

Article

Geophysical Mapping of Cemented Subsoils for Agricultural Development in Southern Peru

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Abstract: Cemented subsoils, commonly referred to as caliche, pose a regular challenge for agricultural development in arid and semi-arid regions like coastal southern Peru. These subsurface features restrict root penetration, limit water infiltration and hinder essential soil processes, ultimately reducing crop yields and agricultural productivity. Accurate and efficient mapping of caliche is important for optimizing land-use planning and implementing sustainable agricultural practices. This study presents the application of near-surface geophysical techniques for mapping caliche deposits in the context of agricultural development at the future Majes II site in the Arequipa region of southern Peru. Specifically, we employed high-frequency ground-penetrating radar (GPR) and frequency-domain electromagnetics (FDEM) at a testbed on the Majes II site to evaluate their ability to delineate the extent, thickness, and depth of caliche within the local geology. GPR offers high-resolution imaging, effectively capturing sharp contrasts between caliche and surrounding materials, providing detailed information on the thickness (approximately 0.4 m) and the depth (up to 1.5 m) of the caliche layers. FDEM provides valuable insights into the presence of caliche at a faster rate of data acquisition and processing, enabling rapid assessment of the extent of caliche deposits, although with the tradeoff of lower resolution and depth information. We demonstrate that these two geophysical methods can be used separately or in an integrated manner for collaborative interpretation at the Majes II site to inform land management decisions, including identifying areas with favorable conditions for crop production and implementing targeted interventions to mitigate the adverse effects of caliche on agricultural productivity.

Keywords: GPR; FDEM; geophysics; caliche; agriculture development; near surface; soils; Peru



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1. Introduction

In the 1980s, the Majes I agricultural development was established atop the coastal plateaus (pampas) in the arid environment of Southern Peru's Arequipa region (Figure 1). Spanning approximately 160 km² of irrigated land, the Majes I project highlighted the challenges and potential of agricultural development in this water-scarce region [1]. To sustain this initiative, the Majes-Siguas irrigation project was launched. This major undertaking involved diverting water resources, fed in part by melting glaciers in the Andes Mountains through a network of aqueducts and canals to support agriculture in this isolated environment [2]. While the Majes I site demonstrates a significant feat of agricultural innovation, the long-term sustainability of the Majes development hinges on several factors including efficient water management and responsible land-use practices. Climate change likely will decrease the volume of glacial meltwater, impacting the future water supply to the site. Additionally, expanding agricultural activities in this fragile ecosystem requires careful consideration of potentially adverse environmental consequences.

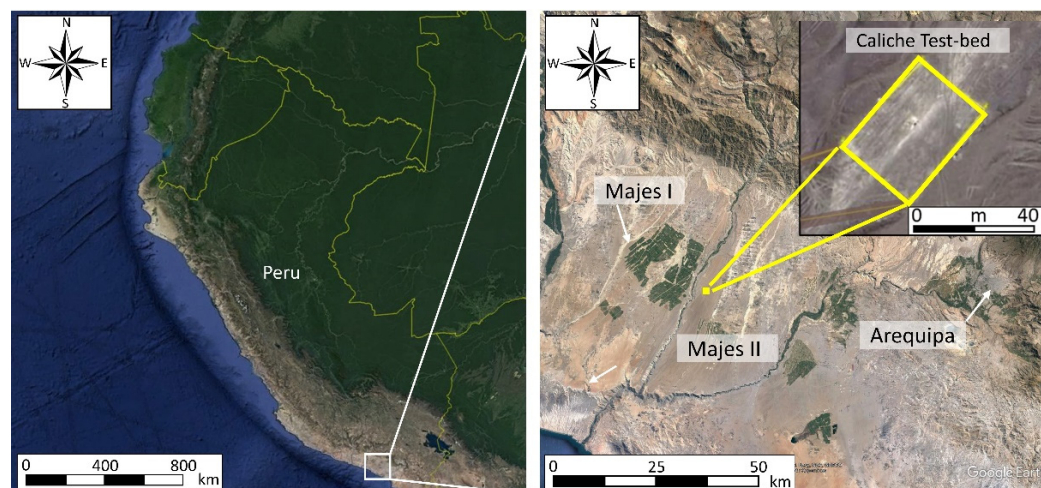


Figure 1. Location of the Majes region (**left panel**) and the geophysical testing area within the future Majes II region (**right panel**). Adapted from [3].

Building on the success of Majes I, plans are underway to extend the Majes–Sigüas irrigation project further, unlocking an additional 460 km² of arable land in the neighboring pampa at the future Majes II site [2]. While this expansion promises significant economic benefits, it necessitates addressing a significant land management challenge—the presence of caliche deposits, which are thick and discontinuous cemented subsoils typically found at shallow subsurface depths. These caliche layers hinder root penetration, water infiltration, and essential soil processes, ultimately limiting agricultural productivity [4].

Despite the significant advances in geophysical methods, current techniques for detecting and mapping caliche deposits have notable limitations. Ground penetrating radar (GPR) offers high-resolution imaging but is often restricted to smaller survey areas due to its detailed and time-consuming nature. Conversely, frequency-domain electromagnetics (FDEM) allows for rapid assessments over larger areas but lacks the fine resolution necessary to accurately detail caliche layers. Traditional soil sampling and trenching, while accurate, are labor-intensive and not feasible for large-scale applications. There is a clear research gap in the literature regarding the combined use of GPR and FDEM to create a comprehensive mapping of caliche deposits. This study aims to fill this gap by demonstrating the effectiveness of integrating GPR and FDEM techniques, addressing the limitations of using these methods independently.

The implications of accurately mapping caliche deposits extend beyond academic interest; they are valuable for sustainable agricultural practices in arid and semi-arid regions. Effective caliche mapping can significantly inform soil management practices and optimize land use, which is particularly important in areas where caliche layers impede root growth and water infiltration, thereby affecting crop yields. By integrating GPR and FDEM, we provide a framework for characterizing caliche distribution, which can guide targeted interventions such as deep ripping to mitigate the adverse effects of caliche on soil health and agricultural productivity. Future research should expand geophysical surveys to broader areas and correlate geophysical data with direct soil sampling and other ground-truthing methods. Additionally, investigating the economic benefits of using these integrated geophysical techniques for agricultural development could provide valuable insights into their cost-effectiveness and long-term impact on sustainable farming practices.

To promote sustainable agricultural practices in Majes II and ensure efficient water resource use, this study presents the application of near-surface geophysical techniques over a focused subsection of the future Majes II site to identify if a practical approach to detecting and mapping these cemented subsoils is possible. For this purpose, we acquired and evaluated two geophysical datasets—ground-penetrating radar (GPR) and frequency-domain electromagnetics (FDEM)—over a flat 30 m × 40 m testbed where outcropping caliche was observed within a shallow erosional channel along one side of the survey grid.

The results of this study demonstrate that GPR with appropriate frequencies successfully images the distribution and depth of the caliche at Majes II with moderate collection time and subsequent processing and visualization. Likewise, the near-surface FDEM method is shown to successfully map the lateral distribution of caliche with a rapid data acquisition rate and minimal data processing and visualization, although with reduced resolution and depth information relative to GPR analyses. Taken independently and together, the GPR and FDEM techniques can serve as powerful additions for promoting sustainable and cost-effective agricultural practices in the future Majes II site. This approach will allow for targeted land management decisions, such as optimizing irrigation strategies and implementing interventions to mitigate the adverse effects of caliche on agricultural productivity. Ultimately, this contributes to a more sustainable future for agriculture in the Majes region.

In this study, we employed near-surface geophysical techniques at Majes II to evaluate their potential for efficiently mapping cemented subsoils (caliche) within the area. The manuscript begins with an overview of the study site, including its climate and geological context. Next, we describe the caliche deposits in the region and their implications for agriculture. The subsequent sections detail our geophysical testbed setup and the specific FDEM and GPR methods used at the site. We then present the results of these surveys, followed by an integrated interpretation of the data. Finally, we discuss the implications of our findings for agricultural development and propose future research directions to further refine caliche mapping techniques.

2. Study Site

The Majes II study area (Figure 1), situated southwest of Arequipa in San Juan de Sigüas District, is scheduled for the implementation of the second phase of the Majes-Sigüas Irrigation Project. Situated adjacent to the Pan-American Highway linking Arequipa to Lima, the study site was accessed via a 3 km drive along the pampas south of the Pan-American Highway at kilometer marker 86. The site is at an average altitude of 1385 m above sea level, and experiences an average temperature range from 23 °C to 25 °C [5].

2.1. Climate

The climatic conditions in this region are influenced by two prevailing wind systems originating from the east (the Atlantic Ocean) and the west (the Pacific Ocean) [6], resulting in an arid climate along the Southern Peruvian coast. These wind systems create a unique climatic environment where moisture from the Atlantic is largely depleted by the time it reaches the Andean Mountains, and the cold Humboldt Current along the Pacific coast suppresses precipitation.

Periodic El Niño events, particularly impacting northern Peru, disrupt this aridity with intense precipitation and consequent flooding [7]. During El Niño events, the usual upwelling of cold water is diminished, leading to warmer sea surface temperatures that can cause significant increases in rainfall. This phenomenon has a profound impact on the hydrology and climate patterns across the region, although its direct effect on the Majes area is somewhat mitigated by its geographical location.

The precipitation pattern in the Majes River headwaters correlates closely with the subtropical jet stream and the Intertropical Convergence Zone (ITCZ), particularly during the austral summer [8]. The ITCZ's seasonal migration brings rainfall to the highlands and headwaters of the Majes River, contributing to the overall water availability in the catchment area. The region experiences marked seasonal variations in rainfall, with the majority of the precipitation occurring between December and March.

The present climate in the coastal and immediate inland areas (covering about 40% of the Majes catchment) is arid, receiving around 250 mm of rainfall annually. These arid conditions are characterized by high evaporation rates and minimal vegetation cover. Farther upstream, approximately 20% of the basin experiences a semi-arid climate, receiving

an annual rainfall between 250 mm and 500 mm [9]. This semi-arid zone supports more diverse vegetation and plays a crucial role in the hydrological cycle of the basin.

These climatic conditions are critical, as they directly impact the formation and persistence of caliche layers. The combination of limited rainfall, high evaporation rates, and periodic intense precipitation events contributes to the unique soil and hydrological characteristics of the region, influencing both natural processes and agricultural practices.

2.2. Geology

Southern Peru lies within the geological realm of the Andes Mountains, characterized by uplift and basin formation throughout the Cenozoic and Quaternary periods. The study area is situated on the coastal plain adjacent to the Andes, where these geological processes have shaped the landscape. At the Majes II study site, the near-surface lithology (Figure 2) is composed of a sequence of poorly consolidated sediments, including conglomerates, and ignimbritic tuff [10]. Immediately beneath the pampas lies the Millo conglomerate with a discontinuous layer of tuff observed along the Sigwas Valley walls. Beneath the Millo conglomerate lies the Moquegua Formation, an older and more substantial geological unit. This formation comprises a variety of rock types, including sandstones and gravels rich in limonite, claystones, and siltstones.

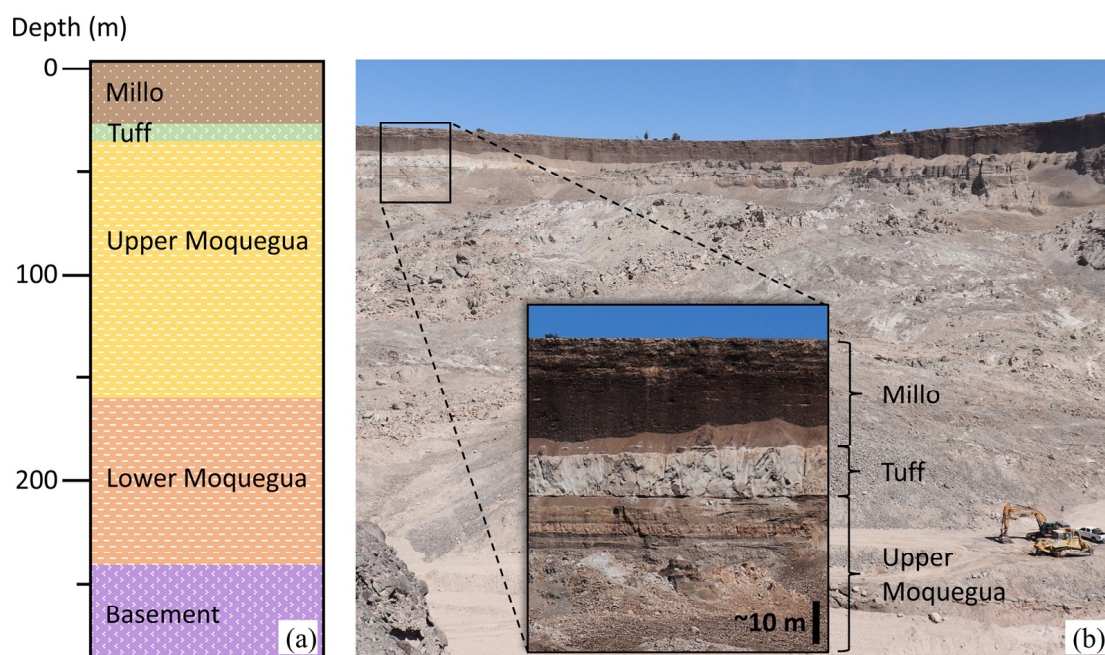


Figure 2. (a) Stratigraphic section showing the significant geologic formations beneath the Majes I agricultural development [3]. (b) Geological photograph of the stratigraphic section taken from the floor of the Sigwas River Valley (photographs taken by H. Flamme, adapted from [3]).

2.2.1. Moquegua Formation

The Moquegua Formation is a key geological unit in the study area. The uplift of the Andes during the Cenozoic Era created basins that were filled with sediments eroded from the mountains. The formation is a composite unit composed of continental sedimentary deposits accumulated in two distinct phases. These phases are separated by a regional tectonic event of low intensity. The lower phase consists of coarse, clast-supported conglomerates with a sandy matrix. These conglomerates form thick beds (50–150 m) and typically are interlayered with medium-grained arkose sandstones and reddish clays. The upper phase is differentiated by lighter colored rocks, likely due to the influence of volcanic ash [11].

The Moquegua Formation is widespread throughout the study area and forms the foundation of the southern Peruvian pampas. Dramatic exposures of the formation are

visible in the Majes, Siguas, and Vitor Valleys. The upper portion of the Moquegua Formation transitions gradually into younger alluvial deposits (Alluvial Structure or AS) that share similar materials with the upper conglomerates of the Moquegua Formation, but become progressively less consolidated and less cohesive towards the surface, transforming into unconsolidated gravel deposits. Locally, the pampas floor and depressions within the eroded surface of the upper Moquegua Formation are filled with accumulations of ancient, well-sorted sediments.

2.2.2. Alluvial Deposits

The Pleistocene conglomerates, a significant lithological unit in the area, rest atop the Moquegua Superior formation along the coastal pampas of Majes and San Juan de Siguas. This layer, with a thickness exceeding 50 m at locations, is asserted to have originated during periods of intense regional erosive activity associated with Quaternary Andean deglaciations. Comprising conglomerates embedded in a sandy and silty matrix, it features clasts ranging from 0.1 m to 1.0 m in diameter and exhibits a diverse composition of volcanic, sedimentary, and metamorphic origin. Predominantly found at the head of drainage lines and the foot of the Andean flank, these conglomerates vary greatly in size, ranging from large blocks to fine clay particles [11].

The Coastal Plain stands as the predominant physiographic feature characterized by extensive, flat surfaces formed from subhorizontal Cenozoic aged sediments. Moderately dissected by wide, shallow ravines that serve as tributaries to the Siguas River, the flat geofoms encompass the La Joya and Siguas Pampas. These areas feature gentle slopes interrupted by dry ravines and parallel drainage patterns, offering fertile grounds for agricultural development, particularly in the vicinity of the city of Arequipa [12].

Within this geological context, the Millo Formation emerges as a distinct feature. Distinguished from recent alluvia and similar formations, the Millo Formation is characterized by thick layers of gravel, boulders, and sand, interspersed with accumulations of ash lenses and aeolian deposits. While its compactness diminishes with increasing granulometry, caliche lenses within these deposits contribute to the overall structural integrity. Originating from erosive and depositional activities during glaciation and volcanism, the Millo Formation has been significantly impacted by the tectonic events of the last Quaternary period, shaping the landscape of the Siguas Pampas [13].

2.3. Caliche Deposits

Caliche is a sedimentary rock that forms as a hard crust in soil layers, predominantly composed of calcite [14,15]. It often includes other minerals such as silica, alumina, iron oxides, and phosphates. This formation occurs in arid and semi-arid environments where evaporation exceeds precipitation, leading to the deposition and cementation of these minerals. In agricultural settings, caliche is known for its role in hindering root penetration, water infiltration, and various essential soil processes that affect agricultural productivity [4].

The caliche in the Majes region of s Cenozoic Age outhern Peru primarily formed during the Pleistocene epoch under a cool and wet winter climate. During this period, extreme precipitation events, combined with the region's soil water-holding capacity and biological activity, facilitated the deposition of calcium carbonate. Local flora and fauna played significant roles in regulating soil CO₂ concentrations and evapotranspiration rates, further aiding in caliche formation.

To correlate geophysical data with caliche during the study, a trench was excavated with a length of 2.0 m and a depth of 1.3 m (Figure 3). In addition to providing visual ground truth for caliche presence within the testbed, samples of caliche collected around the site were analyzed at the Mineralogy Laboratory of the Faculty of Geology, Geophysics, and Mines at the National University of San Agustín of Arequipa (ML-FGGM-UNSA). Chemical analysis of caliche samples (Table 1) reveals the presence of sulfur trioxide, calcium oxide (quicklime), magnesium oxide, silicon dioxide, aluminum oxide, iron III oxide (hematite), and diphosphorus pentoxide.

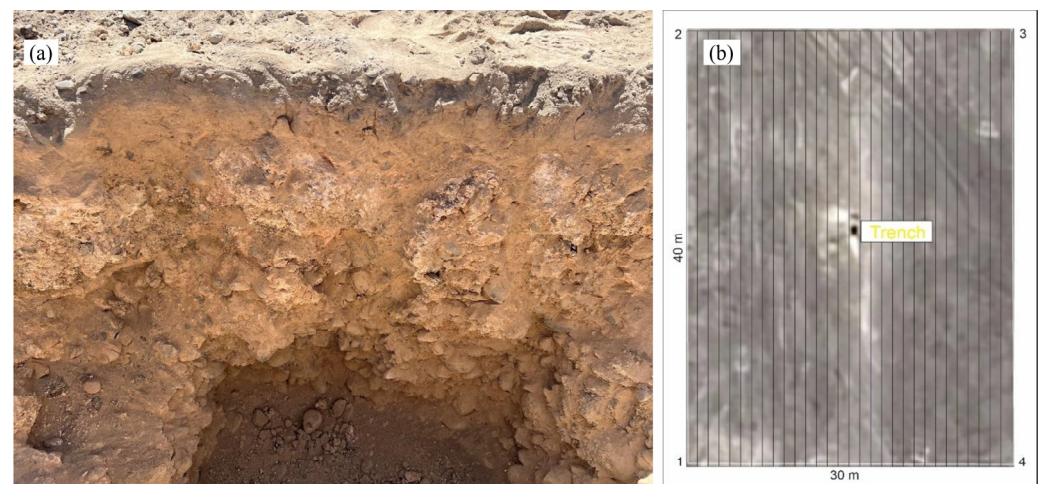


Figure 3. (a) Photograph of the trench made in the study area to observe the interface between the surface structure of sandy and clayey sediments (0.2 m thick) and the underlying heterogeneous caliche (white) that continues to the bottom of the trench (photograph taken by E. Gonzales). (b) GPR survey lines across the geophysical testbed.

Table 1. Results of analysis of caliche samples at the field site.

Mineral	Formula	%
Sulfur trioxide	SO ₃	47.22
Calcium oxide	CaO	30.34
Magnesium oxide	MgO	13.37
Silicon dioxide	SiO ₂	7.21
Aluminum oxide	Al ₂ O ₃	1.20
Ferric oxide (hematite)	Fe ₂ O ₃	0.33
Pentoxide diphosphorus	P ₂ O ₅	0.30

The observed compounds are relevant to the field study, as they provide insights into the physical properties that may influence the selection of geophysical methods such as GPR and FDEM. For example, GPR has the potential to detect caliche due to the high dielectric contrast between caliche and the surrounding materials, which can result in strong reflections in recorded GPR data. Additionally, relatively conductive materials will attenuate GPR signals with depth which may reveal the caliche presence and thickness. FDEM, likewise, has the potential to detect caliche layers by measuring the variations in electrical conductivity relative to the background geology as well as the magnetic susceptibility influenced by the mineral composition of caliche. At Majes II, previous electrical survey results [3] indicate that the background geology is highly resistive, perhaps indistinguishable from caliche within the FDEM quadrature data (a proxy for electrical conductivity distribution). However, the laboratory results confirming the presence of hematite indicate that the caliche deposits at Majes II may generate anomalies within the in-phase component of the FDEM data due to the complex magnetic properties of these elements.

3. Geophysical Testbed and Survey Methods

3.1. Geophysical Testbed

To perform the study, a shallow geophysical testbed was established at the Majes II site to assess the effectiveness of various geophysical techniques for exploration and mapping of the subsurface caliche deposits. The right panel of Figure 1 shows the testbed location that encompassed the 30 m × 40 m grid, rotated approximately 45° east of north. The site was established on a relatively flat surface characterized by the stony alluvial deposits, with the southeastern edge of the grid transected by a shallow erosional channel. This

natural trench exposed the otherwise buried caliche (Figure 4), providing a crucial ground truth validation of the presence of the cemented subsoils at the test site. This strategic combination of a controlled survey area with a natural caliche exposure offers a valuable setting to evaluate and refine near-surface geophysical exploration techniques for caliche detection and mapping throughout the Majes II area in general.



Figure 4. Geophysical testbed established atop the future Majes II agricultural site. A shallow erosional channel exposing caliche deposits was located immediately outside of the 30 m × 40 m survey grid (photographs taken by R. Krahenbuhl).

3.2. Frequency-Domain Electromagnetics

Frequency-domain electromagnetics (FDEM) uses electromagnetic (EM) fields to map variations in the subsurface conductivity and magnetic susceptibility material properties [16], and it has a long history of near-surface geophysical applications including mapping groundwater resources for sustainable water management, delineating soil contamination to guide remediation efforts, detecting buried objects for archaeological or forensic purposes, and characterizing geological structures to understand geological formations.

Non-invasive FDEM instruments for near-surface mapping, often called ground conductivity meters, operate by transmitting a controlled EM field without requiring contact with the soil. The method is often deployed within near-surface geophysical surveying, as it allows for rapid acquisition with dense datasets across diverse geological settings and relatively large areas.

3.2.1. FDEM Theory

The core principle behind FDEM lies in EM induction. The primary transmitted field interacts with the subsurface inducing eddy currents in conductive materials such as groundwater, metallic objects, and certain minerals. In turn, these currents generate a secondary EM field. By measuring the amplitude and phase of this secondary field and comparing it to the known and calibrated primary field, the FDEM method provides valuable insights into the variations in the subsurface electrical conductivity and magnetic property distributions.

The behavior of electromagnetic fields in the subsurface is governed by Maxwell's equations. In the context of FDEM, the relevant equation for the secondary magnetic field (H_s) induced by the primary magnetic field is given by:

$$\nabla \times H_s = \sigma E + \partial D / \partial t, \quad (1)$$

where σ is the electrical conductivity, E is the electric field, and D is the electric displacement field.

The depth of penetration (δ) of the FDEM signal is influenced by the frequency of the primary field and the electrical conductivity of the subsurface materials. It can be approximated by the skin depth formula:

$$\delta = 1 / \sqrt{(\pi f \mu \sigma)}, \quad (2)$$

where δ is the skin depth, f is the frequency of the primary field, μ is the magnetic permeability, and σ is the electrical conductivity. While depth ranges for near-surface FDEM instruments vary with site geology, Table 2 presents an approximate depth of investigation for the common Geophex GEM-2 conductivity meter and Geonics EM-31/38/34 units.

Table 2. Approximate depths of investigation versus frequency with FDEM **.

Instrument	Depth Range (m)
GEM-2	0.5–6
EM-31	0.5–6
EM-38	0.3–1.5
EM-34 (10 m separation)	7.5–15
EM-34 (20 m separation)	15–30
EM-34 (40 m separation)	30–60

** Note: DOIs are general, as they vary with site geology.

3.2.2. FDEM Application at Majes II for Caliche

This study uses the Geophex GEM-2 FDEM system, which is commonly deployed for shallow geophysical investigations. This lightweight and portable system (Figure 5) measures the in-phase and quadrature components of the secondary magnetic field at multiple frequencies to provide sensitivity to physical property distributions over a range of depths. The quadrature component reflects the degree to which the transmitted field is attenuated and how much of a secondary field is generated, ultimately revealing variations in the subsurface conductivity property distribution. Simultaneously, the in-phase component provides insights into the magnetic susceptibility, indicating how easily a material can be magnetized. Further information about the GEM-2 system can be found in [16].



Figure 5. GEM-2 FDEM survey above the caliche testbed at Majes II (photo by R. Krahenbuhl).

While data from the GEM-2 system can be inverted to generate subsurface models, many near-surface geophysical applications including mapping of caliche require minimal processing where anomalies within the resulting map visualizations serve as proxies for the locations of the desired targets. In this study, the target of interest is caliche presence within the surficial deposits of the Millo Formation.

The GEM-2 FDEM data acquired at the caliche testbed above the Majes II pampa were recorded continuously in a bi-directional pattern along the 40.0 m northeast-southwest survey lines with a 1.0 m line separation. Figure 5 shows the operation of the instrument oriented for horizontal coplanar (i.e., vertical dipole) data at a height of 0.3 m above the ground. In-phase and quadrature data were acquired simultaneously at three frequencies typical of shallow investigation: 18.33 kHz, 38.31 kHz, and 80.01 kHz.

3.3. Ground Penetrating Radar

GPR is a well-established geophysical method widely used for shallow subsurface exploration [17]. It uses high-frequency EM waves to probe the subsurface. When these waves encounter material boundaries with contrasting electrical properties (i.e., dielectric permittivity), a portion of the energy is reflected back to the surface and recorded by the receiver antenna, allowing for the reconstruction of subsurface features [18–20]. This scattering wave phenomenon makes GPR a powerful tool for detecting various features including cavities, buried pipes, and variations in soil composition [21]. In the context of soil studies, GPR “radargram” sections can be correlated with boundaries between different stratigraphic units or zones of structural disturbances [22]. GPR shares some similarities with zero-offset seismic methods in terms of information acquisition; however, GPR uses EM waves instead of seismic waves as the energy source [23]. Both methods share similarities in data processing techniques [23].

3.3.1. GPR Theory

GPR systems emit EM waves that travel through the subsurface at a velocity determined by the dielectric properties of the materials. The velocity (v) of the EM wave in a material is (approximately) given by:

$$v = c / \sqrt{\epsilon_r}, \quad (3)$$

where c is the speed of light in a vacuum (3×10^8 m/s), and ϵ_r is the relative dielectric permittivity of the material, a measure of the ability of a material to store a charge when an electric field is applied.

When the emitted EM waves encounter a boundary between materials with different dielectric constants, such as a layer of caliche within the surrounding soils, part of the energy is reflected back to the surface and part is transmitted through the boundary. The reflection coefficient (R) at normal incidence is given by:

$$R = (\sqrt{\epsilon_{r2}} - \sqrt{\epsilon_{r1}}) / (\sqrt{\epsilon_{r2}} + \sqrt{\epsilon_{r1}}), \quad (4)$$

where ϵ_{r1} and ϵ_{r2} are the relative dielectric permittivities of the two materials.

The depth of penetration (d) of GPR signals is influenced by the frequency (f) of the EM waves and the electrical properties of the subsurface materials. Higher frequencies provide better resolution but shallower penetration, while lower frequencies penetrate deeper but with lower resolution. The skin depth (δ) is a measure of how deep the EM wave can penetrate and is given by:

$$\delta = 1/\alpha, \quad (5)$$

where α is the attenuation constant:

$$\alpha = (\pi f \sqrt{\mu \sigma})/c, \quad (6)$$

with μ being the magnetic permeability, and σ being the electrical conductivity of the material. While the penetration depth and resolution of GPR data naturally depend on conductivity beneath the subsurface, i.e., the geology, Table 3 provides an approximate depth of investigation and resolution versus the selected GPR antenna frequency.

Table 3. GPR approximate depths of investigation and resolution versus antenna frequency.

Frequency (MHz)	Depth of Investigation (m)	Resolution (cm)
10–25	10–30	10–20
50–100	5–15	5–10
200–400	2–5	2–5
500–1000	0.5–2	1–3

Beyond its utility in geological investigations, GPR has proven successful in various environmental and agricultural studies due to its non-invasive nature [24]. Soil moisture content is a crucial parameter in fields like engineering, agriculture, and geoscience [25]. Because moisture content can affect various aspects of these disciplines, its accurate characterization is essential [26]. While GPR data can be valuable observations for this purpose, the complex and often heterogeneous nature of the subsurface routinely pose challenges for accurate moisture estimation [26]. Therefore, it is often beneficial to validate GPR results with other geophysical methods [27].

3.3.2. GPR Application at Majes II for Caliche

For this study, GPR data were acquired using a GSSI SIR 4000 model instrument (Geophysical Survey Systems, Nashua, NH, USA), known for its versatility and flexibility [28]. This system allows operation with both analog and digital antennas, catering to a wide range of applications and user needs. Due to the limited prior information about caliche characteristics and the sedimentary environment, two GPR antenna frequencies (350 MHz and 900 MHz) were chosen to balance depth penetration and spatial resolution for optimal caliche detection (Figure 6). The 350 MHz antenna offers greater penetration depth (here down to 4.0 m), but lower resolution, allowing for deeper profiling while still providing longer-wavelength details for near-surface characterization. The 900 MHz antenna prioritizes high-resolution imaging of shallower targets (here down to 1.5 m), but shallower depth penetration, and is suitable for applications like determining the thickness of surficial concrete or depth to shallow pipes. This higher frequency offers improved resolution for near-surface features relevant to caliche investigation, and thus, we selected data from the 900 MHz data for interpretation in the section below.



Figure 6. Ground penetrating radar (GPR) data being acquired above the caliche testbed using the GSSI system.

GPR data were acquired with the 900 MHz antenna over the testbed with 31 parallel lines of 40 m length sampled at an 0.04 m inline and 1.0 m crossline intervals. Each GPR trace was stacked four times and had a temporal sampling rate chosen to ensure that the total record length was about 2.5 m assuming a constant dielectric permittivity of 5.3 (dimensionless) for the dry soils [29].

4. Results

4.1. Frequency-Domain Electromagnetics

The GEM-2 FDEM data acquired provided valuable insights into the electrical and magnetic properties of the subsurface at the Majes II testbed as well as the ability of the method to map caliche at the site. Unlike GPR data, FDEM requires minimal processing before interpretation. The data were primarily leveled to remove heading errors associated with the bi-directional survey.

Figure 7 presents the leveled FDEM data for each frequency, displayed as separate data maps in a two-column format. The left and right columns present the quadrature and in-phase component data, respectively. Decreasing the frequency generally corresponds to increasing the depth of investigation. Coherent features within the data maps are interpreted as the response of caliche deposits within the background alluvium. The quadrature data (Figure 7, left column), which primarily exhibits variations in electrical conductivity, shows minimal coherent structure across all frequencies. This suggests that the FDEM instrument did not detect a significant contrast in electrical conductivity between the caliche and the surrounding alluvium. In the highly resistive environment at Majes II, the electrical properties of the caliche, likely influenced by the minimal clay content and dominated by minerals like calcite, may have small variations from the background alluvium. This weak quadrature data response provides limited insights into caliche presence or absence. Consequently, the FDEM quadrature component is unlikely to be a suitable tool for mapping caliche distribution within the shallow subsurface at Majes II.

In contrast, the in-phase component of the FDEM data (Figure 7, right column) displayed distinct coherent features, particularly at higher frequencies that correspond to shallower depths within the first 1.0 m below the surface. These coherent structures, indicated by the brown color, formed a distinct band with an approximately 10 m width that extended from the northeastern to the southwestern end of the survey grid over a length of approximately 25 m. This spatial correlation strongly suggests the presence of caliche deposits. The detection of these features in the in-phase component can be attributed to magnetic properties of the caliche, influenced by the presence of iron oxide (Fe_2O_3). The in-phase response was sensitive to variations in magnetic susceptibility, making it an effective approach to identifying a caliche layer that exhibits higher magnetic properties than when compared to the surrounding alluvium at the Majes II site.

4.2. GPR Survey

GPR data processing was conducted using the cloud-based Geolix software (<https://www.geolix.com/>, accessed on 8 June 2024) platform that leverages cluster computing and machine learning for data analysis [30]. Following initial tests at the geophysical testbed and considering the predominantly dry soil conditions at the future Majes II site, the processing parameters were set with a propagation velocity of 0.13 m/ns and a constant dielectric permittivity value of 5.3 (dimensionless).

The resulting GPR data reveal valuable insights into the subsurface composition at the Majes II testbed and, by extension, demonstrate the potential of the method to map out caliche throughout the site. A distinct near-surface reflection, observed in radargrams presented in Figures 8 and 9 and estimated to be approximately 0.1 m thick, corresponded to an upper sandy and clay layer beneath the line. Below this, a strong reflection was interpreted as the caliche deposit, with an average thickness of approximately 0.4 m within the section. The presence of caliche gradually diminished at greater depths, with the underlying materials transitioning to predominantly conglomerate with a heterogeneous

distribution. The radargram was aligned with a photo of the trench, highlighting the caliche layer. Regions of relative heterogeneity and high-amplitude diffractions in the radargram corresponded to the presence of caliche, providing visual confirmation of the caliche layer's presence, position, and thickness. This alignment with the trench data supported the results of the GPR survey and served as a reasonable validation in the absence of additional soil profiles.

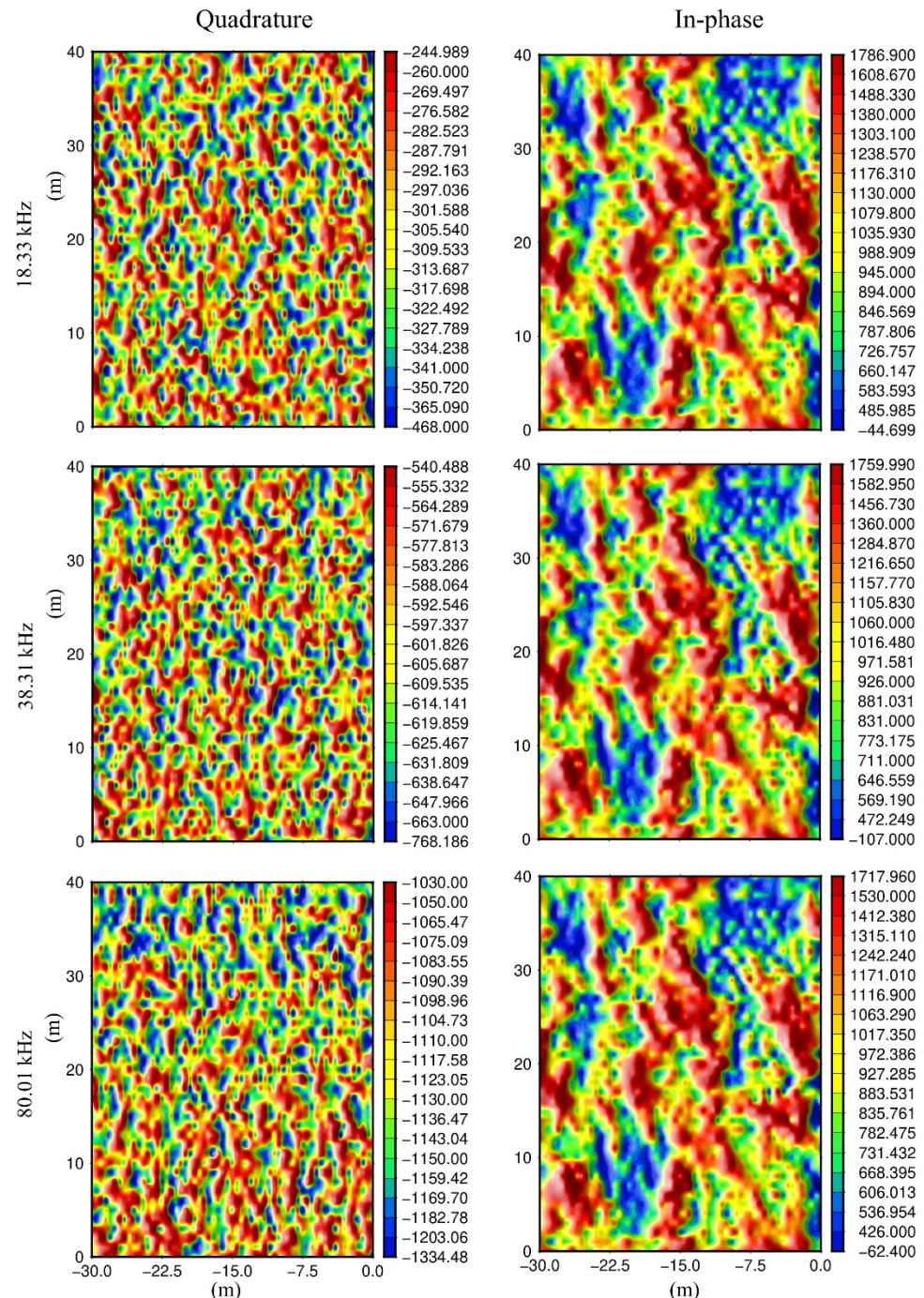


Figure 7. GEM-2 FDEM data maps at the caliche testbed at three frequencies: 18.33 kHz, 38.31 kHz, and 80.01 kHz. The left and right columns provide maps of the quadrature and the associated in-phase data for each frequency.

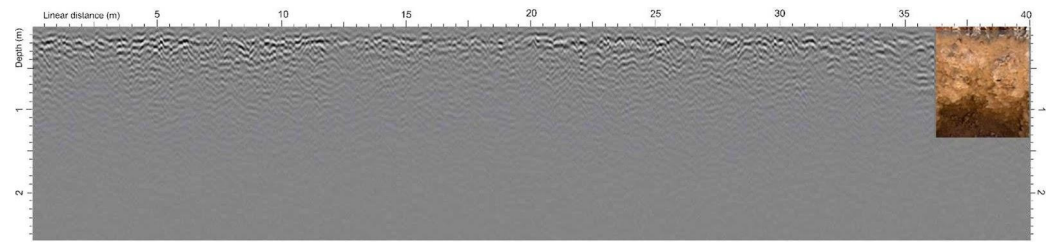


Figure 8. GPR radargram from the 900 MHz antenna showing a 40 m-length and 2.5 m-deep profile slice through the GPR survey area. A photo of the trench is aligned with the radargram which highlights the caliche layer. Regions of relative heterogeneity and high-amplitude diffractions correspond to the presence of caliche.

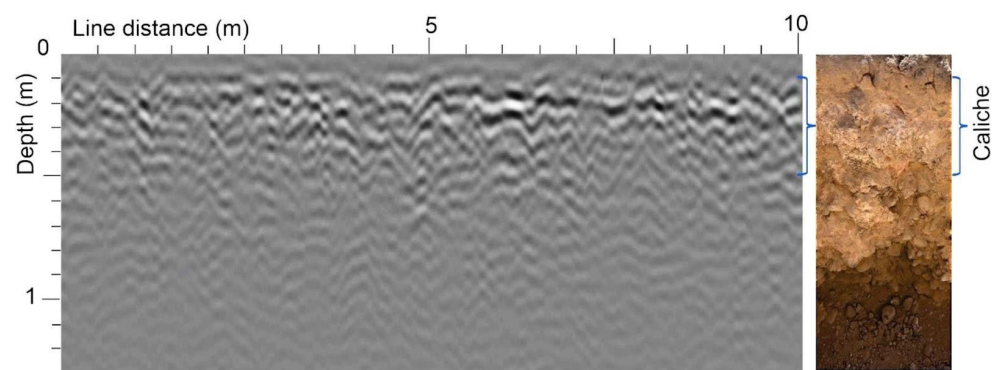


Figure 9. Zoomed-in radargram section, 10 m long and 1.4 m deep, for the improved definition of the GPR data. The surface layer of sandy clay materials was approximately 0.1 m thick. Below this, the caliche layer was identified, with an average thickness of approximately 0.4 m. The trench photo is aligned with the GPR data, illustrating the correlation between radar reflections and the caliche layer.

Compiling the individual 2D lines into a single regularized 3D data volume allowed us to analyze 2D GPR magnitude maps generated at different depth slices within the caliche zone. As an illustrative example, Figure 10a shows a detailed spatial 2D map view of caliche distribution at an average interpreted depth of 0.40 ± 0.05 m with the hotter (cooler) colors indicating weaker (stronger) normalized magnitudes. A striking feature on this map is the spatial pattern of the low magnitude responses associated with attenuated GPR signals through a relatively conductive and shallow caliche layer. This variation in normalized magnitude underneath the strong caliche response at 0.40 m depth is likely associated with caliche thickness. A thicker layer of conductive caliche would attenuate the signal more than a thinner layer.

The identification of caliche using GPR, as evidenced by distinct reflections and zones of significant differential amplitude contrast within the targeted depth range, demonstrates the effectiveness of this geophysical technique for caliche detection at the testbed site. The detailed characterization of the caliche layer's thickness and spatial distribution, achieved through GPR surveying, suggests its potential as a valuable tool for mapping caliche across the broader Majes II site.

4.3. Integrated Interpretation

To gain a comprehensive understanding of the geophysical methods employed to detect and map subsurface caliche distributions, we integrated the results from both GPR and FDEM surveys. Figure 10 illustrates this integration, with Figure 10a displaying a GPR depth slice at approximately 0.4 m beneath the surface and Figure 10b showing the 63.03 kHz in-phase FDEM data.

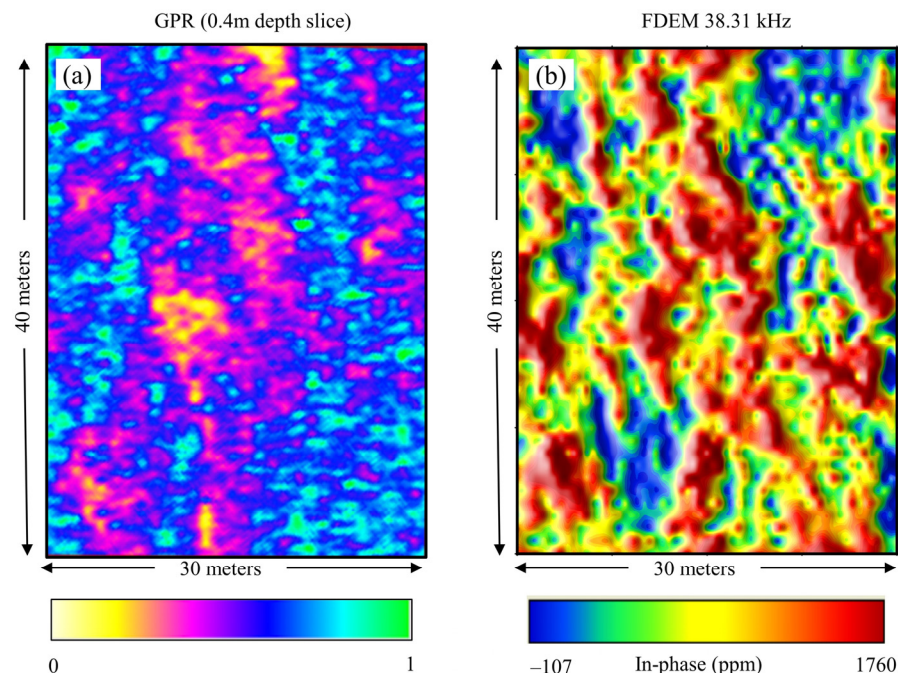


Figure 10. Comparison of GPR (a) and FDEM (b) data showing consistent structure beneath the geophysical testbed. In (a), the hot (cool) colors indicate lower (higher) normalized magnitudes averaged over a 0.1 m window at about 0.4 m depth. The features correlate well across the two methods and are consistent with the presence of caliche at a depth of approximately 0.4 m beneath the surface.

The spatial correlation observed between the GPR and FDEM data sets confirmed the presence and continuity of the caliche layer. In the GPR image, a distinct boundary with weak responses (indicated in pink) was located beneath the relatively conductive caliche layer. The in-phase FDEM data, sensitive to magnetic susceptibility, aligned with these features, likely due to the presence of iron oxides (Fe_2O_3) and other minerals affecting the magnetic properties. This correlation supports the hypothesis that the caliche layer composition, including elements such as Fe_2O_3 , CaO , and MgO , influences both the GPR and FDEM signatures. The use of integrated GPR and FDEM data sets enhanced the accuracy of caliche detection and mapping, providing a reliable method for understanding the extent and properties of the caliche layer in the study area.

Figure 10 serves as a crucial piece of evidence in demonstrating the effectiveness of integrated geophysical methods for subsurface investigations when possible. The consistent patterns observed in both datasets reinforced the identification and spatial characterization of the caliche layer, facilitating better informed decisions for agricultural and construction activities in regions where caliche is prevalent.

5. Discussion

This study investigated the utility of near-surface geophysical techniques for mapping caliche deposits in the context of agricultural development at the Majes II site in southern Peru. The findings demonstrate the effectiveness of both high-frequency GPR and FDEM data sets in characterizing the presence, thickness, and depth of caliche within the subsurface.

5.1. GPR for High-Resolution Caliche Imaging

GPR data revealed reflectivity corresponding to the caliche layer, enabling the estimation of its thickness and depth with high resolution. The distinct reflections from the caliche–soil interface highlight GPR’s capability to effectively capture contrasts between caliche and surrounding materials in profile and map-view. This high-resolution imaging capability is particularly valuable for detailed mapping of caliche variations and identifying

zones potentially more or less favorable for agricultural activities, which is consistent with previous work carried out by Afshar and others [31]. Afshar et al. demonstrated the utility of GPR in detecting subsurface features with high precision, reinforcing our findings that GPR can reliably characterize caliche layers. A study by Kruse et al. [32] further supports this finding, demonstrating that GPR can penetrate to a depth of approximately 2 m and resolve the base of caliche layers, underscoring its effectiveness in similar arid environments [32]. Additionally, a study by Martínez and Byrnes [29] highlighted the utility of GPR in soil mapping by modeling dielectric-constant values of geologic materials, aiding in the interpretation of GPR data for various subsurface features.

5.2. FDEM for Efficient Caliche Delineation

FDEM data provided valuable insights into the spatial distribution of caliche across the geophysical testbed. The strong amplitude responses within the targeted depth range corroborated the presence of caliche, while the faster rate of data acquisition and reduced processing time compared to those with GPR offer advantages for larger-scale surveys. While FDEM offers lower resolution compared to GPR, it is a time-efficient tool for initial caliche detection and guiding more targeted GPR surveys in areas of interest. The results are consistent with the previous work of Minsley et al. [33] who demonstrated the effectiveness of the GEM-2 instrument in soil mapping, highlighting its multi-frequency capabilities for detailed subsurface characterization. Additionally, extensive field applications of the FDEM, as reported by Ground-Spec [34], have shown its utility in mapping soil electrical conductivity, which is crucial for identifying soil type variations and salinity levels. Sams et al. [35] conducted a study using the GEM-2 to monitor subsurface drip irrigation systems, demonstrating the instrument's effectiveness in detecting changes in subsurface electrical properties related to irrigation practices.

5.3. Integration for Comprehensive Caliche Mapping

The combined application of GPR and FDEM offers a comprehensive approach to caliche mapping. GPR's high resolution allows for detailed characterization of caliche thickness and variations, while FDEM's efficiency facilitates rapid delineation of caliche presence across larger areas. This collaborative approach can optimize data collection efforts, providing a more complete understanding of the subsurface caliche distribution critical for agricultural development planning. Integration of multiple geophysical methods to enhance subsurface characterization has become common practice in all fields of application including, but not limited to, karst systems [36], geotechnical hazards [37], geologic interpretation [38], and reservoir monitoring [39].

5.4. Implications for Agricultural Development

The accurate mapping of caliche using GPR and FDEM methods holds significant implications for agricultural development at Majes II and similar regions that face challenges associated with caliche. By identifying areas with favorable caliche thickness or absence, land managers can make informed decisions about crop suitability and resource allocation. In areas with thicker or more extensive caliche presence, targeted interventions (e.g., deep ripping or subsoiling techniques) can be implemented to mitigate the negative effects of caliche on root penetration, water infiltration, and overall crop productivity. Studies by Bolan et al. [4] and Mettier et al. [7] have shown that understanding soil constraints and applying appropriate soil management techniques can significantly enhance agricultural productivity, reinforcing the importance of our findings.

5.5. Future Research Directions

Future research efforts could involve expanding the geophysical surveys across a broader area at Majes II to create a comprehensive caliche distribution map. Additionally, correlating geophysical data with broader core samples or trenching across the pampa for physical verification of caliche properties would further strengthen the interpreta-

tions and applicability of these geophysical methods for agricultural development in this caliche-prone environment. Investigating the economic benefits of using these geophysical techniques could provide valuable insights into their cost-effectiveness and long-term impact on sustainable farming practices.

6. Conclusions

This study demonstrates that high-frequency GPR and FDEM are effective complementary geophysical tools for accurately mapping caliche deposits, which is crucial for agricultural development in areas like southern Peru. GPR provides detailed imaging of caliche layers, including their thickness and depth, while FDEM efficiently identifies caliche over larger areas. Using both GPR and FDEM enhances our understanding of caliche distribution, which is essential for making informed decisions about land use. This combined approach not only improves the accuracy of caliche detection, but also helps optimize resource use by guiding targeted interventions, such as deep ripping, to reduce the negative impacts of caliche on crop productivity.

The primary way in which these geophysical methods benefit agricultural productivity is by enabling focused soil management. Knowing the location and depth of caliche layers allows for targeted soil treatments, which improve soil structure and water retention and facilitate better root growth and water infiltration. Future studies should aim to expand geophysical surveys to cover more areas within the Majes II site and correlate geophysical data with direct soil sampling and other validation methods. Additionally, exploring the economic benefits of these geophysical techniques could provide insights into their cost-effectiveness and long-term impact on sustainable farming practices.

In summary, this study highlights the importance of integrating advanced geophysical methods in modern agriculture. By providing a reliable framework for mapping and managing caliche deposits, these techniques support sustainable agricultural development and improve productivity in regions affected by caliche.

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