INTEGRATION OF NEAR SURFACE COMPLEMENTARY GEOPHYSICAL TECHNIQUES FOR THE STUDY OF ANCIENT ARCHAEOLOGICAL AREAS IN THE ATACAMA DESERT CASE STUDY: ILUGA ARCHAEOLOGICAL SITE, NORTHERN CHILE

FERNANDA ANDREA GALLEGOS POCH

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering.

Advisor:
GONZALO YÁÑEZ CARRIZO

Santiago de Chile, (June, 2022)
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I want to dedicate this thesis to my past self, because when I started, I didn’t think I was capable of doing it and to my future self, because I will always have this to remember that I am.
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RESUMEN

La geofísica somera ha demostrado ser una herramienta de gran utilidad para la caracterización de sitios arqueológicos debido a su capacidad de cubrir grandes superficies en cortos períodos de tiempo obteniendo datos de alta resolución para mapear objetos y estructuras en profundidad. Esto permite caracterizar diversas propiedades del subsuelo y definir zonas anómalas claves para las excavaciones, limitando así la destrucción del sitio. En ambientes hiper áridos, las técnicas utilizadas para la caracterización de sitios arqueológicos se ven afectadas por el bajo contenido de humedad del subsuelo complejizando el estudio de estos.

El presente estudio propone la integración de 3 equipos geofísicos: ‘Ground Penetrating Radar’ (GPR), un equipo electromagnético de inducción (EMI) y un equipo de tomografía sísmica de alta resolución (HRST), para la caracterización de estructuras circulares alineadas en dirección EW que atraviesan al sitio arqueológico de Pampa Iluga, ubicado en la Pampa del Tamarugal (Desierto de atacama). El GPR fue capaz de reconocer depósitos aluviales y el relleno eólico de las estructuras circulares, alrededor de las cuales se encontraron raíces reconocidas como hipérbolobas en la señal. Por otro lado, para el caso del equipo EMI, la componente de in-phase, normalmente desestimada, pudo identificar la presencia de cenizas y zonas quemadas asociadas a un alto local de susceptibilidad magnética. Finalmente, la HRST reconoció el relleno eólico como un bajo de velocidad de la onda sísmica y anomalías puntuales de alta velocidad que se asocian a las raíces en profundidad.

De acuerdo a lo anterior y corroborado por la excavación realizada en el sitio, las estructuras circulares son el resultado de un extenso proceso de deforestación ocurrido en la Pampa del Tamarugal, donde se extrajo tanto del tronco como de las raíces de algarrobos (Prosopis chilensis) o tamarugos (Prosopis tamarugo) probablemente para la producción de carbón. La metodología geofísica propuesta, entrega resultados prometedores para estudios de sitios arqueológicos en ambientes hiper áridos.

Finalmente, una vez reconocida la presencia de árboles en el sitio, se estimaron sus tasas de evapotranspiración mensuales y anuales para determinar la necesidad aproximada de
agua de los árboles que habitaron el sitio. Eventos pluviométricos ocurridos en los últimos 18,000 años, habrían generado las condiciones climáticas e hidrológicas que permitieron el desarrollo de los árboles en el sitio, lugar que hoy es hostil y no permitiría su desarrollo debido a la ausencia de agua en superficie y la profundidad de la napa subterránea.

Palabras Clave: Arqueogeofísica, GPR, EM38, Desierto de Atacama, Zona hiper árida, deforestación.
ABSTRACT

Near surface geophysical techniques are useful for the characterization of archaeological sites because of their ability to rapidly cover large areas and obtain high resolution data to identify the location for archaeological excavations. In hyperarid environments, however, usual techniques may fail to obtain the expected results due the dry near surface.

This study proposes an integration of ground penetrating radar GPR, an electromagnetic induction EMI technique and a high-resolution seismic tomography (HRST) to elucidate the origin of thousands of aligned circular features at the Pampa Iluga archaeological site in the Atacama Desert, one of the driest places on Earth. The GPR was useful to recognize alluvial deposits, sandy aeolian filling in pre-existing holes right underneath the circular features, and roots. EMI in-phase component, usually considered a complementary result, was useful to identify fireplaces. Nevertheless, with respect to the HRST technique, further studies and measurements will be needed in order to understand the results, however, as a first approximation, the equipment might have been able to recognize the aeolian filling of the circular features and recognize the roots in depth.

These geophysical findings were verified with an excavation. It has been interpreted that the circular features resulted from an extensive deforestation process in the Pampa del Tamarugal, and the extraction of both trunk and roots of algarrobos (Prosopis chilensis) or tamarugos (Prosopis tamarugo) likely for charcoal production. The proposed methodology delivers promising results for archaeo-geophysical studies in hyperarid dry environments.

Finally, a preliminary estimation of the evaporation rate was performed to determine the approximate water necessity associated with the presence of the trees in the site. Past pluvial events in the last 18 kyr would have generated climatic conditions that are more favorable than today’s which allowed the presence of these trees in Pampa Iluga.

Keywords: Archaeo-geophysics, GPR, EM38, Atacama Desert, deforestation.
1. CHAPTER 1: INTRODUCTION

This section seeks to provide the reader with a complete idea of the carried-out research and the main conclusions of the master's thesis. For this, a bibliographic review provides context to the research, from which the hypotheses and objectives are proposed. To fulfill these objectives a specific methodology is presented followed by the results and discussion subsections, ending with final conclusions and future works.

1.1 Bibliographic Review

1.1.1 About Near-surface geophysics and hyperarid environments

Geophysics allows characterizing underground features, such as structures, bodies, and geological processes at different scales of depth (from meters to kilometers), through non-invasive measurements usually taken from the surface (Reynolds, 2011; Everett, 2013; Binley et al. 2015). By the use of different techniques (e.g. gravity, magnetism, electricity or seismicity), the contrasts between the physical properties of the objects of interest and the surrounding materials can be determined (Telford et al. 1990; Simpson et al. 2008; Reynolds, 2011; Dentith and Mudge, 2014), which provides information about the location and the physical/chemical attributes of the objects (e.g. moisture content, porosity, mineral composition, etc.) (Romero-Ruiz et al. 2018; Carrière et al. 2020). Each technique is sensitive to different physical properties and, consequently, suitable to the objectives of the study, depending, for example, on (i) the contrast between the physical properties of the object of interest and the surrounding environment setting, (ii) the measurement resolution or (iii) the accessibility to the site. Ideally, different techniques
should be implemented, and the results combined for a proper characterization of complex systems (Piro et al. 2000; Johnson et al. 2006; Dalan, 2008; Scardozzi et al. 2012; Binley, et al. 2015; Deiana et al. 2018, Romero-Ruiz et al. 2018).

Since the 2000's, near surface geophysics has increasingly developed due to its key role in different scientific areas, such as archaeology (Piro et al. 2000; Witten et al. 2003; Santos et al. 2009; Scardozzi et al. 2012; Casas et al. 2018; Deiana et al. 2018; Urban et al. 2019; Colombero et al. 2021), agriculture and subsurface hydrology (Sudduth et al. 2001; Bramley et al. 2011; Binley et al. 2015; Alani and Lantini, 2019; Carrière et al. 2020; Araya Vargas et al. 2021), or construction (Grote et al. 2002; Artagan et al. 2019; Shapovalov et al. 2019; Tosti and Ferrante, 2019), because of its ability to solve problems within the first meters of depth using high spatial resolution data (Osella et al. 2005; Reynolds, 2001; Deiana et al. 2018).

Implemented techniques continue to improve in sensitivity and acquisition speed (Deiana et al. 2018) and the use of mobile platforms and automatic GPS positioning has allowed them to cover larger areas in shorter periods of time (Colombero et al. 2021; dal Bo et al. 2021). These advances and the integration of multiple geophysical methods has led to a more efficient detection of small-scale anomalies (e.g. archaeological materials, roots, steel bar) associated with buried objects or structures, without disturbing the surface (Piro et al. 2000; Reynolds, 2011; Deiana et al. 2018) which is of particular interest in the field of archaeology.

Indeed, near surface geophysics techniques allow, in a non-destructive way, to cover wide areas an accurately identify buried archaeological materials, and so to propose suitable and spatially limited excavation works (Santos et al. 2008; Fassbinder, 2016; Casas et al.
The most employed techniques for archaeo-geophysical studies are the ground penetrating radar (GPR), electrical resistivity tomography (ERT) and magnetic measurements (Johnson et al. 2006; Everett, 2013; Casas et al. 2018; Deiana et al. 2018). Nevertheless, because of the variety of environments in which archaeological sites are emplaced, site-specific methodologies are needed to characterize each one of them.

A specific challenge is faced when measuring in hyperarid dry environments. Due to scarce rain and high evaporation demand, the moisture content in the ground is very low or even nil. Hereafter, “hyperarid dry environments” are defined to make the distinction from areas in hyperarid regions, where stream discharges or groundwater outflows locally (partially) saturate the soils.

For geophysical studies in hyperarid environments, GPR measurements will benefit from the low electrical conductivity of the soil (Everett, 2013; dal Bo et al. 2021; Romero-Ruiz, et al. 2018), allowing a deeper penetration of the signal and obtain better-quality results. On the contrary, ERT measurements are impractical because the injection of electricity into the ground is difficult, due the high contact resistance between the electrodes and the ground that severely hampers good quality direct current (DC) measurements (Wait, 1982; Reynolds, 2011; Lictevout et al. 2020). Therefore, to measure the electrical properties in hyperarid environments, geophysical studies usually implement transient electromagnetic (TEM) methods (Ruthsatz et al. 2018; Viguier et al. 2018; Blanco-Arrué et al. 2022), nevertheless, the poor resolution that is expected in the first few meters of depth makes TEM methods unsuitable for near-surface archaeological exploration that require surface resolutions of less than tens of meters.
On the other hand, electromagnetic induction (EMI) techniques can measure the apparent electrical conductivity and magnetic susceptibility of the underground (Simpson, et al. 2008; Heil and Schmidhalter, 2019; Tang, et al. 2018), without requiring soil contact (Visconti and De Paz, 2020), delivering a robust method capable of replacing ERT and magnetometer measurements. For the first case, apparent electrical conductivity measurements in dry soils are not ideal because low conductive environments could deliver poor results due to the lack of property contrasts, which is the reason why authors like dal Bo et al. 2021 have considered this equipment as a second priority method in these environments. Nevertheless, the magnetic component of the signal can recognize thin horizontal layers of magnetically susceptible materials and is independent of other magnetic sources at larger depths, contrary to the magnetometer principle (potential method), making it a promising technique for near surface magnetic studies in hyperarid dry environments (McNeill, 2013).

The use of other geophysical techniques like seismic tomography for archaeological studies is less common (Vafidis et al. 1995), associated with the difficulty to distinguish the shallow depth archaeological targets (Leucci et al. 2007), and the lower data acquisition rate (Arciniega-Ceballos, 2009) compared to GPR or EMI equipment.

The lack of a wide choice of geophysical techniques for the non-invasive near-surface archaeological exploration in hyperarid dry environments limits the proper characterization of the site and the identification of buried objects or structures, risking the sites preservation. Therefore, an integrated geophysical methodology able to characterize archaeological sites in hyperarid dry environments, would be useful to study for example, the numerous archaeological sites (Grosjean et al. 2005; Latorre et al. 2013)
present in the Atacama Desert (Northern Chile), which extend across the pampa over large extensions, or other archaeological sites worldwide in hyperarid dry environments (e.g. Göbekli Tepe (Turkey), Astana cementery (China), Gobero archaeological site (Niger)).

1.1.2 The Pampa Iluga Archaeological site

Geological and historical framework in the Pampa del Tamarugal

The Pampa Iluga archaeological site is located at 20°S in northern Chile in the Pampa del Tamarugal (Atacama Desert) between 1100 and 1150 m.a.s.l., between the villages of Huara and Tarapacá (Fig. 1.1). The Atacama Desert is characterized by a hyperarid climate with an average annual precipitation of less than 10 mm/yr, below 2000 m.a.s.l, and a high potential evaporation reaching around 2500 mm/yr (Houston, 2006; Viguier et al. 2018), which makes this area one of the driest places on Earth (Garreaud et al. 2003; Houston and Hartley, 2003; Houston, 2006).

The archaeological site is in the basin floor of the Central Depression in an abandoned alluvial fan of the Quebrada de Tarapacá (Fig. 1.1b and 1.1c). The lithological setting is characterized by a several hundred meters thick of late Miocene and Quaternary sequence of un- or poorly consolidated non-marine siliciclastic deposits composed from clast-supported gravels, immature sandstones, silt sheet flood deposits and aeolian features (Farias et al. 2005; Hartley and Evenstar, 2010; Jordan et al. 2010, 2014). Alluvial materials deposited in alluvial fans are transported by high-magnitude floods and result from both climatic and tectonic factors (Hartley & Evenstar, 2010; Jordan et al. 2010, 2014; Armijo et al. 2015; Evenstar et al. 2017; Carretier et al. 2019).
Figure 1.1: Context of the archaeological site. (a) distribution of the dryland and location of the archaeological site in the South American and Chile context, (b) Google Earth view of a section of the Pampa del Tamarugal and central depression between -20.5° and 20° with important cities and geological attributes of the area, (c) Google
Earth view of the archaeological site, red points indicate the circular features aligned on EW semi-parallel segments.

In the study area, shallow layers are considered as entirely dry. Indeed, in addition to the aforementioned hyperarid condition and the disconnection of the Pampa Iluga archaeological site from the current ephemeral drainage areas (Fig. 1.1b and 1.1c), the regional unconfined Pampa del Tamarugal Aquifer, mainly recharged by perennial and ephemeral stream-losses in the Andean Piedmont (Houston, 2003; Jordan et al. 2014; Barnard and Dooley 2017; Viguier et al. 2018, 2019a), shows a thick vadose zone (~50 m) that prevents upward capillary flows from the water table up to the ground surface.

The human activities in the Pampa del Tamarugal span around 13 kyr with several discontinuities associated with wet-dry hydroclimate variations (Gayo et al. 2012; Sáez et al. 2016; Morales et al. 2020) and the resulting changes in both the available resources provided by the environment and the human adaptive strategies (Gayo et al. 2015; Sáez et al. 2016; Santoro et al. 2017).

With respect to the environmental changes, specific pluvial events in the last 18 kyr like the central Andean Pluvial Event (CAPE) or the common El Niño Southern Oscillation (ENSO) (Placzek et al. 2009; Gayo et al. 2012), increased the availability of water during periods of thousands-hundreds of years for the CAPE and tens of years in the case of the ENSO. These events happened between 17.4-14.2, ~11.8 and 1.1-0.7 ka and transformed the Pampa ecosystems characterizing them by forests of P. Tamarugo and Distichlis spicata and facilitating biotic exchange between the highlands and lowlands (Gayo et al. 2012).
On the other hand, the use of seabird guano to fertilize crops (Santana-Sagredo et al. 2021), the deviation of perennial streams in the Andean Piedmont (Barnard and Dooley, 2017) and the opportunistic use of ephemeral surficial water resources during rainy events (Santoro et al. 2017), converted the Pampa del Tamarugal into a fertile, productive, and nutritious area (Santoro et al. 2017; Uribe et al. 2020b; Urrutia et al.). This environmental setting allowed the growth of quinoa, beans, maize, pumpkin, and helped the survival of trees such as the *Prosopis tamarugo* (locally known as tamarugo) and *Prosopis chilensis* (locally known as algarrobo) (Calderon et al. 2015; McRostie, et al. 2017; Uribe et al. 2020 a, b). These species have been a relevant source of food and wood to the communities (Santoro et al. 2016; McRostie, et al. 2017; Rivera-Diaz, 2018) where the *P. tamarugo* gave the name to the Pampa del Tamarugal (Barnard et al. 2017).

The northern Chile socio-economic activities from the Spanish conquest until present day, have been mainly focused on the extraction of mining resources (copper, saltpeter, gold, lithium, among others) modifying the socio-environmental systems of the Pampa del Tamarugal (Santoro et al. 2017; Rivera-Diaz, 2018), and so the availability of natural resources like water (Oyarzún & Oyarzún, 2011; Santoro et al. 2018; Calderon et al. 2015; Viguier et al. 2019b).

To satisfy the increasing demand of charcoal-derived energy, the massive felling of trees started in the sixteenth century for blacksmiths, brickyards, lime manufacturing and bakeries and it was intensified during the nineteenth century for the saltpeter industry.

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(Mendizábal, 1808 in Hidalgo, 1985). During the late twentieth century, the Chilean National Park Service (CONAF) implemented a strategy to reforest the area and preserve stands of *P. tamarugo* and *P. chilensis* (CONAF, 1997), however they are today endangered by the water table drop of the Pampa del Tamarugal aquifer (Chávez et al. 2013, 2016; Calderón et al. 2015; Decuyper et al. 2016; Viguier et al. 2019a).

The aligned Pampa Iluga circular features and some likely assumptions

During the fieldworks conducted in Pampa Iluga by the multidisciplinary group working in the FONDECYT N°1181829 between 2019 and 2021, ca. 4000 circular features were identified, and mapped with the aid of satellite images (Fig. 1.1c). These features are mainly aligned on several EW-oriented semi-parallel segments, reaching up to six kilometers in length in the proximity of the archaeological site and are spatially oriented towards the apex of the Quebrada de Tarapacá alluvial fan, where the stream is still perennial before to entirely infiltrate in the active alluvial fan (Fig. 1.1.c). These circular features are separated from each other by approximately one meter, and can have a well-drawn circular, oval or crescent moon shape with intern diameters ranging from 3 to 5 meters, with a ground surface infill of aeolian sandy deposits (Fig. 1.2). The outer part is composed by coarse alluvial materials (gravel and sand) that overlap pre-existing agricultural fields made up from partially eroded loam deposits at the ground surface, due to “recent” aeolian and runoff erosion processes (Fig. 1.2). These non-natural deposits sequences, stratigraphic inconsistencies together with the observation of circular forms aligned on kilometric-size segments allow us to discard any natural origins, but rather man-made excavation works.
Nevertheless, the reason for these excavations remains unknown and undescribed in both literature and regional memory of inhabitants.

Figure 1.2: Google Earth view of the EW alignments through the archaeological site. (a) Google Earth view of the EW features in the studied area (b) photograph of the EW alignments in the studied area, (c) and (e) present a Google Earth view of the EW alignment through the archaeological site (See Figure 1c to locate them), (d) and (f) present pictures of (c) and (e) satellite views respectively.

1.2 Hypothesis

Two plausible hypotheses to explain the origin of these EW alignments are postulated:
The first one consists in assuming that the observed circular features are shaft-wells of a buried *puquios* (or *socavón*) system (regional name for *qanat*) (Fig. 1.3a), i.e., an underground canal where gravity-driven groundwater flows are conducted from hillslopes up to agricultural fields in the basin floor (Beaumont, 1971; Nasiri and Mafakheri, 2015; Lictevout et al. 2020). Such hydraulic systems are present ca. 70 km further South at Pica and Puquio Núñez (Dingman & Galli, 1965; DGA, 2012; Lictevout et al. 2020) (Fig. 1.1b and 1.3b). Nevertheless, the absence of historical sources referring to puquios in the Pampa Iluga area, unlike those of Pica and Puquio Núñez (Dingman & Galli, 1965; Salazar et al. 1998; DGA, 2012) and, especially, the absence of underground canal outputs, usually shaped by artificial pools, lead us to assume that this first hypothesis might not be the right one.

As a second hypothesis, it is proposed that these circular features are evidence of past productive processes of natural resources like wood (tree felling), between the sixteenth and nineteenth century, to satisfy the increasing demand of charcoal-derived energy in northern Chile (Zelada, 1986; Castro Castro, 2020). Therefore, the circular features would represent the location of the trees (Fig. 1.3c and 1.2d) before they were cut down.

It is postulated that the integration of suitable geophysical techniques such as GPR, an electromagnetic induction equipment (EMI) and a High-Resolution Seismic Tomography (HRST) will deliver the necessary information to discriminate between both working hypothesis and determine what the alignments are.
Figure 1.3: (a) Satellite view of the Puquio Núñez puquios’ system. Circular structures are aligned in a NE-SW direction and flow into an oasis that sustains a small agricultural area downstream, (b) picture of the puquios’ system mouth, (c) picture of multiple Tamarugos in the Pampa del Tamarugal (source: CONAF), (d) picture of a fully grown and healthy Tamarugo in the Pampa del Tamarugal (source: CONAF).
1.3 Objectives

In accordance with the proposed hypotheses, the main objective of the present thesis is to determine what these EW alignments are and the hydrogeological context that allowed their devolvement.

In order to achieve the main objective specific ones are presented:

1. Develop a geophysical approach to study near-surface archaeological features in hyperarid dry environments

2. Determine the hydraulic threshold that allowed the development of this features

The use and validation of these geophysical techniques presents a new approach and provides interesting insights for the non-invasive large scale archaeology studies in hyperarid dry environments, and also for analogous research aims like extraterrestrial planetary exploration (e.g. Fernández-Remolar et al. 2013; dal Bo et al. 2021).

1.4 Methodology

Field campaigns were carried out between 2019 and 2021 in an area of 2.5 Ha. The methodology used to characterize the circular features consisted in the integration of three near surface complementary geophysical techniques to study different soil properties (Fig. 1.2a, 1.2b and 1.4). The proposed methodology includes: (i) a ground penetrating radar (GPR) to identify local objects and stratification through dielectric contrasts; (ii) an Electromagnetic Induction (EMI) equipment to study variations in the electrical and magnetic properties of the underground; and (iii) a High-Resolution Seismic Tomography (HRST) equipment to determine possible seismic velocity contrasts in the seismic wave propagation.
Finally, to check the results and interpretations obtained from the non-invasive geophysical methods, an excavation was carried out in the archaeological site (Fig. 1.4). Depending on the corroborated hypothesis, two possible analyses will be performed. In case the puquios hypothesis is proven correct, a hydraulic analysis associated with the underground water flow through the canal will be done, modeling the amount of water that could carry the underground structure, slope of the canal and possible percolation losses.

On the other hand, if the deforestation hypothesis is proven correct, an evapotranspiration (ET) estimate will be performed, considering that 4000 *P. tamarugos* trees were present in the archaeological site (as many trees as circumferences recognized through satellite
mapping) and estimate the amount of water that these trees needed to survive in this hyperarid dry environment.

1.4.1 Ground Penetrating radar

The Ground Penetrating Radar (GPR) is a high-frequency electromagnetic device, which consists of a transmitting and a receiving antenna that emits and detect short electromagnetic waves through the ground (Daniels, 2004; Reynolds, 2011; Romero-Ruiz et al. 2018; Obrocki et al. 2019). Considering that emitted wave’s propagation, reflection and scattering mechanisms depend on the electrical conductivity and relative permittivity of the medium (Daniels, 2004; Casas et al. 2018; Romero-Ruiz et al. 2018; dal Bo et al. 2021), GPR allows to characterize stratification, shallow structures and to locate buried objects beneath the ground surface (Fig. 1.5b and 1.5c) (Johnson et al. 2006; Forte and Pipan, 2008; Alani and Lantini, 2019; Obrocki et al. 2019; Verdonck et al. 2020).

The GPR technique is one of the most used geophysical methods in archaeology (Conyers and Leckebusch, 2010; Goodman and Piro, 2013; Deiana et al. 2018), because of (i) its high resolution within the first meters of depth (Daniels, 2004; Johnson et al. 2006; Conyers and Leckebusch, 2010), (ii) its ability to evaluate the stratigraphic complexity of the soil and to locate anthropogenic remnants (Johnson et al. 2006; Forte and Pipan, 2008; Obrocki et al. 2019; Verdonck et al. 2020), (iii) its high acquisition speed (Conyers and Leckebusch, 2010) and (iv) its high capacity of integration with other near surface geophysical data (Forte and Pipan, 2008; Casas et al. 2018; Rodrigues et al. 2019; Obrocki et al. 2020). Appendix A: section A.1, presents the basic theory of the methods as well as
a description of the GPR advantages in archaeology applications, and some graphical examples to illustrate its capabilities.

Subsurface feature’s resolution will primarily depend on the applied frequency (Jol and Bristow, 2003; Masini et al. 2018). Low-frequency antennas (10-120 MHz) will be able to penetrate up to tens meters of depth in specific environments but will be capable of solving metric size features, while the high-frequency antennas (>120 MHz) will penetrate about 1 meter depth and will be able to recognize features of centimetric size (Johnson et al. 2006; Masini et al. 2018).

![Figure 1. 5: (a) Mala Easy Locator GPR in the Pampa Iluga archaeological site, (b) schematic soil scenario with a well selected sand strata over a clayey silt with its resulting radargram generated through the measurement, red dotted line indicates the interface between both soils, (c) schematic soil scenario with a homogeneous medium of well selected sand strata with a point object in it and the resulting radargram generated through the measurement, red dot indicates the position of the object in depth.](image)

Figure 1. 5: (a) Mala Easy Locator GPR in the Pampa Iluga archaeological site, (b) schematic soil scenario with a well selected sand strata over a clayey silt with its resulting radargram generated through the measurement, red dotted line indicates the interface between both soils, (c) schematic soil scenario with a homogeneous medium of well selected sand strata with a point object in it and the resulting radargram generated through the measurement, red dot indicates the position of the object in depth.
Expressions that relate the wavelength of the emitted signal and the minimum size that an object must have to be recognized by the antenna are presented in Annan, 2005:

- For radial resolution length ($\Delta r$)

$$\Delta r \geq \frac{\lambda}{4} \quad (1)$$

Where $\lambda$ is the pulse wavelength and $v$ the velocity of propagation.

In ideal scenarios the radial resolution will be independent of the distance between the source and the object, nevertheless, in practice, larger distances involve pulse attenuation and dispersion which will affect radial resolution (Jol, 2009).

- For lateral resolution ($\Delta l$):

$$\Delta l \geq \frac{W\sqrt{v\tau}r}{2} \quad (2)$$

Where $r$ is the distance between the antenna and the studied underground feature. As seen in equation 2, the lateral resolution will always depend on $r$, and therefore, the larger the distance, the larger the size of the feature in order to be recognized by the GPR (Jol, 2009).

Finally, the wave velocity ($\Box$) and attenuation ($\Box$) for high frequencies and non-magnetic environments, are approximated as (Daniels, 2004; Johl, 2009; Reynolds, 2011; dal Bo et al. 2021):

$$\Box = \frac{\Box}{\sqrt{\mu_r}} \quad (3)$$

$$\Box = \frac{\Box}{2} \quad (4)$$
Where, \( v \) is the electromagnetic wave velocity (m/s); \( c \) the Speed of light in free space (3x10^8 m/s); \( \varepsilon_r \) the relative permittivity; \( \alpha \) the attenuation (dB), \( \sigma \) the electric conductivity of the soil (S/m) and \( \mu \) the magnetic permeability (H/m).

Note that following equation (4), the electromagnetic signal emitted by the equipment is highly attenuated in electrically conductive wet soils because of the water’s higher dielectric constant \( (\varepsilon_r \approx 80) \) compared to both air’s \( (\varepsilon_r \approx 1) \) and matrix minerals \( (\varepsilon_r \approx 5) \) (see Table A1). Therefore, measurements in hyperarid dry environments are the ideal scenario for GPR surveys (Jol and Bristow, 2003; Bristow et al. 2007; Everett, 2013; Romero-Ruiz, et al. 2018). Appendix A: section A.2, presents a more detailed description of the GPR functioning and limitations.

For this study, a Mala Easy Locator GPR was used (Fig. 1.5a) which has a dual wide-bandwidth antenna with nominal frequencies of 160 and 670 MHz providing two GPR datasets (low and high frequency, respectively) for every measured profile. As mentioned before, the higher frequency will deliver higher spatial resolution but shallower penetrations, while the lower frequency, will enable us to measure deeper features, but with lower resolution.

4 GPR profiles were performed (Fig. 1.4): two EW-oriented profiles, on top of the alignment of circular features (AA’) and parallel to the alignment (BB’) and two NS-oriented profiles, perpendicular to the alignment of the circular features (CC’ and DD’). Profiles were georeferenced using a differential GPS (Trimble R4 GNSS) with a submeter accuracy.

GPR data were processed, using the REFLEXW software (© Sandmeier Geophysical Research), with a standard processing sequence consisting of the application of a gain
function to compensate the attenuation of the reflected signal and to emphasize signals generated by deeper objects or horizons; subtraction of the mean (DC removal); Butterworth band-pass filter to remove unwanted noise; static shift, and background removal to attenuate the typical horizontal noise from GPR data (Annan, 2005). To convert the two-way-travel time axis (displayed in nano second) to meters depth, a constant average velocity of 0.13 m/ns was estimated by fitting the diffraction hyperbolas that show up in several GPR sections.

1.4.2 EM38-MK2

Electromagnetic induction (EMI) measurements were made using the Geonics Limited EM38-MK2 (Fig. 1.6a), a noninvasive and lightweight equipment (Sudduth et al. 2001; Simpson, et al. 2008) widely used to analyze the spatial distribution of both the electrical resistivity values (Ω·m), inverse of the electrical conductivity (S/m), and the magnetic susceptibility (SI) (Simpson, et al. 2008; Heil and Schmidhalter, 2019; Tang, et al. 2018) in the near surface (~first 1.5 meters of depth).

The EM38-MK2 (Fig. 1.6a) is composed of three coils, one transmitter (Tx) that generates the electromagnetic signal and two receivers (Rx) that measure the electromagnetic response of the ground (Hubbard et al. 2012; Grellier et al. 2013). The first receiver coil is placed at 1 meter (C-1) and the second one at 0.5 meters (C-0.5) from the transmitter coil (Fig. 1.6b) (Heil and Schmidhalter, 2015). As most EMI equipment, while keeping it right over the ground surface, or close to it, the transmitter is energized with an alternating current at a specific frequency (Sudduth et al. 2001; Abdu et al. 2007; Elwaseif et al. 2017) (14.5 kHz for the EM38-MK2), that generates a primary electromagnetic field transmitted
into the soil subsurface (Fig. 1.6b). This induces eddy currents through the underground materials which, in turn, generate a secondary magnetic field measured by the receiver coils (Ward and Hohmann, 1987; McNeill, 1980; Tan et al. 2019; McLachlan et al. 2021). The penetration depth of the signal is defined as ‘the depth at which 70% of the cumulative response of the coil configuration is reached’ (Abdu et al. 2007; Callegary et al. 2007) and will depend on the Tx-Rx orientations/separations, and elevations of the system above the ground surface (Ward and Hohmann, 1987). Therefore, the quadrature signals, which are associated with the apparent electrical conductivity of the soil, will penetrate up to ca. 0.75 m (C-0.5) and ca. 1.5 m (C-1) depth (Abdu et al. 2007; Heil, and Schmidhalter, 2015), and the spatial distribution of the in-phase signals, which are associated with the apparent magnetic susceptibility of the subsurface, will penetrate up to ca. 0.25 m (C-0.5) and ca. 0.5 m (C-1) depth (Ernenwein and Hargrave, 2007; Dalan, 2008; McNeill, 2013).
Figure 1.6: (a) Geonics Limited EM38-MK2 equipment with the transmitter coil (Tx) and both receiver coils at 0.5 (C-0.5) and 1 (C-1) m from Tx. (b) Schematic EMI device with one transmitter coil (Tx) and one receiver coil (Rx) representing the electromagnetic phenomena with its primary (dotted line) and secondary (gray spheres) magnetic fields.

Based on Maxwell’s equations in the frequency domain and assuming a horizontally layered surface (McNeill, 1980; Ward and Hohmann, 1987; Callegary et al. 2007; Tan, et al. 2019), for a Vertical Dipole Mode (VDM) configuration, the equipment response is expressed as the ratio of the vertical secondary magnetic field over the primary magnetic field. Under low induction numbers (β ≪ 1, for more information see Appendix B), the ratio can be expressed as a complex number with a real component (In-phase) associated with the magnetic phenomena and an imaginary component (Quadrature) associated with the electric phenomena (Huang & Won, 2000; McNeill, & Bosnar, 1999). The equipment response in VDM is modeled using the following integral (Huang and Won, 2000; Andrade et al. 2016; Moura De Andrade and Fischer, 2017):

\[
H_s(s) = s^3 \int_0^\infty R(\lambda) \lambda^2 e^{-2\lambda h} J_0(\lambda s) d\lambda
\]  

(5)

Where, \(H_s\) = Secondary magnetic field; \(H_P\) = Primary magnetic field; \(s\) = distance between transmitter and receiver coils (m); \(J_0\) = zero order Bessel’s function; \(h\) = height of the sensor above the ground (m); \(\lambda\) = integration variable.

The function \(R(\lambda)\) can be written as:

\[
R(\lambda) = \frac{\lambda - \mu_1}{\lambda + \mu_1}
\]  

(6)
Where \( u_1 \), for a homogeneous half-space is a function approximated as presented in Ward and Hohmann, 1987; Huang and Won, 2000 and depends on the angular frequency \((\omega)\) of the equipment, the apparent electrical conductivity \((\sigma)\) and apparent magnetic permeability of the half-space \((\mu)\) (Appendix B, presents a detailed explanation of the EMI’s theory):

\[
\Box_1 = \Box^2 + \Box
\]

Post-processing stages are necessary to obtain the apparent electric resistivity \((ER_a)\) and the apparent magnetic susceptibility \((\chi_a)\) values that can provide insight about the distribution of soils or objects in the underground. Of both parameters, the electrical component of the EM38 signal is widely applied for subsurface studies (Dalan, 2008) including measuring of soil moisture contents (Huth and Poulton, 2007; Hubbard et al. 2013; Farzamian et al. 2015); salinity variations (Narjary et al. 2019; Khongnawang et al. 2021), irrigation in agriculture (Sudduth et al. 2001; Hossain et al. 2010; Bramley et al. 2011), mapping soil textural features (Domsch and Giebel, 2004; Visconti and de Paz, 2020), among others.

On the other hand, for archaeological studies, both signals can be equally important to find buried structures, objects and evidence of anthropogenic soils (e.g. Simpson et al. 2008; Santos et al. 2008; Rodrigues et al. 2009; Tang et al. 2018). While the electrical component enables delimiting wall or underground structures, the magnetic component allows the recognition of occupational areas associated with high susceptibility anomalies. The success of magnetic measurements in archaeological sites resides on the surface presence of ferromagnetic oxides (maghemite and magnetite) (Le Borgne, 1955, 1960).
due to pedogenic (Dalan, 2008; Simpson et al. 2008; McNeill, 2013; Bouhsane and Bouhlassa, 2018) and anthropogenic processes which enhance the magnetization in specific areas where objects and bonfires can be recognized (Tite and Mullins 1971; Dalan, 2008; McNeill, 2013; Urban et al. 2019).

Nevertheless, the electrical component of EMI sensors may fail to obtain the expected results in hyperarid dry environments because (i) the sensitivity to resistive targets in a resistive environment can be poor (Tabbagh, 1990; Huang et al. 2008) and (ii) a progressive instrument drift may affect the electric measurements during mapping days due to temperature variations in the equipment (Robinson et al. 2004; Abdu et al. 2007; Grellier et al. 2013). Despite all the shortcomings of electrical measurements in hyperarid conditions both signals were measured and calibrated² to compensate the temperature drift of the equipment throughout the measurements.

The survey was carried out with the EM38, in a Vertical Dipole Mode (VDP) configuration, at 10 cm above the ground (Fig. 1.6a), along numerous profiles perpendicular to the EW-oriented alignments, between and over the circular features (Fig. 1.4). Data was taken using the Mesa³ data logger (Juniper Systems) that includes a GPS/time recording with an accuracy from 2-5 meters.

Apparent Electrical Resistivity and Apparent Magnetic susceptibility modeling

After correcting the instrumental drift that affects the electric and magnetic component of the EM38 signal (Sudduth et al. 2001; Santos et al. 2019; Abdu et al. 2007; Grellier et al.

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² Calibration consisted of filtering the outlier values and a moving average filter to compensate local anomalous values.
2013), and removing all the outliers, the theoretical response of the electromagnetic signal was modeled following equations (5-7), and using the digital filters proposed by Guptasarma and Singh, (1997). As a result, the theoretical response (in-phase and quadrature components) was computed as a function of the apparent electrical conductivity (mS/m) and the apparent magnetic susceptibility (SI) in a homogeneous half-space (Fig. 1.7), considering different scenarios of apparent electrical resistivity ($ERa$) and apparent magnetic susceptibility ($\chi a$) between $1\times10^4 \ \Omega\cdot m$ and $10^{-6}-10^{-2.5} \ SI$, respectively.

Figure 1.7 presents the modeled quadrature signal (panels a and b), which depends only on the $ERa$ of the ground (x-axis), and the in-phase signal (panels c and d), which depends on both $ERa$ (x-axis) and $\chi a$ (color bar). In order to obtain the latter, the in-phase component (delivered in ppt) was intersected on the grid with the $ERa$ measurements (Fig. 1.7c and 1.7d).

In order to constrain the magnetic susceptibility values obtained by the half space modeling, results were compared with magnetic susceptibility measurements from 6 samples, collected in 2021 during the excavation of the archaeological site (Fig. 1.4 and 1.16c-f). Magnetic susceptibility measurements were carried out with a Terraplus KT-10.
Figure 1.7: Theoretical response of the EM38’s quadrature and in-phase component for soils between $1 \times 10^4 \Omega \cdot m$ and $10^{-6} - 10^{-2.5}$ SI (a) Quadrature response for C-1, (b) Quadrature response for C-0.5, (c) In-phase response for C-1, (d) In-phase response for C-0.5. Color bar indicates magnetic susceptibility values between $10^{-6} - 10^{-2.5}$ SI, the quadrature component and therefore the electric resistivity are independent of magnetic susceptibility variation, nonetheless the in-phase component.

1.4.3 High-Resolution Seismic Tomography

High-Resolution Seismic Tomography is an active non-destructive method that records the amount of time that a seismic wave takes to go from the transmitter (external source: shot) to a specific receiver (geophones of the array) (de Domenico et al. 2006; Reynolds,
2011; Everett, 2013; Dentith and Mudge, 2014, Hunter et al. 2022) with a high spatial resolution in the first 2-3 meters of depth. Knowing the travel-time curves, the computation of the seismic wave velocity is possible (Leucci et al. 2007) and can be associated with mechanical properties of the ground (Forte and Pipan, 2008; Everett, 2013; Romero-Ruiz et al. 2018).

For the present thesis a p-wave refraction analysis was performed over the data. This method is based on the principle that seismic waves traveling through two mediums with velocity contrasts, change the direction of wave propagation upon the entry into the new medium (Leucci et al. 2007; Reynolds, 2011, Hunter et al. 2022).

This direction change can be described by Snell’s law:

$$\frac{\sin(\alpha)}{\sin(\beta)} = \frac{V_1}{V_2}$$  \hspace{1cm} (8)

Where $\alpha$ and $\beta$ are the angles of incidence and refraction, and $V_1$ and $V_2$ the seismic velocities of the upper and lower mediums, respectively (Fig. 1.8), under the assumption that $V_2$ is always greater than $V_1$ (Reynolds, 2011; Everett, 2013; Hunter et al. 2022).

When the angle of incidence reaches a particular value (critical angle, $\alpha_c$), the refracted wave travels along the interface of both mediums with the speed of the second one ($V_2$) (Reynolds, 2011; Everett, 2013), and for this case, Snell’s law can be written as follows:

$$\sin(\alpha) = \frac{\sin(\alpha_c)}{\sin(\beta)}$$  \hspace{1cm} (9)

This critically refracted wave that travels through the interface of both mediums, will be subject of an oscillating stress which will generate upward moving waves, that will
eventually reach the surface (Fig. 1.8b). The time of arrival will be recorded by the geophones, enabling the computation the propagation velocity (Hunter et al. 2022).

Figure 1.8: (a) HRST equipment in the archaeological site when measuring P2 (b) Schematic representation of the refraction phenomena (Modified from Reynolds, 2011). Yellow star represents the shot location, triangles represent the geophones spacing specifically for the HRST equipment used in the experiment, dashed gray arrows indicate reflected waves and the black ones represent refracted ones.

Note that the refraction analysis assumes that the wave propagation velocity increases with depth (Reynolds, 2011; Hunter et al. 2022) and that the underground structures follow a semi-horizontal stratification (Hunter et al. 2022). This is a valid assumption for soils, where the first order factor is the compaction with depth.

For the *puquios* hypothesis, the refraction analysis should be able to delimit the underground canal because a low velocity area (void associated with the underground cavity) will be over a higher velocity area (undisturbed soil). On the other hand, for the
deforestation hypothesis, the refraction approach is challenged by the presence of roots in depth because: (i) roots may not be recognized by the equipment because of their size and depth (maximum root’s diameter is 0.15 m and are located 1.1-1.3 meters depth), (ii) a horizontally layered earth does not represent the real underground scenario and (iii) widespread seismic diffraction waves arriving at the geophones may generate too much noise in the system.

The used HRST equipment (Fig. 1.8) is an inhouse device that was developed by the geophysical group of the Engineering Faculty of PUC to map the first two meters of depth with a spatial resolution of 100/10 cm (horizontal/vertical resolution). It uses a land-streamer composed of 8 10 Hz geophones, separated at logarithmic distances from 1 to 4 m, including 8 channels LGR-5325 High Speed Multifunction Data Logger (Fig. 1.8a and 1.8b).

Unlike usual geophones, the ones that are included in the HRST equipment are over a skid and not staked in the ground, this allows to move the array to another position and generate long profiles to compensate for the lower number of geophones in the equipment compared to the usual amount (12-24). Therefore, every shot was made 1 meter away from the first geophone and the equipment was displaced 1 meter from the previous position. Two seismic profiles were performed, P1, emplaced between two circumferences and P2, emplaced on top a circumference (Fig. 1.4). The experiment included 24 and 27 profiles for P1 and P2 respectively and a high sampling rate of 16 kHz to account for the scale of the study problem (decimeter to meter distances).

For the inversion and analysis, the free version of the ZONDST2D software was used. It allowed the picking of the first wave arrival in each geophone and every seismogram,
generating travel-time curves for the starting model. For the inversion, the initial model was iteratively changed to minimize the difference between the input and calculated travel-time data and used a smoothness constrained method which considered a smoothness ratio in the horizontal and vertical directions of 1 and waves speed values between 300-8000 m/s.

1.4.4 Electrical Resistivity Tomography

An electrical resistivity tomography (ERT) experiment was carried out in the archaeological site using a Tigre Resistivity Meter (Allied Associated) to inject current from 0.5 to 50 mA in a pole-dipole arrangement of 16 stakes that was able to penetrate up to 2.5 meters depth. In an attempt to improve the contact resistance between the electrodes and the ground, mud with dissolved salt (NaCl) was used, which allowed the injection of electricity but poor results that ranged between 100-500 $\Omega\cdot$m, with electrical resistivities that increased in depth.

1.5 Results

1.5.1 GPR

Results are shown between 0 and 50 ns (two-way travel-time of the GPR pulses), corresponding to an approximate depth of 3.25 meters (Fig. 1.9 and 1.10). Below this depth, both low and high frequency GPR sections are dominated by random noise and no coherent event can be detected.

All profiles show the existence of a pseudo-horizontal reflector visible as a semi-continuous event on both low and high-frequency datasets, at approximately 1.5 and 2.3
m depth (Fig. 1.9 and 1.10). These reflectors are present over all the studied area and result from sub-horizontal alluvial layers caused by floods that took place in paleo-alluvial fans of the Quebrada de Tarapacá.

Along the AA’’ profile, running on the top of the alignment of circular features, the high frequency radargram (Fig. 1.9a) presents an undulation of the pseudo-horizontal reflector at 1.5 m depth. This undulation is not observed on the BB’ profile (Fig. 1.9c), running outside of the alignment of the circular features, which seems indicating that this wavy signal is not a regional anomaly but a circular features-related signal. Indeed, the section shows that the apexes of the undulation are located where the profile AA’’ crosses the circular-type features at the ground-surface (black arrows in Fig. 1.9a). This fluctuation cannot be explained as an effect of the topographic changes at the ground surface but an increase in the propagation velocity of the electromagnetic pulse can be responsible for pulling up the reflected signal (upward undulation). The higher propagation velocity can be due to unconsolidated materials like aeolian sands, filling the circular-type features. Indeed, beneath each circular-type feature (Fig. 1.9a), the GPR high-frequency signal clearly shows concave forms down to approximately 60-80 cm depth (Fig. 1.9a and 1.9b), with a low reflectivity associated with the expected homogeneous filling material. The signal within the circular-type feature reveals curved stratification (Fig. 1.9b), which are typical of aeolian sandy deposition in wells. Such finding agrees with the aeolian sandy deposition observed in the field, at the ground surface into each circular-type feature (Fig. 1.2b, 1.2d and 21.e).

On the CC’ and DD’ profiles (Fig. 1.10), running perpendicular to the alignment of circular features, well-marked diffraction hyperbolas show up on both high-frequency
(Fig. 1.10a and 1.10c) and low-frequency (Fig. 1.10b and 1.10d) GPR sections (red arrows overlain on the radargram). They are located at an approximate depth of 1 meter, at the positions of 22 and 33 m on CC’ profile (Fig. 1.10a and 1.10b) and at 19 m on DD’ profile (Fig. 1.10c and 1.10d). Note that the lateral position where the diffraction hyperbolas occur coincides with the position of circular-type features at the ground surface (Fig. 1.4 and 1.10). These hyperbolas can be generated by a strong contrast of the dielectric properties resulting from a discrete object or structure at depth. But as visible on the high-frequency datasets (Fig. 1.10a and 1.10c), the anomaly manifests itself as a concentration of smaller high-resolution diffraction hyperbolas, which suggest that the well-marked hyperbolas might in fact correspond to the agglomeration of multiple objects.

Figure 1.9: EW radargrams. (a) High frequency radargram of the A-A’’ profile (blue profile on Fig. 4) emplaced along the EW alignments. Black arrows indicate the location of the circular features on the ground surface. (b) zoomed high frequency A-A’’
radargram between 36-42 m, (c) High frequency radargram of the B-B’ profile (black profile on Fig. 4) emplaced parallel to the EW alignments. To facilitate the reading, only high-frequency data is shown.

Figure 1. 10: NS radargrams perpendicular to the EW alignments. (a) High frequency radargram of the C-C’ profile (yellow profile of Fig. 4), (b) Low frequency radargram of the C-C’ profile, (C) High frequency radargram of the D-D’ profile (red profile of
Fig.4), (b) Low frequency radargram of the D-D’ profile. Black arrows indicate the location of the circular features on the ground surface and red arrows indicate the location and depth of the hyperbolas.

1.5.2 EM38: Apparent electrical resistivity and apparent magnetic susceptibility results

A clear spatial correlation between the apparent resistivity variations and the distribution of the circular features is not identified in neither the two coil measurements. However, high $ER_a$ values from Pampa Iluga are in agreement with observations in other hyperarid dry alluvial fan systems in the Atacama Desert, by EMI (dal Bo et al. 2021) and ERT (Fernández-Remolar et al. 2013) measurements.

The EM38-derived high $ER_a$ values, vary from 125 to 10,000 $\Omega \cdot m$ (Fig. 1.11), which is compatible with the hyperarid conditions of the area. More specifically, in the shallower measured layers, up to 0.75 m depth (C-0.5), $ER_a$ values average $1633 \pm 1635$ $\Omega \cdot m$ (median = $1044 \Omega \cdot m$) (Fig. 1.11a). In the deeper measured layers, up to 1.5 m depth (C-1), the $ER_a$ values significantly decrease and average $595 \pm 697$ $\Omega \cdot m$ (median = $428 \Omega \cdot m$) (Fig. 1.11b).
Figure 1.11: Apparent electrical resistivity $ERa$ (Ω·m) obtained by the EM38 in VCP mode. (a) $ERa$ for 0.75 m penetration depth (C-0.5), (b) $ERa$ for 1.5 m penetration depth (C-1), (c) Data distribution for both coils in a box and whisker plot. Black circles indicate the location of the aligned circular features in (a) and (b).

On the other hand, for the apparent magnetic susceptibility measurements, a space distributed anomaly of high $\chi a$ values is observed along the alignments that is not always coincident with the circular features but surrounds them and follows the same EW direction (Fig. 1.12). Its values are comparatively higher ($3.5 \times 10^{-3}$ SI and around $3.0 \times 10^{-3}$ SI, for the C-0.5 (Fig. 1.12a) and C-1 (Fig. 1.12b) signal, respectively) than the medium outside the alignment.

In the shallower measured layers, up to 0.25 m depth (C-0.5), $\chi a$ values vary from $8.76 \times 10^{-5}$ to $9.15 \times 10^{-3}$ SI and averages $1.69 \times 10^{-3} \pm 1.51 \times 10^{-3}$ SI (median = $1.22 \times 10^{-3}$ SI) (Fig 1.12a). In the deeper measured layers, up to 0.5 m penetration depth (C-1), $\chi a$ values vary from $1.76 \times 10^{-5}$ to $4 \times 10^{-3}$ SI and average $1.09 \times 10^{-3} \pm 7.49 \times 10^{-4}$ SI (median = $9.38 \times 10^{-4}$ SI) (Fig 1.12b).
Figure 1.12: Apparent magnetic susceptibility $\chi_a$ (SI) obtained by EM38 in VCP mode. (a) $\chi_a$ for 0.25 m penetration depth (C-0.5), (b) $\chi_a$ for 0.5 m penetration depth (C-1), (c) Data distribution for both coils in a box and whisker plot. Black circles indicate the location of the aligned circular features.

1.5.3 High-Resolution Seismic Tomography

Because of the dimensions of the HRST and the small spacing between the geophones, the distance from the shot to each geophone is not sufficient to clearly separate the arrival of the P, S, and superficial waves. Therefore, contrary to the usual refraction procedure where the picked wave is the first big arrival, the picking procedure considered the first arrival to be the low amplitude signal that first appeared in the radargram, the following high amplitude signals are assumed as a package of surface and shear waves of larger amplitude. To help the understanding the followed procedure, Figures 1.13a and 1.14a, present the picking for analyzed profiles P1 and P2 respectively.

P1 and P2 2D inverted sections were generated with 24 and 27 shots respectively. For the P1 inversion (Fig. 1.13c), a low velocity area between meters 20-25 meters with velocities from 320-350 m/s can be recognized which is coincident with the intersection between P1 and the aligned circular features, similar results are observed in P2 (Fig. 1.14c) between meters 23-26 meters with velocities from 300-320 m/s.
Figure 1.13: P1 inversion results (green profile of Fig. 4 between two circular features) composed of the 24 profiles spaced every 1 meter. (a) Seismogram picking for shot 6, (b) Picked travel-time curves vs modeled travel-time curves, (c) 2D inversion modeling, black dotted square indicates the intersection between the profile and the circular alignment.

On the other hand, relatively high velocity areas are present in every profile. For P1, high velocity columns at 26, 31 and 37 meters are recognized with velocities from 400-450 m/s (Fig. 1.13c), in P2 shallow high velocity spots are recognized up to 30 cm depth at 16, 19 and 29 meters and columns at 33 and 40 m with velocities between 350-420 m/s (Fig. 1.14c).
Figure 1. 14: P2 inversion results (orange profile of Fig. 4, over a circular features) composed of 27 profiles spaced every 1-meter (a) Seismogram picking for P2- shot 2, (b) Picked travel-time curves vs modeled travel-time curves, (c) 2D inversion modeling, black dotted line square indicates the intersection between the profile and the circular alignment.

1.5.4 Excavation

The excavation was performed and described by the group of archaeologists that oversaw the characterization of the archaeological site³ in a field campaign in November 2020, after the analysis of the GPR results. It includes the digging of one circular feature up to

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³ Benoît Viguier, Pablo Mendez-Quiros, Valentina Mandakovic and Antonio Maldonado. (FONDECYT N° 1181829)
ca. 1.3 m depth (Fig. 1.15) and a trench (AA’) of ca. 3.8 m length, ca. 0.75 m width and ca. 1.3 m depth, between two circular features (Fig. 1.16). This trench was later extended by ca. 3.0 m length southward (A’B) and ca. 0.6 m northward (AC) and, by ca. 0.45 m deep.
Figure 1.15: Excavation of the circular feature. (a) Drone view of the excavation place. The excavated circular feature (eastern half) is indicated by a black circle. Red contours of the excavated materials from both circular structure and trench. (b) Interpreted cross-section of the excavated circular feature, showing the pre-existing hole filling: (1) horizontal sandy coarse aeolian deposits, (2) light-coloured silty-clay layer and (3) aeolian sandy foreset laminae of tabular cross-beds with thin intercalations vegetation-derived materials (leaves); (4) Unsorted sequence of coarse rounded clasts, aeolian sands and vegetation remains, and undisturbed alluvial sequences at the bottom and on lateral bounds of the pre-existing hole: (5) sandy-supported conglomerate, (6) unconsolidated deposits of loam sheetfloods, medium-coarse sand and gravel alluvial bars, (7) cut roots. (c) Zoom (b), (d) Light-coloured silty-clay layer (2) with raindrops impressions. (e) Oriental-view of the excavation with undisturbed alluvial sequences and roots. (f) A cut-root of *Prosopis* discovered during the excavation.

The excavation of the circular feature on its eastern half (Fig. 1.15a) reveals three main sedimentary units (Fig. 1.15b), spatially limited to the internal diameter of the studied circular feature, and laterally bounded by natural undisturbed alluvial sequences. The first unit is located between the ground surface and 10 cm depth (at the center of circular feature). It is characterized by a thin light-colored silty-clay layer intercalated between two horizontal sandy coarse aeolian deposits (Fig. 1.15b and 1.15c). Such a layer results from a high rainy event in the basin floor of the Pampa del Tamarugal, which created a temporary pool onto the circular feature. This intense hydro-meteorologic event probably allows the reworking and depositing of silty-clay elements. Raindrops impressions are still visible in the layer (Fig. 1.15d), which illustrates the exceptional nature of this rainy event in one of the driest places on Earth, at an altitude where annual precipitation rate is near to zero.
A second unit is present between 10 and 94 cm depth, where aeolian sandy forest laminae of tabular cross-beds with thin intercalations of leaves and other vegetation-derived materials like twigs (Fig. 1.15b and 1.15c) are observed. This illustrates a tranquil filling stage of the pre-existing hole by aeolian sedimentary processes. In the deepest section, the third unit is emplaced between 94 and 150 cm depth, and characterized by an unsorted sequence composed of coarse rounded clasts, aeolian sands, vegetation remains (e.g. leaves, twigs) and some human-made materials (e.g. piece of fabric) (Fig. 1.15c). This sequence evidences a massive gravitational collapse in the pre-existing hole (first filling stage).

Beneath this third sedimentary unit, a natural sandy-supported conglomerate forms the unexcavated bottom of the pre-existing hole. It is possible to observe the bounds of the pre-existing hole (Fig. 1.15b and 1.15e), several cut roots of a few cm in diameter (Fig. 1.15e and 1.15f), in-place into the undisturbed alluvial layers between 60 and 150 cm depth.

On the other hand, the excavation of the trench reveals several sequences of unconsolidated deposits of loam sheetfloods, medium-coarse sand and gravel alluvial bars (Fig. 16b), typical of drainage areas in alluvial fans (Reading, 1996). Between 10 and 30 cm depth, beneath a thin layer of sandy loam resulting likely from the last flood event in the area, an irregular in depth layer composed of leaves of *P. tamarugo* or *P. chilensis* (Fig. 1.16b and 1.16c) is observed. Vegetation remains are locally charred as well as the loams right underneath (Fig. 1.16c-f). Note that the further away from the center of the alignment of circular features, the smaller the thickness of the layer of burned leaves (Fig. 1.16c). By realizing several shallow digs (< 0.3 m depth), it was confirmed that such layer
is missing outside of the alignment of the circular features, therefore confirming that these burned areas are associated with the alignments.

Between 110 and 130 cm depth, at the center of the alignment of the circular features (Fig. 1.16b), two thick roots were found during the excavation (ca. 15 cm diameter) with several minor ones (Fig. 1.16g and 1.16h). The location of these roots coincides with that of the well-marked diffraction hyperbolas observed by GPR on both CC’ and DD’ profiles (Fig. 1.6 and Sect. 1.5.1). These roots together with the distribution of leaves in the surface as well as the observed cut roots in the excavated hole, seem indicating there were trees (\textit{P. tamarugo} or \textit{P. chilensis}) at the location of the circular features. The trunk as well as the thickest roots (right underneath the tree) were collected by digging the ground, which has led to an excavated hole, today filled by gravitational collapse and aeolian deposits. Excavated coarse alluvial materials shape the perimeter of the circular features.
Figure 1.16: Excavation of the trench between two circular features. (a) Drone view of the excavation place. The excavated circular feature is indicated by a black circle and red contours point out the excavated materials from both circular feature and trench. (b) Sediment texture-based lithological logs in the AA’ trench (mainly mud, sand and gravel). (c) Panoramic view of the upper part of the trench highlighting the layer of vegetation remains (e.g. leaves) and the charred sections (fireplaces). (d-f) Photo of fireplaces (cross-section) with charred leaves and loam. (g-h) Discovered thick
Prosopis’s roots during the excavation of the trench, near the point A’ position (see Fig. 16b).

1.5.5 Evapotranspiration estimate for Prosopis Tamarugos

With the tree’s discovery in the archaeological site, questions regarding the climatic conditions under which these trees developed and the amount of water that they needed to survive have arisen. In order to answer some of them, this section will estimate evapotranspiration (ET) rates of the trees present in Pampa Iluga, to preliminary estimate the amount of water that these plants needed for its survival in the Pampa del Tamarugal. The ET will be understood as the combination of evaporation and transpiration processes occurring in plant’s surface which generates a loss of water (Allen et al. 2006).

Two assumptions will be considered for the ET estimate:

1. Trees present in Pampa Iluga correspond only to *P. tamarugo*[^4]
2. The number of trees present in the site is the same number of circular features found through satellite mapping (4000 circular features)
3. The principal water loss of the *P. tamarugos* is associated to ET, therefore, the use of Penman-Monteith equation will deliver a good estimate of the water necessity of the trees.

Before the ET computation it is necessary to keep in mind that climatic conditions in the Pampa del Tamarugal and the Atacama Desert have changed throughout history (Placzek et al. 2009; Gayo et al. 2012; Morales et al. 2020). Even though the area is considered as

[^4]: Preliminary analysis found *P. chilensis* and *P. tamarugos* roots in depth, therefore, further analysis will be needed in order to determine the species that predominated in the area.
a hyperarid zone since the last 10 Myr, climate events such as El Niño Southern Oscillation (ENSO) or the Central Andean Pluvial Event (Placzek et al. 2009; Gayo et al. 2012) have increased the availability of water in the Pampa del Tamarugal for years in the case of ENSO or thousands-centenars of years for the CAPE. These pluvial events happened between 17.4-14.2, ~11.8 and 1.1-0.7 ka and transformed the Pampa ecosystems.

Nevertheless, in the present day, the area is characterized by high radiation rates throughout the entire year, low precipitations (less than 10 mm/yr below 2000 m.a.s.l (Houston, 2006; Viguier et al. 2018)) and a constant decrease in the water table due to excessive water extraction (Viguier et al. 2018) since 1990 (Chávez et al. 2016) that has threatened the survival of *P. tamarugo* (CONAF, 1997) and other species.

Because no high-resolution climatic records of the period where these trees developed is available, hourly radiation, temperature, and wind velocity of the past 4 years will be used to estimate ET rates, even though the climatic conditions and water availability where more favorable when the *P. tamarugos* developed. Today’s data will allow the estimate of ET rates in the worst-case scenario (null precipitation, high radiation, and low water table), which is also valuable information to understand the water necessity of the trees in the archaeological site.

Data were obtained from the meteorological network of the Instituto de Investigaciones Agropecuarias of Chile (INIA) and correspond to Pica’s station data (Tarapacá region), the closest station to the archaeological site, with a time series between 2018 and 2022.

Here is presented the Penman-Monteith equation used for the estimate of the ET rates (detailed procedure is presented in Appendix C):
\[
\Delta (R_n - G) + \rho \frac{(e_s - e_a)}{\Delta + \gamma \gamma 1 + \frac{r_s}{r_s}} = (10)
\]

Where \( \lambda ET \) = Latent heat flux (W/m\(^2\)h), \( R_n \) = Net radiation (W/m\(^2\)H), \( G \) = Soil heat flux (W/m\(^2\)H), \( \rho_a \) = average air density (kg/cm\(^3\)), \( c_p \) = Specific heat (1005 J/kg\(^{\circ}\)K), \( e_s - e_a \) = vapor pressure deficit with respect to saturation (kPa), \( r_a \) = Aerodynamic resistance (s/m), \( r_s \) = crop resistance or surface resistance (s/m), \( \Delta \) = Slope of the vapor pressure curve at saturation (kPa/\(^{\circ}\)C) and \( \gamma \gamma \) = piezometric constant (0.067 kPa/\(^{\circ}\)C).

In order to estimate the ET rates for the Pampa Iluga surface, the problem will be divided in two scenarios, (i) a desert scenario where no trees or vegetation covers the surface and (ii) a \( P. tamarugo \) scenario which considers that the whole surface is covered by trees.

Both ET rates will be averaged according to the area that each of them covers in 1 Ha of the archaeological site, therefore:

\[
ET_{P. tamarugo} = \frac{3}{Ha} = ET_{P.tam} \frac{3}{(\square)} \ast \frac{\square}{(\square)} + ET_{desert} \frac{3}{(\square)} \ast \frac{\square}{(\square)} (11)
\]

According to Altamirano, 2006, \( P. tamarugo \) reach up to 25 meters high and 20-30 m crown size in ideal conditions. Nevertheless, under adverse conditions they only reach up to 2 m high and 2-3 m crown size (detailed description of the \( P. tamarugo \) in Appendix C.2). With this information it is assumed that the ratio between the crown size and the tree’s height will be \( \sim 1 \).

Figure 1.17 shows the monthly ET rates (m\(^3\)/Ha) associated to the desert (Fig 1.17a) and covered by \( P. tamarugo \) (Fig. 1.17b) surface. Note that ET estimated rates for the desert’s
surface do not show an important correlation between the seasons of the year and do not present big variations between maximum and minimum values (Maximum, minimum, and mean ET rates are 6.4 m$^3$/Ha, 3.2 m$^3$/Ha and 5.9 m$^3$/Ha respectively).

Figure 1. 17: Monthly ET rates (m$^3$/Ha) for: (a) Desert surface between May-2021 and April-2022, (b) surface covered by P. tamarugo between May-2021 and April-2022. Excluded of the graph, because there is no monthly data for them, so there annual ET rates are not relatable with years 2019, 2020 and 2021.

On the other hand, Figure 1.17b which presents the ET estimated rates for the surface covered by *P. tamarugo*, presents a clear correlation between seasons. Maximum ET rates will happen during summer with a peak of 1578.3 m$^3$/Ha in December, and lower values during winter with a minimum rate of 778.8 m$^3$/Ha in June. It is important to note, that ET
rates will vary considerably through the year where winter rates will be doubled during summer (detailed computation of the ET rates and the used parameters are specified in appendix C)

Once the ET rates for the desert and \textit{P. tamarugo} surface has been estimated, it is necessary to compute the surface that each tree covers and therefore approximate the total area covered by the trees in the archaeological site. Information about the ratio between the height and crown size is extracted from Altamirano, 2006, and, as was mentioned before, the ratio between the tree’s height and the tree’s width (including the foliage) will be considered $\sim 1$.

Because circular features are separated from each other by 1 meter (see site description in section 1.1.2), and the ratio between tree’s height and width is $\sim 1$, the \textit{P. tamarugo} present in the area could not have reached more than 3 meters high, otherwise trees would have been too wide and invade the tree beside them. Therefore, estimates will consider the presence of 4000 \textit{P. tamarugo} trees of 1, 2 or 3 meters high in the archaeological site.

With a satellite analysis, the circular features were identified in a 15 Ha area, where trees cover 2.6\% of it when they are 1 meter high, 5.3\% when they are 2 meters high and 8\% when they are 3 meters high. Table 1.1 summarizes the total area covered by the 4000 trees as a function of their height and the proportion of the total surface that they cover.

Table 1.1: summary of the area covered by the \textit{P. tamarugo} in the archaeological site

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\footnote{Note that Desert’s estimated ET rates are comparably lower than \textit{P. tamarugo} estimated values, this is because the Desert’s scenario was forced to have low ET rates in order to simulate the real values of the desert and the null moisture content of the soil. (Detailed procedure is presented in appendix C)}
<table>
<thead>
<tr>
<th>Tree’s height (m)</th>
<th>Area covered by one tree (m$^2$)</th>
<th>Area covered by the 4000 trees (Ha)</th>
<th>Percentage of area covered by the trees</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.78</td>
<td>0.31</td>
<td>2.1%</td>
</tr>
<tr>
<td>2</td>
<td>3.14</td>
<td>0.25</td>
<td>8.4%</td>
</tr>
<tr>
<td>3</td>
<td>7.06</td>
<td>2.82</td>
<td>18.85%</td>
</tr>
</tbody>
</table>

With the information of Table 1.1, ET rates for the Pampa Iluga surface were computed, as a function of the trees height/width and the percentage of area covered by them Figure 19 shows resulting ET rates (m$^3$/Ha).

![ET rates per Ha as a function of the P. tamarugos height](image)

Figure 1.18: ET rates (m$^3$/ month Ha) in Pampa Iluga considering P. tamarugo of 1, 2 and 3 meters high. Each column indicates the average monthly ET rate calculated from the 2018-2022 time series.

From Figure 1.18, note that ET rates double and triple when increasing the height of the trees to two and three meters respectively, which is not a surprise considering that the assumption under which ET rates where estimated considered the ratio between height/width $\sim 1$. 
Nevertheless, this estimate has enabled the computation of the minimum and maximum values of ET rates as a function of the month of the year and the *P. tamarugo*’s height (summarized in Table 1.2), delivering information about ET rates during the seasons of the year and characteristics of the trees.

ET rates, and therefore water demand in the archaeological site, due to the forest of *P. tamarugo*, will vary from 21.8 m³/Ha (considering the minimum ET rate for 1-meter-high

Table 1. 2: Measures of central tendency of the resulting ET rates

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Maximum ET rate (m³/month Ha)</th>
<th>Mean ET rate (m³/month Ha)</th>
<th>Minimum ET rate (m³/month Ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees of 1 m high</td>
<td>43.3</td>
<td>33.9</td>
<td>21.8</td>
</tr>
<tr>
<td>Trees of 2 m high</td>
<td>85.36</td>
<td>66.6</td>
<td>42.5</td>
</tr>
<tr>
<td>Trees of 3 m high</td>
<td>127.4</td>
<td>99.3</td>
<td>63.3</td>
</tr>
</tbody>
</table>

1.6 Discussion

1.6.1 Relevance and limits of near surface geophysical techniques for the archaeological exploration in Atacama Desert

The GPR technique was able to image the sandy aeolian filling of pre-existing holes, contrasting with the natural undisturbed alluvial layers (Fig. 1.9 and Fig.1.15b), and to detect with a high precision the presence of buried objects that, later during the excavation, were confirmed as thick roots in depth (Fig. 1.10, 1.15e, 1.16g and 1.16h). This manifest themselves on GPR profiles CC’ and DD’ as well-marked diffraction hyperbolas visible, just below 1 m depth, on both high and low-frequency data (Fig. 1.10) and in agreement
with the study of Alani and Lantini (2019) that showed similar hyperbolas when mapping
the roots distribution of a mature tree in Walpole Park, London.

GPR penetration depth and the ability to image inner structures (for example the filled
holes or the alluvial layers), as well as to detect smaller objects (e.g. roots), are compatible
with results obtained by other studies with GPR in dry environments of the Atacama
Desert. According to Barba et al. (2015), the technique has proved useful in archaeological
investigations of burial mounds in the Valle de Azapa, near Arica, Northern Chile,
providing precise information about man-made stratification, coinciding with different
construction stages, and objects (possibly buried corpses) down to approximately 2 m
depth. Dal Bo et al. (2021), on the other hand, successfully applied GPR to infer the
underground sedimentary surface at 1.5 m depth related to changes in texture and
stratigraphy at two pits. Therefore, GPR represents the method of choice, especially in
hyperarid dry environments, to provide precise and reliable images of the subsurface even
without the need of constraining the results with an excavation.

The EM38-derived high \( ERa \) values (Fig. 1.11) are consistent with the hyperarid dry
environment of the Atacama Desert (Fernández-Remolar et al. 2013; Viguier et al. 2018;
dal Bo et al. 2021). Because of the low electrical resistivity contrast between the natural
alluvial sequences, the aeolian filling and buried objects at depth (here, roots), the electric
signal is unable to reveal in this case specific anomalies associated with discrete
archaeological features. However, there is no evidence in the excavated trench to support
the idea of electrical resistivity variations in depth due lithological changes because no
important variations of the sediment’s compaction or granulometry is observed between
the first 0.75 and 1.5 m depth.
Indeed, the decrease in the ERa with depth (Fig. 1.11), overall, the studied area, likely results from a greater accumulation in the vadose zone of chloride ions in the deeper measured layers (up to 1.5 m depth, C-1) than in the shallower ones (up to 0.75 m depth, C-0.5). In arid environments, the formation of a chloride bulge in the vadose zone is usually caused by the combined effect of (i) the root zone, where roots exclude chloride ions when they take up pore water creating higher chloride concentration at the base of root zone and, (ii) the position of the zero-flux plane created by the competition between downward (drainage) and upward (evapotranspiration) flows in the vadose zone (Scanlon et al. 2003; Healy and Scanlon, 2010). Despite the current absence of vegetation in Pampa Iluga, the observed ERa decreasing with depth throughout the study area could suggest the presence a native or planted vegetation cover (with an associated root zone) in the past, in agreement with the present explanation (Sect. 5.2), nevertheless, chemical studies to recognize higher chloride accumulations in the surface will be needed to corroborate this hypothesis.

The spatial distribution of EM38-derived $\chi_a$ values highlights a positive anomaly along the alignment of the circular features (Fig. 1.12), which is likely associated with the fireplaces recognized during the trench excavation (Fig. 1.16c-f). (Le Borgne 1960; Taylor et al. 1986; Clark, 2003; Fassbinder, 2016). High magnetic anomalies associated with fires are consistently found in archaeological sites (e.g., McClean and Kean, 1993; Dalan, 2008; Santos et al. 2008; Urban et al. 2019) and related to the concentration of ferromagnetic minerals (magnetite and maghemite) that increase near surface magnetization (Le Borgne 1960; Taylor et al. 1986; Clark, 2003; Fassbinder, 2016).
Moreover, a small regional increase of the near surface magnetization can be recognized in the shallower C-0.5 signal ($x = 1.69 \times 10^{-3}$ SI, median = $1.22 \times 10^{-3}$ SI)) compared to the deeper C-1 signal ($x = 1.09 \times 10^{-3}$ SI, median = $9.38 \times 10^{-4}$ SI) (Fig. 1.12c), probably associated with pedogenic processes that involve chemical, physical and biological reactions in soils, during drying periods of soil wetting/drying cycles (Le Borgne 1955, 1960). Taking into account that Pampa Iluga had extensive agricultural fields, such as evidenced by the numerous agricultural plots (Couyoumdjian, R. y Larrain, H. 1975; Uribe et al. 2020; Garcia et al. 2022), the irrigation and drying of the area could have regionally enhanced the magnetic susceptibility of the first cm of depth. Finally, it is important to mention that the magnetic susceptibility enhancement of the surface can also be related to the presence of allochthonous industrial particles deposited all over the area (Dearing et al. 1996; Bouhsane and Bouhlassa, 2018), but because of the remoteness of the site from any pollutant sources and the heterogeneous distribution of the $\chi_a$ anomalies, this process was discarded.

In the study area, measurements of magnetic susceptibility, carried out on charred *P. tamarugo* or *P. chilensis* leaves and underneath loam were made, between 10 and 30 cm depth in the near vicinity of the circular features (Fig. 1.16c-f). Susceptibility values of the burned samples are 2.3 times higher (ca. $6.51 \times 10^{-3}$ SI) than the undisturbed alluvial layers in the trench (ca. $2.8 \times 10^{-3}$ SI). Such a difference explains the local anomaly of high $\chi_a$ values observed along the alignment of circular features (Fig. 1.12) validating the fire-related hypothesis. Regarding the observed anomaly, the higher $\chi_a$ values shown up on the C-0.5 signal (Fig. 1.12a) with respect to the C-1 signal (Fig. 1.12b) are explained because of the shallower penetration depth (25 cm) of the magnetic field detected by the
coil C-0.5, which wraps around the complete charred leaves and loam (high measured $\chi_a$); while the magnetic field detected by the C-1 coil (up to ~50 cm depth) includes these charred remains as well as the undisturbed sediments below it, which have lower $\chi_a$ values. Unlike the electric signal, the magnetic component allows to bring out relevant information about past anthropogenic activities in the study area.

HRST results (Fig. 1.13 and 1.14) have not delivered robust results. The performed picking in the seismograms may be recognizing the first arrival as surficial waves instead of refracted P waves leading to an erroneous analysis. Nevertheless results (Fig. 1.13 and 1.14) may recognize an anomaly associated with the alignment. Low velocity areas of profiles P1 and P2 coincide with the intersection between the profiles and the alignment, which is why are associated with the aeolian filling (less compacted than the surrounding material) of the circular features. On the other hand, the observed high velocity anomalies could be associated with the presence of roots recognized by the GPR (Fig. 1.10) and the excavation (Fig. 1.15f, 1.16g and 1.16h). However, two different shapes characterize this type of anomalies: a column-shape-type high velocity anomaly (450 m/s in P1 at 31 m (Fig. 1.13)) that extends in depth, and small superficial anomalies (380 m/s points in P2 at 19 and 29 m (Fig. 1.14)) between 20-40 cm depth. The processes that generate one type of anomaly or the other, are not well understood, and to do so, a greater number of profiles would be necessary.

1.6.2 Evidencing a massive tree felling in the Atacama Desert.

At the beginning of this thesis two hypotheses were presented as plausible explanations for the origin of the EW-oriented semi-parallel alignments composed by thousands of
circular features that run through Pampa Iluga area (Fig. 1.1c). Regarding the puquios (or socavon, qanat) system hypothesis (Section 1.2), it was expected to be able recognize a void associated with the presence of an underground canal (as observed in Pica and Puquios Núñez, Lictevout et al. 2020) manifesting itself as: (i) a reflector with diffraction hyperbolas in the GPR signal (Everett, 2013; Obrocki et al. 2008) (ii) a high electric resistivity anomaly (Tang et al. 2018) complemented by a low magnetic susceptibility signal and (iii) a low velocity area (the void region) surrounded by a higher velocity area in the surrounding domain.

Nevertheless, after integrating the results from the GPR, the EM38 and the HRST geophysical techniques as well as from the performed excavation, the puquios (or socavon, qanat) hypothesis was discarded. The circular features are not shaft-wells but remains of excavation holes for extracting both trunk and thickest roots (right underneath the tree) of algarrobos (*P. chilensis*) or tamarugos (*P. tamarugo*). Trees were likely felled for carbon production to supply the increasing demand of charcoal-derived energy since the sixteenth century and, especially during the nineteenth century for the extraction of mining resources (Mendizábal, 1808 in Hidalgo, 1985; CONAF, 1997). Ongoing $^{14}$C dating on vegetation remains (roots and other) found during the excavation will help define the period of this massive felling of trees in the Atacama Desert and the contemporary mining activities.

1.6.3 Water necessity in Pampa Iluga

The computation of the ET rates considering the presence of 4000 trees in Pampa Iluga has allowed us to estimate the water necessity of the trees in the archaeological site. Even
though the computation does not count with in situ specific parameters for the *P. tamarugo* or climatic data for the period where the trees grew, the results allow the establishment of a threshold to have an estimate of the amount of water that the archaeological site consumed during the life of the *P. tamarugo*.

With the presented ET rates, an estimation of the annual water consumption in the archaeological site is delivered. *P. tamarugo* will consume approximately 407 m$^3$/Ha when trees are 1 m high, 800 m$^3$/Ha when trees are 2 meters high and 1192 m$^3$/Ha when trees are 3 meters high. With these results, new questions arise regarding the source of the water.

Weather conditions were more favorable for the *P. tamarugo* development in specific periods were pluvial events increased the water availability in surface, through perennial rivers, and subsurface, through the recharge of the underground aquifers decreasing the water table depth (Gayo et al. 2012). Therefore, *P. tamarugo* were able to extract water through surface capturing soil moisture and through water pumping from the aquifer with their deep root system (Calderon et al. 2015).

Other question to be answered is if the trees were planted or naturally grew in preferential directions on superficial streams. Due the proximity of the circular features and considering the ratio between height and crown size, *P. tamarugo* could not have been higher than 3 meters in the archaeological site. This specific distribution could imply anthropological action because in nature, trees grow randomly and with sufficient distance from one another, nevertheless, further studies will have to be performed to determine the origin of these trees.
1.7 Conclusions and Future Works

1.7.1 Conclusions

The integration of GPR and EM38 measurements has proven to be a suitable methodology for carrying out successful archaeological studies in hyperarid dry environments, like the Atacama Desert. These geophysical surveys, have permitted characterizing the subsurface over a broad area and help the preservation of the archaeological site by pointing out an exact location for excavation works, restricting them for key areas.

GPR-derived results have best performed in this specific environment identifying buried natural (e.g. sediments, roots, aeolian filling) and human-made structures (e.g. pre-existing holes) with precise detail. On the other hand, the EM38 in-phase component (associated with the magnetic susceptibility property) has brought out crucial results, allowing the identification of near surface magnetic susceptibility enhancements, which, thanks to the excavation where related to the presence of fireplaces. Such a magnetic signal is not used regularly in archaeology or even other near surface problems, however the relevant results presented in this study proves its usefulness. On the contrary, the EM38 quadrature component (associated with the electrical conductivity property) did not have an interesting performance in alluvial hyperarid dry environments due to the very poor conductivity of the surrounding material and/or the low resistivity contrast in this specific problem.

Finally, even though HRST results appear to recognize the EW aligned features as a low velocity area and the roots with high velocity anomalies in depth, there results are not conclusive and do not contribute with complementary information to the present study.
(GPR delivers the similar insight and with higher resolution). This does not mean that the equipment does not work in hyperarid environments, but that the contrasts between the studied features and the surrounding medium is not high enough to be measured by the equipment or that the studied objects are too small and too deep.

It is possible to conclude that the GPR is the most reliable technique to study near-surface features in hyperarid dry environments because it does not need an excavation to calibrate the results and it delivers high resolution data in the first 3 meters of depth that enables to recognize stratigraphical features and local objects in depth. On the other hand, EM38 susceptibility results, demonstrate an unexplored potential for the equipment in hyperarid dry environments, specifically in archaeological sites where high magnetic susceptibility contrasts are expected due to human occupation and fires. By using a GPR and an EM38, different properties and geological or man-made process are studied and characterized, which makes the use of both equipment the appropriate choice.

Thanks to the integration of near surface complementary geophysical techniques (GPR, EM38 and HRST) and the validation by the direct observation from excavation works, the meaning of the thousand aligned circular features has been solved. They are remains of the location of trees (algarrobos or tamarugos), which were felled (trunk) and extracted (right underneath thickest roots) to supply the increasing demand of charcoal-derived energy, likely between the 16th and 19th centuries.

Finally, with respect to the ET rates estimation and the analysis associated with water availability in the Pampa del Tamarugal through time, 3 pluvial events where recognized (between 17.4-14.2 kyr, ~11.8 and 1.1-0.7 kyr), where the most recent one (1.1-0.7 kyr) is considered the event that allowed the thrive of the trees in the archaeological site. These
regional scale events show that in specific periods of history, favorable conditions for the
thrive of *P. tamarugo* in the Pampa where plausible which allowed their development in
areas where today, no perennial streams are recognized, and water table depth is out of
the range of the roots.

By this study, original evidence about the deforestation (ongoing dating) of the Pampa del
Tamarugal in Atacama Desert has been provided, for which the first testimonies speak
about a broad forest cover and deliver a precedent for future archaeo-geophysical studies
in Chile and hyperarid dry environments.

### 1.7.2 Future Work

With respect to GPR measurements, future works could include a 3D model of the
underground using the measured profiles that were performed in the 2019 field campaign.
3D models including numerous 2D radargrams could map the distribution of the roots in
depth and estimate the extent of the phenomena outside the alignment probably
recognizing thicker and thinner agglomeration of roots.

For the EM38, the presented in-phase model was only tested using the VDM data and in
a high resistivity environment, where electrical conductivity is almost constant. Therefore,
to prove the robustness of the model, HDM measurements and tests in environments with
different electrical conductivities should be performed.

The archaeological site is not the ideal environment for the HRST equipment due the low
wave velocity contrasts between the roots and the surrounding material, therefore, to
obtain better results, measurements should be done in environments with higher velocity
contrasts. On the other hand, for characterizing the roots, a greater number of profiles
would be needed to determine the specific anomaly associated with the roots and obtain a statistical distribution of the behavior of the signal between and on top of the circumferences.

The variability of the ET rates presented in Table 1.2 is conditioned by the height and number of trees present in the archaeological, therefore, further studies involving these two variables are critical to understand and know the real amount of water demand in the site and the climatic conditions that enabled the development of these trees.

Finally, with respect to the archaeological site, the origin of the EW aligned trees is not resolved. To which species did these trees correspond? Where these trees planted or grew in the preferential directions of perennial streams? In the case that the trees were cultivated, who planted them? When where they planted? Who oversaw their care? When were these trees felled?

Future works will include a study of the wood and roots found in the site to determine the species of the trees, a bibliographical review, and a hydrological model to understand the origin of the alignment and $^{14}$C dating on vegetation remains (roots and other) found during the excavation will define the period of this massive felling of trees in the Atacama Desert.
2. CHAPTER 2: SUBMITTED PAPER: INTEGRATION OF NEAR SURFACE COMPLEMENTARY GEOPHYSICAL TECHNIQUES FOR THE STUDY OF ARCHAEOLOGICAL SITES IN ATACAMA DESERT (PAMPA ILUGA, NORTHERN CHILE).

This paper will be submitted to the Surveys in Geophysics Journal from Springer.

Authors are: Fernanda Gallegos-Poch, Benoît Viguier, Giovanni Menanno, Gonzalo Yañez, Mauricio Uribe, Sergio Gutierrez, Pablo Mendez-Quirós Aranda, Antonio Maldonado Valentina Mandakovic, Catalina Lizarde, Jaime Araya, Camila Lopez.

2.1 Abstract

Near surface geophysical techniques are useful for the characterization of archaeological sites because of their ability to rapidly cover large areas and obtain high-resolution data to identify the location for archaeological excavations. In hyperarid environments, however, usual techniques may fail to obtain good results due to the dry near surface. This study proposes an integration of ground penetrating radar (GPR) and electromagnetic induction (EMI) techniques to elucidate the origin of thousands of aligned circular features located at the Pampa Iluga archaeological site in the Atacama Desert, one of the driest places on Earth. The GPR was useful to recognize alluvial deposits and sandy aeolian filling in pre-existing holes right underneath circular features, and roots. Magnetic susceptibility data derived from the EMI in-phase component, usually considered a complementary result, was useful to identify fireplaces. These geophysical findings were verified with an archaeological excavation. It has been interpreted that the circular features resulted from an extensive deforestation process in the Pampa del Tamarugal, and the
extraction of both trunk and roots of algarrobos (*Prosopis chilensis*) or tamarugos (*Prosopis tamarugo*) likely for charcoal production. The proposed methodology delivers promising results for archaeological studies in hyperarid and dry environments.

2.2 Introduction

Geophysics allows the characterization of underground features, such as structures, and geological layers or processes through usually non-invasive measurements taken from the surface (Reynolds, 2011; Everett, 2013; Binley et al. 2015), at different scales of depth (from meters to kilometers). By the use of different techniques (e.g. gravity, magnetism, electricity or seismicity), the contrasts between the physical properties of the objects of interest and the surrounding materials can be determined (Telford et al. 1990; Simpson et al. 2008; Reynolds, 2011; Dentith and Mudge, 2014), which provides information about the location of buried objects and, in general, the characterization of the physical/chemical attributes of the subsurface (e.g. moisture content, porosity, mineral composition, etc.) (Romero-Ruiz et al. 2018; Carrière et al. 2020). Each technique is sensitive to different physical properties and, consequently, suitable to the objectives of the study, depending, for example, on (i) the contrast between the physical properties of the object of interest and the surrounding environment setting, (ii) the measurement resolution or (iii) the accessibility to the site. Ideally, different techniques should be implemented, and the results combined for a proper characterization of complex systems (Piro et al. 2000; Johnson et al. 2006; Scardozzi et al. 2012; Binley, et al. 2015; Deiana et al. 2018, Romero-Ruiz et al. 2018).
Since the 2000's, near surface geophysics has increasingly developed due to its key role in different scientific areas, such as archaeology (Piro et al. 2000; Witten et al. 2003; Santos et al. 2009; Scardozzi et al. 2012; Casas et al. 2018; Deiana et al. 2018; Urban et al. 2019; Colombero et al. 2021), agriculture and subsurface hydrology (Sudduth et al. 2001; Bramley et al. 2011; Binley et al. 2015; Alani and Lantini, 2019; Carrière et al. 2020; Araya Vargas et al. 2021), or construction (Grote et al. 2002; Artagan et al. 2019; Shapovalov et al. 2019; Tosti and Ferrante, 2019), because of its ability to solve problems within the first meters of depth using high spatial resolution data (Osella et al. 2005; Reynolds, 2011; Deiana et al. 2018). Geophysical techniques continue to improve in sensitivity and acquisition speed (Deiana et al. 2018) and the use of mobile platforms and automatic GPS positioning has allowed them to cover larger areas in shorter periods of time (Colombero et al. 2021; dal Bo et al. 2021). These advances and the integration of multiple geophysical methods has led to a more effective detection of small-scale anomalies (e.g. archaeological materials, roots, pipes) associated with buried objects or structures, without disturbing the surface (Piro et al. 2000; Reynolds, 2011; Deiana et al. 2018).

The capability to characterize large areas in small periods of time and detect small objects without affecting the site is of particular interest in the field of archaeology. Indeed, near surface geophysics techniques allow, in a non-destructive way, an accurate identification of buried archaeological materials, information which is useful to carry out suitable and spatially limited excavation works (Santos et al. 2008; Fassbinder, 2016; Casas et al. 2018; Colombero et al. 2021). The most employed techniques for archaeo-geophysical studies are the ground penetrating radar (GPR), electrical resistivity tomography (ERT) and
magnetic measurements (Johnson et al. 2006; Everett, 2013; Casas et al. 2018; Deiana et al. 2018).

In hyperarid dry environments, due to both scarce rain and high evaporation demand, the underground moisture content is very low or even nil. Hereafter, we mention “hyperarid dry environments” to make the distinction from areas in hyperarid regions, where stream discharges or groundwater outflows locally (partially) saturate the soils.

For geophysical studies in dry soils, GPR measurements will benefit from the low electrical conductivity of the soil (Jol and Bristow, 2003; Bristow et al. 2007; Everett, 2013; Romero-Ruiz, et al. 2018), allowing us to penetrate deeper and obtain better-quality results. On the contrary, ERT measurements are practically unfeasible because the injection of electricity into the ground is difficult, due the high contact resistance between the electrodes and the ground that severely hampers good quality direct current (DC) measurements (Wait, 1982; Reynolds, 2011; Lictevout et al. 2020). Therefore, to measure the electrical properties in hyperarid environments, geophysical studies usually implement transient electromagnetic (TEM) methods (Ruthsatz et al. 2018; Viguier et al. 2018; Blanco-Arrué et al. 2022), but the poor resolution that is expected in the first few meters of depth makes TEM methods unsuitable for near-surface archaeological exploration that requires surface resolutions of less than tens of meters.

On the other hand, electromagnetic induction (EMI) techniques can measure the apparent electrical conductivity and magnetic susceptibility of the underground (Simpson, et al. 2008; Heil and Schmidhalter, 2019; Tang, et al. 2018), without requiring soil contact (Visconti and De Paz, 2020), delivering a robust method capable of replacing ERT and magnetic measurements. For the first case, apparent electrical conductivity measurements
in dry soils are not ideal because low conductive environments result in low secondary induced magnetic fields, which is the signal that EMI techniques use to probe the subsurface (e.g., dal Bo et al. 2021). Nevertheless, the magnetic component of the signal is able to recognize thin horizontal layers of magnetically susceptible materials and is independent of other magnetic sources at larger depths, contrary to the magnetometer principle (potential method), making it a promising technique for near surface studies in hyperarid dry environments (McNeill, 2013).

While geophysical techniques are able to study wide areas and therefore define specific locations for the archaeological excavations, preventing the destruction of most of the archaeological site, the lack of a wide choice of geophysical techniques for the exploration of hyperarid dry environments may limit the proper characterization of the archaeological site and the identification of buried objects or structures, risking the site's preservation. Therefore, an integrated geophysical methodology that enables to characterize archaeological sites in hyperarid dry environments would be useful to study the numerous archaeological sites (Grosjean et al. 2005; Latorre et al. 2013) present in the Atacama Desert (Northern Chile), which is one of the driest places on Earth (Garreaud et al. 2003; Houston & Hartley, 2003; Houston, 2006) and other archaeological sites located in arid regions worldwide (Novo et al. 2012; Lancelotti et al. 2019; Heggy et al. 2022).

The present work proposes an integration of two complementary geophysical techniques in the Pampa Iluga archaeological site, at the Atacama Desert: GPR and an EMI equipment, with the derived apparent electric resistivity ($ER_a$) and apparent magnetic susceptibility ($\chi_a$) modeling. The use and validation of these geophysical techniques presents a new approach and provides interesting insights for the non-invasive large scale
archaeology studies in hyperarid dry environments, and also for analogous research aims like in extraterrestrial planetary exploration (e.g. Fernández-Remolar et al. 2013; dal Bo et al. 2021). Indeed, the hyperarid Atacama Desert is used as a proxy of Mars context for studying past near-surface environmental changes (Navarro-González et al. 2003; Warren-Rhodes et al. 2006; Catling et al. 2010; Cheng et al. 2016).

2.3 The Pampa Iluga Archaeological Site

2.3.1 Geological and historical framework in the Pampa del Tamarugal

The Pampa Iluga archaeological site is located at 20°S northern Chile in the Pampa del Tamarugal (Atacama Desert) between 1100 and 1150 m.a.s.l, between the villages of Huara and Tarapacá (Fig. 2.1a). The Atacama Desert is characterized by a hyperarid climate with an average annual precipitation of less than 10 mm/yr, below 2000 m.a.s.l, and a high potential evaporation reaching around 3000 mm/yr (Garreaud et al. 2003; Houston and Hartley, 2003; Houston, 2006).

The study area is located in the basin floor of the Central Depression in an abandoned alluvial fan of the Quebrada de Tarapacá (Fig. 2.1b). The lithological setting is characterized by a several hundred meters thick of late Miocene and Quaternary sequence of un- or poorly consolidated non-marine siliciclastic deposits composed from clast-supported gravels, immature sandstones, silt sheet flood deposits and aeolian features (Farias et al. 2005; Hartley and Evenstar, 2010; Jordan et al. 2010, 2014). Alluvial materials deposited in alluvial fans are transported by high-magnitude floods and result from both climatic and tectonic factors (Hartley & Evenstar, 2010; Jordan et al. 2010, 2014; Armijo et al. 2015; Evenstar et al. 2017; Carretier et al. 2019). In the study area,
shallow layers are considered as entirely dry. Indeed, in addition to the aforementioned hyperarid condition and the disconnection of the Pampa Iluga archaeological site from the current ephemeral drainage areas (Fig. 2.1b and 2.1c), the regional unconfined Pampa del Tamarugal Aquifer, mainly recharged by perennial and ephemeral stream-losses in the Andean Piedmont (Fritz et al. 1981; Houston, 2002; Viguier et al. 2018, 2019a; Urrutia et al. 2021), shows in the area a thick vadose zone (~50 m) that prevents upward capillary flows from the water table up to the ground surface.

The human activities in the Pampa del Tamarugal span around 13 kyr with several discontinuities associated with the wet-dry hydroclimate variations (Gayo et al. 2012; Sáez et al. 2016; Morales et al. 2020) and the resulting changes in both the available resources provided by the environment and the human adaptive strategies (Gayo et al. 2015; Sáez et al. 2016; Santoro et al. 2017). The use of seabird guano to fertilize crops (Santana-Sagredo et al. 2021), the deviation of perennial streams in the Andean Piedmont (Barnard and Dooley, 2017) and the opportunistic use of ephemeral surficial water resources during rainy events (Santoro et al. 2017), converted the Pampa del Tamarugal into a fertile, productive, and nutritious area (Santoro et al. 2017; Uribe et al. 2020b). This environmental setting allowed the growth of quinoa, beans, maize, pumpkin, and trees such as the tamarugo (Prosopis tamarugo) and algarrobo (Prosopis chilensis) (Calderon et al. 2015; McRostie, et al. 2017; Uribe et al. 2020 a,b). Species that have been a relevant source of food and wood to the communities (Santoro et al. 2016; McRostie, et al. 2017; Rivera-Diaz, 2018) and have developed an extensive forest cover through the Pampa.
Figure 2.1: Context of the archaeological site. (a) Distribution of the dryland and location of the archaeological site in the South American and Chile context, (b) Satellite
view (Google Earth) of a section of the Pampa del Tamarugal and central depression between 20.5° and 20°S with important cities and geological attributes of the area, (c) Satellite view (Google Earth) of the archaeological site, red points indicate the circular features (n: 3989) aligned on EW semi-parallel segments.

In the northern Chile socio-economic activities, from the Spanish conquest until present day, have been mainly focused on the extraction of mining resources (copper, saltpeter, lithium, among others) modifying the socio-environmental systems of the Pampa del Tamarugal (Santoro et al. 2017; Rivera-Diaz, 2018), and therefore the availability of natural resources like water (Oyarzún & Oyarzún, 2011; Santoro et al. 2018; Viguier et al. 2019b). For satisfying the increasing demand of charcoal-derived energy, a massive felling of trees (Santoro et al. 2017) started in the sixteenth century specially to supply the silver mining activities (Billinghurst 1893), and during the nineteenth century for the saltpeter industry (Mendizábal, 1808 in Hidalgo, 1985). During the late twentieth century, the Chilean National Park Service (CONAF) implemented a strategy to reforest the area and preserve of Prosopis tamarugo and Prosopis chilensis tree species (CONAF, 1997), however they are today endangered by the water table drop of the Pampa del Tamarugal aquifer (Chavez et al. 2013; Chavez et al. 2016; Decuyper et al. 2016; Viguier et al. 2019a).

2.3.2 The aligned Pampa Iluga circular features and some likely assumptions

During the fieldworks conducted in Pampa Iluga between 2019 and 2021, ca. 4000 circular-shaped features were identified, and mapped based on photo interpretation of satellite images (Fig. 2.2c). These features are mainly aligned on several EW-oriented semi-parallel segments, reaching up to six kilometers in length in the proximity of the
archaeological site and are spatially oriented towards the apex of the Quebrada de Tarapacá alluvial fan, where the stream is still perennial before to entirely infiltrate in the active alluvial fan (Fig. 2.1c). Further, they are separated from each other by approximately one meter, and they can have a well-drawn circular, oval or crescent moon shape with intern diameters ranging from 3 to 5 meters, with a ground surface infill of aeolian sandy deposits (Fig. 2.2). The outer part is composed by coarse alluvial materials (gravel and sand) that cover pre-existing agricultural fields (García et al. 2022) made up from partially eroded loam deposits at the ground surface, due to “recent” aeolian and runoff erosion processes (Fig. 2.2). These non-natural deposits sequence and morphological features together with the observation of circular forms aligned on kilometric-size segments allow us to discard any natural origins, but rather anthropic excavation works.
Figure 2.2: Satellite view (Google Earth) of the EW alignments through the archaeological site. (a) Satellite view (Google Earth) of the EW features in the studied area (b) photograph of the EW alignments in the studied area, (c) and (e) present a Satellite view (Google Earth) of the EW alignment through the archaeological site (See Figure 1c to locate them), (d) and (f) present pictures of (c) and (e) satellite views respectively.

Nevertheless, the reason for these excavations remains unknown and undescribed in both the literature and regional memory of inhabitants.
Figure 2.3: (a) Satellite view (Google Earth) of the Puquio Núñez puquios system, circular structures (shaft-wells) are aligned in a NE-SW direction. Groundwater from hillslope, raised by the Longacho thrust fault, is drained up to a tank in an oasis that sustains a local agricultural area downstream. (b) Photo of the underground canal near the puquios’ system mouth (Puquio Núñez). (c) Picture of multiple Tamarugos in the
Pampa del Tamarugal (source: CONAF). (d) Picture of a fully grown and healthy Tamarugo in the Pampa del Tamarugal (source: CONAF).

Therefore, we propose two hypotheses: the first one consists in assuming that the observed circular features would be shaft-wells of a buried puquios (or socavon) system (regional name for qanat) (Fig 2.3a and 2.3b), i.e. an underground canal where gravity-driven groundwater flows are conducted from hillslopes up to agricultural fields in the basin floor (Beaumont, 1971; Nasiri and Mafakheri, 2015; Lictevout et al. 2020). Such a hydraulic system is present ca. 70 km further South at Pica and Puquio Núñez (Dingman & Galli, 1965; DGA, 2012; Lictevout et al. 2020) (Fig. 2.1b, 2.3a and 2.3b). Nevertheless, (i) the absence of historical sources referring to puquios in the Pampa Iluga area, unlike those of Pica and Puquio Núñez (Dingman & Galli, 1965; Salazar et al. 1998; DGA, 2012) and, especially, (ii) the absence of underground canal outputs, usually shaped by artificial pools, in Pampa Iluga, lead us to assume that this first hypothesis might not be the right one. The second hypothesis proposes that these circular features would be evidence of past extraction processes of natural resources like wood (tree felling) (Fig 2.3c and 2.3d) for satisfying the increasing demand of charcoal-derived energy since the sixteenth to the nineteenth century (Billinghurst 1893; Zelada, 1986; CONAF, 1997; Santoro et al. 2017; Castro Castro, 2020). Therefore, the circular features would represent the location of the trees before they were cut down. By using near surface geophysical measurements, this paper aims to provide new evidence for resolving the meaning of the aligned Pampa Iluga circular features.

2.4 Methodology
The methodology used in this study to characterize the circular features consisted in the integration of two near surface complementary geophysical techniques: a ground penetrating radar (GPR) and an electromagnetic induction (EMI) equipment (EM38). Field surveys were conducted between 2019 and 2021 in an area of 2.5 Ha (Fig. 2.4). We also included an electrical resistivity tomography (ERT) experiment using a Tigre Resistivity Meter (Allied Associated) to inject current from 0.5 to 50 mA in a pole-dipole arrangement of 16 stakes. However, despite the use of mud with dissolved salt (Na-Cl) to attempt improving the electrical contact between the electrodes and the ground, the injection of electricity was infeasible due to extremely high contact resistance (above 10 kΩ·m). Finally, to corroborate the results and interpretations obtained from the non-invasive geophysical methods, an archaeological excavation was carried out in the archaeological site (Fig. 2.4).
Figure 2. 4: Measurement zone, light blue rectangle indicates EM38’s covered area, lines blue, red, yellow, and black indicate selected profiles for the GPR measurements analysis and the star represents the location of the excavation.

2.4.1 GPR

The Ground Penetrating Radar (GPR) is a high-frequency electromagnetic device, which consists of a transmitting and a receiving antenna allowing to emit and detect short electromagnetic waves through the ground (Daniels, 2004, Reynolds, 2011; Romero-Ruiz et al. 2018; Obrocki et al. 2019). Considering that emitted wave propagation, reflection and scattering mechanisms depend on the electrical conductivity and relative dielectric permittivity of the medium (Daniels, 2004; Romero-Ruiz et al. 2018; dal Bo et al. 2021), GPR allows to characterize stratification, shallow structures and to locate buried objects beneath the ground surface (Fig. 2.5) (Johnson et al. 2006; Forte and Pipan, 2008; Alani and Lantini, 2019; Obrocki et al. 2019; Verdonck et al. 2020). For high frequencies and low non-magnetic environments, the wave velocity (\(v\)) and attenuation (\(\alpha\)) are approximated as (Daniels, 2004; Johl, 2009; Reynolds, 2011; dal Bo et al. 2021):

\[
\frac{c}{\sqrt{\varepsilon_r}} \quad (1)
\]

\[
\frac{\varepsilon_r}{2} \quad (2)
\]

Where, \(v\) = electromagnetic wave velocity (m/s); \(c\) = Speed of light in free space (3x10^8 m/s); \(\varepsilon_r\) = relative permittivity; \(\alpha\) = Attenuation (dB) \(\sigma\) = electric conductivity of the soil (S/m); \(\mu\) = Magnetic permeability (H/m).
Following equation (2), the electromagnetic signal emitted by the equipment is highly attenuated in electrically conductive wet soils because of the water’s higher dielectric constant ($\varepsilon_r \approx 80$) compared to both air’s ($\varepsilon_r \approx 1$) and matrix minerals ($\varepsilon_r \approx 5$); therefore, measurements in hyperarid dry environments are the ideal scenario for GPR surveys (Everett, 2013; dal Bo et al. 2021; Romero-Ruiz, et al. 2018).

Figure 2. 5: (a) Mala Easy Locator GPR in the Pampa Iluga archaeological site, (b) schematic soil scenario with a well selected sand strata over a clayey silt with its resulting radargram generated through the measurement, red dotted line indicates the interface between both soils, (c) schematic soil scenario with a homogeneous medium of well selected sand strata with a point object in it and the resulting radargram generated through the measurement, red dot indicates the position of the object in depth.

GPR is one of the most used geophysical method in archaeology (Conyers and Leckebusch, 2010; Goodman and Piro, 2013; Deiana et al. 2018), because of its high resolution within the first meters of depth (Daniels, 2004; Johnson et al. 2006; Conyers and Leckebusch, 2010), its ability to evaluate the stratigraphic complexity of the soil,
locate anthropogenic remnants (Johnson et al. 2006; Forte and Pipan, 2008; Obrocki et al. 2019; Verdonck et al. 2020), its high acquisition speed (Conyers and Leckebusch, 2010) and its high capacity of integration with other near surface geophysical data (Forte and Pipan, 2008; Casas et al. 2018; Rodrigues et al. 2019; Obrocki et al. 2020).

For this study, we used a Mala Easy Locator GPR (Fig. 2.5a) with a dual wide-bandwidth antenna with nominal frequencies of 160 and 670 MHz providing two GPR datasets for every measured profile. The higher the frequency, the higher the spatial resolution but the lower the penetration depth.

In the present work, 4 GPR profiles were measured (Fig. 2.4): two NS-oriented profiles, perpendicular to the alignment of the circular features (CC’ and DD’) and two EW-oriented profiles, parallel to the alignment of the circular features, one outside of the alignment (BB’) and another one on top of it (AA’). The profiles were geolocalized using a differential GPS (Trimble R4 GNSS) with a submeter accuracy. GPR data were processed, using the REFLEXW software (© Sandmeier Geophysical Research), with a standard processing sequence consisting of the application of a gain function to compensate the attenuation of the reflected signal and to emphasize signals generated by deeper objects or horizons; subtraction of the mean (DC removal); Butterworth band-pass filter to remove unwanted noise; static shift, and background removal to attenuate the typical horizontal noise from GPR data (Annan, 2005). To convert the two-way-travel-time axis (displayed in nano second) to meters depth, we used a constant average velocity of 0.13 m/ns that was estimated by fitting the diffraction hyperbolas that show up in several GPR sections.
2.4.2 EM38-MK2

Electromagnetic induction (EMI) measurements were made using the Geonics Limited EM38-MK2 (Fig. 2.6a), a noninvasive and lightweight equipment (Sudduth et al. 2001; Simpson, et al. 2008) widely used to analyze the spatial distribution in the shallow subsurface of both the electrical resistivity (Ω·m), inverse of the electrical conductivity (S/m), and the magnetic susceptibility (SI) (Simpson, et al. 2008; Heil and Schmidhalter, 2019; Tang, et al. 2018).

Figure 2. 6: (a) Geonics Limited EM38-MK2 equipment with the transmitter coil (Tx) and both receiver coils at 0.5 (C-0.5) and 1 (C-1) m from Tx. (b) Schematic EMI device with one transmitter coil (Tx) and one receiver coil (Rx) representing the electromagnetic phenomena with its primary (black dotted line) and secondary (grey spheres) magnetic fields.
The EM38-MK2 is composed of three coils, one transmitter (Tx) that generates the electromagnetic signal and two receivers (Rx) that measure the electromagnetic response of the ground (Hubbard et al. 2012; Grellier et al. 2013). The first receiver coil is placed at 1 meter (C-1) and the second one at 0.5 meters (C-0.5) from the transmitter coil (Heil and Schmidhalter, 2015). As all EMI equipment, while keeping it right over the ground surface, or close to it, the transmitter is energized with an alternating current at a specific frequency (Sudduth et al. 2001; Abdu et al. 2007; Elwaseif et al. 2017) (14.5 kHz for the EM38-MK2), generating a primary electromagnetic field transmitted into the soil subsurface (Fig. 2.6b). This induces eddy currents through the underground materials which, in turn, generate a secondary magnetic field measured by the receiver coils (Ward and Hohmann, 1987; McNeill, 1980; Tan et al. 2019; McLachlan et al. 2021).

Based on Maxwell’s equations in the frequency domain and assuming a horizontally layered surface (McNeill, 1980; Ward and Hohmann, 1987; Callegary et al. 2007; Tan, et al. 2019), for a Vertical Dipole Mode (VDM) configuration, the equipment response is expressed as the ratio of the vertical secondary magnetic field over the primary magnetic field. Under low induction numbers (\( \beta \ll 1 \) according to McNeill, 1980), the ratio can be expressed as a complex number with a real component (In-phase) associated with the magnetic phenomena and an imaginary component (Quadrature) associated with the electric phenomena (McNeill, & Bosnar, 1999). The equipment response in VDM is modeled using the following integral (Huang and Won, 2000; Andrade et al. 2016; Moura De Andrade and Fischer, 2017):

\[
\frac{H_s}{\Delta} = s^3 \int_0^\infty R(\lambda) \lambda^2 e^{-2\lambda h} J_0(\lambda s) d\lambda
\]

(3)
Where, $H_s = \text{Secondary magnetic field}; \ H_p = \text{Primary magnetic field}; \ s = \text{distance between transmitter and receiver coils (m)}; \ J_0 = \text{zero order Bessel’s function}; \ h = \text{height of the sensor above the ground (m)}; \ \lambda = \text{integration variable}.$

The function $R(\lambda)$ can be written as:

$$R(\lambda) = \frac{\lambda - u_1}{\Box + \Box_1} \quad (4)$$

Where $u_1$, for a homogeneous half-space is a function approximated as presented in Ward and Hohmann, 1987; Huang and Won, 2000 and depends on the angular frequency ($\omega$) of the equipment, the apparent electrical conductivity ($\sigma$) and apparent magnetic permeability of the half-space ($\mu$) (Appendix B, presents a detailed explanation of the EMI’s theory).

$$\Box_1 = \Box^2 + \Box$$

Post-processing stages are necessary to obtain the apparent electrical resistivity ($\text{Era}$) and the apparent magnetic susceptibility ($\chi_a$) values that can provide insight about the distribution of soils or objects with different properties in the underground. The $\text{Era}$ derived from the EM38 signal is widely applied for subsurface studies (Dalan, 2008) including measuring of soil moisture content (Huth and Poulton, 2007; Hubbard et al. 2013; Farzamian et al. 2015); salinity variations (Narjary et al. 2019; Khongnawang et al. 2021), irrigation processes in agriculture (Sudduth et al. 2001; Hossain et al. 2010; Bramley et al. 2011), mapping soil textural features (Domsch and Giebel, 2004; Visconti and de Paz, 2020), among others.
On the other hand, in archaeological studies, both signals can be equally important to find buried structures or objects and evidence anthropogenic soils (e.g. Simpson et al. 2008; Santos et al. 2008; Rodrigues et al. 2009; Tang et al. 2018). While the Era enables delimiting wall or underground structures, the $\chi_a$ allows the recognition of occupational areas associated with high susceptibility values. The success of magnetic measurements in archaeological sites resides on the surface presence of ferromagnetic oxides (maghemite and magnetite) (Le Borgne, 1955, 1960) due to pedogenic (Dalan, 2008; Simpson et al. 2008; McNeill, 2013; Bouhsane and Bouhlassa, 2018) and anthropogenic processes which enhance the magnetization in specific areas where objects and bonfires can be recognized (Tite and Mullins 1971; Dalan, 2008; McNeill, 2013; Urban et al. 2019).

Nevertheless, the Era of EMI sensors may fail to obtain the expected results in hyperarid dry environments because (i) the sensitivity to resistive targets (e.g., mud brick) in a resistive environment can be poor (Tabbagh, 1990; Huang et al. 2008) and (ii) a progressive instrument drift may affect the electric measurements during mapping days due to temperature variations in the equipment (Robinson et al. 2004; Abdu et al. 2007; Grellier et al. 2013). Despite all the shortcomings of electrical measurements in hyperarid conditions, we measured both signals and calibrated them to compensate for the temperature drift of the equipment throughout the measurements.

The survey was carried out with the EM38, in a Vertical Dipole Mode (VDP) configuration, at 10 cm above the ground, along numerous profiles perpendicular to the EW-oriented alignments, between and over the circular features (Fig 2.4). Data was taken using the Mesa3 data logger (Juniper Systems) that includes a GPS/time recording with
an accuracy from 2-5 meters. As a result, we obtained the spatial distribution of the quadrature signals, which are associated with the apparent electrical conductivity of the soil, up to ca. 0.75 m (C-0.5) and ca. 1.5 m (C-1) penetration depth (Abdu et al. 2007; Callegary et al. 2007; Heil, and Schmidhalter, 2015), and the spatial distribution of the in-phase signals, which are associated with the apparent magnetic susceptibility of the subsurface, up to ca. 0.25 m (C-0.5) and ca. 0.5 m (C-1) penetration depth (Ernenwein and Hargrave, 2007; Dalan, 2008; McNeill, 2013).

**Apparent Electrical Resistivity and Apparent Magnetic susceptibility modeling**

After correcting the instrumental drift that affects the electric and magnetic component of the EM38 signal (Sudduth et al. 2001; Santos et al. 2019; Abdu et al. 2007; Grellier et al. 2013), and removing all the outliers, the theoretical response of the electromagnetic signal was modeled following equations (3) to (5), and using the digital filters proposed by Guptasarma and Singh, (1997). As a result, we computed the theoretical response (in-phase and quadrature components) as a function of the apparent electrical conductivity (mS/m) and the apparent magnetic susceptibility (SI) of a homogeneous half-space (Fig. 2.7), considering different scenarios of apparent electrical resistivity (ERa) and apparent magnetic susceptibility (χa) between 1-10⁴Ω·m and 10⁻⁶-10⁻²⁵ SI, respectively. Figure 2.7 presents the modeled quadrature signal (panels a and b), which depends only on the ERa of the ground (x-axis), and the in-phase signal (panels c and d), which depends on both ERa (x-axis) and χa (colorbar). In order to obtain the latter, the in-phase component (delivered in ppt) was intersected on the grid with the ERa measurements (Fig. 2.7c and 2.7d).
Figure 2.7: Theoretical response of the EM38’s quadrature and in-phase components over a half-space with apparent electrical resistivities and apparent magnetic susceptibilities in the range of $1 \times 10^4 \ \Omega \cdot m$ and $10^{-6} - 10^{-2.5} \ SI$ (a) Quadrature response for C-1, (b) Quadrature response for C-0.5, (c) In-phase response for C-1, (d) In-phase response for C-0.5. Color bar indicates magnetic susceptibility values between $10^{-6}$-$10^{-2.5} \ SI$, the quadrature component and therefore the electric resistivity are independent of magnetic susceptibility variation, nonetheless the in-phase component.

In order to constrain the magnetic susceptibility values obtained by the half-space model, we compared the results with the magnetic susceptibility measurements from 6 samples, collected in 2021 during the excavation of the archaeological site (Fig. 2.4). Magnetic
susceptibility measurements were carried out with a Terraplus KT-10 susceptibility meter, which has a measurement range of 10^{-6}-1.999 SI.

2.5 Results

2.5.1 GPR

In this study, data are shown between 0 and 50 ns (two-way travel-time of the GPR pulses), corresponding to an approximate depth of 3.25 meters (Fig. 2.8 and 2.9, see plan view location in Fig. 2.4). Below this depth, both low and high frequency GPR sections are dominated by random noise and no coherent event can be detected. All profiles show the existence of a pseudo-horizontal reflector visible as a semi-continuous event on both low and high-frequency datasets, at approximately 1.5 m depth and 2.3 m depth (Fig. 2.8 and 2.9).

These reflectors are present over all the studied area and result from sub-horizontal alluvial layers caused by floods that took place in paleo-alluvial fans of the Quebrada de Tarapacá. Along the AA’’ profile, running on the top of the alignment of circular features (blue profile Fig. 2.4), the high frequency radargram (Fig. 2.8a) presents an undulation of the pseudo-horizontal reflector at 1.5 m depth. This undulation is not observed on the BB’ profile (Fig. 2.8c, black profile Fig. 2.4), running outside of the alignment of the circular features, which seems indicating that this ondulated signal is not a regional anomaly but a circular feature-related signal. Indeed, the section shows that the apexes of the undulation are located where the profile AA’’ crosses the circular-type features at the ground-surface (black arrows in Fig. 2.8a).
This fluctuation cannot be explained as an effect of the topographic changes at the ground surface, instead, an increase in the propagation velocity of the electromagnetic pulse can be responsible for pulling up the reflected signal (upward undulation). The higher propagation velocity can be due to unconsolidated materials like aeolian sands filling the circular-type features. Indeed, beneath each circular-type feature (Fig. 2.8a), the GPR high-frequency signal clearly shows concave forms down to approximately 60-80 cm depth (Fig. 2.8a and 2.8b), with a low reflectivity associated with the expected homogeneous filling material. The signal within the circular-type feature reveals curved stratifications (Fig. 2.8b), which are typical of aeolian sandy deposition in wells. Such finding agrees with the aeolian sandy deposition observed in the field, at the ground surface into each circular-type feature.
Figure 2. 8: EW radargrams. (a) High frequency radargram of the A-A’’ profile. Black arrows indicate the location of the circular features on the ground surface. (b) zoomed high frequency A-A’’ radargram between 36-42 m, (c) High frequency radargram of the B-B’ profile. To facilitate the reading, only high-frequency data is shown, the low-frequency data is available as supplementary electronic material.
Figure 2.9: NS radargrams. (a) High frequency radargram of the C-C’ profile, (b) Low frequency radargram of the C-C’ profile, (C) High frequency radargram of the D-D’ profile, (b) Low frequency radargram of the D-D’ profile. Black arrows indicate the location of the circular features on the ground surface and red arrows indicate the location and depth of the hyperbolas.

On CC’ and DD’ profiles (Fig. 2.9), running perpendicular to the alignment of circular features, well-marked diffraction hyperbolas show up on both high-frequency (Fig. 2.9a and 2.9c) and low-frequency (Fig. 2.25b and 2.25d) GPR sections (red arrows overlain on the section). They are at an approximate depth of 1 meter, at the positions of 22 and 33 m on CC’ profile (Fig. 2.9a and 2.9b) and at 19 m on DD’ profile (Fig. 2.9c and 2.9d). We note that the lateral position where the diffraction hyperbolas occur coincides with the position of circular-type features at the ground surface (Fig. 2.9). These hyperbolas can be generated by a strong contrast of the dielectric properties resulting from a discrete object or structure at depth. On the high-frequency datasets (Fig. 2.9a and 2.9c), the anomaly manifests itself as a concentration of smaller high-resolution diffraction hyperbolas, which suggest that the well-marked diffraction hyperbolas might in fact correspond to the agglomeration of multiple objects.

2.5.2 EM38: Apparent electrical resistivity and apparent magnetic susceptibility results

The EM38-derived ERa values vary from 125 to 10,000 Ω·m (Fig. 2.10), which are compatible with the hyperarid conditions of the area. Measurements representative of shallower depths (up to 0.75 m) made with the C-0.5 coil, show ERa average of 1633 ± 1635 Ω·m (median = 1044 Ω·m) (Fig 2.10a). Measurements made with the C-1 coil
(sensitive to deeper layers, up to 1.5 m depth), show significantly lower $ERa$ values (average $595 \pm 697 \, \Omega \cdot m$ and median = $428 \, \Omega \cdot m$) (Fig 2.10b). We do not identify a clear spatial correlation between apparent resistivity variations and the distribution of circular features in neither the two coil measurements. However, high $ERa$ values from Pampa Iluga are in agreement with observations in other hyperarid dry alluvial fan systems in the Atacama Desert, by EMI (dal Bo et al. 2021) and ERT (Fernández-Remolar et al. 2013) measurements.

Figure 2. 10: Apparent electrical resistivity $ERa$ ($\Omega \cdot m$) obtained by the EM38 in VCP mode. (a) $ERa$ for 0.75 m penetration depth (C-0.5), (b) $ERa$ for 1.5 m penetration depth (C-1), (c) Data distribution for both coils in a box and whisker plot. Black circles indicate the location of the aligned circular features.

For both grids (Fig. 2.11), an in space distributed anomaly of high $\chi_a$ values is observed along the alignments that is not always coincident with the circular features but surrounds them and follows the same EW direction. Its values are comparatively higher ($3.5 \times 10^{-3}$ SI and around $3.0 \times 10^{-3}$ SI, for the C-0.5 (Fig. 11a) and C-1 (Fig. 2.11b) signal, respectively) than the medium outside the alignment.
In the shallower measured layers, up to 0.25 m depth (C-0.5), $\chi_a$ values vary from $8.76 \times 10^{-5}$ to $9.15 \times 10^{-3}$ SI and averages $1.69 \times 10^{-3} \pm 1.51 \times 10^{-3}$ SI (median = $1.22 \times 10^{-3}$ SI) (Fig 2.11a). In the deeper measured layers, up to 0.5 m penetration depth (C-1), $\chi_a$ values vary from $1.76 \times 10^{-5}$ to $4 \times 10^{-3}$ SI and average $1.09 \times 10^{-3} \pm 7.49 \times 10^{-4}$ SI (median = $9.38 \times 10^{-4}$ SI) (Fig 2.11b).

![Figure 2.11: Apparent magnetic susceptibility $\chi_a$ (SI) obtained by EM38 in VCP mode. (a) Apparent magnetic susceptibility for 0.25 m penetration depth (C-0.5), (b) Apparent magnetic susceptibility for 0.5 m penetration depth (C-1), (c) Data distribution for both coils in a box and whisker plot. Black circles indicate the location of the aligned circular features.](image)

2.5.3 Archaeological Excavation

The work has consisted in the excavation of one circular feature up to ca. 1.3 m depth (Fig. 2.12) and a trench (AA’) of ca. 3.8 m length, ca. 0.75 m width and ca. 1.3 m depth, between two circular features (Fig. 2.13). This trench was later extended by ca. 3.0 m length southward (A’B) and ca. 0.6 m northward (AC) and, by ca. 0.45 m deep.
The excavation of the eastern half of the circular feature (Fig. 2.11a) reveals three main sedimentary units that refilled the pre-existing hole (Fig. 2.12b), spatially limited to its internal diameter, and laterally bounded by natural undisturbed alluvial sequences. A first sedimentary unit (1, 2 in Fig. 12), between the ground surface and 10 cm depth (at the center of circular feature), a thin light-coloured silty-clay layer (2) is intercalated between two horizontal sandy coarse aeolian deposits (1) (Fig. 2.12b and 2.12c). Such a layer results from a high rainy event in the Pampa del Tamarugal, which created a temporary pool onto the circular feature; this intense hydro-meteorological event probably allows the reworking and depositing silty-clay elements. Raindrops impressions are still visible in the layer (Fig. 2.12d), which illustrate the exceptional nature of this rainy event in the Atacama Desert, at an altitude where the long-term average annual precipitation is near to zero.
Figure 2. 12: Archaeological excavation of a circular feature. (a) Drone view of the excavation place. The excavated circular feature (eastern half) is indicated by a black circle. Red contours of the excavated materials from both circular features and trench. (b) Interpreted cross-section of the excavated circular feature, showing the pre-existing hole filling: (1) horizontal sandy coarse aeolian deposits, (2) light-coloured silty-clay layer and (3): aeolian sandy foreset laminae of tabular cross-beds with thin intercalations vegetation-derived materials (leaves); (4) Unsorted sequence of coarse rounded clasts,
aeolian sands and vegetation remains, and undisturbed alluvial sequences at the bottom and on lateral bounds of the pre-existing hole: (5) sandy-supported conglomerate, (6) unconsolidated deposits of loam sheetfloods, medium-coarse sand and gravel alluvial bars, (7) cut roots. (c) Zoom of Fig. 12b. (d) Light-coloured silty-clay layer (2) with raindrops impressions. (e) Oriental-view of the excavation with undisturbed alluvial sequences and roots. (f) A cut-root of *Prosopis* discovered during the excavation.

A second sedimentary unit was identified between 10 and 94 cm depth (3 in Fig. 2.12), composed of aeolian sandy forest laminae of tabular cross-beds intercalated with thin laminae of leaves and other vegetation-derived materials like twigs (Fig. 2.12b and 2.12c). This illustrates a mild filling stage by aeolian sedimentary processes. Both latter filling entities were also determined by GPR as demonstrated by the comparison between Fig. 2.8b and 2.12b.

A third sedimentary unit was identified (4 in Fig. 2.12), between 94 and 150 cm depth, an unsorted sequence composed of coarse rounded clasts, aeolian sands, vegetation remains (e.g. leaves, twigs) and some anthropic materials (e.g. piece of fabric) (Fig. 2.12c). This sedimentary unit evidences a massive gravitational collapse of the edges of the pre-existing hole (first filling stage). Beneath, the third sedimentary unit, a natural sandy-supported conglomerate forms the unexcavated bottom of the pre-existing hole (5 in Fig. 2.12). We observe the bounds of the pre-existing hole (6 in Fig. 2.12b and 2.12e), several cut roots of a few cm in diameter (7 in Fig. 2.12b, e and 2.12f), in-place into the undisturbed alluvial layers between 60 and 150 cm depth.

On the other hand, the excavated trench reveals several sequences of unconsolidated deposits of loam sheetfloods, medium-coarse sand and gravel alluvial bars (Fig. 2.13b), typical of the drainage areas in alluvial fans (Reading, 1996). Between 10 and 30 cm
depth, beneath a thin layer of sandy loam resulting likely from the last flood event in the area, we observe a layer of irregular thickness composed of a litter of leaves (*Prosopis tamarugo* or *Prosopis chilensis*) (Fig. 2.13b and 2.13c). Vegetation remains are locally charred as well as the loams right underneath (Fig. 2.13c-f). We also observe that the thickness of the layer of leaves decreases further away from the center of the alignment of circular features (Fig. 2.13c). By doing several shallow digs (< 0.3 m depth), we confirmed that such a layer is missing outside of the alignment of the circular feature, therefore confirming that these burned areas are associated with the alignments. Between 110 and 130 cm depth, at the center of the alignment of the circular feature (Fig. 2.13b), we found two thick roots (ca. 15 cm diameter) with several minor ones (Fig. 2.13g and 2.13h). The location of these roots coincides with that of the well-marked diffraction hyperbolas observed by GPR on both CC’ and DD’ profiles (Fig. 2.9 and Sect. 2.5.1). These roots together with the distribution of leaves in the surface as well as the observed cut roots in the excavated hole, consistently prove the past occurrence of trees (*Prosopis tamarugo* or *Prosopis chilensis*) at each circular feature. The trunk as well as the thickest roots (right underneath the tree) were collected by digging the ground, which has led to an excavated hole, today refilled by gravitational collapse and aeolian deposits. Excavated coarse alluvial materials shape the perimeter of the circular features.
Figure 2.13: Excavation of the trench between two circular features. (a) Drone view of the excavation place. The excavated circular feature is indicated by a black circle and red contours point out the excavated materials from both circular features and trench. (b) Sediment texture-based lithological logs in the AA’ trench (mainly mud, sand and gravel). (c) Panoramic view of the upper part of the trench highlighting the layer of vegetation remains (e.g. leaves) and the charred sections (fireplaces). (d-f) Photo of fireplaces (cross-section) with charred leaves and loam. (g-h) Discovered thick
Prosopis’s roots during the excavation of the trench, near the point A’ position (see Fig. 2.13b).

2.6 Discussion

2.6.1 Relevance and limits of near surface geophysical techniques for the archaeological exploration in Atacama Desert

The GPR technique was able to image the sandy aeolian filling of pre-existing holes, contrasting with the natural undisturbed alluvial layers (Fig. 2.8 and 2.12b), and to detect with a high precision the presence of buried objects that, later during the excavation, were confirmed as thick roots in depth (Fig. 2.9, 2.12e, 2.12f and 2.12g). This manifest themselves on GPR profiles CC’ and DD’ as well-marked diffraction hyperbolas visible, just below 1 m depth, on both high and low-frequency data (Fig. 2.9), in agreement with the study of Alani and Lantini (2019) that showed similar hyperbolas when mapping the roots distribution of a mature tree in Walpole Park, London. The penetration depth and the ability to image inner structures (for example the filled holes or the alluvial layers), as well as to detect smaller objects (e.g. roots), are compatible with results obtained by other studies with GPR in dry environments of the Atacama Desert. According to Barba et al. (2015), this technique has proved useful in the archaeological investigations of burial mounds in the Azapa valley, Northern Chile, providing precise information about man-made stratification, coinciding with different construction stages, and objects (possibly buried human corpses) down to approximately 2 m depth. dal Bo et al. (2021), on the other hand, successfully applied GPR to infer the underground sedimentary surface at 1.5 m depth related to changes in texture and stratigraphy at two pits. Therefore, the GPR
represents the method of choice, especially in hyperarid dry environments, to provide precise and reliable images of the subsurface minimizing the need of an excavation to calibrate the signal.

The EM38-derived high $ERa$ values (Fig. 2.8) are consistent with the hyperarid dry environment of the Atacama Desert (Fernández-Remolar et al. 2013; Viguier et al. 2018; dal Bo et al. 2021). Because of the low electrical resistivity contrast between the natural alluvial sequences, the aeolian filling and buried objects at depth (here, roots), the electric signal is unable to reveal in this case specific anomalies associated with discrete archaeological features. There is no evidence in the excavated trench to support the idea of electrical resistivity variations in depth due lithological changes because no important variations of the sediment’s compaction or granulometry is observed between the first 0.75 and 1.5 m depth. Indeed, the decrease in the $ERa$ with depth (Fig. 2.10), overall, the studied area, likely results from a greater accumulation in the vadose zone of chloride ions in the deeper measured layers (up to 1.5 m depth, C-1) than in the shallower ones (up to 0.75 m depth, C-0.5). In arid environments, the formation of a chloride bulge in the vadose zone is usually caused by the combined effect of i) the root zone, where roots exclude chloride ions when they take up pore water creating higher chloride concentration at the base of root zone and, ii) the position of the zero-flux plane created by the competition between downward (drainage) and upward (evapotranspiration) flows in the vadose zone (Scanlon et al. 2003; Healy and Scanlon, 2010). Despite the current absence of vegetation in Pampa Iluga, the observed $ERa$ decreasing with depth throughout the study area could suggest the presence in the past of a native or planted vegetation cover (with an associated root zone), in agreement with the present explanation, nevertheless, chemical studies to
recognize higher chloride accumulations in the surface will be needed to corroborate this hypothesis.

The spatial distribution of EM38-derived $\chi_a$ values highlights a positive anomaly along the alignment of the circular features (Fig. 2.11), which is likely associated with the fireplaces recognized during the trench excavation (Fig 13c-e). (Le Borgne 1960; Taylor et al. 1986; Clark, 2003; Fassbinder, 2016). High magnetic anomalies associated with fires are consistently found in archaeological sites (e.g., McClean and Kean, 1993; Dalan, 2008; Santos et al. 2008; Urban et al. 2019) and related to the concentration of ferromagnetic minerals (magnetite and maghemite) that increase near surface magnetization (Le Borgne 1960; Taylor et al. 1986; Clark, 2003; Fassbinder, 2016). Moreover, a small regional increase of the near surface magnetization can be recognized in the shallower C-0.5 signal ($x = 1.69 \times 10^{-3}$ SI, median = $1.22 \times 10^{-3}$ SI)) compared to the deeper C-1 signal ($x = 1.09 \times 10^{-3}$ SI, median = $9.38 \times 10^{-4}$ SI) (Fig. 2.11c), probably associated with pedogenic processes that involve chemical, physical and biological reactions in soils, during drying periods of soil wetting/drying cycles (Le Borgne 1955, 1960). Taking into account that Pampa Iluga had extensive agricultural fields, such as evidenced by the numerous agricultural plots (Couyoumdjiam, R. y Larrain, H. 1975; Uribe et al. 2020; García et al. 2022), the irrigation and drying of the area could have regionally enhanced the magnetic susceptibility of the first cm of depth. Finally, it is important to mention that the magnetic susceptibility enhancement of the surface can also be related to the presence of allochthonous industrial particles deposited all over the area (Dearing et al. 1996; Bouhsane and Bouhlassa, 2018), but because of the remoteness of
the site from any pollutant sources and the heterogeneous distribution of the $\chi_a$ anomalies, we discard this option.

In the study area, we carried out measurements of the magnetic susceptibility on a few samples of charred *Prosopis tamarugo* or *Prosopis chilensis* leaves and underneath loam, taken at depths between 10 and 30 cm, in the near vicinity of the circular features (Fig. 2.13c-f). Susceptibility values of the burned samples are 2.3 times higher (ca. 6.51x10^{-3} SI) than the undisturbed alluvial layers in the trench (ca. 2.8x10^{-3} SI). Such a difference explains the local anomaly of high $\chi_a$ values observed along the alignment of circular features (Fig. 2.11) validating the fire-related hypothesis. Regarding the observed anomaly, the higher $\chi_a$ values are shown up on the C-0.5 signal (Fig. 2.11a) with respect to the C-1 signal (Fig. 2.11b). This is due to the shallower penetration depth (25 cm) of the magnetic field detected by the coil C-0.5, which wraps around the complete charred leaves and loam (high measured $\chi_a$); while the magnetic field detected by the C-1 coil (up to ~50 cm depth) includes these charred remains as well as the undisturbed sediments below it, which have lower $\chi_a$ values. Unlike the electric signal, the magnetic component allows to bring out relevant information about past anthropogenic activities in the study area, like fireplaces.

2.6.2 Evidencing a massive tree felling in the Atacama Desert.

At the beginning of this article two hypotheses were presented as plausible explanations for the origin of the EW-oriented semi-parallel alignments composed of thousands of circular features that run through the Pampa Iluga area (Fig. 2.1c). Regarding the puquios (or *socavon, qanat*) system hypothesis (see Sect. 2.2), we expected to recognize a void
associated with the presence of an underground canal such as observed in Pica and Puquios Nuñez (Fig. 2.3b) (Lictevout et al. 2020) with a geophysical response characterized by: (i) a reflector with diffraction hyperbolas in the GPR signal (Everett, 2013; Obrocki et al. 2008) and (ii) a high electric resistivity anomaly (Tang et al. 2018) complemented by a low magnetic susceptibility signal due to the presence of air in the underground cavity, in the electrical/magnetic components. Nevertheless, after integrating the results from the GPR and EM38 geophysical techniques as well as from the performed excavation, we discarded the puquios (or socavon, qanat) hypothesis. Circular features are not shaft-wells but remains of excavation holes for extracting both trunk and thickest roots (right underneath the tree) of algarobos (*Prosopis chilensis*) or tamarugos (*Prosopis tamarugo*). Trees were likely felled for charcoal production to supply the increasing demand of charcoal-derived energy since the sixteenth to the nineteenth centuries for the extraction and processing of mining resources (Mendizábal, 1808 in Hidalgo, 1985; CONAF, 1997). Ongoing ¹⁴C dating on vegetation remains (roots and other) collected during the excavation will help define the period of time of this massive felling of trees in the Atacama Desert and the contemporary mining activities.

### 2.7 Conclusions

The integration of GPR and EMI measurements has proven to be a suitable approach for carrying out successful archaeological studies in hyperarid dry environments in the Atacama Desert. The geophysical survey, performed in the Pampa Iluga archaeological site (Pampa del Tamarugal, northern Chile), has allowed the subsurface characterization over a broad area and to point out the exact location for the excavation works. These
contributions of knowledge help in the preservation of archaeological sites restricting excavation works to key areas. The GPR-derived results have best performed in this specific environment identifying buried natural (e.g. sediments, roots) and anthropic features (e.g. pre-existing holes, aeolian filling). The EM38 in-phase component (magnetic susceptibility) has proven to be useful in bringing out crucial results, permitting to identify remnants of anthropogenic activities having led to near surface magnetic susceptibility enhancement mechanisms, like fireplaces. Such a magnetic signal is not used regularly in archaeology or even other near surface problems, however the relevant results presented in this study proves its usefulness. On the contrary, the EMI quadrature component (electrical conductivity) did not have an interesting performance in alluvial hyperarid dry environments due to the very poor conductivity of the surrounding material and/or the low resistivity contrast in this specific problem.

In the study area, thanks to the integration of near surface complementary geophysical techniques (GPR and EMI), validated by direct observation from excavation works, we have been able to resolve the origin of the thousands aligned circular features in Pampa Iluga. They are remains of the location of trees (algarrobos Prosopis chilensis or tamaragos Prosopis tamarugo), which were felled (trunk) and extracted (right underneath thickest roots), to supply the increasing demand of charcoal-derived energy, likely between the 16th and 19th centuries. However, the question on why these trees are aligned, and their association with natural or anthropic processes, is still an open problem. By this study, we provide, for the first time, evidence about the deforestation (ongoing dating) of the Pampa del Tamarugal in Atacama Desert, for which the oldest testimonies speak about a broad forest cover.
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APPENDIX

APPENDIX A: GROUND PENETRATING RADAR METHOD

A.1 GPR in Archaeology

Of all near surface applications in which GPR is used, archaeology is the one in which the equipment has gained a wide acceptance (Johnson, 2006; Reynolds, 2011), becoming one of the most used geophysical techniques (Conyers and Leckebusch, 2010; Goodman and Piro, 2013; Deiana et al. 2018).

Its success resides on the ability to locate buried archaeological features and artifacts (Obrocki et al. 2019; Verdonck et al. 2020; Colombero et al. 2021) and successfully evaluate the stratigraphic complexity of the soil, (Dalan & Bevan, 2002; Romero-Ruiz et al. 2018; dal Bo et al. 2021), between 20 cm and 50 m below the ground surface depending on the type of soil and the used frequency (usually between 10 MHz and 1 GHz (Everett, 2013)), when targets have a significant physical property contrasts (electrical conductivity and dielectric parameters) with respect to the surrounding medium (Johnson et al. 2006; Verdonck et al. 2020).

Other qualities of GPR surveys that are attractive for archaeological exploration include the high acquisition speed (Deiana et al. 2018a; Masini et al. 2018) and its high capacity of integration with other near surface geophysical data such as seismic (Forte and Pipan, 2008; Arciniega-Cevallos et al. 2009), ERT (Piro et al. 2000; Scardozzi et al. 2012; Casas et al. 2018; Obrocki et al. 2020), magnetic (Witten et al. 2003; Rizzo et al. 2018) or EMI techniques (Rodrigues et al. 2019; dal Bo et al. 2021).
Finally, GPR representation may adopt different formats: (i) as an in-floor grid, (ii) a 2D radargram in depth or (iii) as a 3D representation by integrating multiple 2D radargrams. Graphical examples are presented below.

Casas et al. 2018 presents an integrated geophysical survey using a ground penetrating radar and an electrical resistivity tomography (ERT) to study the potential location of the remains of the Roman Temple dedicated to Emperor Augustus, under the Tarragona’s Cathedral. The building was studied with a 270 MHz antenna with parallel profiles every 40 cm and 50 scans per meter. Results are presented in in-floor grids which recognize, a series of individual anomalies (Fig. A.1) near the altar, which by their size, shape and distribution were interpreted as tombs.

Figure A. 1: Figure 9 from Casas et al. 2018, which represents GPR measurements with a 270 MHz antenna and the resulting in-floor grid of 0.3-0.5 meters depth that recognizes tombs (red anomaly), near the altar area.
On the other hand, Rodrigues et al. 2009, uses GPR and an EM38 equipment to study carbonate shell mounds in three archaeological sites in the mid-southern coast of Santa Catarina state, Brazil. A 200 MHz antenna was used to characterize the first 4 meters of depth. As shown in Figure A.2, 2D in depth GPR results were able to recognize ceramic materials (CM), buried objects or structures (ST) and delimit the extension of the shell mound laterally and in depth (SB).

![Figure A.2: Radargram from Rodrigues et al. 2009 showing GPR results from a 200 MHz antenna. (a) Corresponds to Figure 10 and a shell mound radargram from Santa Marta IV archaeological site, (b) corresponds to Figure 12 and shows a shell mound radargram from Encantada III archaeological site.](image)

Finally, a 3D integration of 2D radargrams is presented in Forte and Pipan, 2008. The study aims to provide adequate imaging resolution to large and prominent targets of archaeological interest like pyramids and mounds at all depth levels, by integrating a GPR and a seismic tomography at a burial mound in northern Italy. A 250 MHz antenna was used to measure 12 radial profiles (Fig. A.3) and characterize the shallow layers of the mounds identifying funeral chambers and stratigraphical layering.
Figure A. 3: Figures extracted from Forte and Pipan, 2008. (a) Corresponds to Figure 3 and represents a color-coded elevation map of the mound with the GPR profiles in blue, geophone positions in red and shot points in yellow. (b) Corresponds to Figure 8, where A indicated the 3D view of 2 GPR sections and the seismic tomogram (red indicates higher velocities), B is a picture illustrating the mounds stratigraphy visible after the excavation, C is a picture of the burial chamber visible after the excavation, (v) indicates an ancient looting attempt, (h) a dipping horizon, (s) a top of silty brown soil, (t) the burial chamber and (p) the skeleton deposition zone.

Reflectors recognized in Figure A.2 (SB) and Figure A.3b, represent dielectric or conductivity contrasts between the strata associated to the interface between the mound and the natural soil for the Rodrigues et al. 2009 survey and the interface between different strata in depth for the Forte and Pipan, 2008 survey. Similar reflectors are observed in the theoretical representation of a GPR signal (Fig. 1.5b) and the GPR results in the Pampa Iluga archaeological site where a pseudo-horizontal reflector is recognized in Figure 1.9. On the other hand, hyperbolas recognized in Figure A.2 (CM and ST), represent buried objects, coincident with the theoretical model of a GPR signal over a point object in depth (Fig. 1.5c) and the representations of roots in the resulting radargram (Fig. 1.10).
A.2 Theory

The Ground Penetrating Radar (GPR) is a high-resolution electromagnetic technique, that relies on the propagation of electromagnetic (EM) waves to map the underground (Tosti and Ferrante, 2019). The system is composed by a transmitting antenna that emits high frequency EM waves and a receiving antenna that detects the reflected signal (Daniels, 2004, Reynolds, 2011; Romero-Ruiz et al. 2018; Obrocki et al. 2019). This reflection occurs at the interface of materials with contrasting dielectric properties which allows the interpretation of underground geometry and features (Everett, 2013; Casas et al. 2018; dal Bo et al. 2021; Tosti and Ferrante, 2019) with length scales of 1 m or less (Everett, 2013), depending on the emitting frequency.

Table A.1 presents the dielectric constant of some common geological materials, useful for GPR analysis and interpretation.

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative dielectric constant</th>
<th>Velocity (mm/ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td>Water</td>
<td>81</td>
<td>33</td>
</tr>
<tr>
<td>Pure Ice</td>
<td>3.2</td>
<td>167</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>3-6</td>
<td>120-170</td>
</tr>
<tr>
<td>Wet Sand</td>
<td>25-30</td>
<td>55-60</td>
</tr>
</tbody>
</table>

Table A. 1: Dielectric constant for common geological materials (extracted from Reynolds, 2011 and Dentith and Mudge, 2014).
To understand the GPR functioning, a brief review of the theory of electromagnetic wave propagation in a medium is presented below, starting from Maxwells equations and the constitutive relations that govern the behavior of EM fields:

\[ \nabla \times \vec{H} = \vec{J} + \frac{\varepsilon \varepsilon_0 \vec{E}}{\sigma} \quad (\Box 1) \]

\[ \nabla \times \vec{E} = -\frac{\varepsilon_0 \vec{B}}{\varepsilon} \quad (\Box 2) \]

\[ \vec{J} = \sigma \vec{E} \quad (A3) \]

\[ \vec{B} = \mu \vec{H} \quad (A4) \]

Where \( \vec{H} \) is the magnetic field, \( \vec{J} \) the current density, \( \vec{E} \) the electric field, \( \vec{B} \) the magnetic induction field, \( \varepsilon \varepsilon_0 \) the dielectric constant, \( \sigma \) the electric conductivity and \( \mu \) the magnetic permeability of the medium.

Following Wangsness (1986), \( \nabla \cdot \vec{J} = 0 \) and eliminate \( \vec{B} \) from the previous equations, obtaining the EM wave propagation equation:
\[
\n\nabla \vec{E} = \mu \sigma \frac{\varepsilon \vec{E}}{\varepsilon \varepsilon t} + \mu \varepsilon \frac{\varepsilon^2 \vec{E}}{\varepsilon \varepsilon t^2} \quad (A5)
\]

It can be expressed in the frequency domain as

\[
\nabla \vec{E} = \mu \varepsilon \omega \vec{E} + \mu \varepsilon \omega^2 \vec{E} \quad (A6)
\]

Where \( \omega \) corresponds to the angular frequency and \( i \) to the imaginary number.

Considering that GPRs work in a high frequency range, equation (A6) can be approximated to \((\mu \sigma \omega \sim 0)\):

\[
\nabla \vec{E} = \mu \varepsilon \omega^2 \vec{E} \quad (A7)
\]

On the other hand, the speed of EM waves in a material can be represented as presented in the following equation:

\[
\n = \sqrt{\varepsilon \mu} \approx \sqrt{\varepsilon r} \quad (A9)
\]

Where, \( c \) is the speed of light in free space \((3 \times 10^8 \text{ m/s})\), \( \varepsilon \) the relative dielectric constant, \( \mu \) the relative magnetic permeability and \( \sim \) the loss factor.

When the loss factor is very low, \( P \to 0 \) and the speed of EM waves can be written as:

\[
V_m = \frac{\sqrt{\varepsilon \mu \varepsilon r}}{\sqrt{\varepsilon r}} \approx \sqrt{\varepsilon r} \quad (A9)
\]

Note that the last expression in equation (A9) considers that \( \sim 1 \), which is a valid approximation in non-magnetic environments.

Finally, the wave velocity attenuation can also be modeled and will be conditioned by the electrical conductivity and magnetic susceptibility of the medium and the relative dielectric permittivity:
To summary all the above, Figure A.4 presents the frequency dependence of the attenuation and velocity of the electromagnetic wave in materials with different electrical conductivities.

Figure A. 4: Frequency dependence of attenuation and velocity for GPR (radar) and radio frequency electromagnetic waves for materials of different conductivity. (a) Attenuation, (b) velocity. (The dielectric constant is assumed as 4 in both graphics). (Figure extracted from Dentith and Mudge, 2014 which was redrawn from Davis and Annan, 1989).

Note that the penetration of the emitted signal and its reflection will be conditioned mainly by the relative dielectric constant and the electrical conductivity of the medium. Therefore, conductive mediums with high moisture content or high dissolved salt content (see Table A.1) will rapidly attenuate the signal and reduce its propagation velocity (Fig. A.4). Hence, GPR survey over dry soils will be preferred over humid soils contexts because
results will have a higher quality and penetrate deeper (Jol and Bristow, 2003; Bristow et al. 2007; Romero-Ruiz, et al. 2018).

APPENDIX B: FDEM METHOD (EM38-MK2 EQUIPMENT)

The present appendix presents a detailed explanation of the Frequency Domain Electromagnetic Methods (FDEM) operation principles, focused on the electromagnetic induction equipment of Geonics, the EM38-MK2. The appendix seeks to emphasize the importance of the in-phase component usually not considered in near surface exploration, describing a specific methodology to transform the in-phase signal (ppt) into magnetic susceptibility values (SI).

B.1 FDEM Theory

Frequency-domain electromagnetic induction systems use an alternating current at a specific frequency flowing through a transmitter coil (Tx) to create a magnetic dipole perpendicular to the coil plane (Keller and Frischknecht, 1966; Callegary et al. 2007; Tan et al. 2019). This primary magnetic field penetrates the ground inducing eddy currents through the underground, which in turn generate a secondary magnetic field detected by a receiving coil (Rx) generally in the same EMI equipment (McNeill, 1980; Ward and Hoffman, 1987; Huang and Won, 2000) (Fig. 1.6).

These systems are commonly used in two orientations: the vertical dipole mode (VDM) (Fig. 1.6a) and the horizontal dipole mode (HDM), where coils are oriented parallel and perpendicular to the surface respectively (McNeill, 1980; Abdu et al. 2007).
The theory for FDEM methodology has been developed from the laws governing the behavior of EM fields in homogeneous and inhomogeneous conducting earths (Zhdanov, 2017) starting from the Maxwell’s equations expressed in the frequency domain:

\[
\nabla \times \vec{E} = \sigma \vec{H} + \frac{\varepsilon \varepsilon_0 \vec{E}}{\varepsilon_0} = (\sigma + i \omega \varepsilon) \vec{E} \quad (B1)
\]

\[
\nabla \times \vec{E} = -\mu \frac{\varepsilon \varepsilon_0 \vec{H}}{\varepsilon_0} (\text{Faraday’s law}) = -i \omega \mu \vec{H} \quad (B2)
\]

\[
\nabla \vec{B} = \mu \nabla \vec{H} = 0 \quad (B3)
\]

\[
\nabla \vec{D} = \varepsilon \nabla \vec{E} = 0 \quad (B4)
\]

Where \(\vec{H}\) is the magnetic field, \(\vec{E}\) the electric field, \(\vec{D}\) the electric displacement field, \(\vec{B}\) the magnetic induction field, \(\sigma\) the electric conductivity, \(i\) the imaginary number \((\sqrt{-1})\), \(\omega\) the angular frequency, \(\varepsilon\varepsilon_0\) the dielectric constant and \(\mu\) the magnetic permeability.

In VDM, the magnetic field in the vertical direction \((z)\), is a solution to Maxwell’s equations when expressed as a function of the potential \(F\):

\[
\nabla^2 F = \frac{1}{\varepsilon^2} + k^2 \phi \quad F = \frac{1}{\phi^2} F \quad (B5)
\]

For low frequencies, \(\phi_0\) can be expressed as \(\phi_0 = \phi_0\), where the subindex zero corresponds to free space properties.

Assuming a horizontally layered subsurface model (Ward and Hoffman, 1987; McNeill, and Bosnar, 1999; Tan et al. 2019), with the z-axis positively pointing downward and coils placed at an elevation \(h\) in the Cartesian coordinate system the axial component of the magnetic field along the magnetic dipole direction observed at the receiver position is given by (Ward and Hohmann, 1987):
\[ J_0 = \frac{\infty}{4} \left( e^{-iu_0z+h} + R(\lambda)e^{iu_0z-h} \right) \frac{3}{0} \frac{0}{0} \quad (6) \]

Where, \( J_0 \) represents the zero order Bessel function, \( u_0 = \sqrt{\lambda^2 - k_0^2} \), \( R(\lambda) \) the reflection coefficient and \( \lambda \) the integration variable.

The reflection coefficient \( R(\lambda) \) can be written as (Huang and Won, 2000; Thiesson et al. 2014):

\[ R(\lambda) = \frac{\lambda - u_1}{\lambda + u_1} \quad (7) \]

Where \( u_1 \), for a homogeneous half-space depends on the angular frequency of the equipment, the apparent electrical conductivity and apparent magnetic permeability of the half-space:

\[ u_1 = \frac{2}{3} \quad (8) \]

When the system is placed in free space, the primary magnetic field at the receiver position, \( H^P \), can be computed assuming \( z = 0 \) and \( R(\lambda) \rightarrow 0 \) (Tan et al. 2019) and incorporate the influence of the distances between Tx-Rx (\( \rho \)):

\[ \frac{3}{4} \int_0^\infty e^{-i\rho \lambda} d\lambda \quad (9) \]

On the other hand, the secondary magnetic field (\( H^s \)), generated by the underground materials can be computed using the following relation (Tan et al. 2019):

\[ H^s = H^P - H^s \quad (B10) \]

Resulting:
\[ H_s = \frac{1}{4} \int_0^\infty R(\lambda) e^{\lambda h} \lambda^2 J_0(\lambda \rho) d\lambda \quad (11) \]

Because the receiver coil measures the primary and secondary magnetic field, FDEM measurements are expressed as the ratio of the secondary magnetic field over the primary magnetic field in parts per million (ppm) or parts per thousands (ppt). Therefore, in low induction number scenarios the measured signal is a complex number where the real component (In-phase) is associated with the magnetic phenomena and the imaginary component (Quadrature) is associated with the electric phenomena (McNeill, & Bosnar, 1999).

Hence, the equipment response in VDM is modeled using the following equation (Huang and Won, 2000; Andrade et al. 2016; Moura De Andrade and Fischer, 2017)

\[ H_s = \rho^3 \int_0^\infty R(\lambda) \lambda^2 e^{-2\lambda h} J_0(\lambda \rho) d\lambda \quad (12) \]

Consequently, following a similar procedure, the magnetic field along the magnetic dipole direction observed at the receiver position when carrying the equipment in HDM and in a LIN scenario:

\[ H_{z(x)} = -\frac{1}{4\pi} \int_0^\infty 2 \int_0^2 \left( e^{-\lambda z+h} - r e^{\lambda (z-h)} \right) \lambda J_1(\lambda \rho) d\lambda \]

\[ -\frac{1}{4\pi \rho^2} \int_0^\infty \left( e^{-\lambda(x+h)} - r e^{\lambda (x-h)} \right) \lambda^2 J_0(\lambda \rho) d\lambda \quad (B13) \]

And the equipment’s response will be modeled using the following expression (Thiesson et al. 2014):

\[ H_s = -\rho^2 \int_0^\infty R(\lambda) \lambda e^{-2\lambda h} J_1(\lambda \rho) d\lambda \quad (14) \]
Equations B12 and B14 will always be valid when working under low induction number (LIN) scenarios. To corroborate this assumption, the induction number needs to be computed ($\beta$):

$$\beta = \frac{1}{Z}$$  \hspace{0.5cm} (15)

Nevertheless, there is no global agreement of values for which the LIN approximation is valid. McNeill, 1980 estimated that $\beta \ll 1$, and recommended that LIN FDEM instruments be used in environments where $\beta < 0.23$, Wait, 1962 defined the criterion as $\beta < 0.3$ and Frischknecht, 1988 and $\beta < 0.02$.

**B.2 Geonics EM38-MK2**

For the field campaign a Geonics Limited EM38-MK2 (Fig. 1.6a) was used. It is a noninvasive and lightweight equipment (Sudduth et al. 2001; Simpson, et al. 2008) widely used to analyze the near surface spatial distribution of the electrical resistivity values (\(\Omega \cdot m\)), reverse of the electrical conductivity (S/m), and the magnetic susceptibility (SI) (Simpson, et al. 2008; Heil and Schmidhalter, 2019; Tang, et al. 2018) in the near surface. It is composed of three coils, one transmitter (Tx) that generates the electromagnetic signal with a frequency of 14.5 kHz and two receiver coils (Rx) at 1 (C-1) and 0.5 meters (C-0.5) from Tx (Fig. 1.6) that measure the primary and secondary fields.

As was mentioned in section A2.1, EMI’s measurements deliver a complex result with an imaginary component (quadrature) and a real component (in-phase). The EM38, automatically transforms the quadrature component into apparent electrical conductivity values (mS/m) whereas the in-phase component is delivered in parts per thousand (ppt).
Post-processing stages are necessary to obtain the apparent electrical resistivity and apparent magnetic susceptibility values that can provide insight about the distribution of soils or buried objects with different physical properties.

When analyzing the quadrature component of the signal, under half space conditions, and the equipment is positioned in VDM, the signal will penetrate up to 1.5 meters and 0.75 m, for C-1 and C-0.5 respectively. Whereas in a HDM mode penetration is shallower, up to 0.75 meters and 0.375 meters depth for the same separation coils, respectively (Heil, and Schmidhalter, 2015). On the other hand, when analyzing the in-phase component of the signal (involving variations in the magnetic permeability), the penetration depth is independent of the orientation of the coils and only depend on the distance between the transmitter and the receiver, therefore C-1 will penetrate up to 0.5 m and C-05 up to 0.25 m depth (Ernenwein and Hargrave, 2007; Dalan, 2008; McNeill, 2013).

B.3 The importance of magnetic measurements in archaeo-geophysical studies and the EM38 potential

The success of magnetic measurements in archaeological sites resides on the surface presence of ferromagnetic oxides (mainly magnetite and maghemite) (Le Borgne, 1955, 1960), due to pedogenic (Dalan, 2008; Simpson et al. 2008; McNeill, 2013; Bouhsane and Bouhlassa, 2018) and anthropogenic processes, which enhance the magnetization in specific areas where objects and bonfires (most common process) can be recognized (Tite and Mullins 1971; Dalan, 2008; McNeill, 2013; Urban et al. 2019). The formation and transformation process of iron oxides in soils is a complex interrelation between geochemistry, temperature, temporary weather conditions, and climate.
Magnetic enhancement associated with fires, has been explained through the hematite reduction into magnetite due to the high temperatures reached during a fire (soils can reach 300-400°C) and the oxidation of the magnetite into maghemite once the fire is extinguished (Tite and Mullins, 1971; McClean and Kean 1993; Johnson et al. 2006; McNeill, 2013; Fassbinder, 2016). Nevertheless, it has not been conclusively shown that hematite can be reduced to magnetite under natural soil conditions (Fassbinder, 2016). On the other hand, magnetic enhancement through pedogenic processes involve chemical (oxidation of ferrous iron), physical and biological (magnetite formation by soil bacteria (Fassbinder et al. 1990)) reactions in soils especially during drying periods of soil wetting/drying cycles (Le Borgne 1955, 1960). In addition, magnetic enhancement can also be caused by anthropogenic process such as allochthonous industrial pollutant particles deposited over a wide area (Dearing et al. 1996; Bouhsane and Bouhlassa, 2018). Archaeo-geophysical studies usually perform magnetic surveys with magnetic techniques to recognize occupational areas associated with susceptibility magnetization enhancement (Tite and Mullins, 1971; Desvignes and Tabbagh, 1995; Dalan, 2008).

Magnetometer surveys are used to define spatial variations or anomalies in the Earth’s magnetic field and make no distinction between induced\(^6\), remanent magnetization\(^7\), and sources at different depths (McClean et al. 1993; Dalan, 2008). In contrast, magnetic susceptibility measurements derived from EMI systems only map the induced component, which has several advantages over the magnetometer measurements: (i) susceptibility

---

\(^6\) Induced magnetization: Magnetization of a sample measured in the presence of an induced magnetic Field (Dalan, 2008).

\(^7\) Remanent magnetization: Magnetization of a sample in the absence of an external magnetic field (Dalan, 2008).
anomalies are simpler because they show a single high reading over a magnetic feature and not a dipole signal as the magnetometer (Dalan, 2008; McNeill, 2013), (ii) EMI equipment will not have problems detecting underground feature with diffused boundaries, whether a magnetometer will (Dalan, 2008) and (iii) EMI equipment are sensible to thin horizontal layers of a susceptible material, and because the different depths of penetrations achieved with both coils and operation modes there thickness can be estimated (McNeill, 2013). Nevertheless, it is always important to keep in mind, that magnetometers will be able to detect deeper, but broader, features than EMI techniques (Simpson et al. 2008).

Based on the above, EMI sensors are a promising and useful technique for archaeological exploration (Dalán & Bevan, 2002; Witten et al. 2003; Simpson 2008; McNeill, 2013), because of high spatial resolution measurements and the simultaneous measurement of the electric and magnetic component (Simpson, et al. 2008; Heil and Schmidhalter, 2019; Tang, et al. 2018).

**B.4 Magnetic Susceptibility Modelling**

The magnetic phenomena is represented in equation (B12) as the real part of the solution, and depends on the magnetic permeability of the ground that conditions the reflection coefficient.

\[
H_i = \rho^2 \lambda \left( \lambda^2 + \frac{2 e^{-2\lambda h} f_0(\lambda \rho)}{2 \pi} \int_0^\infty e^{-2\lambda h} f_0(\lambda \rho) d\lambda \right) \quad (B12)
\]
The primary magnetic field induces a secondary magnetic field in which eddy currents flow through the underground as a function of the magnetic permeability (μ). Therefore, the measured field corresponds to the sum between the primary magnetic field in free space (μxH) and the ability of the medium to become magnetized (μxHxμμ). Hence, the relation between magnetic permeability and magnetic susceptibility can be described as represented in equation (B16):

$$\psi = \psi_0(1 + \psi) = \psi$$  \hspace{1cm} (16)

Where the magnetic susceptibility is the only unknown value (μμ) because the resulting magnetic field is being measured (B), H is known (source) and μ0 is a constant (4πx10^{-7} H/m).

The magnetic permeability is located inside the Bessel integral of equation A2.12 without any analytical way to extract it. Therefore, it is necessary to model the quadrature response of a half space medium as a function of a family of magnetic permeabilities, to compare with the observations and extract the magnetic permeability value that achieves the best fit. Bessel equation is resolved using digital filter approach proposed by Guptasarma & Singh, (1997) to model the phenomena, where the integration variable is:

$$\lambda_{ii} = \phi \frac{1}{\pi} x 10^{a + (i-1)b}, \ ii = 1,2, ..., n \quad (B17)$$

Parameters a and b are Guptasarma & Singh (1997) constants considering the 120-parameter digital filter for the zero order Bessel’s function (VDM) and the 140-parameter digital filter for the first order Bessel’s function (HDM).

Because magnetic susceptibility field measurements were performed during the field campaign, the modeled phenomena is presented as a function of the magnetic
susceptibility, even though, the modeled was computed with the magnetic permeability property. Transformation between permeability and susceptibility was done using equation (B16)

For the theoretical functions, considered scenarios of electrical resistivity between $1-10^4 \ \Omega m$ and magnetic susceptibility between $10^{-6}-10^{-2.5} \ SI$ were considered. However, the MATLAB code allows the adjustment of the range of values for both variables.

Figures B.1 and B.2 present the quadrature and in-phase model for both coil separation (C1 and C-05) and equipment orientation (VDM and HDM) carrying the equipment 10 cm above the surface.

In both VDM and HDM orientations, the quadrature response is independent of the magnetic susceptibility and has a similar distribution (Fig. B.1a, B.1b, B.2a, B.2b).

Nevertheless, the in-phase response presents important variations in each orientation. According to the manufacturer, in-phase’s VDM response may be positive or negative depending on the depth of the anomaly (McNeill, 2013), which complex the analysis of the signal. As seen in Figure B.1c and B.1d the created model considers only positive in-phase values, which represent 97% and 65% of the archaeological site’s data of the C-1 and C-05 measurements respectively, therefore, only positive values were considered for the analysis.
Figure B. 1: Theoretical response with the EM38 in VDM at 10 cm above the ground with its quadrature and in-phase component for soils between $10^0-10^4$ Ω-m and $10^{-6}-10^{-2.5}$ SI. (a) Quadrature response for C-0.5, (b) Quadrature response for C-1, (c) In-phase response for C-0.5, (d) In-phase response for C-1. Color bar indicates magnetic susceptibility values between $10^{-6}-10^{-2.5}$ SI, the quadrature component and therefore the electric resistivity is independent of magnetic susceptibility variation, nonetheless the in-phase component.
Figure B.2: Theoretical response with the EM38 in HDM at 10 cm above the ground with its quadrature and in-phase component for soils between $10^0 \text{ - } 10^4 \, \Omega\cdot\text{m}$ and $10^{-6} \text{ - } 10^{-2.5} \, \text{SI}$. (a) Quadrature response for C-0.5, (b) Quadrature response for C-1, (c) In-phase response for C-0.5, (d) In-phase response for C-1. Color bar indicates magnetic susceptibility values between $10^{-6} \text{ - } 10^{-2.5} \, \text{SI}$, the quadrature component and therefore the electric resistivity is independent of magnetic susceptibility variation, nonetheless the in-phase component.

On the other hand, as the manufacturer states, HDM values will always be negative (McNeill, 2013), therefore the analysis is simpler and recommends measuring the magnetic susceptibility anomaly in HDM. Note that the modeled curves in Figure B.2c and B.2d consider mostly negative values but have some positive ones, attributed to noise, and thus not considered.
Results presented in section 1.5.2 (Fig. 1.11 and 1.12), correspond to the VDM measurements made in the archaeological site represented in grid format in Figure B.1. The created half-space model uses the quadrature and in-phase component of the signal to determine the magnetic susceptibility (represented in equation A1.12 as the magnetic permeability). The quadrature component is transformed in electrical apparent resistivity (Fig. B.1a and B.1b), later used with the in-phase component to interpolate the corresponding magnetic apparent susceptibility (Fig. B.1c and B.1d).

**B.5 Magnetic Susceptibility Modelling corroboration**

To constrain the magnetic susceptibility values obtained by the half-space modeling, magnetic susceptibility measurements were made in the excavation (see section 1.5.4), using a Terraplus KT-10 susceptibility meter (measuring range of the equipment between $10^{-6}$-1.999 SI).

The present analysis considers the thirty-two samples extracted from the excavation in the archaeological site’s studied area (Table B.1). These thirty-two samples include the 6 measurements presented in Figure 1.16, but also include roots, sediments, organic material, and coprolites enabling us to compare the modeled susceptibility values with the specific Pampa Iluga archaeological site (PIAS) background.
Table B. 1: Magnetic susceptibility measurements from the samples extracted from the excavation

<table>
<thead>
<tr>
<th>Sample N°</th>
<th>Depth</th>
<th>Magnetic Susc. (10^{-3} SI)</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.10</td>
<td>6.94</td>
<td>Burned Sediment</td>
</tr>
<tr>
<td>2</td>
<td>0.10</td>
<td>0.10</td>
<td>tree trunk</td>
</tr>
<tr>
<td>3 (3a)</td>
<td>0.10</td>
<td>2.92</td>
<td>Sediment + Leaves</td>
</tr>
<tr>
<td>4 (2a)</td>
<td>0.10</td>
<td>7.67</td>
<td>Burned (Sediment + Leaves)</td>
</tr>
<tr>
<td>5 (1a)</td>
<td>0.10</td>
<td>1.52</td>
<td>Sediment + Leaves</td>
</tr>
<tr>
<td>6</td>
<td>0.18</td>
<td>1.20</td>
<td>Sediment</td>
</tr>
<tr>
<td>7</td>
<td>0.20</td>
<td>0.33</td>
<td>Comprolite</td>
</tr>
<tr>
<td>8</td>
<td>0.20</td>
<td>0.01</td>
<td>Roots</td>
</tr>
<tr>
<td>9</td>
<td>0.20</td>
<td>0.01</td>
<td>tree trunk</td>
</tr>
<tr>
<td>10</td>
<td>0.20</td>
<td>5.15</td>
<td>Burned Sediment</td>
</tr>
<tr>
<td>11</td>
<td>0.20</td>
<td>4.85</td>
<td>Comprolite</td>
</tr>
<tr>
<td>12</td>
<td>0.20</td>
<td>0.64</td>
<td>Sediment + Leaves</td>
</tr>
<tr>
<td>13</td>
<td>0.20</td>
<td>0.23</td>
<td>-</td>
</tr>
<tr>
<td>14 (2b)</td>
<td>0.20</td>
<td>3.94</td>
<td>Sediment + Leaves</td>
</tr>
<tr>
<td>15 (1b)</td>
<td>0.20</td>
<td>5.43</td>
<td>Burned (Sediment + Leaves)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>-------</td>
<td>-------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>16 (3b)</td>
<td>0.20</td>
<td>6.41</td>
<td>Burned (Sediment + Leaves)</td>
</tr>
<tr>
<td>17</td>
<td>0.20</td>
<td>0.02</td>
<td>tree trunk</td>
</tr>
<tr>
<td>18</td>
<td>0.20</td>
<td>0.04</td>
<td>tree trunk</td>
</tr>
<tr>
<td>19</td>
<td>0.20</td>
<td>0.03</td>
<td>tree trunk</td>
</tr>
<tr>
<td>20</td>
<td>0.20</td>
<td>0.01</td>
<td>tree trunk</td>
</tr>
<tr>
<td>21</td>
<td>0.67</td>
<td>8.72</td>
<td>Sediment</td>
</tr>
<tr>
<td>22</td>
<td>0.85</td>
<td>5.45</td>
<td>Sediment</td>
</tr>
<tr>
<td>23</td>
<td>1.00</td>
<td>2.25</td>
<td>Sediment</td>
</tr>
<tr>
<td>24</td>
<td>1.15</td>
<td>5.33</td>
<td>Sediment</td>
</tr>
<tr>
<td>25</td>
<td>-</td>
<td>0.01</td>
<td>tree trunk</td>
</tr>
<tr>
<td>26</td>
<td>-</td>
<td>0.00</td>
<td>tree trunk</td>
</tr>
<tr>
<td>27</td>
<td>-</td>
<td>4.19</td>
<td>Sediment + Leaves</td>
</tr>
<tr>
<td>28</td>
<td>-</td>
<td>12.97</td>
<td>Gravitational colapse sample</td>
</tr>
<tr>
<td>29</td>
<td>-</td>
<td>6.31</td>
<td>Sediment</td>
</tr>
<tr>
<td>30</td>
<td>-</td>
<td>12.50</td>
<td>Alluvial material + Leaves</td>
</tr>
<tr>
<td>31</td>
<td>-</td>
<td>10.35</td>
<td>-</td>
</tr>
<tr>
<td>32</td>
<td>-</td>
<td>0.01</td>
<td>tree trunk</td>
</tr>
</tbody>
</table>

(-) indicates that the information is not available.
Figure B.3 summarizes the central tendency measures of the susceptibility measurements for the C-1 and C-05 modeled results and the excavation’s samples of the Pampa Iluga archaeological site (PIAS).

![Magnetic Susceptibility Measurements Comparison](image)

When comparing C-1 and C-05 modeled results with the PIAS measurements, it is important to note that the PIAS range of susceptibility values (average $3.61 \times 10^{-3} \pm 3.88 \times 10^{-3}$ SI) is greater than C.05 (average $1.69 \times 10^{-3} \pm 1.51 \times 10^{-3}$ SI) and C-1 (average $1.09 \times 10^{-3} \pm 7.49 \times 10^{-4}$ SI) and that it includes them.

However, median values of both modeled coil results (C-0.5 = $1.22 \times 10^{-3}$ SI, C-1 = $9.38 \times 10^{-4}$ SI) are least two times lower than the median values of the excavation’s samples (PIAS = $3.43 \times 10^{-3}$SI). This can be explained because EM38 measurements represent the average magnetic susceptibility of the volume penetrated by the signal. Therefore, the
modeled magnetic susceptibility is lower than the maximum values measured in-situ because it measures an average of values along the whole soil column in each site, which include the high magnetic susceptible objects and the lower magnetic susceptible background.

The previous brief analysis allows to constrain the modeled magnetic susceptibility values and therefore present them as a promising result in this thesis. Nevertheless, it is important to emphasize that this specific methodology has only been evaluated in this hyperarid environment and future works should evaluate the model in more conductive scenarios.

**APPENDIX C: EVAPOTRANSPIRATION ESTIMATE OF *P. TAMARUGOS* IN THE PAMPA ILUGA ARCHAEOLOGICAL SITE**

Climatic conditions in the Pampa del Tamarugal and the Atacama Desert have changed throughout history (Placzek et al. 2009; Gayo et al. 2012; Morales et al. 2020). Even though the area is considered as a hyperarid zone since the last 10 Myr and an arid one before that, climatological events such as El Niño Southern Oscillation (ENSO) or the Central Andean Pluvial Event (Placzek et al. 2009; Gayo et al. 2012) have increased the availability of water in the Pampa del Tamarugal for years in the case of ENSO or thousands-centenars of years for the CAPE.

These pluvial events did not happen in the Pampa but in the highlands, where water ran off to the valley through perennial rivers and infiltrated to the Pampa del Tamarugal aquifer, decreasing the water table depth (Gayo et al. 2012). These events happened between 17.4-14.2, ~11.8 and 1.1-0.7 ka and transformed the Pampa ecosystems characterizing them by forests of *P. tamarugo* and *Distichlis spicata*. 
On the other hand, in the present, the area is characterized by high radiation rates throughout the entire year, low precipitations (less than 10 mm/yr below 2000 m.a.s.l (Houston, 2006; Viguier et al. 2018)) and a constant increase in the water table depth due to excessive water extraction (Viguier et al. 2018) since 1990 (Chávez et al. 2016) that has threatened the survival of *P. tamarugos* in the area (CONAF, 1997).

With the tree’s discovery in the archaeological site (section 1.5), questions regarding the climatic conditions under which these trees developed and the amount of water that they need have arisen. In order to answer some of these questions, the appendix seeks to make a gross estimate of the trees’ evapotranspiration to preliminary estimate the amount of water that these plants needed for its survival in the Pampa del Tamarugal. Two assumptions are presented which will condition the computation of the ET rates:

1. Trees in the archaeological site will be considered as *P. tamarugo*

2. Most amount of water loss will be associated with evapotranspiration (ET)

For the analysis, hourly radiation, temperature, and wind velocity of the past 4 years will be used. Even though climatic conditions and water availability were more favorable when the *P. tamarugo* developed, today’s data will allow the estimate of ET rates in the worst scenario (null precipitation, high radiation, and low water table).

In order to estimate the ET rates for the Pampa Iluga surface, the problem will be divided in two scenarios, (i) a desert scenario where no trees or vegetation covers the surface\(^8\) and (ii) a *P. tamarugo* scenario which considers that the whole surface is covered by trees.

---

\(^8\) The Penman-Monteith equation is specifically postulated to evaluate the evapotranspiration of plants. Nevertheless, the desert scenario, which do not consider the presence of plants on the surface will assume that the soil opposes an infinite canopy resistance to ET, and therefore, the Penman-Monteith equation is applicable.
Both ET rates will be averaged according to the area that each of them covers in 1 Ha of the archaeological site, therefore:

\[
ET_{P.\,Ilula} \cdot \frac{3}{3} = \frac{ET_{P.tam}}{Ha} \cdot \frac{3}{3} \cdot (Ha) + ET_{desert} \cdot \frac{3}{3} \cdot (Ha) \quad (\text{1})
\]

C.1 Glossary

A brief glossary is presented to help the reader familiarize with specific concepts mentioned through the appendix:

1. **Albedo (α):** the proportion of the incident light or radiation that is reflected by a surface.

2. **Aerodynamic resistance (r_a):** Resistance from the vegetation upward and involves friction from air flowing over vegetative surfaces.

3. **Evapotranspiration:** Process in which the plant looses humidity/moisture by evaporation and transpiration of its surface.

4. **Plant area index (PAI):** surface in m² that a plant covers in 1m² considering the leaves, branches, and stem.

5. **Prosopis trees:** It’s a genus, composed of 45 species of spiny trees and shrubs found in subtropical and tropical regions of America, Africa, and parts of Asia. They often thrive in arid soil and are resistant to drought, on occasion developing extremely deep root systems. In the present work the specific specie *Prosopis tamarego* (commonly known as Tamarugo) is analyzed.
6. **Stomatal resistance (rₜ):** Describes the resistance of vapor flow through stomata openings, total leaf area and soil surface.

7. **Surface emissivity (Em):** The effectiveness in emitting energy as thermal radiation. It is a dimensionless number between 0 (for a perfect reflector) and 1 (for a perfect emitter)

8. **Turgor:** the state of turgidity and resulting rigidity of cells or tissues, typically due to the absorption of fluid.

**C.2 About the *Prosopis tamarugo***

The *P. tamarugo* is an endemic tree from the Atacama Desert, highly adapted to the high temperature oscillation between night and day, low relative humidity, high solar radiation, and almost absolute absence of precipitation (Lhener et al. 2001).

To avoid the excessive loss of water through ET and maintain a relative high-water content in the leaves, the *P. tamarugo* can perform an osmotic adjustment maintaining its turgor (Acevedo et al. 1985), with which can adjust the leaf angle to avoid direct radiation and photoinhibition (Chávez et al. 2013, Chávez and Oyanadel, 2014).

Under favorable conditions, *P. tamarugo* reach up to 25 m high and 20-30 m crown size, while under adverse conditions *P. tamarugo* reach up to 2 m high and 2-3 m crown size (Altamirano, 2006). Further on, the ET estimate will consider that the ratio between the tree’s height and the tree’s width (including the foliage) is ~ 1.

Its root system is composed by a first system of long pivoting roots that reach the groundwater table and pump water to the surface and a second system of roots distributed as a mat between 30-80 cm depth from the soil surface (Sudzuki, 1969) (Fig. C.1). Because
*P. tamarugo* extract the water from aquifers, they are distributed in areas where water table depth ranges between 4-18 m depth, (Acevedo and Pastenes 1983; Altamirano, 2006) and are unable to reach the reservoirs if the water table depth is deeper that 20 m depth (Calderon et al. 2015).

Since 1993, a decline in the water table, which has been accentuated since 2003 has been recognized (Calderon et al. 2015; Chávez et al. 2016) because human extraction for mining activities and drinking water (Rojas and Dessargues, 2006; Rojas et al. 2010; DGA 2011) exceed the recharge rates of the aquifer, affecting the *P. tamarugo* development. Figure C.1 extracted from Calderon et al. 2015, schematically presents the effects of the water table depth decrease in the *P. tamarugo*.

![Figure C.1](image)

**Figure C.1:** Figure 2 extracted from Calderon et al. 2015 which took the *P. tamarugo* drawing from Sudzuki, 1969. Physiological events triggered at various water table depths in *P. tamarugo* Phil. Tamarugo maintains its water status to a groundwater depth
of approximately 10 m, beyond this depth, the trees start to decrease their predawn water potentials. Early senescence and twig growth diminishment are the first mechanisms in the sequence, followed by twig death caused by xylem cavitation. This biomass reduction strategy contributes to reduce water demand.

C.3 Methodology

As mentioned before total surface ET rates will be computed by averaging ET rates of the surface covered by *P. tamarugo* or directly exposed to radiation (desert’s scenario). Therefore, ET rates for the *P. tamarugo* and the desert will be computed separately, and as a final analysis, the surface proportion that each of them covers in 1 Ha will be computed, to estimate ET rates for the Pampa Iluga scenario.

Nevertheless, it is important to emphasize that the computation will consider radiation rates and climatological variables for today’s scenario, because there is no high-resolution data for the past’s conditions. Therefore, modeled results will present the worst climatic and hydraulic conditions for the *P. tamarugo*.

The Penman-Monteith equation is presented below:

\[
\frac{\Delta (R_n - G) + \rho \frac{e_s - e_a}{a}}{\Delta + \gamma \theta 1 + \frac{r_s}{\theta}} = \lambda ET
\]

Where \( \lambda ET \) = Latent heat flux (W/m²h), \( R_n \) = Net radiation (W/m²H), \( G \) = Soil heat flux (w/m²h), \( \rho_a \) = average air density (kg/cm³), \( c_p \) = Specific heat (1005 (J/kg°C), \( e_s - e_a \) = vapor pressure deficit with respect to saturation (kPa), \( r_a \) = Aerodynamic resistance (s/m), \( r_s \) = crop resistance or surface resistance (s/m), \( \Delta \) = Slope of the vapor pressure curve at saturation (kPa/°C) and \( \gamma \theta \) = piezometric constant (0.067 kPa/°C).
1. **Vapor pressure deficit**

\[
es_s(T[^\circ C]) [kPa] = 0.611 \times \exp\left(\frac{17.27 \times T}{237.3 + T}\right) \quad (C3)
\]

\[
e_a [kPa] = Hr \times e_s \quad (C4)
\]

Where \( e_s \) = saturation pressure at air temperature (kPa), \( e_a \) = air pressure (kPa), \( Hr \) = relative humidity.

2. **Mean air density**

\[
\rho_{atm} = \frac{287 \times (T + 273.15)}{\sqrt[3]{273.15 + T}} \quad (D5)
\]

3. **Net radiation**

To obtain the Net radiation, solar radiation and other parameters were used, the detailed procedure is presented below:

\[
Air\, s\, emissivity\, (E) = 1.72 \times \frac{\sqrt{\frac{273.15 + T}{\alpha}}}{\alpha} \quad (D6)
\]

\[
Air\,'s\, emissivity\, (cloud\, coverage\, (E_{cn})) = (1 - 0.84 \times CN) \times E + (0.84 \times CN) \quad (C7)
\]

\[
\text{Long wave radiatiion} (R_{LW}) = E_{cn} \times 5.67 \times 10^{-8} \times (T + 273.15)^4 \quad (C8)
\]

\[
\text{Surface long wave radiatiion} (L_u) = E_m \times 5.67 \times 10^{-8} \times (T_{sur} + 273.15)^4 \quad (C9)
\]

\[
\text{Net radiatiion} (R_n) = R_s - (\alpha \times R_s) + E_m \times R_{LW} - L_u \quad (C10)
\]

Where, \( CN \) = cloud coverage, \( T_{sur} \) = surface’s temperature (°C), \( \alpha \) = surface’s albedo, \( E_m \) = surface emissivity.

4. **Soil’s heat flux:**

\[
G\, [W/m^2hr] = day[R_n \times 0.1 \text{ and night}[R_n \times 0.05] \quad (C11)
\]

5. **Aerodynamic resistance:**
Approximated as

\[ \frac{208}{u \cdot s'} \]  \hspace{1cm} (12)

Where \( u \) = wind’s velocity (m/s).

6. Piezometric constant

\[ \frac{208}{u \cdot s'} \]  \hspace{1cm} (13)

Where, \( P_{\text{atm}} \) = atmospheric pressure (kPa), \( s' \) = molecular weight ratio of water vapor/dryair (0.622).

"Latent heat of vaporization" \( \lambda \) = \( (2501 - 2.375 \cdot T) \cdot 1000 \) \hspace{1cm} (C14)

7. Slope of the vapor saturation pressure curve

\[ \Delta = 4098 \cdot 0.6108 \cdot \exp \left( \frac{17.27 \cdot T}{237.3 + T} \right) \]  \hspace{1cm} (15)

Solar radiation (W/m²h), atmospheric pressure (kPa), mean air and surface temperature (°C), relative humidity (%) and wind’s velocity (m/s) were obtained from the meteorological network of the Instituto de Investigaciones Agropecuarias of Chile (INIA) and correspond to Pica’s station data (Tarapacá region), the closest station to the archaeological site with a time series between 2018 and 2022⁹ (Table C.1).

<table>
<thead>
<tr>
<th>Year</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
</tr>
</thead>
</table>

⁹ The time lapse between 2018-2022 used for the ET estimates was chosen because previous May 2018, the station did not deliver continuous data.
The specific albedo value associated with the *P. tamarugo* species was not found, therefore, the estimated value from Houspanossian et al. 2013 was considered.

<table>
<thead>
<tr>
<th>Period</th>
<th>May - December</th>
<th>January - December</th>
<th>April - December</th>
<th>January - December</th>
<th>January - April</th>
</tr>
</thead>
</table>

Data prior 2018 is not considered because the station was not constantly available.

The remaining parameters: albedo ($\alpha$), emissivity ($E_m$), stomatic resistance ($r_s$) where obtained from a bibliographical review associated with the Atacama Desert and *P. tamarugo* parameters.

For the desert scenario, the albedo will vary between 0.2-0.45 and the surface emissivity between 0.84-0.90 both obtained from Geophysics’ department of Universidad de Chile.

With respect to the stomatic resistance, 3 scenarios will be considered: (i) soil does not oppose resistance to ET, $r_s = 0$ s/m, (ii) soil opposes the same resistance as average plants $r_s = 100$ s/m (commonly used vegetal resistance for plants) and (iii) because there is no water on the surface and soil moisture content is almost null, $r_s = 500,000$ s/m to force extremely low ET rates.

On the other hand, for the *P. tamarugo* scenario, the albedo will vary between 0.12-0.15, parameter obtained from dry forests in semi-arid climates of central Argentina (Houspanossian et al. 2013)\(^{10}\) and the surface emissivity for forests will be considered 0.975 according to the Geophysics’ department of Universidad de Chile.

Finally, the vegetal resistance range was extracted from Time and Acevedo, 2021, which has estimates for *P. tamarugo* that consider $r_s$ values between 100 – 350 s/m. The modeling of the stomatic resistance is an important parameter when analyzing ET rates in plants. $r_s$ will vary through the day depending on water availability and solar radiation,

---

\(^{10}\) The specific albedo value associated with the *P. tamarugo* species was not found, therefore, the estimated value from Houspanossian et al. 2013 was considered
therefore $r_s = 100, 225$ and $350 \text{ s/m}$ seek to represent conditions of low, medium, and high-water stress in plants, to simplify the analysis, the parameter will be considered constant through the day.

Tables C.2 and C.3 present a summary of all parameter’s that will be used for the analysis. The standard column represents the parameter’s values when other ones are varied.

**Table C.2: Desert parameter’s ranges**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Standard</th>
<th>Modelling cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albedo</td>
<td>0.2</td>
<td>0.2 – 0.30 – 0.45</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.85</td>
<td>0.85 – 0.90</td>
</tr>
<tr>
<td>Vegetal resistance (s/m)</td>
<td>0</td>
<td>0 - 100 – 500,000</td>
</tr>
</tbody>
</table>

**Table C.3: Algarrobo-Tamarugo scenario parameter’s ranges**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Standard</th>
<th>Modelling cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albedo</td>
<td>0.12</td>
<td>0.12 - 0.15</td>
</tr>
<tr>
<td>Vegetal resistance (s/m)</td>
<td>137</td>
<td>100 – 225 - 350</td>
</tr>
<tr>
<td>Tree’s height (m)</td>
<td>2</td>
<td>1 – 2 – 3</td>
</tr>
</tbody>
</table>

**C.4 Results and analysis**

**Desert’s scenario**

Figure C.2, shows the results for the desert’s ET estimates versus albedo, surface emissivity and surface resistance. Every estimated ET rate will be compared to the
standard scenario defined in Table C.2, which considers an albedo = 0.2, emissivity = 0.85 and $r_s = 0$. For this specific scenario monthly ET rates have maximum and minimum values of 173 mm/month and 70 mm/month respectively and a mean value of 120.7 mm/month, this scenario represents the potential (maximum ET rates if the desert had water to evapotranspirate) ET rates of the desert’s scenario.

With respect to the modeled parameters, as the albedo increases, ET rates decrease a 15% for the 0.33 albedo (mean =102.5 mm/month) and 37.5% for the 0.45 albedo (mean = 75.3 mm/month) (Fig. C.2a). This can be explained because, the higher the albedo, higher is the reflected energy, and therefore, less energy is absorbed and available to evaporate water.

On the other hand, emissivity does not considerably influence ET rates (Fig. C.2b), and a decrease of 1.5% is observed when comparing the mean values for the standard scenario ($Em = 0.85$) and the 0.9 emissivity value (mean = 118.8 mm/month).

Finally, with respect to the stomatic resistance (Fig. C.2c), which in this case is considered as the surface resistance, the standard scenario ($r_s = 0$ s/m) presents the maximum ET rates, which decrease in a 2.8% when $r_s = 100$ s/m (mean = 117 mm/month), and drastically decrease (because we force it to) a 99% when $r_s = 500,000$ s/m (mean = 1.19 mm/month) (note that ET rates are so small, that is difficult to see the bar in Fig. C.2c).
Figure C. 2: ET variation rates for the Desert’s scenario varying (a) albedo [0.2, 0.3, 0.45] (b) emissivity [0.85, 0.9] (c) surface resistance [0, 100, 500,000], between May 2018 and April 2022.

Figure C.3 summaries the average monthly ET rates of the studied time series considering the real scenario where ET values are almost zero ($r_s = 500,000$ s/m). Figure C.3a shows the results in mm/month, while Figure C.3b represents the average value per month in
m$^3$/Ha, this are the values that will be considered as the ET rates for surface without $P$. *Tamarugo*.

Figure C. 3: Monthly ET rates for the standard desert’s scenario. (a) ET rates in mm/month, (b) Average ET rates in m$^3$/month Ha. For its computation, ET rates from Fig a, where averaged and transformed in m$^3$/Ha by multiplying 10.

*P. tamarugo*’ scenario

Figure C.4 presents the results for ET rate variations depending on the albedo [0.12, 0.15] and stomatic resistance [100, 225, 350] s/m. For the *P. tamarugo* ET estimate the standard scenario presented in Table C.3, considers an $\alpha = 0.12$, $r_s = 225$ s/m. It has maximum and minimum ET rates of 174.1 mm/month and 73.6 mm/month with a mean value of 122.9 mm/month.
Unlike the desert’s scenario the *P. tamarugo* one does not present important ET variations when varying the albedo (Fig C.4a). When comparing the standard value ($\alpha = 0.12$) and the 0.15 value (mean = 117.7 mm/month) a decrease of 4% is recognized.

Moreover, stomatic resistance will not generate big variations in the ET rates (Fig C.4b). When comparing $r_s = 100$ s/m (mean = 127 mm/month) with $r_s = 225$ s/m (mean = 122.9 mm/month) one can identify a decrease of 3.3% in the ET rates, while when comparing $r_s = 225$ s/m with $r_s = 350$ s/m (mean = 119.1 mm/month) the decrease will be of a 6.2%.
Figure C.5 summaries the average monthly ET rates of the studied time series considering the standard conditions ($\alpha = 0.12$, $r_s = 225$ s/m). Figure C.5a shows ET rates in mm/month, while Figure C.5b represents the monthly average ET rates in m$^3$/Ha, this are the values that will be considered as the ET rates for surface with *P. tamarugo*.

![Figure C.5: Monthly ET rates for the standard *P. tamarugo*’s scenario. (a) ET rates in mm/month, (b) Average ET rates in m$^3$/month Ha. For its computation, ET rates from Fig a, where averaged and transformed in m$^3$/Ha by multiplying 10.](image)

An important correlation in correspondence to the seasons of the year is observed in Figure C.5, higher ET rates are associated to summer with a pick in December ~ 1578.3 m$^3$/Ha, after which ET rates decrease until they reach a minimum value in June ~ 778.8 m$^3$/Ha.
**Pampa Iluga’s Scenario**

In order to model the ET rates associated to the Pampa Iluga surface, ET (m³/month Ha) will be computed by averaging ET rates of the *P. tamarugo* and desert depending on the surface that each of them cover in 1 Ha.

According with the satellite images analysis, the surface that corresponds to the area where the circular features are emplaced is of 15 Ha, where 4000 circular features have been recognized. From now on it will be assumed that each circular feature corresponds to one *P. tamarugo* tree, and therefore, the site was inhabited by 4000 *P. tamarugo*.

To estimate the surface that each tree covers and therefore compute the total covered area by the trees, information about the ratio between the height and crown size will be extracted from Altamirano, 2006. The author states that under favorable conditions, *P. tamarugo* reach up to 25 m high and 20-30 m crown size, while under adverse conditions *P. tamarugo* reach up to 2 m high and 2-3 m crown size. Therefore, it will be considered that the ratio between the tree’s height and the tree’s width (including the foliage) is ~ 1.

Finally, considering that the circular features are separated from each other by 1 meter (see site description in section 1.1.2), the maximum height that the trees could have reached is 3 meters (optimistic assumption). Therefore, for the Pampa Iluga’s scenario, ET estimates will consider trees of 1, 2 and 3 meters high and the reason between there height and the covered surface will be considered ~ 1 (a tree of 1 meter high will cover 1 m² of surface).

Table C.4 summarizes the total area covered by the 4000 trees as a function of their height and the proportion of the total surface that they cover.
Table C. 4: summary of the area covered by the *P. tamarugo* in the archaeological site

<table>
<thead>
<tr>
<th>Tree’s height (m)</th>
<th>Area covered by one tree (m$^2$)</th>
<th>Area covered by the 4000 trees (Ha)</th>
<th>Percentage of area covered by the trees</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.78</td>
<td>0.31</td>
<td>2.1%</td>
</tr>
<tr>
<td>2</td>
<td>3.14</td>
<td>0.25</td>
<td>8.4%</td>
</tr>
<tr>
<td>3</td>
<td>7.06</td>
<td>2.82</td>
<td>18.85%</td>
</tr>
</tbody>
</table>

Figure C. 6: Final estimated monthly ET rates (m$^3$/Ha) in Pampa Iluga considering *P. tamarugo* of 1, 2 and 3 meters high

Of Figure C.6, it is possible to note that ET rates double and triple when increasing the height, which is not a surprise considering that the assumption under which ET rates where estimated considered a ratio of height/width ~ 1.

Nevertheless, this estimation has enabled the computation of the minimum and maximum values of ET rates as a function of the month of the year (summarized in Table C.5) and the *P. tamarugo*’s height, delivering information about ET rates during the seasons of the year.
Table C. 5: Measures of central tendency of the resulting ET rates

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Maximum ET rate (m$^3$/month Ha)</th>
<th>Mean ET rate (m$^3$/month Ha)</th>
<th>Minimum ET rate (m$^3$/month Ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees of 1 m high</td>
<td>43.3</td>
<td>33.9</td>
<td>21.8</td>
</tr>
<tr>
<td>Trees of 2 m high</td>
<td>85.36</td>
<td>66.6</td>
<td>42.5</td>
</tr>
<tr>
<td>Trees of 3 m high</td>
<td>127.4</td>
<td>99.3</td>
<td>63.3</td>
</tr>
</tbody>
</table>

As a result, one can conclude that ET rates, and therefore water demand in the archaeological site will vary from 21.8 m$^3$/Ha (considering 1-meter-high trees in June) to 127.4 m$^3$/Ha (considering 3-meter-high trees in December). The variability of the ET rates will be conditioned by the height and number of trees present in the archaeological, therefore, further studies involving these two variables are critical to understand and know the real amount of water demand in the site and the climatic conditions that enabled the development of these trees.