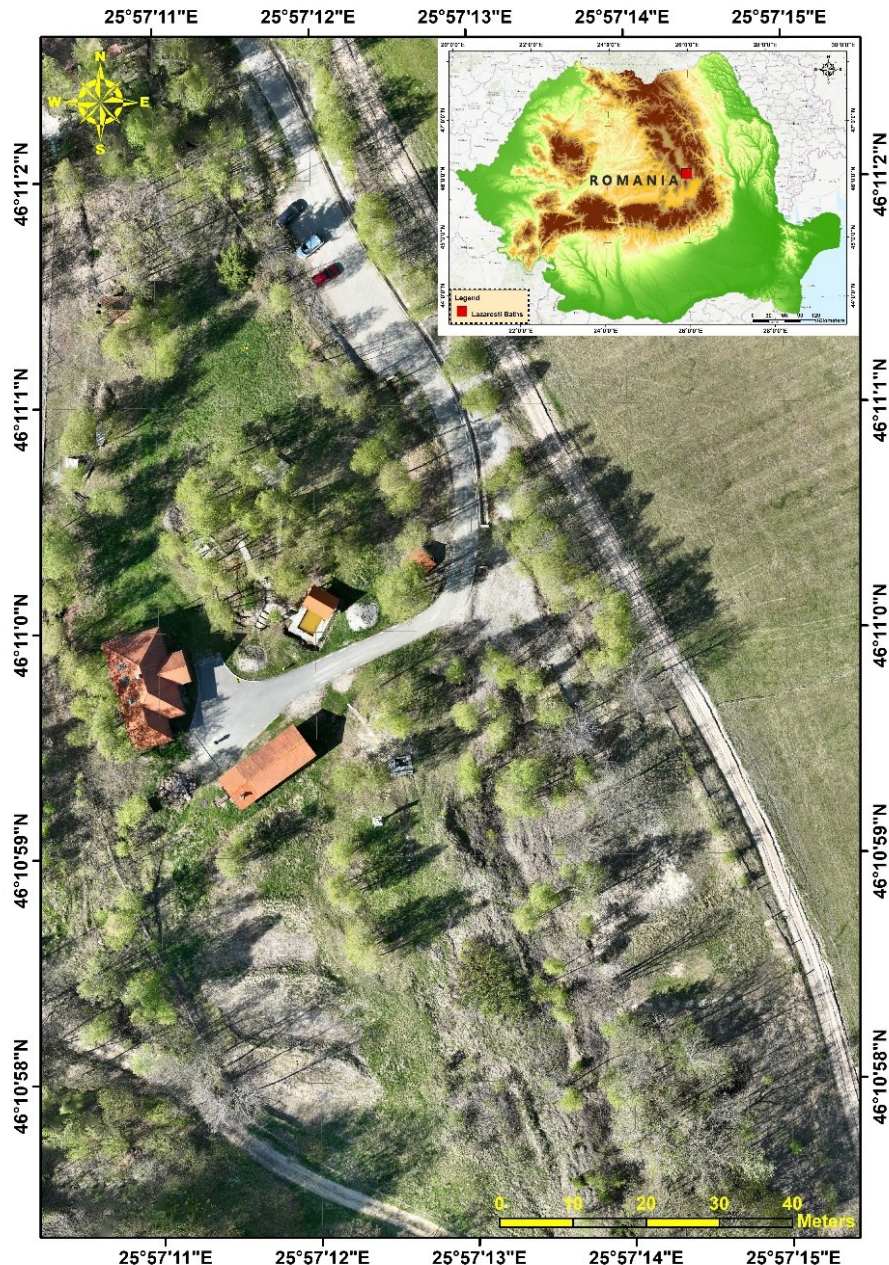


Fig. 1. Map showing the location of Lăzărești area

In the Lăzărești area, post-volcanic emissions circulate along a regional fault – G25 [9], which, together with several active overlying faults, displaces the Cretaceous flysch in the region [8].

Băile Lăzărești site is situated on a stratigraphic succession that begins with Cretaceous flysch deposits (Sânmartin–Bodoc, Barremian–Albian strata) (Fig. 2) at the base and extends up to Quaternary terrace deposits. Structurally, the site is positioned axially on an overturned anticline trending north–south, a tectonic feature that has generated associated morphological expressions such as small valleys, anticline

depressions, buttonholes, and ridges. To the east, a second overturned anticline with the same north–south orientation is observed, with a syncline developing between the two structures. The Lăzărești area is part of the Ceahlău Nappe subunit—specifically, the Bodoc digit—which represents the outermost segment of the Ceahlău Nappe [10]. Within this structural unit, some of the thickest lithostratigraphic successions are found, especially those dating from the Albian stage.

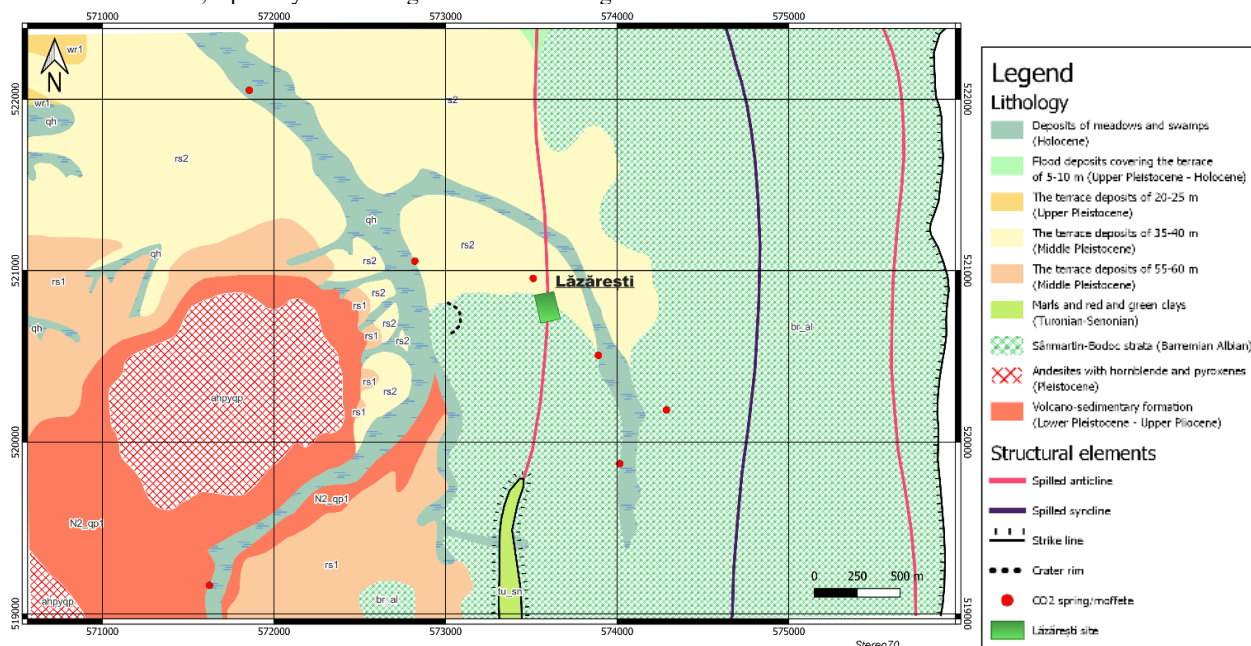


Fig. 2. Digitized geological map (based on the 1:50000 Geological Map, Braşov sheet) for Băile Lăzărești site and adjacent areas

From a lithostratigraphic standpoint, the post-volcanic gas emissions in the Lăzărești area traverse multiple sedimentary units, starting with the Cretaceous flysch at depth and progressing upward through terrace deposits [11]. The Barremian-Albian flysch presents typical flysch facies, characterized by rhythmic alternation of rusty-grey sandstones - often bituminous - and clay shales, which may lack marl-calcareous intercalations.

The flysch, with its low permeability due to the alternating layers of marls and sandstones, can act as a barrier, limiting the free migration of gases. However, regional tectonic activity has induced fracturing within the flysch, creating permeable pathways that allow deep-seated volcanic gases to ascend towards the surface. These fault and fracture systems act as a form of stratigraphic screen, capable of either trapping or channelling gases depending on the orientation, continuity, and mobility of the structures involved.

The Quaternary terrace deposits consist of coarse detrital material, locally overlain or interbedded at slope bases with finer sediments such as sandy shales, marls, grey shales, and fine sands. The genesis of carbonated mineral waters in the region is directly linked to the interaction between ascending mofettic CO₂ and aquifers hosted within these geological formations.

Moreover, the hydrochemical characteristics of the region's mineral springs—such as sulfonated or ferruginous waters—are largely determined by the geochemical signature of the lithologies (volcanic, flysch, Neogene, and Quaternary formations) through which the groundwater circulates.

2.2 Soil flux measurements

Soil flux measurements were carried out during July and August 2022. In total, soil flux was measured in 244 points arranged in a grid of 17 profiles spaced 2 meters apart (Fig. 1). The measurement grid was designed in such a way as to obtain a detailed image of the surface distribution of soil gas emissions at the Lăzărești site, as well as to intersect the alignments of dry and wet mofettes present at the site.

The gas measurements were performed using a portable fluxmeter produced by West Systems (Italy) equipped with sensors for CO₂ (LI-COR LI-830-3, 0–2%; Vaisala GMP251, 0–20%), CH₄ (WS-CH4-TLD), and H₂S (WS-TOX-H2S). The data resulting from the gas measurements were processed using the software provided by the equipment manufacturer, West Systems—specifically, Flux Revision—resulting in gas flux values and average concentrations of the measured gases. Based on the processed data, emission distribution maps for the Lăzărești area were created. The interpolation was made using ArcGIS software, resulting in soil flux distribution maps.

2.3 Resistivity survey

The principle of electrical sounding is injecting an electrical current into the ground through two current electrodes (A, B), and recording the electric potential difference by two other potential electrodes (M, N), based on which an apparent electrical resistivity value is calculated. Following the geoelectrical measurements, the data is transferred from the specialized device (resistivimeter) to a computer and subsequently processed to obtain graphical representations in the form of pseudo-sections, maps, and 3D models of electrical resistivity.

The electrical resistivity survey was carried out during August 2022 campaign on the two perimeters of the Lăzărești site. The implemented method was Vertical Electrical Sounding (VES) – Schlumberger array, on profiles spaced 10 meters apart, with the centre of the array shifted every 2 meters. The device used for these measurements was a MiniSting R1, equipped with four electrodes and manufactured by Advanced Geosciences Inc. (AGI). A total of 7 profiles were carried out on the grid of soil flux measurements, 6 on the northern perimeter and 1 in the southern perimeter (Fig. 3). On each of the 6 profiles measured in the north, 6 VES measurements were performed, each consisting of 9 individual readings (a total of 54 resistivity values collected per profile). The distance between the current electrodes (AB) was 4, 6, 8, 10, 12, 14, 16, 18, and 20 meters, while the MN distance was constantly 2 meters. The investigation depth (theoretically) can be approximated as AB/4 (or a quarter of the interval between current electrodes AB), although, in this particular case, due to the physico-chemical properties of the soil, the maximum penetration depth was calculated to be 4.20 meters. The length of the 6 profiles is 30 meters.

In the southern perimeter, one resistivity profile was measured on the grid of soil flux measurements. The profile is 40 meters long and contains 11 VES (Vertical Electrical Sounding) points, each consisting of 9 measurements (a total of 99 electrical resistivity values per profile). The MN distance was maintained constantly at 2 meters, while the AB distances were set at 4, 6, 8, 10, 12, 14, 16, 18, and 20 meters.

The resistivity data was processed using Earth Imager, AGI software. Data processing resulted in resistivity sections showing depth profiles for each measurement point, as well as a resistivity map for the northern perimeter. Using also the modelling package from AGI, two 3 D models (inverted resistivity models) have been made for the parallel profiles from northern perimeter, one for the profiles on the WSW-ESE direction (P1-P4) and one on the NW-SE (P5 and P6).

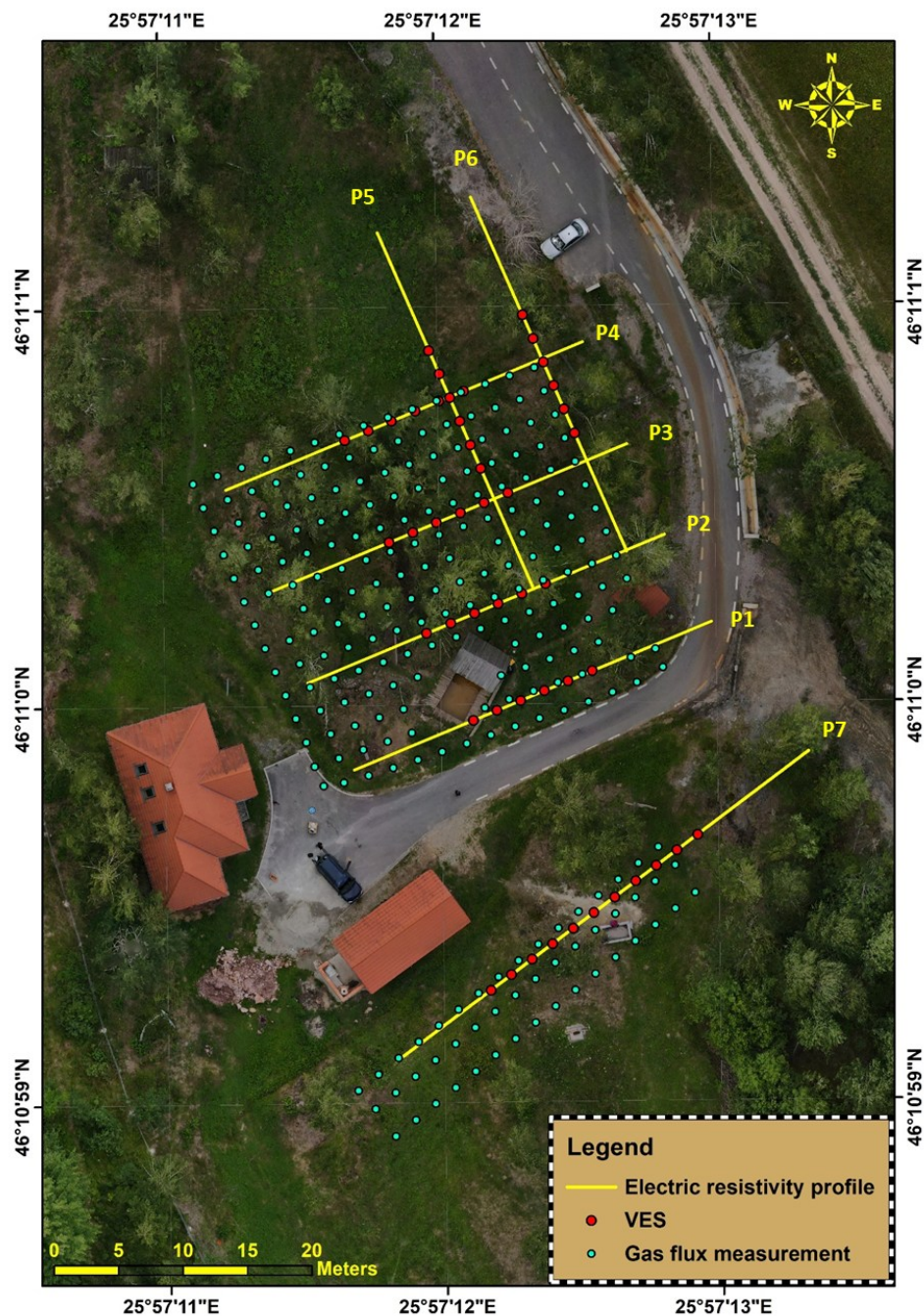


Fig. 3. Location of gas flux measurements and of the resistivity profiles

3. Results and discussion

3.1 Soil flux values

Soil flux values revealed a large variability for CO₂, but low variability for CH₄ and H₂S. Taking into account also the low CH₄ and H₂S average concentrations, these values were considered not relevant for the current study. The CO₂ flux (Fig. 4) varied between 0.43 and 185 mol/m²/day on the northern perimeter and between 0.20 and 178 mol/m²/day on the southern perimeter. The highest CO₂ fluxes were obtained north of the therapeutic bath, in the area with smaller baths/wet mofettes, near the water spring and on the alignment of the dry mofette cabin on the northern perimeter. In the southern perimeter, the maximum CO₂ fluxes were measured near the wet mofette and on the alignment of the water spring.

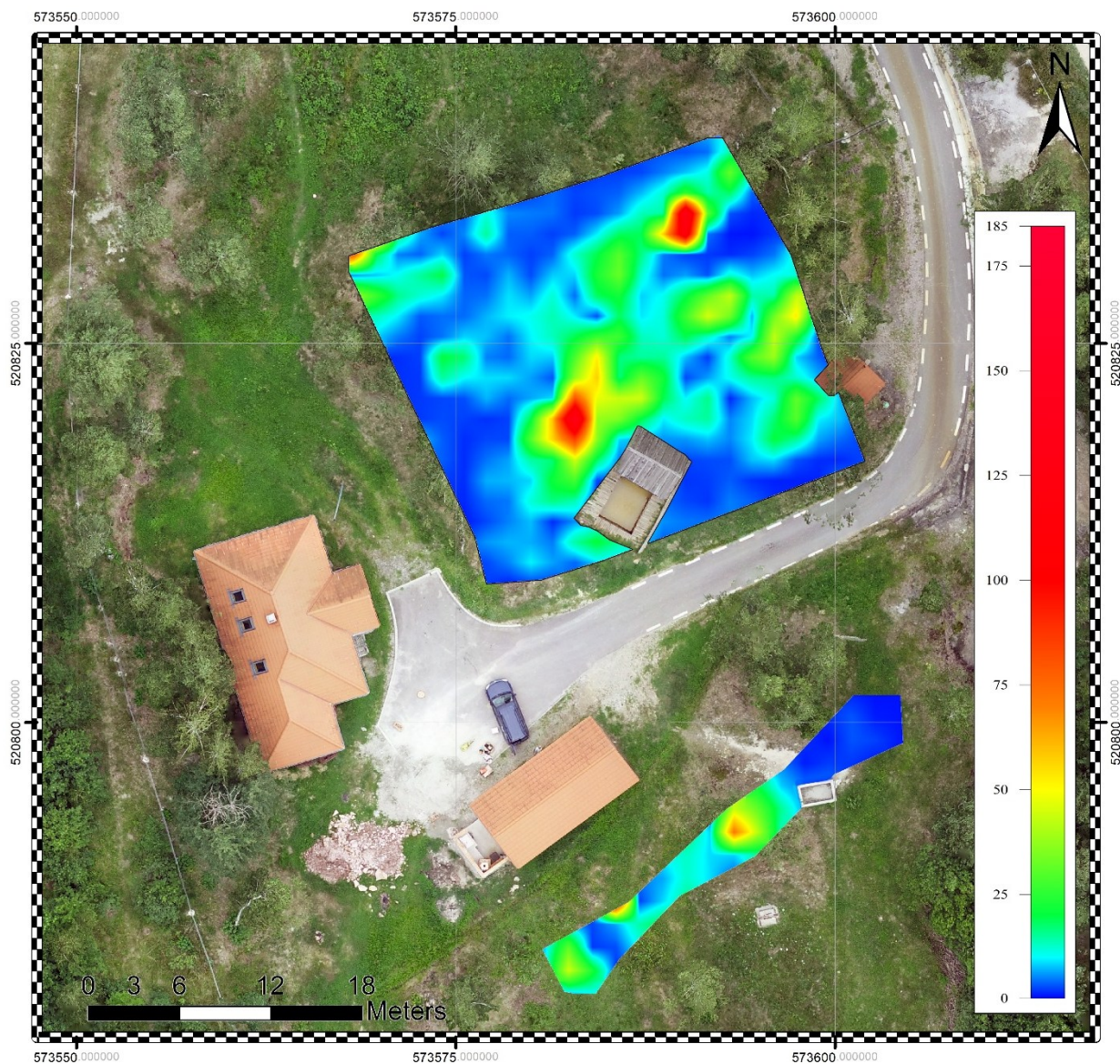


Fig. 4. CO₂ flux variation at Băile Lăzărești site in the summer of 2022

3.2 Resistivity survey

The resistivity map made for the northern perimeter (Fig. 5), based on the data obtained from 6 of the total of 7 profiles (profiles P1-P6) reveals several maximum and minimum resistivity anomalies. The resistivity data was compared with the flux data trying to find a correlation trend. The initial hypothesis was that the maximum resistivity anomalies are correlated with maximum CO₂ flux values due to low resistivity of the CO₂. This effect was in fact reduced due to the presence of water, highly conductive, so no direct correlation could be made between CO₂ flux and resistivity values. In fact, high resistivity anomalies correspond to dry areas in which we can find in the subsol layers of marls and shales. Low resistivity anomalies can be correlated solely with the increase water content.

3D resistivity models highlighted several maximum and minimum anomalies on the northern perimeter of the area. The first model has been made using profiles P1, P2, P3 and P4 (Fig. 6). The highest resistivity values have been obtained between the wet mofettes positions, confirming the correspondence with the presence of water in the near subsurface.

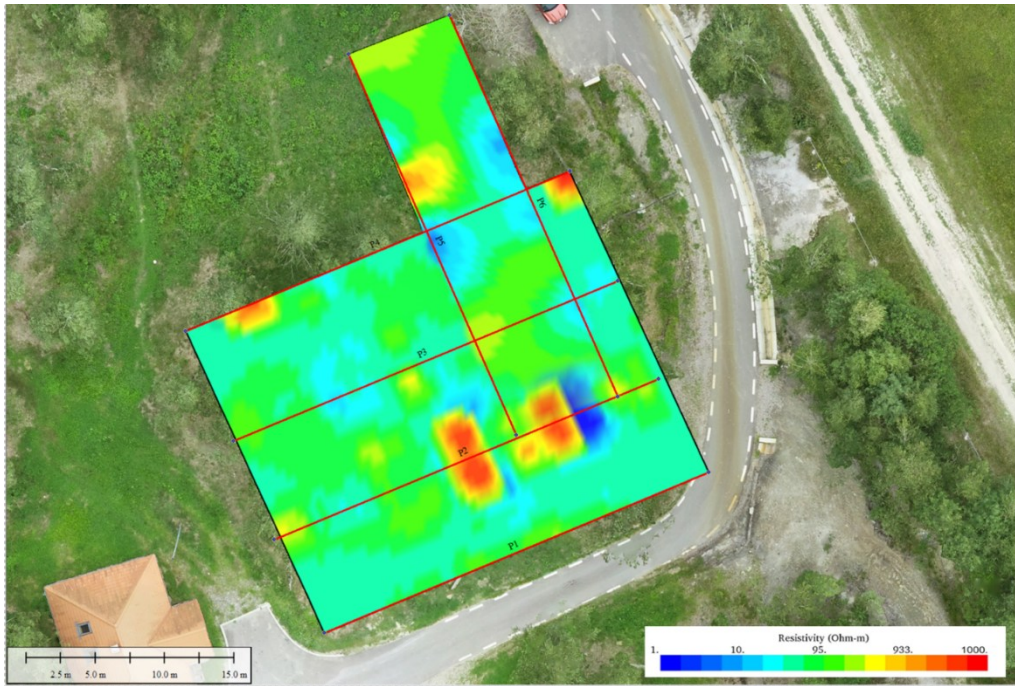


Fig. 5. Resistivity map for the northern perimeter

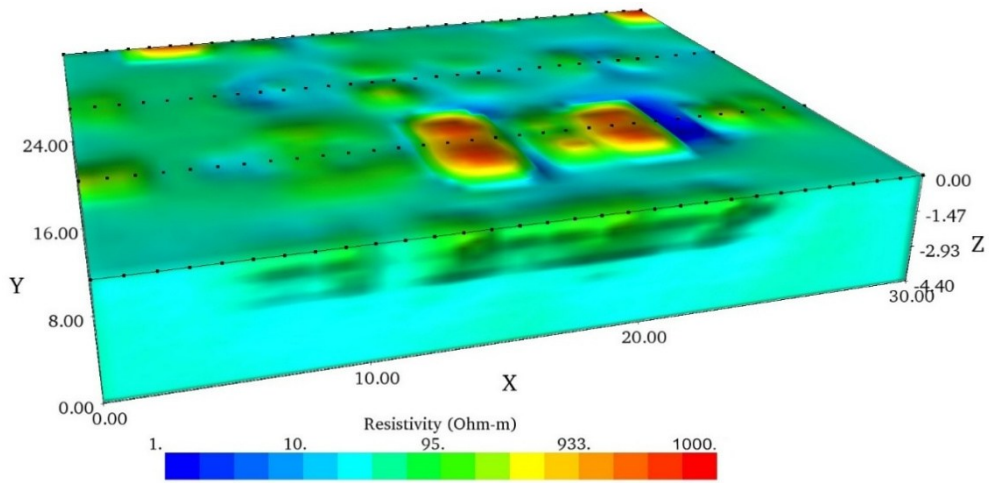


Fig. 6. 3D resistivity model for P1, P2, P3 and P4 profiles

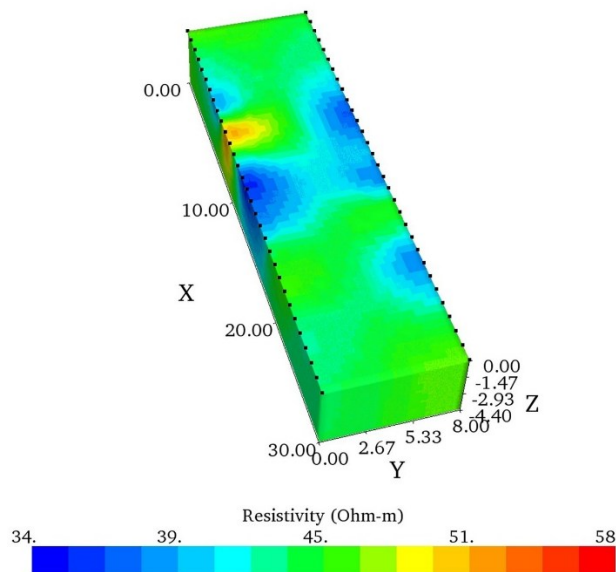


Fig. 7. 3D model made from profiles P5 and P6

The resistivity section (Fig. 8) for the seventh profile (P7), the only profile from the southern perimeter revealed an intense maximum resistivity anomaly that can be correlated with the maximum CO₂ flux anomaly.

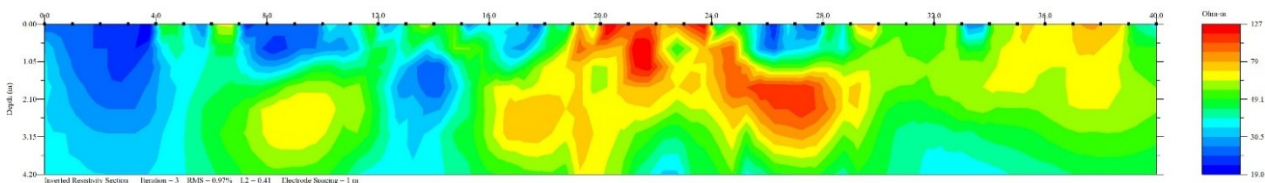


Fig. 8. Resistivity section for P7 profile

4. Conclusions

Soil flux and resistivity surveys were carried out in the summer of 2022 for the study of CO₂ leakage into the near surface environment, in Băile Lăzărești, Harghita County. The site is a suitable analogue, identified in 2019, for leakage of CO₂ from a geological storage reservoir and used since then to test methods and methodologies for monitoring.

The first hypothesis of the study was that the CO₂ flux values will correlate with resistivity values. High fluxes of CO₂ were expected to correspond with high resistivity anomalies, but no such correlation could be done. From the analysis of resistivity values and geological information, it was determined that high resistivity anomalies can be associated with dry layers rich in shale and marl, while low resistivity correlated with high water content, irrespective of CO₂ flux. A singular exception was observed on the single profile from the southern perimeter where a high resistivity anomaly could be correlated with the maximum anomaly of the CO₂ flux.

The study highlights the need for site-specific calibration and supports using multi-method monitoring approaches for CO₂ geological storage sites, especially in complex geological environments. Furthermore, the acquisition network for the geophysical methods should be more correlated with the soil flux measurement grid. The feasibility of using resistivity methods is site specific and a thorough analysis should be made taking into account the geological specifics and especially the distribution of water in the subsoil.

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