Geothermics 105 (2022) 102517

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

# Geophysical exploration for shallow geothermal applications: A case study in Artà, (Balearic Islands, Spain)

Cristina Sáez Blázquez [a,b,*], Ignacio Martín Nieto [a], Miguel Ángel Maté González [a,c], Pedro Carrasco García [a], Arturo Farfán Martín [a], Diego González-Aguilera [a]

[a] *Department of Cartographic and Land Engineering, University of Salamanca, Higher Polytechnic School of Avila, Hornos Caleros 50, Avila 05003, Spain*
[b] *Department of Electric, System and Automatic Engineering, Universidad de León, León, Spain*
[c] *Department of Topographic and Cartography Engineering, Higher Technical School of Engineers in Topography, Geodesy and Cartography, Technical University of Madrid, Mercator 2, Madrid 28031, Spain*

ARTICLE INFO

*Keywords:*
Shallow geothermal energy
Electrical resistivity tomography
Geophysics
GES-CAL software
Thermal behavior
Geothermal design

ABSTRACT

Within the installation of a shallow geothermal system, the lack of information on the subsoil frequently leads to errors in the design of the geothermal wellfield. This research presents the application of geophysics, combining 2D and 3D electrical resistivity tomography surveys and the geological information of a certain area for defining the structural distribution of the underground. Processed electrical resistivity data allow elucidating possible geological units and the thermal behavior of the in-depth materials. Two different assumptions (with different locations of the wells) are designed by using the specific geothermal software GES-CAL. Results show, that Case 1 (based on the geophysical results, so avoiding complex areas) allows the reduction of the global drilling length, and hence, the general initial investment of the system (around 20% lower). Meanwhile, Case 2 (without considering the geophysics) is less economically advantageous and could also present technical difficulties during the drilling process, as well as the possible alteration to the normal system operation. The study highlights the benefits of geophysics as an effective approach to characterize the underground and to help to understand its thermal behavior, which is, in turn, crucial for a proper geothermal design.

## 1. Introduction

Thus far, traditional fossil fuels have been the preferred choice for meeting the society energy needs. However, since these sources have caused more environmental damage in the past century than any other human activity, increasing attention is being paid to clean and sustainable energy. Despite its ideal characteristics, geothermal energy is one of the least known renewable energies. The use of geothermal resources for power generation and heating/cooling purposes is more than a century old, but this energy is still underdeveloped in numerous areas because of several reasons (Minissale, 2018):

- Difficulties in deciding the most appropriate areas for locating the geothermal well field or the exploration areas to greater depths when power production is intended.
- Difficulties in selecting the most appropriate prospecting methodology.
- Insufficient information about the most suitable geothermal practices when exploring, drilling, and managing the whole system operation.
- Involvement of low-qualified experts in geothermal exploration and development.
- Incorrect geothermal system operation due to uncertainties during the initial phase of designing the well field and integrating elements.

Beyond the above limitations, geothermal energy has been recognized as an alternative source for the traditional fuel energy thanks to the attractive advantages of cleanness, renewability, and cost-effectiveness (Yang et al., 2010). Shallow geothermal resources are the most widespread technologies for heating and cooling purposes in residential, industrial, and commercial buildings (Lund and Boyd, 2016), which are generally, exploited either directly or using heat pump systems coupled to ground heat exchangers (Omer, 2008). When evaluating the performance of a shallow geothermal system, it has been widely confirmed the strongly dependence on the particular site conditions. In

* Corresponding author at: Department of Cartographic and Land Engineering, University of Salamanca, Higher Polytechnic School of Avila, Hornos Caleros 50, Avila 05003, Spain.
*E-mail address:* csaeb@unileon.es (C.S. Blázquez).

https://doi.org/10.1016/j.geothermics.2022.102517
Received 6 April 2022; Received in revised form 6 June 2022; Accepted 3 July 2022
Available online 7 July 2022

**Nomenclature**

Acronyms

| | |
|---|---|
| *ERT* | Electrical Resistivity Tomography |
| *GSHP* | Ground Source Heat Pump |
| *UTM* | Universal Transverse Mercator |
| *COP* | Coefficient of Performance |
| *TRT* | Thermal Response Test |
| *NPV* | Net Present Value |

this sense, the geological, hydrogeological, and geothermal specifications must be defined before designing the heat pump installation (Blum et al., 2011; Blázquez et al., 2016; Blázquez and Cristina, 2017). Geological investigations and geothermal mapping have been made worldwide in the past decades, constituting a useful tool when specific information of the site is not available. In this context, different research works have been focused on the development of GIS data bases and maps to estimate the shallow geothermal potential of certain areas (Ondreka et al., 2007; Bertermann et al., 2013; García-Gil et al., 2015; Noorollahi et al., 2017; Blázquez et al., 2017). However, this information is often insufficient to carry out an accurate analysis of the area and additional specifications of the site are required. When testing the shallow geothermal energy potential, it is common to use different methodologies that combine theoretical and technical data, such as numerical simulations, geochemical, hydrologic, and ground geophysical surveys, among others (Song et al., 2018; Yao et al., 2018; Besser et al., 2018; Blázquez et al., 2020; Chambefort et al., 2016).

### *1.1. Geophysical exploration in shallow geothermal practices*

From the mentioned most common approaches, geophysical applications are especially significant in the geothermal field. These methods have been routinely applied in the geothermal decision making, being often included in the geothermal exploration program as a reasonable starting point. Depending on the case, the aim of these tests can be to delineate a geothermal resource or to locate aquifers or structures that can control the location and design of the well field. From the first geophysical exploration step, it is possible to perform the design of the shallow geothermal system by considering the specific conditions of the site such as the prevailing subsoil materials, the geological structures, or the thermal characteristics (CHEN et al., 2020; Sáez Blázquez et al., 2020). Since the use of geothermal energy is frequently shot down because of the relatively high start-up costs and long-term commitment, a reliable and logical exploration and a proper latter design can mean significant savings in the latter stages of drilling and components integration. Future possible problems in the geothermal system operation can only be avoided if the ground has been accordingly characterized.

In function on the specific geophysical technique, crucial information about a certain geothermal site is obtained. In this sense, electrical and electromagnetic prospections constitute the most powerful practices when carrying out a geothermal investigation (Fadillah et al., 2015). The application of these methods enables the location of potential geological structures, as well as the detection of faults and cavities, altered and mineralized zones, or the identification of the geothermal fluid's properties. Electrical Resistivity Tomography (ERT) has long been considered a powerful technique within the exploration of both deep and shallow geothermal resources (Bibby et al., 1992; MAHMUT et al., 2011; Bibby et al., 2005; Hermans et al., 2012). In this sense, ERT is also an excellent tool for better designing Ground Source Heat Pump (GSHP) applications and to prevent any component's failure (Arato et al., 2015; Nieto et al., 2019).

In the context of designing such geothermal systems from a multidisciplinary approach, this research presents the application of ERT prospecting surveys in a certain area as well as its geological characterization to finally evaluate the most suitable GSHP system. The final aim is to highlight the benefits of these exploration techniques when characterizing the underground to ensure the proper operation of the geothermal system but also to optimize the configuration of the well field and the corresponding elements of the system. For this, the paper is organized as follows: first, information about the geological and geothermal conditions of the study area and the geophysical methodology is provided. Then, results of the ERT prospecting are presented, as well as the discussion of its influence on the global design of a certain GSHP system. Finally, the paper ends with the conclusions and future perspectives of applications of the method in the geothermal field.

## 2. Materials and method

### *2.1. Initial description of the study area*

The study site here considered is in the region of Artà on the island of Mallorca (Balearic Islands, Spain). The tourist characteristics of the area make it an ideal location for the establishment of a hotel complex and so, and excellent study case for considering the implementation of a GSHP system as the solution for covering the energy demand. The following subsections include the geological and geothermal conditions of the mentioned area under study.

#### *2.1.1. Geological setting*

The Balearic Islands are the NE prolongation of the Betic orogen, and Early Miocene belt. The stratigraphic history of Mallorca includes deposits ranging from Carboniferous to Quaternary, being the Tertiary an important gap of its geology. The sedimentology of the existing materials is complex and greatly varies depending on the sedimentary environments (Adams, 1988; Fornós and Gelabert, 2011). The thickness of the stratigraphic sequence is approximately 3.000 m, constituting the carbonate rocks the majority. The oldest materials found in the island are Carboniferous grey perlites interlayered with quartz sands, showing weak metamorphism and the effect of the Hercinian orogeny in the form of intense cleavage folding.

Regarding the Mesozoic deposit (over 1.500 m thick), Triassic, Jurassic and Cretaceous rocks constitute most of the outcrops in the main mountain ranges and in some of the small hills at the central area. Cenozoic rocks are widely represented in the island, exceeding 1.500 m in thickness.

In essence, the geological architecture of Mallorca could be explained as the results of a three-fold complex evolution, involving sediment accumulation (principally through Mesozoic times), compressive tectonics during the continental collision and extensional processes from the Upper Neogene to Quaternary (Ginés et al., 2012; Arenas et al., 2007).

As Fig. 1 shows, the area included in this research is specifically constituted by Triassic deposits, mainly dolomite materials (IGME). There is an alternation of gray limestones and black marls and colluvial ridges with clayey silt matrix, corresponding to discharge cones and hillside torrents, reaching great development in the western part with gravels and blocks of dolomitic elements.

#### *2.1.2. Geothermal history*

Mallorca is the largest island of the Balearic Archipelago. The climate is characterized by hot, dry summers and mild winters, being the average annual temperature of around 16.6°C (Sumner et al., 1995). Littoral caves are frequent in the island, being most of them located along the south and east coasts in Upper Miocene reef limestones (Fornós et al., 2014).

The geothermal resources exploration carried out in Spain by the Geological and Mining Institute of Spain (IGME) brought into light the existence of geothermal manifestations in a variety of geological settings. Within the local thermal anomalies detected in the country, the

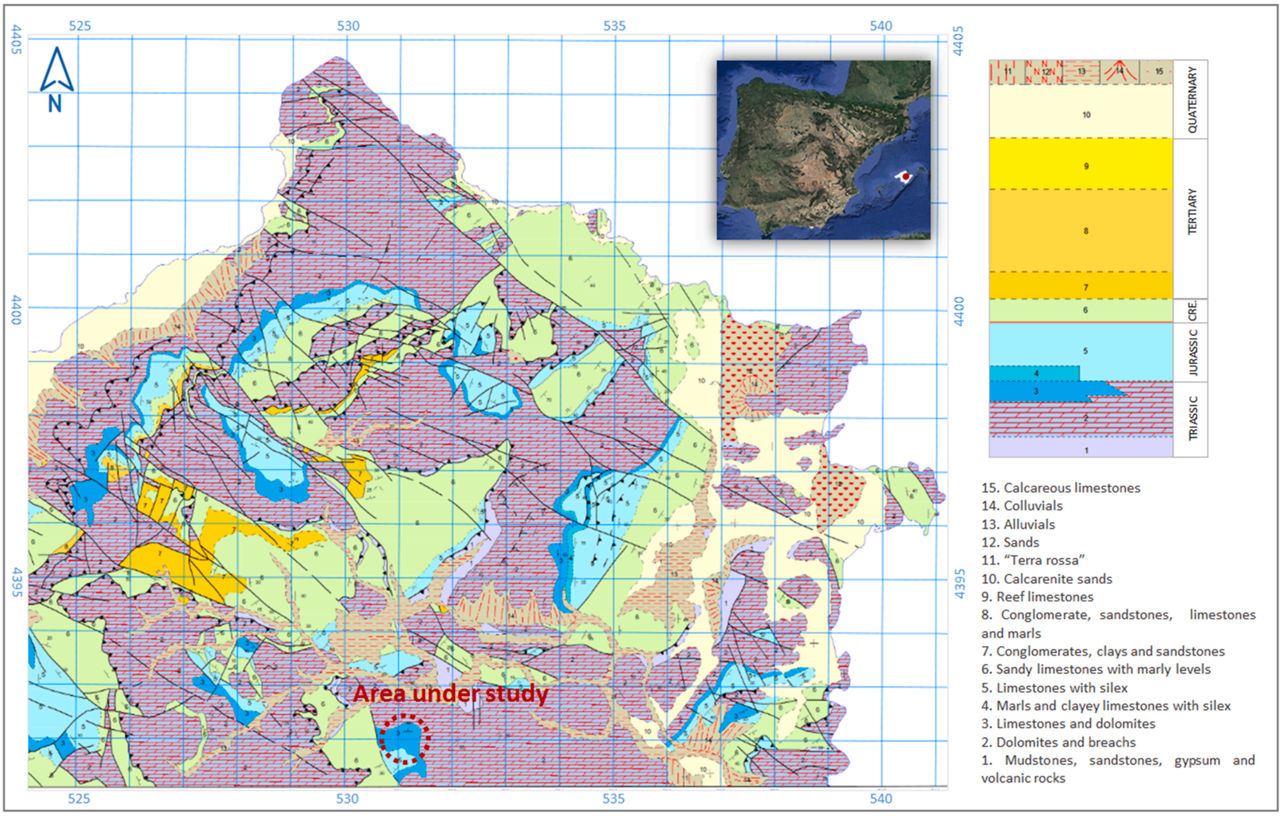


**Fig. 1.** Geological characterization of the area under study.

Betic Cordillera includes the areas of Guadalentin and Llucmajor in Mallorca. These basins are generally filled with Tertiary sediments overlying carbonate formations of considerable permeability and complex structure. In these areas, prospections have identified geothermal reservoirs at depths of less than 1000 m with temperatures in the range of 40–50°C.

Within the shallow geothermal field, the investigations carried out in the island at greater depths indicate that the geothermal potential at this level could be also relevant. However, and given the geological nature of the area, it is advisable to carry out an in-depth analysis of the possible cavities that may arise in the depths of a shallow geothermal system (Sanchez-Guzman and Noceda-Marquez, 2005).

## 2.2. Fieldwork

### 2.2.1. Electrical resistivity tomography

As commented previously, electrical resistivity tomography is the geophysical technique selected for its application in the mentioned study case. In fact, ERT is one of the most used geophysical approaches, based on resistivity contrasts to determine the earth resistivity distribution on the subsurface.

Electrical resistivity tomography has proven its efficiency in different fields (Atekwana et al., 2000; Nguyen et al., 2009; Chambers et al., 2010) and, in the context of geothermal reservoirs; ERT has been extensively applied for hydrothermal deposits to map the flow path or to analyze the heat flow and the heat storage possibilities of aquifers (Kumar et al., 2011; Chabaane et al., 2017; Carrier et al., 2018). Non-invasive surface ERT is also used as a cost-efficient method for monitoring shallow geothermal systems and analyzing the composition of the ground (Firmbach et al., 2013; Gómez-Ortiz et al., 2017; Chabaane et al., 2017; Abdullah et al., 2019).

In the case of the present research, 2D and 3D ERT prospecting campaigns were performed in the area under study for obtaining accurate information of the subsoil. 2D ERT surveys were conducted by using the equipment commercially known as SYSCAL Pro and applying the Pole-Dipole array.

Results obtained from the field were converted into pseudo-sections of apparent resistivity, creating a two-dimensional mesh. With these data of apparent resistivity, a processing is carried out, using an inversion program (RES2DINV) that performs the complete 2D inversion of electrical surface profiles for the different arrays of measurements (Rajesh and Tiwari, 2018; Yasir et al., 2019).

In this research, resistivity measurements were acquired along two profiles (69 m length and consisted of 24 electrodes with 3-m separation) directed NE-SW and NW-SE, respectively. UTM coordinates of the origin and end of the mentioned profiles and their location in the field can be observed in Table 1 and Fig. 2.

Considering the geological context of the area under study, possible cavities of variable sizes could be expected, terribly affecting the performance of a potential shallow geothermal system. For this reason, 3D ERT methodology was also applied to control lateral and depth changes and to reveal possible underground structures.

Using the same SYSCAL Pro device, 3D surveys consisted of the realization of an 8 × 6 mesh (42 × 30 m) with a separation among

**Table 1**
UTM coordinates of the origin and end of the ERT profiles and of each of the vertexes that constitute the ERT 3D mesh.

| PROFILE | X | Y |
|---|---|---|
| 1 – origin | 531.200 | 4.392.949 |
| 1 – end | 531.140 | 4.392.913 |
| 2 – origin | 531.209 | 4.392.918 |
| 2 – end | 531.144 | 4.392.942 |
| V1 | 531.143 | 4.392.931 |
| V2 | 531.179 | 4.392.950 |
| V3 | 531.159 | 4.392.905 |
| V4 | 531.195 | 4.392.926 |

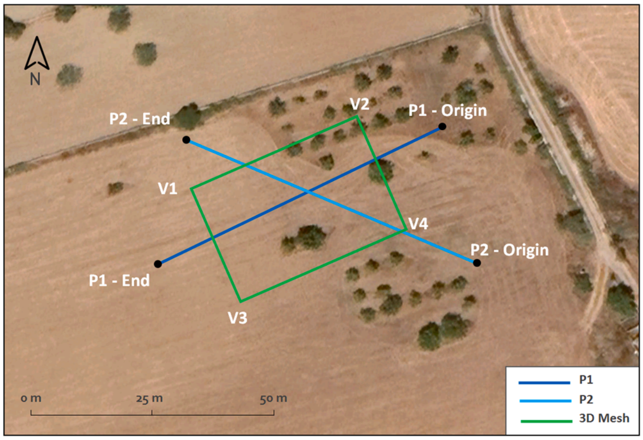


**Fig. 2.** Positioning of the 2D ERT profiles and the 3D mesh performed in the area under study.

electrodes of 6 m, distributed throughout the field (Fig. 2). 48 electrodes were needed to constitute the 3D mesh, also applying the Pole-Dipole array. Table 1 presents the UTM coordinates of each of the vertexes of the mesh and Fig. 2 allows observing the exact location in the field.

Resistivity data were subsequently inverted with the RES3DINV program (Loke and Barker, 1996) that uses a block model in which the resistivity values are assigned in the prisms within a 3D mesh, applying the least squares inversion technique with smoothing constraint.

## 3. Results

### 3.1. 2D ERT surveys

The processing of the field data allows modeling the geoelectric response of the subsoil, by obtaining resistivity sections for the investigated area. In order to associate the geophysical data (resistivity) and the ground lithology, some preliminary criteria were established. Since the parameter of the electrical resistivity depends on multiple factors, the mentioned criteria must be based on the geological information of the study area and the experience in previous geoelectric prospecting surveys in similar contexts.

The results of the interpretations of the geoelectric sections obtained from the 2D ERT profiles are represented in the following Figs. 3 and 4.

Based on the results of the 2D ERT surveys, the geological information of the study area and the electrical resistivity usually associated to each formation, the lithological units included in Table 2 can be differentiated.

### 3.2. 3D ERT surveys

As a result of processing the field data from the 3D ERT surveys, different 3D geoelectric sections were obtained for the area contemplated in the present research. As can be observed in Fig. 5, results are represented for different depth intervals; 0.00 – 2.00 m, 2.00 – 4.00 m, 4.00 – 6.00 m, 6.00 – 8.00 m, 8.00 – 10.00 m, 10.00 – 12.00 m and 12.00 – 14.00 m, with the aim of focusing on the details of the levels studied.

In addition of the above and given the possible presence of cavities in the study area (as deduced from the results of the 2D ERT surveys, Table 2), a specific data treatment was carried out for the visualization of the 3D geoelectric block (Fig. 6). These 3D blocks will be extremely helpful for defining the mentioned formations and, hence the configuration of a possible shallow geothermal system.

## 4. Discussion and results interpretation

### 4.1. Ground thermal characterization

As presented in the above section, ERT inversion results show that the range of resistivity values is considerable, from 50 to > 1000 Ω·m. According to previous experimental studies, typical electrical resistivity values for limestone materials (formations in which the study area is located) oscillate around the interval of 20 – 4000 Ω·m (Gélis et al., 2010; Comeau, 2015; Woźniak et al., 2018). From these values that constitute a valuable indicator the state of alteration of the materials, the methodology applied in this research is based on an approach to the geological processes that have originated the geological structure found from the surface to the common working depth of the electrical methods of geophysical prospecting (around 20 m). In this sense, weathering processes of the rock in situ is not the only factor to consider, (as studied in other research in granite environments), but also the issue of considering the electrical properties by composition and state of aggregation of external materials (not coming from in situ weathering of limestones) included in the strata mainly by sedimentation processes (silts, sands, etc.). As will be described later, it leads to results seldom seen in other geological environments, such as thermal conductivities that can alternate from higher to lower in layers not corresponding to their depth. Based on the interpretation of the ERT results, the following patterns can be interpreted:

(1) The near-surface area is dominated by a mixture of materials with high electrical resistivity values (more than 600 Ω·m), being the thickness of this levels around 2-4 m in most parts, but significantly smaller at the beginning and end of profile 1 and at the beginning of profile 2. These resistivity values indicate that the alteration of the materials is considerably high for the layers here included.

(2) The following deeper layer is characterized by the lowest resistivity values (50 – 250 Ω·m) with a variable thickness of 8 – 16

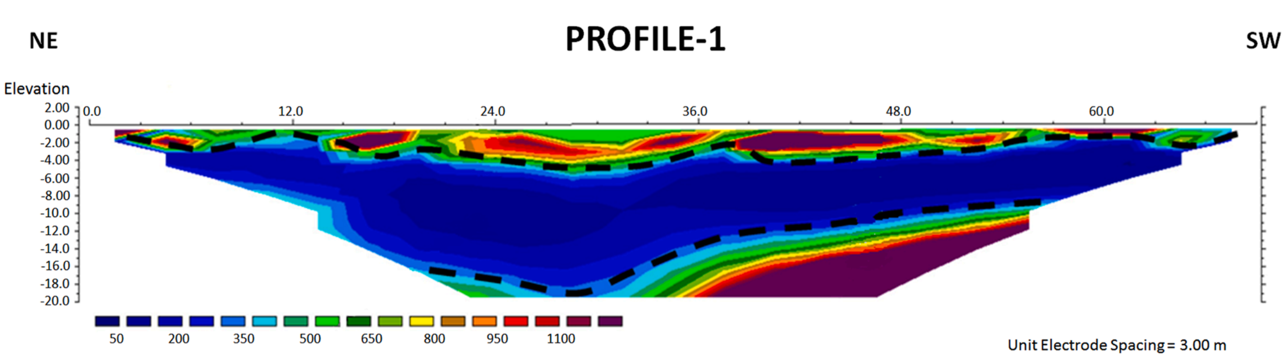


**Fig. 3.** Resistivity section obtained from the 2D ERT surveys, Profile 1.

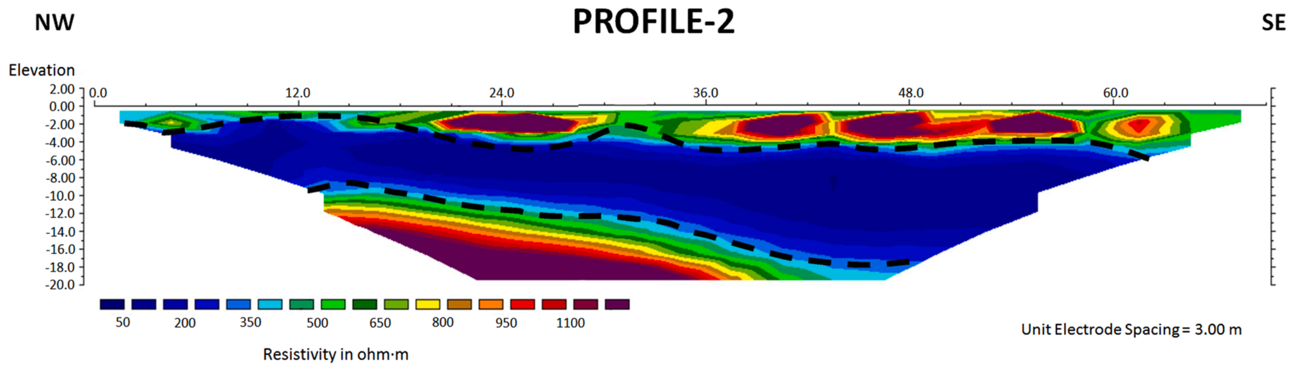


**Fig. 4.** Resistivity section obtained from the 2D ERT surveys, Profile 2.

**Table 2**
Description of the main lithological units identified in the area under study, derived from the interpretation of the 2D ERT results.

| Layer | Description |
|---|---|
| Conglomerates and altered limestone levels | Units discontinuously located at surface levels, down to depths of 2–5 m. |
| Intensively weathered conglomerates | Lithological units located up to the depth of 9–18 m. These conglomerates are characterized by low resistivity values (in the interval of 50–350 ohm·meter) possibly due to intense weathering phenomena. |
| Conglomerates and limestones partially weathered to healthy (possibility of cavities) | These levels are found at the distance of 33–55 m of Profile 1 (Fig. 3) and 12–36 m of Profile 2 (Fig. 4) as a change in depth from the previous unit to the level of 20 m. The high resistivity of these materials may indicate low weathering of conglomerates and limestones. However, the presence of cavities could be also possible since these formations are frequently characterized by high resistivity values such as the ones of this unit. |

m depending on the specific part of the profiles. The low resistivity of these layers constitutes a clear sign of the strong weathering.

(3) A final formation can be observed in the lower left corner of the 3D blocks of Fig. 6, being also perceptible in profiles 1 and 2 of Figs. 3 and 4 characterized by the highest resistivity values. The high resistivity of this unit, its nature and geometry could indicate the presence of voids-cavities. This possible cavity would be located at the depth of 11 m and could extend to more than 20 m (limit of the 2D ERT profiles).

Once the genesis, composition, and state of aggregation of the geological materials that make up the lithological column of the place have been established, it is possible to address the thermal and electrical correlation. Numerous laboratory practices have addressed the measuring of the thermal conductivity of limestones for different levels of solidity for two different conditions: air or water in the pores (Robertson, 1988). In this way, from the determination of the alteration state and solidity of the materials in the study area (from the interpretation of the ERT results), it is possible to deduce the thermal conductivity associated to each level. This thermal parameter is crucial when designing a GSHP system in a proper way that is, optimising the sizing of the geothermal components but also ensuring the correct operation of the installation during the whole lifetime period.

According to the mentioned published research and, considering that limestone pores in the study area are filled with air, the relation between the electrical resistivity of the unit and its thermal conductivity is graphically presented in Fig. 7. It is convenient to mention that, due to the specificity of the geology of the study area, this correlation is exclusive for this type of geological environment.

The above estimation of the thermal conductivity and the determination of the different geological units identified throughout the geophysical practice, make it possible to design (in an accurate way) the geothermal well field of the suggested GSHP system. It is important to highlight that this information is essential to avoid complex areas that could seriously affect the expected behavior of the global geothermal system. The probable existence of a cavity unit in the area (as suggested by the ERT) could alter the thermal exchange of the geothermal system with the ground (in addition to other geotechnical issues), so that more exhaustive designs (increasing the number of wells and hence the initial investment) would be required.

It must be mentioned that the above methodology has been successfully applied in previous author's research (Sáez Blázquez et al., 2020; Nieto et al., 2019), in which the thermal behavior of the ground (in different geological environments) has been defined. The use of shallow geophysics is well-known, but confirmation of thermal properties can be only ensured with a test bore and field test or using more accurate essays such as the Thermal Response Test (TRT). Geophysical study is usually a cost tradeoff in additional knowledge gained versus risk. In applications like the one here presented, geophysics mean a valuable practice for estimating the thermal properties of the ground and avoiding possible structures without deep drillings that would make the design process and subsequent execution of the installation more expensive.

### *4.2. Geothermal design*

With the aim of highlighting how geophysics can improve the thermal and geological knowledge of the area in which the geothermal systems will be placed, two different assumptions will be included in the geothermal design:

- Case 1: the geothermal well field is designed according to the geophysical surveys, so the area of the possible cavity will be avoided.
- Case 2: the geothermal well field is designed without previous geological information of the area so wells could be drilled in the cavity unit.

Considering the above assumptions, the geothermal software GESCAL was used to perform the corresponding designs of both GSHP systems (Bláquez et al., 2020). Given the depth of the geophysical surveys, helical heat exchangers (usually installed until depths of 15 – 20 m) were considered for the calculation of the mentioned geothermal installations.

Before carrying out the geothermal design, it is required to define the initial conditions of the system. For both study cases, the installation is

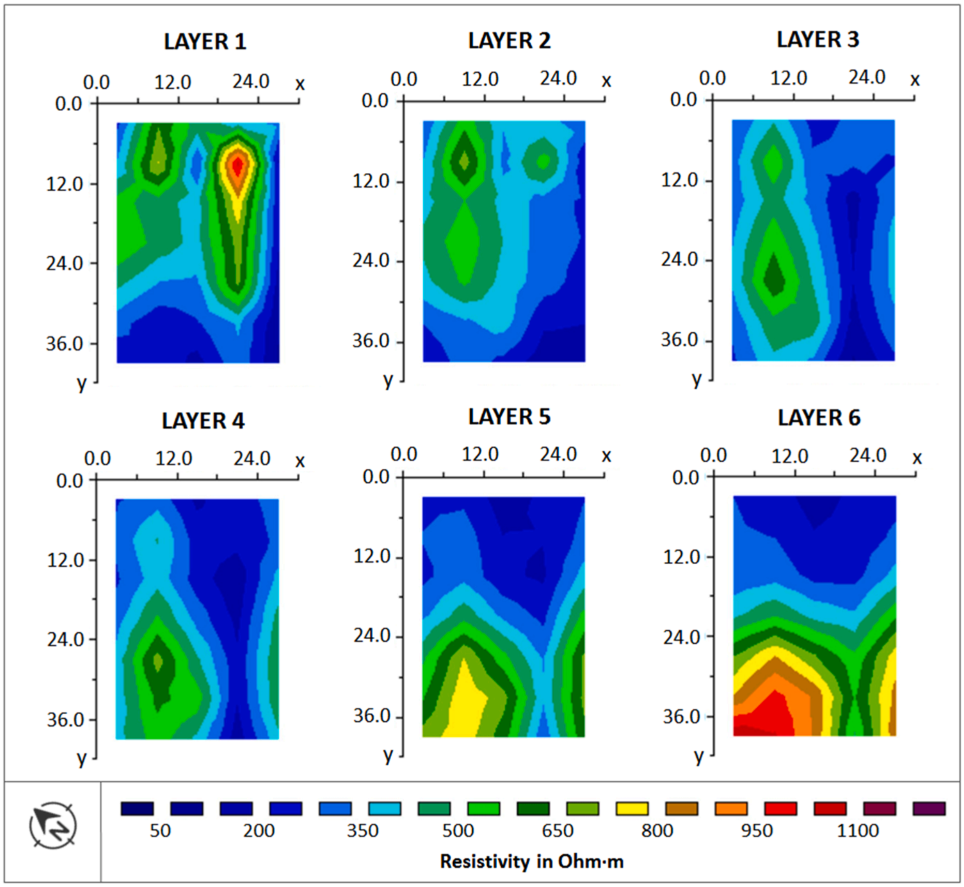


**Fig. 5.** 3D geoelectric sections for the different levels.

planned to cover the energy demand of a small hotel complex of 1200 $m^2$ of surface and 12 m high. The annual energy demand is firstly calculated applying a methodological procedure based on the Standard Regulation UNE-EN ISO 52016-1:2017 (UNE-EN ISO 52016-1 2017), that allows its estimation from the information of the building and the annual average temperatures of the area. The heating energy demand obtained for both assumptions (the same building in the same location is considered in both cases) is of 176,636 kWh/year. The cooling energy demand was not considered since it was comparatively low regarding the calculated heating demand.

Beyond the annual energy demand and the information of the geothermal system, GES-CAL software requires the introduction of the ground thermal conductivity in the area where the GSHP system aims to be installed. From the interpretation of the geophysical results and the relation of the electrical resistivity of the ground and its thermal conductivity, Fig. 8 shows the distribution of this thermal parameter and the preliminary location of the geothermal wells in each of the considered study cases. It is convenient to clarify that the area in which the possible cavity unit could be placed has been considered as a formation of almost zero thermal conductivity, provided the low thermal conductivity of the air.

Based on the thermal distribution of Fig. 8, the global thermal conductivity parameter of the ground in the location of each of the assumptions was defined. These estimations consider the thermal conductivity of each layer and its thickness according to the ERT results. The following Table 3 includes the information of the geothermal system for the assumptions here considered.

Once defined and introduced in GES-CAL software the initial conditions and characteristics of the systems and the ground thermal characterization of both cases, the tool directly calculates the parameters of the whole geothermal installation. All this information can be observed in Table 4.

In addition, GES-CAL tool is also capable of providing an estimation of the initial investment and annual operational costs required in each case, as well as the $CO_2$ emissions that will be annually emitted. The values of these items are also presented in Table 4. Since the heat pump power and its COP are identical for both study cases, also the annual operational costs and $CO_2$ emissions are the same.

As shown in Table 4, the principal difference between Case 1 and Case 2 is the configuration of the well field, and hence, the initial investment required in each solution. For performing a deeper economic analysis, one of the most common heating solutions (natural gas boiler) has been included in successive calculations. One of the additional modules of GES-CAL software includes the comparison of the geothermal solution with different traditional energy sources (such as the natural gas). In this way, from the information provided by GES-CAL for the natural gas solution (initial investment and operational costs), an exhaustive economic comparison was carried out. Considering all this information, Fig. 9 shows the economic evolution (including the initial investment and the operational costs) of each GSHP solution regarding the natural gas installation during a period of useful lifetime of 30 years.

As deduced from the above Fig. 9, despite the higher initial investment of the geothermal solutions, both study cases involve significant economic savings during the whole useful lifetime regarding the natural gas alternative. In addition, and given the difference in the initial investment of both GSHP cases, the investment associated to Case 1 would be amortized in a period of 8 years (considering the differences between its operational costs and those of the natural gas), while Case 2 would require an amortization period of 12 years. It must be also mentioned that the operational costs of each system, included in Fig. 9, are expressed according to a Net Present Value (NPV) with a discount rate of 1.8%.

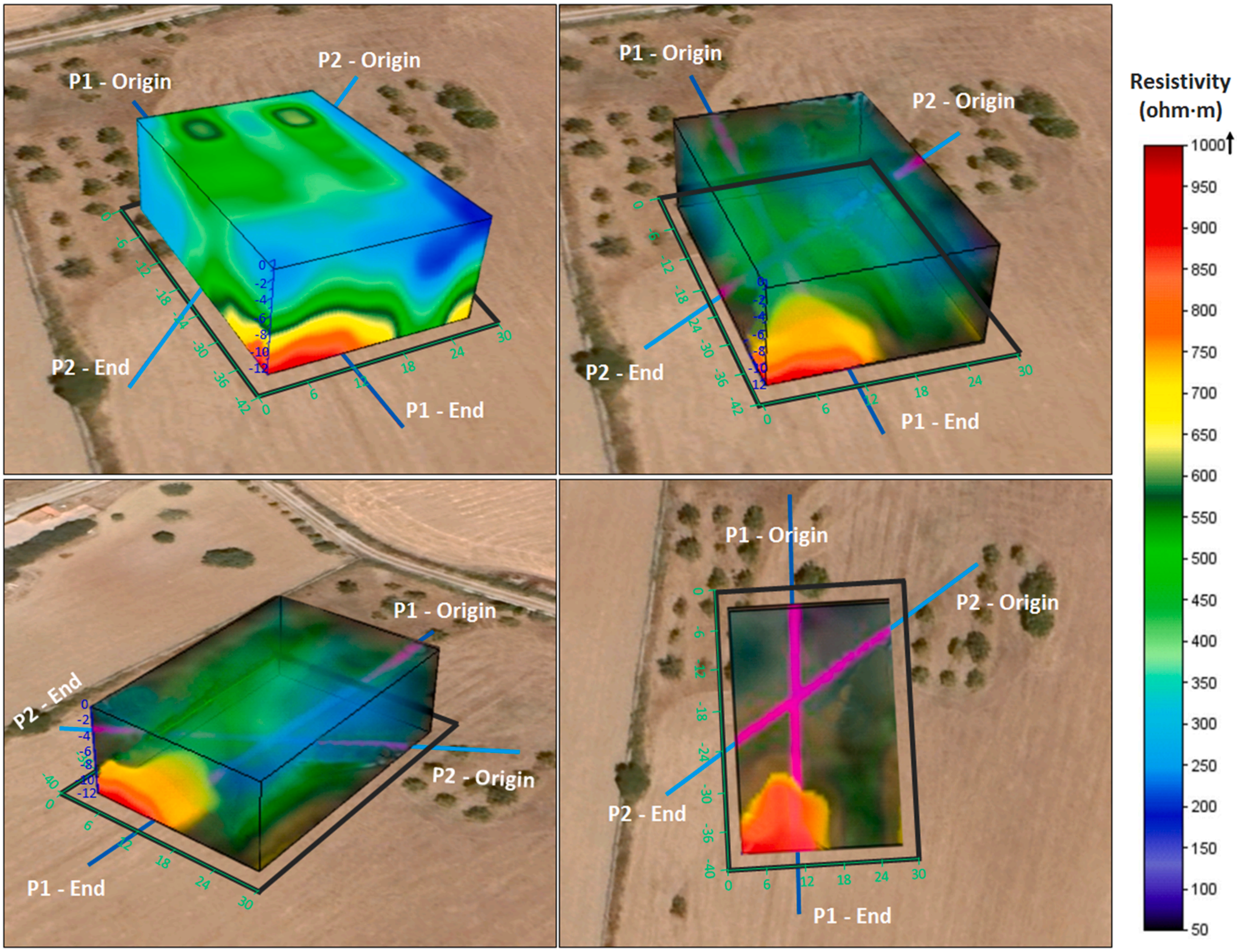


**Fig. 6.** 3D blocks obtained from the interpretation of the ERT surveys.

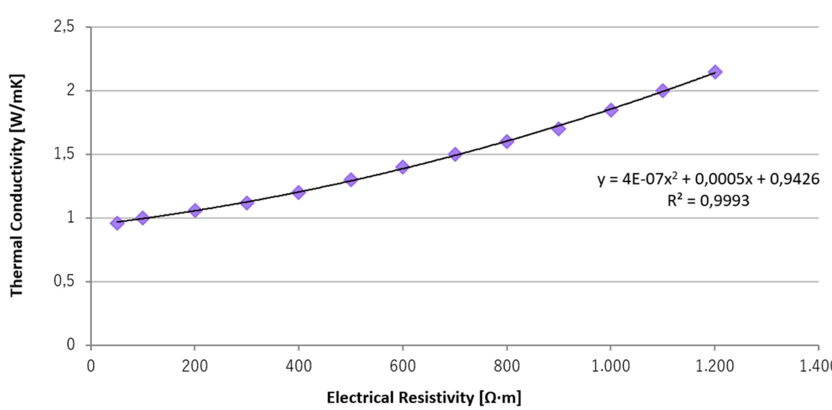


**Fig. 7.** Electrical resistivity vs. thermal conductivity for the geological context of the study.

Beyond the calculation of the most suitable geothermal system (taking into account the geological and thermal information of the subsoil), it is also considered convenient to analyze other possible geothermal solutions. In this sense, the preliminary design for a horizontal geothermal system is presented below (Table 5), also using the results on the thermal conductivity structure obtained.

Observing the previous Table 5, the initial investment required by the horizontal system is higher than that of the helical system in case 1 (based on the geophysical characterization). The principal reason is the also higher thermal conductivity of the ground at the level of the horizontal configuration. However, since the efficiency of the heat exchange (lower COP) is in this scenario lower that in the helical one, the associated annual operational costs and $CO_2$ emissions are considerably higher due to the requirements of the heat pump operation. Thus, as presented in the following Fig. 10, the helical Case 1 is still the most advisable solution considering the information of the geophysical prospecting.

In addition to the discussed alternatives, the vertical geothermal configuration would be the first option usually considered. However, given the lack of in-depth information and the existence of cavities in the

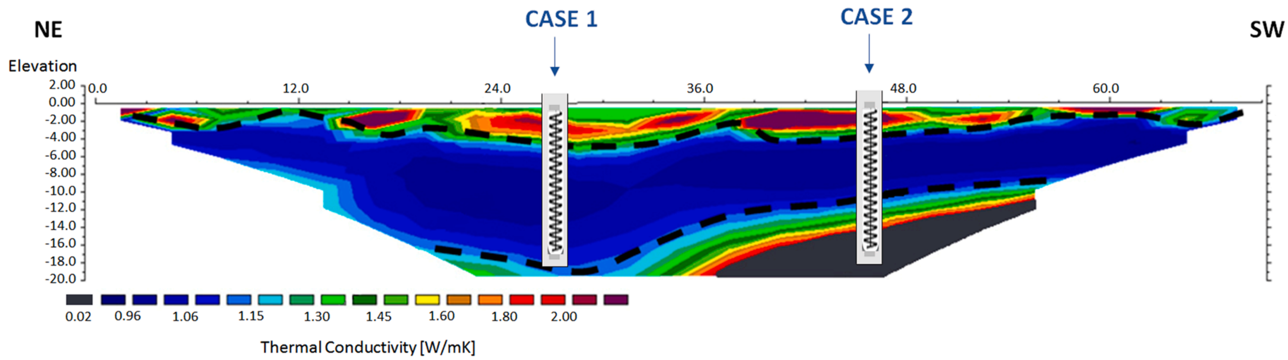


**Fig. 8.** Thermal conductivity of the ground and preliminary location of the boreholes in each study case.

**Table 3**
Initial information to be used for the corresponding geothermal design performed in GES-CAL software.

| Study case | Energy demand (kWh/year) | Ground thermal conductivity (W/mK) | Heat exchanger configuration |
|---|---|---|---|
| Case 1 | 176,636 | 1.254 | Helical |
| Case 2 | 176,636 | 0.896 | Helical |

**Table 4**
Design parameters and economic-environmental analysis obtained with GES-CAL software for both study cases.

| | Case 1 | Case 2 |
|---|---|---|
| Heat pump power (kW)* | 21.28 | 21.28 |
| Heat exchanger length (m) | 2,839.27 | 3,853.51 |
| Total drilling length (m) | 192 | 260 |
| Number of boreholes | 13 | 17 |
| Initial investment (€) | 66,412.90 | 83,274.77 |
| Annual operational cost (€) | 5,419.08 | 5,419.08 |
| Annual $CO_2$ emissions (kg) | 15,764.76 | 15,764.76 |

* In both study cases, electric heat pump with a prelaminar COP of 4 has been considered.

area, considering this type of system is not recommended in the present scenario. The presence of cavities in the planned well field could seriously affect the thermal performance of the installation, in addition to technical difficulties during the drilling process and the placement of the geothermal tubes.

## 5. Conclusions

This research focuses on presenting the advantages of geophysical exploration in the thermal and geological characterization of the ground for the design of a shallow geothermal system. The results of 2D and 3D geophysical surveys and their interpretation through existing geological documentation reveal the distribution of the underground structures and are crucial for defining the configuration of the geothermal wellfield.

In general terms, the principal findings of this research can be summarized as follows:

(1) ERT prospecting has allowed identifying those complex areas in which the operation of the future GSHP system could be seriously affected. The installation of the geothermal wells in complex units could reduce the global performance of the system (for and affect its, thus compromising the initial planned well schema. All the above could mean the uselessness of the geothermal system throughout the useful life period and the possible increase of the initially inversion.
(2) Regarding the economic aspect, avoiding the areas not recommended by the geophysical surveys, allows reducing the initial

**Table 5**
Parameters for a possible horizontal geothermal system in the study area.

| Heat exchanger configuration | Ground thermal conductivity (W/mK) | Initial investment (€) | Annual operational cost (€) | Annual $CO_2$ emissions (kg) |
|---|---|---|---|---|
| Horizontal | 1.350 | 55,959.56 | 7,865.44 | 20,651.60 |

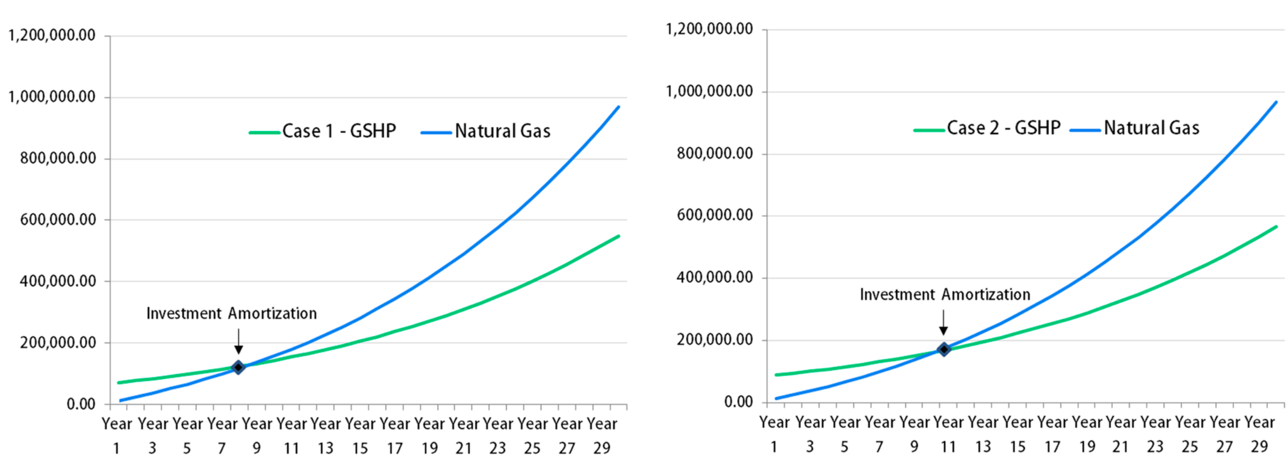


**Fig. 9.** Economic comparative of each of the proposed GSHP assumptions and the natural gas solution.

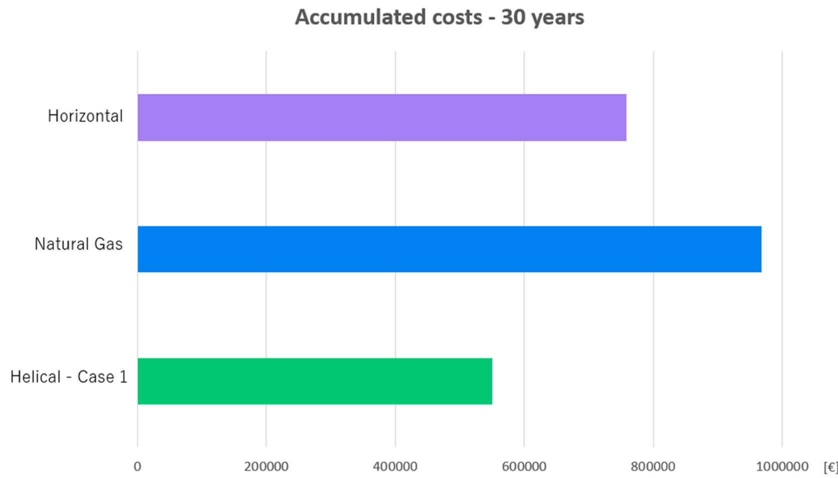


**Fig. 10.** Accumulated costs during the considered useful life for each scenario.

investment of the global shallow geothermal system. As shown in this work, Case 1 (based on ERT results) requires an inversion of around 20% lower than that of Case 2. Comparing them with the natural gas solution, initial investment of Case 1 could be amortized in a period of 8 years, while Case 2 would need 12 years, that is, a reduction in the amortization period of around 33%.

(3) Geological and geophysical surveys are needed for ensuring the correct and optimized operation of shallow geothermal solutions. This information shows that horizontal geothermal configurations could be also possible considering the accurate results of geophysics in the first levels of the ground.

(4) In the case under study, geophysics is mandatory to identify the underground structures and to perform the estimation of the thermal properties of the ground, always starting from the geology and the experience of the authors in this type of practices.

In conclusion, geophysics provides important benefits for understating the underground behavior. Even for shallow drilling systems (as the helical configurations included in this research), the knowledge of the underground structures and their thermal behavior is essential for a correct dimensioning of the geothermal system, and to ensure that the system will operate as expected in the initial planning phase. However, it should always be evaluated, based on the available information, the need or not to carry out this type of exploration, making a balance between the cost of a geophysical campaign, an exploratory borehole survey or a simple geological study.

## CRediT authorship contribution statement

**Cristina Sáez Blázquez:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Ignacio Martín Nieto:** Data curation, Methodology. **Miguel Ángel Maté González:** Investigation, Resources, Formal analysis. **Pedro Carrasco García:** Formal analysis, Validation, Supervision. **Arturo Farfán Martín:** Supervision. **Diego González-Aguilera:** Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

Authors would like to thank the Department of Cartographic and Land Engineering of the Higher Polytechnic School of Avila, University of Salamanca, for allowing us to use their facilities and their collaboration during the experimental phase of this research.

## References

Abdullah, A.I., et al., 2019. Resistivity model of hallow subsurface to find the path of geothermal manifestation in Bora Village of Sigi Regency of Central Sulawesi. J. Phys. Conf. Ser. 1242. -1.
Adams, A.E., 1988. Mallorca Geology. Departament of Extra-Mural Studies. University College.
Arato, A., Boaga, J., Comina, C., De Seta, M., Di Sipio, E., Galgaro, A., & Mandrone, G. (2015). Geophysical monitoring for shallow geothermal applications-Two Italian case histories.
Arenas, C., Cabrera, Ll, Ramos, E., 2007. Sedimentology of tufa facies and continental microbialites from the Palaeogene of Mallorca Island (Spain). Sediment. Geol. 197 (1-2), 1–27.
Atekwana, E.A., Sauck, W.A., Werkema Jr, D.D, 2000. Investigations of geoelectrical signatures at a hydrocarbon contaminated site. J. Appl. Geophys. 44 (2-3), 167–180.
Bertermann, David, et al., 2013. ThermoMap—an open-source web mapping application for illustrating the very shallow geothermal potential in Europe and selected case study areas. European Geothermal Congress, Pisa.
Besser, Houda, et al., 2018. Groundwater mixing and geochemical assessment of low-enthalpy resources in the geothermal field of southwestern Tunisia. Euro-Mediterranean J. Environ. Integr. 3.1, 16.
Bibby, H.M., Dawson, G.B., Rayner, H.H., Bennie, S.L., Bromley, C.J., 1992. Electrical resistivity and magnetic investigations of the geothermal systems in the Rotorua area, New Zealand. Geothermics 21 (1-2), 43–64.
Bibby, H.M., et al., 2005. Misinterpretation of electrical resistivity data in geothermal prospecting: a case study from the Taupo Volcanic Zone. In: Geological and nuclear sciences: Proceedings. World Geothermal Congress, Antalya, Turkey.
Bláquez, C.S., Nieto, I.M., Mora, R., Martín, A.F., González-Aguilera, D., 2020. GES-CAL: A new computer program for the design of closed-loop geothermal energy systems. Geothermics 87, 101852.
Blázquez, Sáez, Cristina, et al., 2017. Efficiency analysis of the main components of a vertical closed-loop system in a borehole heat exchanger. Energies 10.2, 201.
Blázquez, Cristina Sáez, et al., 2016. Analysis of the process of design of a geothermal installation. Renew. Energy 89, 188–199.
Blázquez, Cristina Sáez, et al., 2017. Thermal conductivity map of the Avila region (Spain) based on thermal conductivity measurements of different rock and soil samples. Geothermics 65, 60–71.
Blázquez, Cristina Sáez, et al., 2020. Analysis and optimization of the design parameters of a district groundwater heat pump system in Turin, Italy. Renew. Energy 149, 374–383.
Blum, Philipp, Campillo, Gisela, Kölbel, Thomas, 2011. Techno-economic and spatial analysis of vertical ground source heat pump systems in Germany. Energy 36.5, 3002–3011.
Carrier, Aurore, et al., 2018. Deep-reaching electrical resistivity tomography (ERT) methods for middle-enthalpy geothermal prospection in the Geneva Basin, Switzerland. In: EGU General Assembly Conference Abstracts, p. 20.
Chabaane, Achref, Redhaounia, Belgacem, Gabtni, Hakim, 2017. Combined application of vertical electrical sounding and 2D electrical resistivity imaging for geothermal groundwater characterization: Hammam Sayala hot spring case study (NW Tunisia). J. Afr. Earth Sci. 134, 292–298.
Chabaane, Achref, Redhaounia, Belgacem, Gabtni, Hakim, 2017. Combined application of vertical electrical sounding and 2D electrical resistivity imaging for geothermal groundwater characterization: Hammam Sayala hot spring case study (NW Tunisia). J. Afr. Earth Sci. 134, 292–298.
Chambefort, Isabelle, et al., 2016. Ngatamariki geothermal field, New Zealand: geology, geophysics, chemistry and conceptual model. Geothermics 59, 266–280.

Chambers, J.E., Wilkinson, P.B., Wealthall, G.P., Loke, M.H., Dearden, R., Wilson, R., Ogilvy, R.D., 2010. Hydrogeophysical imaging of deposit heterogeneity and groundwater chemistry changes during DNAPL source zone bioremediation. J. Contam. Hydrol. 118 (1-2), 43–61.

CHEN, C.X., YAN, J.Y., ZHOU, W.Y., WANG, Z.H., ZHANG, D.L., 2020. Status and prospects of geophysical method used in geothermal exploration. Progr. Geophys. 35 (4), 1223–1231.

Comeau, M. J. (2015). Electrical resistivity structure of the Altiplano-Puna magma body and volcan uturuncu from magnetotelluric data.

Fadillah, Taruna, et al. "The resistivity structure of aluvial in geothermal prospect using time domain electromagnetic methode (TDEM) Survey." Proceedings World Geothermal Congress 2015 Melbourne, Australia, (2015), 19-25.

Firmbach, Linda, et al., 2013. Experimental heat flow propagation within porous media using electrical resistivity tomography x (ERT). In: Proceedings of the European Geothermal Congress.

Fornós, Joan J., Gelabert, Bernadí, 2011. Condicionants litològics i estructurals del carst a les illes Balears. Endins: publicació d'espeleologia, pp. 37–52.

Fornós, Joan J., et al., 2014. Cave deposits and sedimentary processes in Cova des Pas de Vallgornera (Mallorca, Western Mediterranean). Int. J. Speleol. 43.2, 5.

Gélis, C., Revil, A., Cushing, M.E., Jougnot, D., Lemeille, F., Cabrera, J., Rocher, M., 2010. Potential of electrical resistivity tomography to detect fault zones in limestone and argillaceous formations in the experimental platform of Tournemire, France. Pure Appl. Geophys. 167 (11), 1405–1418.

Gómez-Ortiz, David, et al., 2017. Identification of shallow geothermal anomalies in the Timanfaya National Park (Lanzarote, Canary Islands) through combined geophysical prospecting techniques. In: EGU General Assembly Conference Abstracts, p. 19.

García-Gil, Alejandro, et al., 2015. GIS-supported mapping of low-temperature geothermal potential taking groundwater flow into account. Renew. Energy 77, 268–278.

Ginés, J., et al. Mallorca: a Mediterranean benchmark for Quaternary studies. Ed. Ángel Ginés. Societat d'Història Natural de les Balears, (2012).

Hermans, T., Vandenbohede, A., Lebbe, L., Nguyen, F., 2012. A shallow geothermal experiment in a sandy aquifer monitored using electric resistivity tomography. Geophysics 77 (1), B11–B21.

IGME, Instituto Geológico y Minero de España, Mapa Geológico de España, escala 1: 50.000, 2a serie (Magna) hoja 672 (Artà).

Kumar, Dewashish, Thiagarajan, S., Rai, S.N., 2011. Deciphering geothermal resources in Deccan Trap region using electrical resistivity tomography technique. J. Geol. Soc. India 78.6, 541–548.

Loke, M.H., Barker, R.D., 1996. Practical techniques for 3D resistivity surveys and data inversion1. Geophys. Prospect. 44 (3), 499–523.

Lund, John W., Boyd, Tonya L., 2016. Direct utilization of geothermal energy 2015 worldwide review. Geothermics 60, 66–93.

MAHMUT, G.DRAHOR, MERIÇ, A.BERGE, ÖZDE, BAKAK, ÖZTÜRK, CANER, 2011. An example of electrical resistivity tomography monitoring in geothermal sites: Balçova-Izmir Case Study. Berichte Geol. 93. B.-A.ISSN 1017-8880 – Applications in Geothermal Monitoring.

Minissale, Angelo A., 2018. A simple geochemical prospecting method for geothermal resources in flat areas. Geothermics 72, 258–267.

Nguyen, F., Kemna, A., Antonsson, A., Engesgaard, P., Kuras, O., Ogilvy, R., Pulido-Bosch, A., 2009. Characterization of seawater intrusion using 2D electrical imaging. Near Surf. Geophys. 7 (5–6), 377–390.

Nieto, I.M., Martín, A.F., Blázquez, C.S., Aguilera, D.G., García, P.C., Vasco, E.F., García, J.C., 2019. Use of 3D electrical resistivity tomography to improve the design of low enthalpy geothermal systems. Geothermics 79, 1–13.

Noorollahi, Younes, Arjenaki, Hamidreza Gholami, Ghasempour, Roghayeh, 2017. Thermo-economic modeling and GIS-based spatial data analysis of ground source heat pump systems for regional shallow geothermal mapping. Renew. Sustain. Energy Rev. 72, 648–660.

Omer, Abdeen Mustafa, 2008. Ground-source heat pumps systems and applications. Renew. Sustain. Energy Rev. 12.2, 344–371.

Ondreka, Joris, et al., 2007. GIS-supported mapping of shallow geothermal potential of representative areas in south-western Germany—possibilities and limitations. Renew. Energy 32.13, 2186–2200.

Rajesh, R., Tiwari, R.K., 2018. FORTRAN code to convert resistivity Vertical Electrical Sounding data to RES2DINV format. Editorial Off. 22 (3), 359–363.

Robertson, E.C., 1988. U. S. Geological Survey Open-File Report, p. 97.

Sáez Blázquez, C., Carrasco García, P., Nieto, I.M., Maté-González, M.Á., Martín, A.F., González-Aguilera, D., 2020. Characterizing geological heterogeneities for geothermal purposes through combined geophysical prospecting methods. Remote Sens. 12 (12), 1948.

Sanchez-Guzman, Jose, Noceda-Marquez, Celestino Garcia de la, 2005. Geothermal energy development in Spain - country update report. In: Proceedings World Geothermal Congress.

Song, Xianzhi, et al., 2018. Numerical simulation of heat extraction performance in enhanced geothermal system with multilateral wells. Appl. Energy 218, 325–337.

Sumner, G., Ramis, C., Guijarro, J.A., 1995. Daily rainfall domains in Mallorca. Theor. Appl. Climatol. 51.4, 199–221.

UNE-EN ISO 52016-1:2017, Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads - Part 1: Calculation procedures (ISO 52016-1:2017) (Endorsed by Asociación Española de Normalización in December of 2017.).

Woźniak, T., Bania, G., Mościcki, W.J., Ćwiklik, M., 2018. Electrical resistivity tomography (ERT) and sedimentological analysis applied to investigation of Upper Jurassic limestones from the Krzeszowice Graben (Kraków Upland, southern Poland). Geol. Q. 62 (2), 287–302.

Yang, H., Cui, P., Fang, Z., 2010. Vertical-borehole ground-coupled heat pumps: a review of models and systems. Appl. Energy 87.1, 16–27.

Yao, Jun, et al., 2018. Numerical simulation of the heat extraction in 3D-EGS with thermal-hydraulic-mechanical coupling method based on discrete fractures model. Geothermics 74, 19–34.

Yasir, S.F., Jani, J., Mukri, M., 2019. A dataset of visualization methods to assessing soil profile using RES2DINV and VOXLER software. Data Brief 24, 103821.