Ground-Penetrating Radar Investigations of GAS Emissions at Băile Lăzarești, Harghita County, Romania

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Abstract

This paper presents the results of ground-penetrating radar (GPR) investigations conducted in 2022 and 2024 at Băile Lăzarești, Harghita County, Romania, an area characterized by post-volcanic activity and active gas emissions. The aim of the study was to identify shallow subsurface anomalies related to the migration and accumulation of carbon dioxide (CO_2). The GPR surveys were carried out using a Sensors & Software Noggin Ground Penetrating Radar system equipped with a 250 MHz antenna and SmartCart survey cart, which facilitated systematic data acquisition. The 2022 GPR survey covered a defined perimeter of approximately 777 square meters and was carried out using continuous profile acquisition, allowing for detailed imaging of subsurface features in both lateral and depth dimensions. In 2024, the survey area was slightly larger and investigated using the same continuous GPR profile acquisition methodology, with a total surveyed area of 865 square meters. The acquisition strategy employed for both survey areas enabled the generation of radargrams, depth slices, and GPR amplitude distribution maps. Data processing was conducted by using standard GPR procedure, including signal filtering, gain correction, time-to-depth conversion, and interpolation. The interpretation highlights zones of contrasts in signal attenuation and reflection, interpreted as preferential pathways for gas migration and accumulation. Some of these anomalies exhibit spatial correspondence with surface features, notably mofette gas emission zones that have cleared their surrounding areas of vegetation. By comparing the GPR measurements with the CO_2 flux data, also presented as spatial distribution maps, it was possible to identify correlations and perform a comparative analysis between the two datasets, demonstrating the benefits of GPR for non-invasive investigations of gas emissions.

Keywords: *CO2 flux, GPR, amplitude maps, anomalies, radargrams*

1. Introduction

Harghita County is characterized by a predominantly volcanic geological framework, being part of the inner volcanic arc of the Eastern Carpathians. The region is composed largely of Neogene volcanic formations, including andesitic and dacitic structures [1], which are associated with one of the youngest volcanic systems in Central and Eastern Europe [2].

Although volcanic activity in the area has ceased, the region remains geodynamically active through a variety of post-volcanic (hydrothermal) processes [3], [4]. The Băile Lăzărești area, located within the Cozmeni commune in the Ciuc Depression, exhibits several manifestations of residual volcanic activity [5]. These include mineral springs, mofettes (CO_2-rich, H_2S, and CH_4 gas emissions), and hydrothermal alterations of the surrounding rocks. [3], [4].

The study area is located within the enclosed sector of Băile Lăzărești (Lázárfalva) and was divided for study purposes into two distinct survey perimeters [6], a southern perimeter with low natural CO_2 emissions and a northern perimeters with high CO_2 fluxes and many post-volcanic features. These perimeters were investigated using Ground Penetrating Radar (GPR) and soil flux measurements, allowing for the integrated analysis of subsurface structure and gas emission patterns.

The datasets derived from the GPR measurements were processed and analyzed using specialized software, with the objective of correlating geophysical anomalies with the subsurface gas emissions. This integrated analysis facilitated the identification of spatial correspondences between soil flux measurements and geophysical signatures, highlighting the complementary character of the two methods in the investigation of subsurface post volcanic features.

Additionally, the raster and vector geophysical datasets were georeferenced and superimposed onto UAV-derived products,

such as orthomosaics (Fig. 1), obtained through the photogrammetric processing of aerial imagery acquired during an aerophotogrammetric mission.

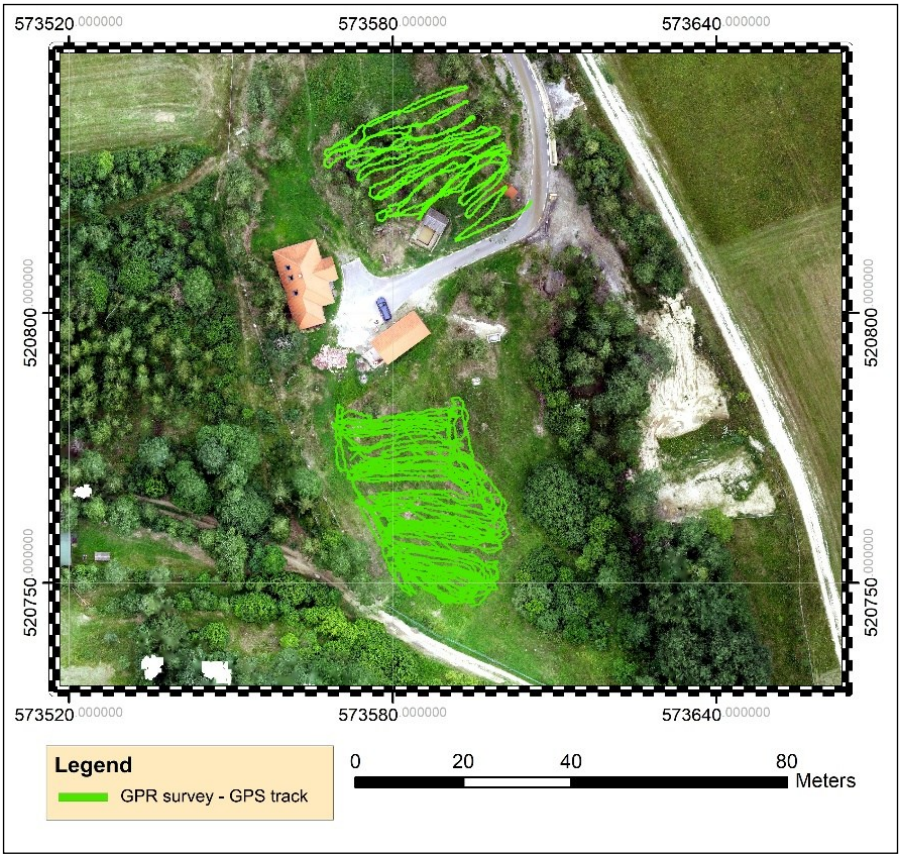

Fig. 1. Georeferenced GPS tracks corresponding to the two GPR survey grids, superimposed on the UAV-derived orthomosaic of the Băile Lăzărești area

2. Materials and Methods

The instrumentation used for the GPR measurements consisted of a Sensors & Software LMX200 system equipped with a Noggin 250 MHz antenna, a SmartCart system for field mobility, a Topcon GPS antenna, and a Digital Video Logger (DVL), which allows for real-time data visualization and quality control during acquisition. In addition, a Trimble R2 GNSS system was employed to ensure accurate spatial positioning of the survey perimeters and precise data localization, particularly for the georeferencing of vector datasets and the resulting geophysical products, such as two-dimensional maps.

For the CO_2 flux measurements, soil gas flux was assessed using a portable West Systems fluxmeter equipped with CO_2, CH_4, and H_2S sensors, enabling quantification of gas emissions.

The raw soil flux dataset was processed using FluxRevision software version 4.11. After the preliminary data analysis, the fluxes of CH4 and H2S were found to be negligible and CO_2 was considered the dominant gas and therefore the main focus of the geochemical study. The CO_2 flux values were interpolated and Oasis Montaj software was used to produce CO_2 distribution maps The GPR-derived amplitude data were processed using the dedicated EKKO Project V5 software. Interpolation of the amplitude values was subsequently performed in Geosoft Oasis Montaj as well, generating GPR amplitude distribution maps. These maps were rendered using a consistent colour scale and visualization scheme comparable to that of the CO_2 flux maps, thereby facilitating direct spatial correlation and integrated interpretation between the two datasets.

2.1. Spatial characteristics of CO_2 flux and GPR survey perimeters

Northern perimeter (Fig. 2) was measured during the summer season of 2022 and encompasses an area of approximately 1269 m², comprising a total of 228 soil flux measurement points. Overlapping this perimeter, and fully contained within its spatial extent, is GPR perimeter 1, which covers an area of approximately 777 m² (Fig. 4). Unlike a conventional grid-based survey, the GPR data acquisition in this case was conducted along a continuous profile, resulting in a total survey length of approximately 767 m. This acquisition strategy was adopted due to local topographic constraints and surface conditions, which limited the implementation of a regular grid-based survey design.

Southern perimeter (Fig 3) and GPR perimeter 2 were investigated during the autumn 2024 field campaign. The soil flux survey covered an area of approximately 1429 m² and included 37 soil flux measurement points. The GPR survey area (Fig. 4) is largely enclosed within the soil flux survey perimeter and, similarly to perimeter 1, was acquired as a continuous profile rather than a grid-based survey for the same reasons. The total profile length reached approximately 2.24 km, corresponding to a coverage area of approximately 865 m².

Fig. 3. The distribution of soil flux measurement points for southern perimeter

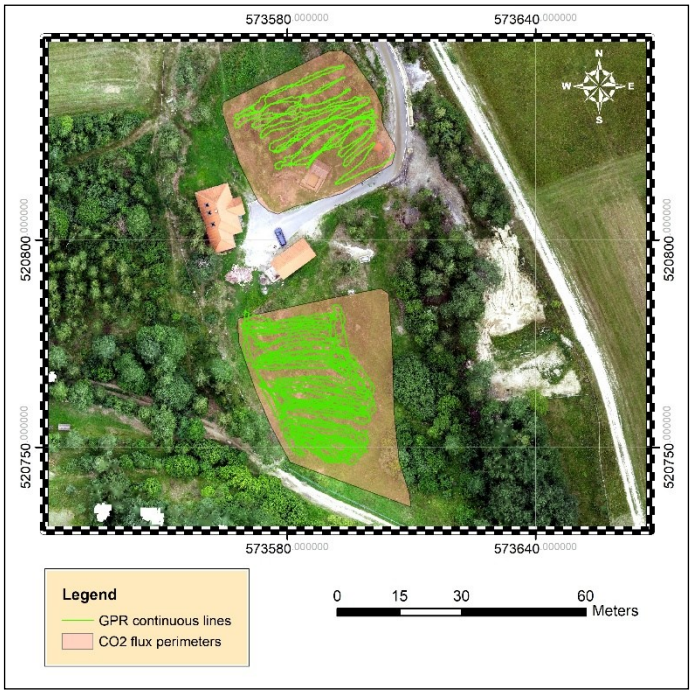

Fig. 4. Georeferenced GPR continuous profiles (green) overlaid on the soil flux survey perimeters, illustrating their spatial overlap in the northern and southern sectors.

3. Results

During the summer campaign (July 2022), CO_2 flux measurements reached values of up to 42.2 mol/m²/day. The highest flux values were recorded immediately north of the therapeutic bath and mineral spring, as well as in the north-eastern sector, along the alignment of a mofette cabin (Fig. 5).

In contrast, during the autumn 2024 campaign, lower CO_2 flux values were observed, with maximum recorded values reaching 11.5 mol/m²/day (Fig. 6). The anomalies defined by these peak values are associated with areas characterized by the presence of dry mofettes. These dry mofettes can be readily identified in the field by the absence of vegetation [5], reflecting the impact of continuous gas emissions on plant development. A similar pattern is also observable in the northern sector, particularly in the vicinity of the mineral spring.

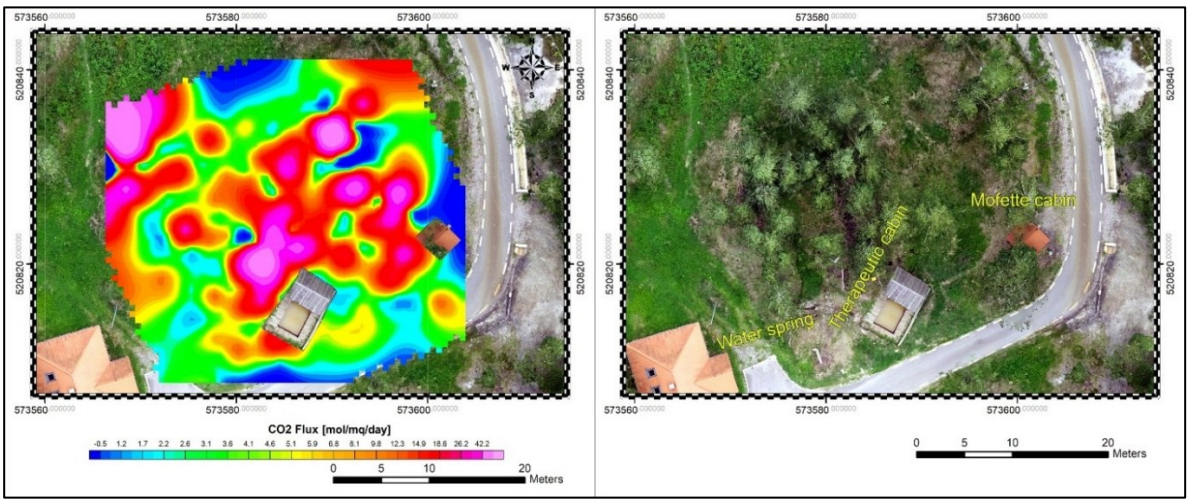

Fig. 5. Left: CO_2 flux distribution map of the northern sector. Right: corresponding orthomosaic displaying key sources of anomaly generation, including a mineral spring, a therapeutic bath, and a dry mofette cabin

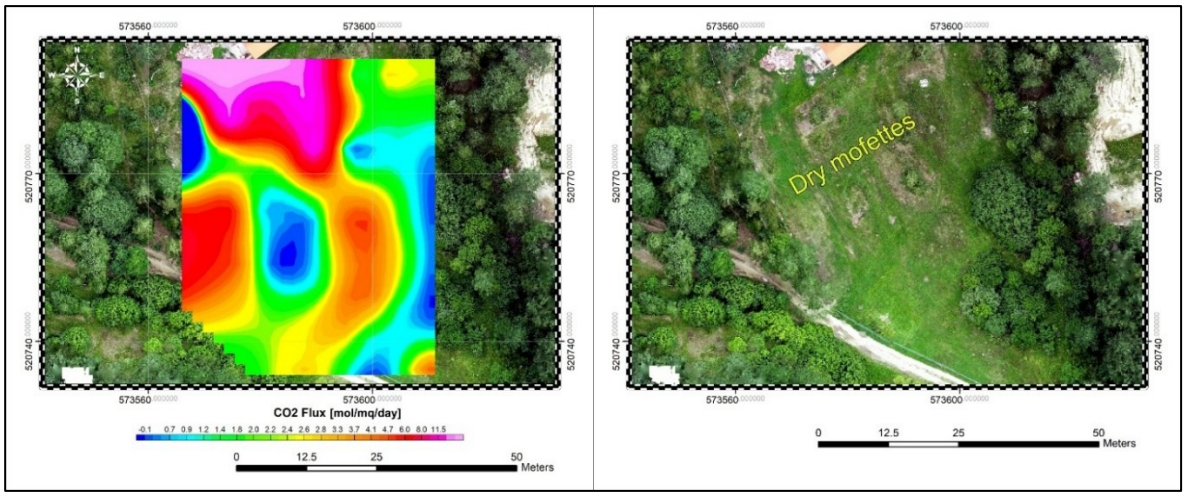

Fig. 6. Left: CO_2 flux distribution map of the southern sector. Right: corresponding orthomosaic displaying key sources of anomaly generation such as dry mofettes

Both the northern and southern GPR survey perimeters exhibit zones of higher signal amplitude that broadly coincide with the areas characterized by high CO_2 flux values (Fig. 7). This spatial correspondence suggests a potential relationship between subsurface dielectric contrasts and zones of active gas emissions. The increased amplitude responses observed in the GPR datasets are likely associated with heterogeneities in the subsurface, such as variations in moisture content, porosity, or sediment composition, which can be influenced by the presence and migration of gas. In particular, ascending CO_2 may alter the physical properties of the soil and sediments, leading to enhanced dielectric contrasts that are detectable in the GPR signal. Furthermore, the alignment between high-amplitude GPR anomalies and elevated CO_2 flux zones supports the interpretation that these areas correspond to preferential pathways for gas migration, potentially controlled by fractures, fissures, or zones of increased permeability.

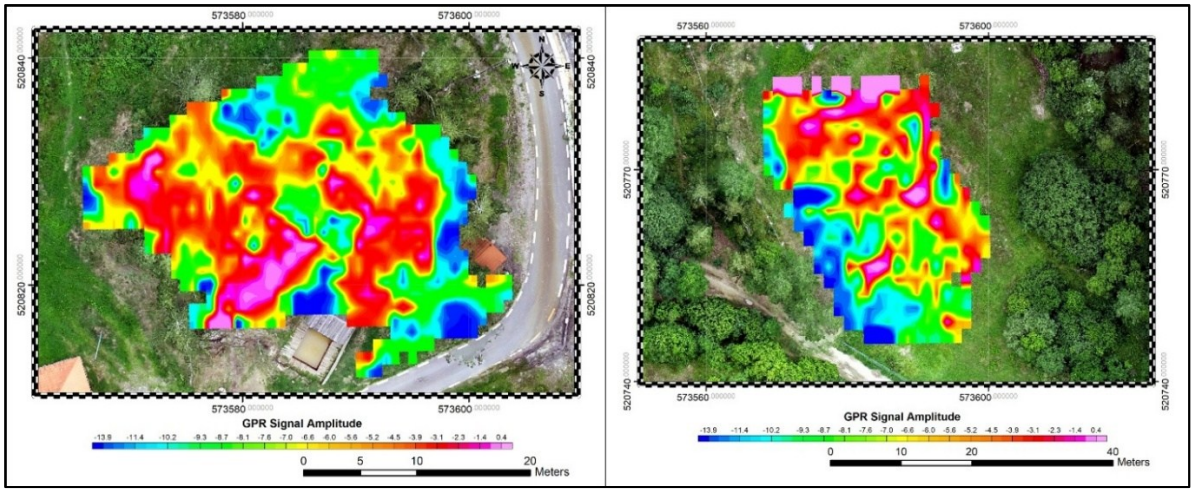

Fig. 7. Left: GPR signal amplitude distribution map for the northern perimeter. Right: GPR signal amplitude distribution map for the southern perimeter

The comparative analysis of the CO_2 flux distribution maps and the GPR amplitude maps for both the northern and southern perimeters reveals a clear spatial correspondence between the anomalies identified by the two independent investigation methods (Fig. 8 and 9). The areas outlined in both datasets highlight zones where high CO_2 flux values coincide with high-amplitude GPR responses, suggesting a strong relationship between subsurface gas migration processes and the recorded electromagnetic signal.

In both perimeters, the CO_2 flux maps display localized zones of increased gas emission, interpreted as active degassing points associated with mofette activity. These zones are consistently mirrored in the GPR amplitude maps by areas of enhanced signal response, indicating the presence of subsurface heterogeneities. The high-amplitude anomalies in the GPR data are likely controlled by variations in dielectric properties, which may result from increased porosity, moisture redistribution, or the presence of gas-filled voids and fractures. The spatial overlap of these anomalies suggests that the identified zones represent preferential pathways for CO2 migration from depth to the surface. These pathways are likely structurally controlled, potentially associated with fractures, fault zones, or zones of increased permeability within the subsurface. The presence of gas within these pathways can significantly alter the electromagnetic properties of the medium, producing strong amplitude contrasts detectable in the GPR data.

Furthermore, the geometry and distribution of the anomalies indicate that gas migration is not uniform across the study area but rather concentrated in discrete zones. In the southern perimeter, the anomalies appear more clustered and exhibit higher spatial variability, which may reflect a more complex subsurface structure or localized permeability contrasts. In contrast, the northern perimeter displays broader and more continuous anomalous zones, suggesting a more extensive or interconnected degassing system.

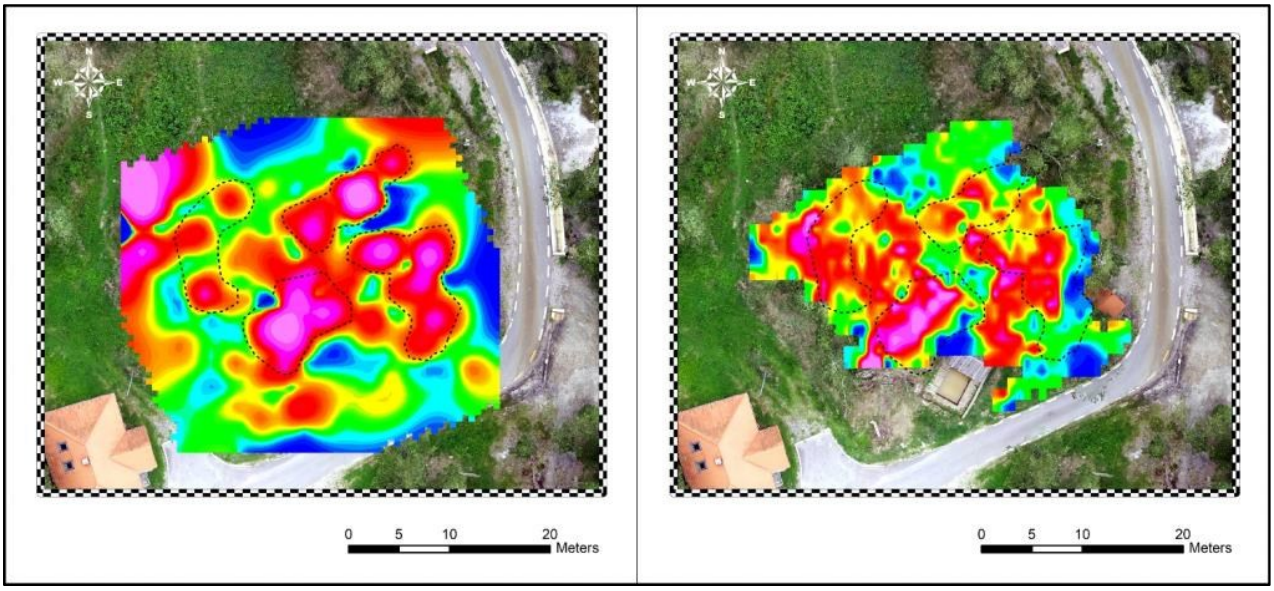

Fig. 8. Left: CO_2 flux map and Right: GPR amplitude map, with dashed outlines indicating spatially coincident anomalies

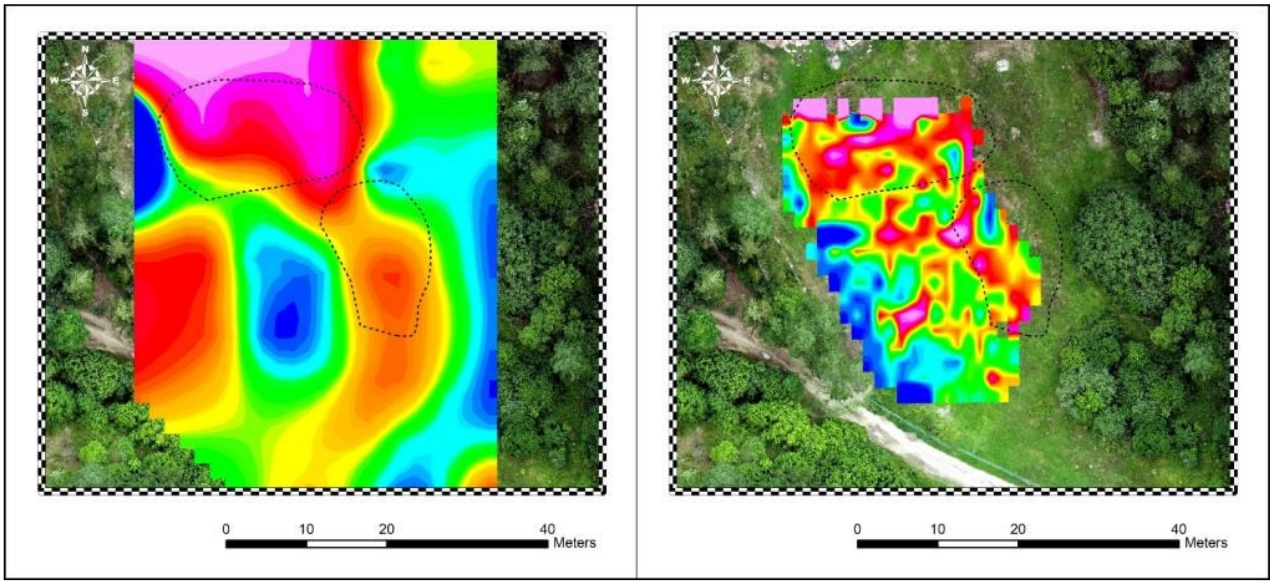

Fig. 9. Left: CO_2 flux map and right: GPR amplitude map, highlighting the correspondence between gas emission zones and high-amplitude GPR anomalies

4. Conclusions

Overall, the correlation between the CO_2 flux and GPR datasets demonstrates the complementary nature of the two methods. While CO_2 flux measurements provide direct evidence of surface degassing intensity, GPR data offer insight into the subsurface structures and physical property variations that control gas migration. The integration of these datasets allows for a more

comprehensive understanding of the degassing system, highlighting both the surface expression and the underlying subsurface controls. This combined approach proves particularly effective in identifying active degassing zones and delineating their spatial extent, making it a valuable methodology for the investigation of post-volcanic environments characterized by mofette activity.

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